Chapter

Microstructural Features and Mechanical Properties of Brazed Titanium Alloy Joints

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Abstract

High-temperature vacuum brazing is one of the most promising methods for producing permanent joints. This process is widely employed in the fabrication of titanium structures used in key industrial sectors, such as aerospace, chemical, medical, and power engineering. This chapter examines the fundamental features of structure and property formation in brazed titanium alloy joints produced by high-temperature vacuum brazing using Ti–Zr–Cu–Ni filler metals. Particular attention is given to the influence of the initial filler metal condition, brazing gap geometry, and isothermal holding time on microstructural evolution, chemical heterogeneity, and mechanical properties of the brazed joints. In wide brazing gaps, bulk solidification of the molten filler metal predominates, resulting in the formation of a dendritic–eutectic microstructure characteristic of cast metal, regardless of whether the filler metal is in an amorphous or crystalline state. For brazed joints of the TA15 alloy, increasing the isothermal holding time from 15 to 60 min was found to result in an increase in the width of the diffusion zone and an improvement in shear strength from 430 to 500 MPa. Reducing the gap width to capillary dimensions significantly alters the morphology of the brazed seam due to the intensification of diffusion processes. This promotes a reduction in the fraction of eutectic and intermetallic constituents and leads to the formation of a more homogeneous lamellar $\alpha + \beta$ microstructure. The generalized results can be used as a scientific basis for a reasonable choice of vacuum brazing modes for titanium structures for aviation and energy purposes.

Keywords: titanium alloy, vacuum brazing, amorphous filler metal, isothermal holding, brazing gap, eutectic phases, microstructure, mechanical properties

1. Introduction

Titanium alloys are among the most strategically important structural materials due to their unique combination of high specific strength, heat resistance, corrosion resistance, and relatively low density. These properties have led to their widespread application in the aerospace, chemical, medical, and power engineering industries [1–4]. However, ensuring stable properties of titanium alloy joints remains

a challenging technological task. The primary reasons are the high chemical reactivity of titanium at elevated temperatures, its tendency to interact with oxygen, nitrogen, and hydrogen, as well as its sensitivity to α↔β phase transformations [2–6]. As a result, plate-like microstructures and intermetallic layers may form within the joint region, reducing the ductility and fracture toughness of the material.

Conventional fusion welding processes, including TIG, laser, and electron-beam welding, despite their extensive industrial application, do not always provide the required level of structural homogeneity, particularly when joining thin-walled titanium components [7]. Significant heat input may result in grain coarsening, the formation of coarse lamellar microstructures, and the development of residual stresses [8]. These phenomena are especially critical in multilayer and thin-walled structures, where even minor distortions can lead to a loss of serviceability [8]. In this regard, high-temperature vacuum brazing is considered one of the most promising methods for producing permanent joints in titanium alloys [3, 9–11]. Its advantages include lower heat input compared with fusion welding, the absence of base metal melting, the capability to produce hermetic joints of complex geometry, and high cleanliness of the interfacial region due to processing under vacuum conditions [11]. These benefits are particularly important in the manufacture of plate-fin heat exchangers, thin-walled components of aircraft engines, and power engineering structures [2, 3, 10–12].

Among titanium alloys, the pseudo-α alloys TC2, TA2, and TA15 are widely used for manufacturing critical structural components [2, 3]. TC2 alloys are characterized by good technological processability combined with sufficiently high mechanical properties and corrosion resistance, making them attractive for structural applications [2, 12]. Owing to this combination of properties, TC2 can be employed in thin-walled aerospace, power engineering, and heat-exchange components. TA15 is a highly alloyed heat-resistant titanium alloy that exhibits enhanced strength characteristics and long-term service capability at elevated temperatures.

Differences in alloying systems, phase composition, and microstructural state of these materials can significantly influence joint formation processes, diffusion kinetics, and the formation of intermetallic phases during brazing. The joint region may contain coarse lamellar structures, intermetallic layers, residual stresses, and other microstructural heterogeneities that adversely affect ductility and fracture resistance [10, 13, 14].

Therefore, investigating the mechanisms governing the formation of microstructure and properties of brazed joints produced from TC2, TA2, and TA15 alloys is an important scientific and technological task aimed at developing reliable joining technologies for titanium materials used in critical aerospace and power engineering applications.

2. Effect of filler metal initial state and brazing gap width on the formation of microstructure in brazed titanium alloy joints

The alloying system and technological characteristics of the filler metal play a crucial role in the brazing process. Aluminum-, silver-, and titanium-based filler metals are commonly used for brazing titanium alloys [9, 15–18]. Among them, filler metals based on the Ti–Zr–(Cu, Ni) system have gained widespread application due to their relatively low melting temperatures, good wettability of titanium surfaces,

and ability to produce joints with satisfactory mechanical properties [10, 11, 13, 19–21].

Particular attention has been paid to amorphous filler metals produced by rapid solidification techniques [22, 23]. The main advantage of amorphous filler metals is that they can be manufactured as homogeneous, ductile thin ribbons with a thickness of 30–50 μm, even from alloys containing brittle intermetallic or eutectic phases [1]. This feature enables the fabrication of preforms of virtually any geometry, precise control of filler metal quantity, and brazing of extremely thin components, such as heat exchangers with separator plate thicknesses of approximately 0.08 mm. Owing to their stable chemical composition and high chemical homogeneity throughout the entire volume, amorphous filler metals exhibit enhanced technological performance [22–27].

The use of amorphous filler metals is particularly advantageous for brazing thin-walled titanium structures, where a local excess of liquid phase may lead to a reduction in wall thickness and promote the formation of brittle eutectic and intermetallic constituents. Therefore, effective control of microstructure evolution within the brazed seam requires a coordinated selection of filler metal composition, brazing temperature, isothermal holding time, and brazing gap width.

Amorphous filler metals are characterized by a homogeneous distribution of alloying elements, which promotes effective wetting of the base metal surface, reduces the likelihood of incomplete filling defects, and consequently improves the reliability of brazed joints [2]. Among such materials, Ti–Zr–Ni–Cu filler metals are widely employed for brazing titanium and its alloys [3–6].

In the present study, commercially pure titanium TA2 (α-alloy) and the pseudo-α titanium alloys TC2 and TA15 were used as base materials (**Table 1**). The microstructure of TC2 consists predominantly of α phase with a small amount of β phase (1–5%). The alloy exhibits good workability in both hot- and cold-worked conditions and is commonly supplied in the form of sheets, strips, and foils. TA15 is a high-strength, heat-resistant wrought titanium alloy. Owing to its unique combination of high strength and the ability to withstand prolonged service at temperatures up to 500 °C, it is widely used in aerospace and defense applications (**Table 1**).

The Ti–23Cu–12Zr–12Ni filler metal was used in both amorphous and crystalline states. The amorphous filler metal was produced as a ductile ribbon with a thickness of 30–50 μm, whereas the crystalline filler metal was prepared by crushing a cast ingot into small pieces.

