

# Interfacial microstructure and mechanical properties of brazed aluminum / stainless steel - joints

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**Abstract.** Due to the demand of mass and cost reduction, joints based on dissimilar metals become more and more interesting. Especially there is a high interest for joints between stainless steel and aluminum, often necessary for example for automotive heat exchangers. Brazing offers the possibilities to manufacture several joints in one step at, in comparison to fusion welding, lower temperatures. In the recent work, aluminum / stainless steel - joints are produced by induction brazing using an AlSi10 filler and a non-corrosive flux. The mechanical properties are determined by tensile shear tests as well as fatigue tests at ambient and elevated temperatures. The microstructure of the brazed joints and the fracture surfaces of the tested samples are investigated by SEM.

## 1. Introduction

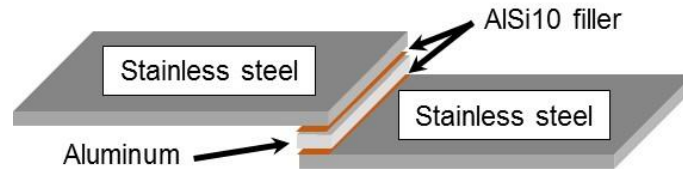
Due to the good mechanical properties and the high corrosion resistance of the stainless steel in the combination with the low specific weight and the excellent corrosion resistance of aluminum alloys, aluminum/stainless steel - joints are of special interest for the automotive industry. Hence, the significant difference of the melting ranges of aluminum and stainless steel leads to the demand of an exact temperature control during the brazing process. The main problem in joining these materials is the formation of brittle Fe-Al intermetallic compounds (IMC) at the interface [1]. This is highly dependent on central parameters, like temperature and duration, of the used process. To realize a high-quality joint between stainless steel and aluminum, several joining processes have been investigated [2]. In the last few years, the welding techniques like friction stir welding [3-5], arc weld-brazing [6-8] and laser weld-brazing [9-11] offer a great potential for aluminum alloy / steel joining. However, these processes are often limited to special part geometries and designs of the welded joints. In comparison to welding, brazing offers the possibilities to manufacture several high-quality joints with a complex geometry in one step at low temperatures. Especially, induction brazing allows a short brazing time and a local heat input. Consequently, good mechanical properties are achievable. The knowledge of the static properties and the fatigue behavior at application temperatures is necessary to determine the potential lifetimes of the dissimilar joints [12]. In this work, the mechanical properties of the aluminum / stainless steel brazed joints are characterized by tensile shear tests as well as fatigue tests at ambient and elevated temperatures.

## 2. Experimental procedures

Aluminum alloy (AA 3003) sheets with dimensions of 5 mm × 20 mm, 1.5 mm thick, and austenitic stainless steel (AISI 304) sheets with 40 mm × 20 mm and a thickness of 1.5 mm are used as base materials. The AlSi10 filler (AA 4045) is applied as a paste. The thickness of the produced brazed



joint is adjusted at 100  $\mu\text{m}$ . Single lap shear samples with an overlap length of 5 mm are used for mechanical testing. The investigated sample geometry is presented in figure 1.



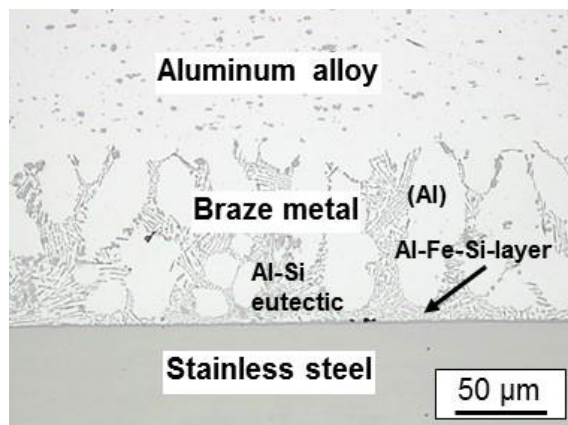
**Figure 1.** Investigated sample geometry.

