Dissimilar Metal Joining Process "Element Arc Spot Welding"

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Dissimilar metal joining between aluminum and steel has mainly been performed mechanically, however, the method has problems such as production constraints. Hence, we have proposed element arc spot welding (EASW) as a new method for dissimilar metal joining. The new method comprises inserting a hollow steel element (rivet) into a hole in an aluminum upper sheet, after which, the molten filler metal is deposited by arc welding in the hollow part of the element; that is, the element and the lower steel sheet are firmly welded, while the upper aluminum-alloy sheet is tightly held between them. Thanks to the features of the joining mechanism, there is no restriction on the strength of the steel sheet. The method is also applicable to members with closed cross sections. With appropriate elements and welding wires, EASW can assure joint strength equal to or greater than mechanical joining. It allows welding in all positions and tolerates a gap of approximately 1 mm.

Introduction

Recently, multi-material structures, in which high-strength steel and lightweight materials such as aluminum alloy are suitably placed, are being increasingly studied and adapted in practice so as to decrease the weight of automobiles for emission reduction. Joining technologies for dissimilar materials such as steel and aluminum are key to multi-material car body design. Joining steel and aluminum alloy, however, has been considered difficult due to the differences in their physical properties, such as melting point, thermal conductivity and corrosion electric potential, and also due to the fact that the general-purpose fusion welding, such as resistance spot welding and arc welding, causes brittle intermetallic compounds to be formed. Currently, mechanical joining, such as

self-pierce riveting (SPR) and mechanical clinching, is being used; however, there are problems such as significant cost increase and production constraints. It is against this backdrop that a new method for joining dissimilar metals, namely, element arc spot welding (hereinafter referred to as "EASW"), has been proposed; this method exploits the existing technologies of arc welding and welding consumables. This paper introduces the joining mechanism and basic characteristics, including joint strength, of EASW.[1)-3)]

1. Mechanism of EASW

Fig. 1 depicts the mechanism of EASW. Herein, the upper sheet is an aluminum alloy sheet, while the lower sheet is a steel sheet, in which the upper sheet is provided with a pre-hole. A hollow flanged steel rivet (hereinafter referred to as an "element"), is inserted into the pre-hole. Then, molten filler metal is deposited by arc welding in the hollow part of the element. That is, by performing arc spot welding from one side, the element and lower steel sheet are firmly welded, while the upper aluminum sheet is tightly held between them. It is desirable for the welding conditions to be controlled so that the weld metal protrudes slightly behind the steel sheet.

Although the EASW is a joining method using arc welding, which generates high heat, no intermetallic compound is formed because the aluminum alloy is not melted at all. It should be noted that the element can be optimally designed in accordance with the requirements for sheet thickness and/or joint strength. The time required for the welding operation is strongly affected by the sheet thickness and is roughly 0.5 to 1.5 seconds. Unlike mechanical joining, the EASW does not require the
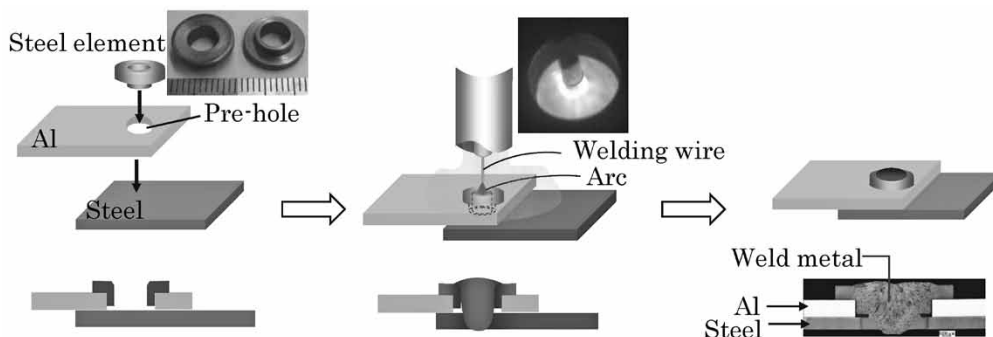

Fig. 1 Mechanism of EASW

steel sheet to be plastically deformed or penetrated; rather, the steel sheet is melted by high-temperature arc heat to form a welding joint. Therefore, there is no limit to the applicable strength of the steel sheets. There is also no need to access the subject from both sides to pressurize the upper and lower sheets. In other words, this single-side-access joining method has the advantage of being applicable, not only to open structures, but also to closed structures, as shown in **Fig. 2**.

2. Joint strength characteristics of EASW

The joint strength of EASW was evaluated by the tensile shear test in accordance with JIS Z 3136 and the cross tensile test in accordance with JIS Z 3137.

