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A Study on Dissimilar Welding of Aluminum Alloy and Advanced High Strength Steel by Spot Welding Process

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Recently, Car makers have required a light weight of vehicles in relation to fuel efficiency. In that respect, dissimilar welding method is very important in the car body assembly process. In this study, resistance spot welding was performed to evaluate the welding quality and mechanical properties for dissimilar materials of the cold rolled DP590 and Al 5052. The welding experiment was carried out changing with the welding current and the other process parameters such as electrode force, weld time, squeezing time and holding time were fixed with the basic welding condition of the ISO18278-2 standard. Especially, the shear tensile strength was evaluated at each condition and the cross-sectional observation for weld zone such as nugget diameter was performed. As a result, the thickness of IMC (Intermetallic Compound) layer at 11.5 kA was thinner than those of 9.5 kA and 10.5 kA conditions. On the other hand, Delta-spot welding experiment was performed using various process tapes at welding current of 11.5 kA. The other conditions were same with that of the conventional spot welding. Sound welds was formed by applying to the optimum welding conditions in the Delta-spot process due to the thermal balance of dissimilar materials.

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NOMENCLATURE

s = second as a unit of time
t = thickness of base material
Hv = unit of Vickers hardness

1. Introduction

Fuel efficiency is not an optional but an essential issue in the automotive industry. For this, weight reduction can improve the acceleration and braking of a vehicle, and a lightweight metal has been used as the material for the vehicle body.[1] A number of studies have been conducted on some lightweight metals, including aluminum, magnesium, plastics, and composite materials, particularly on their potential for replacing the conventional steels used for the vehicle body parts, and it is possible to reduce the vehicle body weight by 50% through the substitution of the conventional steels used for the body parts with the aluminum alloy.[2-4] The use of a high-strength steel sheet is also required to ensure the safety of the passengers, and can improve the vehicle's impact performance. As such, studies on the welded joints of the aluminum alloy and advanced high-strength steel (AHSS) sheets are underway.[5-7] The leading welding technology in the automotive industry is resistance spot welding, which was invented by Elihu Thomson in 1877.[8]

Resistance spot welding is suitable for application in automated welding and mass production because of its fast welding speed.[9,10] There is a problem, however, with the application of resistance spot welding to the aluminum alloy and high-strength steel: the remnants of the aluminum or zinc wear out the electrode tip during welding. This reduces the electrode life, and the dressing for the electrode replacement occasionally lowers the work efficiency in the industrial field. Also, aluminum alloy and high-strength steel sheets have different melting points, degrees of thermal expansion, and thermal characteristics. As such, dissimilar welding, which forms a brittle intermetallic compound (IMC), is generally not preferred.[11,12] IMC formation degrades the spot weldability in the aluminum alloy and high-strength steel, and the welding defects (cracks, porosity) cause an interfacial fracture.[13,14] The studies on IMC formation control in the dissimilar welding process, however, are still insufficient.

Table 1 Experimental spot welding conditions based on ISO 18278-2

Welding parameter	Inverter spot welding	Delta-spot welding
Force [kN]	4.5	4.5
Welding current [kA]	8.0 ~ 13	11.5
Weld time [cycle, 1 cycle = 0.02s]	21	21
Cool time [cycle, 1 cycle = 0.02s]	4	4
Squeeze time [cycle, 1 cycle = 0.02s]	40	40
Hold time [cycle, 1 cycle = 0.02s]	25	25
Process tape type	-	2000 & 3000 series
	-	2000 & 3200 series
	-	2110 & 3000 series
	-	2110 & 3200 series

In this study, the process tape was additionally used for the delta spot welding process to select an optimal welding condition of the different materials of the DP590/Al 5052 alloy, and to analyze the characteristics of IMC during welding. The weldability evaluation was carried out through weld nugget size measurement, tensile shear strength, and also SEM (Scanning Electron Microscope) observation and EDS (energy dispersive x-ray spectroscopy) analysis of the cross-section.

2. Experimental Procedure

For the multi-pulse welding conditions, those specified in ISO 18278-2 were used, as shown in Table 1. In general, the spot welding conditions for dissimilar materials are not specified, but in this case, a selection method is provided with the necessary information, including the thickness and surface treatment of the same steel. To reduce the use of trial and error, the initial experimental design was performed using this method. The squeeze time in the production line was 6-30 cycles, but to ensure greater stability, a longer time is needed. Thus, the initial squeeze time was set at 40 cycles.

