BRAZING & SOLDERING Lightweight Aluminum-Steel Structures FOR AUTOMOTIVE APPLICATIONS

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Reducing the weight of materials in the automotive industry has become more relevant due to the advent of electric cars. The use of lightweight materials can significantly reduce energy consumption, thus increasing the range (mileage) of each electric battery charge. In modern automotive production, the problem of weight reduction is often solved by partially replacing steel with aluminum. As a result, brazing and soldering of steel-aluminum structures are now being extensively tested.

Many attempts have been made to use laser welding for joining steel to aluminum (Refs. 1–3). However, laser welding has two disadvantages that limit application for commercial or mass production: 1) Laser welding requires high precision in the production and assembly of the parts to be joined, increasing production costs; and 2) the geometry of the welded parts is limited to a flat or round shape.

Therefore, there is a demand for torch brazing/soldering as a cost-effective alternative for joining steel to aluminum. Practical applications for the brazing/soldering of lightweight steel-aluminum parts include car trunk lids, doors, roofs, hoods, front fenders, fender liners, front and rear bumpers, battery cases, mirror housings, and more.

Additionally, various solders, fluxes, and brazing/soldering heating methods have been tested in recent years (Refs. 4–8). However, the lack of industrial application indicates that the optimal technology has not yet been found. Additionally, the widespread difference in technical results can be explained by the variety of tested materials (including experimental solders) and the use of various heating methods.

In this work, the following metals were tested: standard aluminum alloys A6061, A6022, and A2024; 1018 low-carbon steel; and solders already used in the automotive industry. These were tested in combination with a new cesium-aluminum-fluoride-based flux. All of these brazing and soldering materials are available in the market, which may speed up industrial implementation. To make the results easy to compare and replicate, the same process was used to heat and test the brazed/soldered joints.

Testing Setup

Table 1 shows the different solders, brazing filler metal, and flux that were used in this work.

Brazed and soldered single-lap specimens were designed according to AWS C3.2M/C3.2:2019, *Standard Method for Evaluating the Strength of Brazed Joints*, which includes symmetrical heat from the bottom and sides with two propane torches. At least three specimens were manufactured and tested for each combination of base metals and solders to ensure the results showed variance. The overlap was two to three times the thickness of the thinnest piece of metal.

The flux paste was preliminarily deposited between the steel and aluminum specimens, while solder pieces were placed at the edge of the aluminum part. Because aluminum has a lower melting temperature than steel, we put an accessory thin piece of steel over the aluminum base metal to help with uniform heating and prevent the aluminum from melting. Once the solder melted and flowed into the joint via capillary forces, we removed the heat and allowed the braze to cool at room temperature for one to a few minutes before quenching the sample under tap water. The wetting test was conducted using 25 × 25-mm (0.984 × 0.984-in.) coupons heated from the bottom with the solder and flux centered on the top.

Wettability of Base Metals

Table 2 shows the contact wetting angles that were averaged over nine

Table 1 — The Brazing Consumables Used

Trade Name	Composition (wt-%)	Melting Range (°C)	Soldering or Brazing Temperature (°C)	Form (diameter)	Supplier
ZA-1	Zn-22Al	440–485	485–510	2.4-mm brazing wire	Bellman-Melcor Inc.
ZA-2	Zn-2Al	380–385	385–405	3-mm brazing rod	Bellman-Melcor Inc.
BAlSi-3	Al-10Si-4Cu	521–585	570–605	2.4-mm brazing rod	Washington Alloys Inc.
TiBraze®330	Zn-4Al-3Cu-0.2Zr	330–380	400–450	2.4-mm brazing rod	Titanium Brazing Inc.
Sn-40Zn	Sn-40Zn	220–345	320–360	3.2-mm brazing wire	Kapp Alloys & Wires Inc.
Flux 028Cs/D	$CsAlF_4$ based	420–470	480–600	Filler metal paste	Flux USA LLC