The aluminum / stainless steel - joints are produced by induction brazing using a non-corrosive flux in an argon atmosphere at 600 °C. The temperature is measured by a two-channel pyrometer. The brazing process including cooling time takes about 2 min. The mechanical properties are determined by monotonic tensile tests as well as fatigue tests at 20, 100 and 200 °C. The tensile shear tests are conducted in a material testing machine Zwick Allround-Line 20 kN. The fatigue tests are carried out on a RUMUL resonance pulsator under load controlled condition with a load ratio of  $R = 0.1$  at a frequency of 55 Hz. The microstructure of the brazed joints and the fracture surface of the tested samples are investigated by SEM.

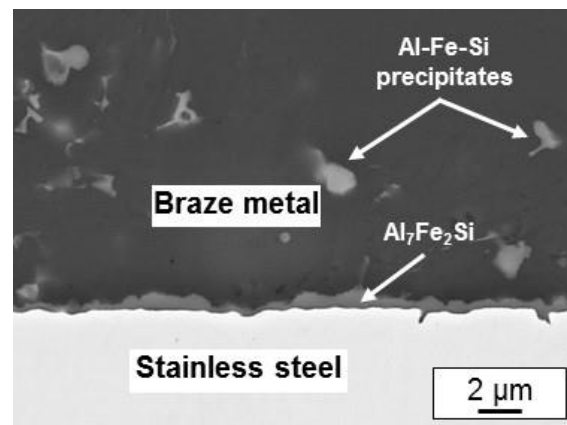
### 3. Results and discussion

#### 3.1 Microstructure

Figure 2 shows the microstructure of a produced aluminum / stainless steel - joint. According to previous work [13], the resulting braze metal consists of a primary Al solid solution and an Al-Si eutectic. Due to diffusion and reaction of Fe, Al and Si, an Al-Fe-Si layer is formed at the interface to the stainless steel. The EDX analyses indicate that the composition of the Al-Fe-Si layer matches the  $\text{Al}_7\text{Fe}_2\text{Si}$  phase, figure 3. Literature data about the Al-Fe-Si system also confirm this assumption [14, 15]. During the short-time induction brazing, no rapid growth of the IMC layer occurs. It can be seen that the Al-Fe-Si layer is about 1  $\mu\text{m}$  thick. Additionally, Al-Fe-Si precipitates (light gray particles) in the braze metal are identified, figure 3. They are formed due to the diffusion of Fe into the braze metal. The EDX analyses show that the precipitates are most probably  $\text{Al}_7\text{Fe}_2\text{Si}$  phases.



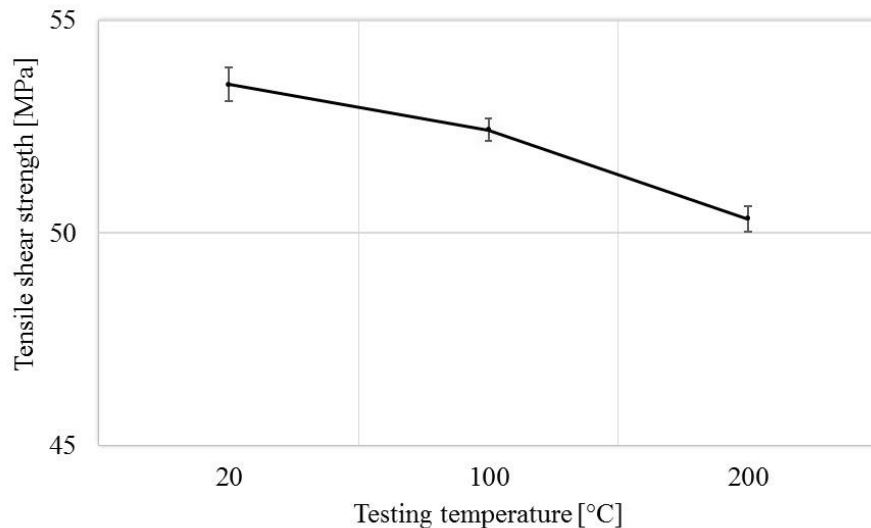
**Figure 2.** Microstructure of the aluminum / stainless steel brazed joint (OM).



