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Novel brazing technologies for hybrid aluminum structures

W. Tillmann[1], L. Wojarski[1] and C. Liu[1]
[1]Institute of Materials Engineering, TU Dortmund, Germany

The demand for hybrid structures is steadily increasing due to the rising requirements concerning material properties. Therefore, brazing dissimilar metals is an interesting approach, especially as it is based on the low thermal affection of the base materials.

In this study, dissimilar metal brazing of AW6060 aluminum alloy to DC04 steel has been conducted with two different approaches. Because of the temperature sensitivity of the aluminum alloy, one approach used self-generated aluminum based filler metals. Hence, a series of Al-Si-Cu and Al-Ag-Cu alloys doping with additional elements were studied in order to develop low-melting filler metals. All alloys possess a brazing temperature below 580°C. Another concept was to utilize diffusion brazing to join the materials. As the diffusion of aluminum and copper at temperatures below 580°C in a vacuum furnace form a transient liquid phase during brazing, pure copper, which serves as a filler metal was deposited onto the parent materials by arc-PVD-coating. Crucial parameters such as dwell time and brazing temperature were investigated to identify their influence on the joint quality.

In order to characterize the brazing properties of the self-generated foils, wetting tests were carried out. The microstructure of the joints for all brazements were investigated by means of light microscopy and SEM analyses. Finally, the joint strengths were measured by shear tension testing.

Keywords: *brazing, self-made filler alloys, PVD coating, aluminium-steel-hybrids*

1. Introduction

The complex structure of modern vehicle components confronts automobile manufacturers with major challenges such as building parts as light as possible, and obtain the highest level of security and stability. Because of the excellent mechanical properties and the easy reusability of aluminum, there are efforts to built vehicles completely constructed of aluminum. The achievable weight reduction of up to 50% by the use of aluminum still remains a costly solution for industrial productions, whereas the introduction of aluminum components in a standard steel conception of cars is an attractive compromise of expenses and performance [1].

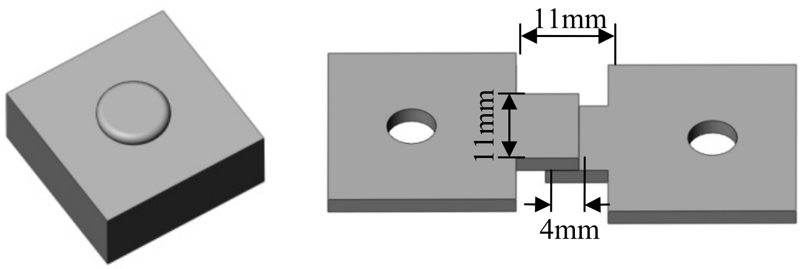
The existing literature shows that aluminum and steel can be joined with different procedures such as arc-welding [2,3], ultrasonic welding [4] and laser beam welding [5-7]. However, a considerable heat input causes an unfavorable energy balance and high residual stress. In contrast, brazing offers advantages such as a low operating temperature and prevents the melting of the base material.

In this work, two different approaches to manufacture aluminum-steel-joints were investigated. One was to produce self generated filler metals as new bonding materials. The second procedure includes coating the parent material using a PVD process prior to the diffusion brazing process, in order to deposit components of the actual filler metal. The brazing of dissimilar metals of AW6060 aluminum alloy to DC04 steel was carried out in a vacuum furnace. Finally, in order to analyze and evaluate the joint quality, the mechanical and the metallurgical properties of the joints were investigated.

2. Experimental Procedure

To investigate the spreading behavior of the self-made filler alloys, which were fabricated in an arc-furnace according to the procedure described in [8], some of the aluminum samples were sandblasted using PK80 sand and others were grinded using 1000 silicon paper. Unlike the aluminum samples, the sandblasted and untreated surfaces of the steel samples were chosen for the wetting tests.

Aluminum- and aluminum-silver-based filler alloys were fabricated and their applicability for aluminum-steel-joints has been evaluated. In order to investigate the spreading behavior of the filler alloys, wetting tests was conducted (Figure 1a). The filler alloys have been applied as round plates with 3mm diameter and were positioned onto the base materials. In order to investigate the mechanical properties, shear strength tests were carried out after brazing. For this process aluminum sheets with a thickness of 2mm and steel sheets with a thickness of 1mm were cut into plates with dimensions of 30x20mm prior to brazing. After joining the samples were shaped according to Figure 1b.



a) Wetting test b) Sample for shear strength tests

Figure 1: Applied spreading ability tests and strength test

All spreading tests and the brazing cycles were carried out in a vacuum furnace. The joints were fixed with a stainless steel clamp and heated with a heating rate of 15K/min. The dwell time was 10min. After brazing the samples were cooled in the furnace after six hours to room temperature.

