Comparison of microstructures and mechanical properties of Al-Ti weld joints prepared by different welding technologies

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Abstract. This study deals with the evaluation of butt welded-brazed joints of two plates with the thickness of 2 mm from EN AW5083-H111 alloy and titanium Grade 2 prepared by two different welding technologies: laser beam welding-brazing (LBWB) and gas tungsten arc welding (GTAW). ER4047 and ER4043 welding wires with the diameter of 1.2 mm were used as filler materials. The macrostructures, microstructures and mechanical properties of experimental weld joints were analysed and compared. In general, the strength of joints produced by LBWB was higher than the strength of GTAW samples. The highest tensile strength at the level of 245 MPa was measured for the experimental joint made by LBWB using following welding parameters: the laser power of 1800 W, the welding speed of 30 mm.s\(^{-1}\), the laser beam offset to Al-sheet of 400 µm and the wire feed rate of 2.4 m.min\(^{-1}\).

1. Introduction
The difficulties in joining aluminium to titanium alloys by fusion welding technologies result not only from significant differences in the physical, mechanical and thermal properties of the two materials but mainly from the unavoidable formation of layers containing brittle intermetallic compounds [1-4]. Various conventional and unconventional welding technologies were tested to obtain sound weld joints of these materials, and the influence of welding technologies on the quality of produced weld joints was evaluated [5-6]. Because of GTA welding technology offers flexibility, low dependence on expensive equipment with complex welding procedures it is widely used in manufacturing application. GTA welding is characterized by relatively small temperature gradients, which contributes to improving the homogeneity of the interfacial reaction. Published research studies related to the GTA welding-brazing of dissimilar Al/Ti materials have reported that the application of the AlSi12 filler metal with the high Si content supressed the growth of intermetallic compounds (IMC), thereby enhancing the mechanical properties of produced joints [7-10]. Many other studies showed the promising results related to Al/Ti laser beam welding-brazing (LBWB) [11-14]. When using this joining method, the molten aluminum alloy only wets the solid surface of the titanium. On the other hand, further investigations have demonstrated that the insufficient width, discontinuity or improper morphology of an interfacial reaction layer could cause reduction of mechanical properties and initiation of joint cracks. Similarly, it was proved that the laser offset influenced the thickness of the IMC layer and its application could improve the mechanical properties of the weld by eliminating the interfacial non-homogeneity and weld porosity [14-15].
The aim of this paper is to evaluate the differences in macrostructure, microstructure and mechanical properties of butt welded-brazed joints of Al/Ti dissimilar materials produced by two different welding technologies using AlSi based filler metals.

2. Experimental materials, equipment and welding technologies

Butt welded-brazed joints of dissimilar experimental base materials, wrought EN AW5083-H111 (AA5083) aluminium alloy and titanium Grade 2 (CP Grade 2) with chemical compositions given in Table 1 were prepared using different welding technologies - laser beam welding-brazing and gas tungsten arc welding. Experimental samples had dimensions of 50 mm × 50 mm × 2 mm. A filler material in the form of a rod and wire, respectively, with the diameter of 1.2 mm was applied. In both technologies, argon was used as a shielding gas with the flow rate of 20 l.min⁻¹. The laser beam and the welding arc, respectively, was deflected to the Al sheet side to reduce the temperature rise of the CP Grade 2 and its possible melting. Experimental robotized welding device, the TruDisk 4002 disk laser was used in continuous mode. The laser beam with the diameter of 400 µm was focused +2 mm above the horizontal reference plane. The laser welding-brazing was accomplished using ER4047 (AlSi12) filler wire and the following welding parameters: laser power of 1800 W, welding speed of 30 mm.s⁻¹, wire feed rate of 240 cm.min⁻¹ and the laser beam offset of 400 µm to Al sheet side with respect to the weld centreline.

