Dissimilar metals Joining Process using GMAW has High strength and One side access characteristic, and the Automation robot system

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Keyword
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1. Demands for car weight reduction

Automakers in the world are now compelled with a sense of urgency to develop and practice the technologies for car weight reduction. This is because the car weight reduction is rated as the solution to the following inconsistent issues. While the fuel-economy regulation to restrict carbon dioxide emissions for global environmental protection has become more stringent internationally, the car weight may become heavier due to the enhancement of the safety measures to car accidents, the development of computerization, and the installation of batteries for electric and hybrid vehicles.

2. Joining problems associated with multi-material applications

One of the plans to achieve the car body weight reduction is the multi-material design that replaces general steel materials, a leading material of conventional car bodies, with new materials such as (1) super-high strength steel, (2) aluminum alloy, and (3) carbon fiber reinforced plastic (CFRP) for the right place according to the individual material's characteristics. Among these challenges, the basic strategy each automobile manufacturer explores preferentially from the viewpoint of cost savings is the combination of (1) maximized utilization of ultra-high strength steel and (2) employment of aluminum alloy, except for ultra-luxury cars.

As for the utilization of ultra-high strength steel sheet, the cold forming type of 980 MPa (1 GPa) class has been adopted, and further the use of 1180 MPa (1.2 GPa) class is at the practical stage. The low ductility grade of 1470 MPa (1.5 GPa) class steel has already been used practically, and the research and development of the high workability grade of 1.5 GPa class steel with both high strength and ductility, defined as "Generation 3," is under progression. Meanwhile, the hot stamp steel which is heated and quenched in the press forming process has become a standard with 1.5 GPa class, and it is aimed currently to upgrade this to 1.8 GPa class.

When ultra-high strength steel and aluminum alloy sheets are combined in the material design, it will be needed to join these components, and the joining method must be a dissimilar-metal joining process. However, as is conventionally known, it is problematic that various fusion welding processes, typically the resistance spot welding process used mainly for the existing steel car bodies, cannot be applied. This is owing to the remarkably brittle intermetallic compound produced by fusing the two base metals — Fig. 1. Therefore, the mechanical joining and chemical joining (bonding) methods without fusing the base metals are already common mainly in Europe for the practicable joining methods for dissimilar metals.

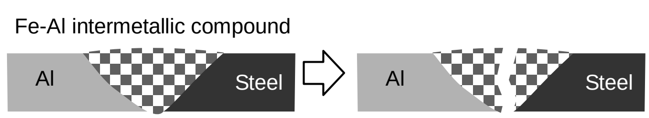


Fig. 1: Generation of intermetallic compound in steel-to-aluminum alloy fusion weld

3. Problems of conventional dissimilar-metal joining methods and present study's objectives

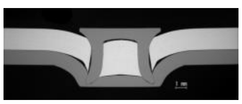
Table 1 shows representative dissimilar-metal joining methods together with their advantages and disadvantages[1). Many dissimilar-metal joining methods have already been used in practical applications, but none of them has yet fulfilled the requisites of (1) one-side accessibility, (2) applicability to ultra-high strength steel sheets, (3) joint reliability, (4) joint strength (shearing, peeling), and (5) applicability to triple-sheet joint (Al / Steel / Steel). Also, no such conventional method has yet been engineered to meet the automation needed for automotive industries. When a joining process has the one-side accessibility, it requires neither the strong pinching of the joining metal sheets from the face and back sides with the C type or X type tool used in general resistance spot welding, nor the insertion of the backside tool used in arc welding and laser welding. With the one-side accessible process, its application can be expanded because the restriction on the shape and size of the work can be reduced. Regarding the applicability to ultra-high strength steel sheets, the popular dissimilar-metal joining processes such as Self Piercing Rivet (SPR) and Clinch, for instance, cannot be applied because the steel sheet work cannot be riveted or plastically deformed.

In this research, the authors aimed to develop the dissimilar-metal joining process that enables the abovementioned performances of (1) through (5) together with robotic automation.

Table 1: Main dissimilar-metal joining processes for car bodies and their characteristics

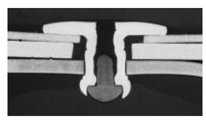
Grouping	Common name	One-side accessibility	For ultra-high strength steel	Joint reliability	Joint strength		For triple-plate joint	Others
					Shearing	Peeling		
Mechanical joining	SPR	×	×	○	○	△	○	
	PSR	×	×	○	△	×	○	
	Clinch	×	×	○	△	×	×	Merit: no consumable needed.
	Blind Rivet	○	○	○	○	○	○	Requires coaxial face and back drilling in advance. Difficult automation.
	Bolt & Nut	×	○	○	○	○	○	
	FDS	○	△	○	○	△	○	
	ImpAct	○	○	○	○	△	○	Problem: noisy impact sound.
	FSW, FSSW	×	○	△	△	×	×	Merit: no consumable needed.
Heat + mechanical joining	REW	×	○	○	○	○	○	Apt to cause LME cracking in galvanized ultra-high strength steel sheet.
	FEW	×	○	○	○	○	×	
Thermal joining	Brazing	○	○	△	×	×	×	
Chemical joining	Adhesive	—	○	×	○	△	○	Valuable anti-corrosion means.

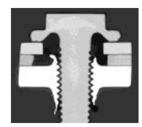
○: Excellent/Possible; △: Slightly inferior; ×: Inferior/Impossible

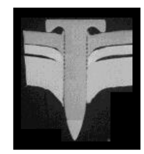

SPR
(Self Piercing Rivet)


PSR
(Punching Solid Rivet)


Clinch


Blind Rivet

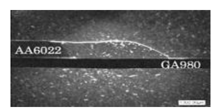

FDS
(Flow Drill Screw)


ImpAcT
(Impulse Accelerated Tracking)


FSSW
(Friction Stir Spot Welding)


REW
(Resistance Element Welding)


FEW
(Friction Element Welding)



MIG Brazing


Adhesive

4. Concept of Element Arc Spot Welding for new dissimilar-metal joining method[2-5]

Figure 2 shows the concept of the new dissimilar-metal joining method that can solve the above-discussed problems. This joining method will be referred to as Element Arc Spot Welding (EASW) in the following paragraphs. EASW can be practiced in some procedures, but the most basic procedure will be explained in this report with the experiment results. The upper sheet of aluminum alloy and the lower sheet of steel are used, and the upper sheet is furnished with a preliminary processed hole (pre-hole) by a particular means beforehand. More specifically, the pre-hole can be processed for typical materials as follows: (1) a sheet material, by die punching when the external shape is formed in the blanking process; (2) an extruded material, by drilling; and (3) a die-cast material, by providing holes in mold design. Next, the flanged steel rivet (referred to as steel element), which has a hollow center and the insert with the outer diameter that is slightly smaller than that of the pre-hole, is inserted into the pre-hole. Afterwards, the molten filler metal is deposited by arc welding in the hollow part of the steel element. That is, the steel element and the lower steel sheet are firmly welded by arc spot welding from one side. For fastening the upper aluminum alloy sheet, its movement is restricted by (a) the flange portion of the steel element in the upward plate-thickness direction, (b) the lower steel sheet in the downward plate-thickness direction, and (c) the insertion portion of the steel element in the planar direction. In order to avoid the fusion of the aluminum alloy sheet, the shape of the steel element and the arc heat input must be controlled.

EASW uses the arc welding process that generates intense heats, but the joining mechanism is a new mechanical fastening. This process also features the capability of one-side access like general arc welding processes.

5. Examination of EASW's components[6,7]

5-1 Steel element's dimensions

The steel element consists of the following dimensions: (1) flange diameter, D_{FL}; (2) flange height, H_{FL}; (3) insert diameter, D_{IN}; (4) insert height, H_{IN}; and (5) inner hole diameter, D_{Hole} — Fig. 3. In the view of car weight reduction and good applicability to narrow structures, the steel element itself should be lightweight with a small, thin overall contour. On the other hand, the joint strength can easily be anticipated to become lower with a smaller and thinner steel element.

