DIFFUSION BONDING OF γ-TiAl BASE ALLOY IN VACUUM BY USING NANOLAYERED INTERLAYERS

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The effect of nanolayered interlayers Ti/Al, Ni/Ti and Ni/Al on structure of the diffusion bonds made in vacuum on γ-TiAl base alloy was studied. It is shown that when using the nanolayered interlayers of a composition differing from that of the base alloy it is necessary to conduct homogenising annealing to lower the degree of chemical heterogeneity in the bonding zone.

Keywords: *diffusion bonding in vacuum, intermetallic titanium-aluminium alloy based on γ-TiAl, nanolayered interlayer, homogenising annealing, joint, heterogeneity, structure, microhardness*

Titanium aluminides and alloys on their base belong to a new class of light heat-resistant materials, which are intended for operation at a temperature of 700–1100 °C, that is much higher than the service temperature of modern titanium superalloys ($T \leq 600$ °C). The interest in titanium aluminides is caused by their high potential for application in aerospace engineering instead of titanium and nickel superalloys.

Studies [1, 2] investigated joinability of titanium aluminides (Ti–45 at.% Cr–2 at.% Nb) when using the Ti–Al system nanolayered interlayers of the Ti–(48–50) at.% Al composition, which were deposited on the mating surfaces by magnetron sputtering. Thickness of the interlayers was 2.0–2.5 μm, thickness of the individual layers being 4 nm. The TiAl nanocrystals with a higher hardness than that of the base metal form in the interlayers during deposition of a film. The authors of the above studies consider the following parameters of the process to be the optimal ones: bonding temperature $T_{\rm bond} = 1000$ °C, pressure $P = 50$ MPa, and bonding time $t_{\rm bond} = 1$ h.

It is shown in study [3] that the optimal parameters for diffusion bonding of γ-TiAl alloys through the nanolayered interlayer Ti/Al produced by vacuum deposition are as follows: $T_{\rm bond} = 1200$ °C, $P = 10$ MPa, and $t_{\rm bond} = 20$ min. With these parameters the bonding zone is free from pores and cracks.

No investigation results on the possibility of using other compositions of nanolayered interlayers are available in the literature.

The purpose of this study was to investigate peculiarities of formation of permanent bonds on the γ-TiAl base alloy by using nanolayered interlayers of the Ti/Al, Ni/Ti and Ni/Al systems in the form of foils 15–30 μm thick, produced by electron beam evaporation and vapour-phase deposition in vacuum [4, 5]. The foils consist of alternating nanolayers of the components, in which solid-phase reactions of synthesis of intermetallics take place during heating.

The following interlayers were chosen for bonding of samples of alloy Ti–48 at.% Al–2 at.% Nb–2 at.% Mn: Ti/Al (Ti–38 at.% Al), Ni/Ti (Ti–44 at.% Ni) and Ni/Al (Al–46 at.% Ni).

Diffusion bonding of the 10 × 10 × 6 mm samples of intermetallic Ti–48 at.% Al–2 at.% Nb–2 at.% Mn (below referred to as γ-TiAl) was performed by using unit U-394. The electron beam heater was employed as a heat source. The mating surfaces were preliminarily prepared by removing the cold worked layer with a diamond wheel, and then by degreasing. Bonding was carried out under the following conditions: heating temperature $T_{\rm h} = 1200$ °C, heating time $t_{\rm h} =$ $= 20$ min, $P = 20$ MPa, and vacuum in the working chamber at a level of $1.33 \cdot 10^{-3}$ MPa.

Microstructure and chemical composition of the base metal and bonds were analysed by using optical microscope «Neophot-32», as well as scanning microscope «CamScan» equipped with energy-dispersive system «Energy 200» for local analysis. Phase composition was evaluated by the X-ray diffraction analysis method using diffractometer DRON-3 in Cu_{K_α} radiation. Microhardness of the samples was measured with meter PMT-3 under a load of 0.1–0.5 N.

Results of X-ray diffraction phase analysis show that the γ-TiAl alloy in the initial state contains two phases — TiAl (γ-phase) and $\mathrm{Ti_3Al}$ (α_2-phase). The volume content of the α_2-phase in the alloy, with respect to the γ-phase, is 7 %. A fragment of the diffraction pattern of the γ-TiAl alloy is shown in Figure 1.

As revealed by metallography, the alloy in the initial state has a fully lamellar structure. The alloy consists of homogeneous, practically equiaxed grains approximately 60–120 μm in size, having the γ- and α_2-phase lamellae of a certain orientation inside them (Figure 2).

