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Dissimilar Metal Joining Technologies for Steel Sheet and Aluminum Alloy Sheet in Auto Body

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Abstract

Multi-material structure of auto body partially employing aluminum alloy sheets may be adopted in order to satisfy requests at the same time improving crash safety and lightweight. This paper described the dissimilar metal joining technologies required to achieve multi-material structure. In resistance spot welding, high current & short time welding condition is conducted to avoid formation of brittle Fe-Al intermetallic compound layer at joint interface and joint strength is investigated. In mechanical joining, current application situation of SPR, Tog-L-Loc®, TOX® and FDS® methods are outlined and application examples of Blind rivet in automobile body are introduced. In addition to that, joint strengths in shear direction of SPR joints for cold rolled steel sheets and 6000 series aluminum alloy sheets are described. In adhesion bonding, it was shown that joint strength of TSS over 20 MPa is obtained by using of recent adhesive for automobile in sheet combinations of cold rolled mild steel sheets and 6000 series aluminum alloy sheets. In FSSW, effects of holding time, rotating speed and coating layer on joint strength were clarified in sheet combinations of Super Dyma® steel sheets and 6000 series aluminum alloy sheets. Also, in laser brazing, it was shown that joining of cold rolled or GA mild steel sheets and 6000 series aluminum alloy sheets are possible by using 4000 series aluminum alloy filler (A4043) with fluoride type NOCOLOK® flux. Finally, direction of development needed in the future in the field of dissimilar metal joining technologies of steel and aluminum alloy was described based on past development history.

1. Introduction

Today, measures to curb global warming are being employed in diverse fields such as energy, ships, aircrafts, rail rolling stocks, automobiles, and household appliances. The automotive industry, too, has been making positive efforts to reduce CO_2 gas emissions through reduction of the weight of car bodies.[1-3)]

The most striking of these efforts is the application of high-strength steel sheets (590 to 1,470 MPa) to automotive parts.[4-5)] Considerable volumes of high-strength steel sheet have already been applied to not only reduce the weight of car bodies but also enhance their crashworthiness. It is expected that efforts to further reduce car body weight by making most effective use of high-strength steel sheet will be continued in the future. However, considering the stiffness required of each member, there is a certain limit to the reduction of weight through the use of thinner steel sheets. If a further weight reduction of 30% or more is called for in the future, it will become necessary to develop and deploy a multi-material structure composed partly of lightweight materials.[6)]

Materials such as aluminum alloy, magnesium alloy, plastics,

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and carbon-fiber-reinforced plastic allow for reduction of car body weight,[3] among which aluminum alloy seems the most promising on the basis of actual use to date and cost. However, in light of the costs and properties of aluminum alloy as a structural material, the most effective way of using aluminum alloy is applying it only where really needed. For this reason, aluminum alloy has so far been applied to only those car body parts that do not require extremely high strength, such as the hood, trunk, doors, and roof.[7] Such partial application of aluminum alloy calls for technology to join aluminum alloy sheet and steel sheet, which exhibit different material properties.

Various methods have been proposed to join materials together, including fusion welding (e.g., resistance spot welding, resistance seam welding, arc welding), solid state bonding (e.g., explosive welding, friction welding, electromagnetic welding, roll bonding, diffusion bonding), brazing (e.g., burner brazing, arc brazing, laser brazing), mechanical joining (e.g., self-pierce riveting (SPR), TOX®, flow drill screw (FDS®), blind riveting), and adhesive bonding.[8] In addition, joining methods using coating or inserts have been studied.[9] For any joining method that requires high temperatures, a brittle layer of intermetallic compound (IMC) is formed at the joint interface, making it difficult to obtain the desired joint strength. In practice, therefore, attention was first paid to mechanical methods that do not form this unwanted layer of IMC.

When two dissimilar metals come into contact, the difference in their ionization tendency causes corrosion to occur at the interface. To prevent this, attempts have been made to use mechanical joining and adhesive bonding in combination.[10] Such methods have been put into practical use ahead of other joining methods and are still used widely.[6] It is also possible to restrain the formation of a brittle layer of IMC by applying solid state bonding. Therefore, friction welding and friction stir spot welding (FSSW) have been put into use for propeller shafts [11] and hatchback doors,[12] respectively. Thus, various methods have been developed for joining steel sheet and aluminum alloy sheet, a process that was previously considered difficult. With the recent strong demand for lighter car bodies, the need for such joining methods is again increasing. Spot welding, mechanical joining, adhesive bonding, FSSW, and laser brazing are considered to be especially promising technologies for joining steel and aluminum alloy sheets; therefore, we describe here the research into these materials and their application to actual cars in recent years.