2.1 Study on failure mechanism of EASW joint

The following explains the failure mechanism of EASW on the basis of its structural features and analysis of the stress state of the joint during the strength test. In the schematic diagram of a tensile-shear specimen in **Fig. 3**, the nugget (weld metal) is pulled on its right side by the aluminum alloy sheet in the right side of the pre-hole and receives a shear force (P) and bending moment (M) during the tensile shear test. Therefore, it is believed that the fracture occurs from (i) the heat-affected zone (hereinafter referred to as "HAZ") in the right side of the lower sheet (steel sheet), (ii) the weld metal, or from (iii) the aluminum alloy sheet in the right side of the pre-hole. In other words, it is easier for the weld metal to fail when its strength is lower, or when the weld metal diameter (corresponding to the nugget diameter of resistance spot welding) is small,
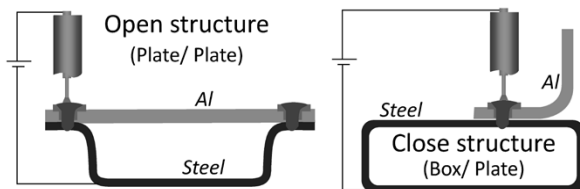
whereas the aluminum alloy sheet tends to fail when it is less strong, or it is thinner. In all other cases, it is believed that the lower sheet fails in its HAZ.

During the cross tensile test, as schematically depicted in the cross-sectional diagram in the longitudinal direction (the top diagram in **Fig. 4**), the force (P) acting on both ends of the upper aluminum alloy sheet causes the flange of the element to receive a shear force (Q) and bending moment (M). Therefore, the flange of the element may fail if it is thin and low in strength, or if the bending moment received is great (i). Alternatively, the aluminum alloy sheet may be damaged by the flange of the element, if the aluminum alloy sheet is thin with low strength (ii).

Also, as depicted in the cross-sectional schematic diagram in the longitudinal direction of the lower sheet (the bottom diagram in Fig. 4), the lower steel sheet is believed to receive a maximum bending moment in the proximity of the weld interface and is plastically deformed. For this reason, it is considered that the weld metal fails when it is low in strength (iii), and the HAZ (iv) of the lower plate or the weld interface fails when the HAZ of the lower sheet has high hardness with small elongation.

2.2 Effect of welding wire and element on joining strength

As described above, the strength of an EASW joint is affected by all of its components, namely, the material and strength of the upper and lower sheets, the strength of the weld metal, and the material and

Fig. 2 Joining schematic of open/close structures
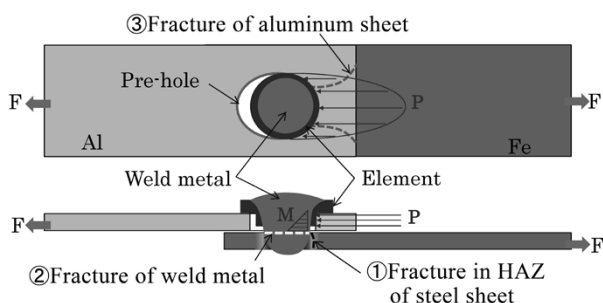
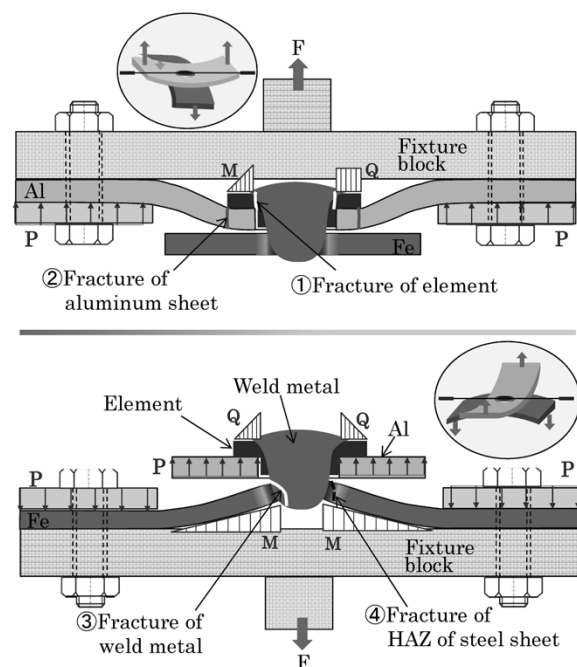Fig. 3 Schematic diagram of specimen for tensile shear test

Fig. 4 Schematic diagram of specimen for cross tensile test

size of the element.