For selected conventional welding technology GTAW, the SELCO Genesis 3200 AD/DC inverter-type welding machine was exploited. The 2-step welding method with direct current was applied to produce a double-square-groove type of joint in flat position using ER4043 (AlSi5) filler material with the chemical composition listed in Table 1. The welding speed was 2.5 mm.s⁻¹ along with the arc voltage of (12.8 ± 0.4) V and the welding current of 50 A. The arc offset was approximately 400 µm to Al sheet side.

| Element   | Mg | Si  | Fe  | Mn | Cu | Zn | Al  | C   | O   | N   | H   | Ti  |
|-----------|----|-----|-----|----|----|----|-----|-----|-----|-----|-----|-----|
| CP Grade2 | -  | -   | 0.25| -  | -  | -  | -   | 0.393| 0.737| 0.101| 0.702| Bal.|
| AA5083    | 5.22| 0.38| 0.15| 0.13| 0.08| -  | Bal.| -   | -   | -   | -   | -   |
| AlSi12    | 0.11| 11.67| 0.39| 0.08| 0.13| 0.08| Bal.| -   | -   | -   | -   | -   |
| AlSi5     | 0.06| 5.09| 0.39| 0.03| 0.13| 0.04| Bal.| -   | -   | -   | -   | -   |

Measured mechanical properties of experimental base materials and mechanical properties of the filler materials according to material datasheets are summarized in Table 2 [16-17]. The AA5083 base Al alloy with the main alloying element Mg was strain hardened and cold rolled. The analysed microstructure of the experimental alloy AA5083 was homogeneous, with the grains slightly elongated in the rolling direction. The grains reached an average size of (35 ± 4) µm in the rolling direction and (27 ± 2) µm in the direction transverse to the rolling direction. The microstructure of CP Grade 2 consists of fine equiaxed α grains with an average grain size diameter of (22 ± 2) µm. The experimental material was cold strain hardened [16].

| Material   | Tensile strength [MPa] | Young modulus [MPa] | Elongation [%] | Microhardness [HV0.1] | Ref. |
|------------|------------------------|---------------------|----------------|------------------------|------|
| CP Grade2  | 330 ± 13               | 105                 | 20             | 170 ± 5                | [16] |
| AA5083     | 267 ± 15               | 73.4                | 29.7 ± 1       | 72 ± 2                 | [16] |
| AlSi12     | 290 ± 320              | 79                  | 15 - 22        | 120 - 140              | [17] |
| AlSi5      | 145 - 227              | 79                  | 5 - 12         | -                      | [17] |
Test specimens prepared from experimentally produced welded-brazed joints were examined using mechanical testing, macrostructural and microstructural observations including chemical EDX analysis and fractographic evaluation. The destructive transverse tensile tests were performed on LabTest 5.250 SP1-VM testing machine with testing speed of 1 mm.s\(^{-1}\), according to standards STN EN ISO 6829-1 [18] and STN EN ISO 4136 [19]. The microhardness was measured by Buehler IndentAmet 1100 microhardness testing machine using testing load HV 0.1 during 10 s in accordance with STN EN ISO 6507-1 [20] and STN EN ISO 9015-2 [21]. Specimens for macroscopic and microscopic examinations were prepared from cross-sections perpendicular to the weld centreline and etched with Keller’s etchant (consisting in volume and in order of mixing from 950 ml water, 15 ml hydrochloric, 10 ml hydrofluoric acid) for 3-5 seconds [22]. ZEISS Stemi 2000-C equipment with AxioCam ERC5s camera and NEOPHOT 32 light microscope were used for macroscopic and microscopic examination of specimens. Chemical compositions at the joint interfaces were measured using JEOL 7600 scanning electron microscope equipped with EDX analyser.

3. Experimental results
Comparison of welded-brazed joints produced by conventional and unconventional welding technologies was accomplished on the base of measured mechanical properties, differences in welded-brazed joints macrostructure and microstructure, chemical composition of WM-Ti interface and the examination of fracture surfaces after transverse tensile strength tests. Using similar filler metal AlSi12 with LBWB and AlSi5 at double-square-groove type of joint produced with GTAW, the influence of the Si content was neglected. The heat input in both welding technologies was deflected to the Al sheet to reduce the amount of Ti melting at the joint interface.