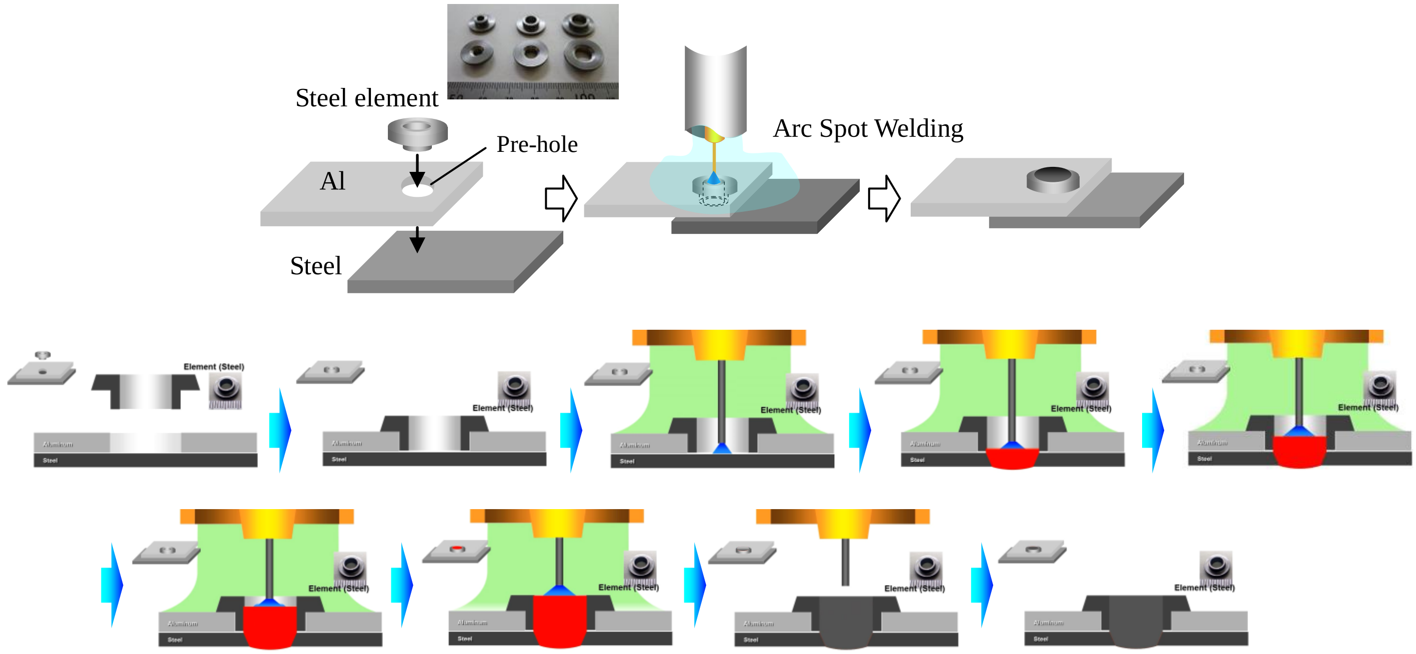


Fig. 2: Concept of Element Arc Spot Welding

5-1-1 Experimental procedures

In consideration of the conflicting nature of steel element's size and joint strength, the optimum size of steel element should be determined according to the characteristics required for an actual joint. For example, an A6061 aluminum alloy sheet with a thickness of 2.0 mm and a 980 MPa class steel sheet having a thickness of 1.4 mm were joined to examine the effects of the variation in the inner hole diameter D_{Hole} and the flange diameter D_{FL}; the experimental results are discussed below. The joining conditions for these experiments are shown in Table 2. The joint shear strength was evaluated with the tensile shear strength (TSS) specimen prepared per JIS Z3136 (Fig. 4), and the joint peeling strength was tested with the cross tensile strength (CTS) specimen (Fig. 5) as per JIS Z3137.

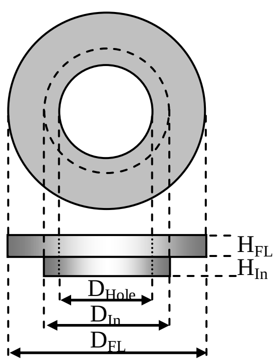


Fig. 3: Dimensions of steel element for EASW

Table 2: Joining test conditions

Base metal	Upper	Aluminum A6061-T6 (2.0mm)	
	Lower	Steel (980 Dual Phase) (1.4mm)	
Gap between base metals		None	
Size of steel element	D_{Hole} (mm)	5.0	6.0
	D_{IN} (mm)	7.0	9.0
Grade of steel element		440MPa class carbon steel	
Arc welding condition	Current (A)	200	160
	Time (sec)	0.8	1.5
	Shielding gas	80%Ar+20%CO_2	
	Position	Flat	
	Welding wire	JIS Z3312 G 59J 3M1T (590MPa-class)	
	Power source	Wire feed and current control type	

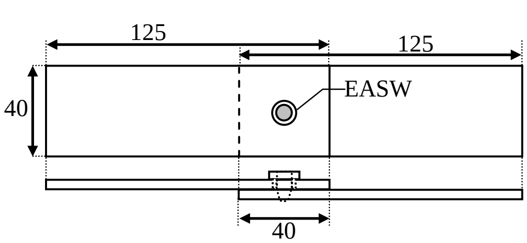


Fig. 4: JIS Z3136 TSS test specimen

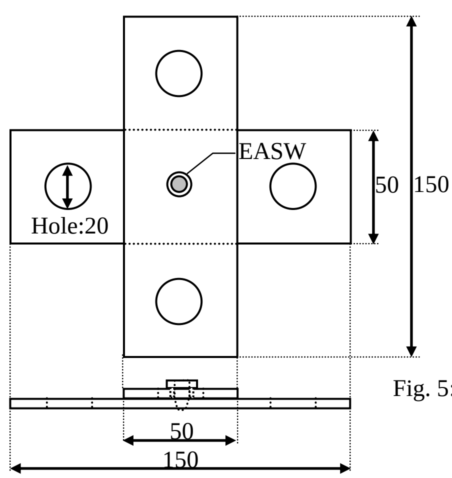


Fig. 5: JIS Z3137 CTS test specimen

5-1-2 Test results

Figure 6 shows the test results of joint strength in relation to the inner hole diameter D_{Hole} of the steel element. Since the joint strength relates directly to the dominant factor of weld metal's cross-sectional area and indirectly to the inner-hole diameter D_{Hole}, the actual measurements of the weld metal's interfacial cross-sectional area A_{Nugget} at the base metal interface (equivalent to the plug area in the resistance spot welding process) are given for the X axis of the graph. In addition, the reason why A_{Nugget} varied even with the same D_{Hole} can probably be attributed to the minute variability in the predetermined welding conditions for forming the weld metal.

These results have clarified that the weld metal cross-sectional area has the strong relation to the shear strength and the loose relation to the peeling strength. Hence, in order to obtain a higher joint strength, the effective way is to enlarge the weld metal cross-sectional area. For this purpose, an increase in the inner-hole diameter of the steel element is a practical means.

Figure 7 shows the test results of joint strength in relation to the flange diameter D_{FL} of the steel element. Since the diameters of the steel element's insert and inner hole were kept constant, an increase in D_{FL} means the increase in the expanded flange width W.

These results have revealed that the shear strength had little correlation with the expanded flange width, whereas the correlation with the peeling strength was significant, i.e., CTS decreased as the expanded flange width increased. The reason for this can be considered in such a way that when the expanded flange width of the steel element was larger, the steel element received a stronger bending stress affected by the upward peeling force at both ends of the aluminum alloy sheet. Meanwhile, when the expanded flange width W was smaller than 2 mm under this test condition, the flange was fused wholly at the time of arc welding, thereby losing the original shape. This is probably because the heat capacity of the steel element reduced when the volume of the steel element decreased, and thereby the whole part of the steel element reached the melting point of steel due to the heat input during arc welding. From the above study results, it has been found that the expanded flange width W of the steel element should be smaller to obtain a larger joint strength, but the lower limit value exists.

