

Dissimilar Metal Joining Technology, SP-ray™, for Realizing Circular Economy

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Abstract

The industrial sector has recently placed increasing importance on material recycling to realize a circular economy. Mechanical fastening is the mainstream joining method for dissimilar metals in automobiles. Although this method assures high joint strength, disassembly of these joints is complicated. It is not the optimal joining method from the viewpoint of the material separation required for recycling. Against this backdrop, a laser joining technology, SP-ray™, which uses cold-spray coating as an intermediate layer, has been developed as a dissimilar metal joining method that achieves high joint strength together with assuring ease of disassembly. This paper presents the results which show that SP-ray™ joints can achieve joint strength equivalent to that achieved by mechanical fastening, and that heat treatment renders the steel and aluminum parts separable.

Introduction

Efforts toward a decarbonized society are being promoted worldwide, with Western countries, and Japan aiming for carbon neutrality by 2050.¹⁾ Vehicles emit more CO₂ per unit volume of cargo transported in comparison with rail and vessel transport and account for about 15% of Japan's total emissions.²⁾ As such, vehicles have a significant impact on global warming, and carbon emissions from this mode of transport must be reduced. Against this backdrop, vehicle electrification has been progressing in recent years, with electric vehicles (EVs) that run only on a motor rapidly gaining popularity. EVs reduce the environmental burden of vehicle operation but require high-capacity batteries of around 60 to 100 kWh to ensure the same driving range as conventional internal combustion engine vehicles.³⁾ Since high-capacity batteries are heavy and thus reduce efficiency, one of the challenges in EV design is to reduce the overall weight of the vehicle, including the battery.^{3), 4)}

Most of a vehicle's parts are steel, so attempts to reduce weight have often centered around increasing the tensile-strength of steel sheets to reduce part thickness. Multi-material parts combining lightweight materials such as aluminum alloys with high-tensile-strength steel sheets have started becoming more common, especially in

luxury vehicles in Europe and the United States. For example, aluminum alloy sheets are used for exterior panels such as hoods and doors, extrusions are used for reinforcing parts such as bumper reinforcements and door intrusion beams, and die castings are used for components with complex shapes such as strut towers and subframes.^{5), 6)} In EVs, aluminum extrusions and die castings are used for battery boxes.^{7), 8)}

One challenge in manufacturing multi-material vehicle bodies is joining dissimilar metals. Resistance spot welding and laser welding were the traditional methods for assembling steel vehicle bodies. However, weak intermetallic compounds (IMCs) such as FeAl₃ and Fe₂Al₅ are produced when steel and aluminum alloys are welded together, making it difficult to achieve high joint strength. Therefore, mechanical fastening, which does not involve melting the joint, is generally used nowadays. The most widely used joining methods are SPR (self-piercing rivets) and FDS® (flow-drill screws, trademark EJOT GmbH & Co. KG), shown in Fig. 1. A given vehicle model may require several thousand SPR joints and several hundred FDS® joints on a single vehicle body. SPR, which involves the use of a punch and die to drive rivets into the parts to be joined, has recently become feasible for sheet

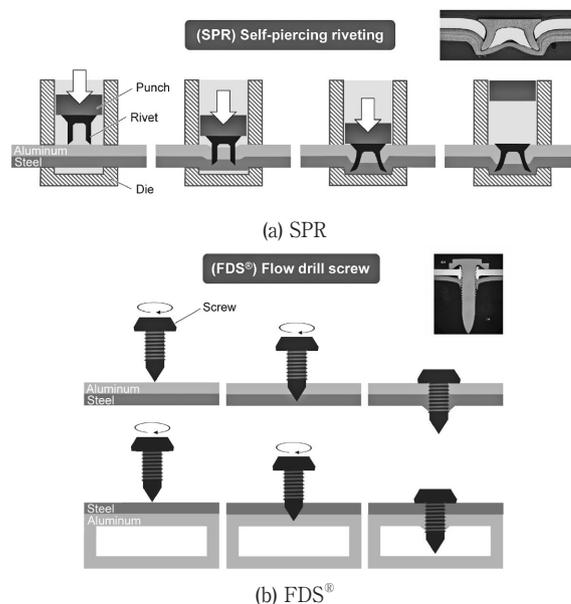


Fig. 1 Schematic illustrations of (a) SPR, (b) FDS®

assemblies including high-tensile-strength steel sheets.