2. Spot Welding

When steel sheet and aluminum alloy sheet are spot welded, the very brittle IMC produced at the interface during welding becomes a problem.[13] The presence of this material can decrease joint strength, especially the cross-tension strength (CTS). Therefore, for today's car bodies, a joining method that combines mechanical joining (e.g., SPR, TOX®, etc.) and adhesive bonding is most widely used.[7] In this section, the weldability and joint strength of spot welding are examined by the combination of a 0.8-mm-thick galvannealed (GA) mild steel sheet and a 1.0-mm-thick 6000-series aluminum alloy sheet.

The welding machine used was a pneumatic, single-phase, rectifier-type welder (power frequency: 50 Hz) with a rated capacity of 150 kVA, and the electrode used was a chromium-copper electrode of Dome Radius (DR) type with a tip diameter of 8 mm. The welding conditions were as follows: squeeze time, 70 cycles; upslope time, 2 cycles; weld time, 3 cycles; hold time, 20 cycles; and electrode force, 5.89 kN.

Fig. 1 illustrates the relationship between welding current and CTS. In the welding current range, the average value of CTS was about 0.7 kN/spot. Any welding current lower than the welding current range resulted in an unwelded condition, while any welding current higher than the welding current range caused the aluminum alloy sheet and the electrode to fuse. The welding current range was less than 1.0 kA and the fracture mode in this range was always a plug fracture at the aluminum alloy sheet side. **Fig. 2** shows the dependence of CTS on plug diameter of spot weld, obtained by a cross-tension test. Thus, the correlation between plug diameter and CTS is unclear.

CTS can be expressed by the following equation.[14]

$$CTS = B \cdot t \cdot (\pi \cdot FDc) \cdot TS \cdot \sin\theta \qquad (1)$$

where B denotes a coefficient, t is sheet thickness, FDc plug diameter, TS base metal tensile strength, and θ the base metal deformation angle right before fracture. Specifically, t is the sheet thickness (plug thickness) at the fractured part. **Fig. 3** shows a macroscopic view of

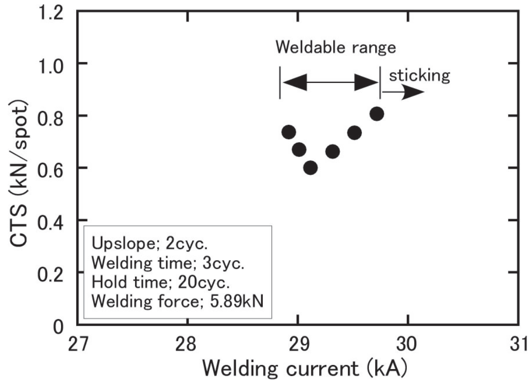

Fig. 1 Dependence of cross tension strength on welding current

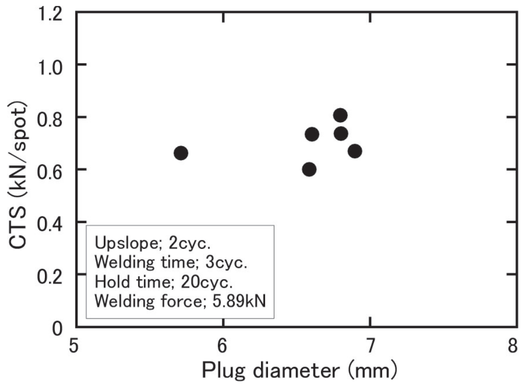

Fig. 2 Dependence of cross tension strength on plug diameter

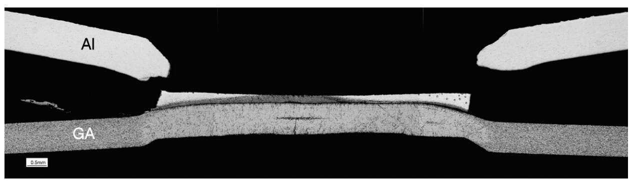

Fig. 3 Macro cross section of spot weld after cross tension test (welding current 29.5kA)

the cross section of a weld subjected to a cross tension test. It can be seen that the plug thickness is about 25% of the thickness of the base metal of the aluminum alloy sheet. Thus, in spot welding of steel sheet and aluminum alloy sheet, the decrease in aluminum alloy sheet thickness is so large that the joint strength cannot be expressed by the plug diameter alone. Thus, it is necessary to consider the plug thickness too.