**Figure 3.** Interface to stainless steel (SEM, BSD).

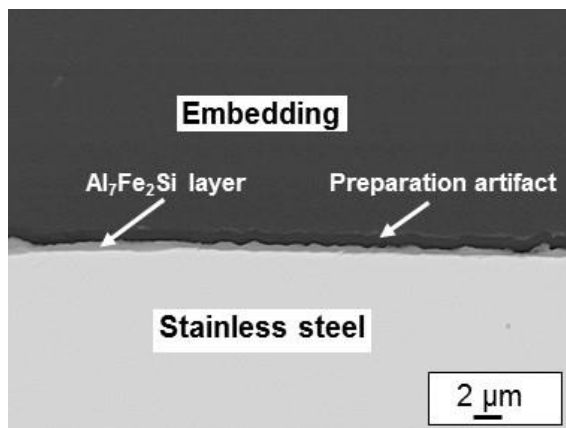
### 3.2 Tensile shear test

To evaluate the mechanical properties of the joints, tensile shear tests are carried out at ambient (20 °C) and elevated temperatures (100 and 200 °C). Three single lap shear samples per testing temperature are produced with an overlap of 5 mm. In figure 4 the results of the tensile shear tests of the brazed samples are presented. At ambient temperature, a tensile shear strength of 53 MPa is determined. The values are significantly higher than the results of Roulin et al. (21 MPa) [16]. Roulin et al. produced aluminum / stainless steel joints in a furnace at a temperature of 600 °C with a holding time of 10 min. The low strength values can be explained by the longer holding time compared to induction brazing. The interfacial zone of the brazed joints has a complex structure, it consists of two intermetallic layers:  $\text{FeSiAl}_5$  and  $\text{FeAl}_3$ . The formation of the second, more brittle intermetallic layer is a main cause for the mechanical degradation of the joints. The solution of this problem is a short holding time to avoid the formation of the intermetallic  $\text{FeAl}_3$  layer. With an increase of testing temperature, a strength decrease is registered. The joining strength is 52 MPa at 100 °C and 50 MPa at 200 °C. The decrease of the strength can be explained by dislocation movements like slip of screw dislocations and climb of edge dislocations. The diffusion, activated by the temperature, increases the effect of dislocation movement. This leads to a higher brittleness of the brazed joint.

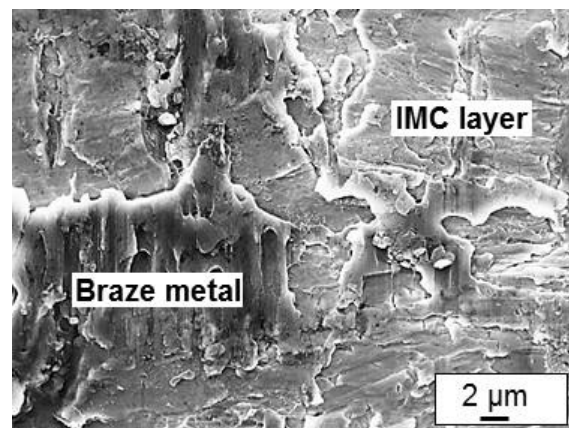


**Figure 4.** Tensile shear strength of brazed joints as a function of the testing temperature.

The fracture surfaces of the tensile shear tested samples are investigated using the top view and the cross sections. It can be seen that the brazed samples fail in the joint interface, especially in the  $\text{Al}_7\text{Fe}_2\text{Si}$  layer. The rough surface of the IMC indicates a fracture within the layer, figure 5. There are some residues of braze metal adhering at the IMC, figure 6. Due to the heat input during the brazing process, thermal induced stresses occur at the interface because of the high differences in hardness of the  $\text{Al}_7\text{Fe}_2\text{Si}$  layer (1020 HV0.0025), the braze metal (105 HV0.0025) and the stainless steel (245 HV0.0025). Consequently, this causes the crack initiation at the interface of the aluminum / stainless steel brazed joints.