The geometry of the brazed seam is one of the key factors affecting microstructure formation and the mechanical properties of brazed joints. Unlike fusion welds, where the primary role is played by the local melting of the base metal,

Grade	Chemical composition, wt.%							
	Ti	Al	Zr	V	Mo	Mn	Fe	Si
TA15 (VT20)	Rem.	5.5–7.0	1.5–2.5	0.8–2.5	0.5–2.0	–	0.25	0.15
TC2 (OT4)	Rem.	3.5–5.0	–	–	–	0.8–2.0	<0.1	<0.1
TA2 (VT1-0)	Rem.	–	–	–	–	–	≤0.20	<0.1

Table 1.
Chemical composition of titanium-based alloys.

the microstructure of a brazed joint is formed through the wetting of the mating surfaces, capillary flow of the molten filler metal, mutual diffusion between the filler metal and base metal constituents, and subsequent solidification of the liquid phase. Consequently, even under identical brazing temperatures, holding times, and filler metal compositions, variations in the brazing gap width may result in significant differences in seam morphology.

When brazing titanium alloys with Ti–Zr–Cu–Ni filler metals, the phase composition and microstructural state of the seam are strongly influenced by the volume of liquid phase retained within the joint gap [11, 22, 28]. Wider gaps accommodate a larger volume of molten filler metal, while the diffusion of low-melting-point elements into the titanium matrix proceeds more slowly. Under such conditions, regions enriched in Cu, Ni, and Zr may remain in the central part of the seam, promoting the formation of eutectic constituents and intermetallic compounds such as Ti_2Cu, Ti_2Ni, TiCu, or complex phases of the $(Ti,Zr)_2(Cu,Ni)$ type [22].

Therefore, the brazing gap width should be considered not only as a technological parameter required for capillary filling of the joint but also as an important factor governing microstructure evolution, phase distribution, and diffusion-controlled redistribution of filler metal constituents within the brazed seam.

To analyze the effect of brazing gap width on microstructure formation, specimens with a variable gap configuration were employed. In this approach, a wedge-shaped gap was created between two TC2 titanium alloy plates, allowing the evolution of microstructure to be examined within both wide-gap and capillary-gap regions of a single brazed specimen (**Figure 1a**). The wider region of the joint contains a larger volume of molten filler metal, whereas the capillary region contains only a minimal amount. This configuration makes it possible to evaluate changes in microstructure formation and variations in the volume fractions of individual phase constituents as a function of gap width.

Specimens with a variable brazing gap allow for an approximate reproduction of the brazed joint formation conditions typical of thin-walled components with complex geometry, where the actual gap width may vary along the contact interface. This approach is consistent with established practices of using variable-gap

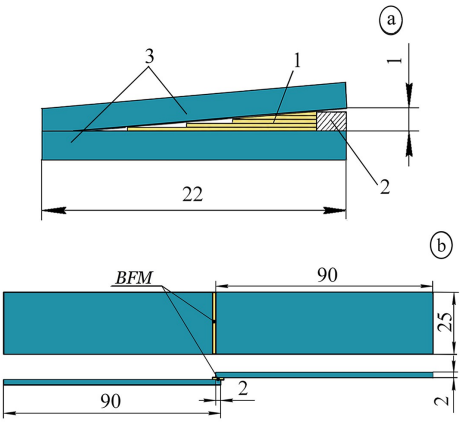


Figure 1.
Schematic representation of a specimen with a variable brazing gap (a): 1 – filler metal; 2 – insert element for fixing the gap width; 3 – base metal; (b) specimen for mechanical tests.

specimens to evaluate capillary filling behavior and to determine the allowable gap limits in brazing processes [29–32].

In the present study, the amorphous Ti–Zr–Cu–Ni filler metal, in the form of a thin ribbon, was placed directly within the joint gap, whereas fragments of cast crystalline filler metal of the same composition were positioned adjacent to the gap. During heating, the cast filler metal melts and, under capillary forces, flows into and fills the joint gap. This approach enables the assessment not only of the influence of gap width but also of the role of the initial structural state of the filler metal-amorphous or crystalline. Before brazing, the sample blanks were mechanically processed (polished using a diamond wheel with a grain size of 125 μm) and treated with B-70 gasoline and technical alcohol. Brazing was performed in a vacuum furnace (SGV 2.4-2/15-I3) with radiant heating at a temperature of 1000 °C and a holding time of 10 min under a working chamber pressure of 1.33×10^{-3} Pa. The heating rate was 18–20 °C/min, while the cooling rate in the temperature range of 1000–250 °C was 10–15 °C/min. The temperature measurement error was ± 5 °C. To evaluate the shear strength of the brazed joints (**Figure 1b**), tests were carried out at ambient temperature according to DIN EN 12,797 [33]. Lap joints (with an overlap width b = 2 mm) were brazed at a fixed clearance of 50 μm.

The experimental results showed that, under identical temperature–time processing conditions, the nature of filler metal crystallization and the morphological features of structure formation in fillet regions and wide gaps are similar. In particular, during brazing with crystalline filler metal, the formation of a cast-like microstructure is observed in the fillet regions (**Figure 2**). This effect is attributed to the relatively large volume of filler metal and the sufficient distance from the base metal interface, which limits mutual diffusion processes. Under these conditions, the brazed seam metal solidifies according to the fundamental laws of cast alloy crystallization.

Micro-energy-dispersive X-ray spectroscopy analysis revealed that a eutectic constituent enriched in zirconium is formed in the intergranular regions (**Table 2**; Spectrum 2; **Figure 2**).

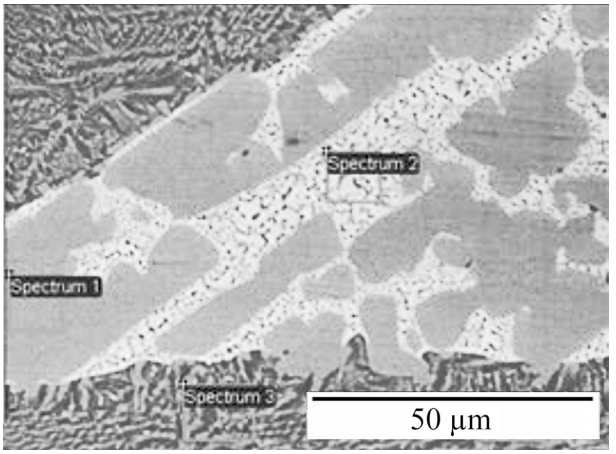


Figure 2.
Microstructure of the straight fillet region formed using crystalline filler metal.

No of spectrum	Al	Ti	Mn	Ni	Cu	Zr
1	0.44	57.06	–	6.4	30.75	5.34
2	1.51	44.81	0.73	13.37	15.82	23.76
3	2	73.08	0.47	5.29	11.74	7.42

Table 2.
Distribution of chemical elements in individual phases of the fillet region formed using cast filler metal.

Analysis of the microstructure of brazed joints showed that, when using amorphous filler metal in a wide gap (40–100 μm), the same structural constituents are formed (**Figure 3a**) as in the case of brazing with crystalline filler metal under comparable conditions (**Figure 3b**). During solidification, a primary dendritic phase based on titanium is formed first, containing copper, nickel, and zirconium (**Table 3**; Spectrum 3; **Figure 3a**).

