Dissimilar Metal Joining Technology Using Newly Developed Aluminum Flux-Cored Wire (FCW) to Join Aluminum Alloy and Steel

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We have developed a technology for joining dissimilar metals, an aluminum alloy and steel, using MIG and laser welding equipment. A newly developed aluminum flux-cored wire has been found to suppress the formation of brittle intermetallic compound in the bonding interface and to realize a joint strength that compares with the strength obtained by a similar joint of the aluminum alloy. The corrosion resistance of the welds was evaluated. The butt joint was found not to exhibit any electrolytic corrosion. This technology was used to build prototype car structure members to evaluate their strength and the applicability of the technology.

Introduction

In an effort to reduce global warming, there is an accelerating trend toward automotive weight reduction. To achieve this purpose, it is desirable to use the right material for the right parts so that the intrinsic features of each material are fully exploited. Such use of materials requires an extensive deployment of elemental technologies, including joining, forming and analyzing. Dissimilar metal joining between aluminum alloy and steel is one such elemental technology and is an area where much effort has been made[1)]. When joined by conventional welding methods, aluminum alloy and steel form a brittle intermetallic compound (hereinafter, "IMC") of Fe-Al at the joint interface, which deteriorates the joint characteristics. Thus, the joining used to rely on other methods such as mechanical fastening and adhesive bonding.

We have studied the technology for fusion joining between aluminum alloy materials and steel sheets, such as galvannealed steel sheets (hereinafter, "GA steel sheets") and cold-rolled steel sheets (hereinafter, "CR steel sheets"), which are commonly used for automobiles[1)]. This paper reports a newly developed technology for joining dissimilar metals, an aluminum alloy and steel, by fusion joining[2)]. The technology employs an apparatus for conventional welding, such as metal inert gas (MIG) welding and laser welding, and still produces a joint strength as high as that obtained for the similar joint of aluminum alloys.

1. A study on an aluminum flux-cored wire

1.1 Problems with the conventional flux cored wires

When an aluminum alloy material is welded to a steel material, a brittle IMC is formed at their joint interface, which decreases the joining strength. Therefore, the formation of the IMC must be suppressed to improve the strength properties.

Previous studies on a laboratory scale show that the formation of IMC is somewhat suppressed when conventional aluminum flux-cored wires (hereinafter, "aluminum FCWs") for brazing are used for MIG[3)] and laser[4)] welding. In those cases, the tensile shear strengths have been achieved that compare with those obtained for the similar joint of aluminum alloys. However, the practical application of aluminum FCWs to the dissimilar metal joint between aluminum alloy and steel has been considered to be difficult due to the buckling of the wires, instability of droplet transfer, excessive slag formation and the lack of joining strength.

We therefore started to solve these problems by developing a new aluminum FCW that is feasible for industrial applications.

1.2 Samples tested

The following samples were tested. For the aluminum materials, aluminum alloy sheets of AA6022P (thickness, 1.0mm and 2.0mm) and extruded shapes of 6061S alloy (wall thickness, 2.2mm and 2.5mm) were used. For the steel materials, a 590MPa class GA steel sheet (thickness, 1.2mm), a 590MPa class CR steel sheet (thickness, 1.2mm), and a 980MPa class CR steel sheet (thickness, 1.4mm) were used. Welded joints were formed mainly by lap fillet welding, in which an aluminum alloy material is placed on a steel sheet and is melted such that the aluminum material forms a joint with the steel sheet. In addition, butt welding joints were made between the aluminum alloy and steel. These joining processes are herein called "braze welding" because they melt the aluminum alloy, but not the steel. To study the suitable sheath

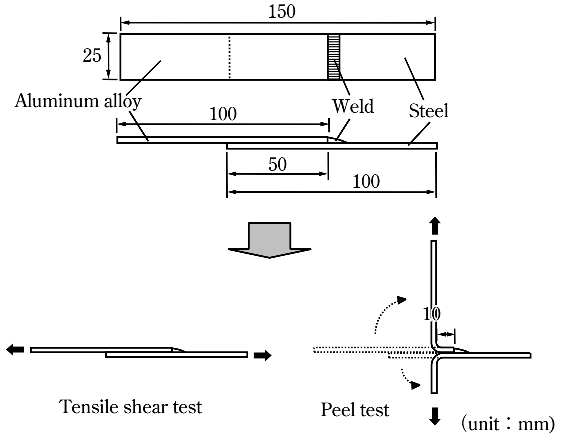


Fig. 1 Methods for evaluating the joint strength[2)]

composition for the aluminum FCW, solid wires were used to emulate the sheath material, and the aluminum alloy and steel materials were pre-coated with flux. The solid wires used were A5356-WY, A4043-WY and A4047-WY. A new composition was also used as a solid wire. This new solid wire has a composition with decreased Mg and additional Si, the former element being known to preferentially react with fluorides in the flux and result in poor joint quality, and the latter element being expected to improve the wettability of the molten metal.