3. Mechanical Joining

3.1 Trends of mechanical joining methods

Various methods exist for mechanical joining.[15] In the field of automobiles (in addition to conventional joining methods such as using nuts, bolts, and screws), new methods such as SPR, Blind Rivet, TOX®, Tog-L-Loc®, and FDS® have come to be applied in recent years.[6, 16-19]. Mechanical joining provides joints of high quality and allows for automatic operation. Because of these advantages, study of the application of SPR and TOX® began early,[20-23] and these methods came to be applied to high-grade cars ahead of other new joining methods.

SPR offers strong joints but can cause significant damage to the material surface. Therefore, it is applied mainly to parts that demand strong joints. Blind riveting permits access to the material from one side, causes little damage to the material, and offers strong joints. Thus, both SPR and blind riveting result in joints with high strength. However, the rivets used are relatively expensive. Furthermore, the latter method requires previous drilling of the materials to be joined.

TOX® and Tog-L-Loc® clinch two materials together by pressing them with a punch and die.[17] These techniques result in very little damage to the material surface, although the joints obtained are not very strong. Therefore, they are applied to parts that demand good appearance and corrosion resistance. FDS®, which was proposed only recently, is a method in which a screw turning at high speed is pushed into the material and fused with the base metal by the resultant frictional heat.[6] **Fig. 4** (a) illustrates a macroscopic view of the cross section of a joint between GA mild steel sheet and 6000-series aluminum alloy sheet obtained by Tog-L-Loc®; Fig. 4 (b) shows the FDS® joining process. TOX® and FDS® are applied to the car bodies of Audi, which can be considered representative of multi-material structures.[6]

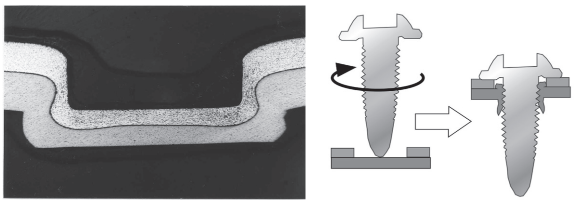

Fig. 4 Examples of mechanical joint for steel sheet and aluminum alloy sheet

Fig. 5 shows the joint strengths obtained by various methods of joining dissimilar metals.[24] In Fig. 5, F denotes cold-rolled mild steel sheet; A2, 5000-series aluminum alloy sheet; F(A), aluminum-coated mild steel sheet; FA, aluminum-clad steel sheet; SP, spot welding; MC, Tog-L-Loc® joining; SR, SPR joining; RJ, rivet joining; and AD, adhesive bonding. The above mechanical joining methods are used to compensate for the drawbacks of spot welding. However, they are also used with adhesive bonding to increase the static and fatigue strength of joints and prevent the deterioration of corrosion resistance of joints caused by contact between dissimilar metals. In fact, these materials have already been put into practical use.

Mechanical joining methods were first applied to joints between aluminum alloy sheets and between dissimilar materials by BMW, Daimler, Audi, and other European automakers,[6, 25, 26] and were subsequently applied by Japanese automakers.[27, 28] In the future, with the spread of multi-material structures, mechanical joining methods with or without adhesive bonding will increasingly be applied to joints of dissimilar metals to which fusion welding cannot be applied.[6] Presented below is an example of the application of blind riveting to domestic cars. Subsequently, we describe the strength characteristics of SPR joints.

3.2 Example of application of blind riveting

As mentioned in a separate report in this Special Issue ("Current Problems and the Answer Techniques in Welding Technique of Auto Bodies – Second Part"), blind riveting requires previous drilling of the materials to be joined together and incorporates the extra weight and cost of rivets. However, this method permits access to the material from one side, causes little damage to the material, and offers joints as strong as those offered by spot welding. In particular, when especially strong joints between steel and aluminum alloy sheets are required, a riveting method that does not produce any brittle IMC is