It is noted in study [6] that normally the α_2-phase is present in the lamellar structure in the form of thin

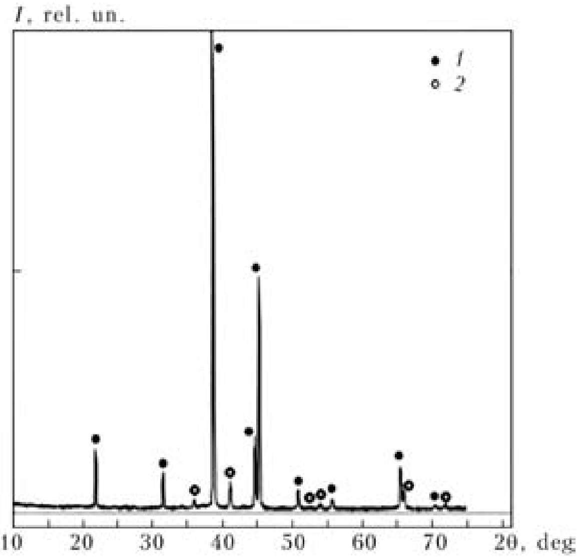

Figure 1. Fragment of diffraction pattern of γ-TiAl alloy in the initial state: *1* — TiAl phase; *2* — Ti_3Al phase; *I* — radiation intensity; 2θ — diffraction angle

plates at the twin boundaries of the γ-phase, which may inhibit its growth. Moreover, dispersed dark inclusions of a different shape form in the alloy at the background of the lamellar structure. These inclusions are uniformly distributed in the bulk of the matrix and have the increased niobium content. The alloy comprises isolated micropores. No coarse pores and cracks were detected. Microhardness of the alloy in the initial state was *HV* 3000–4000 MPa.

Earlier the authors of study [3] conducted metallographic examinations of the bond on the γ-TiAl alloy produced by diffusion bonding in vacuum without an interlayer. As seen in Figure 3, *a*, structure of the transition zone has a clearly defined interface, and no common grains form within the bonding zone. The presence of an interlayer of intermetallic Ti_3Al was revealed at the interface in microstructure of the alloy at high magnifications in the phase contrast mode (Figure 3, *b*).

Bonding through interlayers Ti/Al. Microstructures of the bond made through the nanolayered interlayer Ti/Al are shown in Figure 4, *b*, *c*. Here the points where microhardness and local chemical composition were investigated are designated by numerals.

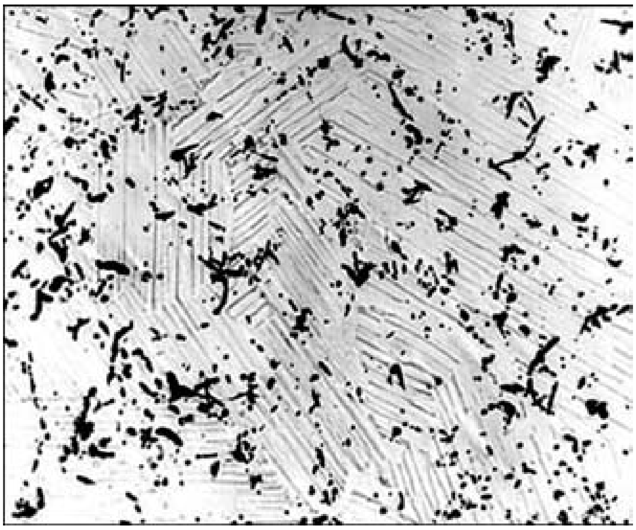

Figure 2. Microstructure (×400) of γ-TiAl alloy in the initial state

The metallography results showed that the bonds were free from defects in the form of pores, oxide inclusions and cracks. A homogeneous transition zone about 20 μm thick formed in the bond (Figure 4, *a*). According to the data of local chemical analysis, this zone had a composition of 49.26 at.% Al–50.07 at.% Ti–0.67 at.% Mn, which is close to the composition of the main intermetallic phase γ-TiAl. When using the Ti/Al interlayer, fine equiaxed grains growing into the base metal formed within the bonding zone (see Figure 4, *b*). However, this did not deteriorate strength properties of the bond. Microhardness of the bonding zone was *HV* 3500–4200 MPa, and that of the base metal was *HV* 3000–4000 MPa.

