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BRAZE WELDING TIG OF TITANIUM AND ALUMINIUM ALLOY TYPE Al – Mg

The article presents the course and the results of technological tests related to TIG-based arc braze welding of titanium and AW-5754 (AlMg3) aluminium alloy. The tests involved the use of an aluminium filler metal (Al99.5) and two filler metals based on Al-Si alloys (AlSi5 and AlSi12). Braze welded joints underwent tensile tests, metallographic examinations using a light microscope as well as structural examinations involving the use of a scanning electron microscope and an X-ray energy dispersive spectrometer (EDS). The highest strength and quality of welds was obtained when the Al99.5 filler metal was used in a braze welding process. The tests enabled the development of the most convenient braze welding conditions and parameters.

Keywords: braze welding, aluminium alloy, titanium, mechanical properties of braze welded joints, structural properties of braze welded joints, braze welding parameters.

1. Introduction

Joining titanium and aluminium as well as their alloys using welding methods is difficult due to diversified physico-chemical properties of these materials (fusibility, conductivity and thermal expansion), their reactivity with surrounding gases and the formation of brittle intermetallic phases in the impact zone [1 ÷ 5]. It is recommended that such dissimilar joints should be made using few specialist fusion welding methods (electron beam welding, laser welding) and friction welding methods (diffusion welding, classic stir welding and FSW), diffusion brazing and, recently, arc braze welding and laser braze welding [6 ÷ 15]. Few available publications concerned with arc braze welding of the materials mentioned above, presenting examples of such applications in a fragmentary manner, indicate that the issue is still at the stage of laboratory tests [14, 15]. No such tests have been conducted in Poland until today.

The necessity of joining titanium and aluminium as well as their alloys appears when some elements of titanium structures and components can be replaced with cheaper stainless steels or with cheaper and lighter aluminium or its alloys. A condition set by constructors for such structural systems applied in the modern sectors of industry and economy, i.e. automotive industry, aviation, electronics as well as in the production of equipment and heat exchangers in the chemical industry, is concerned with ensuring good quality and required operational properties of joints [1, 7, 8].

This work presents the results of investigation concerning TIG-based arc braze welding of titanium and AW-5754 (AlMg3) aluminium alloy. These tests constitute the continuation of previous research conducted at Instytut Spawalnictwa and focused on brazing titanium and stainless steels [16, 17].

2. Braze welding of titanium with aluminium and its alloys – current status of the issue.

Braze welding is usually defined as brazing by means of a welding technique. This method utilises a welding technique and the use of a filler metal of lower temperature fusibility than that of materials to be joined, which is characteristic of brazing. The mechanism of joint formation, including wetting and diffusion, as well as the morphological structure of joints are similar as in the case of brazed joints. For this reason, braze welding is often referred to as arc brazing, laser brazing etc. [2 ÷ 4]. Braze welding of titanium and aluminium using aluminium-based filler metals is a specific variant of braze welding as there is a brazed joint on the titanium side and a welded joint on the aluminium alloy side.

As mentioned in the Introduction, the titanium – aluminium material system as well a system containing alloys of these metals belong to hard-to-braze and to hard-to-braze weld systems [2 ÷ 4, 10 ÷ 15] due to significantly differing melting points of materials joined, the formation of very durable and close-adhesive oxides (non-wettable by filler metals) on the surface of aluminium and that of titanium, the high reactivity of titanium forming brittle and hard intermetallic phases with aluminium (aluminides) and due to the diversified thermal expansion and conductivity of these metals (favouring non-uniform heating during joining and the formation of thermal stresses and cracks) (Table 1).

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TABLE 1

Basic physico-chemical properties of aluminum and titanium [1 ÷ 4]

No.	Properties	Aluminium	Titanium
1	Melting point, °C	660	1668
2	Density, kg/dm^3	2.7	4.05
3	The coefficient of linear thermal expansion, 1/K in temp. 0 ÷ 1000°C	$(24 \div 33)\times10^{-6}$	$(7 \div 12)\div10^{-6}$
4	Thermal conductivity, W/m·K	200 ÷ 240	22,6
5	Tensile strength, MPa	90 ÷ 120	500 ÷ 700
6	Energy forming oxides (enthalpy), kJ/molO$_2$	Al_2O_3 / 1116.2	TiO_2 / 916.9

Available specialist reference publications inform about cases of TIG-based braze welding of 5A06 (AlMg6.3Mn0.6) aluminium alloy and TiAl6V4 titanium alloy using Al1100 and AlCu0.3La2 [14] filler metals as well as contain examples of TIG-based braze welding of 2024 (AlCu4Mg1) aluminium alloy and TiAl6V4 titanium alloy using AlSi12 filler metal [15]. The authors presented the courses and results of technological tests as well as test results concerning mechanical and structural properties of joints.