In both cases, a lower-melting phase crystallizes within the interdendritic regions in the form of a eutectic constituent composed of a zirconium-enriched phase (**Table 3**, Spectrum 2, **Figure 3a**). A more detailed investigation of the eutectic region revealed that one of its constituents is a light phase enriched in zirconium (28.89 wt.%) and contains the other elements of the filler metal (**Table 3**, Spectrum 2, **Figure 3a**). The second constituent of the eutectic is a dark titanium-based phase that crystallizes as fine dispersed precipitates with sizes ranging from 0.4 to 1.6 μm (**Table 3**, Spectrum 1, **Figure 3a**), where the zirconium content decreases to 10.82 wt.%.

It should be noted that small amounts of aluminum and manganese, which are alloying elements of the titanium alloy being brazed, are present in both the brazed seams and the fillet regions. This can be explained by mutual diffusion processes between the base material and the filler metal occurring at the filler metal–base metal interface during brazing [34], under concentration-gradient conditions and non-equilibrium solidification of the brazed seam metal.

When the brazing gap is reduced to 4–5 μm, the morphological structure of the brazed seams undergoes significant changes, both in joints produced using the amorphous filler metal (**Figure 4a,c**) and those produced using the crystalline filler metal (**Figure 4b,d**).

Compared with wider seam regions, the volume fraction of the liquid phase decreases, while the contribution of diffusion processes and interfacial interactions between the filler metal and the base material increases. As a result, the dendritic–eutectic microstructure characteristic of wider gaps and fillet regions is no longer observed. However, complete structural homogenization has not yet occurred. Localized dispersed phases enriched with filler-metal constituents remain in the central region of the seam, together with thin layers or individual microstructural constituents that differ in contrast from the adjacent base metal and contain elevated concentrations of zirconium, copper, and nickel (**Table 4**).

The results of metallographic investigations of heat exchanger fragments brazed with the amorphous Ti–Zr–Cu–Ni filler metal confirm the established mechanisms governing the formation of seam microstructures. It was shown that the brazing gap width has a significant influence on the morphology of the seam metal (**Figure 5a–c**). In the fillet regions, solidification results in the formation of

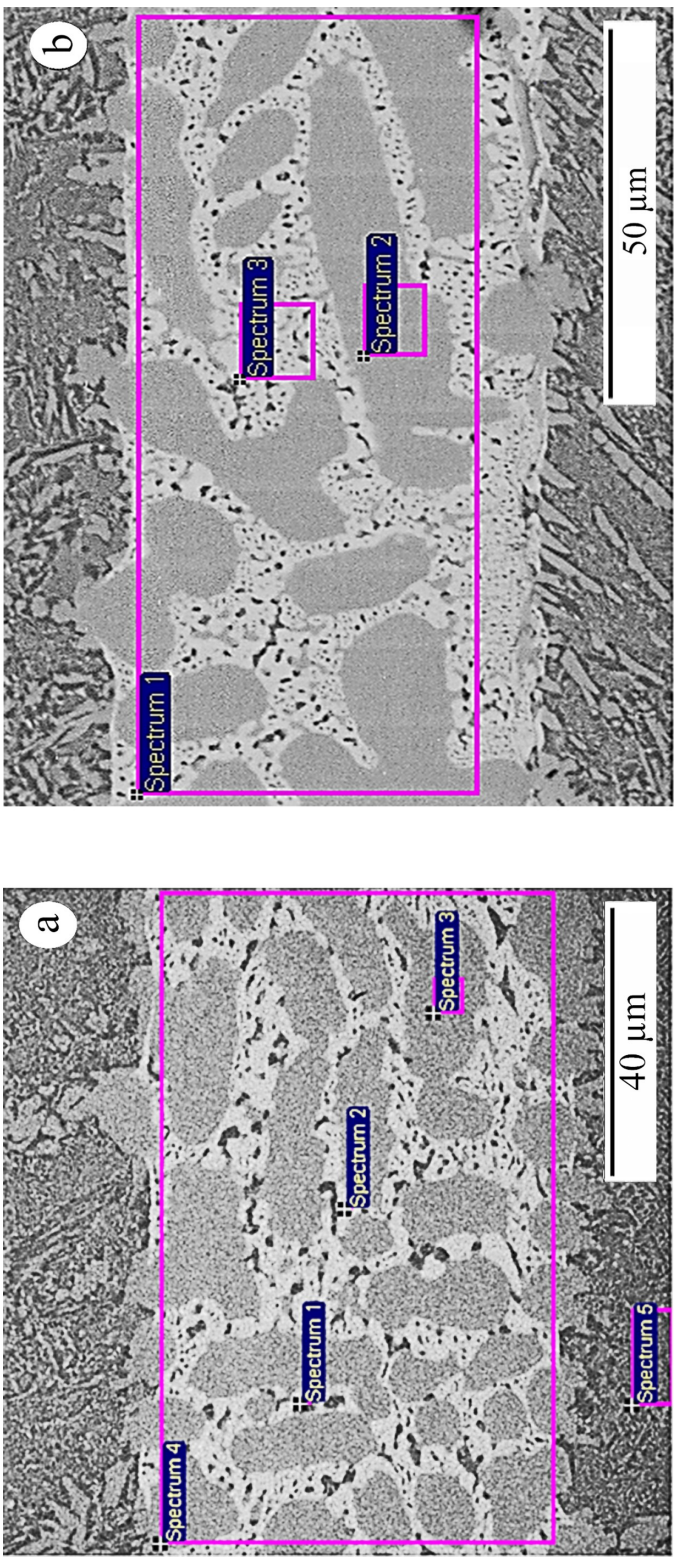


Figure 3.
(a) Microstructure of the wide region of the brazed joint produced using amorphous and (b) crystalline Ti–Zr–Cu–Ni filler metal.

No ofspectrum	Al	Ti	Mn	Ni	Cu	Zr
Brazed seam (Ti–Zr–Cu–Ni filler metal in the form of an amorphous ribbon, **Figure 3a**)						
1	1.39	80.65	0.46	3.16	3.52	10.82
2	1.19	32.34	0.69	18.26	18.64	28.89
3	0.36	48.20	0.15	10.05	32.37	8.88
4	0.65	45.24	0.32	12.55	25.51	15.73
5	1.53	69.51	0.39	7.19	13.02	8.36
Brazed seam (crystalline Ti–Zr–Cu–Ni filler metal, **Figure 3b**)						
1	0.64	51.25	0.2	10.63	22.35	14.94
2	0.33	54.61	0.13	8.5	28.84	7.59
3	1.11	46.01	0.47	13.61	15.69	23.12

Table 3.
Chemical inhomogeneity of the wide region of the brazed joint produced using Ti–Zr–Cu–Ni filler metal, wt.%.

