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VACUUM DIFFUSION WELDING OF γ-TiAl INTERMETALLIC WITH HIGH-TEMPERATURE NICKEL ALLOY WITH APPLICATION OF INTERMEDIATE Al/Ni NANOLAYERS

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Effect of structural characteristics and chemical composition of nanolayered interlayers based on Al–Ni system on formation of joints of γ-TiAl-based alloy and high-temperature nickel alloy in vacuum diffusion welding was studied. It is shown that application of nanolayered clad interlayers ensures formation of a diffusion zone with monotonic change of the content of components, where the phase composition and micromechanical characteristics are determined by the interlayer chemical composition, as well as lowers the probability of brittle phase appearance in the butt joint. 18 Ref., 6 Tables, 7 Figures.

Keywords: *vacuum diffusion welding, intermetallics, nanolayered interlayers*

Titanium aluminides are a promising materials for manufacturing parts of aircraft engines, sheathing and honeycomb structures of supersonic flying vehicles [1]. Casing seals, air filters, nozzle parts, compressor blades, combustion chamber structure elements, car engine valves, etc. are manufactured from cast titanium aluminides [2].

With progress of aerospace technologies and development of new structural high-temperature alloys, the need arises for joining pairs of dissimilar materials, for instance, γ-TiAl intermetallic alloys and nickel-based high-temperature alloys. Combination of dissimilar high-temperature materials in the structure widens the possibilities of its functional application.

The currently available technologies of fusion welding of these materials do not allow obtaining high-quality welded joints, because of liquation phenomena, structural and phase transformations in the weld metal and HAZ, that leads to hot cracking in the joint [3, 4]. Vacuum diffusion welding (VDW) is the most promising method of joining γ-TiAl-based alloys to nickel-based high-temperature alloys [5–7]. However, with this welding method, joint formation is accompanied by appearance of a diffusion zone of a complex phase composition, including brittle phases, which can have a negative effect on the joint mechanical properties. On the other hand, such low ductility of γ-TiAl makes it more difficult to establish physical contact in VDW. Ductile interlayers are usually used for activation of the surfaces being joined in diffusion welding of dissimilar materials and intensification of diffusion processes [8]. However, application of interlayers, produced by rolling and having 50–300 μm thickness, leads to formation of a diffusion zone with chemical composition and mechanical properties, markedly different from those of the materials being welded [9]. At application of such an approach, preliminary hydrogenation of the interlayers is used for intensification of diffusion processes in the joint zone. However, to prevent hydrogen evolution at the heating stage, welding is performed with application of high-intensity heat sources, capable of ensuring the rate of temperature rise of up to 1200 °C/min [6].

In order to activate the diffusion processes at formation of the joint, it is promising to apply coatings or intermediate foils with nano- and submicrocrystalline structure, characterized by superplasticity that allows localizing plastic deformation of the surfaces being welded directly in the butt. So, the authors of [6] conducted laser modification of titanium aluminide surface that in combination with deposition of TiAl layer on the nickel alloy surface ensured producing a sound joint. The authors of [7, 10, 11] showed that application of nanolayered interlayers in the form of foil or coatings in VDW of dissimilar and difficult-to-deform materials, allows activation of the surfaces being welded, increasing the intensity of the diffusion processes and reducing the thermomechanical impact on the materials being welded. From this viewpoint, it is promising to apply an interlayer in the form of nanolayered reactive foil, produced by EBPVD method, which is characterized by intensive running of phase transformations and low-temperature plastic deformation at thermomechanical loading [12, 13]. Selection of chemical composition and structural characteristics of the interlayer is determined by chemical composition of the materials being welded and product operating temperature.

Table 1. Alloy chemical composition

Alloy	Chemical composition, wt.%							
	Al	Si	Ti	Cr	Mn	Fe	Ni	Nb
Ni-alloy EI437B	0.92	0.46	2.65	21.01	0.25	0.83	73.88	–
γ-TiAl alloy	32.65	–	59.24	3.9	–	–	–	4.21

The objective of this work is studying the features of formation of joints of γ-TiAl-based alloy and high-temperature nickel alloy with chromium content > 20 wt.% and with volume fraction of γ′-phase < 10 vol.% by VDW method through nanolayered interlayers.