The joints revealed similar structures, i.e. a brazed joint on the titanium alloy side and a welded joint on the aluminium alloy side. On the titanium alloy side it was possible to observe layers containing brittle $TiAl_3$ and $Ti(AlSi)_3$ phases and $Ti_7Al_5Si_{12}$ phase. It was also in this area that the rupture during tensile tests took place. The maximum tensile strength of the joints mentioned above exceeded 100 MPa.

3. Course and results of tests

3.1. Parent and filler metals

The tests involved the use of the following parent metals in the form of samples (150x50x2 mm) cut out of sheets made of:

- Grade 2 titanium according to ASTM B265;
- AW-5754 (AlMg3) aluminium alloy according to PN-EN 573-3:2014.

In order to fully identify materials used in the tests it was necessary, similarly as in the case of diffusion brazing, to perform the analysis of their chemical composition. The analysis results are presented in Table 2 (for AW-5754 alloy) and Table 3 (for Grade 2 titanium). The chemical composition analysis was performed using a Bruker-manufactured Q4 TASMAN spark emission spectrometer.

Filler metals used for making braze welded joints were wires having diameters of 2.4 and 3.2 mm according to PN-EN ISO 18273:2007:

- Al1050 (Al99.5) grade aluminium wire,
- Al4043 (AlSi5) alloy wire,
- Al4047 (AlSi12) alloy wire.

TIG-based braze welding was conducted using inert gas (I1 grade argon according to PN-EN ISO 14175:2009).

3.2. Braze welding tests and preparation of joint samples for investigation

The TIG method-based braze welding of titanium samples with AlMg3 aluminium alloy samples was performed using a Fronius-manufactured MagicWave 500 welding machine, an AC power source and a WT10 thoriated tungsten electrode according to PN-EN ISO 6848:2008 (electrode bevel angle of 90°). The tests invoked making butt and overlap joints. While making overlap joints, the titanium sample was

TABLE 2

The results of chemical analysis of aluminium alloy AW-5754

Type of material	The content of elements, % wt.								
	Mg	Mn	Fe	Si	Cu	Zn	Cr	Ti	Al
AW-5754, acc. PN-EN 573-3:2014	2.60 ÷ 3.60	≤ 0.50	≤ 0.40	≤ 0.40	≤ 0.10	≤ 0.20	≤ 0.30	≤ 0.15	rest
Aluminium alloy AW-5754 acc. chemical analysis (used in the study)	2.95	0.226	0.216	0.163	0.037	0.026	0.024	0.009	96.29

TABLE 3

The results of chemical analysis of titanium Grade 2

Type of material	The content of elements, % wt.					
	Fe	O	N	C	H	Ti
Grade 2 acc. ASTM B265	≤ 0.30	≤ 0.25	≤ 0.03	≤ 0.10	≤ 0.015	rest
Grade 2 acc. chemical analysis (used in the study)	0.051	not determined	not determined	< 0.002	not determined	99.86

placed on the aluminium alloy sample and vice versa. During technological tests the best quality of brazewelds was observed in the joints made using Al99.5 (Al 1050) filler metal (ø 2.4 and 3.2 mm) (Tables 4, 5). In addition, the tests revealed that while braze welding the joints using the aforesaid filler metal, it was possible to obtain better quality of the joints when the titanium sample was at the top and the aluminium alloy sample was at the bottom. Such an arrangement of the samples has a more advantageous effect on thermal conditions and on the wettability of the titanium surface with the filler metal. The lowest quality of brazewelds was obtained for the overlap joints, in which the aluminium alloy sample was placed on the titanium sample and AlSi12 was used as a filler metal. In addition, the use of the aforesaid filler metal when the aluminium alloy sample was placed on the titanium sample led to the formation of a so-called erratic arc, indicating process instability. This filler metal also required the use of higher braze welding current (56 ÷ 64 A) than that used with AlSi5 (44 ÷ 62 A) and Al99.5 (48 ÷ 62 A) filler metals.