Hence, this section reports the results of the test on joining strength when the types of the upper and lower sheets are fixed. In such a case, the main controlling factors of the joining strength are considered to be (i) the strength of the weld metal and (ii) the cross-sectional area of the weld metal at the interface between the upper sheet and lower sheet. Furthermore, it is considered that (i) the strength of the weld metal is roughly determined by the welding wire, and (ii) the cross-sectional area of the weld metal at the interface is roughly determined by the hole diameter of the element and the welding conditions. As for the element, besides the hole diameter, the material and flange size affect the joining strength as described in Section 2.1. The following reports the results of the examination on the way that the type of welding wire and the size/material of the element affect the tensile shear strength (TSS) and cross tensile strength (CTS).

2.2.1 Test method

An upper sheet of aluminum alloy, A6061 (2.0 mm thick), T6 heat treated, was combined with a lower sheet of 980 MPa class high-tensile steel designed to have a dual phase microstructure (1.4 mm thick, hereinafter referred to as "980DP").[4), 5)] Two types of welding wires (both ϕ1.2 mm) were used: i.e., JIS Z 3312 YGW11 (490 MPa class) and JIS Z 3312 G 59J 3M1T (590 MPa class). Two elements, having hole diameters of ϕ5.0 mm and ϕ6.0 mm respectively, were prepared using a steel in the strength class of 450-650 MPa. The shielding gas was

a mixed gas of 80%Ar+20%CO_2. In order to minimize spattering, the welding power was controlled by a high-accuracy feed control mode, in which the wire was fed forward and backward repeatedly.

2.2.2 Effect of welding-wire types and inner element diameter

The effects of the strength class of welding wires and of the interface cross-sectional areas of the weld metals on the TSS and CTS were examined, and the results are shown in **Fig. 5**. The elements were sized as shown in the figure, and were made of one type of material, SM490A (tensile strength: approximately 550 MPa). For the combinations of sheets in this test, the high-strength class wire resulted in both higher TSS and higher CTS. An element with a greater hole diameter also resulted in a greater interface cross-sectional area of the weld metal, leading to both higher TSS and CTS. With regard to the failure position, the TSS specimens based on the welding wire of 490 MPa class all failed in the weld metal at their sheet metal interfaces (part ② in Fig. 3), while the CTS specimens all failed in the weld metal (part ③ in Fig. 4). On the other hand, the TSS and CTS specimens based on the welding wire of 590 MPa class both failed in the HAZ of the steel sheets (part ① in Fig. 3 and part ④ in Fig. 4). From these results, it can be inferred that failure tends to occur from the weld metal when the strength of the weld metal is low, while failure tends to occur from other parts, such as the HAZ of the lower sheet, when the strength of the weld metal is sufficiently high.

2.2.3 Effect of element material on joining strength

The tests in the previous section have used elements all made of 550 MPa class strength steel, and no element damage was seen for any of the testing conditions. This section confirms the effect of elements made of different materials on the joining strength. Three types of elements, each having a hole diameter of ϕ 6.0 mm, were made of three types of steel, i.e., 450 MPa class, 550 MPa class and 650 MPa class strength, respectively. Only one type of welding wire, JIS Z 3312 G 59J 3M1T (590 MPa class) was used, and the other conditions were the same as in 2.2.1.

The joining-strength was tested on the elements of the respective strength classes, and the results are shown in **Fig. 6**. These test results show no effect of the element strength on the TSS. In the case of the cross tensile test, on the

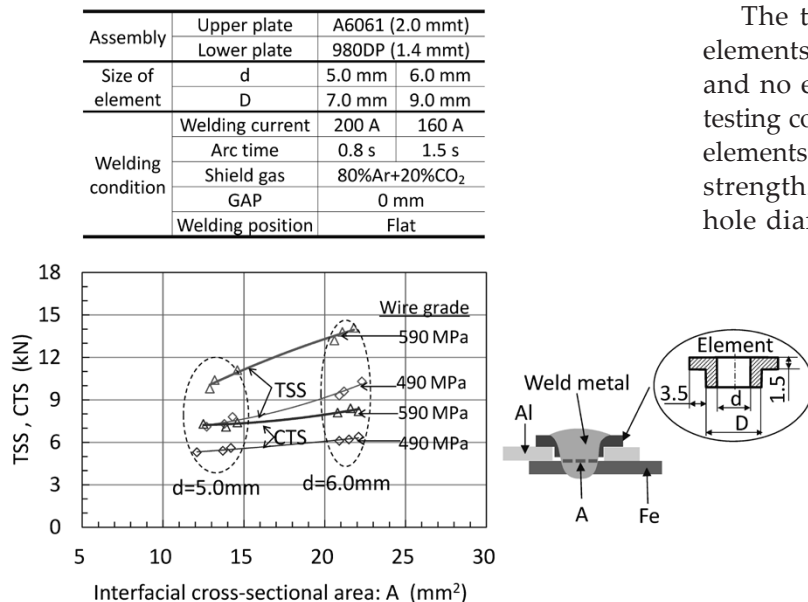| Assembly	Upper plate	A6061 (2.0 mmt)	
	Lower plate	980DP (1.4 mmt)	
Size of element	d	5.0 mm	6.0 mm
	D	7.0 mm	9.0 mm
Welding condition	Welding current	200 A	160 A
	Arc time	0.8 s	1.5 s
	Shield gas	80%Ar+20%CO₂	
	GAP	0 mm	
	Welding position	Flat	