Next, a lap fillet weld joint was produced between the AA6022P sheet (thickness 1mm) and the 590MPa class CR steel sheet (thickness 1.2mm) by laser braze welding. The welded material was used to prepare the specimen, shown in **Fig. 1**, for joint strength evaluation. The tensile shear strength was evaluated on a joint specimen having an elongated rectangular shape with a width of 25mm, in which the welding bead lies in the transverse direction. The peel strength was evaluated on a specimen prepared from the welded material, in which each elongated rectangular sheet is bent to a right angle at a position 10mm away from the welded end. Both the strengths were evaluated by the breaking load per unit welding length.

1.3 A study on aluminum FCWs

Fig. 2 shows the results of joint strength evaluation. In the comparison of solid wires, the solid wire with the new composition resulted in the highest joint peel strength, while the A5356-WY (Al-Mg series) resulted in the lowest joint strength.

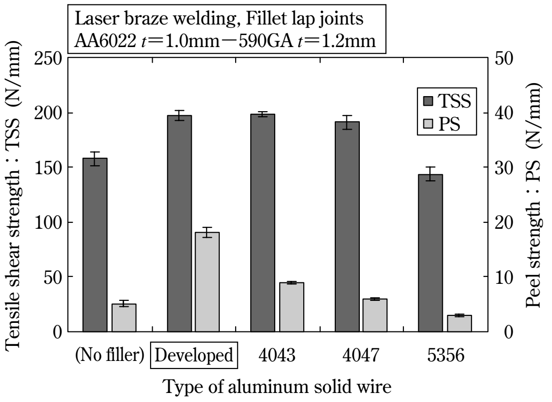


Fig. 2 Comparison of joint strength by the types of aluminum solid wire[2)]

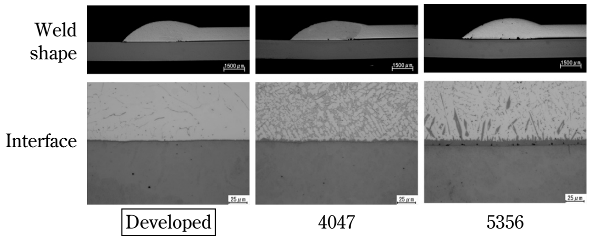


Fig. 3 Macro and micro structures of weld shape and interface[7)]

Fig. 3 shows the macrographs of the joint cross-sections and the optical micrographs of the IMC layers formed at the joint interfaces. The weld formed by the A5356-WY exhibited the thickest IMC layer in the present comparison and also exhibited needle-like IMC inside the aluminum welding metal. On the other hand, the A4047-WY and new composition resulted in IMC layers that are thin throughout the interface. In particular, the solid wire with the new composition has been found to distribute the IMC layer the most thinly with an average thickness of approximately 1μm.

A similar evaluation was conducted on joints formed by MIG braze welding. It turns out that the new composition exhibits the highest joint strength with the thickness of its IMC layer significantly reduced; this is the same phenomenon that was observed for the laser braze welding.

Five types of fluxes (A1-A4, B2) were tested, including the non-corrosive fluoride based flux, NOCOLOK[5)], used for the aluminum FCW for brazing (**Table 1**). The criteria for selecting the flux compositions were that the flux should dissolve the film of aluminum oxide, have no influence on corrosion resistance and be easy to fill into the sheath interior. As a result, the mixtures that were selected were based on potassium aluminum fluoride and contained either aluminum fluoride or cesium fluoride. The selected flux was filled into the sheath made of the new composition at an optimized flux-filling ratio to prepare aluminum FCW samples.