3.1. Macrostructural and microstructural analysis of welded-brazed joints
The macrostructures of welded-brazed joints prepared by laser beam and GTAW welding-brazing technologies are compared in Figure 1. Significant differences can be clearly seen in the dimensions of WM. The cross-sectional area of WM is depended mainly on the heat input to the joint. Using GTAW welding technology, the linear heat input of 190.5 J.mm\(^{-1}\) was supplied into the joint, thus obtaining a WM area with a relatively large size of 21.34 mm\(^2\) (Figure 1b). It is also necessary to notice that by GTAW welding technology a double-square-groove type of joint was produced. In contrast to conventional GTAW welding technology, in unconventional LBWB welding technology, the linear heat input of approximately 45 J.mm\(^{-1}\) was applied to the joint, producing a WM cross-sectional area of 6.20 mm\(^2\) (Figure 1a).

Detailed evaluation of experimental joints macrostructures proved that the areas of joint interface fit for typically welded-brazed joints cross-sections, where two different zones are formed. From the Ti side, where the joint is partially melted, a Ti-WM brazed interface was developed. In the WM zone, complete melting and mixing of the AA5083 base material and the filler metal took place.

![Figure 1. Macrostructures of experimental joints produced by a) LBWB and b) GTAW.](image-url)
Figure 2 shows the microstructure of welded-brazed joints after LBWB and GTAW at the Ti-WM interface. The WM microstructure consists of quasi-globular grains (Figures 2a and 2c) formed by mixing the filler material (AlSi12 or AlSi5) and AA5083 Al alloy and following solidification of the melt. It is assumed that the WM consists of a solid solution of α, where the interdendritic spaces are enriched with alloying elements Si and Mg creating fine precipitates due to segregation. The finer-grained globular shaped microstructure in Figure 2a was developed due to the rapid temperature cycle (rapid heating and rapid cooling of materials) characteristic for the laser welding technology.

A more detailed comparison of the Ti-WM interface of welded-brazed joints experimentally produced by different technologies is shown in Figures 2b and 2d. Generally, if the heat supplied to the weld during the Al-Ti joining process is sufficient to partially melt the titanium sheet, the diffusion of Ti, Al and other atoms of the alloying elements occurs at the Ti-WM interface, resulting in the formation of different layers of intermetallic compounds. From this point of view, a typical welded-brazed joint was developed at the Ti-WM interface during GTAW welding, where the melting of CP Grade 2 was minimal and not continuous along the entire Ti front surface. As a result of these conditions, one thin discontinuous IMC layer was formed at the Ti-WM interface with an average thickness of 1 μm (Figure 2d). On the other hand, the Ti-WM interface of the LBWB joint consists of one continuous and one quasi-continuous IMC layer with a total thickness of 10.2 μm (Figure 2b).

Figure 2. Microstructures of joints at Ti-WM interface prepared by a,b) LBWB and c,d) GTAW.
3.2. **EDX chemical analysis**

Figure 3 shows a detail from the Ti-WM interface of an experimental welded-brazed joint prepared by LBWB technology with the points selected for the EDX analysis. At the Ti-WM interface of this joint two kinds of IMC layers have been formed, one continuous layer followed by another quasi-continuous layer (in the direction from the Ti side to WM).