TABLE 4

Tests brazewelds of butt joints of aluminum alloy AW-5754 (AlMg3) with titanium Grade 2, using Al99.5 filler metal ø 2.4 mm.

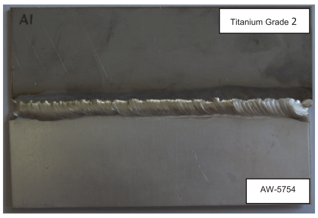
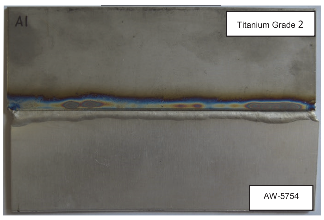
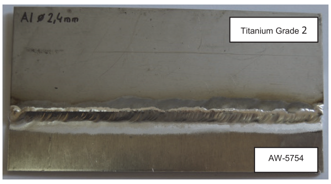
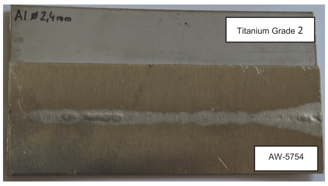
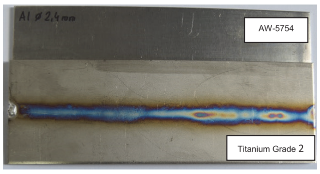
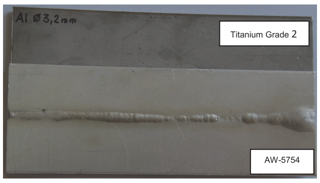
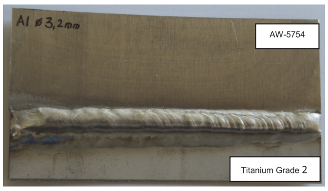
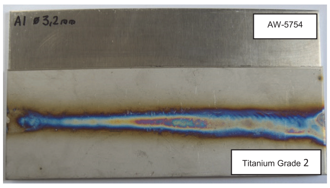
Braze welding parameters					
Filler metal	Current, A	The arc voltage, V	The welding speed, cm/min	Stream vol. shielding gas, l/min	The tilt angle of the handle, °
Al 1050 (Al99.5)	46 ÷ 52	13.5 ÷ 14.5	10.0	12.0	80.0
 face of weld			 back of weld		

TABLE 5

Tests brazewelds of overlap joints of aluminum alloy AW-5754 (AlMg3) with titanium Grade 2, using Al99.5 filler metals ø 2.4 and 3.2 mm.

Braze welding parameters					
Filler metal	Current, A	The arc voltage, V	The welding speed, cm/min	Stream vol. shielding gas, l/min	The tilt angle of the handle, °
Al 1050 (Al99.5) ø 2.4 mm	48 ÷ 58	13.7 ÷ 14.5	9.5	12.0	80.0
 face of weld (Ti on the top)			 back of weld (Ti on the top)		
 face of weld (aluminium alloy on the top)			 back of weld (aluminium alloy on the top)		
Al 1050 (Al99.5) ø 3.2 mm	50 ÷ 62	14.0 ÷ 15.1	10.0	12.0	80.0
 face of weld (Ti on the top)			 back of weld (Ti on the top)		
 face of weld (aluminium alloy on the top)			 back of weld (aluminium alloy on the top)		

3.3. Strength tests of braze welded joints

In order to determine the mechanical properties (maximum rupture strength, tensile strength R_m) of the titanium-aluminium butt joints, it was necessary to perform a static tensile test at the ambient temperature. The tests were conducted using an Instron model 4210 testing machine, having a measurement range of ± 600 kN and featuring a computer-aided system for recording and archiving test results.

Tensile tests were performed for three samples and for each filler metal, i.e. Al99.5, AlSi5 and AlSi12. The results of the tests after statistical processing are presented in Table 6. In all of the cases, the rupture took place in the brazeweld on the titanium side.

TABLE 6

Mechanical properties of titanium Grade 2 - aluminium alloy AW-5754 butt joints, braze welding TIG method for each filler metal, i.e. Al99.5, AlSi5 and AlSi12

No.	Filler metal	Maximum rupture strength, kN	Tensile strength, MPa	
		Average value *	Average value *	Standard deviation
1	Al99.5	10.77	115.85	23.75
2	AlSi5	7.76	82.97	12.16
3	AlSi12	7.32	80.30	13.72

/* - the average value of 3 measurements

The results obtained revealed that the highest tensile strength of approximately 115 MPa was obtained for the joint made using Al99.5 filler metal. For other filler metals

(AlSi5, AlSi12), a tensile strength was similar and amounted to approximately 80 - 83 MPa.