These aluminum FCW samples were used to form a lap fillet weld joint between an aluminum alloy sheet and the GA steel sheet. This dissimilar metal joining was performed by laser braze welding. Joint tensile tests were conducted for evaluation. The

Table 1 Combination ratio of flux[2)]

Kind of Al. FCW	Combination ratio of flux (wt%)		
	K-Al-F	Al-F	Cs-F
A1	100		
A2	75	25	
A3	50	50	
A4	25	75	
B2	75		25

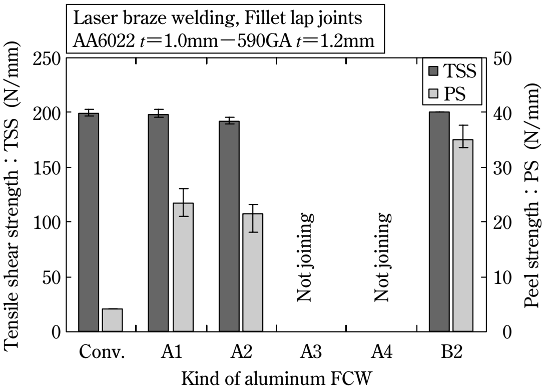


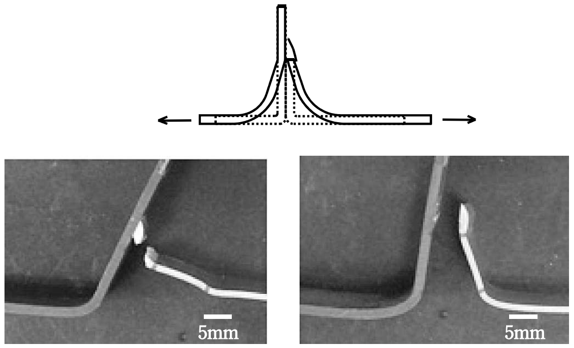
Fig. 4 Comparison of joint strength by the types of aluminum FCW[2)]

results are shown in **Fig. 4**. Specimens A3 and A4 exhibit no bonding. Specimens A1, A2 and B2 show similar tensile shear strength. Their peel strengths are B2>>A1>A2 in descending order. **Fig. 5** shows the failure mode of these specimens. Specimen B2 shows a favorable result with its interface remaining intact and the failure occurring in the aluminum alloy. Similar testing conducted on MIG braze welding has revealed that specimen A2 has the highest peel strength.

Fig. 6 shows the appearances of welds obtained by laser braze welding and MIG braze welding. The newly developed aluminum FCW exhibits a significantly improved bead appearance compared with the conventional aluminum FCW for brazing.

Fig. 7 summarizes the relation between the joint performance of the dissimilar metal weld joints (between the aluminum alloy and steel) and the thickness of the IMC layer at the joint interface. As shown, the newly developed aluminum FCW suppresses the growth of the IMC, yielding a thinner IMC layer. This suppression of the IMC formation over the entire area is considered to have caused the significant improvement, especially in the peel strength.

These results have clarified the concept of an aluminum FCW suitable for the dissimilar metal joining of aluminum alloy and steel by laser braze welding and MIG braze welding.



B2
Aluminum alloy side

A1, A2
Exfoliation of interface

Fig. 5 Fracture mode after peel test

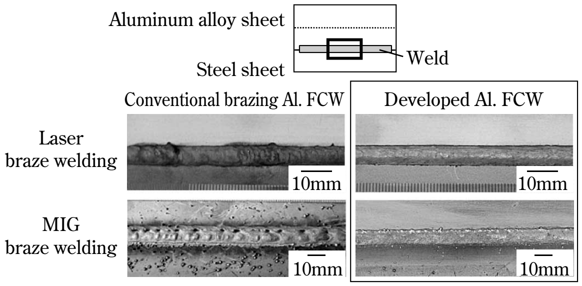


Fig. 6 Appearance of welded part

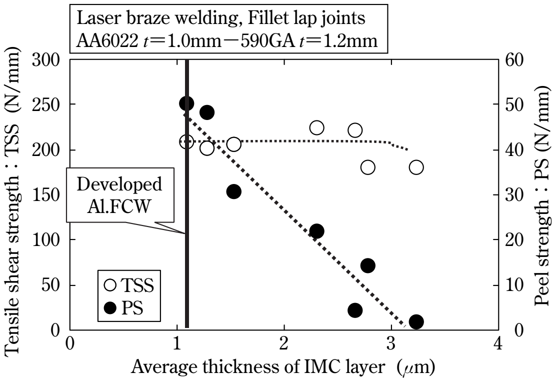


Fig. 7 Relationship between the thickness of IMC layer and joint strength[2)]

2. Corrosion resistance

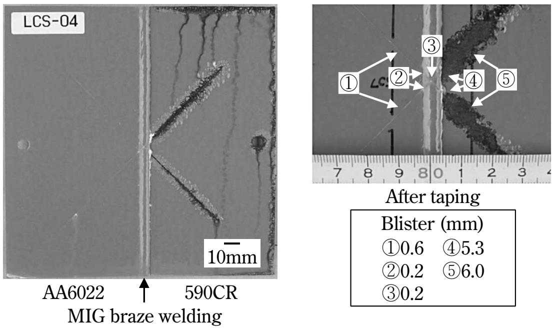
In a dissimilar metal joint between an aluminum alloy and steel, the potential difference between the two materials causes a corrosion current to flow. This produces greater corrosion, or contact corrosion, than in the case of similar joints involving aluminum alloys[6)].

