Dissimilar Metal Joining between Aluminum Alloy and Hot-dip Aluminized Steel Sheet

Tetsu IWASE, Seiji SASABE, Tsuyoshi MATSUMOTO; Technology Control Department, Aluminum & Copper Company
Masaki TANIGAWA, Makoto TAWARA; Aluminum Sheet & Coil Research Department, Moka Plant, Aluminum & Copper Company
Yasunori HATTORI; Nissin Steel Co., Ltd.

Characteristics of joints between dissimilar metals, in particular aluminum alloy and a newly developed Hot-dip Aluminized Steel Sheet, were evaluated through experiments using resistance spot-welding, MIG welding and laser braze welding. The joining mechanisms of dissimilar metals were also studied from the aspect of the interface structures between aluminum alloy and steel. Special attention was paid to the formation of intermetallic compounds and to a method for controlling such compounds. This article also includes evaluation results on corrosion resistance of such joints in corrosive environments.

Introduction

Each material has its own unique properties. When designing a structure, materials should be selected so that the uniqueness of each material is fully exploited. This may not necessarily be easy when dissimilar materials have to be joined together. In particular, welding joint of steel and aluminum alloy is difficult to make, because conventional welding causes brittle intermetallic compounds (IMC) to form in the joint or deposit, making the joint brittle and weak. Thus, joining between steel and aluminum has relied on mechanical fasteners and adhesive joining.

Kobe Steel and Nissin Steel have developed a hot-dip aluminized steel sheet which is joinable to aluminum using conventional welding equipment. Also developed were welding methods which enable dissimilar joints between steel and aluminum to have strength equivalent to that of the joints between aluminum alloys themselves (hereinafter denoted as "Al-Al joint"). The welding methods developed are classified into three types: resistance spot-welding, MIG braze welding and laser braze welding. The spot-welding allows the use of conventional welding apparatuses used for steel. The MIG braze welding and laser-braze welding are used for line joining. The following describes these three methods.

1. Resistance spot-welding[1) - 4)]

Sample sheets of aluminized steel, hot-dip galvannealed steel (GA steel) and cold-rolled carbon steel (SPCC) were spot-welded respectively to aluminum alloy sheets. The joined samples were subjected to the tensile-shear test (JIS Z3136) and tensile test (JIS Z3137). **Fig. 1** shows the test results along with the welding conditions.

The spot-welded joint, between an aluminum alloy and either the GA steel or the SPCC steel, tends to fracture at its joint interface (shear fracture) in the tensile-shear test, even though each joint exhibits a tensile-shear strength (TSS) almost equivalent to that of an Al-Al joint (not shown in the figure). The cross-tension strengths (CTS) of these joints are low. On the other hand, the joint between the aluminized steel sheet and an aluminum alloy sheet of either 6K21 (equivalent of AA6022) or 5182 exhibits a high TSS and CTS, both comparable to those of an Al-Al joint (not shown in the figure; TSS ≈ 3.2 kN, CTS ≈ 1.5 kN). Button fractures were observed to occur in the periphery of the nugget on the side of the aluminum sheet. **Photo 1** shows the fractured portions after cross tension tests.

The above difference is explained as follows. As shown in **Photo 2**, a sheet of GA or SPCC steel reacts with the aluminum alloy to form Fe-Al intermetallic compounds (IMC) through the joint interfaces at the time of spot-welding, making the joints brittle. Meanwhile, aluminized steel sheet creates an IMC-free zone, in which no intermetallic compound is formed, in the periphery of the nugget after welding.