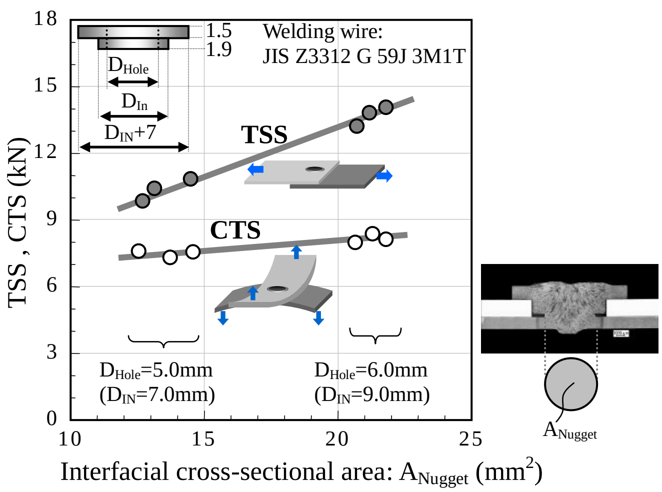


Fig. 6: Joint strength as a function of weld metal's cross-sectional area at the base metal interface

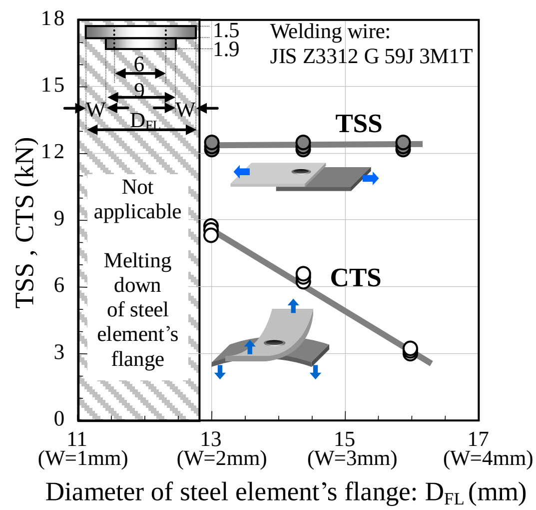


Fig. 7: Joint strength as a function of steel element's flange diameter D_{FL}

5-2 Characteristics of arc welding consumables

For one of the features of the EASW process, it is possible to control rather intentionally the chemical composition, metallurgical structure, and mechanical strength and ductility of the weld metal at the central part of the joint by selecting a desired welding consumable. In this study, the authors have examined the carbon steel wires distributed widely for gas-shielded arc welding, though special metal welding consumables such as stainless steel and nickel alloy wires should probably be examined in the future.

5-2-1 Experimental procedures

In the experimental procedure that is basically the same as that in Section 5-1, the welding wires were compared between 490 and 590 MPa classes in EASW under the joining conditions shown in Table 3.

5-2-2 Test results

The welding wire with the relatively lower strength than that shown in the previous Fig. 6 was tested, and the resultant data were plotted in Fig. 8 together with the data shown in Fig. 6 to compare both wires. These results have clarified that with the welding wire of lower strength class, both TSS and CTS decreased. The investigation of the fracture locations has revealed that with a 590 MPa class welding wire, the fracture location was the weld metal-to-base metal interface (fusion line) in the lower steel sheet, i.e. the fracture in base metal, whereas with a 490 MPa class welding wire, the fracture location was in the weld metal. In other words, the decrease in the joint strength can probably be attributed to the lower strength of the weld as compared to that of the steel sheet. From this result, it can be said that it is necessary to select the welding wire according to the steel sheet strength in order to obtain the high joint strength in EASW.

Table 3: Joining test conditions

Base metal	Upper	Aluminum A6061-T6 (2.0mm)	
	Lower	Steel (980 Dual Phase) (1.4mm)	
Gap between base metals		None	
Size of steel element	D_{Hole} (mm)	5.0	6.0
	D_{IN} (mm)	7.0	9.0
Grade of steel element		440MPa class carbon steel	
Arc welding condition	Current (A)	200	160
	Time (sec)	0.8	1.5
	Shielding gas	80%Ar+20%CO_2	
	Position	Flat	
	Welding wire	JIS Z3312 YGW11 (490MPa-class) JIS Z3312 G 59J 3M1T (590MPa-class)	
	Power source	Wire feed and current control type	

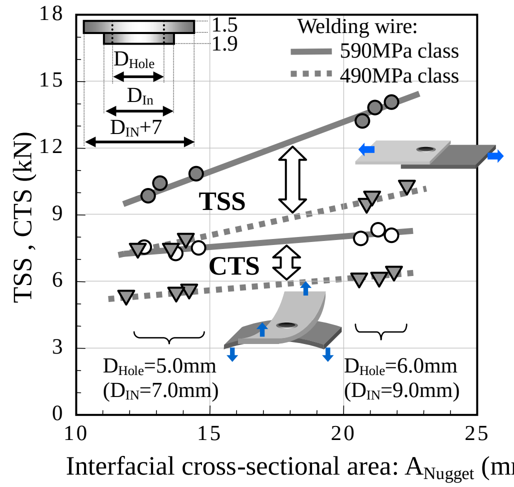


Fig. 8: Relation between strength level of arc welding wire and joint strength

5-3 Welding power source

The heat input control is important in the EASW process in order to reduce the heat effect to aluminum alloy and steel sheets, prevent the steel element from the entire fusion, and avoid the burn through and a lack of penetration in the steel sheet. Moreover, since the intended application is car body flames, it is necessary for better practicality to pay attention to the spatter generation and adhesion phenomena peculiar to arc welding. In response to these problems, the high-performance welding power source is widely used lately, which combines the electric current control and the wire feed control (Fig. 9) that repeats feeding and retreating the welding wire periodically in order to reduce the heat input and spatter generation; this type of power source is suitable for use in combination with EASW.

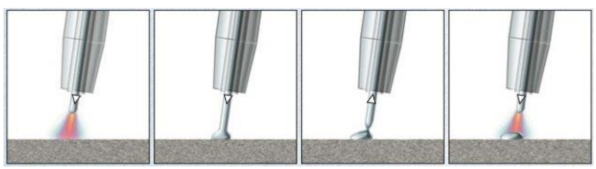


Fig. 9: Mechanism of wire feed control[8)]

In order to verify the spatter generation in the electric current range used in EASW, a simple comparative welding test was carried out using the welding power sources of the conventional inverter controlled type and the wire feed controlled type. For ease of comparison, arc spot welding was conducted on a steel sheet without the steel element and aluminum alloy sheet. As shown in Photo 1, it is obvious that the amount of spatter is very small with the wire feed controlled type. This suggests that almost non-spatter welding will be realized by using the welding power source of this type in EASW.

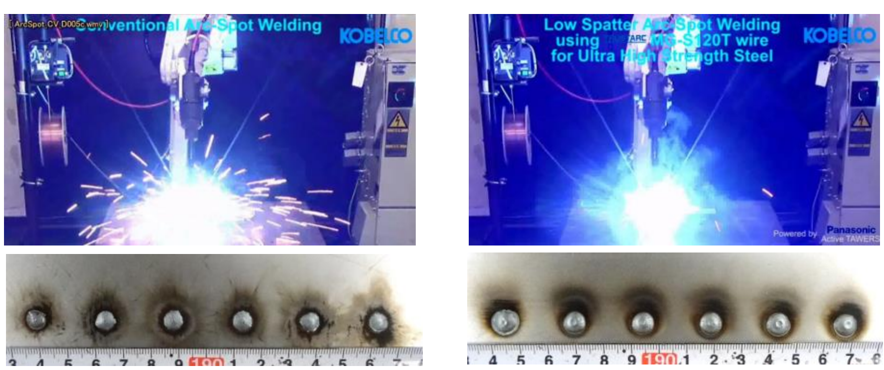


Photo 1: Difference in spatter generation between welding power sources of conventional type (left) and wire feed controlled type (right)

The droplet transfer mode with the wire feed controlled welding power source belongs to the short circuiting transfer mode in which droplets are transferred to the molten pool, mainly by the surface tension. With the stabilized droplet transfer driven by the surface tension of the droplet, EASW can be carried out in all positions, including horizontal and overhead positions. Photo 2 illustrates examples of all-position welding.