The conventional inverter resistance welding process was first carried out to evaluate the characteristics of the dissimilar welded joint, and the welding conditions were set based on the ISO 18278-2 specifications.[15] The electrode tip was the dome radius type with an 8 mm diameter, and the material was the Cu-Cr alloy.

Meanwhile, delta spot welding, developed by Fronius Co. Ltd. in Austria, has an advantage: it can achieve sound weldability, which increases the contact resistance between the base metal and the electrode tip, allowing the insertion of process tape as an additive metal, as shown in Fig. 1.[15] The experiment that was performed in this study was carried out using the process tapes No. 3000 series of Cr-Ni alloy and No. 3200 series of Ni base alloy, among others, which were attached to the Al 5052 side. The No. 2000 and 2110 series, on the other hand, which were attached to the DP590 steel side, were Cu-based alloys containing at least 70% Cu.

The target materials were the Al 5052 alloy with excellent corrosion resistance, weldability, and workability, and DP steel, which is the most

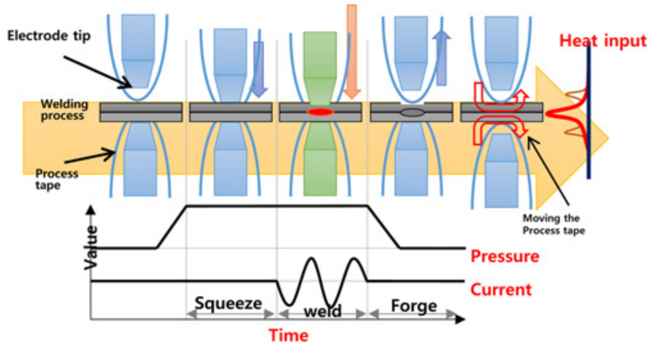

Fig. 1 Principle of delta spot welding process

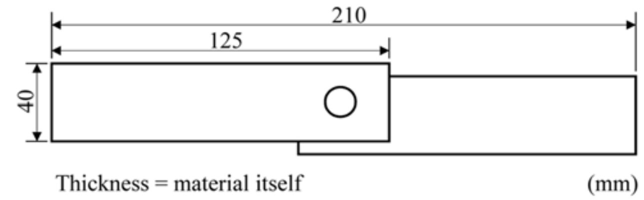

Fig. 2 Schematic drawing of the test specimen of spot welding (DP590 1.4 t, Al 5052 1.5 t)

frequently used material in AHSS.[16,17] The welded joint (DP590; 1.4 t, Al5052; 1.5 t) specimen was made based on ISO 14272, as shown in Fig. 2. Table 2 shows the chemical composition and mechanical properties of the base material.

3. Results and Discussions

3.1 Microstructural analysis of the IMC layer in the welded joints

3.1.1 Test results of inverter spot welding

As the welding current was 11.5 kA, a thin IMC layer was formed, as shown in Fig. 3, and the tensile shear strength (TSS) had a much higher value than the other variables. The weld zone was formed more widely at the higher current, and the indentation of the welds was generated deeply by the increase of the heat input according to the current rise.

In general, IMC formation increases with increasing heat input, but it was confirmed in this study that the IMC layer welded at the lower current of 10.5 kA was thicker than that welded at 11.5 kA. There is a big difference, however, between 9.5 and 11.5 kA. This seems irregular, and the thickness of the IMC layer was affected not only by the change in the heat input along with the current but also by the effects of the other variables, such as the heat conduction of the dissimilar weld interface, the solidification behavior, and the surface conditions of the materials. A further detailed study will be required to investigate this matter.

Fig. 4 is an image of measuring points in weld interface observed by SEM, and Fig. 5 shows their EDS result. Based on the atomic content ratios of Al and Fe, the three types of IMC were formed: (a) an Al matrix, (b) $FeAl_3$, (c) $FeAl_2$, (d) FeAl.

Table 2 Chemical composition and mechanical properties of DP590 and Al 5052 alloy

Chemical composition (wt%)							Mechanical properties		
Material	Fe	C	Mn	Si	Mg	Al	T.S (MPa)	Y.S (MPa)	El. (%)
DP590	97.36	0.14	2.1	0.40	-	-	600-700	330-410	28
Al5052	0.40	-	1.0	0.25	2.8	Bal.	190-200	90-100	27

