CONCLUSIONS

1. Required set of mechanical properties of the deposited metal at reconditioning of worn surfaces of railway wheels (hardness *HB* ≥ 2500, strength $\sigma_t \geq$ 700 MPa) can be ensured by cladding consumables of bainite or bainite-martensite classes, namely solid wires Sv-08KhM, Sv-08KhMF and flux-cored wire PP-AN180MN.

2. Metal, deposited with flux-cored wire PP-AN180MN, combines high strength, hardness and crack resistance. All the regions of welded joints, made with this wire, have homogeneous finely-dispersed bainite-martensite structure with uniform distribution of local internal stresses.

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NEW SYSTEM OF FILLER METALS FOR BRAZING OF TITANIUM ALLOYS

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Based on the results of systematic studies of Ti–Zr–Co system alloys and allowing for published data, the liquidus surface of this system was plotted by using the simplex-lattice experimental design method. This system was found to have a region of alloys with decreased liquidus temperature, the most promising in terms of filler metal development. Spreading of experimental filler metals over titanium alloys of different classes (OT4, VT6 and VT22) was studied. The data on mechanical properties of the brazed joints are given.

Keywords: *brazing, titanium alloys, new system of brazing filler metals, liquidus surface, wetting, mechanical properties*

Titanium alloys play an important role in modern industry, especially in aircraft engineering, owing to their high characteristics, low density, high strength, high corrosion and fatigue resistance in particular, as well as high value of specific strength.

Meanwhile, the problem of current importance is fabrication of brazed structures of titanium alloys which cannot be manufactured by welding. Such structures include critical heat exchangers for cooling of compact nuclear reactors, as well as lamellar-ribbed and honeycomb structures used in aircraft engineering, ship building, etc. [1].

The modern brazing technology and filler metals should provide seams with the properties close to those of the base metal. This specifies important temperature-time bounds of the brazing cycles determined by the nature of titanium alloys. These bounds limit the probability of undesired changes in structure and properties of the alloys caused by polymorphism of titanium.

At a temperature below 882 °C titanium is in the α-state (hexagonal lattice), while above this temperature it is in the β-state (cubic lattice). This circumstance has a considerable effect on diffusion of depressant elements from the seam to a metal brazed and, as a consequence, on structure and properties of the brazed joints.

According to study [2], the need to limit the brazing temperature of titanium and its alloys is caused by a high rate of growth of its grain at temperatures above 1000 °C. Therefore, the melting point of a filler metal should not exceed 950–1000 °C.

In study [3] the upper bound of the brazing temperature was decreased to 900 °C for α- and pseudo-α-alloys, to 935 °C for α + β-alloys, to 870 °C for pseudo-β-alloys, and to 760–800 °C for β-alloys.

Limitation of the brazing temperature to a value of the $\alpha \rightarrow \beta$ transformation temperature is especially important for thin-walled structures

Commercial titanium-base filler metals

Filler metal	Composition, wt.%	Temperature, °C		
		Solidus	Liquidus	Brazing
VTi-1	Ti–15Cu–15Ni	902	950	980–1050
VTi-2	Ti–15Cu–25Ni	901	914	930–950
VTi-3	Ti–26Zr–14Cu–14Ni–0.5Mo			820–920
VTi-4	Ti–20Zr–20Cu–20Ni	848	856	
Ticuni 70	Ti–15Cu–15Ni	902	950	980–1050
MBF 5011	Ti–18.5Cu–27.5Ni	910	920	
MBF 5012	Ti–20Cu–20Ni	915	936	
VPr16	Ti–(8–16)Ni–(11–14)Zr–(21–24)Cu	880	900	920–970
STEMET1201	Ti–12Zr–12Ni–23Cu	830	955	900–1000
Ti–Zr–Be–Al	Ti–45Zr–4.7Be–5Al		910	
Ti–Zr–Be	Ti–48Zr–2Be		930	

usually applied in aircraft engineering, as active growth of grains and active diffusion of filler metal components to the base metal of a small thickness lead to embrittlement of the seam.

Today the most common filler metals for high-temperature brazing of titanium, which are successfully used for fabrication of different-purpose structures, are filler metals of the Ti–Cu–Ni and Ti–Zr–Cu–Ni systems (Table).

