

Joint Properties of Dissimilar Al/Steel Sheets Formed by Magnetic Pulse Welding

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Abstract

In countries with major demand for automobiles such as the US, Japan, and China, the governments have steadily tightened fuel economy and greenhouse gases (GHG) regulations since 2015. To improve fuel efficiency and reduce emissions, light weighting is considered the most realistic and effective way that can counter the limitations associated with fuel efficiency technologies.

Production of existing steel bodies requires the use of traditional welding methods, such as resistance welding and arc welding. However, as the industry transitions to the use of non-ferrous material along with steel, a novel welding process must be developed. Additionally, as steel materials in use are continually getting thinner, it is important to develop improved sheet welding technology to obtain joints with high strength. In particular, aluminum requires a stronger bond welding technology than resistance welding. The purpose of this work was to study the joints between aluminum and steel using magnetic pulse welding and analyze the interface characteristics of electromagnetic bonding.

Key Words : Dissimilar welding, Multi-materials, Magnetic pulse welding, Plating steels

1. Introduction

In the United States, Japan, and China, which are countries with a high demand for automobiles, regulations on fuel efficiency and greenhouse gas emissions have been gradually reinforced since 2015. Weight reduction is the most realistic and effective method to improve fuel efficiency and reduce emissions. It is an important technology to address the weight increase due to the improvement of vehicular safety and convenience and to overcome the limitations of other fuel efficiency improvement technologies.

In relation to weight reduction, resistance welding and arc welding, which are traditional welding methods, have been mainly applied to the existing steel bodies, but it is necessary to develop processes as materials are changing to non-ferrous materials. As the strength of steel materials increases and their thickness decreases, it is important to secure a process for thin-plate welding

technology. In the case of aluminum (Al), in particular, a strong bonding technology that can replace resistance welding is required. The dissimilar welding of Al to steel, however, causes the degradation of the material properties of welded joints due to the generation of various intermetallic compounds.

Zhang et al.¹⁾ reported that GMAW welding between an Al alloy and STS caused cracks in the center of the weld due to the generation of $Al_{4.5}FeSi$ at the interface. Su et al.²⁾ reported that GMAW welding between Al5052 alloy and GA coated steel sheet led to a decrease in weld strength due to the generation of $FeAl_5$, $FeAl_3$, and Fe_3Al .

Lee et al.³⁾ also reported that laser welding between Al5052 alloy and steel plate cold commercial (SPCC) materials generated $Al_{13}Fe_4$, Al_5Fe_2 , Al_2Fe , $FeAl$, Fe_3Al , and Al_6Fe . Qiu et al.^{4,5)} reported that the dissimilar welding of Al5052 alloy to SPCC generated $FeAl_3$ and Fe_2Al_5 . As mentioned in previous studies, the generation of intermetallic compounds is inevitable in fusion welding.

Therefore, it is necessary to control the size and distribution of intermetallic compounds to achieve sound welded joints.

Meanwhile, various attempts have been made to inhibit the generation of intermetallic compounds during dissimilar welding, and solid-state bonding can be a candidate. In particular, magnetic pulse welding (MPW) that uses electromagnetic force is one of the processes that can inhibit the generation of intermetallic compounds because the materials do not melt. Aizawa et al.⁽⁶⁾ conducted research on the application of the MPW process to plate-shaped materials, and showed that welding between SPCC and Al materials is possible. Afterwards, various researchers^(7,8) have reported cases in which the MPW process was applied to various parts, including automotive parts.

Therefore, this study aimed to produce joints between Al and steel using MPW and to conduct research on electromagnetic bonding characteristics through the analysis of joint interface characteristics and strength evaluation.

2. Materials Used and Experimental Method

2.1 Materials used

As steel materials applied to automobiles are used in the coated state, a bonding experiment was performed on various coated steel sheets considering the actual situation. As for the Al material, A11050 material, which is a basic material, was used for MPW.