Experimental procedure. Chemical composition of γ-TiAl-based alloy and high-temperature nickel alloy is given in Table 1.

γ-TiAl-based alloy was produced by the method of electron beam remelting with subsequent isostatic pressing under pressure of 120–150 MPa at the temperature of 1260 °C for 4 h that ensured heating of casting defects. The produced material was subjected to homogenizing annealing at 1100 °C for 6–8 h, low-speed rolling at the temperature of 1200 °C and homogenizing heat treatment at 1100 °C for 6–8 h. Produced alloy based on γ-TiAl intermetallic is characterized by lamellar two-phase structure of γ/α_2.

High-temperature nickel alloy with < 10 vol.% volume fraction of γ′-phase belongs to the group of satisfactorily weldable alloys and is characterized by high heat resistance, low heat conductivity, high susceptibility to mechanical hardening (work hardening) during mechanical treatment [14].

Sample preparation for welding consisted in their cutting in electroerosion machine, surface grinding and degreasing. Samples were butt welded in U-394M unit. Diffusion welding of γ-TiAl intermetallic alloy with high-temperature nickel alloy was conducted in vacuum V_w = 1.33.10^{-3} Pa at temperature T_w = 1050 °C, pressure P_w = 20 MPa, and welding time t_w = 20 min.

Interlayers based on Al–Ni system in the form of nanolayered foil with uniform distribution of components and clad by metal layers 20–35 μm thick, with layer alternation period of 60–200 nm (Figure 1, *a*, *b*),

