https://doi.org/10.37434/tpwj2020.03.05

BRAZING AS A PROMISING METHOD OF PRODUCING PERMANENT JOINTS

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The paper presents practical results of developments and investigations in the field of brazing different materials: aluminium, copper, high-temperature nickel and titanium alloys, as well as promising materials based on Ni_3Al and γ-TiAl intermetallics and steels of different grades. Data on reactive-flux brazing of aluminium thin-walled structures in a controlled gas environment are given. A lot of attention is paid to producing brazed joints from dissimilar materials: Mo+C (stainless steel), W+Cu, hard alloy material (VK 20)+steel, Al+steel, etc. Effective application of the developed technologies of brazing high-temperature nickel and titanium alloys in fabrication of critical structures for high temperature applications and results of mechanical testing of brazed joints are shown. The developed brazing filler metal and technologies of high-temperature vacuum brazing were applied to produce joints from new generation alloys based on nickel and titanium aluminides, which have been successfully tested for long-term strength under the conditions of higher temperature and continuously applied stresses. 17 Ref., 1 Table, 14 Figures.

Keywords: brazed joints, brazing filler metals, vacuum, reactive-flux, flame brazing, high-temperature nickel, titanium alloys, long-term strength, dissimilar materials, aluminium, copper alloys

Nowadays, brazing occupies an important place among the different methods of producing permanent joints and is widely used in different industries: aircraft, space, instrument making, automotive during manufacture of refrigeration and cryogenic engineering, at jewelry enterprises and other [1, 2]. The advantages of brazing over welding consist in the ability of combining different materials without their melting, which provides preservation of the initial structure of base metal, provided that the temperature and time parameters of brazing process and chemical composition of the brazing filler material are correctly selected. A great importance belongs to the application of brazing process for joining materials characterized by poor weldability, because of cracking in the heat-affected zone and in the weld [3]. One more factor in favor of brazing is the ability of combining the heat treatment mode of the base metal with a thermal mode of brazing and automation with a simultaneous producing of several elements of a complex geometric configuration [4]. The decisive factor in brazing is the ability of producing joints in hard-to-reach areas where it is impossible to join base materials with the use of conventional welding methods. In such cases, brazing is the only possible method of producing joints.

However, notwithstanding such positive characteristics of brazing process, there are some peculiarities and problems that need to be solved in order to provide the operational properties of the brazed structures. They include chemical composition and form of a used brazing filler metal. Currently, there are many brazing filler metals on different bases: tin, aluminium, copper, silver, nickel, titanium, iron, etc. They are applied in the cast state, in the form of powders, wires of different diameters, plastic tapes, produced with the use of traditional methods of metallurgical processing or by ultrafast hardening, etc. [4, 5]. The choice of chemical composition of brazing filler metal is predetermined by physical and chemical properties of the base metal and performance characteristics of brazed products. One of the indices of brazing filler metal compatibility with the base metal is the ability of brazing filler metal to wet the base metal and spread over its surface at the brazing temperature [6, 7]. The use of brazing filler metals with a wide interval of melting leads to the development of chemical heterogeneity and liquation processes in the weld metal, as well as porosity. The use of eutectic brazing filler metals allows a brazed joint to solidify at a constant temperature, but at the same time an eutectic structure is formed, which often contributes to embrittlement of the weld metal. Therefore, each pair of materials to be brazed requires an individual approach and a specific chemical composition of brazing filler metal with a predetermined temperature interval and mechanical properties.

At PWI for many years systematic investigations in the field of brazing has been conducting, the physicochemical processes have been studied that occur during heating to brazing temperature, the relationship between mechanical properties of brazed joints, structure of brazed joints, chemical composition of brazing filler metal and base metal have been studied. Based on the results of the investigations, brazing filler metals were created that are compatible with the base metal, brazing technological processes were developed to provide the brazed joints with the necessary service properties. This paper presents some results of the carried out investigstions and the examples of practical applications in different industries.

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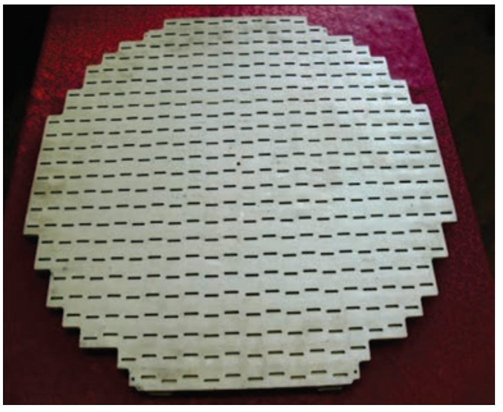

Figure 1. General view of brazed antenna array

Aluminium brazed joints. At PWI the technology of brazing aluminium alloys was developed and a method for furnace brazing of aluminium thin-walled structures was proposed (Figure 1) in a controlled gas environment (nitrogen, argon). This method is environmentally friendly and less energy intensive as compared to existing brazing methods (for example, immersion in salt melts).