Thus, the prevention of contact corrosion between dissimilar metals is an important issue in realizing hybrid structures. In the current practice, mechanically fastened joints are completely coated, for example, with paint, structural adhesive and waterproof sealant to secure corrosion resistance. This approach is considered to be effective in preventing the contact corrosion of the welded portions in the present study.

To prove this, a fundamental study was conducted to clarify the effect of painting on the contact corrosion of a joint between an aluminum alloy and steel. Butt welds were prepared for this purpose. The newly developed aluminum FCW was used to butt weld the AA6022P sheet (thickness 2mm) to the 590MPa class CR steel sheet (thickness 1.2mm) by MIG braze welding. The welding end zones, each having a width of 25mm, were cut to prepare test samples. The samples were phosphate treated before electro deposition. The evaluation was done according to the cyclic corrosion test (CCT), JASOM0609, set forth by the Japanese Automotive Standards Organization (JASO). The CCT is a type of acceleration test for evaluating corrosion, in which test cycles are repeated, each cycle consisting of salt spraying twice at 35 ± 1 degrees C, drying 4 times at 60 ± 1 degrees C and moistening twice at 50 ± 1 degrees C.

For a preliminary test, the butt weld sample was painted and subjected to 51 cycles of the test. The tested sample exhibited some red rust near the end of the steel sheet, with the weld portion remaining intact and almost no blistering in the coating. Then, considering harsher conditions, the coating was provided with cross-cuts for corrosion origin, and the sample was corrosion tested for up to 150 cycles. **Fig. 8** shows the appearance of a test sample with cross-cuts after 150 test cycles. The aluminum alloy, on the left side of the weld line in the photo, exhibited almost no blistering, nor white rust. On the other hand, the steel exhibited an increasing amount of blistering and red rust as the CCT proceeded. The welding bead exhibited neither rust nor blistering.

The blistering of the coating was evaluated by applying adhesive tape to the cross-cut portion and peeling it off and by measuring the width of the peeled portion (taping test). As a result, the aluminum alloy side (Fig. 8①) exhibited peeling neither in the vicinity of the weld (Fig. 8②), nor in the weld (Fig. 8③), and exhibited almost no corrosion under the coating. On the other hand, the steel side (Fig. 8④, ⑤) exhibited a significant amount of corrosion; however, almost no difference was observed in the amount of blistering between portion ④ near the weld line and portion ⑤.



Blister (mm)
①0.6 ④5.3
②0.2 ⑤6.0
③0.2

Fig. 8 Corrosion test specimen after 150 cycles[2)]

The above results indicate that the corrosion behavior near the joint between the aluminum alloy and steel is not different from that in the portions away from the weld line. In other words, no contact-corrosion occurred between the dissimilar metals in the butt weld joint of the present study. This means that no electrical circuit was created to allow current in the butt weld portion. The reason and mechanisms for this will be the subject of a further study.

3. Prototype examples of the hybrid structure

Dissimilar metal joining, using the newly developed aluminum FCW, was employed to prepare model members, having hybrid structures, for automobiles. The strength of the members was evaluated to study the applicability of the technology. The following introduces examples of the application, according to the results.

3.1 Hat shaped members with closed cross-sections

To simulate an axially loaded member, such as a B pillar, a sample was prepared for an offset axial compression test, as shown in **Fig. 9**[7)]. This sample consists of an aluminum alloy shape and steel shape, each having a hat shaped cross-section. These shapes were put together with their open sides facing each other and were joined at their flanges by laser braze welding. The aluminum alloy material used was an A6061S-T6 extrusion (wall thickness of the weld; 2.2mm), and the steel material was a 980MPa class CR steel sheet (thickness 1.4mm). The test sample (total length 900mm) was welded together at three locations on each edge of the aluminum alloy hat by continuous beads, each having a length of 200mm. In the crush test, a hydraulic cylinder was used to apply an axial compressive load on the side plate shown in Fig.9.

Fig.10 shows the load-stroke diagram obtained from the test. The deformation proceeded for a while after the maximum load was reached, before a weld was fractured. The test result indicates that the present welding method is applicable to structural members that are not subject to large deformations.