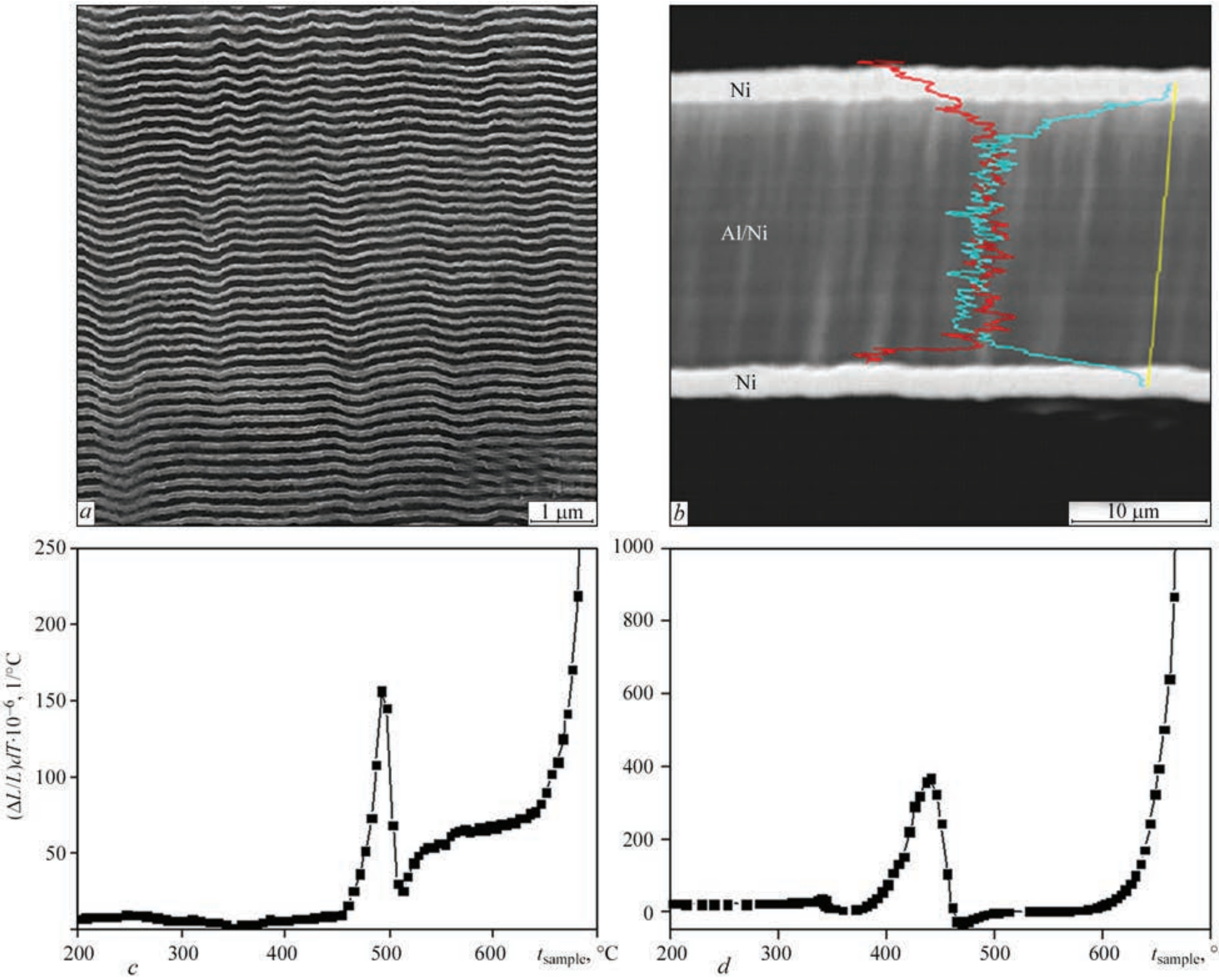

Figure 1. Microstructure and strain rate at heating under uniaxial tension of nanolayered foil with uniform distribution of the components (*a*, *b*) and of clad foil (*b*, *d*), respectively

Table 2. Interlayer characteristics

Interlayer	Chemical composition of Al/Ni reactive interlayer, wt.%		Thickness of reactive and cladding interlayers, μm		
	Al	Ni	Reactive interlayer	Cu	Ni
Al/Ni (AlNi)	34.82	65.18	30	–	–
Al/Ni ($AlNi_3$)	13.32	86.68	34	–	–
Ni–Al/Ni–Ni	32.56	67.44	17	–	3+3
Cu–Al/Ni–Ni	12.03	87.97	22	2	1

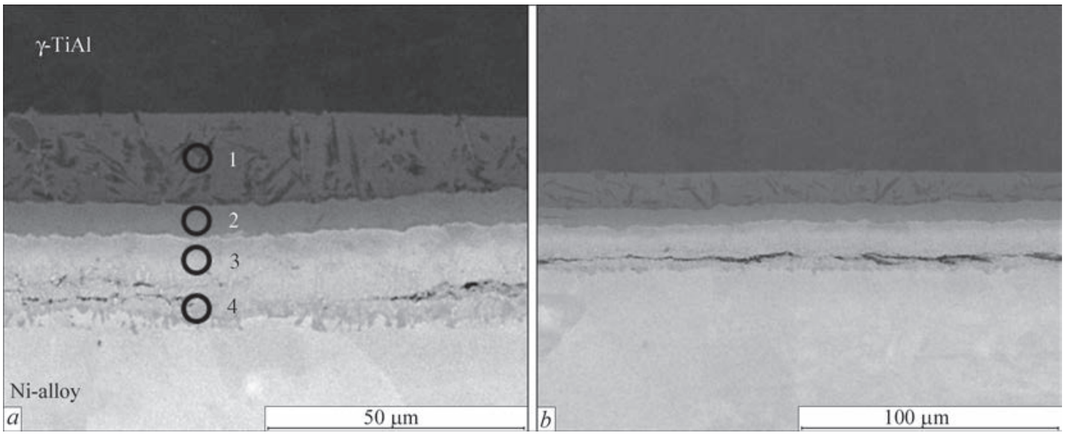

Figure 2. Microstructure of the joint of γ-TiAl — nickel alloy, produced by diffusion welding without an interlayer (*1–4* —analysis region)

were produced by the method of layer-by-layer electron beam deposition of vapour phases of aluminium and nickel, described in detail in [15]. Structure and chemical composition of interlayers are shown in Table 2. At heating of multilayer foil under the conditions of uniaxial tension, it undergoes low-temperature intensive plastic deformation, similar to superplastic deformation, that is due to phase and structural transformations, occurring in it at heating [13] (Figure 1, *c*, *d*).

