Microstructural and mechanical properties of dissimilar Al-Ti joints prepared by GTAW welding-brazing

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Abstract. Joining of light metals and alloys including Al-Ti is of great interest of many producers particularly from automotive and aerospace industries. In this paper, conventional gas tungsten arc welding-brazing method was applied to join 2 mm thick plates of wrought AA5083-H111 aluminium alloy with commercially pure titanium Grade 2 using ER4043 filler rod. Butt type of joints with single- and double-square-groove welds were produced using various welding currents. Mechanical properties of prepared welded-brazed joints were evaluated by tensile tests and microhardness measurements. Microstructural analyses were carried out using light microscopy. The weld zones and Al-Ti interfaces were observed by scanning electron microscope. EDX microanalysis was used to identify variations in chemical composition across the welded-brazed joint interface. Finally, the analysis of the influence of welding parameters on the mechanical properties and dimensions of the fusion zone was accomplished.

1. Introduction

Dissimilar joining of light metals and alloys including Al-Ti is of great interest of researchers and producers particularly from automotive and aerospace industries. It results from the combination of increasing demands on production of lightweight but on the other hand high-strength constructions [1-3]. Joining titanium and aluminium as well as their alloys using fusion welding technologies is difficult due to very different material properties and especially because of the formation of brittle intermetallic compounds (IMC) in the interphase layers [4-5]. To produce high-quality weld joints of Al-Ti alloys, the thickness of the brittle intermetallic layer shall be minimized. Many studies have been focused on eliminating the thickness of the IMC layers using different filler metals [1-2, 6], varying the type of joint [4, 7] or by changing the welding method [6-10]. According to the low energy input, technology of gas tungsten arc welding-brazing offers a flexible and relatively inexpensive method for material joining in many industries [1, 3-5, 11].

The main objective of this research was to produce the reliable butt type of joints with the single- and double-square-groove welds from different types of base materials, wrought AA5083-H111 aluminium alloy and commercially pure titanium Grade 2, exploiting the welding-brazing technology of gas tungsten arc welding (GTAW) using ER4043 filler rod in order to study the influence of welding parameters on the microstructure and mechanical properties of welded-brazed joints.
2. Materials and methods

The experimental test samples of dissimilar base materials, the wrought AA5083-H111 aluminium alloy and commercially pure titanium Grade 2 (CP Grade 2) with dimensions of 50 mm × 50 mm × 2 mm were experimentally single- and double-square-groove welded in the flat position using ER4043 filler rod 1.2 mm in diameter. The experimental joints were produced using SELCO Genesis 3200 AC/DC welding machine. The constant welding parameters according to GTAW technology were: the arc voltage \( U_v = (12.8 ± 0.4) \) V, the welding speed \( v = 2.5 \) mm.s\(^{-1}\), argon shielding gas with the flow rate of 20 L.min\(^{-1}\) and the welding mode (2-step welding method with the direct current). As the variable parameters were used the welding current (ranging from 40 A to 60 A) and the number of welds.

The chemical analysis of the base materials was carried out using JEOL 7600 scanning electron microscope equipped with EDX analyzer and compared with the data from data sheets [8]. The chemical composition of welded material is given in Table 1 together with the chemical composition of the filler material specified according to the material data sheet [11-12].

| Element | Mg | Si | Cr | Cu | Mn | Fe | O | N | H | Ti | Al |
|---------|----|----|----|----|----|----|---|---|---|----|----|
| CP Grade 2 | -  | -  | -  | -  | -  | -  | 0.25 | 0.03 | 0.015 | Bal. | -  |
| AA5083  | 4.7 | 0.4 | 0.13 | 0.19 | 0.26 | 0.31 | -  | -  | -  | -  | Bal. |
| ER4043  | 0.05 | 4.5 | 6  | -  | 0.3 | 0.05 | 0.8 | -  | -  | 0.2 | Bal. |

The measured mechanical properties of the base materials and reference mechanical properties of the filler material are summarized in Table 2 [12].

|          | Tensile strength [MPa] | Young modulus [MPa] | Elongation [%] | Yield strength [MPa] | Microhardness [HV0.1] |
|----------|------------------------|---------------------|---------------|----------------------|----------------------|
| CP Grade 2 | 441 ± 3.5 | 105 | 20 | 330 | 178 ± 3 |
| AA5083   | 267 ± 2  | 73.35 | 29.7 | 180 ± 2 | 75 ± 2 |
| ER4043   | 190      | 74  | 8  | 164 | -      |

The experimental weld joints prepared by GTAW technology were investigated using mechanical testing, macrostructural and microstructural observations and the chemical analysis in the region of the Ti and weld metal (WM) interface. The test specimens were prepared by milling machine from the center of experimentally welded-brazed joints.