Besides the development of filler alloys for aluminum-steel-joints, diffusion brazing using arc-PVD-coating was investigated. For this process, copper was deposited onto the polished and plasma etched surfaces of the steel and aluminum samples. Copper was chosen because of the fact that there is a eutectic composition with a low melting point in the binary phase diagram of aluminum and copper. Therefore it is possible by the selection of appropriate process parameters to force the formation of a transient liquid phase due to diffusion processes at elevated temperatures during brazing. Due to further diffusion processes, this transient liquid phase acts as a filler metal and solidifies isothermally. The dwell time as well as the brazing temperature were varied to investigate their influence on the resulting microstructure and joint strength. In order to make a comparison of the two approaches, the geometry of the shear strength specimen which was used to evaluate the self generated alloys was used for the diffusion brazed samples as well.

3. Results

First of all, the melting points of the self generated filler metals were determined with Differential Thermal Analysis (Table 1). The AlAg40.4Cu19 filler metal has the lowest melting temperature due to its eutectic composition. The addition of 3 wt.-% gallium only has a minor influence on the melting point.

	Filler metal	Al	Si	Cu	La	Ga	Ag	Melting temperature
Al based	AlSi10Cu20La	69	10	20	1			546°C
	AlSi10Cu20Ga	69	10	20		1		548.5°C
AlAg based	AlAg40.4Cu19	40.6		19			40.4	505°C
	AlAg40.4Cu16Ga	40.6		16		3	40.4	511°C

Table 1: Composition in wt-% and melting temperatures of the applied filler metals

The wetting tests were carried out on AW6060 and DC04 surfaces with varying pre-treatments and showed very different results. The aluminum based filler metals revealed relatively good spreading behaviors on the grinded aluminum surface (Figure 2a, b). Doping with gallium reduced the surface tension and hence, the largest spreading area is formed. On the contrary, the same Al-based filler metals do not wet on sandblasted DC04 surfaces (Figure 2c, d). Therefore aluminum based filler metals have been assessed as not suitable fillers and excluded from the following investigations.

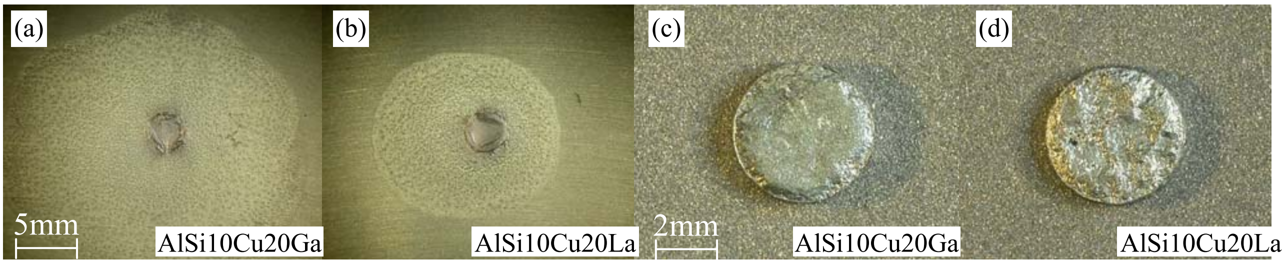


Figure 2: Wetting tests of Al-based filler metals on AW6060 (a, b) and on DC04 (c, d)

The presence of silver in Al-Ag-based filler metals has a positive influence on the wetting behavior on sandblasted as well as on untreated DC04 surfaces (Figure 3). The spreading on the untreated surfaces has an irregular shape (Figure 3b, c), whereas the spreading on the sandblasted specimens was regular and showed the best wetting behavior (Figure 3a, c).