However, it can be difficult to insert a punch and die into the cavity of hollow parts such as aluminum extrusions, invalidating this as a potential method. FDS[®], a joining method employing single-side access, is used for such materials. FDS[®] is highly robust and maintains strength.³⁾ However, it has as a relatively long joining time of about 2 to 3 seconds,⁹⁾ requires pilot holes for high-tensile-strength steel sheets, and precludes a flat surface at the joint because the head and shaft of the screw protrude. However, there is a limited number of automated joining methods employing single-side access; FDS[®] is currently the mainstream method for joining high-tensile-strength steel sheets and hollow aluminum alloy parts.

Reuse and recycling are also major issues with multi-material components. Key concepts pertinent to vehicle carbon emissions include tank-to-wheel (TtW) emissions, which comprises only emissions from driving, and well-to-wheel (WtW) emissions, which include emissions from fuel production as well. Another concept that has recently gained popularity is that of the life cycle assessment (LCA). This assessment evaluates carbon emissions from the entire process, including the procurement of raw materials and the production, disassembly, and disposal of parts and vehicle bodies. Depending on the method of power generation, the production of a new aluminum alloy ingot can generate up to 4 - 5 times more carbon emissions than steel ingot. Furthermore, the production of recycled aluminum alloy reduces carbon emissions by more than 90% compared with the production of new ingot.¹⁰⁾ Therefore, the reuse and recycling of aluminum alloy is crucial in terms of LCA. There are already some car models that make use of recycled aluminum.⁶⁾

In such cases, it is necessary to have a method for disassembling joints of dissimilar metals to retrieve the aluminum alloy from the multi-material vehicle body. The aforementioned mechanical fastening methods would require the laborious task of disassembling one joint at a time. Although it seems viable to consider soluble adhesive as a joining method¹¹⁾, vehicle manufacturing conditions are usually not conducive to adhesive for assembly because of rust-preventive oil and oil from hydraulic presses adhering to surfaces. Adhesive must also be kept cool to maintain performance, complicating storage and logistics.¹²⁾

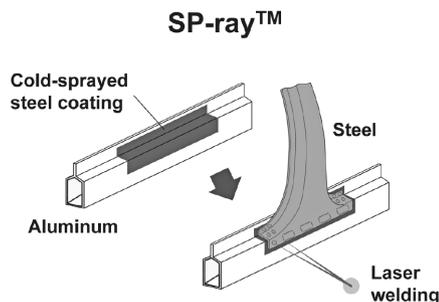
To overcome these challenges, we developed SP-rayTM Note 1), an indirect laser joining method for steel and aluminum alloys. This dissimilar metal joining

method uses a cold-spray coating as an intermediate layer. It yields excellent strength and ease of disassembly, can be used with high-tensile-strength steel sheets, is a single-side access technique, and supports high-speed assembly. This paper describes the basic concept of SP-rayTM, including its joint strength and disassembly properties.

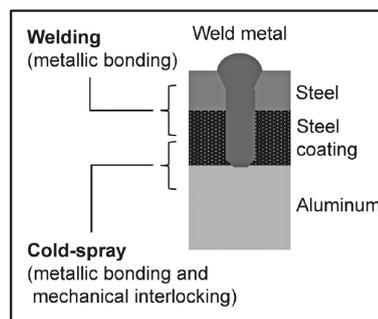
1. Basic concept of SP-rayTM

Fig. 2(a) depicts the SP-rayTM process. First, a steel coating is deposited on the aluminum alloy by cold-spraying, a type of thermal spraying method. A steel sheet is then layered over the steel coating and laser welded to that coating. Fig. 2(b) depicts the structure. The steel coating is firmly joined to both the steel sheet and the aluminum alloy by different mechanisms for high joint performance without unnecessary melting of the aluminum alloy during laser welding. Unlike other thermal spraying methods, cold-spraying occurs at a temperature at which the powder does not melt, resulting in a coating suitable for welding with almost no oxidation. The resulting adhesion strength is about 50-100 MPa, depending on the material and process conditions, which is higher than the conventional thermal spraying method of plasma spraying.¹³⁾

Although there is no consensus regarding the mechanism of adhesion in cold-spraying, a leading



(a) schematic illustration of whole process



(b) joining mechanism

Fig. 2 (a) Schematic illustration of whole process, (b) joining mechanism of SP-rayTM

Note 1) SP-ray is a trademark of Kobe Steel (6738793).

hypothesis is that there is solid-state bonding or mechanical interlocking (anchor effect) at the interface.¹⁴ Another dissimilar metal joining technology that uses welding, like SP-ray™, is weld bonding. This method combines the use of welding and adhesive. However, as stated previously, adhesives are difficult to manage and result in a bond strength of about 30 MPa¹⁵, which is less than that of cold-spraying. Hence, Kobe Steel's research centers around SP-ray™.