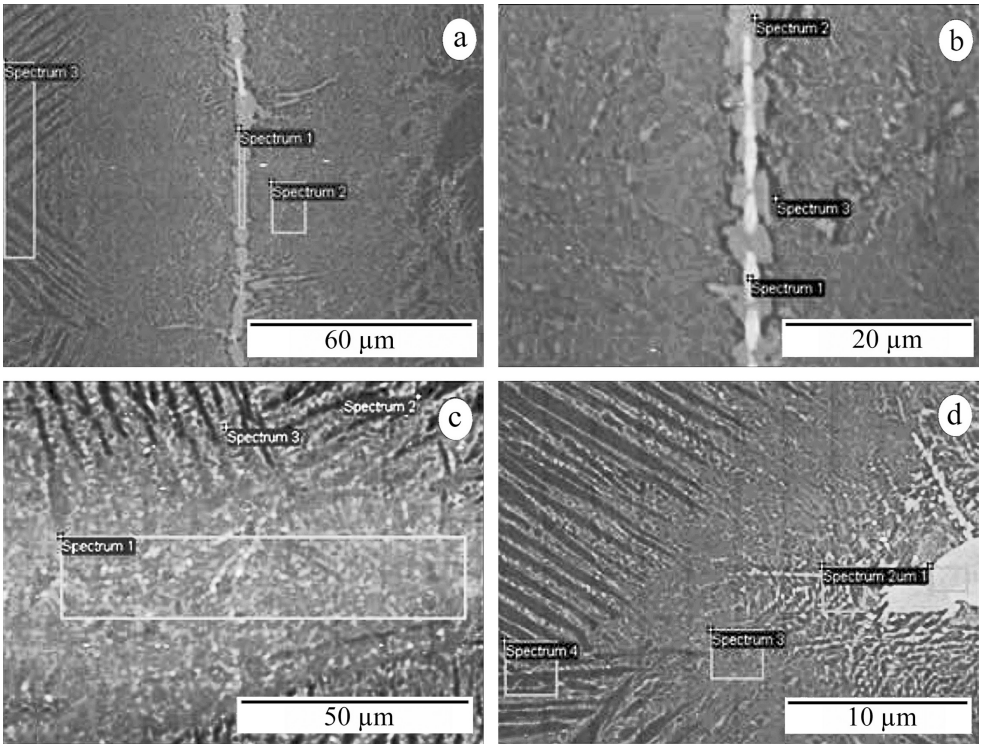


Figure 4.
(a, c) Microstructures of brazed seams produced with a reduced brazing gap using amorphous and (b, d) crystalline filler metals.

a three-phase microstructure (**Figure 5c**), consisting primarily of a titanium-rich phase containing increased copper content and approximately 15 wt.% zirconium.

No of spectrum	Al	Ti	Mn	Ni	Cu	Zr
Amorphous filler metal, **Figure 4a**.						
1	0.64	55.03	–	6.53	26.66	11.15
2	1.86	75.93	0.55	4.49	8.49	8.68
3	3.40	85.98	0.56	2.64	5.03	2.38
Crystalline filler metal, **Figure 4b**.						
1	1.73	39.04	0.39	12.80	17.44	28.60
2	0.40	54.99	–	7.34	27.73	9.53
3	2.79	86.16	0.39	1.41	2.72	8.52
Amorphous filler metal, **Figure 4c**.						
1	2.11	79.60	0.50	3.19	7.93	6.67
2	3.33	91.69	–	–	2.47	2.51
3	2.02	79.52	1.36	4.90	6.81	5.40
Crystalline filler metal, **Figure 4d**.						
1	0.58	56.51	–	6.58	30.16	6.15
2	2.01	76.25	–	4.08	11.16	6.50
3	2.13	80.63	0.51	3.48	8.86	4.39
4	3.00	89.08	–	1.53	4.43	1.96

Table 4.
Local elemental distribution in brazed seams, wt.%.

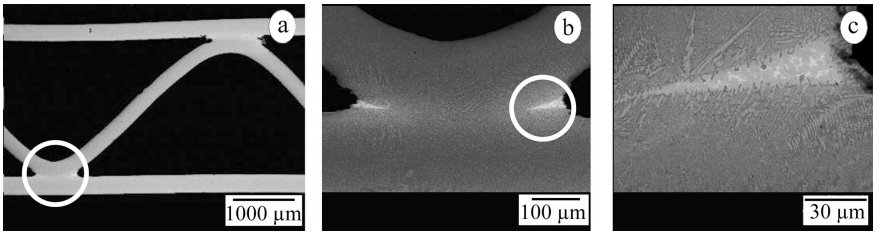


Figure 5.
(a) Fragment of a brazed titanium heat exchanger: general view; (b) microstructure of the brazed seam; and (c) the fillet region.

A eutectic constituent is localized along the grain boundaries; this constituent is characterized by an elevated zirconium concentration and reduced titanium content.

A further reduction of the brazing gap to the so-called "zero-gap" condition results in the formation of a diffusion zone in the central region of the seam that does not contain distinct phases. This seam region loses the characteristics of a cast solidification structure: pronounced dendritic regions, continuous eutectic layers, and coarse accumulations of intermetallic phases are practically absent. The volume of molten filler metal becomes minimal, whereas the contact area with the base metal is relatively large. This promotes intensive diffusion-driven redistribution of filler-metal constituents between the liquid phase and the titanium alloy, leading

to the formation of a diffusion zone composed of common grains of the base metal, which effectively constitutes the brazed seam itself (**Figure 6a**).

This observation is confirmed by the results of electron beam scanning of the brazed seam (**Figure 6**), which indicates an increased zirconium concentration within this region (**Figure 6b**). Such a microstructure is attributed to the fact that both the filler metal and the base material share the same metallic basis, namely