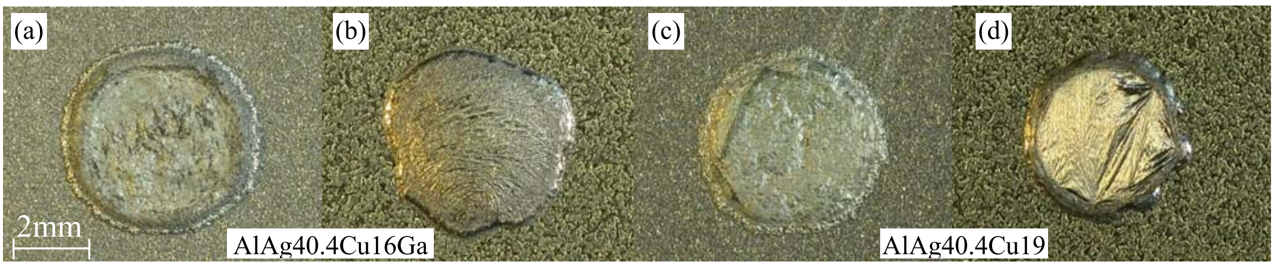


Figure 3: Wetting tests of Al-Ag-based filler metals on DC04

The wetting tests of Al-Ag-based filler metals on sandblasted and grinded AW6060 surfaces showed significant differences in the wetting behavior as well. The molten metal has a preferential spreading direction on grinded surfaces and forms an ellipse due to small grooves on the grinded surfaces (Figure 4b, d). A similar spreading behavior on sandblasted aluminum surfaces to the sandblasted steel surfaces could be observed. The filler metals spread outwards evenly, although the AlAgCu filler metal showed erosion occurrences and the AlAgCuGa filler metal had a smaller spreading area.

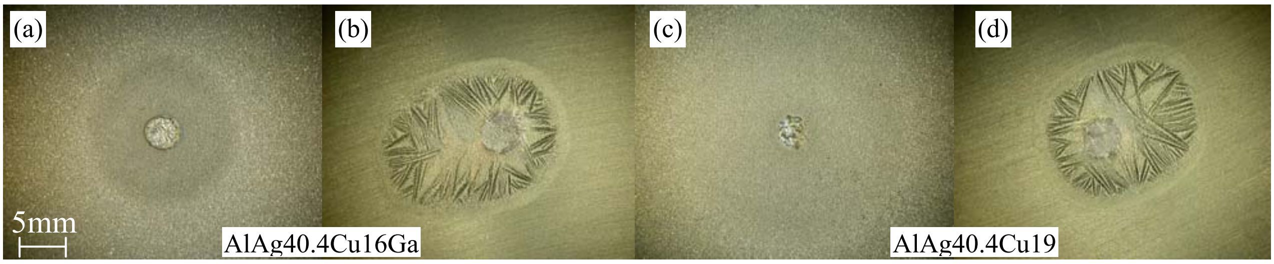


Figure 4: Wetting tests of Al-Ag-based filler metals on AW6060

The wetting tests revealed that the wetting behavior highly depends on the surface morphology. Hence, grinded aluminum and sandblasted steel samples were selected for the flowability and gap filling tests. Within these tests Al-Ag-based filler metals showed good results as well. All the gaps could be filled completely. However, more or less erosion occurrences were observed at the braze/aluminum interface. Fe_xAl_y intermetallic phases at the braze/steel interface were measured.

Figure 5 shows two representative micrographs of brazed joints using the Al-Ag-based filler metals. Both joint-zones feature a similar structure. At the braze/aluminum interface, strong diffusion of silver into aluminum was detected. Dendritic phases, which mainly consist of Al-Cu and Al-Ag intermetallic precipitations, are embedded in an Al-based solid solution alloyed with Ag in the middle of the joint–zones. Some voids and micro cracks are visible in the micrographs as well. Two continuous reaction layers can be noticed between the braze and the steel substrate. These reaction layers, which mainly are comprised of Fe_xAl_y intermetallic phases, were formed by mutual diffusion of Al to Fe and Fe to Al. It has to be emphasized that a high silver concentration is detected between the two reaction layers of the joint using the AlAgCuGa filler metal, which is effected by the presence of gallium.