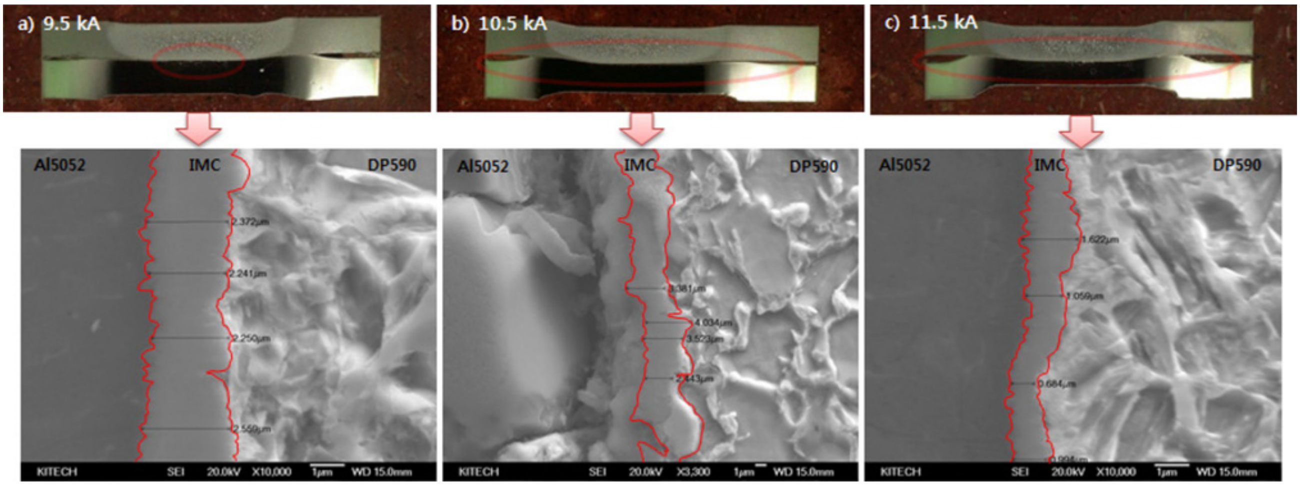

Fig. 3 Observation of SEM Images of IMC zone in the inverter spot welding and its thickness: (a) = 2.4 μm, (b) = 3.4 μm, (c) = 1.9 μm