To understand the role of nanolayered foils in formation of the bonds and investigate the intensity of the diffusion processes occurring in the bonds, we performed bonding by using radioactive isotopes preliminarily deposited on titanium aluminide. It was established [7] that application of the nanolayered interlayers Ti/Al for diffusion bonding in vacuum considerably increased mobility of atoms ^{63}Ni within the bonding zone. In bonding through the nanolayered interlayer the diffusion zone grew approximately 4 times in size, compared to bonding without the interlayer. The calculated value of the effective diffusion coefficient in bonding without the interlayer is about

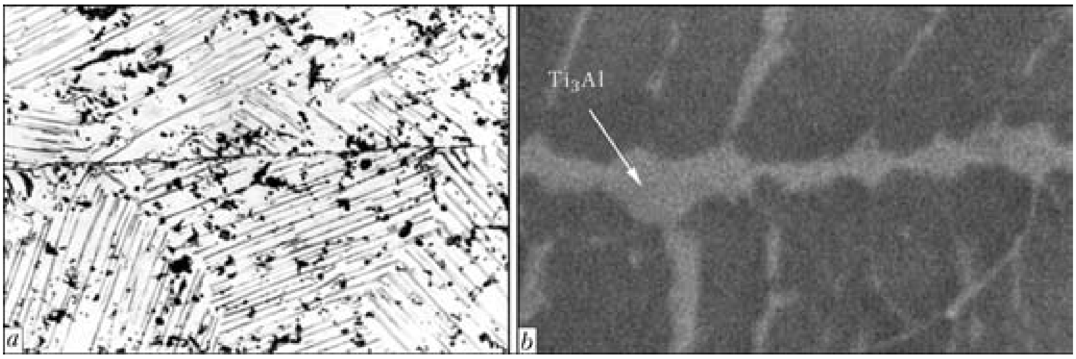

Figure 3. Microstructures of the bonding zone on γ-TiAl alloy in bonding without an interlayer, obtained by optical (*a* — ×500) and scanning electron microscopy (SEM) in phase contrast mode (*b* — ×3000)

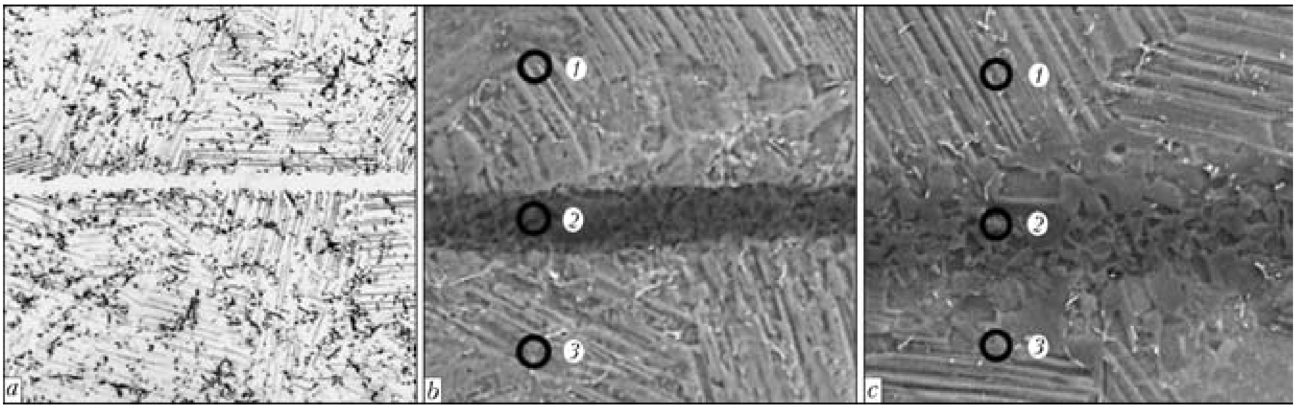

Figure 4. Microstructures of the bonding zone on γ-TiAl alloy in bonding through nanolayered interlayer Ti/Al, obtained by optical microscopy (*a* — ×200), SEM (*b* — ×300) and SEM after bonding and homogenising annealing at 1200 °C for 2 h (*c* — ×300)