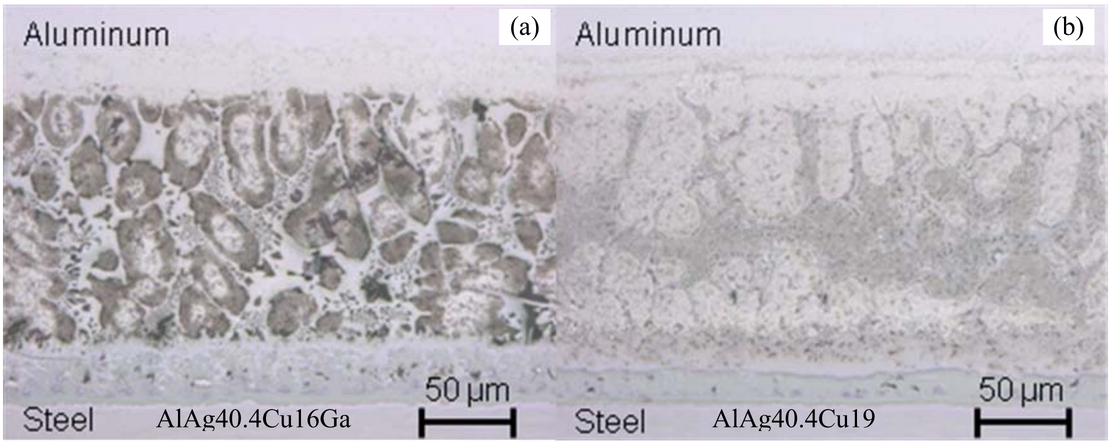


Figure 5: Micrograph of aluminum/steel joints brazed at 570°C using Al-Ag-based filler metals

The resulting microstructures of the pre-coated and diffusion brazed samples are illustrated in Figure 6. All joints are brazed well and do not contain any noticeable pores or joint flaws. In comparison to brazements using self-generated filler alloys, the brazing seams are significantly thinner and mainly comprise of just two different phases. Regarding the brazements at 580°C (Figure 6a), the phase at the steel side is rich in iron and is stripe-shaped with well defined borders, whereas the phase on the aluminum side is rich in aluminum and has partially infiltrated the aluminum. With an increase of the dwell time, there is a clear trend that both phases are growing and become thicker due to the diffusion of aluminum. A decrease of the brazing temperature to 560°C, which is close to the melting point of eutectic AlCu, leads to the formation of another phase. Because of a decrease of the diffusion rate in dependence on the temperature, a certain amount of the liquid phase did not solidify isothermally. This was later achieved by the cooling process.

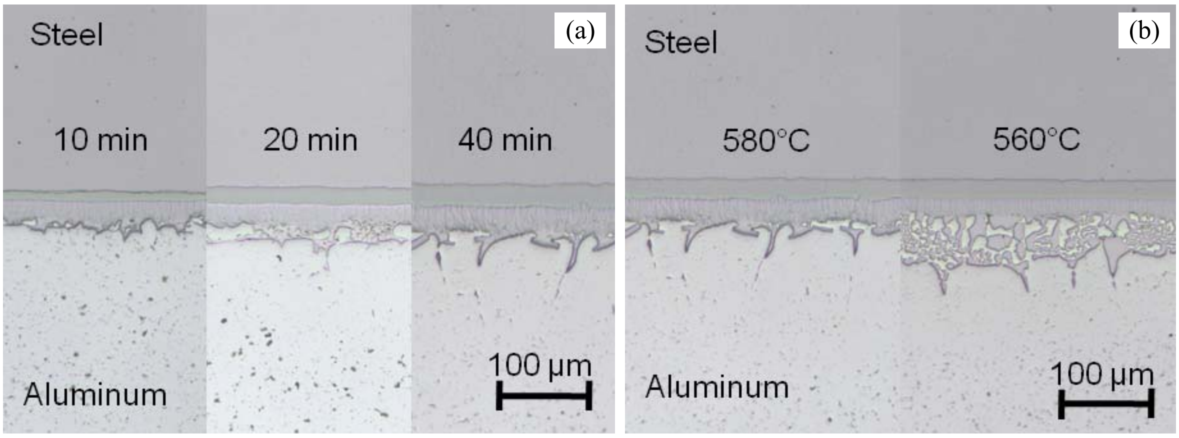


Figure 6: Micrographs of diffusion brazed aluminum/steel joints using arc-PVD coating varying dwell time at 580°C (a) and varying the brazing temperature at constant dwell time of 40 min (b)

The comparison of the achieved joint strengths using self-generated filler alloys and applying diffusion brazing on PVD coated samples is summarized in Figure 7. Both approaches lead to a high joint strength of about 30MPa, which is higher than the shear strength obtained in [9]. The strongest joints were obtained using the filler alloy AlAgCuGa3, which reached 35MPa.