The destructive transverse tensile tests of experimental welds were performed according to standards STN EN ISO 6892-1 [13] and STN EN ISO 4136 [14] applying the LabTest 5.250 SP1-VM testing machine using the testing speed 1 mm.s\(^{-1}\). The microhardness measurements were performed according to STN EN ISO 6507-1 [15] and STN EN 9015-2 [16] standards applying the Buehler IndentaMet 1100 microhardness testing machine. The testing load was HV 0.1 acting during 10 s. The distance between indents was 250 µm.

For macroscopic and microscopic examination, the metallographically prepared joint cross sections were etched by Keller’s etchant with the composition in volume and in order of mixing: 950 ml water (H\(_2\)O) 25 ml nitric acid (HNO\(_3\)), 15 ml hydrochloric (HCl), 10 ml hydrofluoric acid (HF) etching for 3 to 5 s [17]. The macroscopic analysis of samples was performed using ZEISS Stemi 2000-C equipment with the AxioCam ERc5s camera. The sample microstructures were observed by NEOPHOT 32 light microscope and the JEOL 7600 scanning electron microscope equipped with EDX analyzer. The microstructures of base materials are illustrated in Figure 1. The CP Grade 2 microstructure consists of fine equiaxial \( \alpha \) grains with the average size of 20 ± 5 µm. The microstructure AA5083-H111 alloy is formed by \( \alpha \)Al solid solution with dispersed Mg particles.
3. Results and discussion

Butt type of joints with single- and double-square-groove welds were experimentally GTAW welded-brazed using ER4043 filler rod and welding parameters given in Table 3. The appearance of produced experimental joints is illustrated in this table as well. During the examination of the joint quality, the test samples from welded-brazed joints were subjected to mechanical strength tests and microhardness measurements. The macroscopic investigation of the weld quality was completed with the measurements of the weld metal widths ($W_{WM}$) and weld metal areas ($S_{WM}$). The microstructural characterization and EDX chemical analysis of the WM and Ti-WM interface was performed applying the experimental sample number 5.

Table 3. Experimental parameters and appearance of prepared welded-brazed joints.

| Weld | $I_1$ [A] | $U_1$ [V] | $v$ [mm.s$^{-1}$] | Top of the weld | Weld root |
|------|-----------|-----------|------------------|-----------------|-----------|
| 1    | Single    | 40        | 12.7             | 2.5             |           |
| 2    | Single    | 50        | 12.6             | 2.5             |           |
| 3    | Single    | 60        | 12.9             | 2.5             |           |
| 4    | Double    | 40        | 13               | 2.5             |           |
| 5    | Double    | 50        | 12.7             | 2.5             |           |
| 6    | Double    | 60        | 12.8             | 2.5             |           |

3.1. Mechanical testing

Results of the tensile strength tests of produced dissimilar joints are shown in Figure 2. All samples tested by tensile strength tests were broken in the WM. The ultimate tensile strength ($R_m$) of samples with the double-square-groove welds are higher than the values measured for single-square-groove welds. The highest value of the ultimate tensile strength was reached for the sample 5 with a double-square-groove weld prepared using the welding current of 50 A. The achieved value of 153 MPa represents 57% of the ultimate tensile strength of the AA5083-H111 base material.
Results of microhardness examination of experimental samples across the weld centreline are plotted in Figure 3. On the titanium side, for the samples with single-square-groove welds the higher values of microhardness were measured in comparison with microhardness of the CP Grade 2 base material (Table 2). It can be supposed that the increase in microhardness results mainly from the martensitic and polymorphic transformations typical for Ti alloys [2]. The decrease in microhardness of titanium CP Grade 2 base metal in samples with double-square-groove welds prepared with higher currents is probably related to the tempering effects during formation of the second weld. The microhardness in the WM zone is higher than the microhardness AA5083-H111 base material due to the intermixing of molten aluminium alloy and the filler material. The lowest microhardness of WM was measured for the sample 2 with the single-square-groove weld produced using the welding current of 50 A. The microhardness of AA5083-H111 base material in a heat affected zone (HAZ) slightly decreases as a results of the grain size increase [4-6].