![Figure 3. Positions of EDX analysis at the Ti-WM interface of a joint produced by LBWB.](image)

Results of EDX analysis for the spectra 1-8 are summarized in Table 3. Based on the chemical composition, phase diagrams and the literature sources [23-25], possible phases present were predicted. Spectra 1-3 are characterized by a high Al content typical for WM. In the darker interdendritic spaces in spectrum 1, a higher atomic percentage of Mg in the Al matrix was identified in comparison with spectrum 3, where the amount of Si [at. %] increases due to segregation and the Mg content decreases. The chemical composition of the discontinuous IMC layer at the Ti-WM interface is represented by the spectrum 4. The measured Ti content and Al content is 24 at. % and 72 at. %, respectively, what corresponds to the composition of TiAl₃ intermetallic compound.

| Spectrum | Al  | Ti   | Si    | Mg   | Mn  | Fe  | Possible phases [23-25] |
|----------|-----|------|-------|------|-----|-----|------------------------|
| 1        | 90.87 | 0.14 | 7.37  | 1.51 | 0.06 | 0.06 | Al matrix              |
| 2        | 97.20 | 0.43 | 0.77  | 1.55 | 0.06 | 0.00 | Al matrix              |
| 3        | 89.02 | 0.11 | 8.29  | 0.76 | 0.22 | 0.96 | Al matrix              |
| 4        | 71.44 | 23.94 | 4.56  | 0.00 | 0.00 | 0.22 | TiAl₃                  |
| 5        | 47.76 | 43.06 | 9.18  | 0.00 | 0.00 | 0.07 | TiAl                  |
| 6        | 0.43  | 99.42 | 0.15  | 0.00 | 0.00 | 0.00 | αTi                   |
| 7        | 0.24  | 99.76 | 0.00  | 0.00 | 0.00 | 0.00 | αTi                   |
| 8        | 2.35  | 97.48 | 0.16  | 0.00 | 0.00 | 0.00 | αTi                   |
The chemical composition of the continuous IMC layer located closer to Ti is represented by spectrum 5 with the Al content of 47.76 at. % and the Ti content of 43.03 at. %. That could indicate the presence of AlTi IMC. The chemical compositions of spectra 6-8 are very similar to the chemical composition of the base material CP Grade 2. In these spectra, a slight decrease of Al concentration with an increasing distance of the point from the Ti-WM interface towards CP Grade 2 can be observed.

A detail from the area of Ti-WM interface of a welded-brazed joint produced by GTAW technology is shown in Figure 4 with the spectra where the chemical composition was measured using EDX analysis. In contrast to the weld prepared by LBWB technology, in the case of GTAW welding, only one thin discontinuous layer of intermetallic compound was formed at the Ti-WM interface. Table 4 summarizes the chemical composition in selected points according to Figure 4, i.e. in WM (spectra 1 - 4 and 8), at the interface of Ti-WM (spectra 5 and 7) and in the HAZ of the CP Grade 2 (spectrum 6). The possible phases present were predicted in this case as well. Spectra 2-4 and 8 exhibited high content of Si element (above 12 at. %) and suggested development of Al-Si eutectics with a silumin-like structure.

![Figure 4. Positions of EDX spectra at the Ti-WM interface of a joint produced GTAW.](image_url)

**Table 4.** EDX analysis [at. %] in the points according to Figure 4.

| Spectrum | Al   | Ti   | Si    | Mg   | Fe   | Possible phases [23-25]     |
|----------|------|------|-------|------|------|-----------------------------|
| 1        | 97.8 | 0.11 | 0.97  | 0.21 | 0.00 | Al matrix                   |
| 2        | 63.19| 0.08 | 32.76 | 3.27 | 0.20 | Al-Si                       |
| 3        | 86.30| 0.00 | 12.63 | 0.56 | 0.00 | Al-Si                       |
| 4        | 69.49| 0.00 | 19.71 | 8.10 | 2.18 | Mg$_2$Al$_3$, Al-Si         |
| 5        | 6.14 | 92.83| 0.77  | 0.00 | 0.26 | Ti$_3$Al, Ti$_5$Si         |
| 6        | 0.47 | 99.53| 0.00  | 0.00 | 0.00 | αTi                         |
| 7        | 42.08| 55.87| 1.88  | 0.00 | 0.00 | Ti-Al                       |
| 8        | 76.69| 0.10 | 22.30 | 0.34 | 0.00 | Al-Si                       |
3.3. Mechanical properties of welded-brazed joints