2.2 MPW

For MPW, the equipment fabricated in South Korea was used. As shown in Fig. 1, the equipment with eight capacitors capable of discharging the energy of up to 60 kJ was used. For plate bonding, a U-shaped coil was mounted and the specimen was fixed under the coil in the bonding experiment for plate bonding as shown in Fig. 1. In this instance, a one-coil system, in which bonding is performed by discharging the magnetic field generated around the coil by the current flowing in the U-shaped coil within tens of μ s, was used.

Table 1 Used materials in this study

| Materials | Thickness (mm) | Coating thickness (μ m) |
|--|----------------|------------------------------|
| Al 1050 sheet | 0.5 | - |
| Zn- coated steel sheet | 0.3 | 20 |
| Ni-coated steel sheet | 0.2 | 10 |
| Steel plate cold deep drawn extra (SPCE) | 0.5 | - |

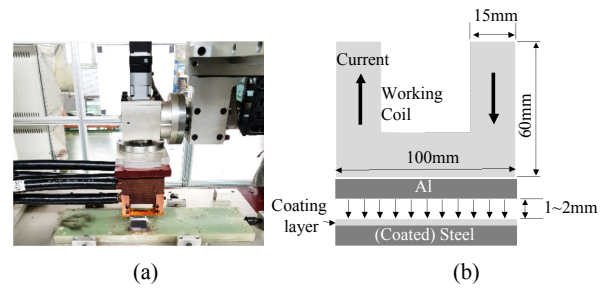


Fig. 1 Schematic arrangement of EMPW (a) Head for electromagnetic welding (b) Specimen arrangement

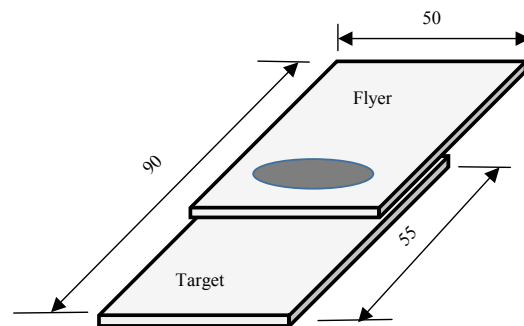


Fig. 2 Schematic arrangement of test specimen of the EMPW(Unit: mm)

For bonding, specimens with the shape shown in Fig. 2 were used. Bonding was performed using Al as a flyer material under the direct influence of electromagnetic pulse after the coated steel sheet was fixed under the flyer as a target material.

2.3 Structural analysis

To observe the interfacial characteristics and the generation of intermetallic compounds at welded joints, the joints were mechanically polished and etched using 3% Nital at room temperature for approximately ten seconds. As for the observation of microstructures, macroscopic structural changes were observed using an optical microscope. Microscopic structural changes and especially the generation of new structures at the joint interface were observed using a scanning electron microscope (SEM).

2.4 Strength evaluation

To evaluate the bonding strength between the A11050 material and the coated steel plate, the bonding specimen was subjected to a tensile shear test using a small tensile tester with a capacity of 5 kN. Due to the nature of MPW in which welded and non-welded joints coexist, the strength was evaluated based on the failure load.

3. Experiment Results and Discussion

3.1 Results of the MPW experiment

The heat input of the MPW process can be expressed as energy as shown below.

$$E = \{1/2 C \cdot V^2\} \cdot B \quad (1)$$

where E is the bonding energy (J), C is the capacitor capacity (uF), V is the applied voltage (V), and B is the number of the capacitors used.

Fig. 3 shows the measured waveform of the equipment used in the experiment during bonding. As shown in Fig. 3(a), when the applied voltage was 13 kV, the waveform was measured and the peak current was found to be approximately 480 kA. In this instance, the peak current discharge time was approximately 6.4 us, indicating that the energy was released instantaneously. Fig. 3(b) shows the peak current according to the applied voltage. The peak current increased from 355 to 650 kV as the applied current increased from 10 to 17 kV.