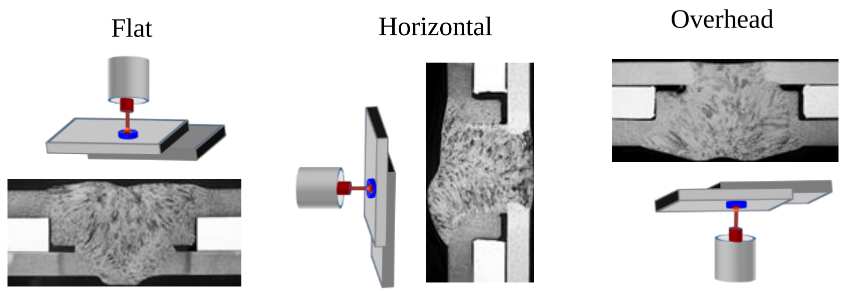


Photo 2: Cross-sectional macrographs of welds by EASW in flat, horizontal and overhead positions

6. Comparison of joint strength between EASW and other dissimilar-metal joining methods

Based on the various test results discussed above, EASW was optimized for steel element's size, welding wire, and welding power source to compare with other dissimilar-metal joining methods about the joint strength. However, the test results and comparative rankings discussed below should be taken as an example because they may change depending on the following factors: combination of the thickness and grade of steel and aluminum alloy sheets, optimization of the joining conditions, and possible technical development of other individual dissimilar-metal joining methods. For other dissimilar-metal joining methods, the authors left the testing procedures, including the testing conditions, to the discretion of the individual manufacturers or the testing companies that conform to the manufacturers. The common testing material was a set of two pieces of 2.0-mm thick aluminum alloy sheet of A6K21 (equivalent to A6022) and 1.4-mm thick 980 MPa class high strength steel sheet of dual phase structure design.

Figure 10 shows the tensile shear test results of the joints made by spot joining with the existing dissimilar-metal joining methods of various types and EASW. In this experiment, EASW was compared with the following dissimilar-metal joining methods: SPR, PSR, FDS, ImpAcT, FEW, and REW. However, 980MPa steel sheet could not be joined by SPR and FDS because through-thickness piercing was difficult for this steel sheet. This is why the figure includes the joint strength data of 590 MPa class high-strength steel sheet for reference. In comparison with the joining methods that use only the fastening force of frictional resistance and swaging mechanism, EASW, REW and FEW demonstrated the higher strength of approx. 10 kN because the joining mechanism of these methods include the welding process that enables metallic bonding.

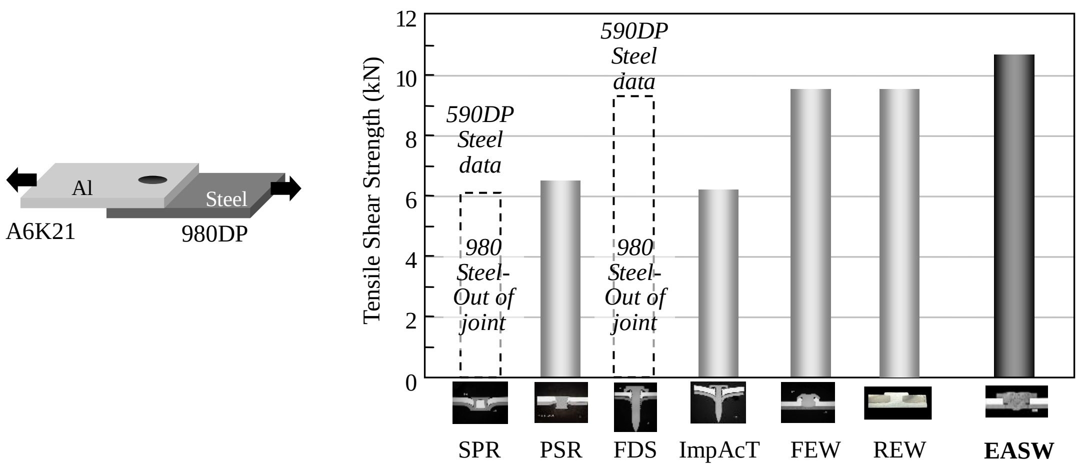


Fig. 10: Comparison of various joining methods about the TSS of dissimilar-metal joints with aluminum alloy and high strength steel sheets (incl. 980MPa class)

The fracture pattern of the EASW joint fractured by tensile shear test varied depending on the grade and thickness of the base metal. Photo 3 shows the typical fracture profiles of the joint that consists of steel sheet and aluminum alloy sheet with a relatively large thickness of 2.0mm in the same way as in the experiment discussed above. The aluminum alloy grade was A6061, and the steel grade was the highly processable ultra-high-strength galvannealed steel sheet of 1180MPa class with a plate thickness of 1.4mm. The TSS of this combined metal joint was 12.1 kN. The aluminum alloy sheet was plastically deformed around the pre-hole but was not the final rupture location. The rupture location was the boundary of the steel plate and the weld metal. The weld metal was detached from the steel sheet while maintaining its shape. This is schematically shown in Fig. 11.

When the aluminum alloy sheet was of a soft grade or thin in plate thickness, the fracture portion was not located in the steel sheet but appeared as a tear in the aluminum alloy sheet.

Figure 12 shows the cross-tensile test results of the joints with the same sheet assembly in relation to a variety of joining methods. Similarly to the results of tensile shear test, EASW, REW and FEW whose mechanisms include the welding process exhibited higher strengths, and EASW in particular demonstrated the highest strength. This is probably because the soundness of the joint interface, the quality of weld metal, and the heat input differed between the arc welding, resistance welding, and pressure welding processes, thereby affecting the peeling strength characteristics, though these processes are classified into the common category of welding.