The course of micro-hardness was measured on the cross-sections along the centre of the sheet thickness with spacing of 250 μm between the indentations. In Figure 5a, the measured values of microhardness for welded-brazed joints produced by different welding technologies are compared. The width of the weld metal for the joint prepared by LBWB technology (≈ 2.4 mm) is approximately two times lower in comparison with WM width of the joint produced by GTAW method (4.9 mm). On the other hand, the maximum values of WM microhardness are slightly higher for LBWB joint (max. 110 HV0.1) than the comparative values of microhardness in WM of joint produced by GTAW technology (max. 90 HV0.1). This trend can also be recognized in heat-affected zones (HAZ), where the difference in microhardness is approximately 15%, while the difference in HAZ width is even greater (HAZ LBWB width ≈ 2.1 mm and HAZ GTAW width > 5 mm).

The increase in the microhardness values of the weld metal by almost 40 % compared to the microhardness values of the base material (AA5083) for joints prepared by LBWB may be due to grain refinement resulting from the rapid temperature cycle and mixing the base material with the filler metal. On the Ti side, at the interface and in the HAZ, there is an increase of the microhardness compared to the microhardness of the CP Grade 2 base material due to the polymorphic transformation of Ti. The width of the HAZ on the Ti side is approximately two times smaller than the HAZ width on the Al side.

The microhardness decrease in the HAZ of the GTAW joint could be caused by grain coarsening and diffusion of Mg from the Al matrix. Fine, recrystallized Al grains, enriched mainly with silicon, forms eutectics at the grain boundaries of Al-Si, which increase the microhardness values of the weld metal by consolidating the solid solution α. The microhardness values HV0.1 at the WM rise above the measured microhardness values of the base Al alloy. At Ti side, there was a decrease of microhardness values in contrast to the Ti base material values.

![Figure 5](image_url)

**Figure 5.** Results of mechanical testing of experimental joints a) microhardness measurements across the weld centreline and b) transversal tensile strength tests.

Figure 5b illustrates the results of transversal tensile tests of welded-brazed joints prepared by LBWB and GTAW technologies. The ultimate tensile strength of test specimens from joints produced by LBWB reached the value of 245 MPa, what is nearly 90 % of the tensile strength of the AA5083 base material. Experimental specimens prepared from GTAW joints reached only 57 % of the ultimate tensile strength of the Al base material, which was 153 MPa. At both technologies, the fracture occurred in the Ti-WM interface. The welded-brazed joints prepared by GTAW technology exhibited better elongation values at failure than the joint prepared by LBWB. This may be due to the type of joint prepared by GTAW technology (butt double-square-groove type of joint), in which a larger volume of a filler metal is used.
3.4. Fractographic analysis of welded-brazed joints

The mode of fracture of Ti–Al welds depends on the morphology and phase composition of the interface [26]. The fracture of transversal tension test specimen prepared by LBWB technology took place in the Ti-WM interface. Both fracture surfaces (at WM side and Ti side) documented in Figure 6 were evaluated. Figures 6a and 6b illustrate the fracture surface at the WM side where the cleavage cracks and transcry staline fracture trace can be observed. From the energetic point of view, this fracture can be considered as a brittle fracture with low fracture energy, which is characteristic for cleavage cracks. The fracture surface at the Ti side in Figure 6c with a detail in Figure 6d is very similar to the fracture surface at WM. The entire investigated fracture surface was melted on the Ti side. During the melt solidification, microcavities developed which acted as stress concentrators. Cleavage cracks were initiated mainly in the zones containing microcavities and/or discontinuous IMC layers. In the right upper corner in Figure 6c, cleavage facets in groups, typical for a brittle fracture can be seen.