However, these filler metals have application limitations because of the copper and nickel content. So, it is necessary to investigate new alloy systems in which these elements are absent. The Ti–Zr–Fe [4–6] and Ti–Zr–Mn [5, 6] systems have been considered in literature as an alternative to the known systems of filler metals. Filler metals of the above systems have good operational properties and provide good strength of the brazed joints. However, melting temperature T_{melt} of these filler metals is within 960 (for the Ti–Zr–Fe system) and 1050 °C (for the Ti–Zr–Mn system) [5, 6]. Accordingly, the brazing temperatures for these filler metals exceed the upper bound of the permissible temperatures.

The purpose of this study was development of a new generation of filler metals for brazing of titanium alloys to widen the field of application of the brazed titanium structures. Such filler metals should not contain the above element and have a decreased melting point (below 900 °C).

Investigation of the constitutional diagrams showed that unlimited solid solutions with titanium are formed only by refractory metals (zirconium, vanadium, molybdenum, niobium). Among them, zirconium and vanadium form solid solutions with a minimum on the liquidus curve, this making it possible to use the Ti–Zr and Ti–V systems as a base for development of filler metals. In particular, in our opinion the promising system is Ti–Zr–Co.

To determine optimal proportions of elements in an alloy, it was necessary to plot the liquidus diagram for the Ti–Zr–Co ternary system. Plotting of such a surface by traditional experimental methods is difficult and time-consuming. Therefore, we used a combination of the calculation and experimental method, in particular the simplex-lattice experimental design method, the

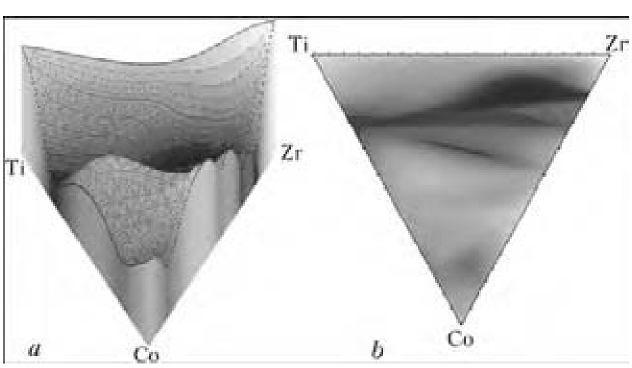

Figure 1. Results of calculation of liquidus surface for the Ti–Zr–Co system alloy in the 3D form (*a*) and on a plane (*b*)

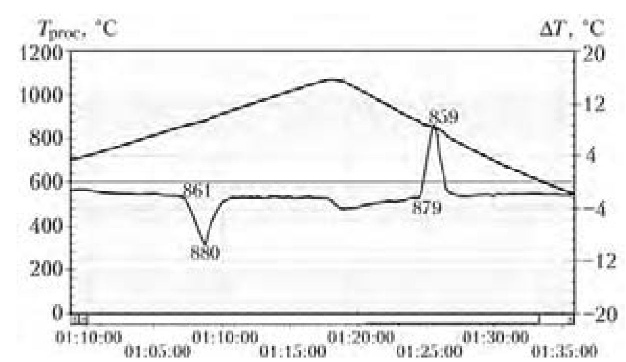

Figure 2. Results of high-temperature differential thermal analysis of experimental alloy of the Ti–Zr–Co system

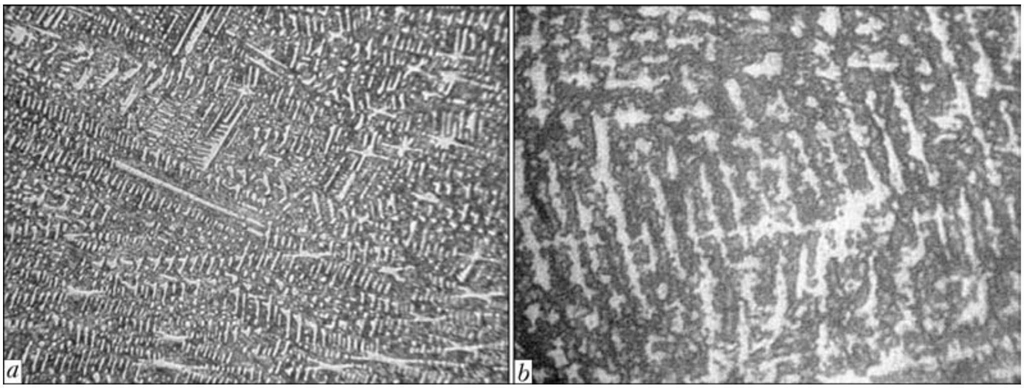

Figure 3. Microstructure of alloy Ti–Zr–Co in the cast state (*a* — ×500; *b* — ×1000)