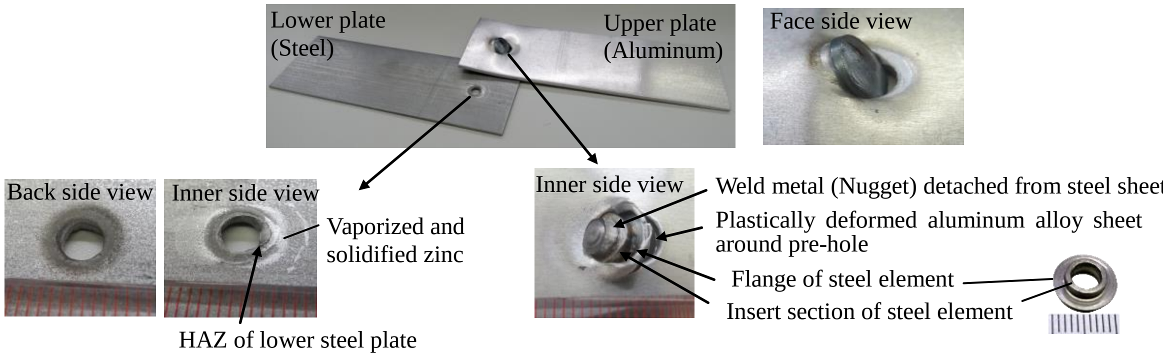


Photo 3: Typical fracture appearance of EASW joint in tensile shear test

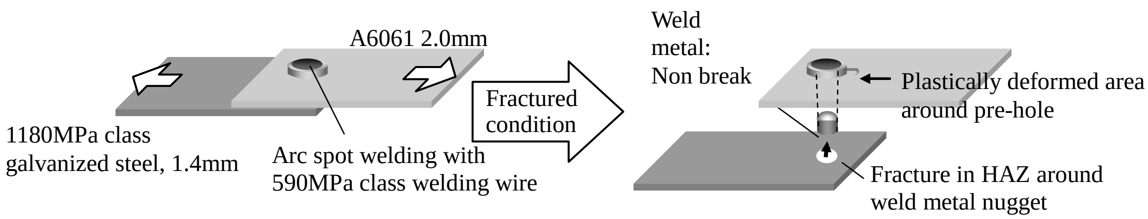


Fig. 11: Typical schematic fracture pattern of EASW joint in tensile shear test

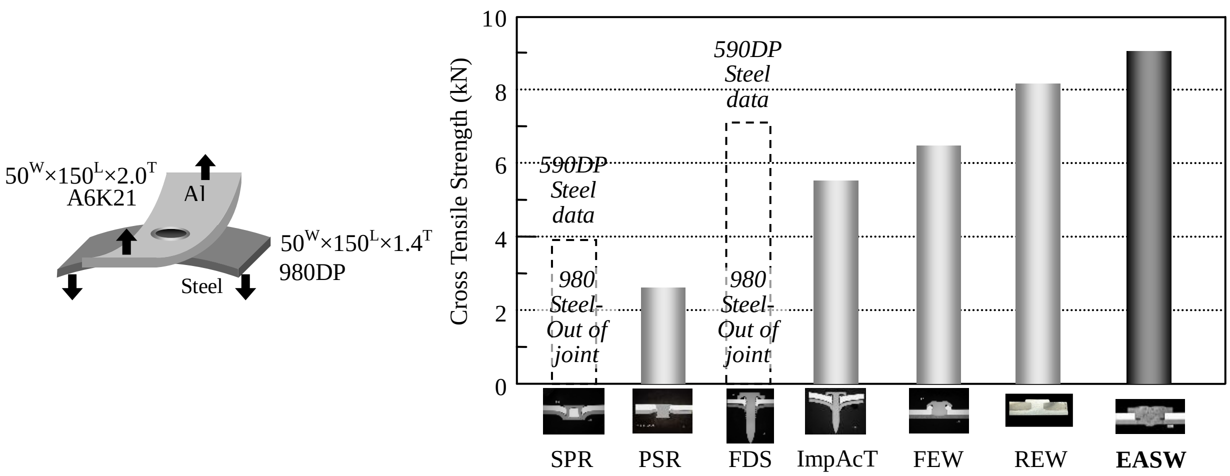


Fig. 12: Comparison of a variety of joining methods about the CTS of dissimilar-metal joints with aluminum alloy and high strength steel sheets (incl. 980MPa class)

Similarly to the results of tensile shear test, the fracture pattern of the EASW joint ruptured by cross-tensile test varied depending on the grade and thickness of the base metal. Photo 4 shows the typical fracture profiles of the joint ruptured in the cross-tensile test under the same joining conditions as those for the specimen shown in Photo 3. The CTS of this dissimilar-metal joint was 8.6kN. The fractured location was the interface between the steel sheet and the weld metal, similarly to the results of tensile shear test. The weld metal was detached from the steel sheet while maintaining its shape. This is schematically shown in Fig. 13.

When the aluminum alloy sheet was of a soft grade or thin in plate thickness, the fracture portion was not located in the steel sheet but appears as an empty hole caused by the plastic deformation around the pre-hole in the aluminum alloy sheet.

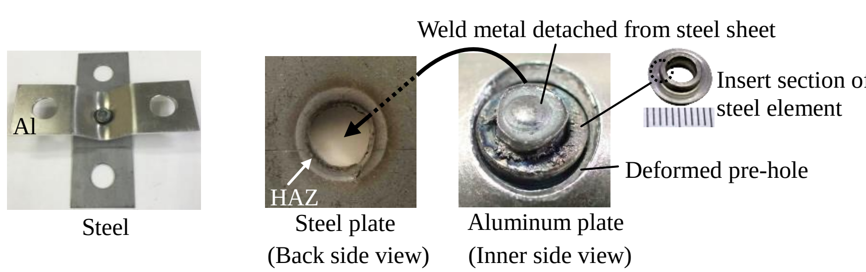


Photo 4: Typical fracture appearance of EASW joint in cross-tensile test

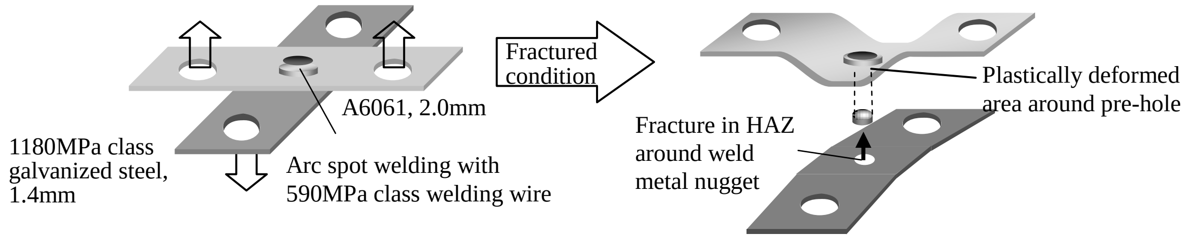


Fig. 13: Typical schematic fracture pattern of EASW joint in cross-tensile test

As discussed above, EASW is suitable for the dissimilar-metal joint of ultra-high strength steel and aluminum alloy sheets, demonstrating the high joint strength. On the other hand, its arc causes the higher heat input into the joint when compared to such mechanical joining methods as SPR, of course, and other welding processes that use the heat sources such as electrical resistance, friction, and laser. Taking this into account, the Vickers hardness distribution of the weld cross section was investigated in order to verify whether or not the weld and its perimeters were heat affected causing a metallurgical change. The investigation results are shown in Fig. 14. In this experiment, the combination of sheet metals used was the same as those shown in the previous Photos 3 and 4; i.e. the highly processable, 1180MPa-class ultra-high-strength galvannealed steel sheet with a thickness of 1.4 mm and A6061 aluminum alloy sheet with a thickness of 2.0 mm. The parameters affecting the heat input were as follows: electric current of 180A, arc voltage of 18V, and welding time of 1.5 seconds. As obvious in Fig. 14 (right), there were no hardness change at all in the upper sheet of aluminum alloy, and the hardness measurements suggest that the heat input caused no metallurgical change.