For high-temperature brazing of aluminium alloys of series 1000 ((90.3–99.98) A1) and 3000 (Al–Mn systems), brazing filler metals of Al–Si system and non-hygroscopic reactive flux of the salt system K, Al, Si/F are used, which provide the equal strength of brazed joints in the conditions of multiple shocks, vibration according to TU U 14307274-009:2016.

The melting point of brazing filler metal and flux should be lower than solidus temperature of the brazed aluminium alloy, which determines the upper limit of the brazing temperature interval. The antenna arrays with the overall dimensions (640×640×26 mm) were manufactured. The weight of the antenna is 2.07 kg. It should be noted that during the manufacture of this antenna it is necessary to produce brazed joints about 6000 mm in length. However, the flux consumption are insignificant and amount to ≤50 g, which favorably differentiates the cost of this method as compared to the existing ones.

The thin-walled aluminium waveguides made in the controlled gas medium (Figure 2) are characterized by a large total area of a brazed joint, which is about 1562 mm^2. The consumption of brazing filler metal per a unit of product is 1.1–1.5 g, flux — 2–3 g.

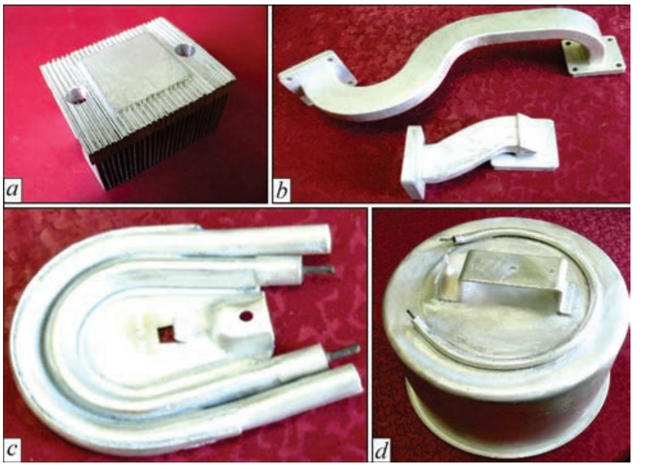

Figure 3. Brazed products of aluminium alloys: *a* — plate aluminium heat exchanger; *b* — element of ultra-high frequency module; *c* — tubulat heating elements for household appliances (*d*)

The produced brazed weld of a thin-walled structure is characterized by the presence of a smooth fillet and the absence of defects (Figure 2, *b*).

The technological process of reactive-flux brazing is used in the manufacture of plate-type aluminium heat exchangers of the electrothermal module of the rolling stock used for preparation of water, microwave antenna elements and a number of other products of the national economy (Figure 3).

The overall dimensions of such heat exchangers are 145×160×82 mm, the number of plates is 82 pieces and the total area of a brazed joint is 1740 mm^2. The flux consumption is negligible and is ≤ 20 g.

In this case, brazing proceeds with the use of reactive fluoride flux, which melts during heating to brazing temperature and interacts with aluminium and forms a liquid phase of the Al–Si system, which is close to the eutectic composition and serves as a brazing filler metal [8]. The produced brazed joints are characterized by the presence of brazed welds, whose width is much smaller than the width of the welds produced with the use of flux with brazing filler metal (Figure 4).

Dissimilar brazed joints. The choice and use of dissimilar metals as structural materials is determined by the service requirements and economic indicators specified to the finished products. Most high-tech

