Kovove Mater. 51 2013 19–24
DOI: 10.4149/km_2013_1_19

Mechanical properties of joints of stainless steel and titanium brazed with silver filler metals

A. Winiowski*

Department of Welding Technology, Institute of Welding, Gliwice, Poland

Received 7 March 2012, received in revised form 25 September 2012, accepted 1 October 2012

Abstract

Joining of titanium and its alloys with stainless steel by means of welding methods and obtaining joints characterised by good operation properties constitutes nowadays a significant problem in relation to research and technology. Apart from specialised welding technologies, brazing is one of the basic methods applied for joining these material combinations having diversified physical and chemical properties. Brazing is especially recommendable in the production of systems and heat exchangers for chemical industry as well as subassemblies of nuclear reactors and aircraft engines and accessories. Similarly as in case of welded joints of stainless steel and titanium, mechanical properties of brazed joints of the aforesaid materials are connected with the occurrence of hard and brittle intermetallic phases appearing often in the form of continuous layers on braze boundaries.

This work reports testing of strength properties and investigation of structures of vacuum-brazed joints of stainless chromium-nickel steel (X6CrNiTi18-10) and titanium (Grade 2) at 820–900 °C for 5–20 min by means of silver brazing filler metals grade B-Ag72Cu-780 (Ag72Cu28), B-Ag68CuSn-730/755 (Ag68Cu28Sn4), and B-Ag65CuSnNi-740/767 (Ag65Cu28Sn5Ni2). Conducted investigation of joint structures indicates brittle layers of solid solutions on the base intermetallic phase where the test pieces lost their continuity in the shear test.

The test results allowed to specify the most convenient brazing parameters of the tested material system from the mechanical properties point of view. Kinetic of creation and development of brittle layers of solid solutions on the base intermetallic phases in structures of brazed joints will be presented in separate publication. This publication regards only to the results of structural test which are connected with mechanical properties of joints.

Key words: vacuum brazing, stainless steel, titanium, mechanical properties of brazed joints, brazing parameters

1. Introduction

Joining of materials having diversified physical and chemical properties and obtaining joints characterised by good operation properties constitutes today a significant problem with reference to research and technology. The issue is related to constructions and subassemblies used in modern sectors of industry and economy [1–6, 9].

Apart from specialised welding technologies, brazing is one of the basic methods applied for joining titanium and its alloys with stainless steel in the production of systems and heat exchangers for chemical industry as well as subassemblies of nuclear reactors and aircraft engines and accessories [1–6].

Quite often in case of titanium constructions, technical specifications allow for the replacement of some titanium elements with those made of considerably cheaper stainless steel. This, however, is conditioned by good operation properties (especially mechanical) of joints. Brazing is applicable also in the aforesaid area.

Similarly as in case of welded joints of titanium and stainless steel, the mechanical properties of brazed joints of the aforesaid materials are connected with the occurrence of hard and brittle intermetallic phases [7, 8, 10]. Titanium, being a reactive metal, forms intermetallic phases with the basic components of

* Tel.: 48 32 3358235; fax: 48 32 231 4652; e-mail address: andrzej.winiowski@is.gliwice.pl

most brazing filler metals. Particularly negative on the mechanical properties of brazed joints is the impact of intermetallic phases formed in a peritectic reaction as continuous brittle and hard layers on braze boundaries. Such layers, poorly connected to a parent metal and braze, being significantly different from them in relation to thermal expansion coefficient, facilitate cracking as early as at the stage of braze solidification. In the event of the occurrence of tensile or shearing stress, the layers are also responsible for significant weakening of the joint.

Available information concerning mechanical properties of such joints, usually formed with silver brazing filler metals, is quite diversified and so are recommendable temperature- and time-related brazing parameters [1–6, 10–15].

Research on brazing technology of titanium (Grade 2) with stainless steel (grade X6CrNiTi18-10) using silver brazing alloys was conducted in previous years in Institute of Welding in Gliwice [18–20].

This article presents the results of tests related to time and temperature conditions of vacuum brazing of stainless chromium-nickel steel with titanium by means of B-Ag72Cu-780 (Ag72Cu28), B-Ag68CuSn-730/755 (Ag68Cu28Sn4) and B-Ag65CuSnNi-740/767 (Ag65Cu28Sn5Ni2) silver brazing alloys and their influence on the quality and mechanical properties of joints. The purpose of the above investigation was to determine the optimum technological brazing conditions ensuring the best possible quality and mechanical properties of joints.