2. SP-ray™ joint properties and effect of cold-spray intermediate layer

Fig. 3(a) shows the cross-section of an SP-ray™ joint fabricated by laser welding a 1.5 GPa-grade steel sheet (thickness 1.4 mm) and a cold-spray sample. For comparison, Fig. 3(b) shows the cross-section of a direct-laser-welded joint without cold-spray coating. The cold-spray sample comprises AA7204-T6 (thickness 3 mm) with a 2 mm thickness steel coating made from pure iron powder. Nitrogen at 1,273 K and 5 MPa was the process gas for cold-spraying. The direct-laser-welded joint was created using a 5 mm thickness sheet of AA7204-T6 to match the total sheet thickness at the SP-ray™ joint. Welding was performed under the conditions in Table 1 using a fiber laser with a wavelength of 1,070 nm as the laser oscillator. Whereas the weld metal of the direct-laser-welded joint has pits

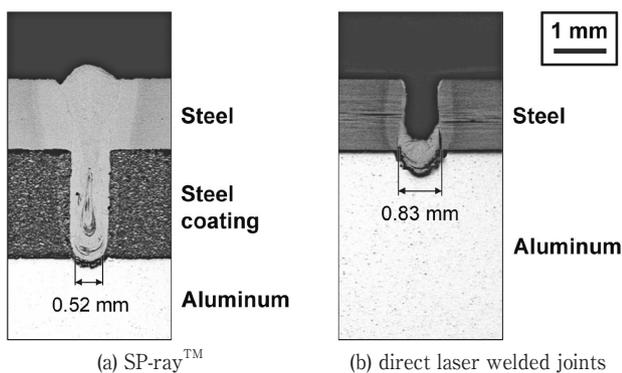


Fig. 3 Cross-section image of (a) SP-ray™, (b) direct laser welded joints

Table 1 Laser welding conditions

Spot size (μm)		330
Power density (×10 ⁶ W/cm ²)	Without coating	2.6
	With coating	4.4
Scanning speed (mm/s)		67
Bead shape		Circle
Weld diameter (mm)		φ12

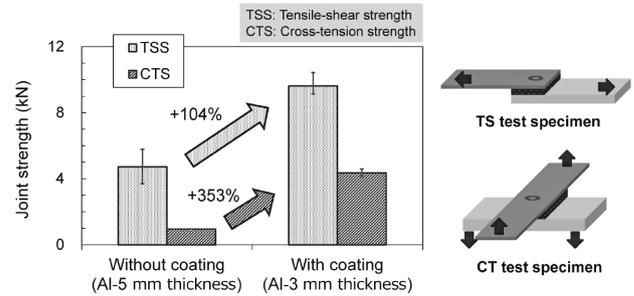


Fig. 4 Comparison of joint strengths between SP-ray™ and direct laser welding

and cracks, the SP-ray™ joint has a sound weld nearly free of weld defects. Fig. 4 compares the joint strengths of the SP-ray™ and direct-laser-welded joints. SP-ray™ yields significantly greater joint strength in comparison with direct laser welding in terms of its tensile-shear strength (TSS), at approximately two times greater, and its cross-tension strength (CTS), at approximately 4.5 times greater. A previous study showed the TSS of an FDS® joint in a sheet assembly of high-tensile-strength steel (1.0 to 1.6 mm thickness, 0.6 to 1.5 GPa-grade high-tensile-strength steel sheet as base metal) and aluminum alloy (3.0 mm thickness) to be 6 to 10 kN.¹⁶ Notably, SP-ray™ can provide the same TSS as FDS®.