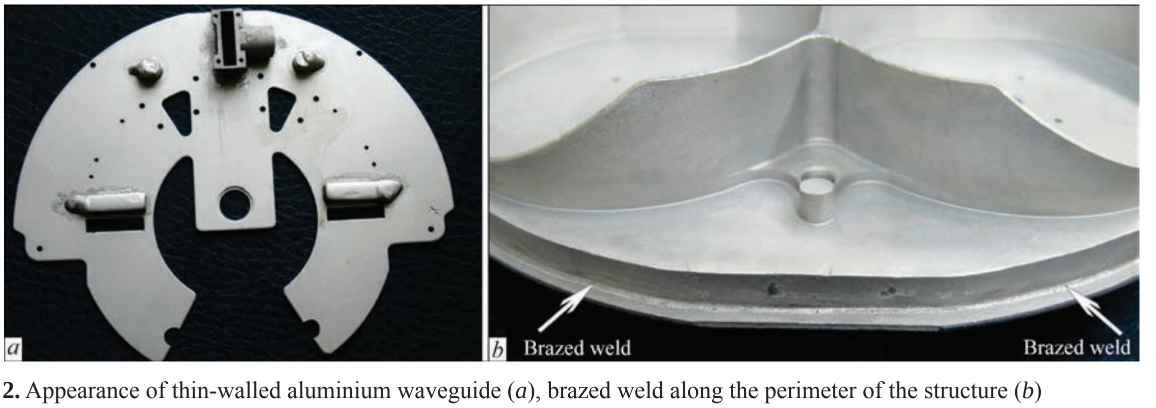

Figure 2. Appearance of thin-walled aluminium waveguide (*a*), brazed weld along the perimeter of the structure (*b*)

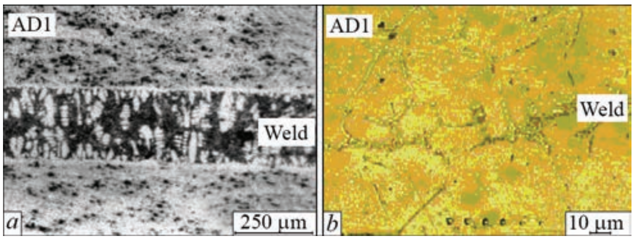

Figure 4. Microstructure of brazed weld of aluminium brazed joint produced using brazing filler metal and flux (*a*) and with flux without brazing filler metal (*b*)

equipment contains separate assemblies of dissimilar materials that are produced by brazing. It should be noted that during brazing of dissimilar materials, the problems arise caused by different physical and chemical properties of base materials. The quality of brazed joints is significantly affected by the difference in the coefficients of thermal expansion, which contributes to the arising of inner stresses. Reducing the effect of inner stresses provides a correct choice of brazing filler metal composition and temperature-time parameters of the brazing process.

The developed technology of flux induction brazing of steel-aluminium pipe adapters (SAPA) with an inside diameter (10–300 mm) in an argon medium (for cryogenic engineering) was developed. As far as the coefficients of thermal expansion of the basic dissimilar materials (corrosion-resistant steel 12Kh18N10T and aluminium alloy of the series 3000 (AMts)) differ, during brazing in the brazed joint residual stresses occur. Their level is much lower as compared to the welded joints produced with the use of existing arc welding

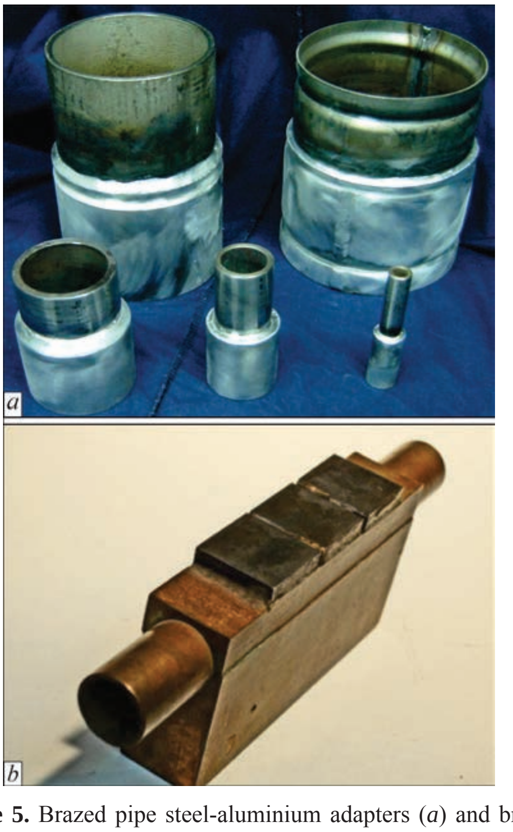

Figure 5. Brazed pipe steel-aluminium adapters (*a*) and brazed model of Cu–W diverter assembly for thermocyclic tests (*b*)

methods. The brazed steel-aluminium pipe adapters (Figure 5, *a*) were successfully tested for strength and sealing according to the requirements of TA.