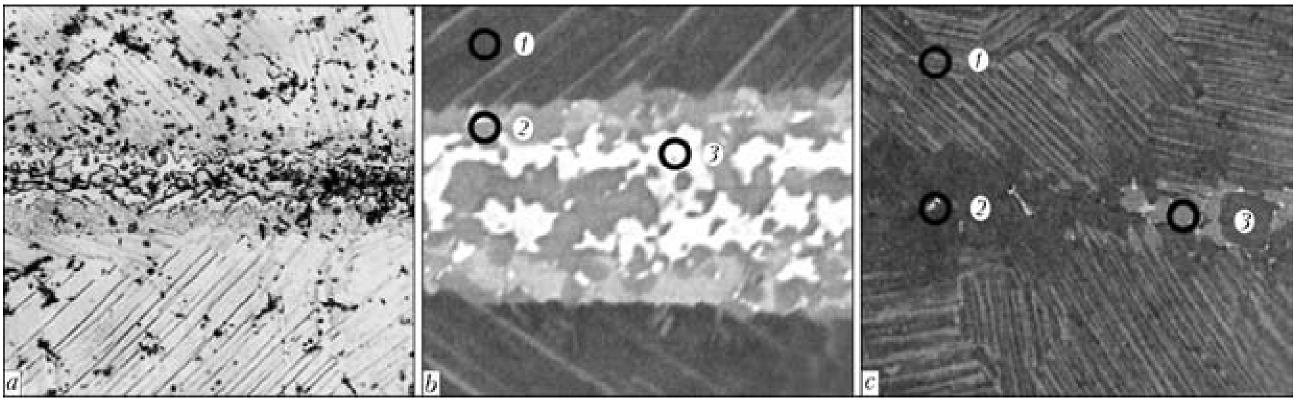

Figure 5. Microstructures of the bonding zone in bonding through nanolayered interlayer Ni/Ti, obtained by optical microscopy (*a* — ×400), SEM (*b* — ×1000) and SEM after bonding and homogenising annealing at 1200 °C for 2 h (*c* — ×200)

$1\cdot10^{-7}$, and with the interlayer — about $1\cdot10^{-5}$ cm^2/s. Therefore, when using the nanolayered interlayer the mobility of atoms ^{63}Ni increases almost by two orders of magnitude.

Activation of the diffusion processes is evidenced by the presence of manganese in the bonding zone (Table 1). Unlike manganese, niobium does not transfer from the base metal into the interlayer during bonding. As heterogeneity of structure and chemical composition of the bond is probably related to an insufficiently long thermal effect during bonding, the resulting samples were subjected to homogenising annealing in vacuum for 2 h at a temperature of 1200 °C in order to increase homogeneity of the composition and structure. After annealing, levelling of chemical compositions of the interlayer and base metal took place in the bond (see Figure 4, *c* and Table 1).

Table 1. Indicators of the bonding zone on γ-TiAl alloy produced through nanolayered interlayer Ti/Al

Treatment method	Investigated points*	Chemical composition, at.%				*HV*, MPa
		Al	Ti	Mn	Nb	
Bonding	*1*	45.58	50.97	1.44	2.01	5000
	2	49.26	50.07	0.67	—	4000
	3	43.05	54.18	0.99	0.78	4500
Bonding + annealing	*1*	44.57	52.03	1.36	2.04	3800
	2	46.69	51.39	1.02	0.90	3500
	3	43.18	53.85	0.84	2.13	3900

*Here and in Tables 2 and 3, see Figure 4, *b*, *c*.

Bonding through interlayers Ni/Ti. As revealed by metallographic examinations, the nanolayered interlayer Ni/Ti causes a considerable activation of the diffusion processes within the bonding zone. The transition zone of a variable thickness (about 30 μm), which is heterogeneous in structure and composition and consists of two phases (Figure 5, *a*, *b*), forms during bonding in place of the initial interlayer. According to the data of local chemical analysis (Table 2), the dark-gray phase component contains the following elements, at.%: up to 0.7 Ni, 59.2 Ti, 37.4 Al, 1.8 Nb, and 0.9 Mn. The light phase compo-

Table 2. Indicators of the bonding zone on γ-TiAl alloy produced through nanolayered interlayer Ni/Ti

Treatment method	Investigated points	Chemical composition, at.%					*HV*, MPa
		Al	Ti	Mn	Ni	Nb	
Bonding	*1*	44.1	52.4	1.2	0	2.3	3900
	2	37.4	59.2	0.9	0.7	1.8	5500
	3	43.0	36.0	2.3	16.9	1.8	9000
Bonding + annealing	*1*	44.8	51.8	1.4	–	2.0	4200
	2	45.8	50.3	0.9	0.9	2.0	4400
	3	41.3	54.5	1.2	0.9	2.1	5300