Fig. 5 Effect of welding wire and hole diameter of element on strength of joint

other hand, the element with a low strength, 450 MPa class, failed in the flange (part ① in Fig. 4), resulting in a low CTS. When the strength of the element is sufficiently high (550 MPa in this test), the position of failure shifted to the HAZ of the lower sheet, improving the CTS. It should be noted that the element with even greater strength (650 MPa in this test) led to the same result, failing in the HAZ of the lower sheet. In other words, an element with sufficient strength shows no further improvement in the CTS because its HAZ dominates the joining strength.

2.2.4 Effect of element's flange width

As described in the previous section, when the strength of the element itself is low, at the 450 MPa class, the flange of the element fails during the cross tensile test, resulting in a low CTS. It is believed that the failure of element's flange is caused by bending moment. The bending moment received is considered to change with the width of the flange. In other words, it is believed that the deformation and failure mode of a flange changes depending on the width of the flange, affecting the CTS, even if the strength classes of the elements are the same. **Fig. 7** shows the results of the test on the joining strength when the width of element flanges is changed. The material of the elements used for this test is SS400 (tensile strength 450 MPa), and three flange widths of 2.0 to 3.5 mm were chosen. When the flange width was 2.0 mm, the lower sheet failed in its HAZ, but, when the flange width was 2.7 mm or 3.5 mm, the flange of the element failed, resulting in a low CTS. Furthermore, the CTS was lower for the flange width of 3.5 mm compared with that of 2.7 mm. This may be attributed to the fact that an element with a small flange width is subjected to a smaller bending moment. On the other hand, the effect of the flange width on TSS has not been confirmed. In the cross tensile test, the smaller the flange width of
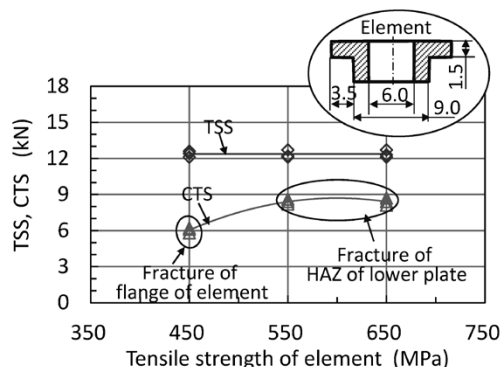
an element, the higher the resulting CTS. However, if the flange width is too small, the pre-hole may expand in association with the plastic deformation of the aluminum alloy sheet, raising a concern that the element and weld metal may fall from the pre-hole. In addition, the flange of such an element may be melted by the heat of arc, making it impossible to engage the aluminum alloy sheet between the element flange and steel sheet. This suggests that an optimum width exists for a flange.

2.3 Comparison of joining strength in EASW and in other existing methods for joining dissimilar materials

By choosing appropriate welding consumables and elements, EASW can achieve a joining strength higher than the existing methods for joining dissimilar materials. In one example of the test, joints were prepared using an aluminum alloy, 6K21 (a Kobe Steel product equivalent to AA6022), 2.0 mm thick, and a 980 DP steel sheet, 1.4 mm thick, joined by EASW and various other existing methods for joining dissimilar materials. **Fig. 8** shows the results of the shear tensile test and cross tensile test. The methods of joining dissimilar materials that were used for comparison are self-pierce riveting (SPR), Tuk Rivet®, Flow Drilling Screw (FDS®), Impulse Accelerated Tacking (ImpAcT) and Friction Element Welding (FEW). The rivet size and the joining conditions were in accordance with the manufacturers' recommendations. It should be noted, however, that the SPR and FDS® were unable to penetrate the 980 MPa steel sheet, rendering joining impossible. Hence, this figure shows reference values for the joining strength data when high-tensile strength steel sheets of 590 MPa class are used. Compared with the joining methods whose joining force relies only on friction resistance or swage structure, EASW and FEW,
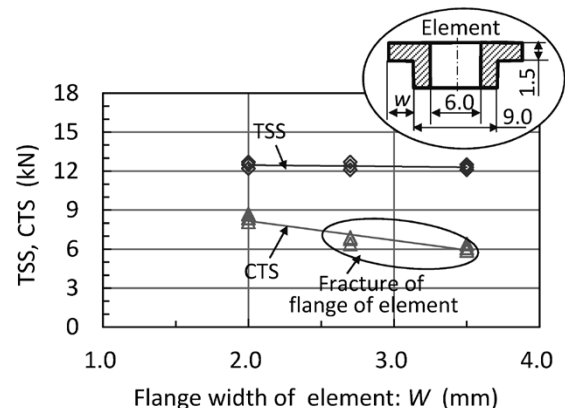