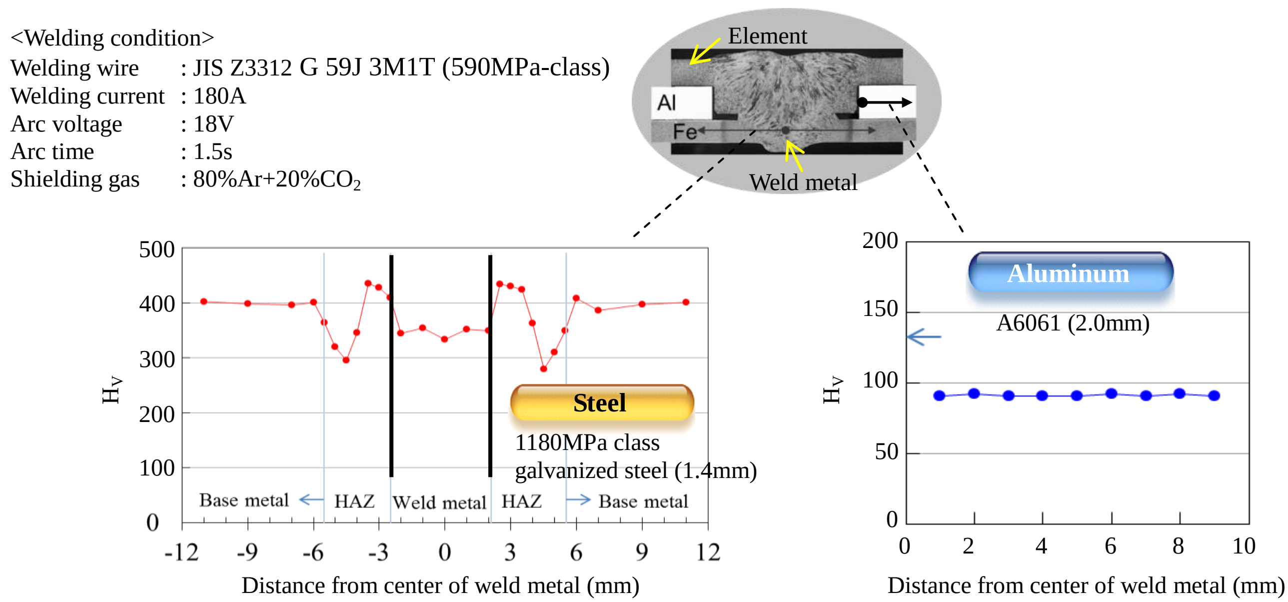


Fig. 14: Cross-sectional hardness distributions of ultra-high strength steel-to-aluminum alloy joint by EASW

The reasons why the arc welding, in spite of high-heat input, did not affect the metallurgical properties of the aluminum alloy sheet can probably be explained by the following two phenomena.

(a) The arc and the aluminum alloy was separated by the steel element, and thus the arc heat could not directly be conducted to the aluminum alloy sheet.

(b) Because the thermal conductivity of aluminum alloy is large, some quantity of the arc heat promptly diffused in the direction across the sheet width, and thus the temperature of the aluminum alloy sheet did not reach the temperature range that causes a structural change.

However, it should be confirmed in the future whether or not the arc heat changes the properties of other heat-treatable aluminum alloys and 7000-series aluminum alloys which are sensitive to natural aging.

With respect to the heat affection on the lower sheet of ultra-high strength steel, as obvious in Fig. 14 (left), the hardness in the heat-affected zone next to the weld metal slightly increased but not so high degree as compared to that of the non-heat-affected zone. The reason why the hardness of the heat-affected zone was not so high can probably be attributed to the cooling rate that was relatively small due to the high heat input in the arc welding. In the area that is 2-3 millimeters away from the interface between the weld metal and the base metal, the softened points are observed. Nevertheless, the softened part probably did not affect the joint strength because this part is different from the rupture locations in the tensile shear test and cross-tensile test.

The Vickers hardness of the weld metal exhibited around 350, which is not in the excessively high hardness region where the weld metal's structure necessarily becomes embrittled. This is owing to the appropriate chemistry design of the welding wire. Due to these preferable properties observed in the cross section of the joint, the high joint strength has presumably been established.

7. Applicable structures for EASW

As detailed above, EASW is capable of joining dissimilar metals of ultra-high strength steel and aluminum alloy, and its significant feature is the joint strength higher than that by other dissimilar-metal joining methods. In addition, its one-side accessibility makes this joining process suitable even for the structures that have no access or space for the C-type tool used in the SPR process. Photo 5 shows the work samples for EASW.

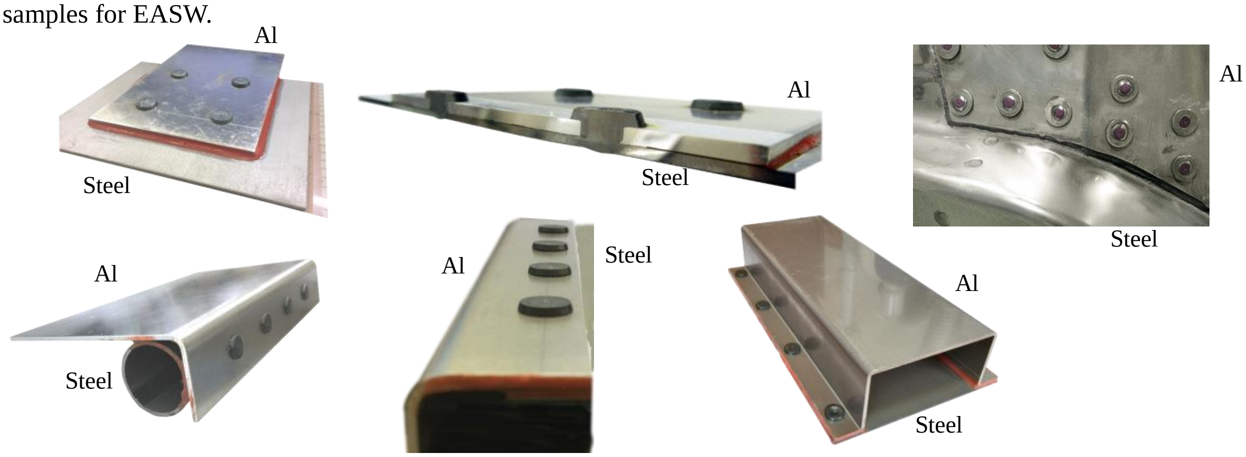


Photo 5: Work samples joined by EASW

This process can also be applied to the joining of a triple-layer structure joint of aluminum/steel/steel. An example of such specific application is shown in Photo 6. The pre-hole is needed only for the aluminum sheet on the top surface but not needed for the remaining two steel sheets. This is because the welding conditions can be adjusted for making the arc force strong enough to penetrate through the two steel sheets.

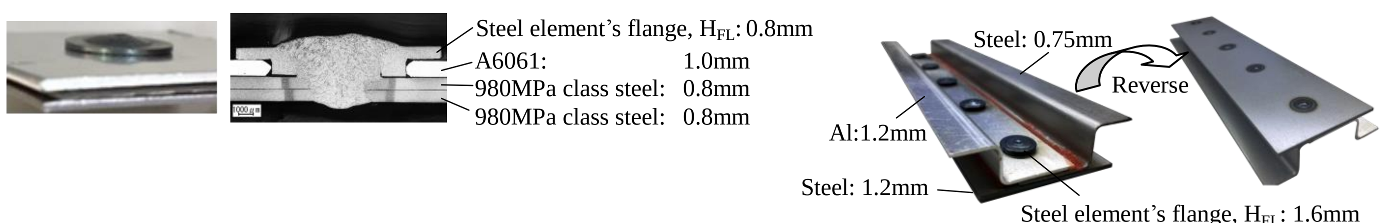


Photo 6: Example of triple-sheet dissimilar-metal joint made by EASW

8. Prevention of electrolytic corrosion by the combined use of adhesive and sealant for EASW

The important issues on dissimilar-metal joints include not only the securement of joint strength, but also the preventive measure against electrolytic corrosion. Electrolytic corrosion is the phenomenon that takes place, when aluminum alloy and steel, for instance, are kept in immediate contact with each other, by the electrochemical reaction between aluminum with less noble potential and steel with noble potential; as a result, the less noble metal will be corroded remarkably. The most effective measure to prevent electrolytic corrosion is to keep out the contacting area from a wet environment, the practical measures for which are the adhesive coating before joining and further the electrodeposition coating and sealing after joining for almost all dissimilar-metal joints — Fig. 15. Furthermore, the steel element itself is plated with less noble metal. These treatments are useful also for EASW. The adhesive coating is expected to be effective not only for the electrolytic corrosion prevention but also for increasing the strength and rigidity of the joint.