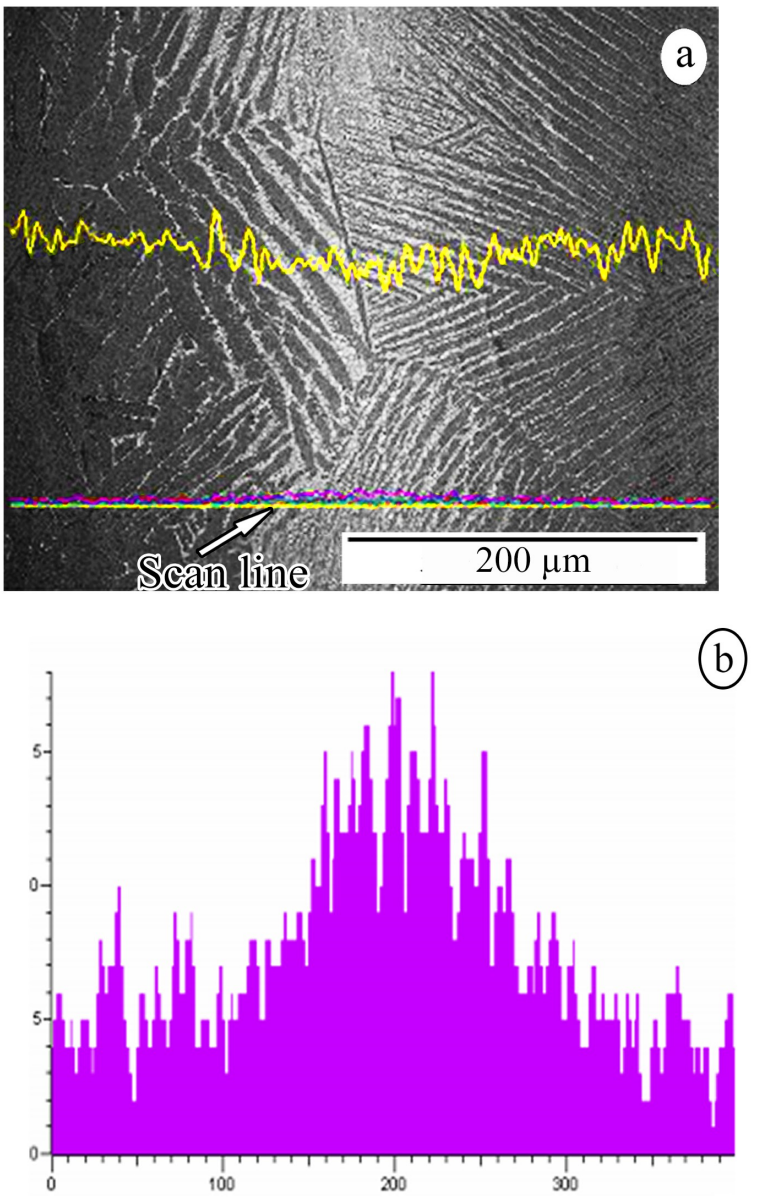


Figure 6.
(a) Microstructure of the brazed titanium alloy joint and (b) zirconium distribution across the brazed seam obtained by electron beam scanning.

titanium. According to the binary Ti–Zr phase diagram, these elements form continuous solid solutions throughout the entire concentration range [35].

Metallographic examinations and electron probe microanalysis confirmed a similar mechanism of brazed seam formation when the filler metal was used in either the amorphous or crystalline state. For such capillary and near-zero gaps, the formation of a Widmanstätten microstructure within the joint region is of particular importance. In titanium alloys, this microstructure is associated with the existence of the high-temperature β-phase and its subsequent decomposition during cooling. After heating to temperatures close to the β-transus or within the β-phase field, plates or needles of the α-phase precipitate within the β grains during cooling. As a result, a characteristic lamellar α + β microstructure is formed [10, 11].

Based on the results of metallographic investigations and electron probe microanalysis, it was established that the microstructure of the seam metal in titanium brazed joints produced using the Ti–23Cu–12Zr–12Ni filler metal under a constant vacuum brazing cycle depends on the width of the brazing gap. The smaller the brazing gap, the more closely the seam microstructure resembles that of the base metal. The morphological features and chemical composition of the phases crystallized in wide brazed seams produced using the Ti–23Cu–12Zr–12Ni filler metal in the amorphous state are similar to those observed in wide seams obtained with the crystalline filler metal. In large gaps, bulk solidification predominates, which is characteristic of cast alloys.

The shear strength of the brazed lap joints is within the range of 400–420 MPa, indicating effective seam formation when either cast crystalline or rapidly quenched amorphous filler metal is used. The determining factor is the phase-structural state of the seam, which is governed by the combined effects of gap width, brazing temperature, holding time, and cooling rate, rather than the initial condition of the filler metal (amorphous or crystalline).

In addition to the geometric parameters of the brazing gap, the evolution of brazed seam microstructures is significantly influenced by variations in the temperature–time parameters of the brazing process [4, 8, 23, 36, 37]. In particular, increasing the brazing temperature contributes to increasing the strength of brazed joints of titanium alloy TA2 [38]. Therefore, further studies will focus on investigating these effects and their relationship with the technological characteristics of brazed joints.

3. Effect of isothermal holding time on the structure and properties of brazed titanium alloy joints

The duration of isothermal holding at the brazing temperature is one of the key parameters governing the formation of the brazed seam in titanium alloys. It affects the extent of filler metal dissolution, mutual diffusion between the filler metal and the base material, the solidification conditions of the brazed seam metal, and the development of phase transformations in the regions adjacent to the joint. In titanium alloys, the holding time has a significant influence on the seam microstructure because their microstructure is highly sensitive to high-temperature thermal cycles, while prolonged exposure at elevated temperatures may result in grain coarsening and changes in the morphology of the α + β microstructure [3, 10, 11].

When the holding time is insufficient, diffusion processes cannot ensure adequate homogenization of the seam composition. As a consequence, regions of non-equilibrium solidification, increased chemical heterogeneity, and a higher volume fraction of eutectic or intermetallic constituents remain within the seam [39–42]. Conversely, excessive holding may produce the opposite undesirable effect: although the seam becomes more homogeneous, coarsening of the β grains occurs, accompanied by the formation of a coarse lamellar microstructure and a reduction in joint ductility [43]. Therefore, the optimum holding time should provide a balanced diffusion process, ensuring sufficient seam homogenization without adversely affecting the microstructural condition of the base metal.

These relationships are particularly important for titanium alloys with predominantly α-type microstructures used in critical structural applications operating under elevated temperatures and thermomechanical loading conditions. One such material is the near-α titanium alloy TA15 (**Table 1**), which, owing to alloying with Al, Zr, Mo, and V, combines good high-temperature strength, creep resistance, and processability. This alloy is widely employed in aerospace and power-generation components, particularly in thin-walled structures where dimensional stability and retention of mechanical properties after high-temperature joining cycles are essential.

At the same time, the relatively high content of α-stabilizing elements and the proximity of the brazing temperature to the range of intensive phase transformations make TA15 particularly sensitive to the temperature–time parameters of the thermal cycle. Consequently, during vacuum brazing, the isothermal holding time determines not only the degree of diffusion interaction between the filler metal and the base material but also the morphology of the α + β microstructure in the seam and adjacent regions.

More pronounced changes in seam microstructure evolution are associated specifically with the holding time. Metallographic investigations showed that at a relatively short holding time of approximately 15 min, a distinctly heterogeneous microstructure is formed within the joint region, consisting of coarse lamellar α constituents (5.5–8.5 μm wide) and interlamellar regions (3.0–6.5 μm wide) enriched with filler-metal components. Under these conditions, the seam width is approximately 70–80 μm (**Figure 7a–c**).

In the brazed seam metal, broad α-phase plates with a random orientation are clearly observed. Light interlayers enriched in copper, nickel, and zirconium are present between these plates. Such a morphology results from the incomplete development of diffusion interactions between the filler metal and the base material. At short holding times, part of the molten filler solidifies under non-equilibrium conditions, promoting significant chemical heterogeneity and the formation of eutectic and intermetallic constituents.

Copper and nickel are β-stabilizing elements in titanium and reduce the α→β transformation temperature [1]. As a consequence, a locally enriched β-phase is formed within the seam region, which transforms into a lamellar Widmanstätten-type microstructure during cooling. This explains the occurrence of coarse, acicular, and plate-like microstructural constituents in the seam when the holding time is insufficient.