3.4. Metallographic and structural investigation of braze welded joints

For macroscopic metallographic tests the samples were prepared by making the cross-sections of previously braze welded butt and overlap joints. Afterwards, prior to macroscopic observations, the samples underwent grinding and etching in the Kroll's reagent. The photographic documentation was prepared using an OLYMPUS Camedia digital camera. More important metallographic test results are presented in Figures 1 ÷ 4.

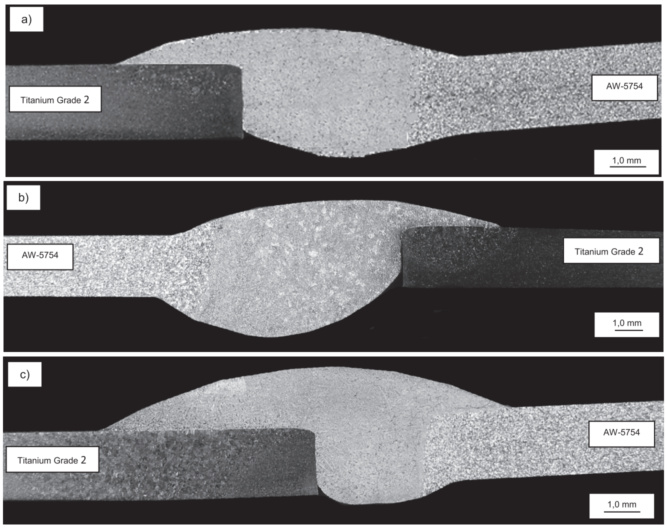


Fig. 1. Macrostructure of the butt joints of Grade 2 titanium – aluminium alloy AW-5754 braze welded with filler metals Al99.5 (a), AlSi5 (b), AlSi12 (c), chemical etching using Kroll's reagent

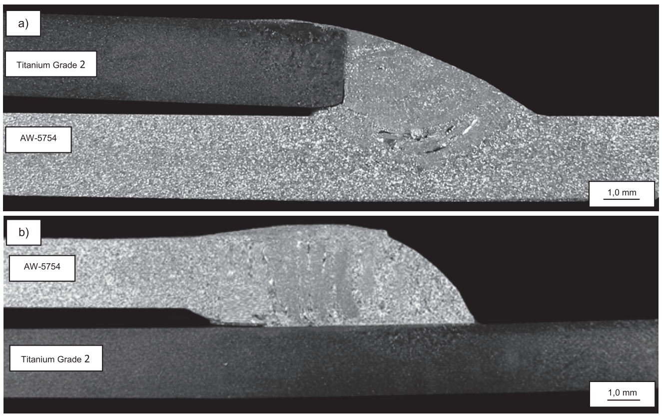


Fig. 2. Macrostructure of the overlap joints of Grade 2 titanium – aluminium alloy AW-5754 braze welded with Al99.5 filler metal ø 2.4 mm, titanium on the top (a) titanium at the bottom (b), chemical etching using Kroll's reagent

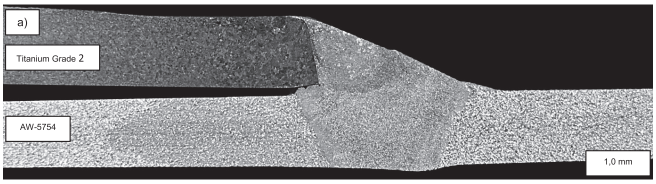


Fig. 3. Macrostructure of the overlap joints of Grade 2 titanium – aluminium alloy AW-5754 braze welded with AlSi5 filler metal ø 2.4 mm, titanium on the top (a) titanium at the bottom (b), chemical etching using Kroll's reagent