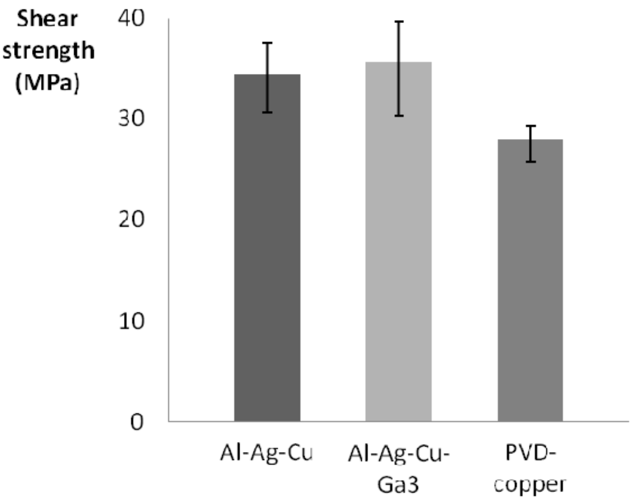


Figure 7: Shear strength of the brazements

Finally, the fracture surfaces of the brazements using the self-generated Al-Ag-based filler alloys were investigated by means of scanning electron microscopy (Figure 8). The fracture surfaces of both brazements bonded with AlAg-based filler metals are similar in their structure. The fracture surface of the AlAgCu brazement is relatively smooth and composed of cracked and scaled slabs (Figure 8b), in contrast, the brazement using the AlAgCuGa filler metal has a slightly rough fracture surface (Figure 8a). The corresponding microscope fractography of the fracture surface showed a similar structure yet, with more small raptures and fragements, which is favorable for the strength of the joint. This tendency was verified in the shear tests. The joints failed at the braze/steel interface. It is assumed, that the brittle reaction layer is the source of the fracture. The fracture proceeds within the interior of the braze, mainly through the aluminum/steel intermetallic phases. This implies that the Fe_xAl_y intermetallic compound is the most detrimental phase in the joint.

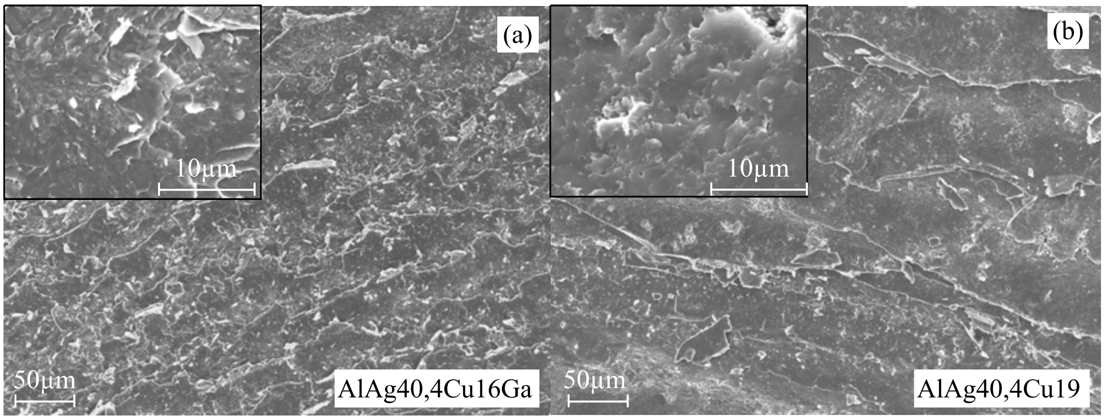


Figure 8: Fracture surfaces of the aluminum-steel-joints using Al-Ag-based filler metals

4. Conclusion

The manufacturing of aluminum-steel-joints using self-generated filler metals on Al-Ag-basis for vacuum brazing and diffusion bonding of pre-coated samples in a vacuum furnace without the application of fluxes was carried out successfully and high joint strengths have been obtained. Due to the poor spreading behavior of Al-based filler metals on steel, no further investigations of these filler alloys have been conducted. The Al-Ag-based filler metals showed a good spreading behavior on aluminum surfaces and a satisfying spreading behavior on steel surfaces. Gallium as a doping element can reduce surface tension and fosters the spreading of the filler metals. Therefore, the joints bonded with AlAgCuGa filler metal have the highest shear strength. The source of fracture could be localized at the braze/steel interface. Intermetallic compounds at the interface act like notches and decrease the joint strength. One possibility to prevent the formation of these compounds is to decrease the exposure time in the furnace. Regarding the pre-coated and diffusion brazed samples, a significant dependency of the resulting microstructure on the dwell time and the brazing temperature was verifiable. Higher dwell times lead to thicker phases in the brazing seam. A decrease of the brazing temperature caused a lower diffusion rate and an uncompleted isothermal solidification during diffusion brazing.

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