Increasing the holding time to 30 min is accompanied by a significant modification of the seam microstructure. The seam width increases to approximately 100 μm, mutual redistribution of elements between the filler metal and the titanium

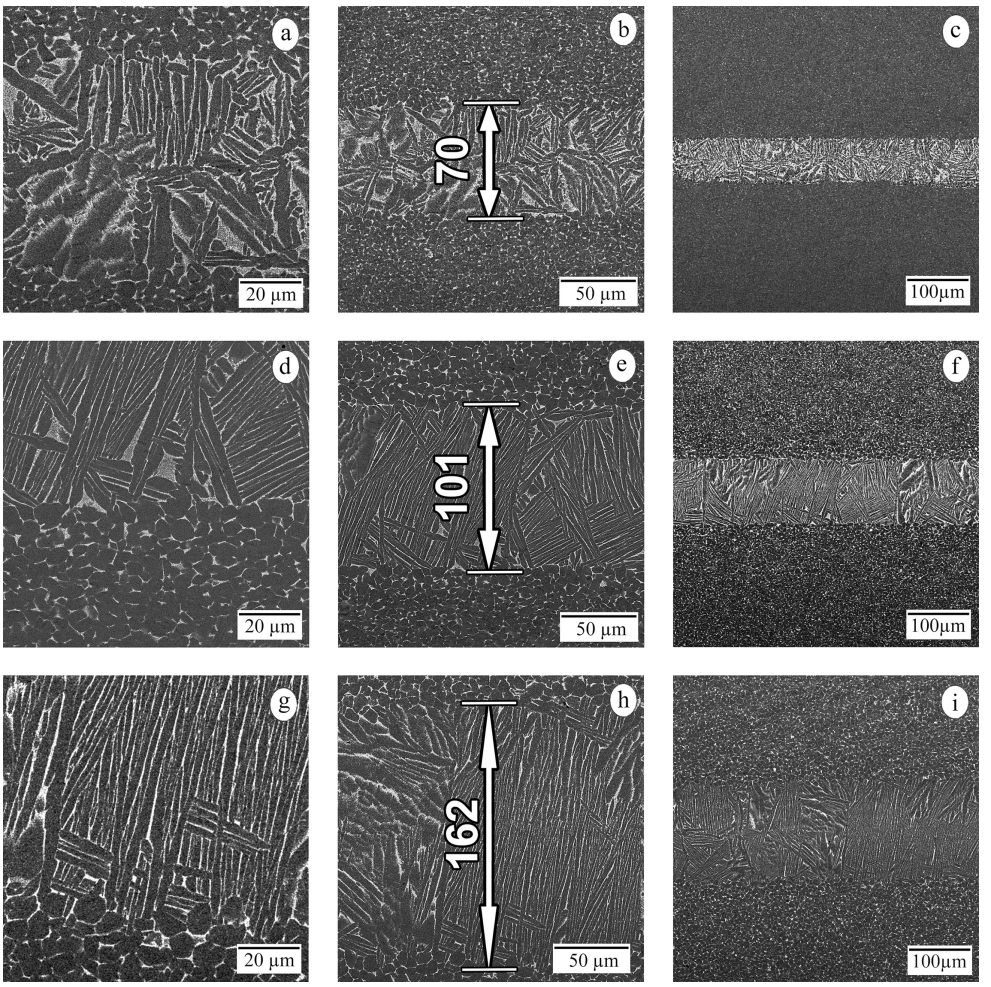


Figure 7.
Microstructures of TA15 alloy brazed joints produced at a brazing temperature of 950 °C with holding times of: (a, b, c) 15 min; (d, e, f) 30 min; and (g, h, i) 60 min.

alloy becomes more pronounced, and the volume fraction of the α-phase increases simultaneously. At the same time, the thickness of α-lamellas decreases to 1.3–4.1 μm, and light β-layers to 0.5–5.5 μm (**Figure 7d–f**).

The microstructure becomes more ordered: the α-phase plates exhibit a predominantly aligned orientation, while the width of the interlamellar regions decreases.

A further increase in the holding time to 60 min promotes even more pronounced structural homogenization. The seam exhibits a reduction in the transverse dimensions of the α-phase (1.2–3.5 μm) plates, together with a more ordered orientation of these structural constituents (**Figure 7g–i**). The seam width increases to approximately 160 μm, indicating the continued development of mutual diffusion processes. These observations are in good agreement with the results of electron probe microanalysis obtained by line scanning across the brazed seam, which confirm an increase in its chemical homogeneity (**Figure 8**).

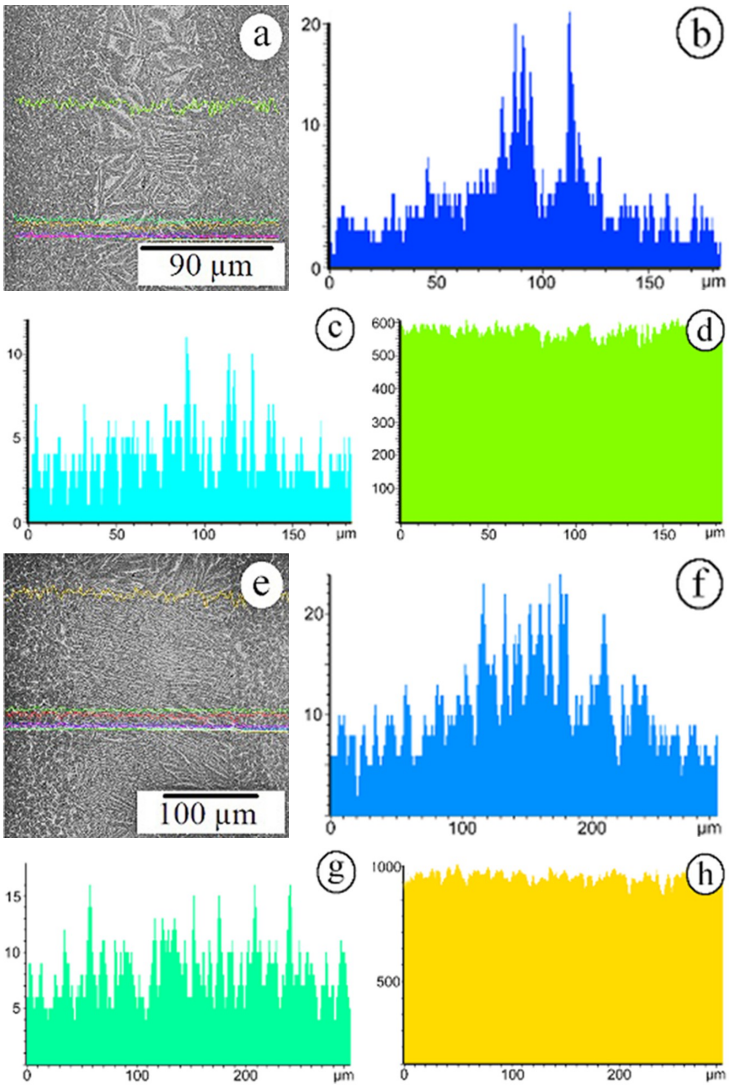


Figure 8.
The microstructure of the brazed seam (a, e) and the distribution of alloying elements (b, f – Cu; c, g – Ni; d, h – Ti) in the brazed seam obtained at different holding times (min): 15 (a–d) and 60 (e–h).