![Figure 6. SEM photographs of fracture surfaces of transverse tensile test specimen prepared from LBWB joint a, b) at WM side and c, d) at Ti side.](image)

The fracture of transverse tension test specimen prepared from welded-brazed joint produced by GTAW technology occurred as well as at the WM-Ti interface. Figure 7a shows the fracture surface at the weld metal side, which is formed by the Al matrix and Al-Si eutectics. It is possible to observe cavities and pores developed due to the trapped gases (especially hydrogen), which could not escape during solidification. The pores and impurities in the WM were most likely the initiators of defects, the growth of which caused a weld failure. A detail in Figure 7b confirms a mixed type of the obtained
fracture. Based on the trace of the fracture in the lower left corner, the fracture can be classified as a predominantly intercrystalline quasi-cleavage fracture, which changes into a transcrystalline ductile fracture in the upper right corner.

![Figure 7. SEM photographs of fracture surfaces of transverse tensile test specimen prepared from GTAW joint a, b) at WM side and c, d) at Ti side.](image)

The fracture surface at the Ti side, where the joint was formed mainly with brazing, exhibits mixed character (Figures 7c and 7d). The surface of unmelted CP Grade 2 sheet was only wetted with the molten WM consisting of a mixture of the AA5083 alloy and the filler metal (Figure 7c). Despite the higher heat input during the GTAW welding and the double-square-groove type of joint, the Ti side was only partially melted. This fact was probably caused by a larger deflection of the welding arc to the Al side during manual GTAW welding process compared to the automatized LBWB process. The surface and the root of the fracture surface on the Ti side shows more-less ductile fracture in contrast to the brittle fracture of the LBWB specimen. In a detail in Figure 7d, a brittle, low-energy ductile failure can be seen, which also indicates the extent of plastic deformation of the fracture surface. From the morphological point of view, the fracture surface on the Ti side corresponds to a quasi-cleavage fracture in which microcracks are located.

4. Conclusions
The paper presents the comparison of macrostructures, microstructures and mechanical properties of welded-brazed Al/Ti joints prepared by different welding technologies. Butt joints of dissimilar
experimental base materials, wrought AA5083 aluminium alloy and titanium Grade 2 were produced by unconventional laser beam welding-brazing technology and conventional gas tungsten arc welding technology. Plates with the thickness of 2 mm were butt joined using AlSi12 and AlSi5 filler materials.

The welded-brazed joint prepared by LBWB technology exhibits higher strength at the level of 245 MPa compared to the strength of GTAW sample. The width of WM was two times lower for samples produced by LBWB technology, than in the GTAW samples. This trend was confirmed also by the microhardness measurements on the joint cross-sections along their horizontal centreline.

The macroscopic analysis of joints prepared by both welding technologies shows the typical welded-brazed characteristics of joint at the Ti-WM interface. When comparing the microstructures of WM near the Ti interface of experimentally produced joints, the differences can be found in the grain size, grain morphology and the degree of mixing the experimental materials. In both cases, the weld metal consists of α solid solution and the Al-Si eutectics located in the interdendritic spaces but the finer-grained microstructure was developed in the WM of joint produced by LBWB technology. In addition, IMF layers with the total thickness of 10.2 μm were formed at the Ti-WM interface due to the melting of Ti surface and occurrence of diffusion processes at the Ti-WM interface. Chemical EDX analysis of the Ti-WM interface of LBWB joint using a higher resolution revealed one continuous IMC layer with the chemical composition corresponding to the TiAl IMC followed by a discontinuous IMC layer with the composition similar to TiAl3. In case of GTAW joint, only one thin discontinuous IMC layer was formed at the Ti-WM interface with an average thickness of 1 μm.

The fractographic analysis showed that the fracture of transverse tension test specimen prepared from the joint produced by LBWB technology occurred by a brittle fracture with a transcrysalline fracture traces. The fracture surfaces of the GTAW joint exhibit a mixed character of the fracture resulting probably from insufficient melting of the Ti surface.

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