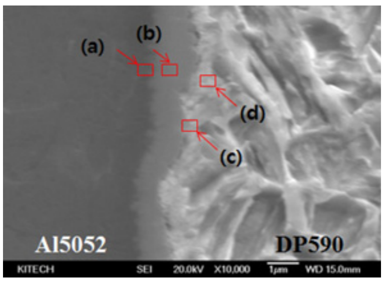

Fig. 4 EDS measuring points of the dissimilar weld zone

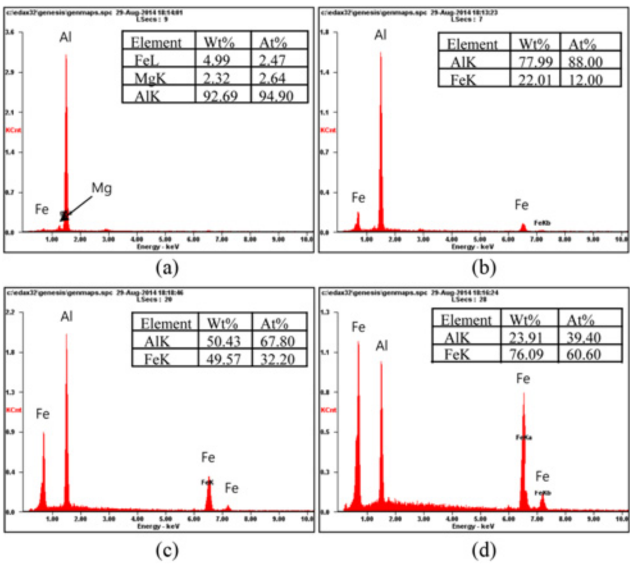

Fig. 5 EDS results of the dissimilar weld zone in Fig. 4

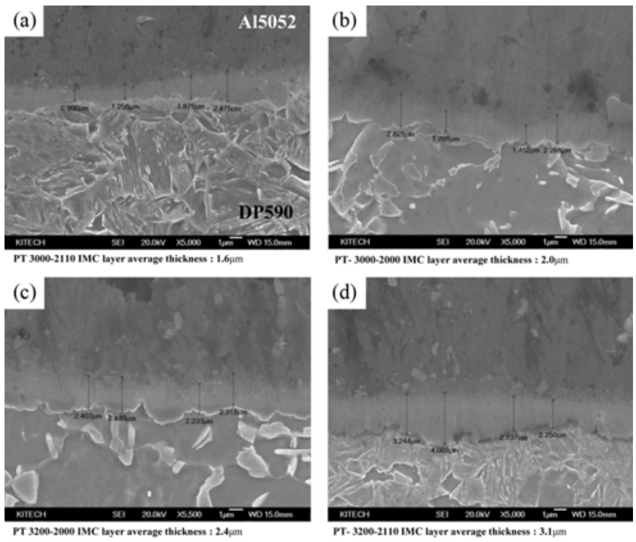

Fig. 6 Observation of SEM Images of IMC zone in the delta spot welding and its thickness: (a) No. 3000 & 2110 = 1.6 μm, (b) No. 3000 & 2000 = 2.0 μm, (c) No. 3200 & 2000 = 2.4 μm, (d) No. 3200 & 2110 = 3.1 μm

3.1.2 Test results of delta spot welding

Fig. 6 shows the SEM images of the weld zone applied through the delta spot welding process. The IMC layers of the No. 3000 & 2000, No. 3200 & 2000, and No. 3200 & 2110 series were formed as in the inverter spot welding. The IMC layer was thinner (1.6 mm) when the process tape was used compared to that in the inverter spot welding using the No. 3000 & 2110 series.

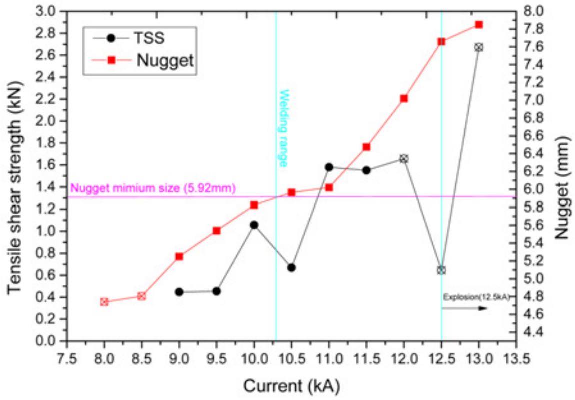

Fig. 7 Variations of tensile shear strength and nugget diameters according to welding current

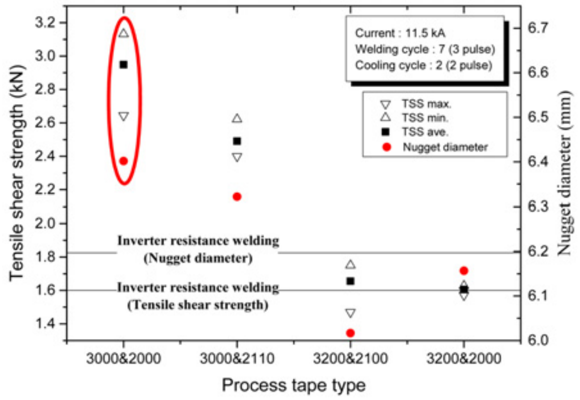

Fig. 9 Evaluation of welds strength and nugget diameter according to the various process tapes

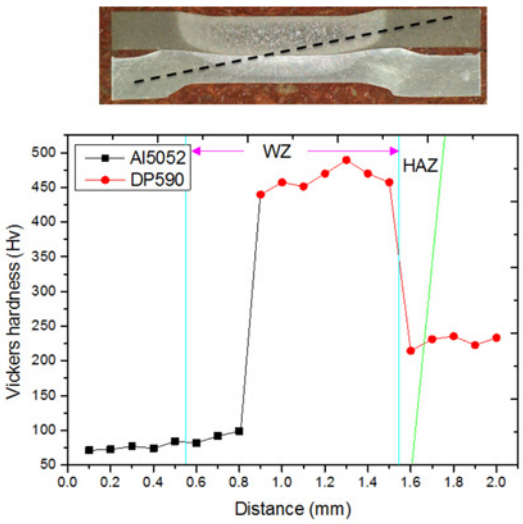

Fig. 8 Hardness distribution on welding zone of IRW in weld current 11.5 kA

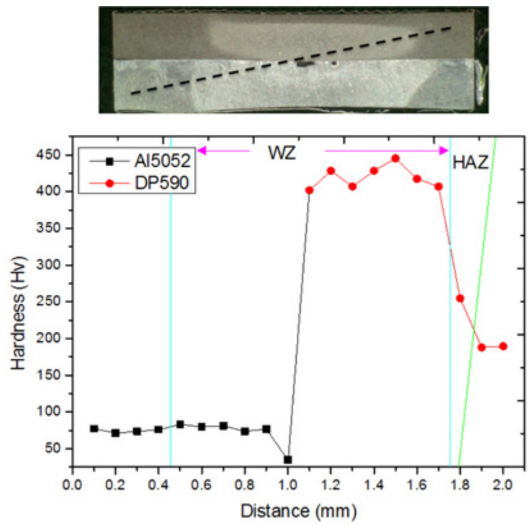

Fig. 10 Hardness distribution of test specimen using by No.3000 & 2000 at 11.5 kA

