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Mechanical and microstructural behavior of brazed aluminum / stainless steel mixed joints

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Abstract. There is a requirement to combine different materials such as aluminum and stainless steel in industrial applications like automotive heat exchangers. Brazing offers the possibility to reduce the joining temperature in comparison to welding due to the lower liquidus temperature of the fillers. In the present work, the mechanical and microstructural behavior of aluminum / stainless steel mixed joints is investigated. The specimens are produced by induction brazing using an AlSi10filler and a non-corrosive flux. To evaluate the mechanical properties of the joints, tensile tests at elevated temperatures are carried out. Additionally, long-term thermal exposure experiments are done in order to investigate the changes in the microstructure.

1. Introduction

In the last years, mixed joints became more and more interesting in the automotive industry due to the potential in weight and cost reduction. Especially joints of aluminum and stainless steel are required. However, joining of these materials is complicated due to significant differences in the melting ranges and the formation of brittle AlFe intermetallic compounds (IMC) [1]. The phase formation is caused by the diffusion and reaction of Fe and Al, these effects are highly dependent on the temperature and holding time of the joining process. A higher thermal impact leads to thicker IMC layers at the interface to the stainless steel. These layers are generally considered to be the main cause for the mechanical degradation of the joints. In order to minimize the layer thickness, it is necessary to reduce the heat input and therefore the intensity of chemical reactions and diffusion. In this case, brazing offers a possibility to reduce the joining temperature in comparison to welding because of the lower liquidus temperature of the used fillers. Due to the short brazing time and the local heat input into the joint, induction-brazing leads to the formation of IMC layers less than 10 µm in thickness, resulting in a sufficient mechanical strength [2]. In the present work, the microstructural evolution of the joints during long-term thermal exposure experiments is investigated. The mechanical properties of the joints are evaluated by tensile tests at elevated temperatures.

2. Experimental procedures

Aluminum alloy 3003 (AA 3003) and AISI 304 austenitic stainless steel plates with dimensions of 40 mm × 20 mm × 1,5 mm were used as base materials. The AlSi10 filler (composition corresponds to aluminum alloy 4045) was applied as a paste. Before brazing, the surfaces were cleaned by abrasive paper and ethanol. A non-corrosive flux was applied and dried. The aluminum / stainless steel mixed joints were produced by induction brazing in an argon atmosphere at 600 °C according to the eutectic temperature of the AlSi10 filler (575 °C) and liquidus temperature of 3003 aluminum alloy (630 °C). The temperature measurement was carried out using a twin-channel pyrometer. The brazing process including cooling time takes about 2 min. The thickness of the produced brazed joint was adjusted at 50 µm. After brazing, the specimens were prepared metallographically. Long-term thermal exposure experiments were done in a muffle furnace at 200 °C for 6 h, 48 h and 120 h to observe the growth kinetics the IMC layer. The exposure temperature corresponds to the maximum application temperature of automotive heat exchangers. The microstructure of the mixed joints was characterized by optical microscopy (OM) and scanning electron microscopy (SEM). The chemical composition was analyzed by energy-dispersive X-ray spectroscopy (EDX). The mechanical properties were determined by tensile tests at 20, 100, 150 and 200 °C. Furthermore, the fracture behavior was observed and discussed.

3. Results and discussion

3.1. Microstructure

Figure 1 shows the typical microstructure of the produced aluminum / stainless steel mixed joints. A primary Al solid solution and in between an Al-Si eutectic are formed. At the interface to the stainless steel, the expected IMC layer is formed due to diffusion and reaction of Fe, Al and Si. This layer is shown in more detail in the SEM micrographs, figure 2. Without a holding time at brazing temperature, a thickness of about 0.5 µm can be observed, it increases with extended holding time.

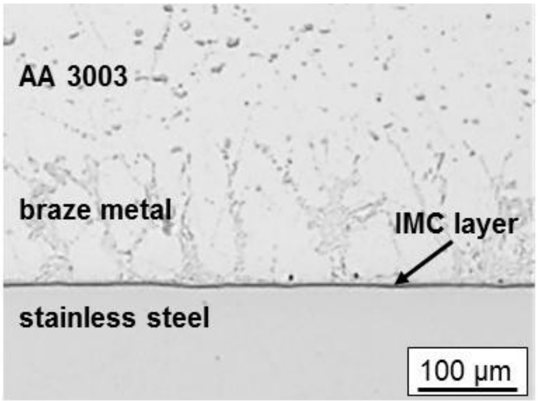

Figure 1. Microstructure of the brazed aluminum / stainless steel joint (OM)

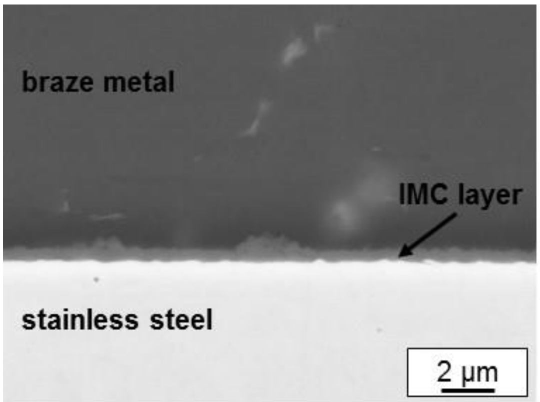

Figure 2. Interface to stainless steel (SEM)