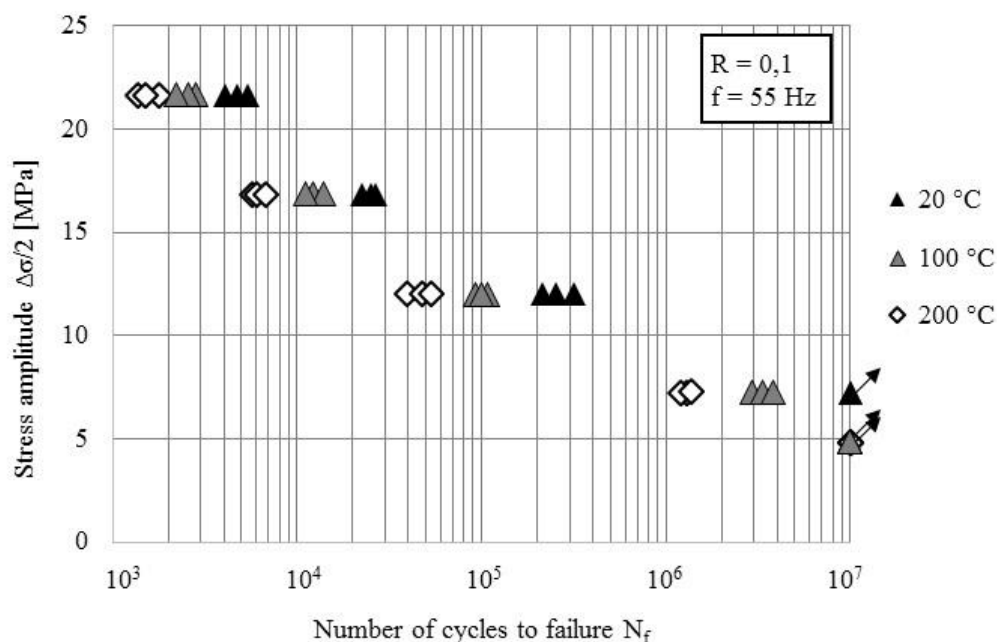
**Figure 5.** Cross section of the fracture surface of the tensile shear tested samples.