Fig. 6 Effect of tensile strength of element on strength of joint

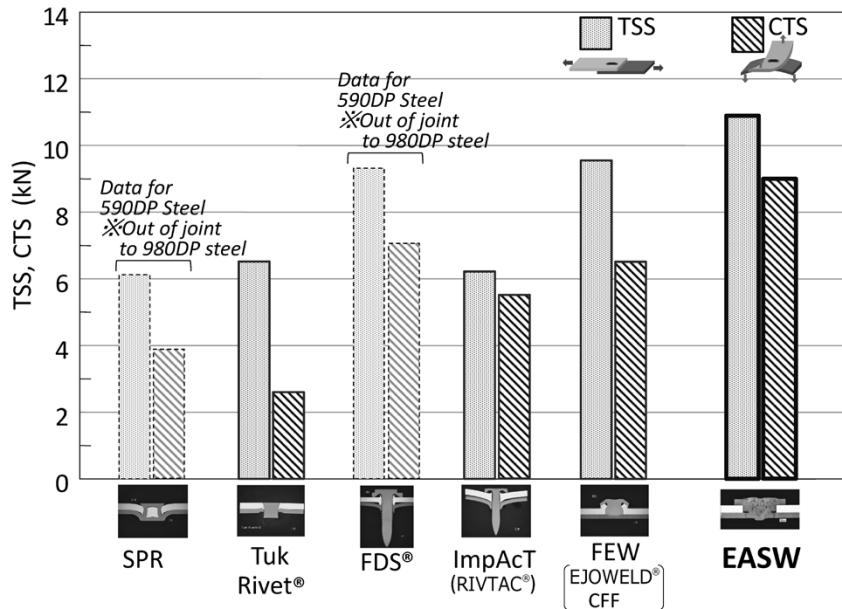**Fig. 7** Effect of flange width of element on strength of joint

Fig. 8 Strength comparison of dissimilar metal joints

whose joining mechanisms include metalic bond achieved by welding, result in higher TSS and CTS. In particular, EASW yields high values. The reason is considered to be the fact that, although both are welding methods, arc welding and pressure welding have differences in the soundness of the joining interface, weld metal quality and heat input, which affects their peeling strength characteristics.

3. Robustness of EASW

Some existing mechanical joining methods may be constrained by the strength of the steel sheet, the cross-sectional shape of the structure to be joined, gap, joining positions, etc. In Section 1, describing the mechanism of EASW, it has been explained that EASW has few constraints on the strength of the steel sheet and the cross-sectional shape of the structure to be joined. This section explains the tolerance of the effective range of welding conditions, the range necessary for applying EASW in production sites, or so-called robustness.

3.1 Gap tolerance of EASW

At production sites, gaps may be generated between the joining objects of aluminum alloy sheet and steel sheet, due to the assembly accuracies of parts and processing accuracy, etc., and it is difficult to completely eliminate these gaps. Since excessively large gaps render joining difficult, the gap tolerance of EASW was investigated. The shapes of welding joints were evaluated in combinations of an upper sheet made of aluminum alloy A6061 (2.0 mm thick, fixed sheet thickness) and a lower sheet of DP 980

steel, while changing the thickness of the lower sheet from 0.5 to 2.0 mm and the gap from 0 to 2.5 mm. The shielding gas was a mixture of 80% Ar+20% CO_2, and three kinds of elements with hole diameters of ϕ 3.8 mm, ϕ 5.0 mm and ϕ 6.0 mm, respectively, were prepared.

Fig. 9 shows the results of the test. When the lower sheet is thin, and a gap exists, the lower sheet becomes more prone to burn through. By using an element with a small hole diameter, the arc heat can be removed by the element, limiting the amount of heat transmitted to the lower sheet, which makes it possible to suppress the burning-through of the lower sheet. Meanwhile, a thicker lower sheet has a greater resistance against burn-through, increasing the gap tolerance. When the hole diameter of the element becomes too small, however, the lower sheet becomes difficult to melt, making it impossible to form a sound nugget.

These test results confirm that a lower sheet in the thickness range of 0.5 to 2.0 mm can be welded with a gap of up to approximately 1.0 mm, if an element with the appropriate hole diameter is used. There is also the possibility that the gap tolerance could be further expanded by taking measures such as making the shielding gas Ar rich, or narrowing the wire diameter.