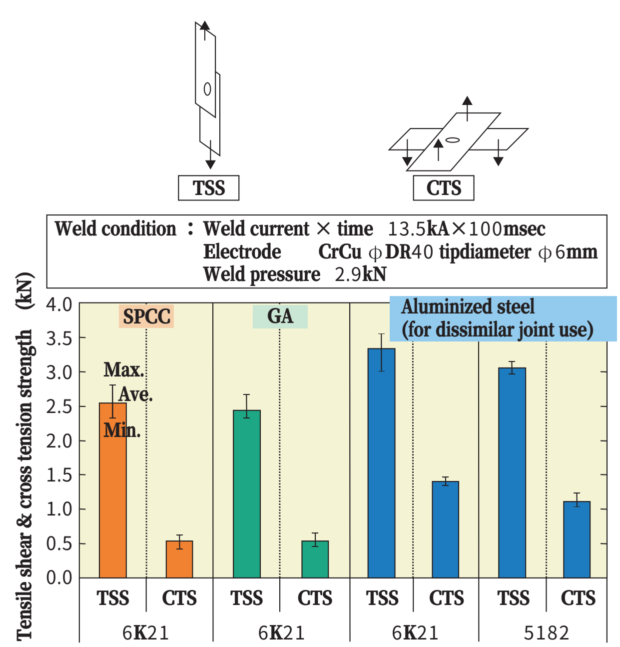

Fig. 1 Tensile shear strength and cross tension strength of resistance spot joints

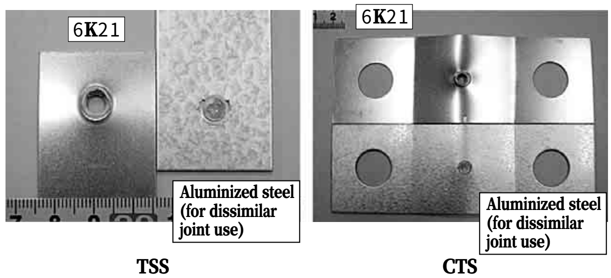

Photo 1 Fracture appearance after tensile shear and cross tension tests

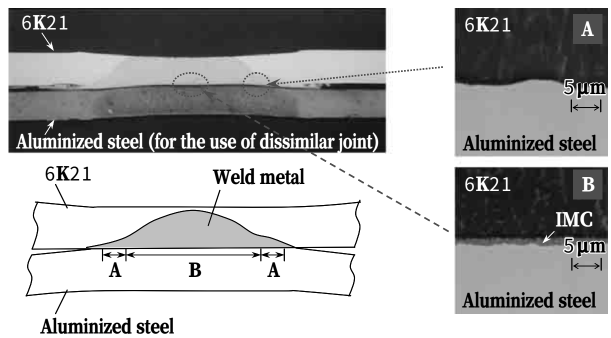

Photo 2 Cross section and interface structure between aluminized steel (for dissimilar joint use) and 6K21 (A: IMC free area, B: IMC formed area)

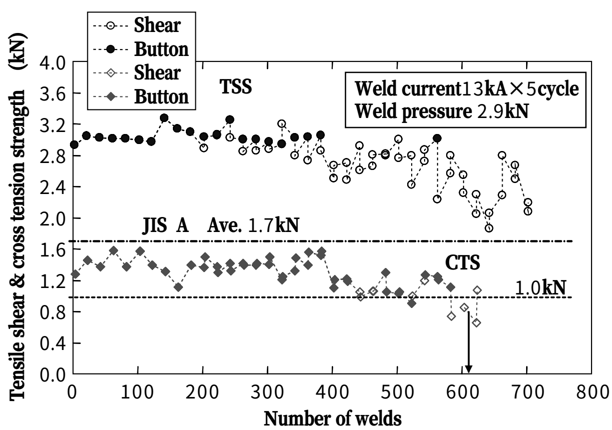

Fig. 2 Results of electrode life test of resistance spot dissimilar joints (oiled)

The IMC-free zone offers a high strength, preventing cracks from propagating toward the joint interface. Instead, the cracks propagate in the thickness direction on the side of aluminum sheet, and thus causing button fracture. The IMC-free zone forms only for this aluminized steel developed for dissimilar joint. This is because the newly developed steel has a nitrogen-rich layer formed at the interface of the base steel and the aluminum coating layer and the layer prevents the inter-diffusion between Fe and Al[4].

Fig. 2 shows the result of a life test of spot-welding electrodes performed for the joining of the developed steel and a 6K21 aluminum alloy sheet (oiled). The electrodes demonstrate almost the same life as used for the welding of Al-Al joint. Although the results are not shown here, an axial fatigue test (R=0.1) revealed that the dissimilar joint exhibits even better fatigue performance compared to Al-Al joints. Further, additional steel sheets can be welded at the same time to the outer side of the aluminized steel to form a threefold or fourfold structure.