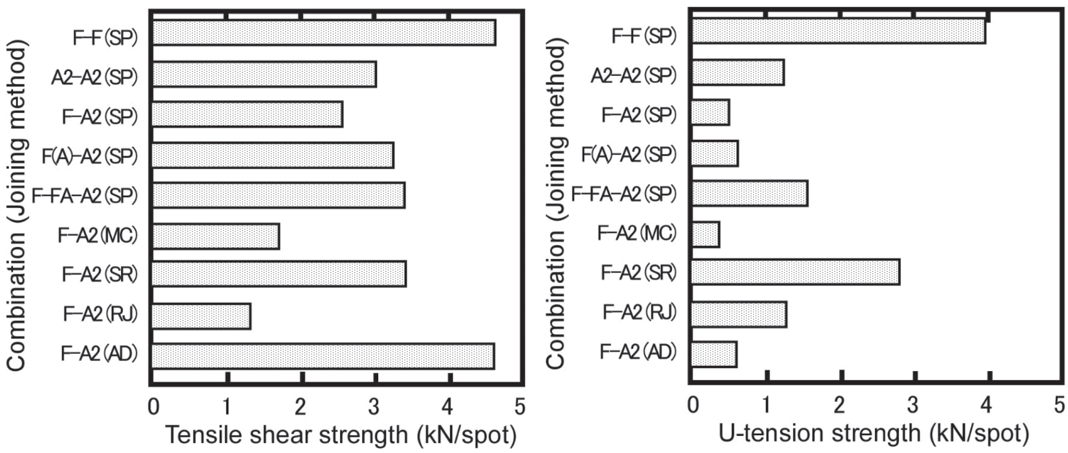

Fig. 5 Comparison of joint strength of steel and aluminum alloy sheet joints

appealing and should be applied where appropriate. **Fig. 6** illustrates rivets used in the aluminum alloy rear doors of the RX-8®. In this example, the rivets are used to fix the steel door impact beam.

3.3 SPR

As noted in the preceding section, the decline in joint strength and corrosion of metals caused by a brittle IMC formed at the interface in spot welding of steel sheet and aluminum alloy sheet can be problematic. However, such problems have been solved previously by applying a combination of spot welding and SPR or adhesive bonding,[10, 29-32] making it possible to materialize a hybrid structure.

Here, we describe the results of our study of the tensile shear strength (TSS) of SPR joints of a 1.0-mm-thick steel sheet (base metal tensile strength: 270 to 980 MPa) and a 1.2-mm-thick 6000-series aluminum alloy sheet. The rivets used were 5-mm-diameter steel rivets, which were driven in from the aluminum alloy sheet surface. As shown in **Fig. 7**, the TSS of joints tended to continue increasing until the base metal tensile strength had increased to 590 MPa; however, TSS tended to remain the same or decrease slightly as the base metal tensile strength was increased above 780 MPa. As noted in the figure, the rivets that were driven into the 780 MPa steel sheet buckled, while the 980 MPa steel sheet that was set in the die cracked (**Fig. 8**). In SPR of a high-strength steel sheet and an aluminum alloy sheet, it is important to select a suitable combination of rivets and dies. The above results indicate that, as long as the tensile strength of the steel sheet is within 590 MPa, SPR offers good joints between high-strength steel sheet and aluminum alloy sheet.

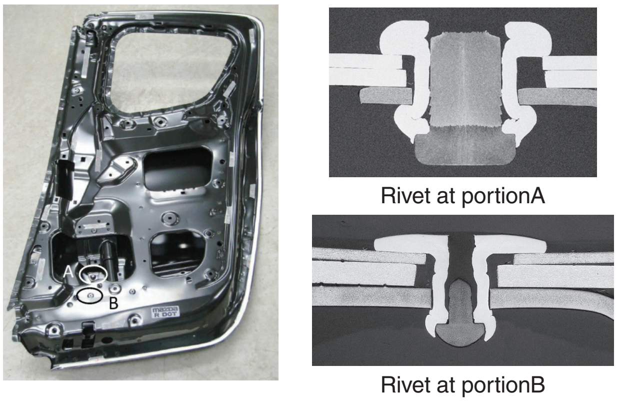

Fig. 6 Examples of blind rivet joints in aluminum alloy door

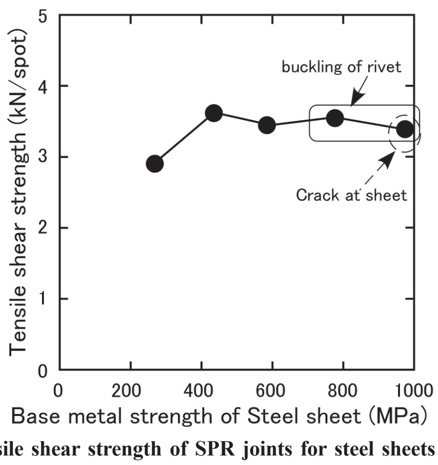

Fig. 7 Tensile shear strength of SPR joints for steel sheets and aluminum alloy sheet