Analysis of microstructure of welded joints and nanolayered foils was conducted using scanning electron microscope CamScan-4, fitted with a system of energy-dispersive analysis EDX INCA 200 for determination of chemical composition of material on flat samples. Samples for investigations in the form of transverse sections of the foils and welded joints were prepared by a standard procedure, using grinding-polishing equipment of Struers Company.

Evaluation of microhardness and coefficient of ductility of welded joints was performed by determination of micromechanical characteristics in Micron-gamma unit by the method of automatic indentation, using Berkovich diamond pyramid ($\alpha = 65°$) at 0.4 N load [16].

Table 3. Chemical composition of sections in the joint zone, shown in Figure 2, *a*

Analysis region	Chemical composition of analysis zones, wt.%						Phase
	Al	Ti	Cr	Fe	Ni	Nb	
1	22.92	65.48	4.3	–	3.78	3.52	–
2	24.45	39.41	4.4	0.48	28.15	3.11	τ_3
3	12.77	13.36	7.06	–	66.8	–	τ_4
4	7.7	5.83	35.66	–	50.82	–	–

Investigation results. *Welding of* γ-TiAl *intermetallic alloy with high-temperature nickel alloy.* In VDW of titanium aluminide with EI437B alloy without interlayers the joint forms a diffusion zone approximately 35 μm thick, made up by intermetallic layers based on Ti–Ni–Al system of different composition (Figure 2, Table 3), predominantly consisting of τ_3-Al_3NiTi_2 and τ_4-$AlNi_2Ti$ phases [17]. Formation of intermetallic layers leads to an increase of diffusion zone microhardness up to 14 GPa.

Formation of intermetallics with mechanical characteristics, markedly different from those of the alloys being welded, is due to stresses arising in the joint, leading to cracking at cooling (Figure 2) in the zones, adjacent to the nickel alloy, in which chromium diffusion results in formation of $CrNi_2$ brittle phase (Figure 2, *b*).

It can be assumed that the ductile nanolayered interlayer will not only ensure physical contact of the surfaces being welded, but will also have an effect on the nature of diffusion processes in the joint and formation of the diffusion zone phase composition. In order to assess such an effect, we studied the role of nanolayered interlayers based on Al–Ni system, having chemical composition, corresponding to the stoichiometry of AlNi and $AlNi_3$ intermetallics and of clad interlayers on their base, namely Ni–Al/Ni(AlNi)–Ni, Cu–Al/Ni($AlNi_3$)–Ni in formation of γ-TiAl joints with the high-temperature nickel alloy.

Table 4. Chemical composition of sections in the joint zone, shown in Figure 4, *a*

Analysis region	Chemical composition of joint zones, wt.%					Phase
	Al	Ti	Cr	Ni	Nb	
1	22.94	59.72	1.76	11.62	3.97	–
2	13.69	24.27	–	60.64	1.4	τ_4
3	12.25	5.59	–	82.16	–	–
4	12.83	0.31	1.35	85.51	–	–

Investigation of the effect of Al/Ni interlayer on formation of the joint of intermetallic γ-TiAl alloy and nickel alloy.

1. Interlayer of AlNi composition.

Use of nanolayered foil of AlNi composition as an interlayer does not lead to joint formation (Figure 3), that, apparently, is the consequence of high reactivity of the foil and formation of a brittle intermetallic layer based on AlNi compound in the joint, the presence of which promotes cracking in the butt joint at cooling.

2. Interlayer of $AlNi_3$ composition.

Diffusion welding of γ-TiAl alloys and high-temperature nickel alloy was conducted using nanolayered foil of Al–Ni system as an interlayer, the composition of which corresponds to $AlNi_3$ intermetallics. As one can see from analysis of the joint microstructure (Figure 4, *a*), use of such an interlayer ensures activation of interdiffusion of the components of foil and alloys with formation of a sound joint. Considering the fact that the reactivity of nanolayered foil of $AlNi_3$ composition is by an order of magnitude lower [18] than of that of AlNi composition, it can be assumed that the nature of phase transformations at nanolayered interlayer heating has an effect on the diffusion processes in the joint. Interdiffusion of the components results in formation of a diffusion zone approximately 50 μm wide with a monotonic change of the component concentration in it (Figure 4, *b*, Table 4). Reaction diffusion of the alloys and interlayer components from the side of γ-TiAl results in formation of a ternary intermetallic phase τ_4 in the joint, leading to increase of the material microhardness in the butt joint area (Figure 4, *c*).