The obtained results of thermocyclic tests show that under the conditions of working pressure of 1 MPa/cm^2 brazed steel-aluminium pipe adapters can withstand 50 cycles at the temperature variation from 35 to −196 °C preserving sealing and without fracturing. They are characterized by a high strength, which amounts to 0.95–0.98 of the strength of the AMts alloy.

Brazing a pair of dissimilar materials copper-tungsten represents a particular interest and considerable difficulties. They find application in the manufacture of plasmatrons, powerful X-ray tubes, individual units of the thermonuclear fusion diverter, etc. On the basis of systematic investigations the technological process of vacuum brazing of dissimilar joints copper–tungsten, designed for application in rigid conditions of thermocyclic loading and neutron irradiation, was developed. For such tests, by means of brazing the models of diverters copper-tungsten were produced (Figure 5, *b*). Under the action of a pulsating heat flux, in the model an uneven temperature distribution is generated. The heat flux power and the duration of its action were determined in such a way that the maximum temperature on the surface of the tungsten coating and in the zone of brazed weld at the interface with the copper base corresponded to the design temperature at a constant flux with the power Q = 10 MW/m^2. The results of thermocyclic tests showed good thermal fatigue properties on the base of $1\cdot10^3$ cycles (Table).

After neutron irradiation with the dose of $5\cdot10^{21}$ neutr/cm^2 at a temperature of 100 °C, an increase in the tensile strength of the brazed joints from 200 (in the initial state after brazing) to 250 MPa, which is associated with the processes of ordering the solid solution in the brazed weld, the specimens preserve a sufficient strength also at 400 °C (Figure 6).

The technological process of vacuum high-temperature brazing of dissimilar joints molybdenum–carbon alloys (stainless steel), which are serviceable under rigid conditions of thermal loads (Figure 7, *a*, *b*), was created.

The brazed tubular joints molybdenum–stainless steel with tight brazed welds were produced, where cracks and a formed structure of solid solution were absent (Figure 7, *c*).

The dissimilar joints kovar–titanium alloy are widely used in instrument making. To produce them by brazing, a special technology of preliminary treatment of the base metal (titanium alloy) was developed and applying vacuum radiation heating individual brazed assemblies were manufactured (Figure 8). The carried out tests on sealing gave positive results and testify to the quality formation of brazed welds.

The flux brazing of hard-alloy plates for sawing discs and holders were worked out during the manu-

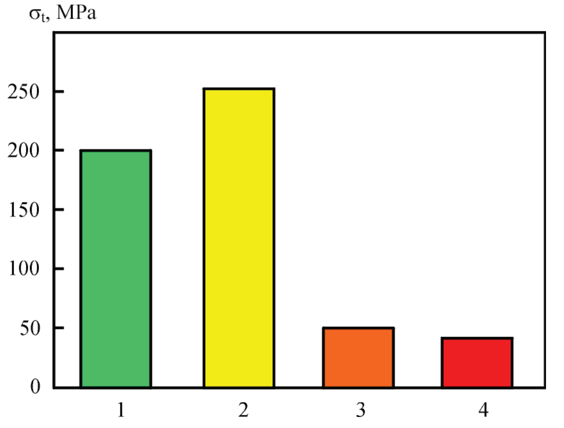

Figure 6. Strength of brazed Cu−W joints: in the initial state after brazing (*1*); after neutron irradiation in the SM-2 reactor at T = = 100 °C and a dose of 5−10[21] neutron/cm[2] (*2*); at T = 310 °C, in the SM-2 reactor, dose of 5−10[21] neutron/cm[2] (*3*); in the BOR-60 reactor at T = 400 °C, dose of 5−10[22] neutrons/cm[2] (*4*)

facture of circular saw blades for woodworking and metalworking tools.

The brazing process is used in the manufacture of cylindrical elements for semiconductor devices consisting of dissimilar materials, such as metallic 22XC ceramics and kovar (or copper).

The brazing of dissimilar materials of hard-alloy cutters for body blades (made of steel) during manufacture of drill bits was mastered [9]. In addition, during operation of drill bits a partial fracture of the surface of hard-alloy cutters occurs and spallings are observed (Figure 9, *a*), which deteriorates their serviceability.

Therefore, it becomes necessary to perform defect restoration and repair works with the use of flux brazing of dissimilar steel materials with hard-alloy

Results of thermocyclic tests of brazed models of Cu−W diverter

Loading type	Pulse/pause duration, s	Heat flow capacity, MW/m^2	Number of cycles, N
1	0.3/18−25	26−28	1000
2	0.5/26−28	26−28	200
3	10/13	13/14	1000

cutters, as well as in the use of strength carbide-containing coatings. It allows continuing drilling with the recovered drilling tool (Figure 9, *b*) with a considerable saving of material resources.