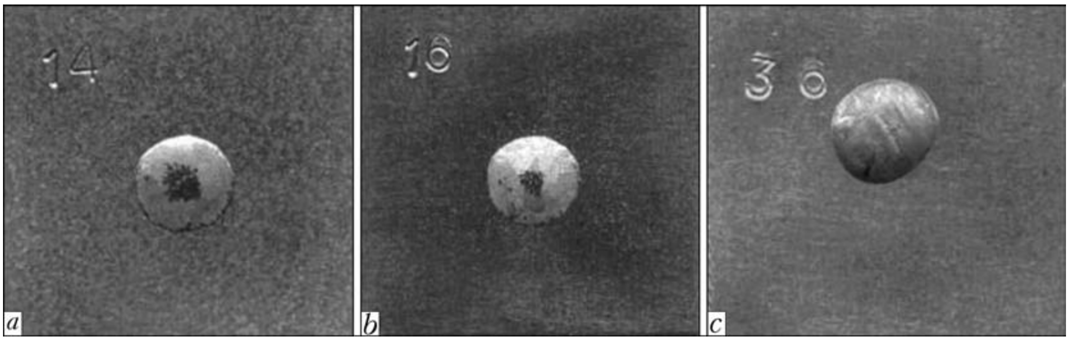

Figure 4. Appearances of specimens with filler metals spread over the substrate of alloy OT4: *a* — VPr16 (STEMET 1201) (T_{melt} = 990 °C, t = 10 min); *b* — Ti–Zr–Fe (T_{melt} = 1000 °C, t = 10 min); *c* — Ti–Zr–Co (T_{melt} = 920 °C, t = = 10 min)

mathematical tools for which are described in detail in studies [7, 8].

About 50 alloys melted on a cold substrate by electron beam heating were studied in the process of plotting the liquidus diagram for the Ti–Zr–Co system. The calculation results are shown in Figure 1.

It can be assumed on the basis of this diagram that the given system in a range of alloys with a low cobalt content (approximately along the line passing from alloy Ti–22Co to alloy Zr–15Co) has the line of monovariant eutectic, as well as the region with a decreased liquidus temperature (less that 900 °C), which in our opinion is most promising for development of filler metals.

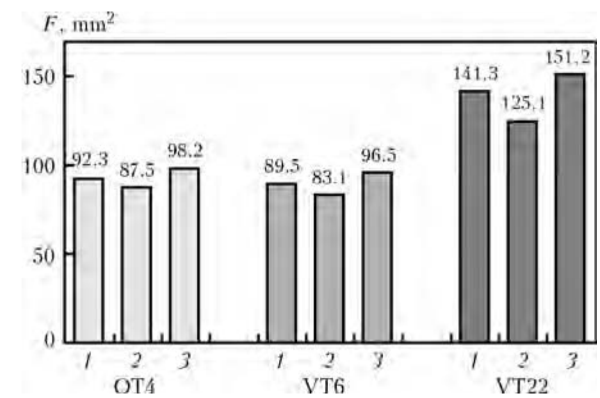

Figure 5. Area of spreading of cast filler metals over alloys OT4, VT6 and VT22 (heating in vacuum $5\cdot10^{-5}$ mm Hg): *1* — VPr16 (STEMET 1201) (T_{melt} = 990 °C, t = 10 min); *2* — Ti–Zr–Fe (T_{melt} = 1000 °C, t = 10 min); *3* — Ti–Zr–Co (T_{melt} = 920 °C, t = 10 min)

Based on the calculation results and the plotted liquidus surface, several alloys of the Ti–Zr–Co system were chosen for further investigations.

After melting of experimental alloys, the differential thermal analysis and metallographic examinations of these alloys were carried out to check agreement of the calculation method results and experimental data.

Differential thermal analysis of the alloys was conducted by using instrument VDTA 8M-3 (heating and cooling rate was 30 °C/min).

One potentially promising alloy was chosen on the basis of the experimental results for further, more detailed investigations. As seen from the data in Figure 2, the chosen alloy has a temperature of the beginning of melting equal to 861 °C and that of complete melting — equal to 880 °C.

As seen from Figure 3, *a*, *b*, this alloy is a mixture of two phases — solid solution (white phase) and eutectic (dark phase). The fact that the differential curve in heating and cooling of the chosen alloy (see Figure 2) has only one peak can be explained so that these phases seem to have close melting temperatures.