The MPW experiment was performed by varying the number of the capacitors used. The experiment was carried out using four and six capacitors. Bonding was not performed when four capacitors were used, but it was possible when six capacitors were used.

Fig. 4 shows the surface image of an incomplete MPW

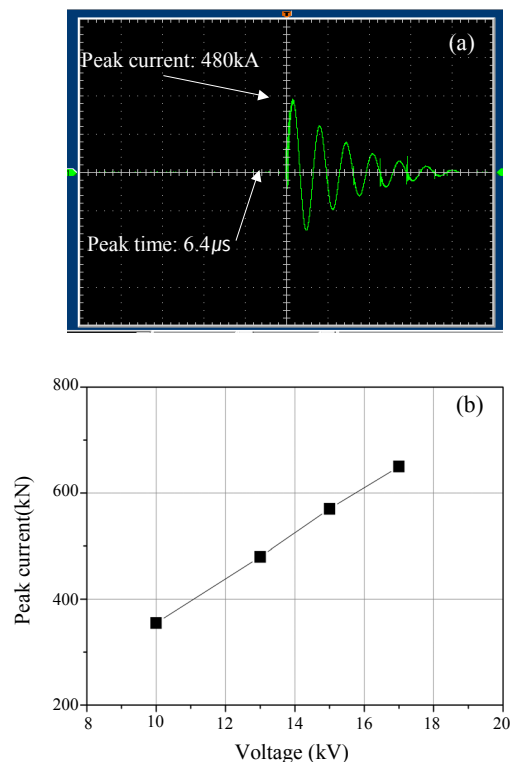


Fig. 3 Variation of peak current with the loaded voltage of EMPW welding machine

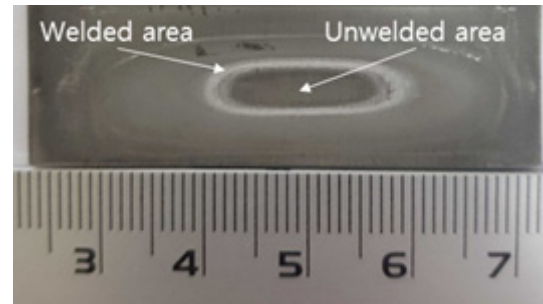


Fig. 4 Photograph of joint surface of EMPW weldment

joint, which provides information on the joint. As shown in the figure, the trace of bonding with the shape of an oval band was generated, but there was no trace of bonding inside. The trace of bonding depends on the size or geometry of the bonding coil that generates the electromagnetic pulse. In the experiment, the oval size was found to be approximately 20 mm based on the long axis. After all, it was found that bonding was performed in the white band-shaped area.

When the applied voltage was increased to more than 14 kV, normal bonding began to occur. Fig. 5 shows one of the results of the preliminary bonding experiment. When the heat input was approximately 34 kJ (applied voltage 13 kV), bonding was not performed and only an oval trace was left for both the zinc (Zn) coated steel sheet and the nickel (Ni) coated steel sheet.

Fig. 6 shows the images of the specimens when the

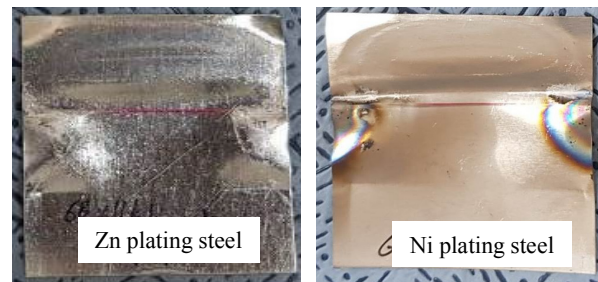


Fig. 5 Specimens after electromagnetic pulse welding process under 17kJ heat input