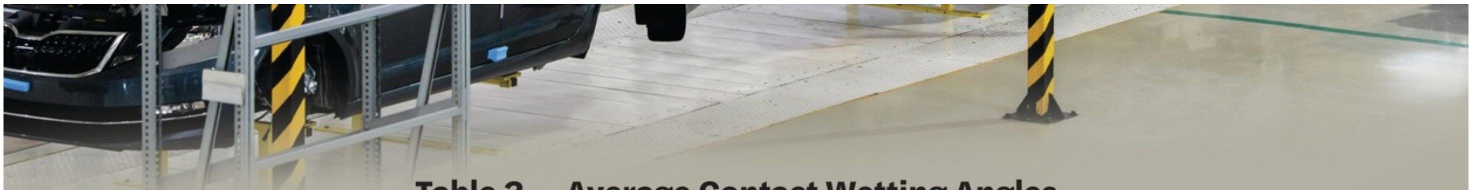

Table 2 — Average Contact Wetting Angles

	Wetting Angles (in deg)		
Base Metal	Zn2Al	Zn22Al	BAlSi-3
1018 steel	4.84	14.41	20.26
Alloy A6061	21.19	15.38	5.76
Alloy A2024	26.07	15.80	6.31
Alloy A6022	40.25	3.20	38.02

measurements. This data shows it is impossible to choose a solder based only on this indicator. Solder Zn2Al revealed the best metallurgic compatibility with the steel, yet it showed the worst compatibility with the aluminum alloys. Solder Zn22Al was the best for soldering aluminum alloy A6022 and demonstrated good compatibility with steel and other aluminum alloys.

Furthermore, Figs. 1 and 2 show the highest strength of alloy A6022 joints soldered to steel using solder Zn22Al, which can be characterized as an expected result based on the very good wettability of both base metals. BAlSi-3 brazing filler metal was compatible with steel and the A6061/A2024 alloys.

Strength of Aluminum-to-Steel Joints

The results of the tensile tests for single-lap brazed and soldered joints are presented in diagrams (see Figs. 1, 2, and 4). The strength values portrayed in Fig. 1 show that reliable brazed and soldered joints of aluminum alloy A6061 with low-carbon steel can be manufactured by any tested filler metal if the overlap distance can be adjusted according to the appropriate shear strength. The strength of the brazed or soldered joints (except solder Sn40Zn) was ~ 60 MPa. BAlSi-3 brazing filler metal didn't have any advantage against

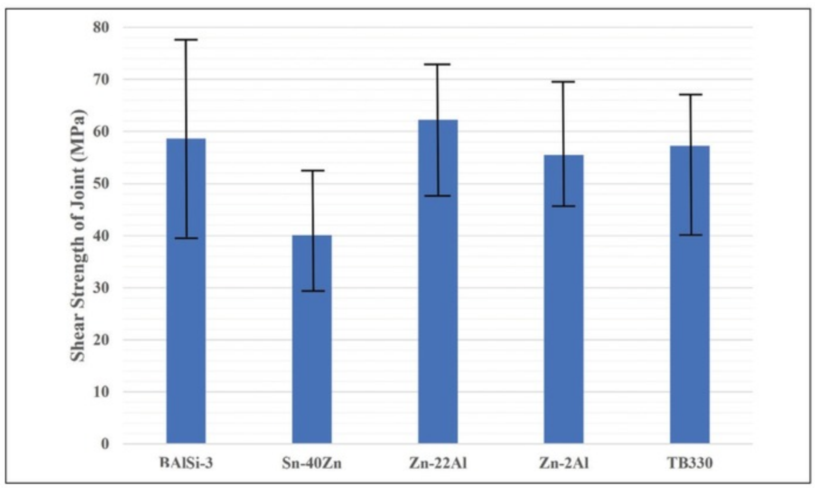

Fig. 1 — Shear strengths of low-carbon steel-aluminum A6061 joints.

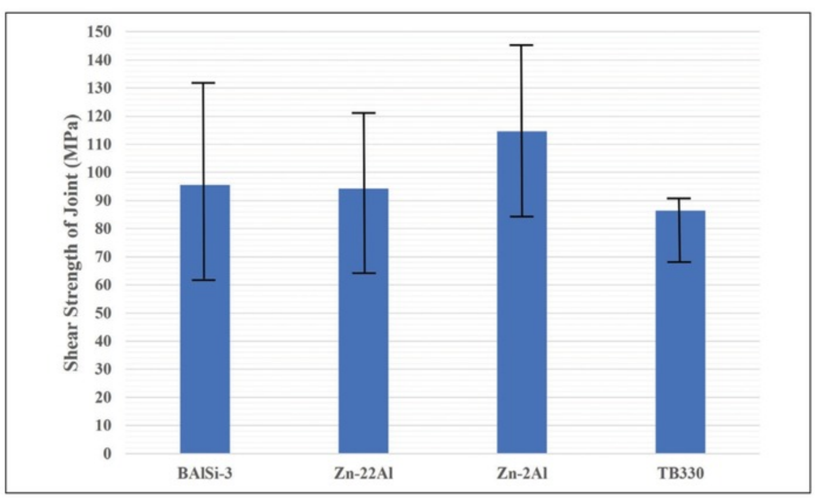

Fig. 2 — Shear strengths of low-carbon steel-aluminum A6022 joints.