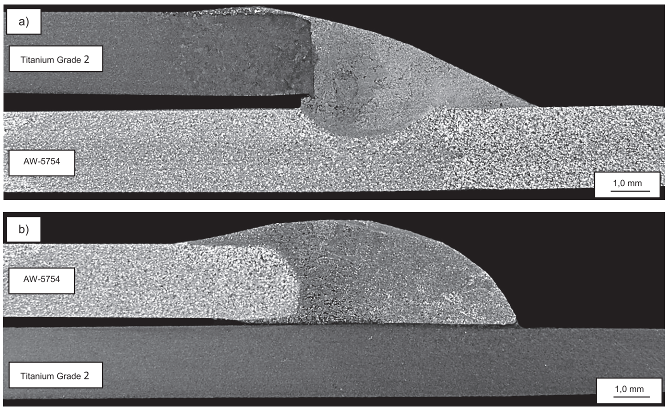
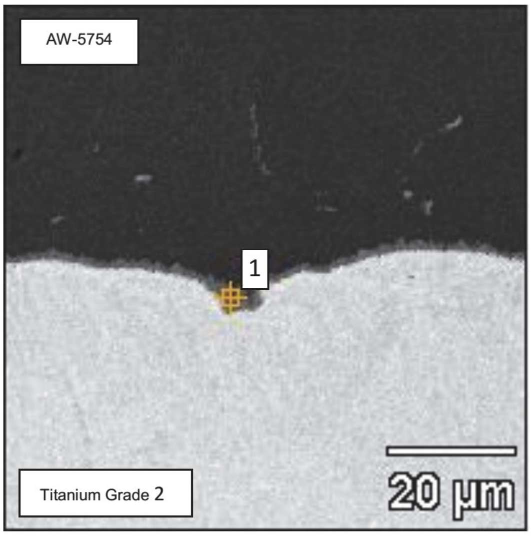


Fig. 4. Macrostructure of the overlap joints of Grade 2 titanium – aluminium alloy AW-5754 braze welded with AlSi12 filler metal ø 2.4 mm, titanium on the top (a) titanium at the bottom (b), chemical etching using Kroll's reagent

The metallographic examinations conducted confirmed the good quality of the butt and overlap joints.

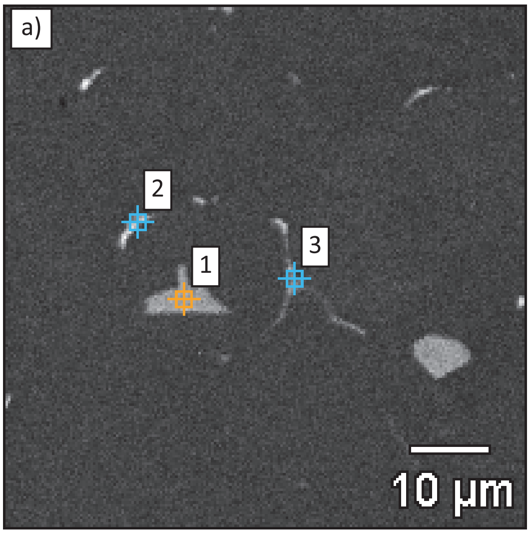
In the case of the butt joints, the highest quality was observed in the joint made using Al99.5 filler metal (Fig.1). Slightly worse quality was observed in the joints made using AlSi5 and AlSi12 filler metals, wetting the titanium worse than Al99.5. In turn, as regards the overlap joints, the tests confirmed that the best quality of the joints was obtained when the titanium sample was placed on the aluminium alloy sample (Figures 2 ÷ 4). Such an arrangement ensured a significantly smaller angle at which titanium was wetted by the filler metal, thus providing better wettability. Otherwise, the brazeweld cross-section shape indicated worse wettability of titanium. The brazewelds obtained were free from any major braze welding imperfections.

Structural examinations of joints braze welded using the TIG method were performed using a Hitachi S-3400N scanning electron microscope (SEM) and the technique of back-scattered electrons (BSE). The local microanalysis of the chemical composition of the phases in the joint structures was carried out using a Thermo Noran System Six X-ray energy dispersive spectrometer collaborating with an electron microscope. The tests involved the braze welded butt test joints made using Al99.5, AlSi5 and AlSi12 filler metals. Special attention was paid to the part adjacent to titanium, i.e. the area where the brazed joint was present (the welded joint was present on the aluminium alloy side) and the samples ruptured during the strength tests. The test results are presented in Figures 5 ÷ 10.