3. Ease of disassembly of SP-ray™

3.1 Disassembly by heating using an atmospheric furnace

The cold-spray sample used in the SP-ray™ joint has an aluminum alloy substrate and a steel coating, so a thick IMC layer on the order of several dozen micrometers forms at the interface upon heating to a high temperature, as shown in Fig. 5. This characteristic can be exploited to separate the joined steel and aluminum alloy. Fig. 6 shows images of the surface and cross-section of the SP-ray™ joint fabricated with the same sheet assembly as in Section 2 after heat treatment at 600°C for 15-60 minutes in an atmospheric furnace. Heating for 30 minutes or more causes peeling at the interface between the steel coating and the aluminum alloy, making it possible to separate the joint into the steel and the aluminum alloy. Fig. 7 shows a mapping analysis of the coating side of the peeled interface using an electron probe microanalyzer (EMPA). An extensive amount of Al was detected, suggesting fracture in the IMC layer. Furthermore, point analysis via EPMA reveals a weak IMC layer with a higher composition ratio of Al than Fe, such as in FeAl₃ or Fe₂Al₃. Since Al diffuses into Fe at

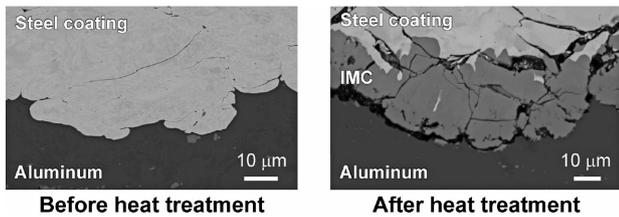


Fig. 5 SEM images of interface between cold-spray coating and aluminum before and after heat treatment

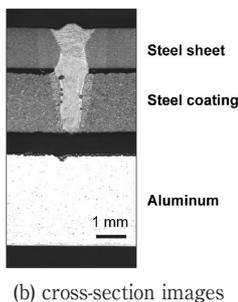
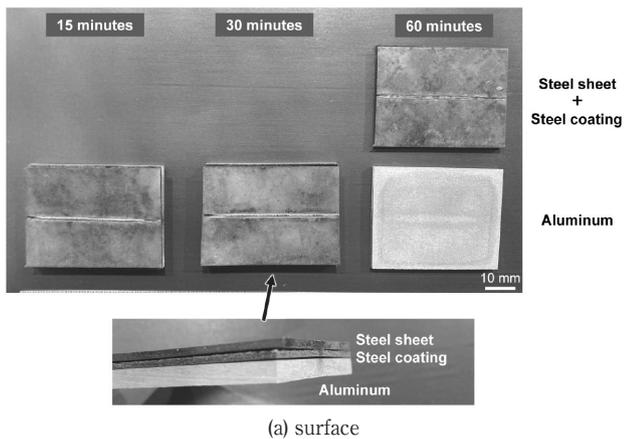


Fig. 6 (a) surface, (b) cross-section images of SP-ray™ joint after heat treatment

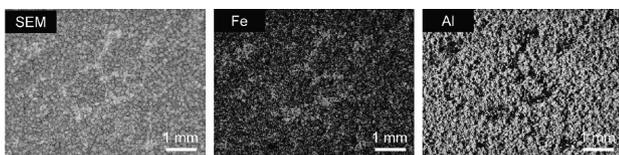


Fig. 7 Result of mapping analysis at surface of cold-spray coating, peeled from aluminum

temperatures above about 400°C,¹⁷⁾ IMCs should not form at the interface between the coating and the aluminum alloy during paint baking at around 170°C for a few dozen minutes (typical parameters in vehicle manufacturing).

Based on the information above, when an SP-ray™ joint is heat treated at a high temperature, a weak IMC layer develops over time, and thermal stress caused by differing coefficients of linear expansion at the interface between the steel coating and aluminum alloy causes fracture in the IMC layer, enabling separation of the steel and aluminum

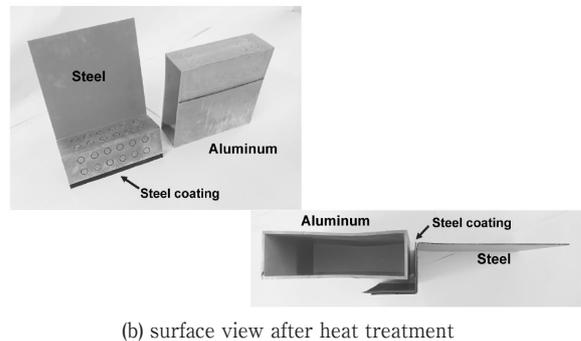
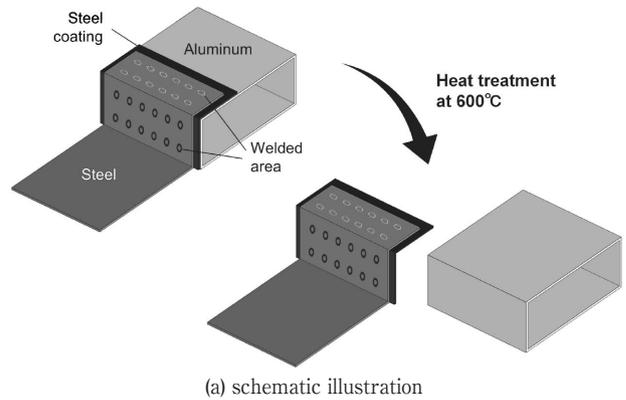