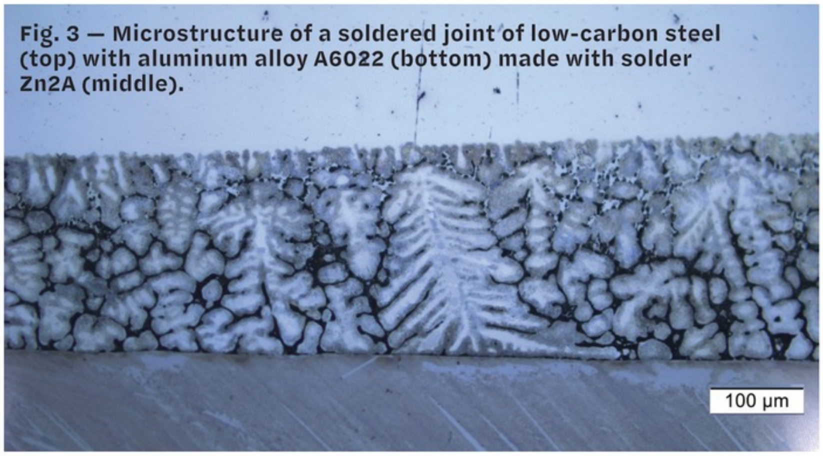

Fig. 3 — Microstructure of a soldered joint of low-carbon steel (top) with aluminum alloy A6022 (bottom) made with solder Zn2A (middle).

low-temperature solders (neither zinc- nor tin-based solders).

The yield strength of aluminum alloy A6061-T6 was 276 MPa. Therefore, the overlap distance of ≥ 5T (where T was the thickness of the aluminum part) provided a strength of brazed/soldered joints that was higher than that of the yield strength of a base metal. The thickness of most metal car parts, such as the roof or fenders, is about 1 mm (0.0393 in.). This means that an overlap of ≥ 5 mm (0.1968 in.) will provide sufficient reliability of the soldered joints. Filling the 5-mm-long gap with solder is practically attainable. Even application of the soft solder Sn40Zn can be effective if the overlap is ≥ 7T. These overlap distances can be easily met using aluminum-steel sandwiches or multilayer plates (Fig. 5).

Considering a much-longer overlap distance in brazed or soldered aluminum-steel structures, such as with lightweight sandwiches or multilayer plates (Fig. 5), we proved that low-temperature solders can be successively used. In other words, there are many advantages in switching from traditional automotive manufacturing techniques to using brazing and soldering. Aluminum alloys quickly lose yield strength when heated to temperatures above 500°C (932°F). Application of low-melting solders (Table 1) used at temperatures < 500°C, especially solders Sn40Zn or Zn2Al, will save the strength of aluminum-based metals joined to steel. Overall, this improves reliability of the entire soldered structure. This can only be achieved using the low-temperature ranges of soldering, which is not attainable with traditional brazing or welding.

Soldered joints of low-carbon steel with aluminum alloy A6022 showed a shear strength of ~ 15–20% higher than that of steel joints with aluminum alloy A6061 (Fig. 2). Aluminum alloy A6022 had the highest yield stress among all tested aluminum alloys, which may suggest that the negative effects of heating during brazing/soldering on the aluminum base metal are less than for A6061 or A2024 base metals. This means that aluminum alloy A6022 is preferred for joints having a small overlap distance.

Unexpectedly, the highest shear strength of 120–145 MPa among all tested materials was reached by application of low-temperature solder Zn2Al in combination with aluminum alloy A6022. The microstructure of the soldered joints (Fig. 3) confirmed the absence of a brittle intermetallic layer at the steel-solder interface that was found in all other brazed and soldered joints using other filler metals tested in this work. Even brazed joints made with BAlSi-3 filler metal, which was the strongest filler metal among those tested, showed a lower shear strength of 95–132 MPa. However, the microstructures of these samples showed the presence of a brittle $Fe_2Al_9Si_2$ intermetallic layer at the steel-joint metal interface.

The setup of steel with aluminum alloy A6022 base metal and solder Zn2Al is the recommended combination for manufacturing thin-wall or multilayer soldered structures in automotive features (e.g., doors, roofs, trunk lids).