Brazing of copper and its alloys. Brazing filler metals based on copper-phosphorus system were developed, flux and vacuum brazing (repair) of copper alloys, including bronzes of different grades (dispersion-hardening type BrKhTsr), dispersion-hardening alloys (of type Glidcop), 0.25 $A1_2O_3$), cupronickels (MNZhMts31-1), cunials (Cu−Ni−Al), non-silbers (MNTs15-20), etc. were worked out. Corrosion-resistant cupronickels are used in the manufacture of seawater desalting plants, medical tools and marine shipbuilding.

In the production of refrigeration and heat exchange (Figure 10, *b*) equipment, capillary brazing of copper pipelines is used. Heat exchangers (of copper, cupronickel — MNZhMts3-1) are used in shipbuilding.

In diesel locomotive building and in the production of gas columns heat exchangers are used (Figure 10, *b*), whose components are brazed elements of copper (or brass). The carried out investigations of strength of brazed joints made of copper M3 and alloys MNZh-5-1 and MNZhMts 30-1-1 under static and cyclic loads gave

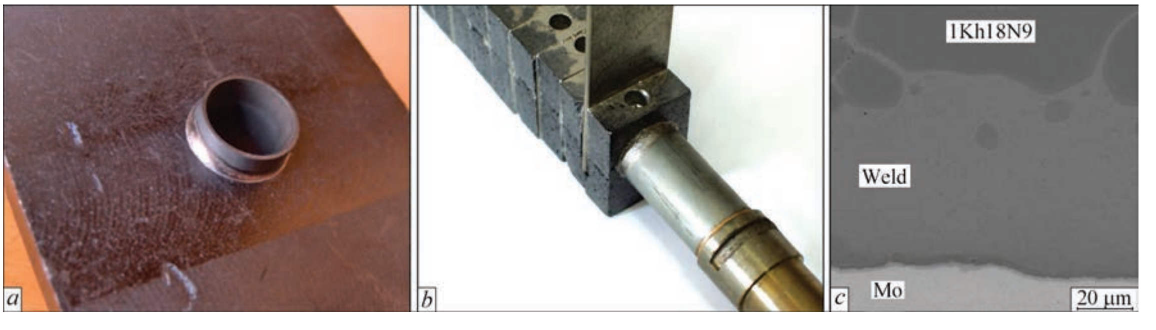

Figure 7. Brazed assembly graphite–molybdenum (*a*) and model of diverter device (**b**) containing brazed elements Mo−C (stainless steel) produced by vacuum high-temperature brazing for thermocyclic tests; microstructure of brazed joint molybdenum–stainless steel (*c*)

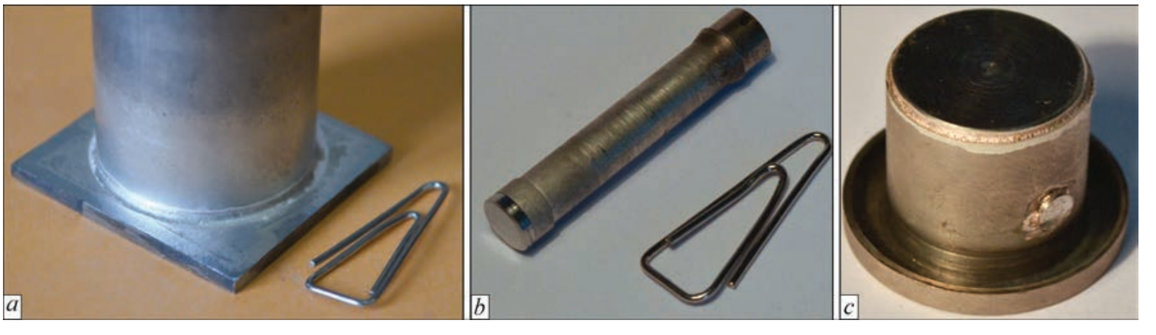

Figure 8. Brazed specimens of dissimilar materials kovar–titanium alloy: model specimen for tests on sealing (*a*); tubular element (*b*); brazed assembly with plug (*c*)

Figure 9. Matrix drill bit of 215.9 mm diameter for surface drilling during oil and gas production before (*a*) and after repair (*b*)

a positive result and provided a reliable operability of telescopic and collar-pipe tubular structures.