Fig. 8 Disassembly of SP-ray™ joint with 24 laser welded areas: (a) schematic illustration, (b) surface view after heat treatment

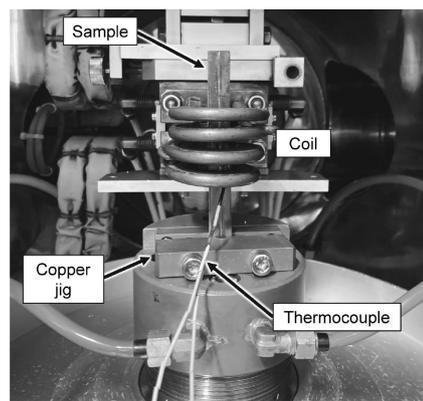


Fig. 9 Appearance of high-frequency induction heating machine

alloy. This method is also effective for disassembling multiple weldments in a sample in a single round of heat treatment (e.g., Fig. 8).

3.2 Disassembly using high-frequency induction heating

The previous section described how the SP-ray™ joint can be disassembled upon heat treatment. However, it is best to minimize heat treatment time from the perspective of reducing cost and environmental burden.

This led us to research the feasibility of a high-frequency induction heater (Fig. 9), which heats

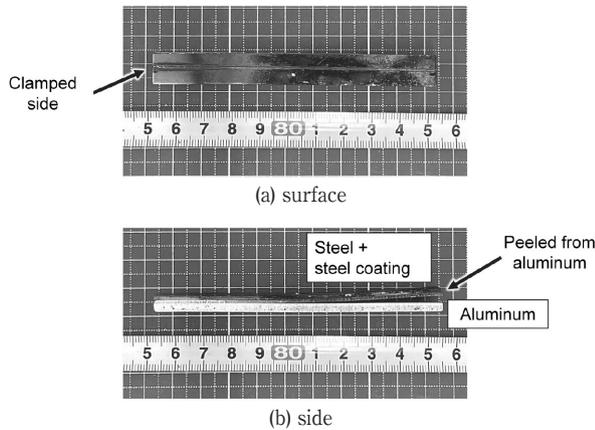


Fig.10 Surface view of SP-ray™ joint after high-frequency induction heating: (a) surface, (b) side

specimens much faster than an atmospheric furnace. We tested the same sheet assembly with the SP-ray™ joint as in Section 2. All specimens were 100 mm × 20 mm. We placed a 35 mm section at the center of the joint in the longitudinal direction into the coil and subjected it to high-frequency induction heating. For temperature control, a thermocouple was centered in the longitudinal direction on the 1.5 GPa-grade steel sheet. One end of the joint was clamped in place by a copper jig, and it is assumed that the temperature in that area did not rise to the specified level due to heat dissipation by the jig. Fig.10 shows the sample after heat treatment at 600°C for 15 minutes. The coating peeled off the aluminum alloy a substantial distance from the jig, indicating that high-frequency induction heating may enable faster disassembly than furnace heating.

Conclusions

Since the 1990s, automakers around the world have been working to improve engine efficiency, reduce vehicle weight, and develop electric and fuel cell vehicles to mitigate global warming. Such efforts are projected to intensify to foster carbon neutrality. Multi-material components will be a key pathway toward further weight reduction while safeguarding collision safety, necessitating an understanding of the advantages and disadvantages of both steel and aluminum alloys so each may be used as effectively as possible. As one of the few manufacturers

offering both steel and aluminum alloys, Kobe Steel will contribute to reducing carbon emissions through developments not only in materials but also in automobile design. SP-ray™, the joining method introduced in this paper, is a highly reliable dissimilar metal joining method that enables ease of disassembly. This technology will support safety and weight reduction in vehicles and will foster a circular economy, in turn advancing the objective of a carbon-neutral society.

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