2. Parent and brazing filler metals

The following parent metals were used during the investigation:

– stainless steel – 28 mm diameter rod, grade X6CrNiTi18-10 according to PN-EN 10088-1, with the chemical composition according to the analysis: 0.017 % C, 18.09 % Cr, 9.64 % Ni, 0.78 % Si, 1.37 % Mn, 0.20 % Ti;

– titanium – a 25-mm thick sheet, Grade 2, according to ASTM B 265-09 (maximum impurity content: 0.1 % C, 0.25 % O, 0.03 % N, 0.0125 % H, 0.03 % Fe).

The brazing filler metals used in the tests were silver brazing alloys, grade B-Ag72Cu-780 (Ag72Cu28), B-Ag68CuSn-730/755 (Ag68Cu28Sn4) and B-Ag65-CuSnNi-740/767 (Ag65Cu28Sn5Ni2) in the form of a band being 0.1 mm thick.

3. Brazing of samples for strength and structural tests

Shear strength tests and structural investigation of brazed joints of stainless steel (X6CrNiTi18-10) with titanium (Grade 2) involved the application of butt-brazed samples of cylindrical elements having slightly diversified diameters, i.e. stainless steel – ø $25 \times 15\ mm^2$, titanium – ø $20 \times 15\ mm^2$.

Silver brazing filler metals grade B-Ag72Cu-780 (Ag72Cu28), B-Ag68CuSn-730/755 (Ag68Cu28Sn4) and B-Ag65CuSnNi-740/767 (Ag65Cu28Sn5Ni2) in the form of profiles having the dimensions of ø $20 \times 0.1\ mm^2$ were inserted (3 pieces) between elements to be joined distancing in this way brazing gaps between these elements (total thickness of braze layer 0.3 mm).

As it has been proved during tests conducted with limited wettability materials creating brittle phases in joints when used with brazing alloy, this type of a sample (cylindrical sample used for the testing of diffusion-brazed joints) ensures a free course of diffusion processes in a braze and features quite a strong reaction in case of the occurrence of brittle phases impairing the quality of joints [18].

The brazing of steel – titanium samples etched in solutions of appropriate acids was performed in TORVAC S-16 furnace in vacuum conditions within the range of 10^{-3}–10^{-4} mbar applying brazing temperatures of 820, 860 and 900 ℃ measured directly on the samples subject to brazing.

The selection of brazing temperatures in case of steel – titanium joints was conditioned by the brazing properties of the metals to be joined. On the one hand, due to the occurrence of allotropic change ($\alpha \rightarrow \beta$) and excessive growth of titanium grains resulting in the reduction of titanium mechanical properties and creation of brittle intermetallic phases in the braze, the brazing temperature should not exceed 900 ℃. On the other hand, however, owing to the poor wettability of stainless chromium-nickel steel by silver brazing alloy in vacuum conditions, the brazing temperature should be over 850 ℃ and even exceed 900 ℃ [1–6, 18].

The hold time of the samples at the brazing temperature was selected within quite a vast range of 5–20 min. It needs to be emphasized that in case of titanium, the commonly recommended hold time should be possibly short in order to limit the formation of brittle intermetallic phases with brazing alloy components, especially with copper. However, in order to ensure complete wetting of stainless steel, a slightly longer time than that for brazing is required.

The brazed joints used in tests were first subject to a qualitative visual inspection which revealed the incomplete fusion of the brazing filler metal and incomplete filling of the gaps in joints produced at 820 ℃, with the hold times of 5 and 10 min, respectively. The joints made at 820 ℃/15–20 min, 860 ℃/5–20 min and 900 ℃/5–20 min demonstrated comparably good quality and entirely filled-up brazing gaps.

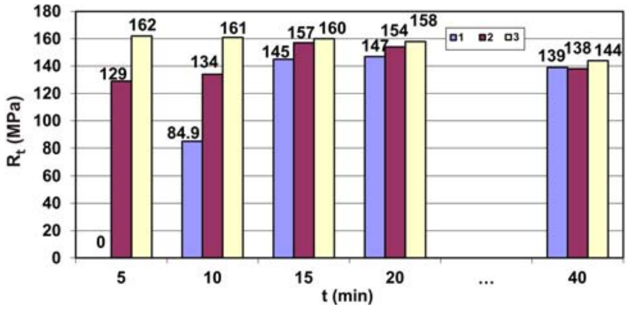

Fig. 1. Shear strength (R_t) for stainless steel – titanium joints brazed with B-Ag72Cu-780 silver brazing alloy at temperatures of 820 °C (1), 860 °C (2), 900 °C (3) and time 5–40 min.