After coating a structural adhesive around the joining area on the faying surfaces of the metals to be joined, EASW can be applied for joining. The adhesive will vaporize if it is exposed to an arc heat of high temperature, but when the amount of the adhesive is little, there will be almost no problem. However, if the amount of the adhesive coating is so excessive that it clogs the pre-hole, it will vaporize in high volume instantaneously, and thereby the molten pool will be blown off, failing to form a sound joint. This is why, when the adhesive coating is required, its procedure and quantity should carefully be determined to prevent the adhesive from entering the pre-hole.

The study on the electrolytic corrosion for EASW is promoted by the authors but is not reported in this paper for lack of space.

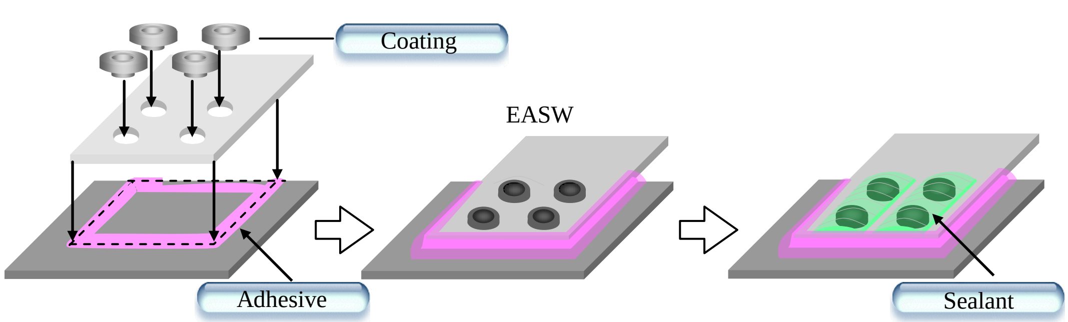


Fig. 15: Preventive measures against electrolytic corrosion for EASW

9. Research on automated EASW system

An automatic joining system with robot is indispensable for practical application of EASW in a car production line. In order to automate the concept of the EASW process shown in Fig. 2, it is most difficult to insert accurately the steel element with the insertion portion of almost the same diameter as that of the pre-hole prepared in the aluminum alloy sheet. For achieving this, the position detection of the pre-hole and the feeding mechanism of the steel element are necessary.

9-1 Position detection by image processing

The position of the pre-hole can vary according to the pressing accuracy and the alignment precision, thereby causing a deviation of about 2 mm in the X and Y directions; therefore, the feeding of steel elements must be adjusted to the deviation amount. Though the deviation can instantaneously be recognized visually by a human, it is impossible for the robotic system to identify it if no suitable sensor is installed. The well-known position sensors for the welding robots are as follows: (a) wire-touch sensor, (b) arc sensor, and (c) laser sensor, but it is problematic that (a) and (b) are not applicable for EASW, and (c) is very expensive. Therefore, the authors decided to employ the image processing method (vision sensor) with CCD camera for developing the automatic robot system for EASW. Specifically, before entering the joining step, the peripheries of all the joining points are scanned by a CCD camera to identify the difference in color between the pre-hole and the lower steel plate by image processing, and thereby the outline of the pre-hole is extracted — Fig. 16. The center position is calculated from the extracted contour and fed back to the teaching program as the deviation from the teaching point. With this technology, it is possible to correct automatically a positional deviation of 5 mm max., theoretically.

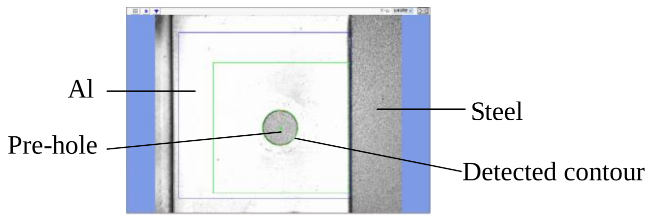


Fig. 16: Position detection by image processing

9-2 Arc welding robot system equipped with steel element feeder and CCD camera

Figure 17 and Photo 7 show the 3D design model of prototype and actual profiles of the EASW robot system equipped with the following units: (1) steel element feeder, (2) CCD camera and image processor, and (3) wire feed controlled welding power source.

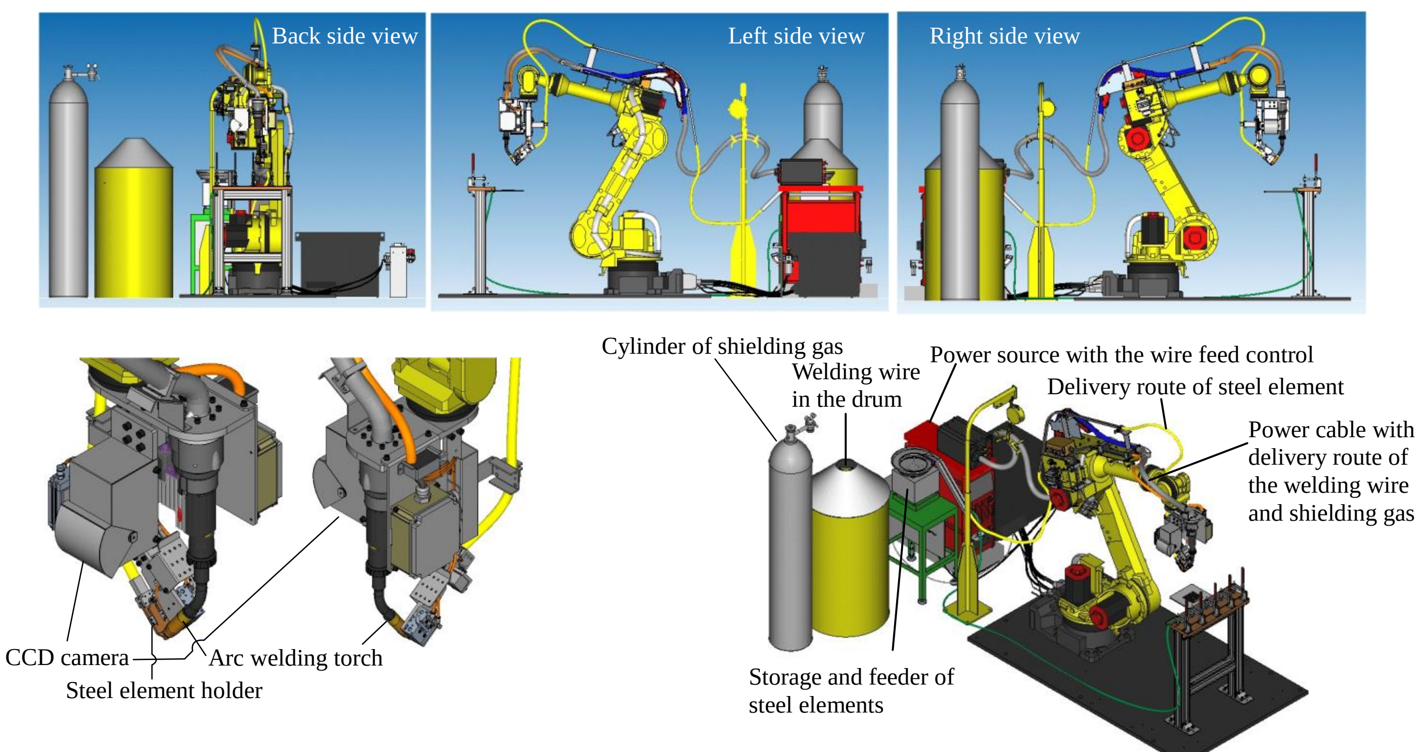


Fig. 17: CAD drawings of EASW robot system (prototype version)