The evolution of the microstructure is directly related to the mechanical properties of brazed joints. Brittle intermetallic phases in the Ti–Cu and Ti–Ni systems, particularly Ti_2Cu, Ti_2Ni, TiCu, and complex phases of the $(Ti,Zr)_2(Cu,Ni)$ type, may act as stress concentrators and initiate brittle fracture [39–42]. Therefore, a reduction in their volume fraction, as a result of enhanced diffusion processes, has a beneficial effect on both the strength and fracture resistance of the joint.

At the same time, when evaluating the influence of holding time, it is necessary to consider the possible adverse effects of excessive thermal exposure. Titanium alloys exhibit a tendency for β-grain growth during prolonged exposure to elevated temperatures. Upon cooling, this may result in the formation of a coarse lamellar

microstructure which, despite providing relatively high strength, is generally characterized by reduced ductility and impact toughness [43]. For thin-walled structures, excessively long holding times are also undesirable because of the excessive widening of the brazed seam and possible microstructural changes in the adjacent regions of the base metal.

Based on the results of the electron probe microanalysis investigations, a schematic sequence of brazed joint formation in titanium alloys during the solidification of a Ti–Zr–Cu–Ni filler metal can be proposed (**Figure 9**). The schematic illustrates the evolution of the brazed seam microstructure, beginning with the molten state of the filler metal and progressing through the formation of a seam containing intermetallic and eutectic constituents, followed by a gradual reduction in the fraction of intermetallic phases as a result of the diffusion of melting-point depressants, primarily Cu and Ni, into the base metal.

Mechanical testing of TA15 (**Figure 10**) alloy lap-jointed specimens is in good agreement with the microstructural observations and demonstrates that increasing the holding time from 15 to 60 min results in a 15% increase in shear strength, from 430 to 500 MPa. This improvement in strength is attributed not only to the reduction in the amount of brittle phases but also to the formation of a fine-dispersed and chemically homogeneous microstructure [44].

Thus, the duration of isothermal holding is one of the principal parameters governing microstructure evolution during vacuum brazing of titanium alloys. Increasing the holding time promotes diffusion processes, enhances seam homogenization, reduces the amount of eutectic and intermetallic constituents, and improves the mechanical performance of brazed joints. The optimum holding time

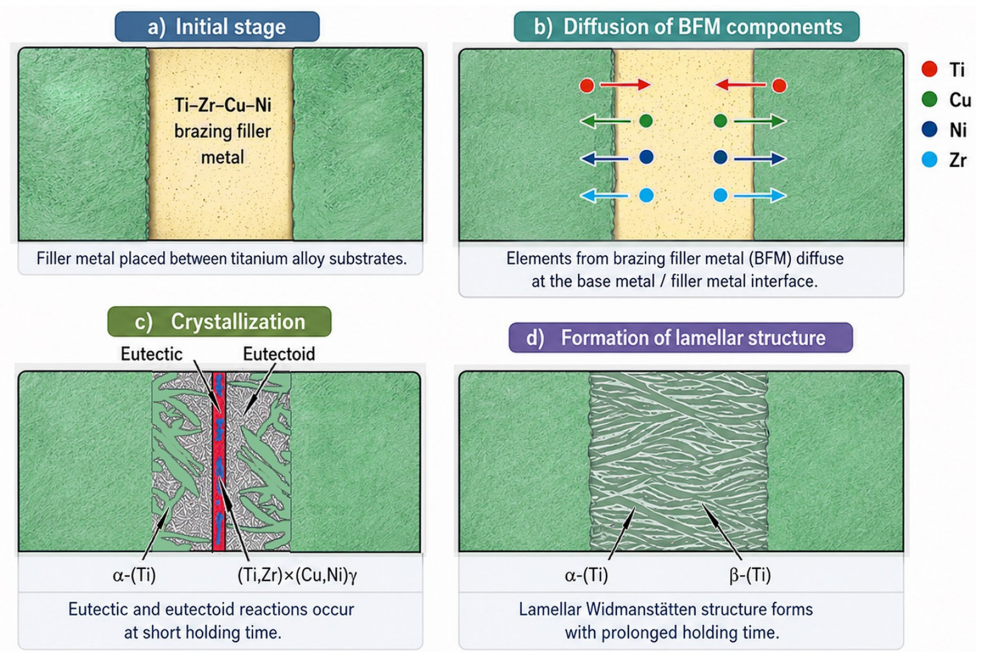


Figure 9.
Schematic representation of brazed joint formation in titanium alloys using a Ti–Zr–Cu–Ni filler metal.

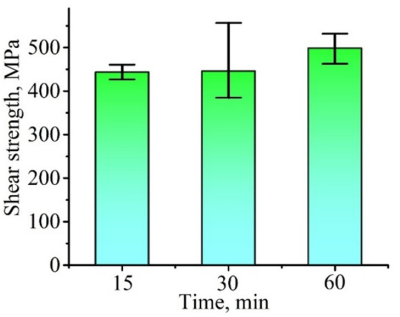


Figure 10.
Shear strength of brazed lap samples from TA15 alloy obtained at a temperature of 900 °C with isothermal holding (15, 30, 60 min).

should provide sufficient diffusion interaction without causing excessive coarsening of either the seam microstructure or the base metal.

Vacuum brazing of titanium alloys, particularly using Ti–Zr–Cu–Ni filler metals, is an effective method for producing permanent joints with a high level of strength and microstructural stability.

The structure and properties of brazed joints are determined by the thermal–time parameters of the brazing process and by the geometry of the brazing gap. In particular, the duration of isothermal holding is a key factor controlling the intensity of diffusion processes, the degree of seam homogenization, and the fraction of eutectic and intermetallic constituents. Increasing the holding time promotes seam widening and improves joint strength, which is associated with a more uniform distribution of alloying elements and a reduction in the amount of brittle phases. In turn, the geometry of the brazing gap governs the mechanism of microstructure formation. In wide gaps, solidification with the formation of a dendritic–eutectic microstructure predominates, whereas in narrow and capillary gaps, a diffusion-controlled mechanism becomes dominant, leading to a more homogeneous $\alpha + \beta$ morphology and reducing the likelihood of forming continuous intermetallic layers.

4. Applications of brazed titanium alloy structures

An important advantage of vacuum brazing is its ability to produce complex thin-walled structures with minimal thermal impact on the base material. This makes it possible to preserve the original properties of titanium alloys, reduce the level of residual stresses, and ensure high dimensional stability of the fabricated components. In addition, the brazing process is characterized by high productivity, the capability of simultaneously forming a large number of joints, the production of hermetic assemblies, and suitability for manufacturing multilayer structures with complex internal architectures. Owing to these advantages, vacuum brazing has become one of the principal technologies for the production of titanium heat exchangers, honeycomb panels, aerospace engine components, and other critical engineering products [3, 10, 45].