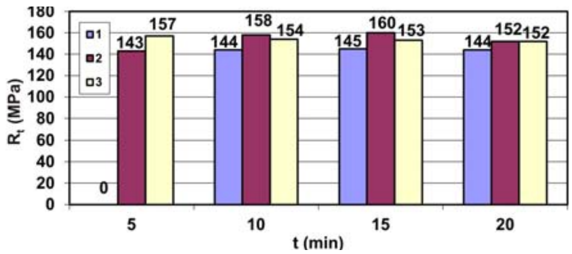

Fig. 2. Shear strength (R_t) for stainless steel – titanium joints brazed with B-Ag68CuSn-730/755 (Ag68Cu28Sn4) silver brazing alloy at temperatures of 820 °C (1), 860 °C (2), 900 °C (3) and time 5–20 min.

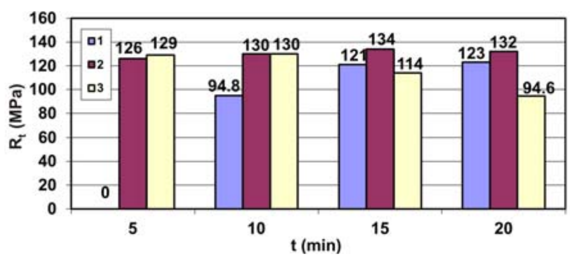

Fig. 3. Shear strength (R_t) for stainless steel – titanium joints brazed with B-Ag65CuSnNi-740/767 (Ag65Cu28-Sn5Ni2) silver brazing alloy at temperatures of 820 °C (1), 860 °C (2), 900 °C (3) and time 5–20 min.

4. Brazed joint strength tests

The cylindrical test pieces were subjected to shearing tests involving the application of special shearing shackles eliminating the effect of crosswise bending during shearing. The tests were carried out using an Instron-manufactured testing machine (model 4210). The test results are presented in Figs. 1–3.

All the samples became separated on the steel side.

The highest strength values of the joints made of three silver filler metals were obtained:

– for joints made with B-Ag72Cu-780 filler metal, brazed at 860 °C with the hold time of 15 min (157 MPa), as well as for joints brazed at 900 °C with the hold time of 5–20 min (158–162 MPa);

– for joints made with Ag68CuSn-730/755 filler metal, brazed at 860 °C with the hold time of 10–15 min (158–160 MPa), as well as for joints brazed at 900 °C with the hold time of 5 min (157 MPa);

– for joints made with B-Ag65CuSnNi-740/767 filler metal, brazed at 860 °C with the hold time of 10–20 min (130–134 MPa), as well as for joints brazed at 900 °C with the hold time of 5–10 min (129–130 MPa).

The remaining joints obtained at 820 °C as well as 860 and 900 °C, but with shorter or longer hold times, demonstrated lower strength properties. The reasons for the weakening of such joints may be attributed to lower wettability of stainless steel at lower temperatures and shorter hold times and, which was demonstrated during the structural investigation, to the growth of brittle intermetallic phases at higher temperatures and longer hold times.

For comparison, the strength of the joints connecting elements of chromium-nickel (austenitic) stainless steel brazed with B-Ag72Cu-780 filler metal is 210–250 MPa, whereas for joints connecting titanium elements it amounts to 130–180 MPa [5, 6].

5. Metallographic and structural investigation of brazed joints

The joints of the X6CrNiTi18-10 stainless steel with titanium (Grade 2) brazed with the B-Ag72Cu-780 (Ag72Cu28), B-Ag68CuSn-730/755 (Ag68Cu28-Sn4) and B-Ag65CuSnNi-740/767 (Ag65Cu28Sn5Ni2) silver brazing alloys in specific and changeable technological conditions were subjected to structural investigation including: optical microscope, scanning electron microscope (SEM), energy-dispersion spectrometer (EDS) and transmission electron microscope (TEM).