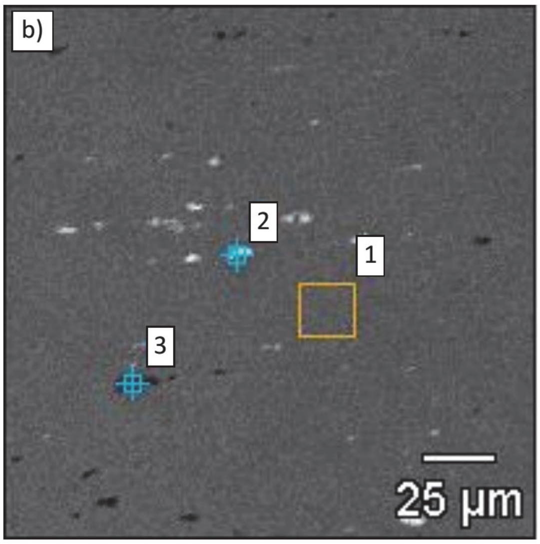


Point	Content, % wt.			Content, % atomic			Phase
	Al-K	Si-K	Ti-K	Al-K	Si-K	Ti-K	
1	60.8	0.3	39.0	73.2	0.3	26.5	TiAl3

Fig. 5. Microstructure of the butt joint of Grade 2 titanium – aluminium alloy AW-5754 (diffusion zone from the titanium), braze welded Al99.5 filler metal with EDS measurements in 1 point

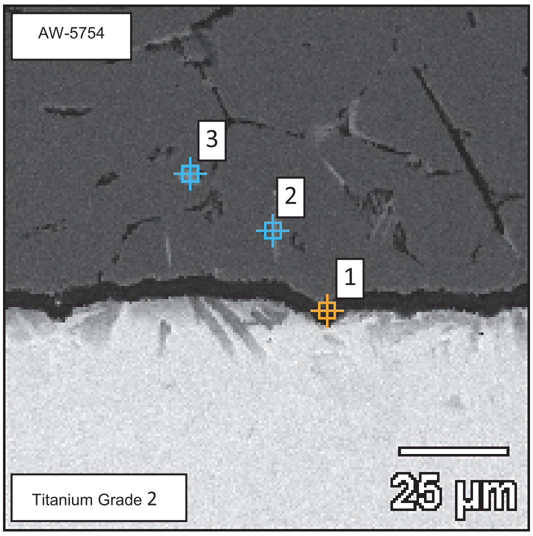


Point	Content, % wt.					Content, % atomic					Phase
	Mg-K	Al-K	Si-K	Ti-K	Fe-K	Mg-K	Al-K	Si-K	Ti-K	Fe-K	
1	0	58.2	0.4	41.4	0	0	71.1	0.4	28.5	0	TiAl3
2	1.0	82.7	0.4	0	16.0	1.2	90.0	0.4	0	8.4	FeAl3
3	1.0	85.3	0	0	13.7	1.2	91.7	0	0	7.1	FeAl3



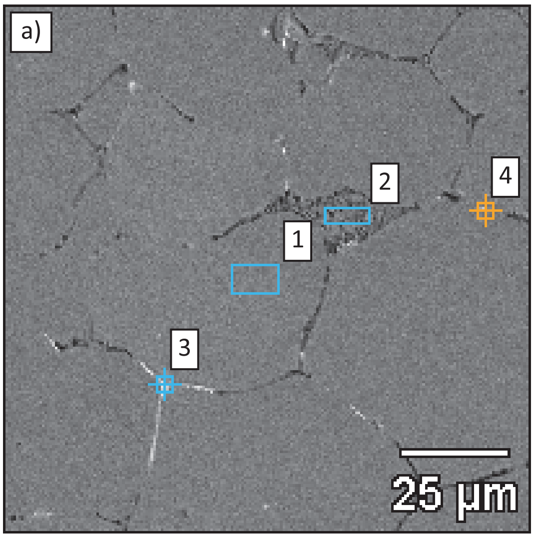
Point	Content, % wt.					Content, % atomic					Phase
	Mg-K	Al-K	Si-K	Mn-K	Fe-K	Mg-K	Al-K	Si-K	Mn-K	Fe-K	
1	2.4	97.6	0	0	0	2.6	97.4	0	0	0	Al
2	0.2	59.6	0.8	5.1	34.3	0.3	74.8	0.9	3.2	20.8	FeAl3
3	0	1.9	98.1	0	0	0	2.0	98.0	0	0	Si

Fig. 6. Microstructures (a and b) of the brazeweld butt joint of Grade 2 titanium – aluminium alloy AW-5754, braze welded Al99.5 filler metal with EDS measurements in 3 points