**Figure 6.** Fracture surface of the tensile shear tested samples.

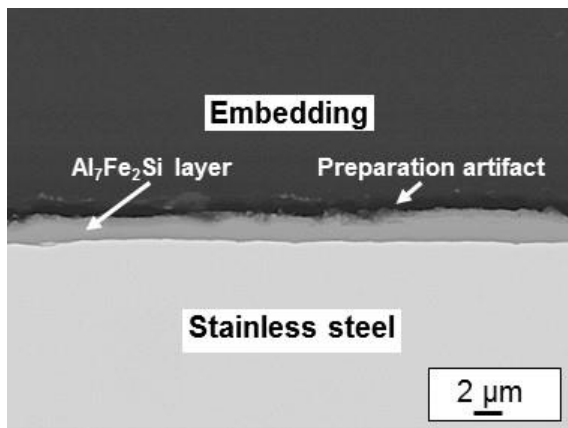
### 3.3 Fatigue tests

The fatigue tests are carried out up to a fatigue endurance limit of  $10^7$  cycles. Based on the measured tensile shear strength of the brazed joints four stress levels (90, 70, 50, 30 %) are set. Three single lap shear samples per stress level are tested at ambient (20 °C) and elevated temperatures (100 and 200 °C). The S-N curves given in figure 7 represent the results of the fatigue tests of the brazed joints. The curves show three distinct fatigue ranges: low cycle fatigue (LCF), high cycle fatigue (HCF) and long life fatigue (LLF). It can be seen that the aluminum / stainless steel brazed joints, tested at ambient temperature, reach a fatigue life of  $10^7$  cycles at a stress amplitude of 7 MPa, whereas for elevated temperatures the fatigue endurance life of  $10^7$  cycles is not reached. Therefore, tests at a stress level of 20 % equivalent to 5 MPa are successful carried out. In addition to the operation of the basic fatigue mechanism, creep has an influence on the damage mechanism of the brazed joints. Due to the cyclic loading and the thermal activation, a slip of the grain boundaries and changes in the dislocation movement take place. In these places, an agglomeration of microstructural defects and pores occurs, which favors the progressive crack growth.

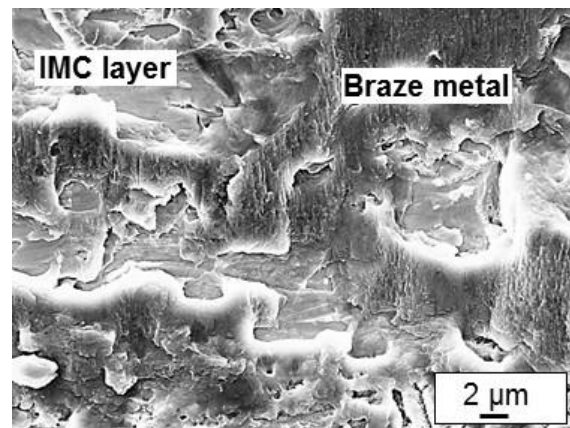


**Figure 7.** S-N data of the aluminum / stainless steel brazed joints.

In figures 8 and 9 a cross section and a top view of the fracture surfaces of the tested samples are presented. It can be supposed that the cracks start in ductile braze metal and run through. After fatigue tests, the entire  $\text{Al}_7\text{Fe}_2\text{Si}$  layer as well as residues of the braze metal adhere at the stainless steel, figure 8. The amount of residues of braze metal at the IMC surface is higher than after monotonic tensile testing, figure 9. This indicates that the fracture occurs in the joint interface near the  $\text{Al}_7\text{Fe}_2\text{Si}$  layer, where the thermal induced stresses are concentrated. Consequently, the Al-Fe-Si intermetallic layer has an influence on the fatigue behavior of the aluminum / stainless steel brazed joints at high stress amplitudes as well as at a low stress amplitudes.



**Figure 8.** Cross section of the fracture surface of the fatigue tested samples.



**Figure 9.** Fracture surface of the fatigue tested samples,  $S = 12 \text{ MPa}$ ,  $N = 2 \times 10^5$ .

It can be summarized that the  $\text{Al}_7\text{Fe}_2\text{Si}$  layer influences the tensile shear strength and the fatigue behavior of the aluminum / stainless steel brazed joints predominantly. The degree of this influence must be determined by investigation of the initiation and the propagation of cracks depending on the number of cycles.

#### 4. Conclusions

Aluminum / stainless steel - joints are produced by induction brazing using an AlSi10 filler. The brazed joints possess a tensile shear strength of 53 MPa at ambient temperature. With an increase of the testing temperature, a strength decrease is registered. The joining strength is 52 MPa at 100 °C and 50 MPa at 200 °C. Moreover, fatigue tests are carried out up to a fatigue endurance limit of  $10^7$  cycles. The aluminum / stainless steel brazed joints, tested at ambient temperature, reach a fatigue life of  $10^7$  cycles at a stress amplitude of 7 MPa. It is figured out that the fatigue life decreases with an increase of testing temperature. The aluminum / stainless steel – joints, tested at elevated temperatures, reach a fatigue life of  $10^7$  cycles at a stress amplitude of 5 MPa. The results of these investigations show that the  $\text{Al}_7\text{Fe}_2\text{Si}$  layer influences the tensile shear strength and the fatigue behavior of the aluminum / stainless steel brazed joints predominantly. In further investigations, the initiation and the propagation of cracks depending on the number of cycles will be observed.

#### Acknowledgments

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