Copper-phosphorus brazing filler metals are used to braze copper joints, which consist of tubular elements and plates applied in solar collectors for heating water (Figure 10, *a*). Solar collectors are a great way to save energy resources. Due to the free solar energy, it is possible to provide hot water for economic needs (for at least) 6−7 months a year and in other months also to support the heating system [10]. In the manufacture of solar collectors, the process of brazing steel components can also be applied.

Different heating for brazing copper tubular structures, including flame arc or plasma methods can be effectively used, where as a filler material copper-phosphorus brazing filler metals by additional alloying with different elements are applied.

Vacuum brazing of high-temperature nickel alloys. The creation of permanent brazed joints in the manufacture of critical structures from nickel cast, dispersion-solid, intermetallic alloys based on Ni_3Al, which are operated at high temperatures, is an important task today, and its solution determines the possibility of using these materials in the manufacture of parts of the hot passage of gas turbine engines, power plants, jet engines and heat engineering equipment.

For brazing high-temperature nickel alloys, commercial nickel-based brazing filler metals are widely used, in which as depressants silicon and boron are applied. These elements, on the one hand, reduce the melting point and improve spreading and on the other hand, they form low-melting brittle (eutectic) phases in brazed welds and in the base material [11−13], which cannot be dissolved even at a long-term isothermal holding, which adversely affects the mechanical properties of brazed joints during a long-term operation under the conditions of high temperature and permanent stresses. The use of brazing filler metals containing silver, copper, nickel does not provide the required level of heat resistance.

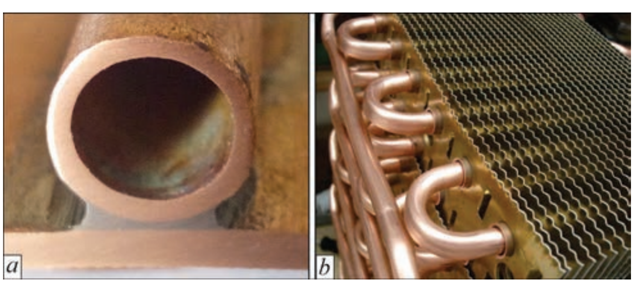

Figure 10. Brazed element of solar collector (*a*) and heat exchanger (*b*)

In this regard, the fundamental investigations of physico-metallurgical processes occurring during vacuum brazing of high-temperature dispersion-solid nickel alloys (IN 718) were carried out and regularities of the structure formation of brazed joints were determined. It was established that producing single-phase structure of a brazed weld provides stable results of short-term strength of brazed joints at a room and elevated (550 °C) temperature, respectively (Figure 11, *a*), as well as high values of long-term strength (132 h without fracturing) at a temperature of 550 °C and set stresses of 785 MPa (Figure 11, *b*). The obtained data of long-term strength more than twice exceed the similar data obtained with the use of industrial brazing filler metal. This technology is used in the manufacture of a closed centrifugal wheel (Figure 11, *c*).

Brazing of intermetallic alloys. For today, the traditional metal alloys providing solid-soluble and carbide strengthening are almost obsolete in terms of radical improvement of properties, especially for high-temperature applications. Some reserve for the near future is constituted by dispersion-strengthened, single-crystal and eutectic alloys. The increase of temperature in gas turbine engines is achieved due to intensive cooling of the blades, which, in turn, leads to decrease in efficiency. A real alternative to metal alloys is represented by alloys based on intermetallics, which are designed for high-temperature applications and contribute to expanding the field of using cooled blades with providing a high heat resistance without the use of coating [14].

The brazing filler metals together with the technological process of vacuum brazing (repair) of heat-temperature nickel alloys of different grades were created: casting alloys (ZhS6U), perspective heat-temperature nickel alloys based on intermetallic Ni_3A1 (Ni–8A1–14Mo–0.05V), operating under the conditions of high temperature, aggressive environment and continuous loads. They are used for the manufacture of individual parts and assemblies in the hot sections of gas turbine engines (Figure 12, *a*, *b*). The produced brazed joints of nickel alloy based on Ni_3A1 are characterized by a high long-term strength at an elevated temperature of 900 °C and permanent stresses of 150 MPa (Figure 12, c).