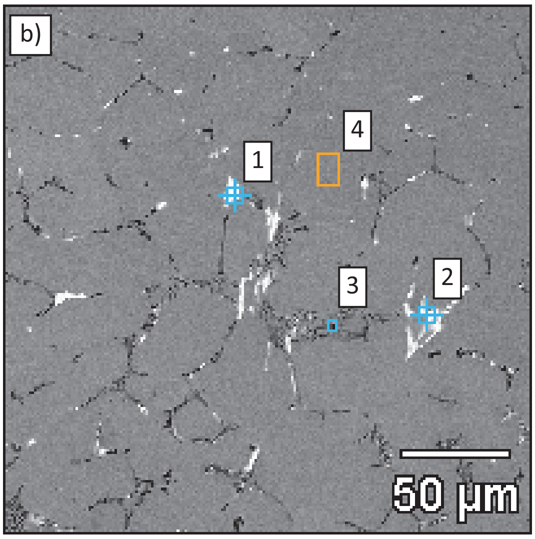


Point	Content, % wt.			Content, % atomic			Phase
	Al-K	Si-K	Ti-K	Al-K	Si-K	Ti-K	
1	22.7	55.5	21.8	25.7	60.4	13.9	Si
2	55.6	8.1	36.3	66.3	9.3	24.4	TiAl3
3	58.6	5.9	35.5	69.5	6.7	23.8	TiAl3

Fig. 7. Microstructure of the butt joint of Grade 2 titanium – aluminium alloy AW-5754, braze welded AlSi5 filler metal with EDS measurements in 3 points

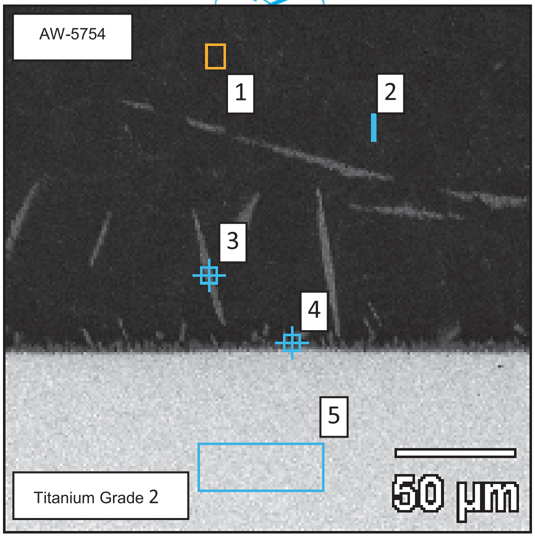


Point	Content, % wt.					Content, % atomic					Phase
	Mg-K	Al-K	Si-K	Mn-K	Fe-K	Mg-K	Al-K	Si-K	Mn-K	Fe-K	
1	1.7	98.1	0.2	0	0	1.9	97.9	0.2	0	0	Al
2	4.0	93.8	2.2	0	0	4.4	93.5	2.1	0	0	Al
3	0	72.3	0	5.7	22.1	0	84.3	0	3.3	12.4	FeAl3
4	3.9	90.4	4.1	0	1.6	4.3	90.9	4.0	0	0.8	Al



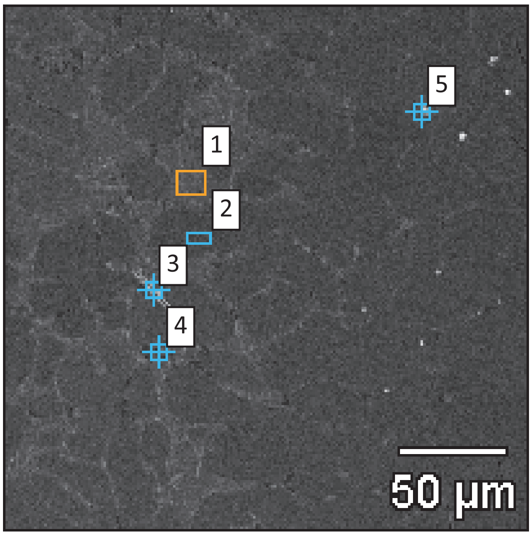
Point	Content, % wt.					Content, % atomic					Phase
	Mg-K	Al-K	Si-K	Mn-K	Fe-K	Mg-K	Al-K	Si-K	Mn-K	Fe-K	
1	0	68.2	0.2	6.5	25.1	0	81.4	0.3	3.8	14.5	Al
2	0	68.3	0.3	6.9	24.5	0	81.5	0.3	4.1	14.1	Al
3	3.3	87.7	9.0	0	0	3.7	87.7	8.6	0	0	Al
4	2.0	98.0	0	0	0	2.2	97.8	0	0	0	Al