The following summarizes the features of the spot-welding method developed:

1) The formation of brittle intermetallic compound of Fe-Al at the interface is effectively prevented. The resultant joint demonstrates strength almost equivalent to that of Al-Al joint and exhibits a button fracture.
2) A conventional spot-welding apparatus may be used, depending on the sheet combinations, despite the low volume resistance of aluminum. This is because the base steel provides sufficient resistance heating and thermal capacity.
3) The electrode life and joint fatigue strength are achieved which are almost equivalent to those for an Al-Al joint.
4) Multifold, e.g., threefold, sheets can be welded together.

2. Line joining

2.1 MIG braze welding[5)-8)]

Lap joints were prepared with 6K21 aluminum sheets (t=1.0 mm) placed on top of the aluminized steel sheets using four different kind of filler wire. The filler wires used were 4047 (Al-12Si), 4043 (Al-5Si), 5554 (Al-2.7Mg) and 5356 (Al-5Mg). An alternating current MIG power source was selected to prevent the aluminum molten metals from reacting with steel to form IMC. Low heat input conditions were also chosen, which include welding current of 50A, welding voltage of 7V and welding speed of 50 cm / min. The resultant joints constitute "MIG braze welding", in which the aluminum sheets are melted together with the filler wires, whereas the steel is not melted.

The strengths of these joints were evaluated in two different methods shown in **Fig. 3**, i.e., tensile shear test and peel test. The peel test was performed on each test piece consisting of strips of the materials bent into L-shapes at a position 10 mm away from the bead. **Fig. 4** depicts the strength per unit length (N / mm). In the cases where the filler wires 4047, 4043 and 5554 are used, the tensile shear tests resulted in fractures in the heat affected zones (HAZ) of the 6K21 alloy, while the peel test resulted in fractures in the weld-metal. In all the cases, almost the same level of joint strength was achieved.

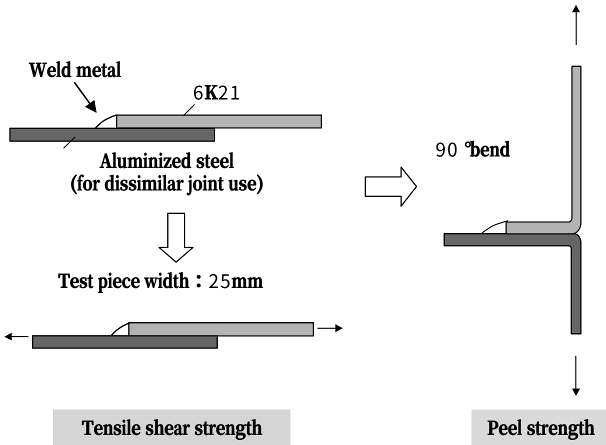

Fig. 3 Evaluation method (tensile shear & peel)

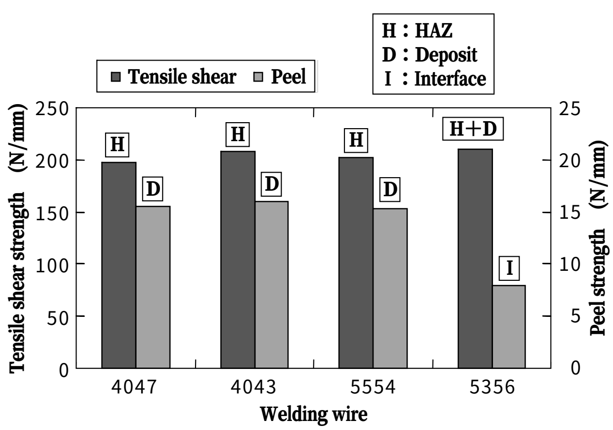

Fig. 4 Relation between welding wire materials and joints strength (H : Heat affected zone, D : Deposit, I : Interface)

Meanwhile, in the case where the filler wire 5356 is used, tensile-shear caused fracture in the weld-metal in some cases, and all the test pieces failed at the steel / weld-metal interfaces in the peel test. In this case, tensile-shear strength is in the same range as other samples, however, the peel strength is significantly low.