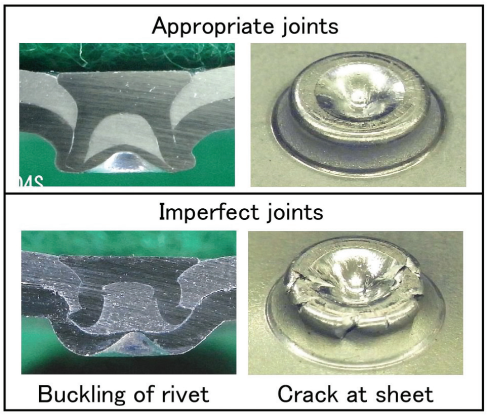

Fig. 8 Examples of SPR joints

4. Adhesive Bonding

Of the joining methods for multi-material structures, adhesive bonding is the most representative nonfusion welding method. In this section, we discuss the TSS of adhesive-bonded joints between a 0.8-mm-thick cold-rolled steel sheet of 270 MPa and a 1.2-mm-thick aluminum alloy sheet (A5182/A6022). The adhesive used was Sumitomo 3M's one-component, heat-curing epoxy adhesive for structural use. Before making adhesive-bonded joints, rust-preventive press oil was applied to test pieces measuring 100 mm (L) × 25 mm (W) and the test pieces were left until the conditions of the applied oil became almost uniform. Then, the adhesive was applied to each of the test pieces. In order to maintain the prescribed adhesive layer thickness, the test pieces were stacked on each other (with a lap space of 10 mm, on a 0.1-mm-diameter stainless steel wire) and heat cured in an atmospheric furnace at 170°C for 20 min. The testing speed in the tension test was 50 mm/min.

Fig. 9 illustrates the TSS of each of the adhesive-bonded joints for various combinations of materials. All combinations resulted in joint strength exceeding 20 MPa, and the mode of failure was always a cohesive failure of the adhesive. Note that the TSS shown indicates the value obtained by dividing the shear load by the bonding area. Fig. 9 indicates that the TSS of an adhesive-bonded joint

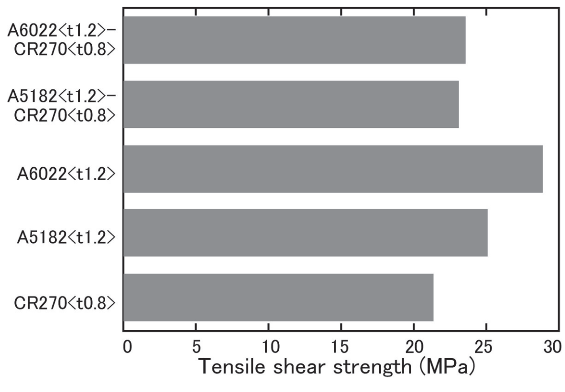

Fig. 9 Tensile shear strength of adhesive joints for steel sheets and aluminum alloy sheets

depends on the product of tensile strength and thickness of the base metal; that is, the larger the product, the higher the TSS.

5. FSSW

We attempted to join a coated steel sheet and an aluminum alloy sheet using FSSW,[33-36] which has attracted attention as a solid state bonding method with low heat input and which has become widespread as a lap joint technique to weld together aluminum alloy sheets.

The specimens used were a 6000-series aluminum alloy sheet (thickness: 1.0 mm) and a SuperDyma® (hot-dipped Zn-11%Al-3%Mg-0.2%Si-alloy-coated steel sheet; 0.7 mm in thickness). The welding tool made from SKD61 has a pin 0.8 mm in length and 4 mm in diameter and a flat shoulder 10 mm in diameter, as shown in **Fig. 10**. FSSW was applied to join the specimens, with the aluminum alloy sheet placed on the steel sheet. The tool insertion depth was 0.9 mm (i.e., the depth at which the shoulder was inserted 0.1 mm into the aluminum alloy sheet), and only the aluminum alloy sheet was stirred under a controlled load. Joints were prepared using different tool rotational speeds and different hold times from the time the tool reached the prescribed depth. The applied load was set by changing the hold time—6.0 kN by 1 s, 5.5 kN by 2 s and 3 s, and 5.0 kN by 4 s. Since the hold time for making the load constant after the prescribed insertion depth was reached was set, the final tool insertion depth was 0.91 to 1.02 mm.