Fig. 8. Microstructures (a and b) of the brazeweld butt joint of Grade 2 titanium – aluminium alloy AW-5754, braze welded AlSi5 filler metal with EDS measurements in 4 points



Point	Content, % wt.			Content, % atomic			Phase
	Al-K	Si-K	Ti-K	Al-K	Si-K	Ti-K	
1	98.0	2.0	0	98.1	1.9	0	Al
2	76.5	23.5	0	77.3	22.7	0	Al
3	46.7	11.6	41.8	57.4	13.7	28.9	TiAl3
4	60.5	9.2	30.3	70.1	10.2	19.8	TiAl3
5	0	0	100.0	0	0	100.0	Ti

Fig. 9. Microstructure of the butt joint of Grade 2 titanium – aluminium alloy AW-5754 (diffusion zone from the titanium), braze welded AlSi12 filler metal with EDS measurements in 5 point



Point	Content, % wt.							Phase
	Mg-K	Al-K	Si-K	Ti-K	Cr-K	Mn-K	Fe-K	
1	0.9	74.1	25.0	0	0	0	0	Al
2	0	98.4	1.6	0	0	0	0	Al
3	0	50.9	15.9	33.2	0	0	0	TiAl3
4	4,4	65,8	29,8	0	0	0	0	Al
5	0	57,3	9,4	0	2,5	13,3	17,4	Al

Point	Content, % atomic							Phase
	Mg-K	Al-K	Si-K	Ti-K	Cr-K	Mn-K	Fe-K	
1	1.0	74.8	24.2	0	0	0	0	Al
2	0	98.4	1.6	0	0	0	0	Al
3	0	60.0	18.0	22.0	0	0	0	TiAl3
4	4.9	66.3	28.8	0	0	0	0	Al
5	0	69.4	11.0	0	1.6	7.9	10.2	Al

Fig. 10. Microstructure of the brazeweld butt joint of Grade 2 titanium – aluminium alloy AW-5754, braze welded AlSi12 filler metal with EDS measurements in 5 points

Analysing the results presented above it was observed that a layer of solid solution based on a phase stoichiometrically corresponding to an intermetallic phase of TiAl3 was formed (Figures 5, 7 and 9) in the diffusive zone of the joint, on the titanium side. In the joints made using each of the three filler metals (Al99.5, AlSi5, and AlSi12), depending on a filler metal applied, this layer differed only in variable silicon content. The brazewelds of the test joints (Figures 6, 8, 9 and 10) also contained partial precipitates of these solid solutions as well as $FeAl_3$ phase-based solutions, aluminium–based solutions (Al-Mg, Al-Si, Al-Mg-Si, Al-Mg-Si-Fe and Al-Fe-Mn) and silicon-based solutions (Si-Al, Si-Al-Ti).

4. Conclusions

1. The use of Al 1050 (Al99.5) filler metal enables the obtainment of the good quality and the highest tensile strength (115 MPa) of dissimilar joints made of Grade 2 titanium sheets and AW-5754 (AlMg3) aluminium alloy, braze welded using the TIG method with Al 1050 (Al99.5), Al4043 (AlSi5) and A4047 (AlSi12) filler metals.
2. In the case of the overlap joints made of Grade 2 titanium and AW-5754 (AlMg3) aluminium alloy it was observed that the best quality was that of the brazewelds made with the titanium sheet placed at the top. Such a solution facilitates wetting the titanium with the filler metal and enables the obtainment of brazewelds free from braze welding imperfections.
3. For each of the three filler metals (Al99.5, AlSi5, AlSi12) the structural examinations involving braze welded joints made of titanium and AW-5754 aluminium alloy sheets, performed using scanning electron microscopy (SEM) and X-ray energy dispersive spectroscopy (EDS), revealed the presence of a layer composed of a solid solution based on a phase stoichiometrically corresponding to a brittle and hard TiAl3 phase. The layer was present on the titanium side.

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