Thus, joint performance is affected by the type of filler wires used and the difference in performance appears more significantly in peel strength, rather than in the tensile-shear strength. The cause of the difference is considered to be due to the formation of Fe-Al intermetallic at the joint interfaces. **Fig. 5** depicts the thicknesses of Fe-Al intermetallic compounds (IMC) formed at the interfaces between the developed steel and 6K21 aluminum alloy using various filler wires. All the filler wires result in thickness distributions which are thicker in the middle of the leg-length and thinner at leg-ends. The distributions are more enhanced in the case of Al-Mg type filler wires, 5554 and 5356, compared to Al-Si type filler wires, 4043 and 4047. IMC-free zones were observed at the toe and root of the welding beads

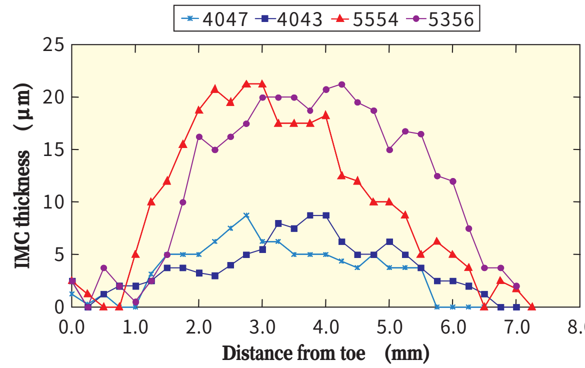

Fig. 5 Distribution of IMC thickness (MIG brazing)

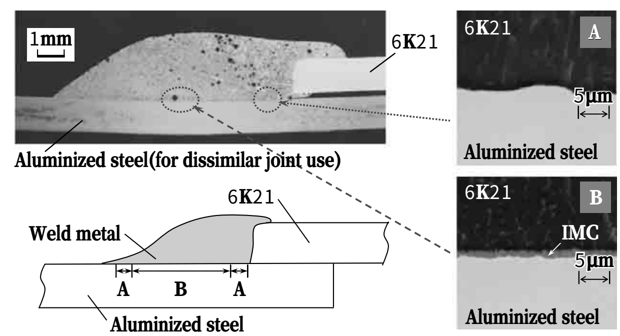

Photo 3 Cross section and interface structure between aluminized steel (for dissimilar joint use) and 6K21 of MIG brazing (A : IMC free area , B : IMC formed area)

when one of filler wires, 4047, 4043 or 5554 was used. On the other hand, no such zone was observed in the case of 5356.

Photo 3 shows a cross-section of a MIG brazed dissimilar joint between the developed steel and an aluminum alloy (filler wire, 4047).

As a comparison, the IMC thickness distributions were evaluated using a ordinary hot-dip aluminized steel sheet in the same manner as described above. For all the filler wires, no IMC-free zone was observed and all the specimens failed at the joint interfaces in the peel test[5]. For each specimen, cracks were initiated at its root and propagated in the direction of the joint interface. In the case where the developed steel is used, the IMC-free zone serves to make cracks propagate into the weld-metal and causes fracture in the weld-metal. Thus, it has been shown that the existence of the IMC-free zone contributes to the joint performance of MIG braze welding. It should be noted that the filler wire of 5356 caused fracture at the joint interface even when the developed steel was used. This is considered to be due to an insufficient formation of IMC-free zone. Thus, it is important to select a filler wire which provides good joint performance even when the developed steel is used.

It has been shown that good joint performance is achieved in the MIG braze welding between aluminum alloy and the developed steel by selecting appropriate conditions such as welding current, voltage and filler-wire. The following summarizes the features of the present method.

1) The MIG braze welding using the developed steel allows the use of conventional welding equipment used for joining aluminum;
2) The developed steel prevents the formation of brittle Fe-Al intermetallic compounds during MIG braze welding, as in the case of spot-welding, which leads to fractures in the weld-metal rather than at the interfaces, unlike the cases of the ordinary hot-dip aluminized steel sheet; and
3) Excellent joint performance is achieved by selecting appropriate filler wires.

2.2 Laser braze welding[5), 10)]

Sheets of aluminum alloy 5182 are known to be capable of being welded together by laser without using any filler wires. In order to demonstrate the feasibility of the developed steel sheet, a sheet of 5182 alloy (1.0 mm thick) was overlapped on the developed steel sheet and fillet joint was produced by melting the edge of aluminum sheet with laser beam.