The class of promising intermetallic alloys includes titanium alloys based on TiAl. They are prominent representatives of high-strength and heat-resistant intermetallic alloys of the new generation, which are promising for the use in aircraft construction in the manufacture of a number of parts of the hot sections of gas turbine engines. In terms of heat-resistant

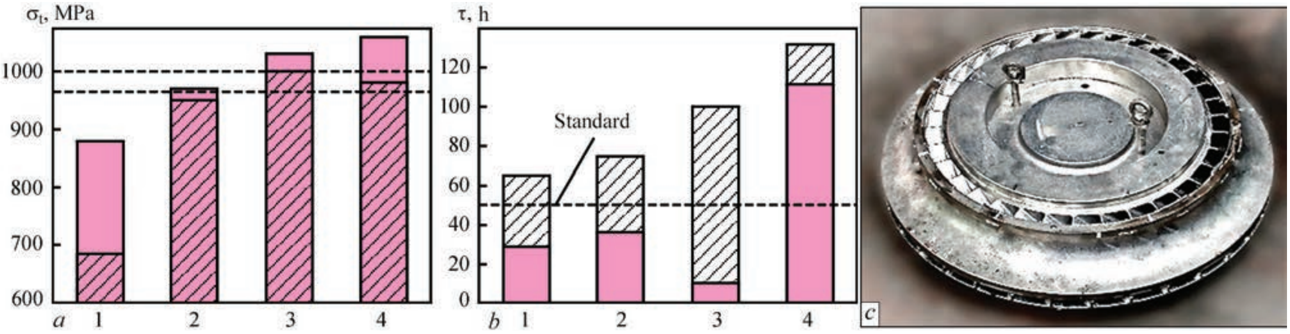

Figure 11. Tensile strength of butt brazed joints (*a*) produced using filler metals of the system: Ni–Pd–Cr–Si (*1*); Ni–Pd–Cr–Co–Si (*2*); Ni–Pd–Cr–B (*3*); Ni–Pd–Cr–Ge (*4*); long-term strength (*b*); double shrouded centrifugal wheel of axial flow compressor of gas-turbine engine (*c*)

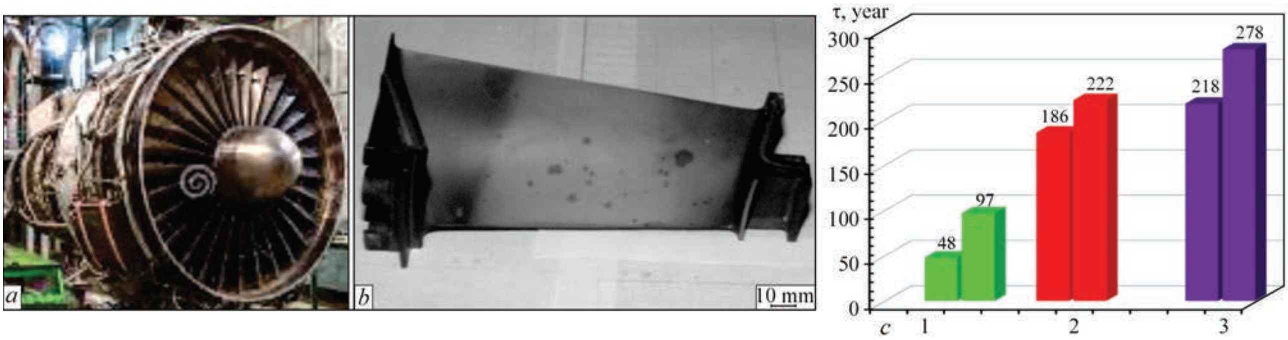

Figure 12. Gas-turbine engine (*a*), blade (*b*), long-term strength of butt similar brazed joints Ni_3Al+Ni_3Al produced using multicomponent nickel brazing filler metal without heat treatment (*1*), with heat treatment (*2*) and dissimilar joints Ni_3Al+ZhS6U with heat treatment

characteristics at a temperature of 700–750 °C, they can compete with highly alloyed nickel alloys due to a low specific weight of 3.8 g/cm^3 (8.9 g/cm^3 in nickel). This will provide a reduction in the weight of the gas turbine engine by 30 % and an increase in its operating characteristics. As a classic example of intermetallic titanium alloys Ti–48A1–2Cr–2Nb (at.%) can be, the main structural component of which is an ordered γ-phase (TiAl), on the boundaries of which a small amount of α_2-phase (Ti_3A1) is evolved in the form of lamellar grains. Due to such layered structure, this alloy has a good balance of ductility at a room temperature, strength at a high temperature and resistance to oxidation. The alloys, in which the volume fraction of α_2-phase is at the level of 10–15 %, have the maximum level of ductility [15]. The γ-TiA1 alloy (47KhD) has a high strength both at a room temperature (650–700 MPa) as well as at elevated temperature (at 700 °C, 320–350 MPa).