The results of the metallographic and structural investigation of the brazed joints of titanium and stainless steel demonstrated significant (related to titanium reactivity) diffusion changes in brazes and relatively big diffusion zones of brazes on the boundaries with joined metals. The structures of the aforementioned brazes varied quite significantly depending on brazing temperature (820, 860, 900 °C) (Figs. 4–6). As was demonstrated by the electron diffraction [20], the phases present in the structures were mostly solid solutions, very often based on intermetallic phases. The compositions of the solutions were diversified and in some cases diverged from stoichiometric compositions attributable strictly to such phases [7, 8], the decisive factor being the location in the braze structure.

As mentioned before, kinetic of creation and de-

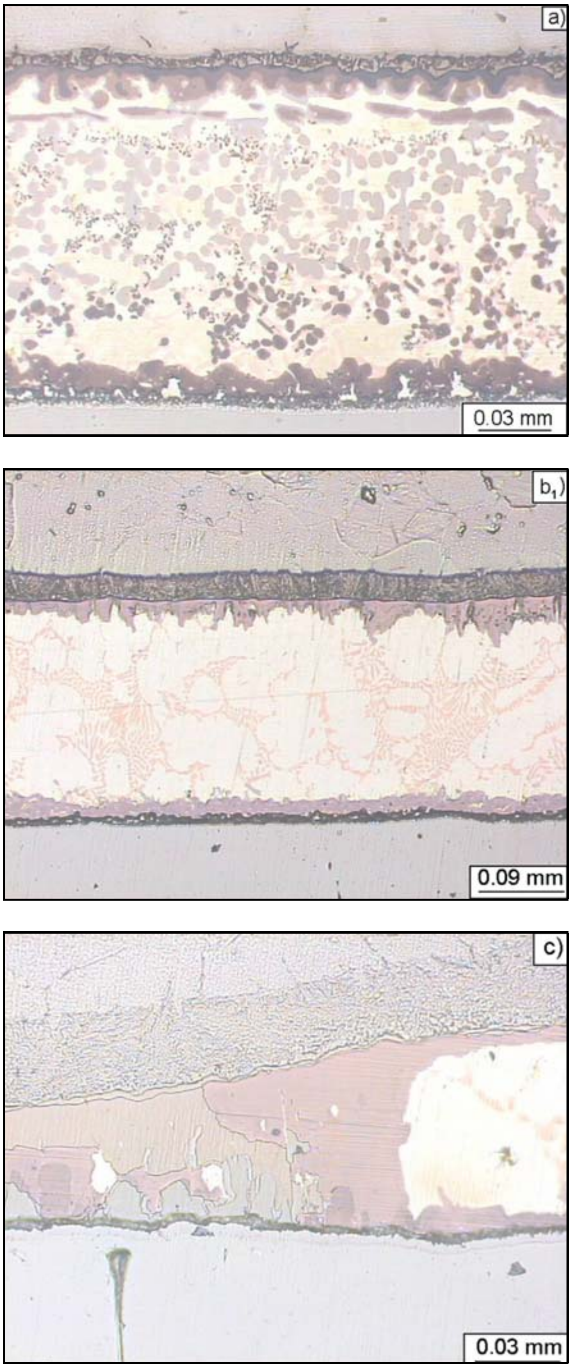

Fig. 4. Microstructure of stainless steel (down) – titanium (up) joints brazed with silver B-Ag72Cu-780 brazing alloy at temperatures of 820 °C (a), 860 °C (b_1), 900 °C (c) and time 15 min. Etch. Buehler.