Soldered joints of low-carbon steel and aluminum alloy A2024 showed lower strength than those of joints with alloys A6061 and A6022. The highest strength of alloy A2024 joints (~ 80 MPa) was obtained with BAlSi-3 brazing filler metal despite its brazing temperature being above the solidus point of the aluminum base metal. This circumstance was the reason for the base metal porosity found during the study of the microstructure. In addition, the soldered joints of alloy A2024 did not show ductility during mechanical tests. Therefore, alloy A2024 cannot be recommended for industrial use in brazed or soldered joints with steel.

All joints of aluminum alloy A6062 and A6061, especially those manufactured with solder Zn-2Al, demonstrated good ductility on the load-displacement diagrams (Fig. 4). Thus, brazing and soldering for industrial applications can be used not only for joining ready automotive steel-aluminum parts but also for parts before deformation for a final shape. Bending tests of steel + A6061 + Zn2Al joints showed that soldered joints can be deformed up to ~ 40–45 deg without failure (Fig. 5).

Since mechanical tests of soldered joints give hope for industrial application, we manufactured several prototypes of lightweight materials: two- and three-layered steel-aluminum soldered structures, which were subject to bend or compression tests (Fig. 5). These prototypes all show the ability of soldered structures to develop plastic deformation.

Some prototype samples were made in the form of steel-aluminum-steel sandwiches, where a plate of A6061 alloy or aluminum foam was used as the aluminum layer between the steel plates. When compressing down to 50% of the total thickness, the solder joints did not collapse. There was also success in bending double-layer plates up to 45 deg. The weight savings of aluminum-steel sandwiched panels were 35% for the solid steel-aluminum core plate and 72% for the aluminum foam core plate when compared to the solid steel. The steel base, aluminum shell geometry saved 54% of weight when compared to only steel, and the long steel-aluminum strip saved 49%.

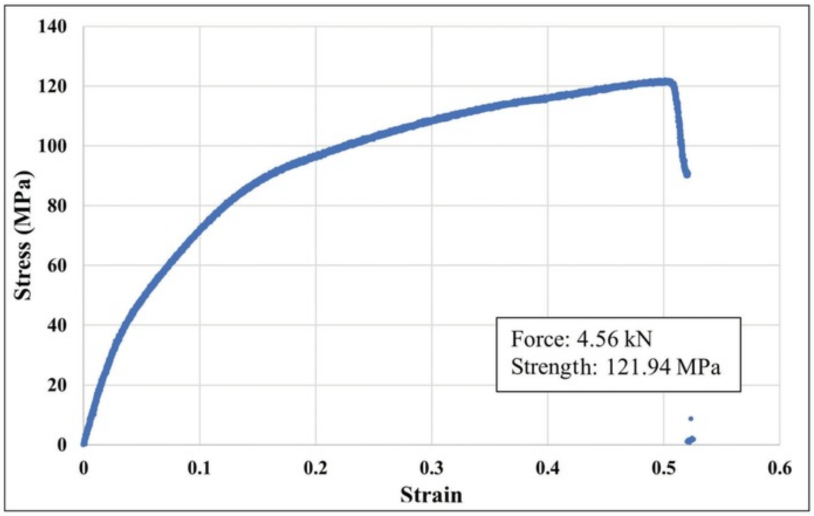

Fig. 4 — Stress-strain diagram of low-carbon steel-aluminum A6022 lap joints made using solder Zn-22Al.

Fig. 5 — Soldered lightweight aluminum-steel prototypes with weight savings from 35 to 72%.

Conclusions

1. Lightweight aluminum-steel structures can be manufactured by brazing or soldering in air using a propane torch or hot plate heating sources. This can be done without expensive equipment, such as laser or ultrasonic welding units.

2. Brazed and soldered joints of aluminum alloys A6022 and A6061 made with solders Zn2Al, Zn22Al, and BAlSi-3 possess sufficient strength and ductility that improves their reliability and allows control over their shear strength.

3. The shear strength of alloy A6022 aluminum-steel joints made with solder Zn2Al and cesium-aluminum-fluoride flux is higher by about 25% compared to joints manufactured in prior art.

4. Despite the lower shear strength of aluminum-to-steel joints made with Zn22Al, BAlSi-3, or TiBraze330 filler metals when compared to some prior art tests, the reliability of these joints can be easily improved by increasing the overlap size due to the significant ductility of brazed joints. WJ

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