Due to its low thickness, the chemical composition of the IMC layer is difficult to determine quantitatively by EDX analysis. A maximum thickness of about 10 µm was reached at holding times of 10 min. These specimens were used to measure the chemical composition of the IMC layer by EDX: 71–74 at.% Al, 17–19 at.% Fe and 7–10 at.% Si. Additionally, traces of Cr and Ni were detected. The results indicate that the IMC layer conforms the Al_7Fe_2Si phase. Song et al. reported that an $Al_{7,2}Fe_{1,8}Si$ layer is formed at the interface of TIG welded joints of aluminum alloy und stainless steel [3]. Literature data about the Al–Fe–Si system also confirm this conclusion [4].

3.2. Long-term thermal exposure

In order to investigate the growth of IMC layers depending on of the application temperature, long-term thermal exposure experiments were conducted at 200 °C for 6 h, 24 h and 120 h, figures 3, 4, 5 and 6 show the results:

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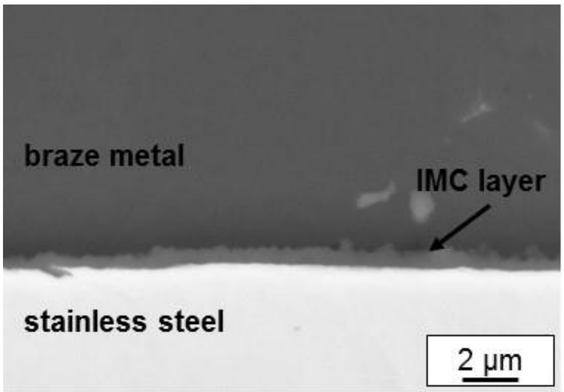

Figure 3. Micrograph of long-term thermal exposure experiments, initial state

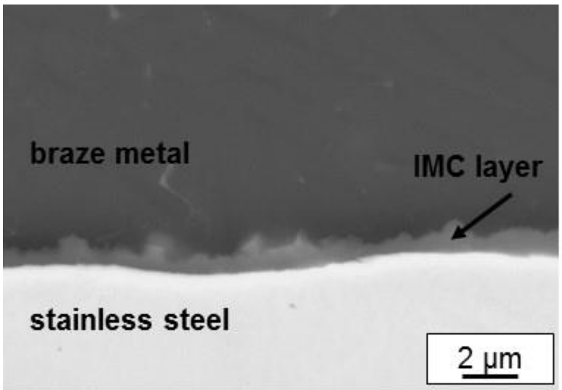

Figure 4. Micrograph of long-term thermal exposure experiments at 200 °C for 6 h

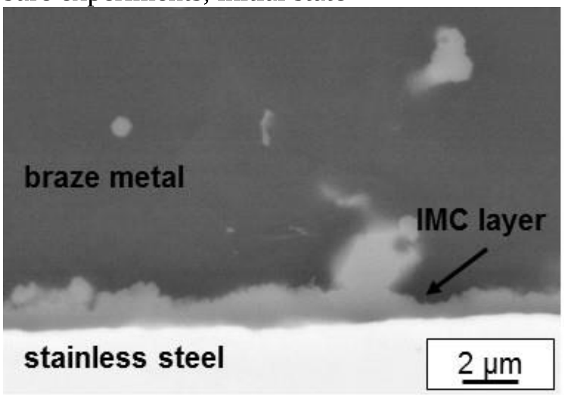

Figure 5. Micrograph of long-term thermal exposure experiments at 200 °C for 24 h

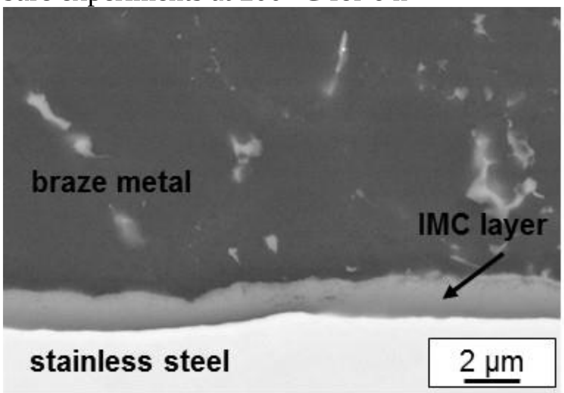

Figure 6. Micrograph of long-term thermal exposure experiments at 200 °C for 120 h

The IMC layer in the as brazed condition is about 0,5 µm thick, figure 3. It slowly begins to grow during thermal exposure at 200 °C for 6 h, figure 4. The diffusion of Fe, Al and Si is reactivated. In addition, the time has a great influence on the diffusion process. With further exposure time for 24 h and 120 h, the thickness is increasing to approx. 2 µm, figures 5 and 6. Summarized, the long-term thermal exposure has a significant effect on the growth of the IMC layer. Nevertheless, the thickness is lower than 10 µm, which is known to be uncritically from literature data [2]. Therefore, good mechanical strength of the brazed joints is expected.