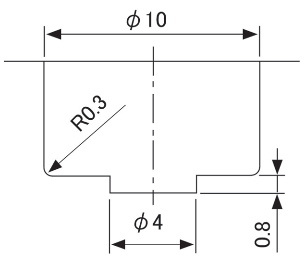

Fig. 10 Schematic illustration of welding tool

Fig. 11 shows the results of a tensile shear test. It is clear that the TSS depends more on the tool rotational speed than on the hold time and that the joint strength increases as the tool rotational speed is increased. **Fig. 12** shows the results of a cross-tension test. Joint strength increases with increases in tool rotational speed and hold time. Even so, the maximum CTS did not exceed 0.3 kN to 0.4 kN. The fracture mode was always interfacial.

Fig. 13 shows microphotographs of the interface of the welded section. The coating layer that had existed on the steel sheet surface was not found in the portion up to 4 mm from the weld center. Conversely, a difference in contrast was found and a "whisker-shaped" region extending into the aluminum alloy sheet was observed. A coating layer was observed 5 mm from the weld center (immediately under the shoulder). However, over a wide range up to 5 mm from the weld center, scanning electron microscope (SEM) observations did not reveal any IMC at the interface, regardless of the welding conditions.

Fig. 14 illustrates the results of an electron probe microanalyzer (EPMA) observation of the whisker-shaped region for welding conditions under which strong joints could be obtained. It is clear that the whisker-shaped part consisted of Zn from the coating metal dis-

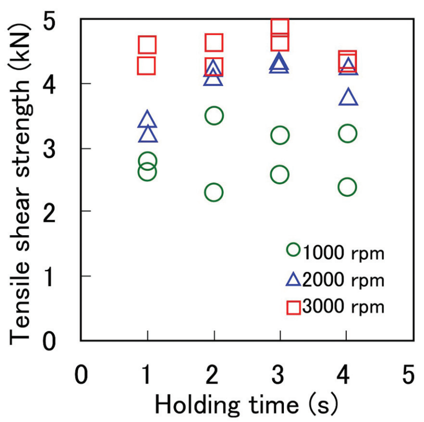

Fig. 11 Effect of tool rotational speed and holding time on TSS

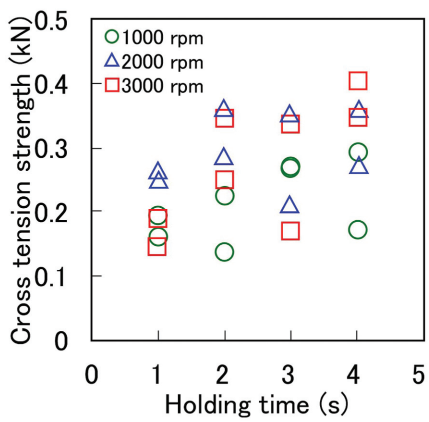

Fig. 12 Effect of tool rotational speed and holding time on CTS

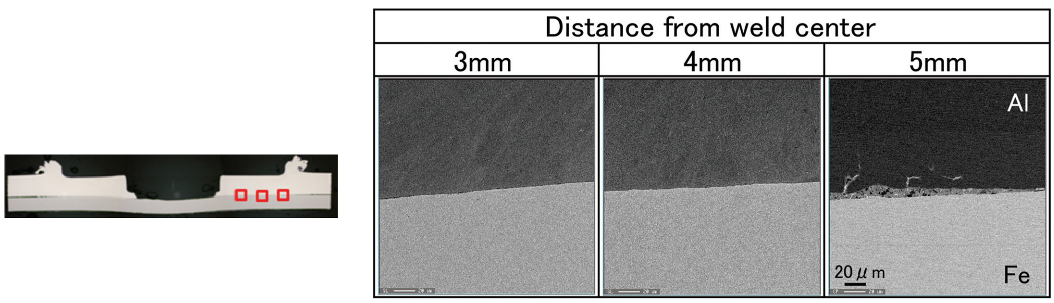

Fig. 13 SEM images of the interface between Al and steel (welding conditions: 3,000rpm-4s, TSS corresponding to 4.2kN)

