# APPLICATION OF MAGNETIC PULSE WELDING FOR ALUMINIUM ALLOYS AND SPCC STEEL SHEET JOINTS

Tomokatsu Aizawa, Mehrdad Kashani and Keigo Okagawa

## ABSTRACT

The magnetic pulse welding (MPW) is a cold weld process of conductive metals to the similar or dissimilar material. MPW uses magnetic pressure to drive the primary metal against the target metal sweeping away surface contaminants while forcing intimate metal-to-metal contact, thereby producing a solid-state weld. In this paper the MPW method and its application for several aluminium alloy (A1050, A2017, A3004, A5182, A5052, A6016, and A7075) and steel (SPCC) sheets joint were investigated and the process parameters and welding characteristics are reported.

## KEYWORDS

Magnetic Pulse Welding, Seam welding, Dissimilar metal, Aluminium alloys, Steel

## AUTHOR DETAILS

Dr. Tomokatsu Aizawa is Professor of Tokyo Metropolitan College of Technology, Department of Electronic and Information Engineering, Shinagawa-Ku, Tokyo, Japan.

Dr. Mehrdad Kashani is Guest Researcher of Tokyo Metropolitan College of Technology, Department of Electronic and Information Engineering, Shinagawa-Ku, Tokyo, Japan.

Mr. Keigo Okagawa is Professor of Tokyo Metropolitan College of Technology, Department of Electrical Engineering, Shinagawa-Ku, Tokyo, Japan.

## 1 Introduction

One of the most difficult problems in the welding process is to weld dissimilar metals such as aluminium and steel together. Hybrid structures of aluminium alloy and steel are suggested for reducing the weight of automobiles to improve fuel efficiency and control air pollution. Therefore, joining steel and aluminium alloy in different shapes is receiving attention. However, steel and aluminium are not compatible metals as far as fusion welding is concerned. The reason for this is attributed to the large difference between their melting points (660 °C for *Al* and 1497 °C for Steel), the nearly zero solid solubility of iron in aluminium, and the formation of brittle intermetallic compounds such as $Fe_2Al_5$ and $FeAl_3$. Further, differences in their thermal properties like expansion coefficients, conductivities, and specific heats lead to internal stresses after fusion welding. Therefore, fusion welds of steel and aluminium suffer from heavy cracking with brittle failure in service. The material properties of aluminium and steel were summarized in Table 1.

**Table 1 — Aluminium and Steel Properties**

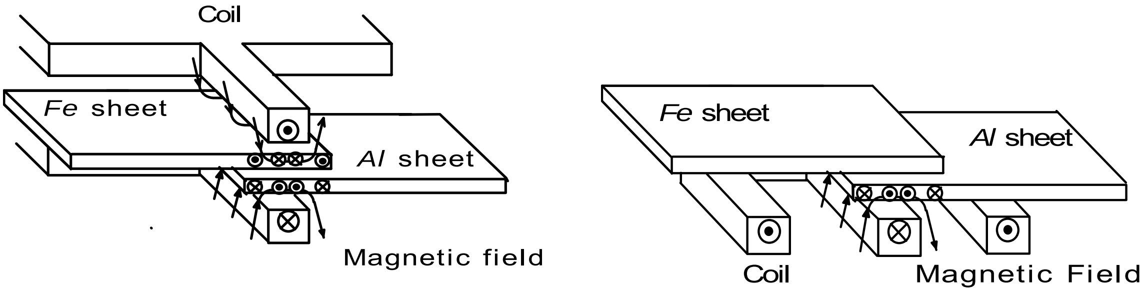
| | Melting Point °C | Specific Heat J/Kg.°C | Density Kg/m$^3$ | Thermal Conductivity J/m$^3$.°C.s | Electrical Resistivity μΩ.cm |
|---|---|---|---|---|---|
| **Aluminium** | 660 | 900 | 2700 | 220 | 2.65 |
| **Steel** | 1497 | 460 | 7870 | 73 | 13.30 |
| ***Al*/Steel Ratio** | 0.44 | 1.96 | 0.34 | 0.33 | 0.20 |

The magnetic pulse welding (MPW) provides an excellent tool for achieving aluminium alloy and Steel sheet joint. The magnetic pulse welding is solid-state joining process of conductive metals. The welding process is a heat-free which can eliminate localized annealing. This paper describes MPW formation in the dissimilar joining of aluminium alloy (A1050, A2017, A3004, A5182, A5052, A6016 and A7075) and Steel Plate Cold rolled Commercial grade (SPCC).

A typical MPW system includes a power supply, which contains a bank of capacitors, a high-speed switching system and a coil. The parts to be joined are inserted into the coil, the capacitor bank is charged and the high-speed switch is activated. When current is applied to the coil, a high-density magnetic flux is created around the coil, and as a result an eddy current is created in the parts. The eddy currents oppose the magnetic field in the coil and a repulsive force is created. This force can drive the materials together at an extremely high rate of speed and creates an explosive or impact type of weld. For more conductive metals such as aluminium and copper, the less energy is required to achieve a weld. The conventional MPW method with solenoidal coil is used for joining tubular parts and its features are almost well known [1-3]. However, a few papers on MPW of sheet work-piece have been reported.