![Figure 3](image-url)

**Figure 3.** Microhardness measurements across the weld centerlines of a) single-square-groove welds and b) double-square-groove welds prepared using different welding currents.
3.2. Macroscopic analysis

Macrostructures of experimental joints are shown in Figure 4. The WM is asymmetric with a prevailed fusion extent on the Al side resulting from the essentially lower liquidus temperature of Al alloy compared to the melting temperature of CP Grade 2. Some geometrical imperfections such as incomplete root penetration (Figure 4a, 4d) and linear misalignment between plates (Figure 4b, 4d) were found.

On the cross-sections from the experimentally produced welded-brazed joints, several zones characteristic for welding-brazing of dissimilar materials can be identified, i.e. a brazed joint on the titanium side, weld metal and the typical weld joint at the aluminium alloy side. The not melted or partially melted zone at the Ti and WM interface is characteristic for dissimilar joints prepared by brazing. The applied heat input during GTAW process was not sufficient to melt the titanium sheet along the whole thickness. The molten filler material only wetted the titanium sheet resulting in the brazed joint formation on the titanium side. On the AA5083 aluminium alloy side, melting of the base metal and also filler material occurred, producing a weld joint with the as-cast microstructure.

![Figure 4. Macrostructures in cross-sections of experimental joints.](image)

Using macrostructures in Figure 4 and results of microhardness testing (Figure 3), the widths of WM in the middle of the welded-brazed joints and the areas of WM were measured. The results are summarized in Table 4 together with the welding-brazing process parameters, measured ultimate tensile strength $R_m$ and the heat input $P$ and linear heat input $Q_l$ computed according to relationships

$$P = UI \eta \quad \text{[W]} \quad (1)$$

$$Q_l = \frac{P}{v} \quad \text{[J.m}^{-1}] \quad (2)$$

in which the efficiency $\eta$ was supposed to be 75% [11]. With increasing heat input and/or linear heat input the width of WM $W_{WM}$ and also the WM area $S_{WM}$ enlarge owing to the increase in volume of molten filler material.

3.3. Microscopic analysis

The microscopic analysis of the Al HAZ-WM and Ti-WM interfaces was carried out for the experimental sample no. 5 exhibited the highest tensile strength. Figure 5a illustrates the microstructure in the area of the interface between WM and the HAZ at the AA5083-H111 side.

![Figure 5. Microstructures in the area of the interface between WM and the HAZ.](image)
Table 4. Experimental welding parameters, calculated and measured results.

| Weld | $I_a$ [A] | $U_v$ [V] | $P$ [W] | $Q_l$ [J.mm$^{-1}$] | $R_m$ [MPa] | $W_{WM}$ [mm] | $S_{WM}$ [mm$^2$] |
|------|----------|----------|--------|---------------------|-------------|---------------|----------------|
| 1    | Single   | 40       | 12.7   | 381                 | 152.4       | 52            | 2.5            | 6.99 |
| 2    | Single   | 50       | 12.6   | 472.5               | 189.0       | 40            | 3              | 9.30 |
| 3    | Single   | 60       | 12.9   | 580.5               | 232.2       | 88            | 3.75           | 11.95 |
| 4    | Double   | 40       | 13     | 780                 | 312.0       | 111           | 4.25           | 20   |
| 5    | Double   | 50       | 12.7   | 952.5               | 381.0       | 156           | 4.5            | 21.34 |
| 6    | Double   | 60       | 12.8   | 1152.0              | 460.0       | 117           | 4.75           | 22.96 |

In the fusion zone, the mixing of the molten Al base alloy and filler material occurred leading to the enrichment of weld metal by Si. The grain refinement in the WM and the change in grain morphology at the interface Al HAZ-WM can be also observed in Figure 5a. Figure 5b demonstrates the Ti-WM interface formed by quasi-continual IMC layer in the upper part of the welded-brazed joint where the Ti base metal was partially melted. Columnar grains connected to this layer are oriented towards the weld centre creating the dispersed non-continuous layer. In the bottom part of the welded-brazed joint, it is possible to observe continuous oxide layer with micro-pores along the Ti-WM interface. A large pore developed by Ar capture in WM is visible in Figure 5b as well.