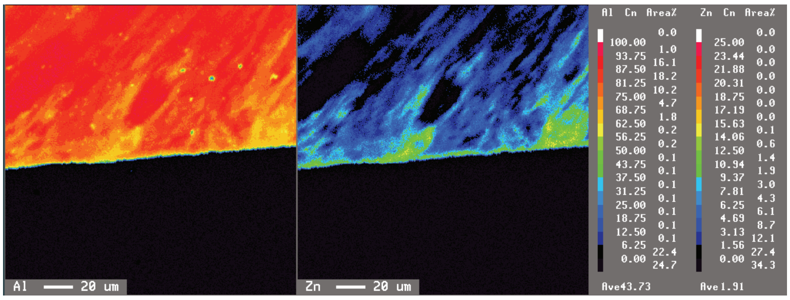

Fig. 14 EPMA images of interface at 3mm from the weld center (welding conditions: 3,000rpm-4s, TSS corresponding to 4.2kN)

solved in the aluminum alloy in the form of solid solution. When the joint strength was low, the whisker-shaped region contained a high concentration of Zn and was distributed widely. In addition, a joint cross section of a fractured specimen revealed a crack propagating through the whisker-shaped region. In order to obtain strong joints, therefore, it was considered important not only to secure a thin layer of IMC extensively in the direction of sheet thickness [37] but also to let the coating metal be dissolved in the aluminum alloy speedily, allowing it to be diffused extensively and uniformly during welding.

6. Laser Brazing

When iron and aluminum are fused together, the formation of a brittle IMC of the two metals is unavoidable. Therefore, it is difficult ordinarily to apply fusion welding to these materials. Conversely, brazing joins two base metals together by filling the gap between them using a metal with a melting point lower than that of either base metal; therefore, it fuses the base metals slightly, preventing the formation of a brittle IMC. Incidentally, aluminum has a hard oxide film on its surface that prevents brazing filler metal from wetting the surface of aluminum alloy. However, in order to secure the desired joint strength, the brazing filler metal itself is required to possess sufficient strength. In view of these facts, we attempted laser brazing using a fluoride-based flux to fuse and remove the oxide film and an aluminum alloy as the brazing filler.

The brazing filler used was Sholux® of Toyometal Co. (headquartered in Sakai City, Osaka) (**Table 1**). As shown in **Fig. 15**, the brazing filler is an aluminum alloy wire in which NOCOLOK® flux is mixed. Aluminum alloy used was the Al-Si-based 4043. For comparison, a solid wire and a flux-cored wire (FCW) made of the same material were used. The steel sheet specimens used were 0.8-mm-thick GA steel sheet and cold-rolled steel sheet. These are mild steel sheets whose base metals have tensile strength of 270 MPa. The aluminum alloy specimen used was a 1.2-mm-thick Al-Mg-Si-based 6000-series aluminum alloy sheet. The specimens were overlapped by 20 mm and subjected to laser brazing while the brazing filler was supplied to the lapped corner. The beam source used was a semiconductor laser, whose beam was condensed to 3 mm in diameter. The brazing conditions were as follows: laser output was 4 kW at working point; brazing speed was 2 m/min; and filler feeding rate was 3.5 m/min (6 m/min for 1.2-mm-diameter wire).

Fig. 16 illustrates photographs of cross sections of the brazed joints. It is clear that the flux improved the wettability of brazing filler metal and increased the width of brazing for both the GA steel sheet and the cold-rolled sheet. In addition, as shown in **Fig. 17**, the flux restrained the formation of a layer of IMC of iron and aluminum at the interface of the brazed joint. In the case of FCW, however, no increase in brazing width was observed, suggesting that the flux did not work effectively.

We conducted a tensile shear test to measure the strength of brazed joints (**Fig. 18**). It is clear that the use of a flux increases joint strength. Regrettably, the tested joints fractured at the interface of brazing. However, it would have been possible to prevent such fracturing by increasing the laser beam diameter slightly, thereby increasing the width of brazing. When the flux was not used, the GA steel sheet exhibited higher joint strength than the cold rolled steel sheet, suggesting that galvanizing improves brazeability.