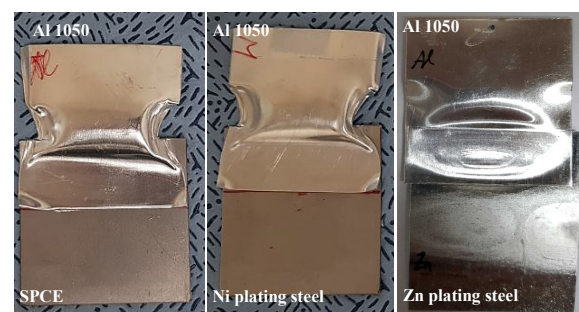


Fig. 6 Specimens after electromagnetic pulse welding process under 40kJ heat input

heat input was increased to approximately 40 kJ (applied voltage 14 kV). All of the cold-rolled steel sheet, Ni-coated steel sheet, and Zn-coated steel sheet exhibited excellent bonding.

As for bonding specimens, three specimens, i.e. Al1050-cold-rolled steel sheet (Al-Fe), Al1050-Ni-coated steel sheet (Al-Ni-Fe), and Al1050-Zn-coated steel sheet (Al-Zn-Fe), were fabricated. As bonding is performed while plasticity caused by electromagnetic force is applied to a specimen, some plastic deformation occurs in the entire specimen. In the case of MPW, however, a heat-affected zone does not occur in a specimen because heat is not applied. In Fig. 6, the deformation of the specimens is observed at the interface between the flyer and target materials. This appears to be related to the direction of electromagnetic force release, but the exact cause is under investigation.

3.2 Electromagnetic pulse joint structure

The MPW joint can be divided into the welded joint and non-welded joint in the center. The joint interface may also appear in a wavy or flat shape. It is known that the joint interface in a wavy shape is required for high strength^{1,2)}.

The reason that the interface in a wavy shape occurs at the MPW joint is explained by the Kelvin–Helmholtz instability mechanism. According to this theory, the interaction between fluids with different velocities causes instability due to mutual interference, and this instability includes the flow of mass from a high-density material to a low-density material. As shown in Fig. 7(a), whenever instability occurs, it has a specific direction and velocity (energy), which causes a flow from one material to the other. The material flow in the opposite direction occurs due to the reaction force of the material caused by the complementary energy of the system as shown in Fig. 7(b). This interaction causes a new wavy interface as shown in Fig. 7(c). Here, the flu-

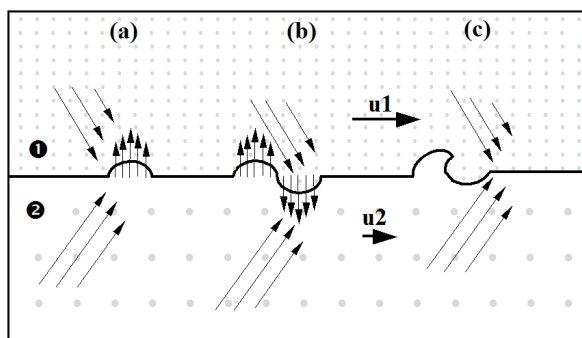


Fig. 7 Kelvin-Helmholtz instability mechanism (from left to right $u_1 > u_2$). (u_1 : flow velocity of material 1, u_2 : flow velocity of material 2)

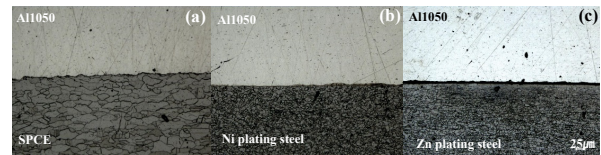


Fig. 8 Optical microstructure of EMPW weldments of various materials (a) Al/SPCC (b) Al/Ni plating steel (c) Al/Zn plating steel