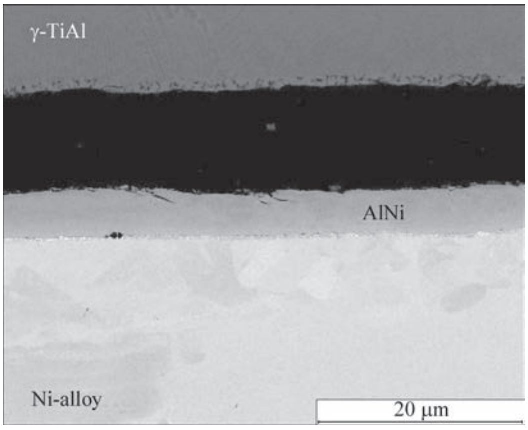

Figure 3. Microstructure of the joint of γ-TiAl — nickel alloy, produced using AlNi interlayer

Effect of the clad interlayer based on Al-Ni system on formation of the joint of intermetallic alloy γ-TiAl and nickel alloy.

1. Ni–Al/Ni–Ni interlayer.

Absence of the joint formation when using an interlayer of the composition, corresponding to AlNi stoichiometry, gave grounds to assume that the presence of cladding interlayers of nickel on the nanolayered foil surfaces allows improving the physical contact of the surfaces being welded due to chemical affinity of nickel interlayers to γ-TiAl and nickel alloy [12].

Diffusion welding of γ-TiAl and nickel alloy was conducted through a clad Ni–Al/Ni–Ni interlayer, which consists of nanolayered foil of Al–Ni composition, corresponding to AlNi stoichiometry, and nickel cladding layers (Table 2). As shown by metallographic studies of welded joints, the butt joint does not have any pores or cracks (Figure 5).

Application of clad nanolayered foil in welding provides joint formation and promotes activation of

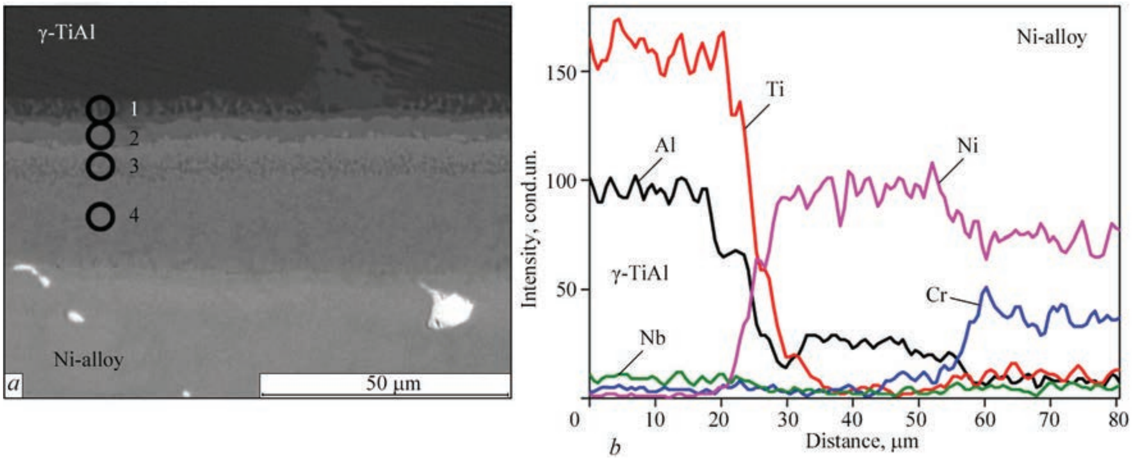

Figure 4. Microstructure (*a*) and component distribution (*b*) in the joint of γ-TiAl — nickel alloy produced using a nanolayered interlayer of $AlNi_3$ composition