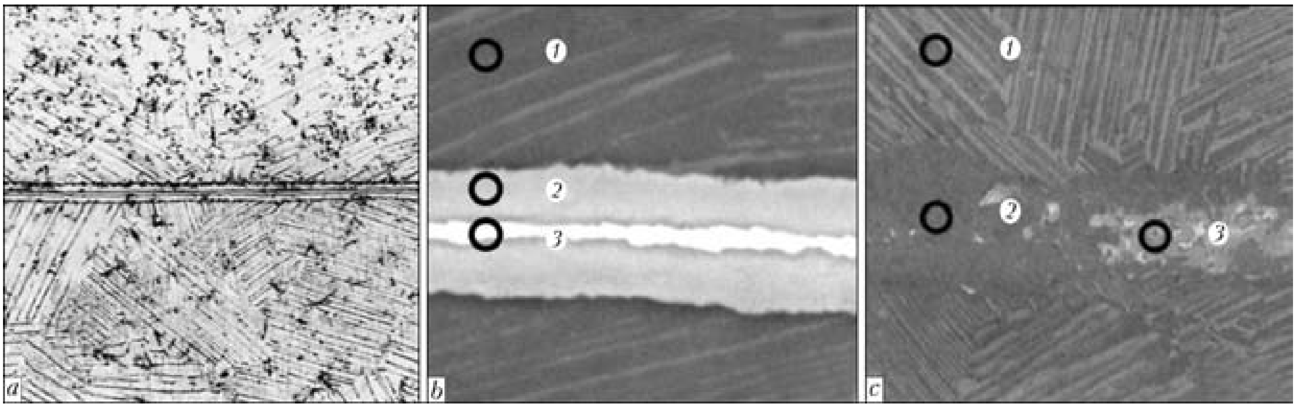

Figure 6. Microstructures of the bonding zone in bonding through nanolayered interlayer Ni/Al, obtained by optical microscopy (*a* — ×200), SEM (*b* — ×1000) and SEM after bonding and homogenising annealing at 1200 °C for 2 h (*c* — ×200)

Table 3. Indicators of the bonding zone on γ-TiAl alloy produced through nanolayered interlayer Ni/Al

Treatment method	Investigated points	Chemical composition, at.%					*HV*, MPa
		Al	Ti	Mn	Ni	Nb	
Bonding	*1*	44.5	51.5	1.2	0.5	2.3	4100
	2	41.6	34.8	1.1	21.0	21.0	11400
	3	44.7	9.7	0.25	45.2	0.15	7900
Bonding + annealing	*1*	43.0	53.3	1.3	0.2	2.2	4200
	2	48.5	48.2	0.9	0.4	2.0	4000
	3	43.2	46.5	2.1	6.6	1.6	10300

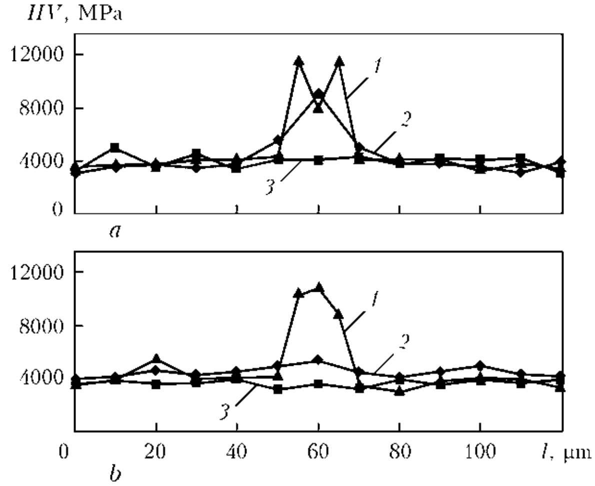

Figure 7. Distribution of microhardness in the bonding zone after bonding through nanolayered interlayers Ni/Al (*1*), Ni/Ti (*2*) and Ti/Al (*3*) (*a*), and after bonding and homogenising annealing at 1200 °C for 2 h (*b*): *l* — distance between indenter impressions

nent contains the following elements, at.%: 16.9 Ni, 36 Ti, 43 Al, 1.8 Nb, and 2.3 Mn. Niobium, like manganese, penetrates into the transition zone through all its thickness during the process of diffusion bonding (see Table 2). Nickel concentrates mostly in the light phase component, which is a complex intermetallic (Ti, Ni)Al. Microhardness of the dark-gray diffusion regions is *HV* 4500–5500 MPa, and that of the central region consisting mostly of the complex intermetallic is *HV* 8000–10000 MPa, which is much higher than microhardness of the base metal (*HV* 3500–3900 MPa). No marked changes of structure in the base metal regions adjoining the transition zone were detected, the lamellar structure persisting (see Figure 5, *b*). After annealing, levelling of the distribution of manganese and niobium, which are contained in the alloy and interlayer, take place in the bond. The nickel content of the bond decreases to 0.9 at.% (see Figure 5, *c* and Table 2).