The high corrosion resistance, favorable specific strength, and capability to fabricate complex thin-walled structures have led to the widespread use of titanium

in heat-exchange equipment [46]. Today, titanium heat exchangers are available in a wide variety of designs, including plate-type and plate-fin configurations, which are extensively employed in aerospace, power generation, chemical processing, marine, and cryogenic industries [47, 48]. Such structures consist of numerous thin plates, fins, and separating partitions that form an intricate network of flow channels for heat-transfer media (**Figure 11**).

A distinctive feature of such products is the presence of a large number of brazed joints located within thin-walled elements, whose thickness may be only a few tenths of a millimeter. The use of conventional welding techniques for manufacturing such structures is practically impossible because of significant distortions and the risk of damaging the thin-walled components. Vacuum brazing makes it possible to form all joints simultaneously during a single heating cycle, ensuring a high level of leak-tightness and dimensional stability of the assembly [8].

In modern aerospace engineering, titanium heat exchangers are widely employed in oil-cooling systems, fuel systems, air coolers, and thermal management systems [3]. In military and defense applications, titanium-alloy heat exchangers are gradually replacing radiators made of aluminum, copper, and stainless steel because of their superior combination of strength, corrosion resistance, and durability [8].

Titanium-alloy honeycomb structures have also found widespread application (**Figure 12**) [49]. These components consist of thin outer face sheets and an internal honeycomb core, joined primarily by vacuum brazing techniques. Owing to their exceptionally high stiffness-to-weight ratio, they are extensively used in aircraft fuselage structures, wing control surfaces, air-intake systems, and aerodynamic fairings.

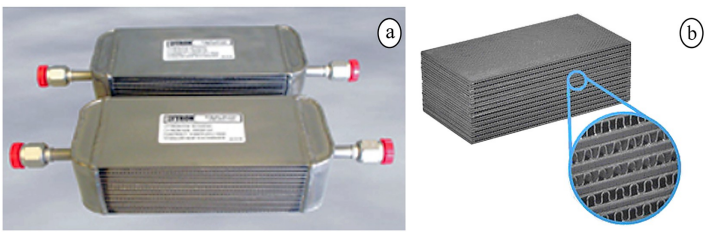


Figure 11.
(a) General view and (b) fragment of a heat exchanger manufactured using vacuum brazing *[48]*.

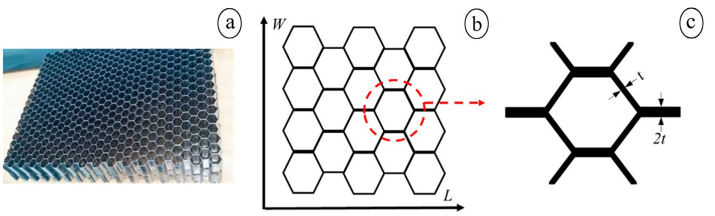


Figure 12.
Ti-6Al-4 V metal honeycomb core: (a) honeycomb core fabricated, (b) sketch diagram along the L and W directions, and (c) cell unit *[49]*.

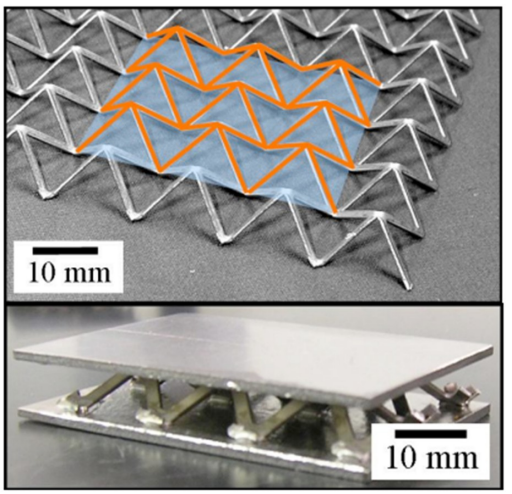


Figure 13.
Examples of the geometry of titanium pyramidal core without and with brazed facesheets [9].

Sandwich panels and multilayer structures based on titanium alloys (**Figure 13**) are also considered promising materials for armor protection elements in modern tactical and armored combat vehicles. The use of titanium makes it possible to significantly reduce structural weight compared with conventional steel armor while maintaining a high level of ballistic protection. This contributes to improved vehicle mobility, enhanced fuel efficiency, and increased payload capacity [9].

Practical experience in the manufacture and operation of such structures demonstrates that vacuum brazing provides the required strength and durability of thin-walled honeycomb panels operating under vibration and cyclic loading conditions.

A separate field of application involves the use of brazed titanium components in gas turbine engine manufacturing. Vacuum brazing of titanium alloys is widely employed in the production of compressor blades, air duct components, casing parts, sealing structures, centrifugal impellers to which steam turbine blades are attached (brazed), and other critical components [3].

In many cases, brazing makes it possible to replace the mechanical fastening of a large number of parts with more technologically advanced brazed assemblies, thereby reducing component weight and improving reliability. In particular, during the manufacture of the 5th–8th stage compressor components of aircraft gas turbine engines made from the Ti-6Al-4 V titanium alloy, the technology involves the simultaneous brazing of 60–80 blades to the inner and outer rings, clearly demonstrating the potential of vacuum brazing for the fabrication of complex multi-component aerospace structures [50].

An important area of application for brazed titanium structures is chemical and petrochemical engineering. Owing to titanium's excellent corrosion resistance in chloride-containing environments, seawater, and many acidic media, titanium heat exchangers and reactor equipment are successfully operated under aggressive service conditions, where conventional materials rapidly degrade [51, 52].

In recent years, the importance of brazed titanium structures in cryogenic engineering and hydrogen energy systems has been steadily increasing [53, 54].

Titanium is known to retain high mechanical properties at low temperatures, making it a promising material for heat exchangers, gas liquefaction systems, hydrogen fuel systems, and cryogenic pipelines. The high level of hermeticity achieved through vacuum brazing is particularly important for equipment operating with liquid hydrogen, helium, and other cryogenic media.

5. Conclusions and outlook

Analysis and justification of the obtained data show that the formation of the structure of titanium joints and their properties are determined not only by the chemical composition of the brazing filler metal but also by the complex action of the technological parameters of the high-temperature vacuum brazing process: temperature, isothermal holding time, and the width of the brazing gap. Optimization of these factors ensures the production of high-quality joints suitable for operation in various industries: aviation, energy, medical, chemical, etc.

Further development of high-temperature brazing technology is associated with a deepening understanding of the physicochemical processes that occur during the formation of brazed joints under non-equilibrium crystallization conditions, in the presence of a concentration gradient at the interface. Improving methods for controlling the processes of isothermal crystallization, diffusion interaction, and the creation of new brazing filler metals opens up prospects for the further expansion of the areas of application of brazed structures made of titanium alloys.

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Conflict of Interest

The author declares that there is no conflict of interest.

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