![Figure 5](image_url)

**Figure 5.** Microstructure of a welded-brazed joint in the area of a) HAZ-WM interface and b) Ti-WM interface.

### 3.4. EDX analysis

The EDX analysis in the area of Ti-WM interface was carried out on sample 5. The distribution maps of chemical elements Al, Ti, Si, Mg, Fe and O in the Ti-WM region are shown in Figure 6. The results of EDX line analysis are plotted in Figure 7. The line scan analysis from the WM toward the Ti side shows that the Al content falls and the Ti content rises relatively sharply to a constant level. The detail of the line scan from WM (upper diagram) suggests that WM is formed mainly by Al-Si eutectics. This assumption corresponds to the previously obtained results [2, 4-6]. At the WM-Ti interface the concentration of Mg drops down. The slightly increased concentration of the oxygen indicate the presence of an oxides layer at the WM-Ti interface.
Figure 6. Distribution maps of chemical elements in the area of the Ti-WM interface.

Figure 7. Concentration profiles of chemical elements across Ti-WM interface.

The selected spectra in the points near the Ti-WM interface according to Figure 8 were evaluated to identify the chemical composition and possible phases. The spectra from 1 to 4 and 8 were measured in the WM while the spectra from 5 to 7 at the WM-Ti interface and in Ti side, respectively. According to phase diagrams and published results, the possible phases indicated in Table 5 were proposed.
Table 5. EDX analysis [at.%] in the points according to Figure 8.

| Spectrum | Al   | Ti   | Si   | Mg   | Fe  | Cu  | Mn  | Ar  | Possible phases                      | References |
|----------|------|------|------|------|-----|-----|-----|-----|--------------------------------------|------------|
| 1        | 97.8 | 0.11 | 0.97 | 0.21 | 0   | 0   | 0   | 0.91| Al matrix                            | [19]       |
| 2        | 63.19| 0.08 | 32.76| 3.27 | 0.2 | 0.1 | 0   | 0.39| Al$_2$Cu, Mg$_2$Si                    | [20-22]    |
| 3        | 86.3 | 0    | 12.63| 0.56 | 0   | 0   | 0   | 0.51| AlMgSi                               |            |
| 4        | 69.46| 0    | 19.71| 8.1  | 2.18| 0   | 0.17| 0.39| Mg$_5$Si, Mg$_2$Al$_3$, Al$_2$Mn, AlMgFeSi | [18, 20-22]|
| 5        | 6.14 | 92.83| 0.77 | 0    | 0.26| 0   | 0   | 0   | Ti$_3$Al, Ti$_3$Si                    | [20, 5-6]  |
| 6        | 0.47 | 99.53| 0    | 0    | 0   | 0   | 0   | 0   | Ti$_3$Al, $\alpha$Ti                 | [8, 20]    |
| 7        | 42.08| 55.87| 1.88 | 0    | 0   | 0   | 0   | 0.17| TiAl, Ti$_3$Si$_3$                    | [8, 5-6]   |
| 8        | 76.69| 0.1  | 22.3 | 0.34 | 0   | 0   | 0   | 0.57| AlMgSi                               | [19-21]    |

Figure 8. Positions of EDX spectra.

4. Conclusions
The sheets of AA5083-H111 aluminium alloy and titanium CP Grade 2 were experimentally butt-welded-brazed using conventional GTAW welding-brazing method with separately added ER4043 filler rod. Using the welding current ranging from 40 A to 60 A, single- and double-square-groove welds were prepared. The quality evaluation of welded-brazed joints was carried out applying mechanical strength tests, microhardness examination and microstructure characterization including EDX analysis.

All experimental samples from the welded-brazed joints tested under uniaxial tensile loading were broken in the weld metal. The maximum ultimate tensile strength at the level of 153 MPa was achieved for the sample 5 produced with the welding current of 50 A and double-square-groove weld. This value represents the 57% of AA5083-H111 base material ultimate tensile strength. The lowest microhardness of weld metal was measured for the sample 2 with the single-square-groove weld prepared using the welding current of 50 A.

Macroscopic examination of welded-brazed joint cross-sections revealed the asymmetric shape of the fusion zones with a larger extent of molten material on the Al alloy side. Some geometric imperfections such as incomplete root penetration and linear misalignment between welded-brazed sheets were found. The interface between WM and the CP Grade 2 base material was formed mainly by brazing with solid-liquid interface while the joint on the Al alloy side exhibited the typical features of fusion welding. With increasing welding current or heat input the width of WM as well as the area of WM increased.
The microscopic analysis of the Al HAZ-WM and Ti-WM interfaces was carried out for the experimental sample no. 5 exhibited the highest ultimate tensile strength. In the area of Ti-WM interface, the EDX analysis was performed as well.

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