A lamp pumped YAG laser was employed in the welding with an output power of 4 kW (defocus beam) and welding speeds in the range from 80 to 160 cm / min. The tensile-shear strengths and peel strengths of the joints were evaluated in the same method as described previously.

As shown in **Fig. 6**, the shear strength becomes slightly lower for lower welding speed of 80 cm / min, however, fracture occurs in the weld material (deposit) in all the cases. Meanwhile, the peel strength becomes the highest for higher welding speed of 160 cm / min and, only in this case, the fracture occurs in the deposit as shown in **Photo 4**. In other cases, the samples failed mostly at their interfaces. **Fig. 7** depicts the relation between welding speed and IMC distribution of the laser-brazed samples. As in the cases of spot-welding and MIG braze welding described above, the beads have IMC-free zones. The IMC-free zone extends wider for higher welding speeds (smaller heat input) and the IMCs at the center also become thinner.

The crack behavior depends on the characteristics of the joint, including interface, welding root and weld-metal. A high speed welding makes IMC layer thinner and increases joint strength. A high joint strength is considered to direct cracks to propagate in the weld-metal, causing the fracture in the weld-metal.

Thus, the hot-dip aluminized steel developed is capable of being joined together with aluminum with a tensile-shear strength as high as that for Al-Al joint. A high quality joint with high peel strength can be obtained by optimizing the welding conditions.

The following summarizes the features of the laser-brazed welding method developed.

1) A high welding speed reduces the formation of IMCs to an optimal level, allowing joining at high productivities; and
2) No filler metal may be required, depending on the combination of the materials welded, as in the case of Al - Al welding.

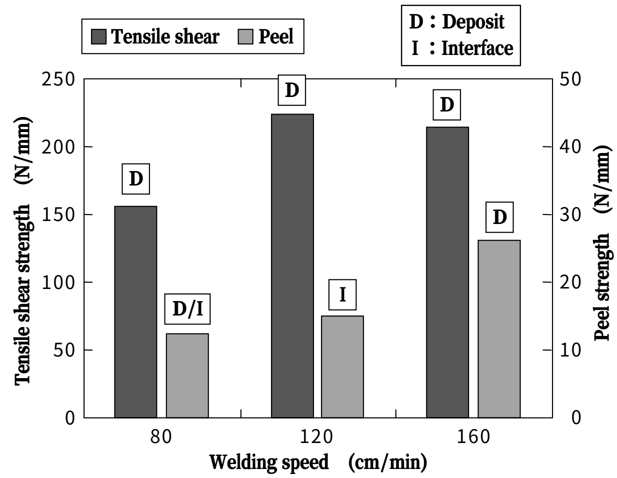

Fig. 6 Relation between welding speed and joints strength

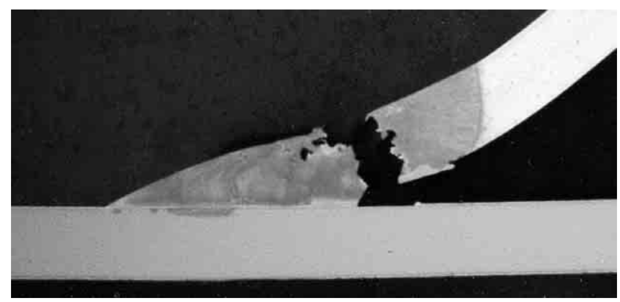

Photo 4 Cross section after peel fracture (welding speed : 160 cm/min)

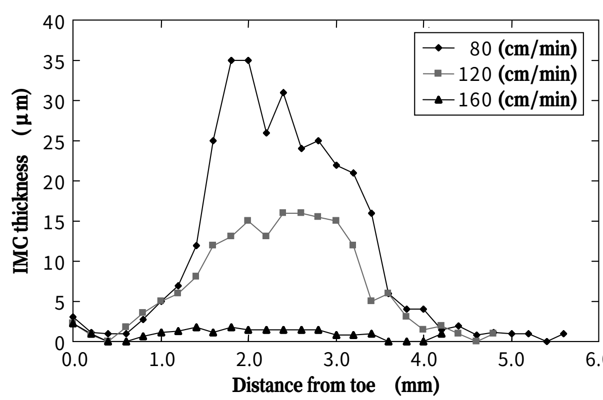

Fig. 7 Relation between welding speed and IMC thickness distribution at joining interface

3. Corrosion resistance of the welding joint

The corrosion resistance was evaluated, based on an automotive standard, for the MIG brazed joint between the developed aluminized steel sheet and aluminum alloy sheet. After corrosion, the test samples were subjected to tensile-shear test. Their internal corrosion was also investigated. After joining, the specimens were coated with electrocoating generally used for automotive coat and were subjected to a corrosion test. Combined cyclic corrosion tests (JASO M609-91) were performed on each specimen up to 200 cycles. The tests were performed in a standard method generally applied in the auto industry.