3.2 Lid-shaped structural members and pipe fastening model members

The following describes an example of lid-shaped members, such as doors and trunk lids, utilizing the dissimilar metal joining between aluminum alloy and steel. Also described is a structural member

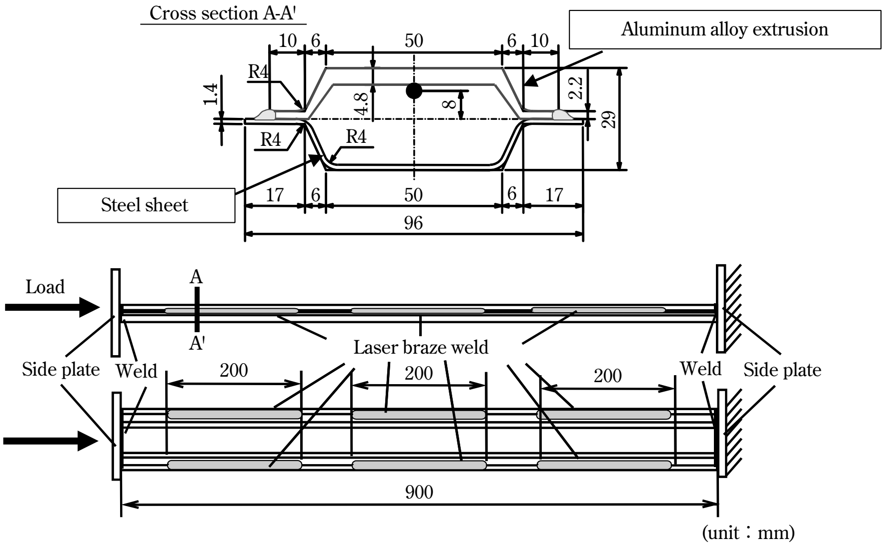


Fig. 9 Specimen for axial crush test[2)]

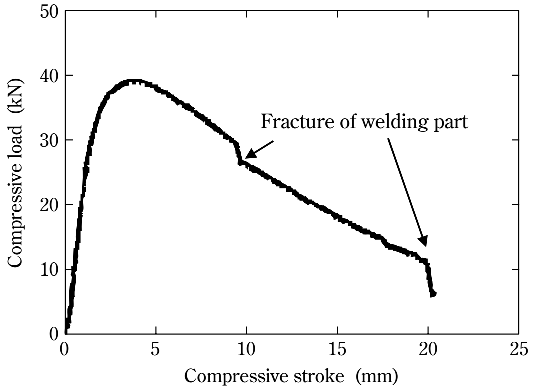
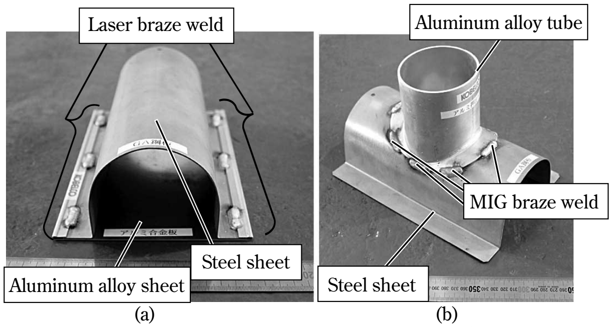


Fig.10 Experimental result of the axial crush test[2)]



(a) (b)

Fig.11 Example of welded parts[8)]

modeling a pipe fastener. **Fig.11** (a) shows a lid-shaped member using an AA6022P sheet (thickness 1.0mm) for the outer panel and a 980MPa class GA steel sheet (thickness 1.2mm) for the inner panel[8)]. The hem was joined in a stitch-like manner by MIG braze welding.

Fig.11 (b) shows a member in which the flange formed on a A6063S pipe (thickness of the welded portion; 2.5mm) is joined to the center of a bent form made of a 980MPa class GA steel sheet (thickness 1.2mm) by MIG braze welding[8)]. Weight reduction is expected in this structure, wherein one of the pipe faster members, both of which used to be steel, is replaced by an aluminum alloy. The members shown in Fig.11 (a), (b) are small samples, but provide examples of basic structures that can be developed into actual members, such as lid-shaped panels and pipe fasteners.

Conclusions

The fusion joining of the dissimilar metals of aluminum alloy and steel has conventionally been difficult. An aluminum FCW has been developed in order to realize this joining. The newly developed FCW was used for braze welding, such as MIG and laser, and achieved favorable joint performance. The corrosion resistance evaluation and the prototype manufacturing of hybrid structures have yielded promising results.

However, new issues may arise in the actual application of the technology. We will strive to bring it to a higher level of quality and expand its applicability so as to contribute to the weight reduction of automobiles.

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