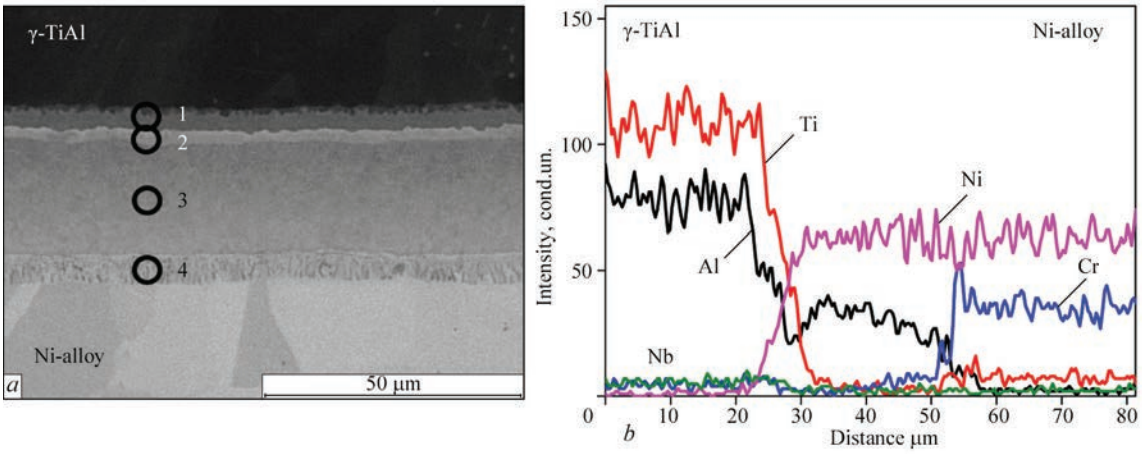

Figure 5. Microstructure (*a*) and component distribution (*b*) in the joint of γ-TiAl — nickel alloy, produced using clad Ni/Al–Ni/Ni interlayer

Table 5. Chemical composition of sections in the joint zone, shown in Figure 5, *a*

Analysis region	Chemical composition of the joint zones, wt.%				
	Al	Ti	Cr	Ni	Nb
1	24.94	40.39	3.52	28.05	3.11
2	13.77	24.07	0.40	60.67	1.10
3	21.78	0.75	1.06	76.41	–
4	6.20	3.01	24.56	66.23	–

the diffusion processes in the interlayer. Interdiffusion of the alloy and foil components leads to formation in the butt of a diffusion zone 45 μm wide with a monotonic change of component concentration (Figure 5, *b*) and laminated structure. Layers of intermetallic phases based on Ti–Ni–Al with different component ratios form from γ-TiAl side (Table 5). Presence of nickel layers on the intermediate foil surface, on the one hand, promotes reduction of chromium diffusion from the nickel alloy, that is indicated by a low chromium content in the diffusion zone, and on the other hand, ensures formation of an intermetallic enriched in nickel (Al_3Ni_5) in the central part of the diffusion zone (Table 5, analysis region 3), that promotes lowering of material microhardness to 6.8 GPa.

2. Cu–Al/Ni–Ni interlayer.

Diffusion welding of γ-TiAl and nickel alloy was conducted through a clad Cu–Al/Ni–Ni interlayer, consisting of nanolayered foil of Al–Ni system, corresponding to stoichiometry of $AlNi_3$ and cladding layers of copper and nickel (Table 2). The interlayer was placed so that the copper layer contacted γ-TiAl, and the nickel layer was in contact with the nickel alloy. Such a placement of the interlayer is predetermined by the chemical affinity of the components of the cladding layers and the alloys.

The joint microstructure is shown in Figure 6, *a*. Diffusion mixing of the alloy components ensures formation of the diffusion zone, consisting of layers with different phase composition (Figure 6, *b*, Table 6), where copper is concentrated in the area close to titanium intermetallic, that is the consequence of chemical affinity of titanium and copper and, probably, formation of a low-temperature eutectic component, that improves the physical contact of the surfaces being welded.