It is to be noted that the corrosion test assumes a severe condition in which salt solution accumulates inside the overlapped portion of the joint. To simulate the condition, each specimen was placed such that its welding bead face downward. For each sample, salt solution was sprayed on the steel-sheet edge without a welding bead. The gap between the joined materials was placed facing upward so that salt solution could easily penetrate into the gap.

3.1 Tensile shear test

Tensile shear tests were conducted at 0 cycle and 200 cycles of corrosion to evaluate the change in strength under the corrosive environment. **Fig. 8** shows the strength ratio for each sample after the salt-spray test, where the initial strength was 100%. No change in tensile shear strength was recognized for a combination of either 6K21/developed steel, GA / GA or 6K21 / 6K21. As shown in **Photo 5,** none of the combinations exhibited any significant corrosion on the outer surface or inside the gap.

3.2 Corrosion inside the overlapped joint

The inside of the overlapped joints were observed after the tensile test to investigate the internal condition of corrosion. As shown in **Photo 6**, the GA/GA sample exhibited red rust, while the 6K21/developed-sheet and 6K21 / 6K21 samples exhibited no red rust with some white rust.

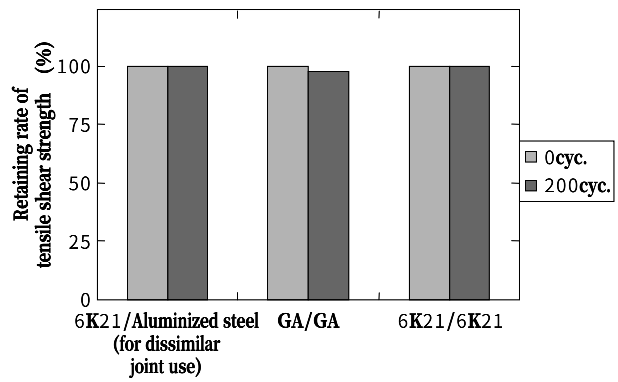

Fig. 8 Retaining rate of tensile shear strength after corrosion test

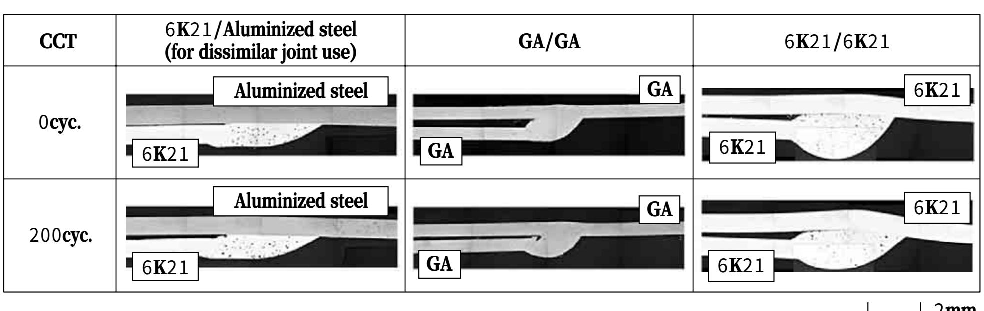

Photo 5 Cross section of joining region before and after corrosion test

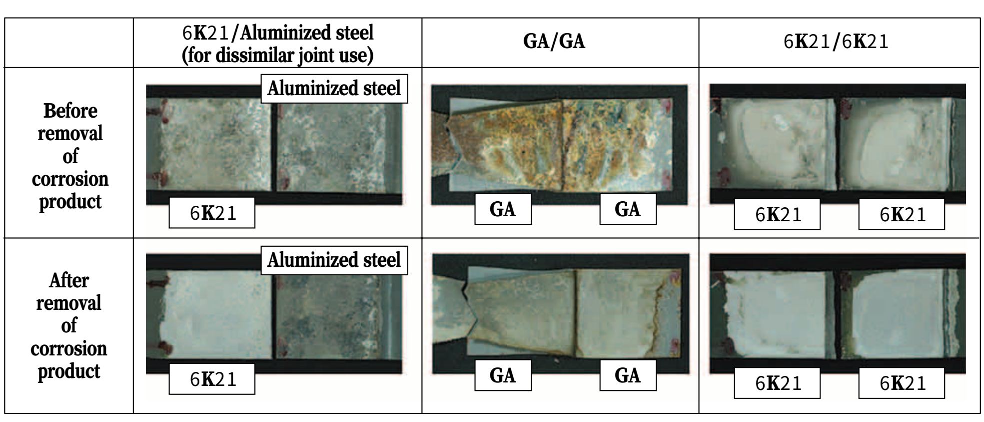

Photo 6 Internal lap of specimens after corrosion test

In addition, as shown in **Photo 7**, the GA / GA sample has lost the plating layer at the overlapped portion, whereas the 6K21/developed-sheet sample still retains the aluminum layer even after the corrosion test. No galvanic corrosion seems to have occurred between the 6K21 and developed steel sheet.