3.3. Tensile tests at elevated temperatures

To evaluate the mechanical properties of the joints, tensile tests were carried out at 20, 100, 150 and 200 °C in a material testing machine Zwick Allround-Line 20 kN. Three samples per testing temperature were produced with an overlap of 10 mm. The fractured samples are shown in figure 7. In addition, the front and side projections of the brazed samples are plotted schematically. The brazed area is tagged with the dashed box. The fracture of all samples occurs in the Al base material. The brazed joints did not break. Consequently, the results of the tensile tests correspond to the strength of the Al base material, figure 8. At room temperature (20 °C), a tensile strength of 145 MPa is determined. Thus, the brazing process did not significantly affect the strength of the Al base material: strain hardened, 120–160 MPa [5]. With an increase of testing temperature, a strength decrease is registered. With regard of these results to the brazed area, minimal joining strengths of 22 MPa at 20 °C, 20 MPa at 100 °C, 14 MPa at 150 °C and 10 MPa at 200 °C can be ensured. This is matching with results of Lugscheider et al. (15–30 MPa) [6].

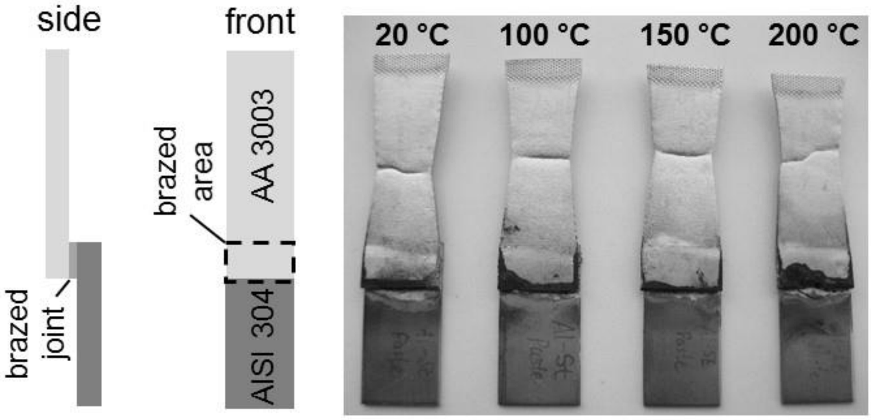

Figure 7. Fracture image of brazed aluminum / stainless steel samples

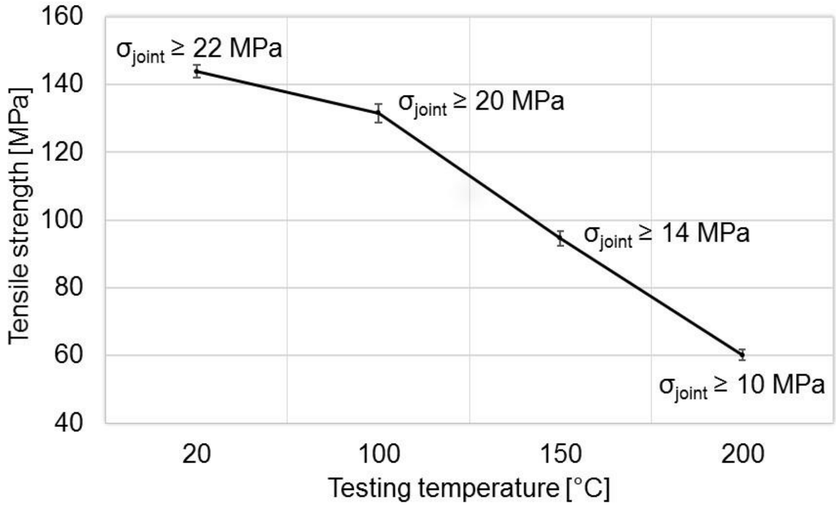

Figure 8. Tensile strength of the base material AA 3003 after the brazing process as a function of the testing resp. application temperature

4. Conclusions

Aluminum / stainless steel mixed joints, produced by induction brazing using an AlSi10filler, show thin IMC layers at the stainless steel interface. EDX analyses indicate a chemical composition of Al_7Fe_2Si. It was figured out that the layers grow depending on exposure time in long-term thermal exposure experiments. However, the thickness remains under 10 µm, expecting good mechanical properties of the brazed joints. The results of the tensile tests show that the fracture of all brazed samples occurs in the Al base material. The brazed joints did not break. With regard to the brazed area, minimal joining strengths of 22 MPa at 20 °C, 20 MPa at 100 °C, 14 MPa at 150 °C and 10 MPa at 200 °C can be ensured. In further investigations, the overlap will be reduced in order to cause the fracture within brazed joint.

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