3.2 Compatibility with welding positions of EASW

In each of the above tests the welding position was flat. However, at production sites, the welding position depends on the shapes of structures, etc., and may not necessarily be flat. Welding is required to be compatible, not only with a horizontal flat
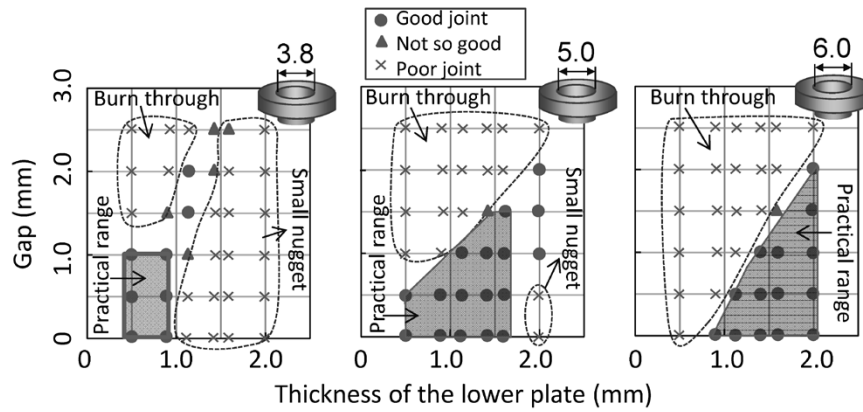
Fig. 9 Test results of gap tolerance by thickness of the lower sheet

position, but also with any other positions, including inclined or vertical ones. **Fig.10** exemplifies EASW conducted in various positions. This confirms that EASW is compatible, not only with flat positions, but also with all positions, including those that are vertical and overhead. In general, arc welding using solid wires suffers from difficulty in vertical and overhead welding because the molten metal tends to drop due to gravity. EASW also uses arc welding with solid wire; however, it is compatible with welding in all positions. This has been enabled by incorporating a welding apparatus with a highly-accurate wire-feed control for repeated forward and backward feeding in which the wire tip and molten pool come in contact approximately 80 times per second, such that the small hole in the element can be filled in a very short period of approximately 1 second. The phenomenon of the molten part (droplet) of the wire tip being transferred into the molten pool by surface tension while the droplets are being positively brought into contact with the pool is referred to as short-circuit transfer and is capable of preventing the fall-off of the droplets due to gravity.

3.3 Robustness of wire aiming positions

EASW is based on the principle of depositing molten filler wire into the through-hole of an element by arc welding; hence, it is most desirable for the wire to be positioned at the center of the hole. In production sites, however, it is difficult to position the wire at the center of an element all the time, due to the curling of the wires and minute deviations of welding positions in the structure to be welded. Hence, an investigation was carried out to find the tolerance of positional deviation of wires from the center of an element.

An upper sheet (2.0 mm thick) of aluminum alloy A6061 was combined with a lower sheet (1.4 mm thick) of DP 980 steel, and an element having a hole with a diameter of ϕ 6.0 mm was used. A welding

A6061 (2.0 mmt) / 980DP (1.4 mmt)
Wire: JIS Z3312 G 59J 3M1T
Hole dia. of Element: ϕ 6.0 mm
Welding current: 180 A
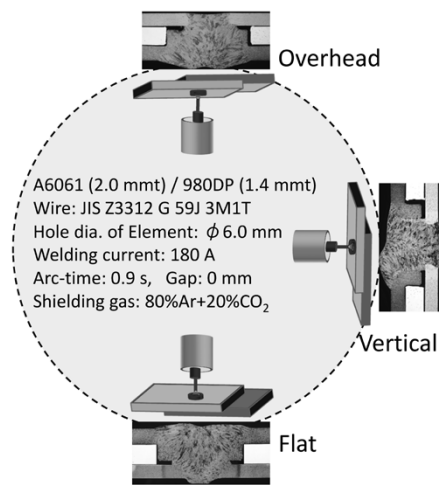Arc-time: 0.9 s, Gap: 0 mm
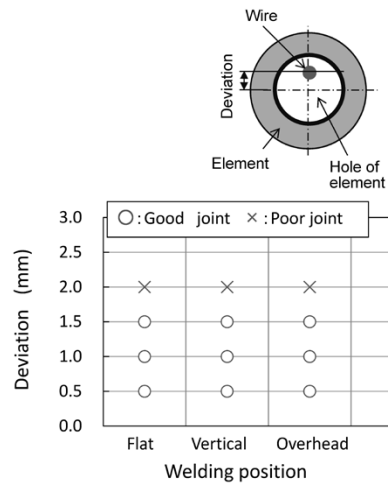Shielding gas: 80%Ar+20%CO_2

Fig.10 EASW in all position welding

Fig.11 Relationship among appearances of welding joints, welding positions and deviation of wire tip

joint was formed with a gap of 0 mm, while the aim position of the wire was deviated. The evaluation results of the resulting appearance are shown in **Fig.11**. A welding joint with a favorable appearance was obtained for each of the welding positions, as long as the deviation of the aim position of the wire from the center of the hole of the element was no greater than approximately 1.5 mm.