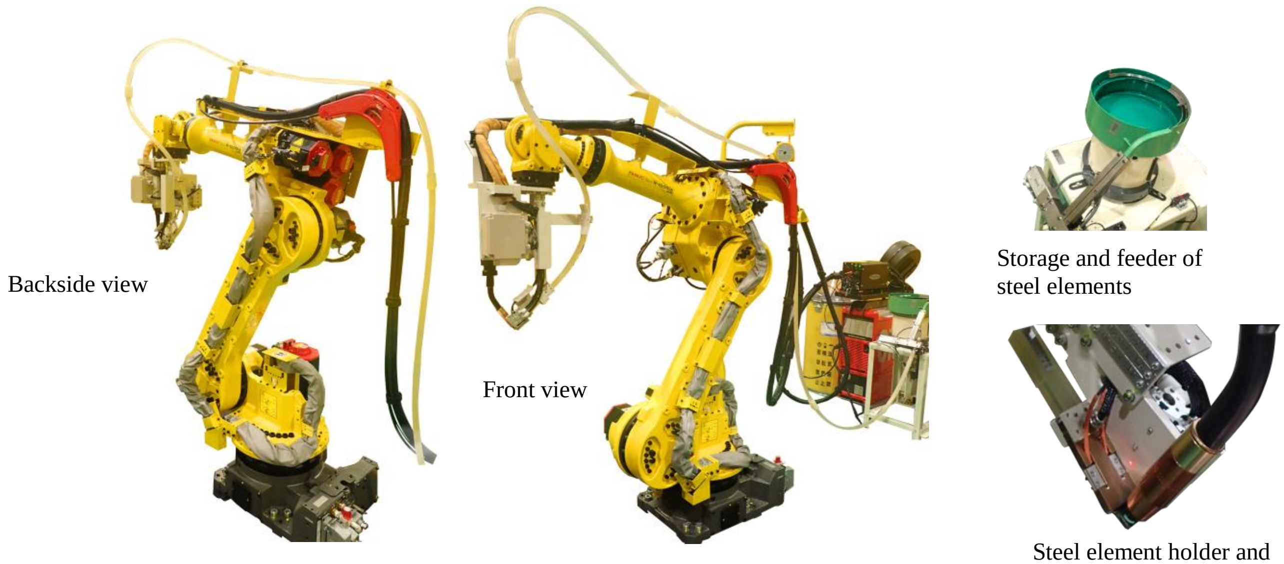


Photo 7: Actual profiles of EASW robot system (prototype version)

Photo 8 shows the process of inserting the steel element in the use of this prototype robot (arc is OFF). Photo 9 shows the consecutive processes of inserting the steel element and arc welding. Steel element's insert diameter D_{IN} was 6.9 mm, and the pre-hole diameter prepared in the aluminum alloy sheet was 7.1 mm. Hence, the difference of these diameters was only 0.2 mm. In spite of such a small difference, steel elements could accurately be inserted without tilt, and the subsequent arc welding process could also be performed without spatter to form satisfactory welds.

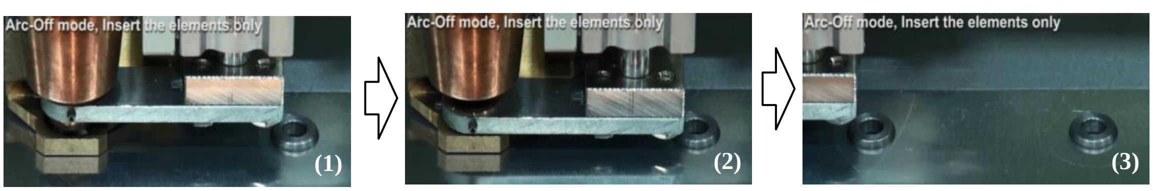


Photo 8: Automatic insertion of steel elements

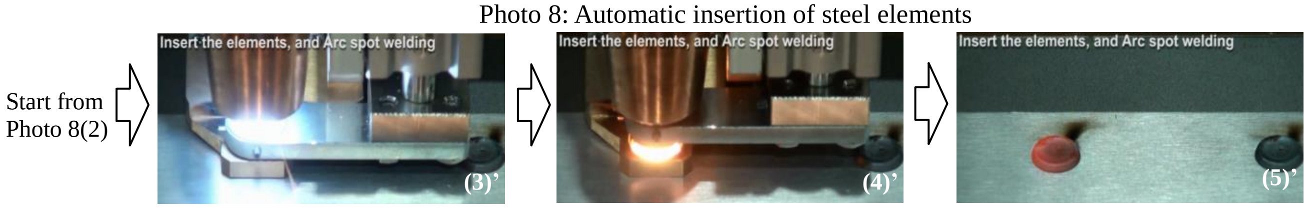


Photo 9: Automatic insertion of steel elements and consecutive arc welding of dissimilar-metal joint.

In the next, it was confirmed whether the function of detecting the pre-hole position by image processing works in the actual joining operation. Figure 18 is the design drawing of the pre-hole drilled test plate, which was prepared assuming that the pre-hole positions were deviated from the teaching points by 3 mm towards the plus or minus directions along the X and Y axes. As a result, it was confirmed that all the steel elements were accurately inserted and joined. Photo 10 shows the joint profiles with misaligned pre-holes.

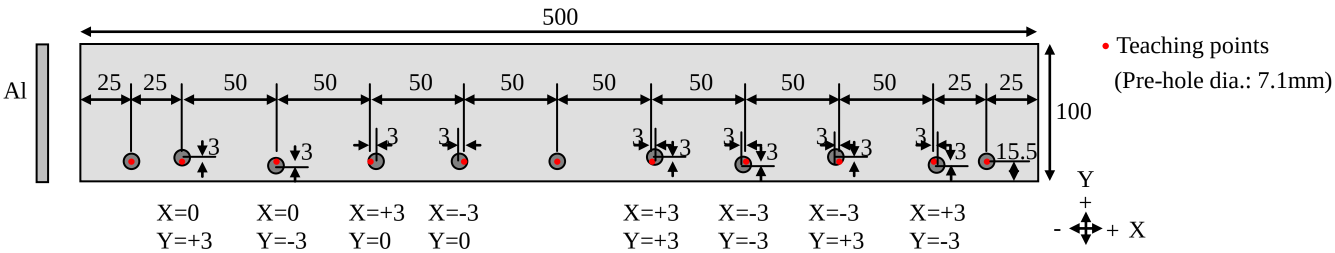


Fig. 18: Test plate design drawing with pre-holes deviated from teaching points

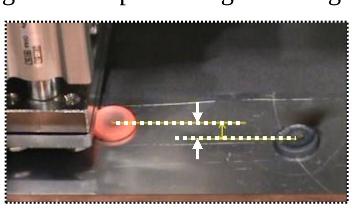


Photo 10: Examples of weld joints where pre-hole misalignment was automatically detected for position adjustment

The secondary function of this robot system enables this system to be applicable to ordinary arc spot welding of steel sheets by teaching it with the steel-element feed function set off. Hence, for manufacturing the parts that consist of aluminum alloy and steel, the alternative functions equipped in this robot system may make it needless to prepare separately a robot system for dissimilar metal joining and that for steel-to-steel joining.

10. Conclusions

The authors have developed the new dissimilar-metal joining method, the Element Arc Spot Welding (EASW) process, suitable for joining ultra-high strength steel and aluminum alloy sheets and the automatic welding robotic system for this process. The features of this system are summarized in the following.

1) The joining mechanism is one type of fastening, though the process includes arc welding.
2) Steel and other dissimilar metals can be joined, regardless of the strength of the steel sheet.
3) High-strength joint can be obtained. (for tensile shear strength and cross-tensile strength)
4) One-side accessibility enables the process to be suitable for a wide range of applications.
5) Optimal steel element's size and welding wire can be selected according to the characteristics and required strength of the base metals.
6) The automatic welding robot system is equipped with the image-processing function with CCD camera for detecting the pre-hole positions.
7) One set of the automatic welding robot system is equipped with the package of the following functions: the position sensor with the image-processing function, the feeding and inserting function for steel elements, the wire feed controlled welding power source, and the gas shielded arc welding function.

Since the newly developed EASW robot system is still a prototype version, there are many performances to be improved for practical applications, which include operation speed, structural compactness, and pressurizing function; the authors will improve them in the future.

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