As described above, the joint between 6K21 and developed sheet exhibits an excellent corrosion resistance up to 200 cycles of the corrosion test.

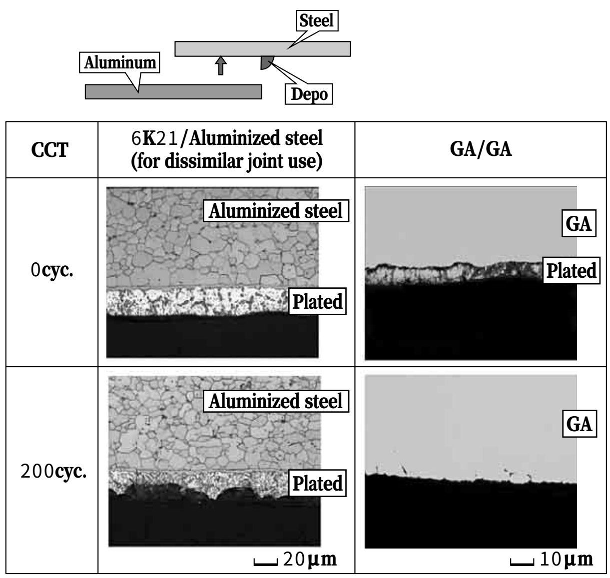

Photo 7 Cross section of plated coating before and after corrosion test

Conclusions

The method for joining aluminum alloy and steel is characterized by: the versatility of equipment which allows the use of conventional welding apparatuses; and, the resultant high-strength of joint comparable to that of Al-Al joint, which is owed to the prevention of intermetallic compound formation and optimized joint interface structure.

This technology is expected to widen the choice of materials for automotive use so that the features of each material are fully exploited.

References

1) T. Iwase et al.: *Preprints of the national meeting of J.W.S*, Vol.77 (2005-9), p.324.
2) Y. Hattori et al.: *Preprints of the national meeting of J.W.S*, Vol.77 (2005-9), p.326.
3) T. Miono et al.: *Preprints of the national meeting of J.W.S*, Vol.78 (2006-4), p.160.
4) Y. Hattori et al.: *Preprints of the national meeting of J.W.S*, Vol.79 (2006-9), p.380.
5) S. Sasabe et al.: *Preprints of the national meeting of J.W.S*, Vol.77 (2005-9), p.116.
6) S. Sasabe et al.: *Preprints of the national meeting of J.W.S*, Vol.78 (2006-4), p.16.
7) S. Sasabe et al.: *Preprints of the national meeting of J.W.S*, Vol.79 (2006-9), p.14.
8) T. Iwase et al.: *Preprints of the national meeting of J.W.S*, Vol.79 (2006-9), p.16.
9) T. Matsumoto et al.: *Preprints of the national meeting of J.W.S*, Vol.79 (2006-9), p.304.
10) Y. Hattori et al.: *Welding Technique* Vol.55 (2007-3), pp.84-85.