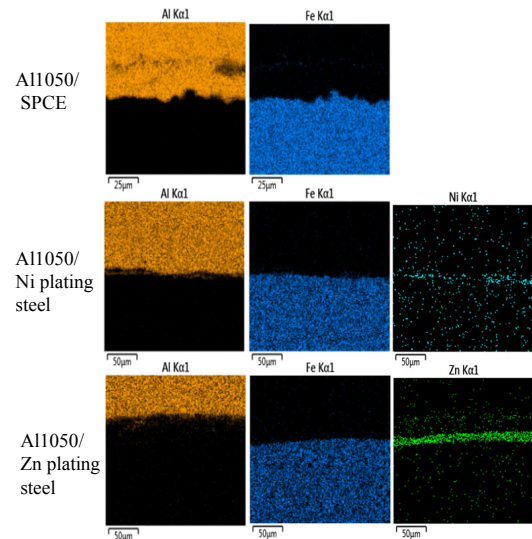


Fig. 9 EDAX analysis results of weldments of various materials

ids correspond to the welded metals¹²⁾.

Fig. 8 shows the microstructures of the specimens bonded in this study. The combination of Al1050 and a cold-rolled steel sheet exhibited a fine but wavy interface. In the other two combinations, i.e. the Al/Ni-coated steel sheet and Al/Zn-coated steel sheet combinations, however, no wavy interface was observed and only flat interfaces were observed.

Fig. 9 shows the EDAX analysis results of the MPW joints. The Ni and Zn layers were observed at the interfaces of the coated steel sheets. In the case of MPW joints, it is known that the oxide layer or the coating layer is peeled off due to the jetting phenomenon, but the coated layer remained without being peeled off in many cases in this experiment.

3.3 Electromagnetic pulse joint strength

Fig. 10 shows the tensile strength evaluation results of the MPW specimens fabricated with Al materials and various coated steel sheets. For all the specimens, no separation of the joint interface was observed and a rupture occurred in the Al1050 base metal.

It is known that the joint strength of MPW is higher at

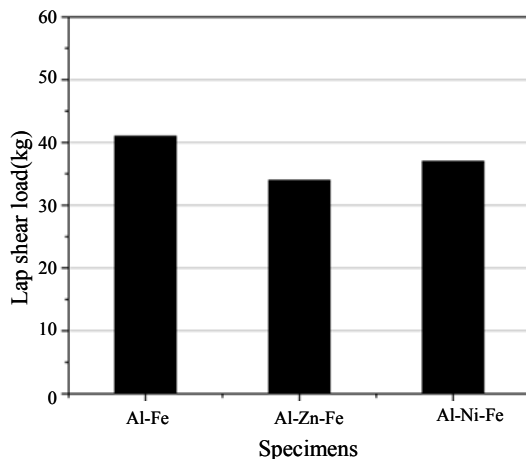


Fig. 10 Tensile test results of EMPW joint

a wavy interface than at a flat interface because it is affected by the shape of the joint interface. Under the experimental conditions of this study, however, both the fine wavy interface and flat interfaces exhibited no separation of the joint interface. Although it was expected that the joints between the coated steel sheets and the Al material would exhibit lower strength than the direct joint between Al and steel because the coated layers remained at the joints without being completely removed as shown in Fig. 8, but they exhibited a strength level high enough to cause a rupture in the Al1050 base metal. The differences in the tensile test results of the specimens appear to be caused by the difference in base metal rather than the difference in welded joint.

To improve the bonding strength of Al to coated steel by magnetic pulse welding should need higher electromagnetic force to eliminate the coated layer.

4. Conclusions

In this study, the characteristics of the dissimilar welding of aluminum (Al) to coated steel sheets were investigated using the magnetic pulse welding (MPW) process, and the following conclusions were drawn.

1) The electromagnetic energy required for the dissimilar welding of Al to coated steel plates was approximately 40 kJ. In this instance, the required voltage was 14 kV or higher.

2) When the joint interfaces were observed, the Al/steel combination exhibited a fine wavy interface, but the Al/nickel (Ni) coated steel plate and Al/zinc (Zn) coated steel plate combinations showed only flat joint interfaces.

3) The failure load of the joints between the Al1050 material and coated steel sheets produced through the MPW process was 34 kg or higher, and a rupture occurred in the Al1050 base metal.

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