At PWI the investigations on joining intermetallic titanium alloys based on γ-TiAl (Ti–45Al–2Nb–2Mn + 0.8 vol. % TiB_2) with the use of vacuum heating and adhesion-active brazing filler metals based on titanium-zirconium system were carried out [16]. The pro-

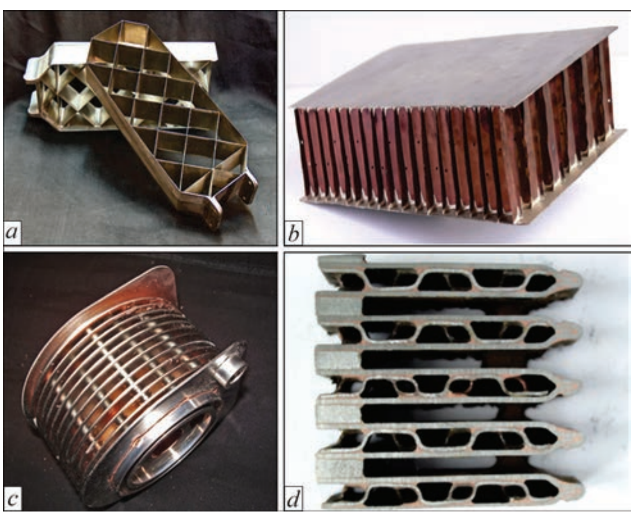

Figure 13. Brazed thin-walled stainless steel structures: rocket rudders (*a*); plate heat exchanger (*b*); automotive oil cooler: exterior (*c*) and vertical section (*d*)

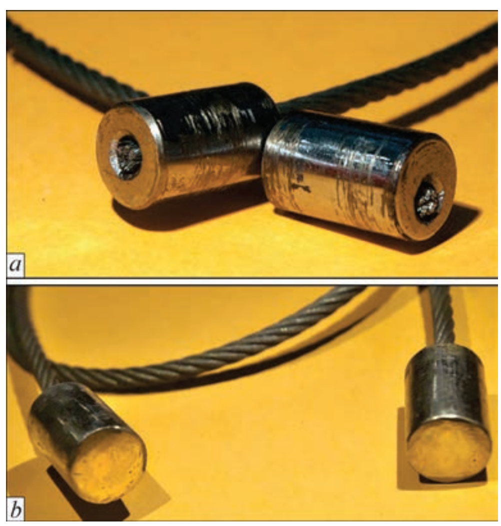

Figure 14. Brazed elements of high-strength austenitic steel and steel 45 before (*a*) and after brazing (*b*)

duced joints successfully passed mechanical strength tests at a room, elevated temperature and showed a good long-term strength at an elevated temperature and a constant stress.

Brazing of stainless steel. Stainless steel structures are often operated under the conditions of aggressive environments and elevated temperature. The technological process of vacuum brazing of stainless steel relating to thin-walled products such as: rudders of rockets, faceted structures [17], automobile heat exchangers (Figure 13) was worked out.

The car heat exchangers of stainless steel (Figure 13, *c*, *d*) are designed to maintain the optimum temperature conditions in cars, tractors, combines and other machines.

In industry, brazed assemblies of steels of different grades are widely used. The brazing process can be performed in a vacuum, in the environment of shielding gas and in the air. An example is a brazed assembly of high-strength austenitic steel and plugs of steel 45 (Figure 14), characterized by a uniform strength and used in a laboratory bench to test structures of rolling stock (rail cars) on rail transport.

A special attention should be paid to the experiments on brazing in outer space: in the conditions of zero-gravity and a significant temperature gradient, which affect the process of brazed joints formation and differ significantly from the earth's conditions. Only the first steps were made in this direction, and to study the physical and metallurgical features of the formation of brazed joints in more details, the further systematic investigations are needed.

Conclusions

In this paper some aspects of practical application of investigations results and created scientific and technological developments in the field of brazing of dissimilar materials are briefly covered such as: aluminium, copper, steel, high-temperature nickel, titanium alloys and advanced materials of the new generation based on Ni_3A1 and γ-TiAl intermetalics. A particular attention should be paid to the considerable volume of experimental investigations while producing brazed joints, designed for operation in severe conditions of high temperature and continuously applied stresses. The examples of the application of brazed joints of dissimilar materials, differing in physicochemical properties and requiring a complex approach during the selection (development) of chemical composition of a brazing filler metal and the technological process of brazing, are shown. The practical solutions mentioned in the work are of great importance to many industries and extend the scope of brazed structures applications.

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Received 11.02.2020