To evaluate the level of wetting and spreading of the experimental filler metal over the substrate of titanium alloys of different classes, a series of experiments was conducted to determine the areas of spreading of filler metals of the Ti–Zr–Co system over the substrate of alloys OT4 (low pseudo-α-alloy), VT6 (medium α + β-alloy) and VT22 (high α + β-alloy). Filler metal Ti–12Zr–12Ni–23Cu (STEMET 1201) in the cast state and a new experimental filler metal Ti–35Zr–25Fe developed by the E.O. Paton Electric Welding Institute were investigated for comparison.

The specimens were heated in vacuum furnace SGV 2.4–2/15I3 under the following conditions: environment of a work space of the furnace — vacuum $5\cdot10^{-5}$ mm Hg, heating rate ~30 °C/min, brazing temperature for filler metal Ti–Zr–Co — 920 °C, and for filler metals Ti–Zr–Fe and STEMET 1201 — 1000 °C.

The area of spreading of filler metals over the substrate was determined by using software AUTOCAD 2007. The experimental results are shown in Figures 4 and 5.

It can be seen from the given diagrams that the area of spreading of filler metal Ti–Zr–Co over titanium substrates of the three types is higher compared to filler metals of the other systems, which is probably related to an increased zirconium content in the experimental alloy.

Preliminary mechanical tests of the joints brazed with filler metal of the Ti–Zr–Co system (Figure 6) showed that strength of the joints of alloy VT6 brazed with the experimental filler metal is higher than that of the joints brazed with standard filler metals, despite a lower brazing temperature.

The results given demonstrate that the experimental filler metal of the Ti–Zr–Co system meet the requirements imposed on filler metals for fabrication of different-application structures of titanium alloys.

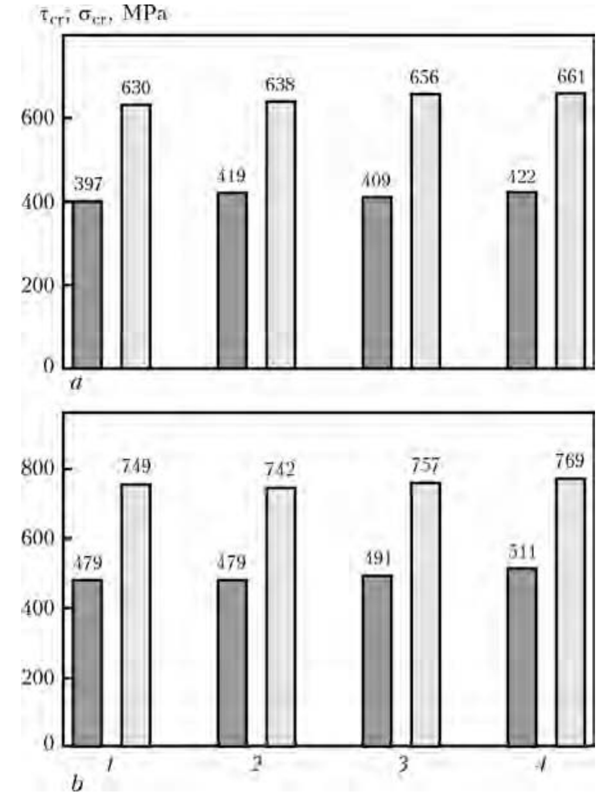

Figure 6. Mechanical properties of overlap (dark columns) and butt (light columns) joints of alloys OT4 (*a*) and VT6 (*b*) brazed by using different filler metals: *1*, *2* — VPr16, cast, and STEMET 1201, amorphous strip (T_{melt} = 990 °C, t = 10 min), respectively; *3* — Ti–Zr–Fe (T_{melt} = 1000 °C, t = 10 min); *4* — Ti–Zr–Co (T_{melt} = 920 °C, t = 10 min)

CONCLUSIONS

1. The promising filler metal was chosen for brazing of titanium alloys of different classes on the basis of the results of investigations of the Ti–Zr–Co system alloys, as well as the plotted liquidus surface for this system.

2. It was established that the area of spreading of the experimental alloy over the substrates of titanium alloys of different classes is higher than that of standard filler metals for brazing of titanium alloys.

3. The area of spreading of all investigated alloys increases with increase in the concentration of alloying elements in the brazed titanium alloys. For instance, in investigation of spreading the best results were obtained on high pseudo-β-alloy VT22.

4. Mechanical properties of the brazed joints on alloys OT4 and VT6 made with the experimental filler metal are in excess of strength of the joints brazed with known filler metals.

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