Table 1 Brazing filler employed in this study

Diameter (mm)	Type of brazing filler	Flux content (%)	Flux
1.2	–	–	–
1.6	Sholux®	5	$KAlF_4$, K_2AlF_5, H_2O, K_3AlF_6
		7	Al: 16.0 - 19.5%
		12	F : 45 - 54.5%
		18	K : 26.5 - 32.5%
	FCW	12	$KAlF_4$, K_2AlF_5, H_2O

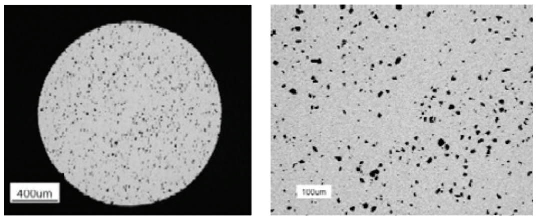

Fig. 15 Cross-sectional structures of brazing filler "Sholux®"

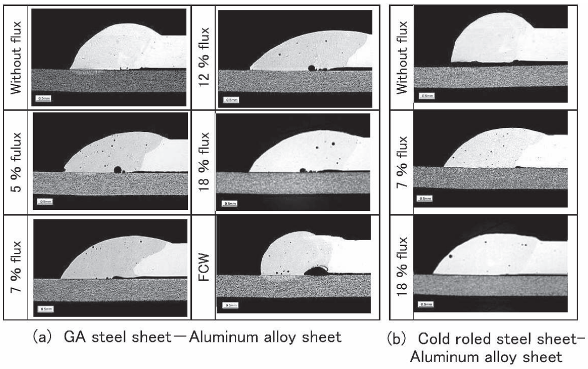

Fig. 16 Cross-section of brazed joint

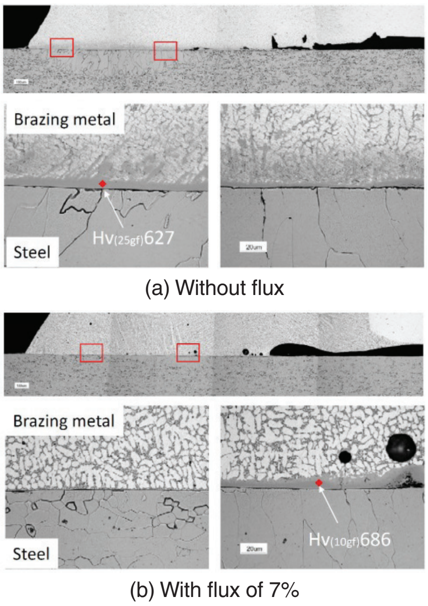

Fig. 17 Comparison of brazed interface structures without flux and with flux

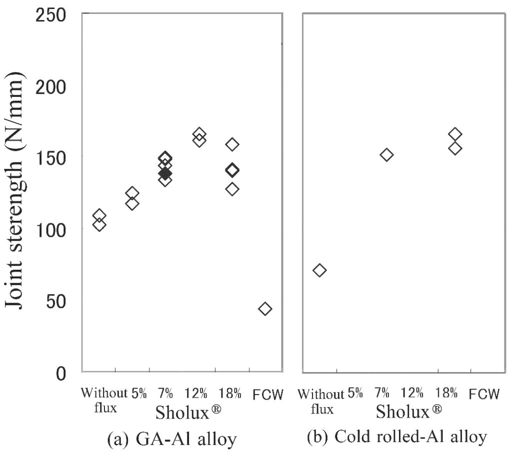

Fig. 18 Tensile shear strength of brazed joints

7. Conclusions

Here, we have described the latest developments in and applications of spot welding, mechanical joining, adhesive bonding, FSSW, and laser brazing as representative technologies for joining steel and aluminum alloy sheet. Study of such technologies began in earnest 20 years ago, when the use of aluminum in car bodies was first required. Since then, mechanical joining combined with adhesive bonding and FSSW have been put into practical use ahead of other joining methods for two main reasons: a) the ease of restraining the formation of a layer of IMC, and b) the availability of effective means of preventing the corrosion caused by contact between two dissimilar metals. Even so, there is still a need for spot welding, arc welding, and other economical, efficient, and reliable joining methods that have been applied mainly to car bodies.

When joining steel sheet and aluminum alloy sheet, it is necessary to pay attention not only to the two points mentioned above but also to several other factors: a) improving the work efficiency, b) reducing the amount of deformation of joints, c) minimizing the effect of the difference in thermal expansion between the two metals, and d) reducing the cost. In the future, the development of advanced new joining methods, with due consideration given to these challenges, will be necessary.

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