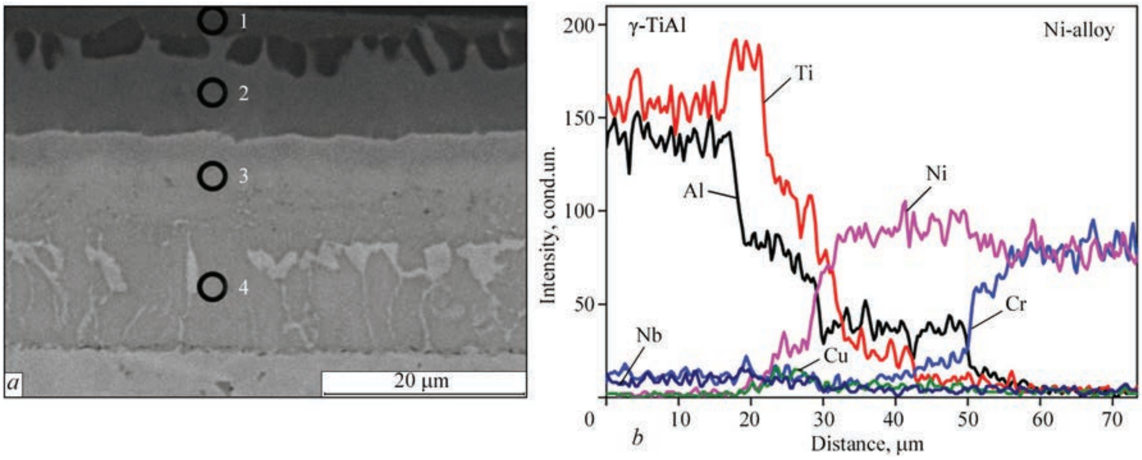

Figure 6. Microstructure (*a*) and component distribution (*b*) in the joint of γ-TiAl — nickel alloy, produced with application of clad Cu/Al–Ni/Ni interlayer

Table 6. Chemical composition of sections in the joint zone shown in Figure 6, *a*

Analysis region	Chemical composition of the joint zones, shown in Figure 6, *a*						
	Al	Ti	Cr	Fe	Ni	Cu	Nb
1	22.74	62.65	6.24	–	1.63	3.07	3.66
2	25.38	39.19	4.70	–	16.48	11.32	2.94
3	15.34	10.45	2.37	0.92	67.40	3.51	–
4	16.14	4.69	4.92	1.96	72.30	–	–

Figure 7 gives the values of microhardness and coefficient of ductility of the alloys being welded and the diffusion zone of the joints, produced by VDW without an interlayer and with a clad interlayer of different composition. One can see that application of a clad nanolayered interlayer allows lowering the material microhardness in the diffusion zone more than two times, compared to the joints produced without an interlayer at preservation of the coefficient of ductility on the level of that of the base materials.

Conclusions

1. Defects in the form of extended cracking sections appear in the joint from the nickel alloy side in diffusion welding of γ-TiAl alloy and high-temperature nickel alloy, that is the consequence of formation of brittle intermetallic phases with high microhardness (up to 14 GPa) and of $CrNi_2$ phase.

2. Application of a clad nanolayered interlayer based on Al–Ni system in diffusion welding of γ-AlNi alloy with the high-temperature alloy ensures producing sound joints due to formation of a diffusion zone with the monotonic nature of component distribution and lowering of its microhardness.

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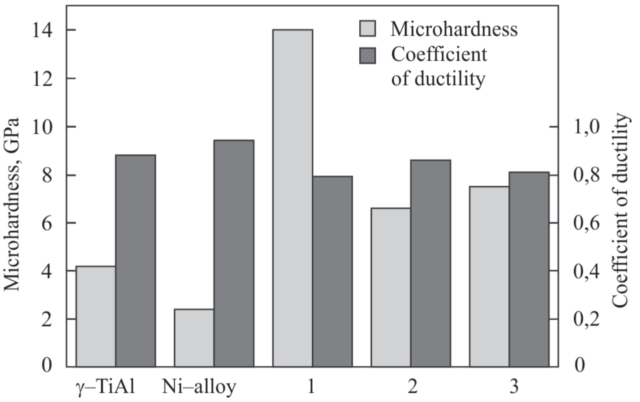

Figure 7. Microhardness and coefficient of ductility of γ-TiAl based alloy and nickel alloy, as well as their joints, produced by diffusion welding without the interlayer (1), with Ni–Al/Ni–Ni (2) and Cu–Al/Ni–Ni (3) interlayers

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