3.2 Selection of optimal welding condition and evaluation of mechanical characteristics

3.2.1 Test results of inverter spot welding

The results of the tensile shear test and the nugget diameter measurement are shown in Fig. 7. The minimum nugget diameter should ensure 4√t, but domestic carmakers occasionally require 5√t. Therefore, the optimal welding current range was determined from a minimum nugget diameter of 5.92 mm, which was substituted to the thickness of DP590 (t = 1.4 mm) until the expulsion current was reached in the experiment. Also, the experiment was carried out from the 8.0 kA current, as shown in Fig. 7. It was difficult to perform the tensile shear test, however, because the test specimens (8.0 kA, 8.5 kA) were of very poor quality due to the insufficient heat input. Generally, it is known that the nugget diameter increases with increasing welding current, and that the tensile shear strength also increases. The tensile shear strengths at 10.5 and 12.5 kA, however, indicated lower values. This could not be clearly explained, but it is considered that the values might have decreased because a large and flat-shaped IMC layer was formed at 10.5 kA, and that the decrease of the strength was caused by the expulsion at 12.5 kA due to the excess heat input. It can be said that the weldable range was 10.5-12.0 kA, but as a sound fracture occurred at 11.0 and 11.5 kA, it was considered that the optimal welding condition was 11.5 kA in this experiment. Moreover, it can be seen in Fig. 4 and 7 that the IMC layer for carrying out the high current during a short time was thinner.

The Vickers hardness was measured diagonally on the cross-section from Al 5052 to DP590, as shown in Fig. 8. Usually, the spot welds composed of similar materials are formed with an “O” shape. On the other hand, the dissimilar weld nugget is differently formed (U-shaped), like a wine cup.

The hardness of the weld zone (WZ) was about 470 Hv, but it showed a significant increase to 240 Hv compared to that of the DP590 base metal (about 230 Hv). This is because the temperature is raised up to above the A3 transformation point and is then rapidly lowered during solidification. Finally, the martensite structure is formed in the weld metal.

3.2.2 Test results of delta spot welding

Fig. 9 shows the delta spot welding test results. In the combination of the No. 3000 & 2000 and No. 3000 & 2110 series, it can be seen that the tensile shear strength and the nugget diameter have typically higher values in delta spot welding than in conventional resistance welding. The strength and the nugget diameter, however, were similar to the values in the inverter resistance welding or were lower in the case of the No. 3200 & 2110 and No. 3200 & 2000 series. It is important for the process tape to have a metallic property so that it could generate additional contact resistance with the components of each base material. Moreover, the additional heat input exhibited excellent weldability, better than in the conventional spot welding, thus improving the thermal electric characteristics. As can be seen in Fig. 9, the process tape combinations of the No. 3000 & 2000 and No. 3000 & 2110 series showed nugget diameter and tensile shear strength values higher than those of the combination of the No. 3200 series. The welding quality was superior to that in the conventional inverter spot welding, and the expulsion phenomenon was significantly reduced by the use of the process tape. The lesser expulsion improved the welding quality. Thus, it is possible to control the shape and thickness of the IMC layer, and to derive sound welding conditions for the process. It was determined to be most desirable to use the No. 3000 and 2000 series process tape to improve the welding efficiency.

4. Conclusions

For the dissimilar spot welding of the Al 5052 and DP590 materials, various experiments were performed using inverter and delta spot welding, respectively, and the welding quality and mechanical properties were evaluated. Below are the main results of the experiments.

1) According to the results of the weld lobe test of Al 5052/DP590, sound welded joints were made at 10.5-11.5 kA, but the expulsion current was 12.5 kA, which had excessive heat input in the inverter spot welding.

2) The formation of an IMC layer in dissimilar spot welding was easy to control at the boundary, and was more effective with the use of the delta spot welding process than with the use of inverter spot welding due to the good thermal balance of the former.

3) For the delta spot welding of Al/steel, the Fe/Al IMC layer that was formed was less than 2 mm thick, and the use of the proper process tape controlled its welding quality.

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