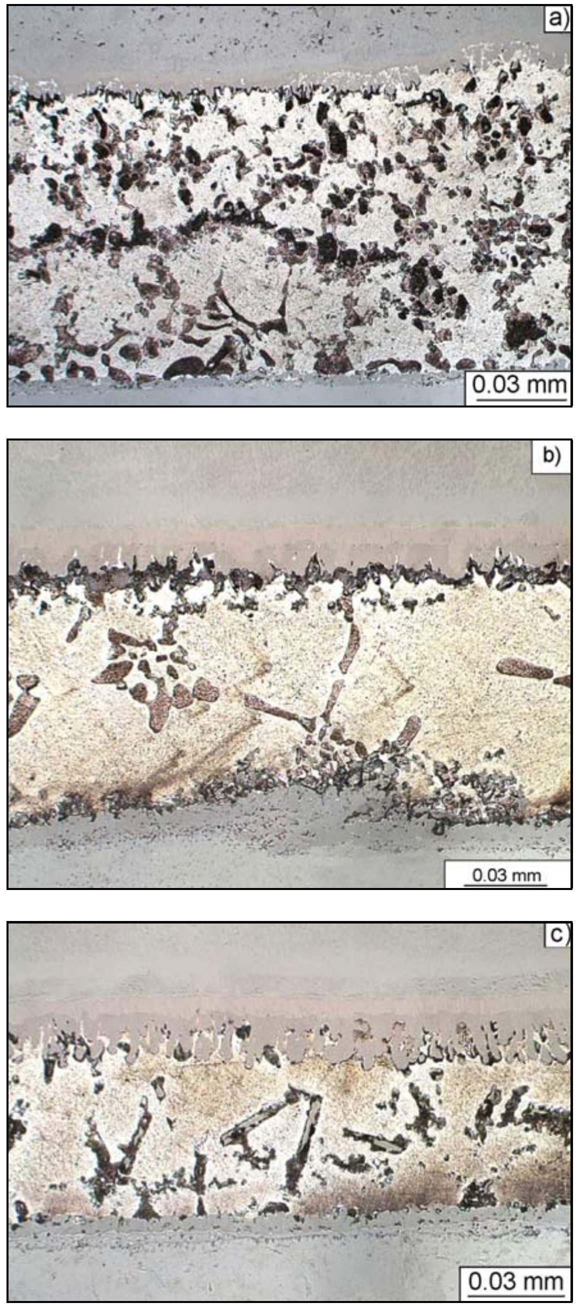

Fig. 5. Microstructure of stainless steel (down) – titanium (up) joints brazed with silver B-Ag68CuSn-730/755 (Ag68Cu28Sn4) brazing alloy at temperatures of 820 °C (a), 860 °C (b), 900 °C (c) and time 15 min. Etch. Buehler.

velopment of brittle layers of solid solutions on base intermetallic phases in structures of brazed joints will be presented in separate publication. This publication regards only to the results of structural test, which are connected to mechanical properties of joints.

In case of the joints brazed with B-Ag72Cu-780 filler metal at higher temperatures, i.e. 860 and 900 °C (Fig. 4a,b_1,c) it was possible to observe two types of structures in the brazes, i.e. the one "enriched in copper and titanium" (darker) and the one "enriched in silver" (brighter). This fact confirmed the observation of the disintegration of the eutectic structure of Ag-Cu alloy after dissolution of Ti therein – the observation being published in works [16–18]. It was also

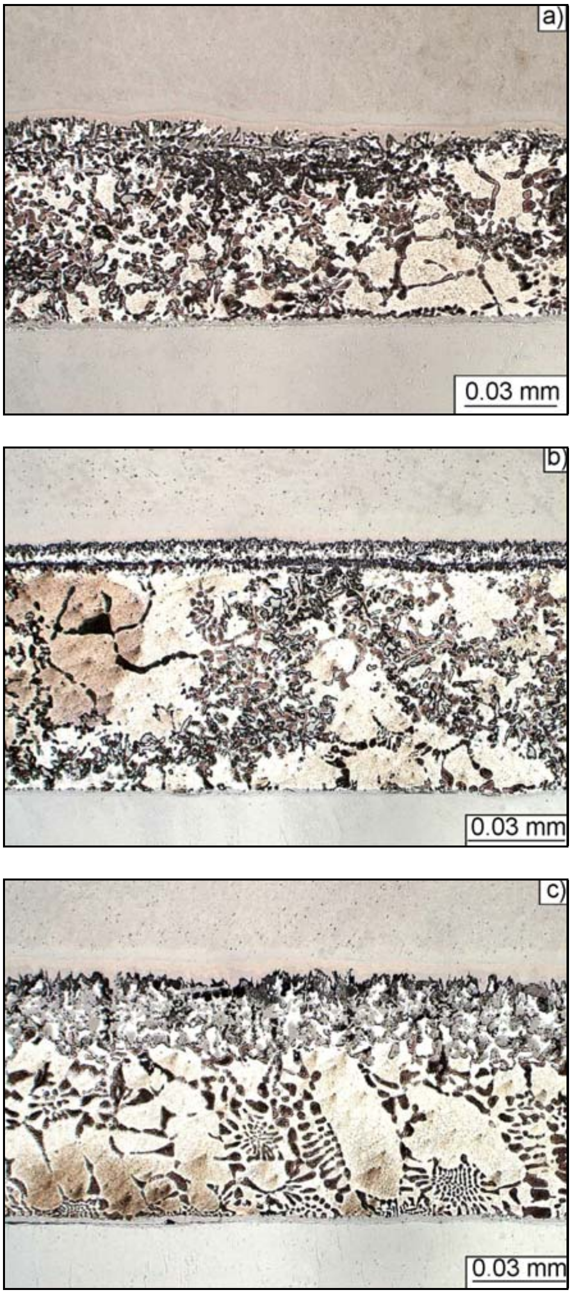

Fig. 6. Microstructure of stainless steel (down) – titanium (up) joints brazed with silver B-Ag65CuSnNi-740/767 (Ag65Cu28Sn5Ni2) brazing alloy at temperatures of 820 °C (a), 860 °C (b), 900 °C (c) and time 15 min. Etch. Buehler.