4. Corrosion resistance of EASW welding joint

Dissimilar metal joining has issues not only of joining strength, but also of galvanic corrosion (dissimilar metal contact corrosion). Galvanic corrosion (hereinafter simply referred to as "corrosion") is a corrosion phenomenon that occurs when dissimilar metals are brought into contact with electrolyte solution as shown in **Fig.12**. In general, a metal with a base potential becomes the anode and corrodes faster than when it is placed alone. On the other hand, a metal with a noble potential on the cathode side generally corrodes slower than when it is placed alone, so-called cathodic corrosion prevention phenomenon. When aluminum in an electrolyte solution comes in contact with iron, which is a more noble metal, for an extended period of time, a local cell is formed, in which the aluminum ionizes and dissolves into the solution. The remaining electrons move through the aluminum alloy-iron and are released into the solution from the surface of the iron, a noble metal, generating hydroxide ion from the water and oxygen in the solution.[6]

The most effective means of preventing corrosion is to prevent the contact points from being exposed to a wet environment. The practical measures for this purpose are to apply adhesives before the joining and, furthermore, to apply electro-deposition and sealing after the joining. Hence, the corrosion of the contact interface between aluminum alloy sheet and steel sheet has been investigated with
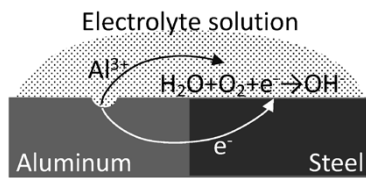
and without the application of an adhesive. The specimen consisting of an upper sheet, aluminum alloy 6K21 (2.0 mm thick), and a lower sheet, a bare sheet (1.4 mm thick) of ultra-high-tensile 980DP steel, was prepared with a prototype element made of SS400 steel. No surface treatment such as plating was provided. The corrosion test was conducted in accordance with the JASO M 609-91 CCT standard. **Fig.13** shows an example of the corrosion test results for a specimen coated with adhesive on the contact interface between the aluminum alloy sheet and steel sheet and a specimen without coating.

When there is no adhesive, corrosion occurred on the contact interface between the aluminum alloy sheet and the steel sheet. No significant corrosion was observed when an adhesive (DOW Chemical Betamate 1630, insulative) had been applied to the contact interface between the aluminum alloy sheet and the steel sheet.

On the other hand, no adhesive can be applied to the contact interface between the element and aluminum alloy. For this reason, there was some corrosion observed, although it was lighter in extent than the corrosion on the contact interface (without adhesive) between the aluminum alloy sheet and the steel sheet. Countermeasures were considered, approached from the point of view of (i) surface treatment and (ii) size of the element: (i) For the surface treatment, we considered plating the element with a metal having an electrical potential close to that of the aluminum alloy, or applying heat resistant insulation paint to the contact surface between the aluminum alloy sheet and element. (ii) As for the size of the element, it is believed that the anti-corrosion effect increases when the flange of the element in contact with the aluminum alloy sheet is minimized. This is because the corrosion of the aluminum alloy is expected to decrease as the area of steel decreases relative to the area of aluminum alloy. The feasibility and validity of these measures