Bonding through interlayers Ni/Al. Metallographic examinations of the bonds produced through the Ni/Al interlayer showed that the transition zone about 20 μm thick, which is heterogeneous in structure and composition (Figure 6, *a*, *b*), formed within the bonding zone. The Ni/Al base intermetallic layer 3–4 μm thick formed in its central part. The central region of the transition zone (Figure 6, *b*; Table 3) contained the following elements, at.%: 45.2 Ni, 44.7 Al, 9.7 Ti, 0.25 Mn, and 0.15 Nb. It should be noted that niobium did not practically penetrate into the central part of the transition zone. Its peripheral part contained the following elements, at.%: 21 Ni, 41.6 Al, 34.8 Ti, 1.1 Mn, and 1.4 Nb. It is a complex intermetallic (Ti, Ni)Al alloyed with niobium and manganese. Microhardness of the peripheral region of the transition zone was *HV* 9000–11400 MPa.

Also investigated was the character of changes of microhardness in the γ-TiAl bonding zone produced through nanolayered interlayers Ni/Ti, Ni/Al and Ti/Al. The character of changes of microhardness in the bonds produced through the Ni/Ti and Ni/Al interlayers is indicative of the fact that the bonding zone contains regions of a material with a high microhardness, much higher than that of the base metal. When using the Ti/Al interlayers, which are close in composition to the base metal, microhardness in the bonding zone remains almost unchanged.

After annealing, microhardness of the bonds produced through the Ti/Al and Ni/Ti interlayers is close in value to that of the base metal (*HV* 4000–5000 MPa). In the case of using the Ni/Al interlayers, annealing has no effect on microhardness (*HV* 10000–11000 MPa) of the bonds.

CONCLUSIONS

1. Application of nanolayered interlayers Al/Ti for diffusion bonding in vacuum of intermetallic alloy Ti–48 at.% Al–2 at.% Nb–2 at.% Mn allows producing the bonds with a uniform distribution of the alloying elements contained in the base alloy.

2. When using nanolayered interlayers Ni/Al, additional annealing does not remove heterogeneity of chemical composition and structure, and has no effect on microhardness of the bond.

3. Additional annealing of the bonds produced through nanolayered interlayers Ni/Ti provides the bonds with a chemical composition close to that of the base metal.

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TECHNOLOGY FOR REPAIR OF AIRCRAFT ENGINEERING PARTS BY THE DETONATION SPRAYING METHOD

The E.O. Paton Electric Welding Institute developed detonation spraying unit «Perun-S» and technology for deposition of coatings to protect parts from wear and corrosion and repair machine parts and equipment operating in different industries: aircraft engineering, motor car construction, turbine construction, power engineering, petrochemistry, etc.

Detonation spraying provides coatings with adhesion strength of up to 100–150 MPa at a porosity of less than 1 %. One of the main fields of application of detonation spraying is hardening of new parts and repair of various aircraft engineering parts and units after wear. In particular, it is applied for hardening of contact surfaces of band flanges of blades and vanes, compressor blades, fuel injection nozzles, etc.

A result of application of the detonation coatings containing tungsten and chromium carbides is a 7–12 times increase in service life of parts. Experience has been accumulated in applying the detonation coatings in repair of stages II and III of aircraft engine gas turbines, cover III of helicopter engine bearers, spacer plates of high-pressure compressors of aircraft engines, nozzle diaphragms of stage III, helicopter engine turbines, and antivibration flanges of blades of aircraft gas turbine engines. One of the examples is repair of worn-out surface of wing flap runway of IL-76 after operation with a simultaneous substantial increase of its wear resistance by spraying the coating of the 35 % WC + 65 % Ni–Cr–B–Si mechanical mixture powder (microhardness of a layer — 10500 MPa).

Purpose and application fields: increase of wear and corrosion resistance, hardening or repair after wear of different types of machine parts, such as aircraft engineering parts and units, ship fixtures, hydraulic cylinder rods, feed rollers of welding automatic devices, units and parts of oil-pumping plants, magnetic recording devices, end sealing rings of mining machines, etc.

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