ascertained that with an increase in temperature and time of brazing, the areas of the structure "enriched in silver", originally in the form of intermittent sections present in the intersection of the joint, became concentrated in its central part to form the shape of a "flattened drop" (Fig. 4c).

As mentioned earlier, all the samples in strength tests became separated on the steel side.

On the stainless steel side, in the brazes made with filler metal B-Ag72Cu-780 at 820–860 °C, it was possible to observe the layers of solutions with high iron content, of the composition of the basis CuTi intermetallic phase with inclusions of grains of solutions based on the Cu_3Ti_2, $CuFeTi_2$, Cu_4Ti_3, $CuTi_2$, and $Ag_{17}Cu_{17}Ti_{66}$ phases as well as of solid solutions based on silver and copper.

In the samples made at 900 °C it was possible to observe a separated solid solution based on the $CuFeTi_2$ phase and in the structure "enriched in silver" – additionally with inclusions of a solution based on the $Ag_{17}Cu_{17}Ti_{66}$ phase.

In all of the above brazed joints, the steel was separated from braze by a relatively thin layer of a solid solution based on the $Cr_{13}Fe_{35}Ni_3Ti_7$ phase.

In case of the steel-titanium joints brazed with a B-Ag68CuSn-730/755 and B-Ag65CuSnNi-740/767 filler metals at 820–900 °C it was possible to observe the layer of the CuTi phase (solid solution based on this phase with high iron content) with the inclusions of the copper-based Cu-Ag-Ti and Cu-Ag-Sn solid solutions and the silver-based Ag-Cu solid solutions on the stainless steel side.

The strength and metallographic tests of the said brazed joints and microhardness measurements of the structural phases demonstrated that the hard (microhardness of 407–420 HV0.01) and brittle layers located nearest to the boundary between the braze and the steel had the strongest impact on the strength of the joints. These layers were composed of solid solutions based on the $Cr_{13}Fe_{35}Ni_3Ti_7$ and $CuFeTi_2$ intermetallic phases as well as on the CuTi phase with a significant content of Fe. The aforesaid area was also subjected to cracking and separation of samples caused by the load exerted during the shear tests.

6. Conclusions

1. The tests of the vacuum brazing of steel (X6CrNiTi18-10) and titanium (Grade 2) joints revealed good repeatable quality of the joints made with B-Ag72Cu-780, B-Ag68CuSn-730/755 and B-Ag65CuSnNi-740/767 brazing filler metals, brazed at 820 °C, with the hold-time of 15–20 min and brazed at 860–900 °C, with the hold-time of 5–20 min, respectively.

2. The steel-titanium joints made with B-Ag72Cu-780, B-Ag68CuSn-730/755 and B-Ag65CuSnNi-740/767 brazing filler metals represented the highest shear strength, in 158–162 MPa, 158–160 MPa and 130–134 MPa ranges, respectively, in case of applying the brazing temperature of 900 °C and hold-time of 5–20 min for B-Ag72Cu-780 filler metal, 860 °C, and the hold-time of 10–15 min for B-Ag68CuSn-730/755 filler metal and 860 °C, and the hold-time of 10–20 min for B-Ag65CuSnNi-740/767 filler metal.

3. The structural examination of the steel-titanium joints made with B-Ag72Cu-780, B-Ag68CuSn-730/755 and B-Ag65CuSnNi-740/767 brazing filler metals revealed the presence of extensively expanded diffusional zones; the test pieces lost their continuity in shear test on the steel-braze border, respectively, just behind the brittle layers of $Cr_{13}Fe_{35}Ni_3Ti_7$, $CuFeTi_2$, or CuTi phase with high Fe content.

4. On the basis of the presented test results and technological observations made during the investigation it was possible to meet the assumed objective of this work and develop technological guidelines for brazing stainless steel with titanium by means of silver brazing filler metals.

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