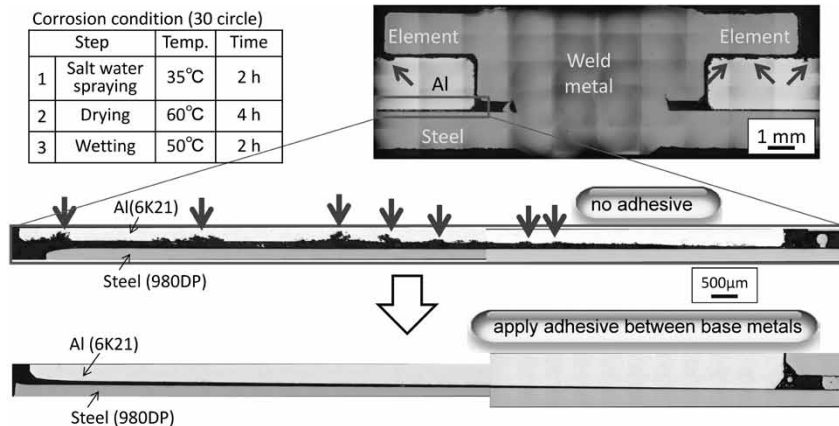Fig.12 Mechanism of galvanic corrosion

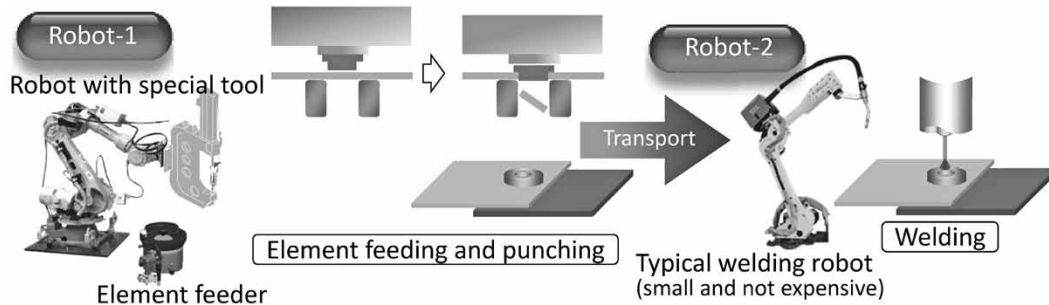Fig.13 Results of corrosion tests with/without adhesive

Fig.14 Conceptual diagram of 2 Robot/ 2 Step-type system for automatic EASW
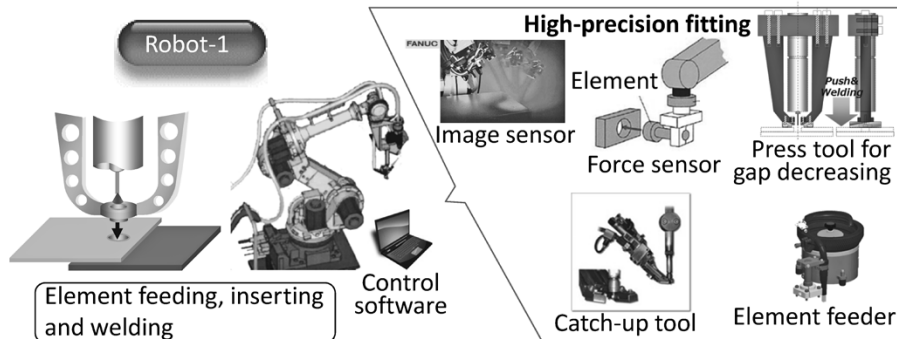

Fig.15 Conceptual diagram of 1 Robot/ 1 Step-type system for automatic EASW

must be confirmed by future tests.

5. Automatic system for EASW

Implementing EASW in the factory production process essentially requires its automation using robots. The automation of EASW is a step for future development, and this paper introduces two possible scenarios although this deviates from the purpose of introducing basic principles and effects.

A two-robot/two-step type system (**Fig.14**), in which the element insertion and arc welding are separated, is based on readily available fundamental technologies and easier to implement. This system allows simultaneous pre-hole formation and element insertion. This system has already been utilized in resistance element welding (REW), in which punching, and swage fastening is performed with the first robot tool using an element. The system is relatively large, being equipped with a pressurizing tool. The second robot performs standard arc welding. An inexpensive compact robot specified for arc welding can be applied as it is. It is also possible to carry out the 1st step and the 2nd step in separate factories or in separate companies. The drawback of this system is that one side accessibility, a major advantage of EASW, cannot be realized with the first robot.

Meanwhile, a one-robot/one-step type system (**Fig.**15) is more difficult to develop, but should perform joining highly efficiently with one compact robot. Although this system carries out all the functions of element feed, position correction, insertion, base material pressurization and arc welding with one robot, it is a prerequisite that the pre-hole formation be provided by other means. The step that is in general considered to be the most difficult is inserting an element into a pre-hole, which inevitably involves a positional deviation. It is an extremely easy task for human eyes, but a robot requires a sensor with high accuracy. In recent years, however, the development of sensor technology has been remarkable, as represented by the prevalence of in-vehicle sensors, and robot-mounted sensors are also exhibiting high functionality. It is already possible to perform the mating process with high accuracy, and this technology should enable the reliable insertion of the elements. The pressurization of base materials is a function that reduces the root opening between base materials. Unlike resistance welding, which requires zero gaps for joining, no strong pressurization function is required.

Conclusions

An element arc spot welding method (EASW), based on arc spot welding, has been developed as a method for joining dissimilar metals of aluminum alloy and steel. Its advantages include the following:
(i) Being a single-side access joining method, EASW can be applied to a wide range of structural shapes, such as closed cross-sectional shapes and open cross-sectional shapes.

(ii) There is no restriction on the applicable steel sheet strength.

(iii) A high joining strength can be obtained.

(iv) Relatively inexpensive and compact arc-welding robots can be used.

We will continue to work on the development of practical equipment in cooperation with the manufacturers of robots and equipment, as well as with system integrators.

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