In our previous paper we proposed a new one-turn flat coil instead of the solenoidal coil. This coil consisted of upper and lower H-shape plates which we call that the double layer H-shaped coil. The overlapped sheet work pieces were inserted between these two H-shape plates. When the high current flows through the coil, that can create the magnetic field to the both side of the overlapped sheet work pieces and as a result the sheet metals were welded in the seam state. The magnetic flux produced by this type of coil is shown in Figure 1(a). In this method, eddy currents which flowing in both sheets are considerably different, when dissimilar sheets metals like *Al/Steel* sheets are welded. And also the thickness of the work-pieces was limited by the space between two H-shape plates. Therefore, for more application some contrivance or improvement was needed. These experimental results and welding characteristics for several samples such as *Al-Al* [4], *Al-Cu* [5], *Al-Mg*, *Al-Ti* and *Al-Fe* [6] were reported in our previous papers.

In our present experiment, a new coil was designed to improve the welding characteristics of *Al* alloy and SPCC-Steel sheet joint. This new coil is one layer E-shaped flat coil that the overlapped sheet work pieces were put on the one side of the coil (Figure 1(b)). This type of the coil can be designed for application ranging from short and small to the large and long work-piece and also T-shaped joint with higher weld quality.



**(a)** **(b)**

**Figure 1 — MPW coil structure: a) Double layer H-shaped flat coil and b) One layer E-shaped flat coil**

## 2 Experimental Procedures

### 2.1 MPW Principle

The principle of the magnetic pulse welding method was shown in Figure 2 for one *Al/Fe* sheets sample. When a high current is applied to coil, a high magnetic flux density ***B*** is suddenly generated and penetrated into *Al/Fe* sheets, then the eddy currents (current density ***i***) pass through them to hinder its further penetration. As a result, an electromagnetic force of ***i* ×*B*** acts mainly on the *Al* sheet and the *Al* sheet is accelerated away from the coil and collides rapidly with the steel sheet. At the moment of collision the colliding surfaces can be cleared by a large kinetic energy getting before the collision. After the collision, the cleared surfaces are being pressed together by electromagnetic force and a fixture.

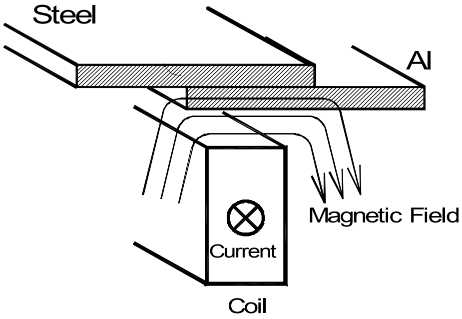


**Figure 2 — Principle of the MPW for welding of *Al/Steel* sheets sample (cross section view)**

The eddy current ***i*** and the magnetic pressure ***p*** are given as following:

$$\nabla \times i = -\kappa \left( \frac{\partial B}{\partial t} \right) \quad (1)$$

$$p = (B_o^{\,2} - B_i^{2}) / 2\mu = \left( \frac{B_o^{\,2}}{2\mu} \right) \left( 1 - e^{-2\tau/\delta} \right) \qquad \text{and} \qquad \delta = \sqrt{2/\omega\kappa\mu} \quad (2)$$

Where $\kappa, \mu$ , $\tau$ , $B_o$ and $B_i$ are the electrical conductivity, magnetic permeability, thickness, the magnetic flux density at lower and upper surfaces of *Al* sheet, respectively.

The depth of skin effect can be obtained by $\delta = \sqrt{2/\omega\kappa\mu}$ , where $\omega$ is the angular frequency of changing field.

When the eddy current is flowing, *Al* sheet is pressed to the *Fe* sheet by magnetic pressure and are heated by Joule heat $i^2/\kappa$ . As is evident from equation (1), for the materials with higher electrical conductivity $\kappa$ , more eddy currents create at surface and as a result, stronger magnetic pressure *p* and a large amount of Joule heat are generated. In addition, magnetic pressure will increase according to equation (2) because the depth of skin effect decreases by increasing of the electrical conductivity. Consequently this method is applicable to welding metal sheets with higher electrical conductivity such as aluminium and copper to dissimilar sheet metal. As eddy current pass through the sheets very fast with a short duration of about 50µs, there is negligible heating of the metal. Therefore, in this welding method materials will not be suffered from bad influences of heat that resulted from the conventional spot or fusion welding method.

## 2.2 Experimental Apparatus

Figures 3 shows the general outlines of the magnetic pulse welding apparatus which is consisted of a capacitor bank (*C*) and a spark gap switch (*G*) with a one layer E-shaped flat coil. These parts form a low-impedance discharge circuit that can generate a high-density magnetic flux around the coil area.

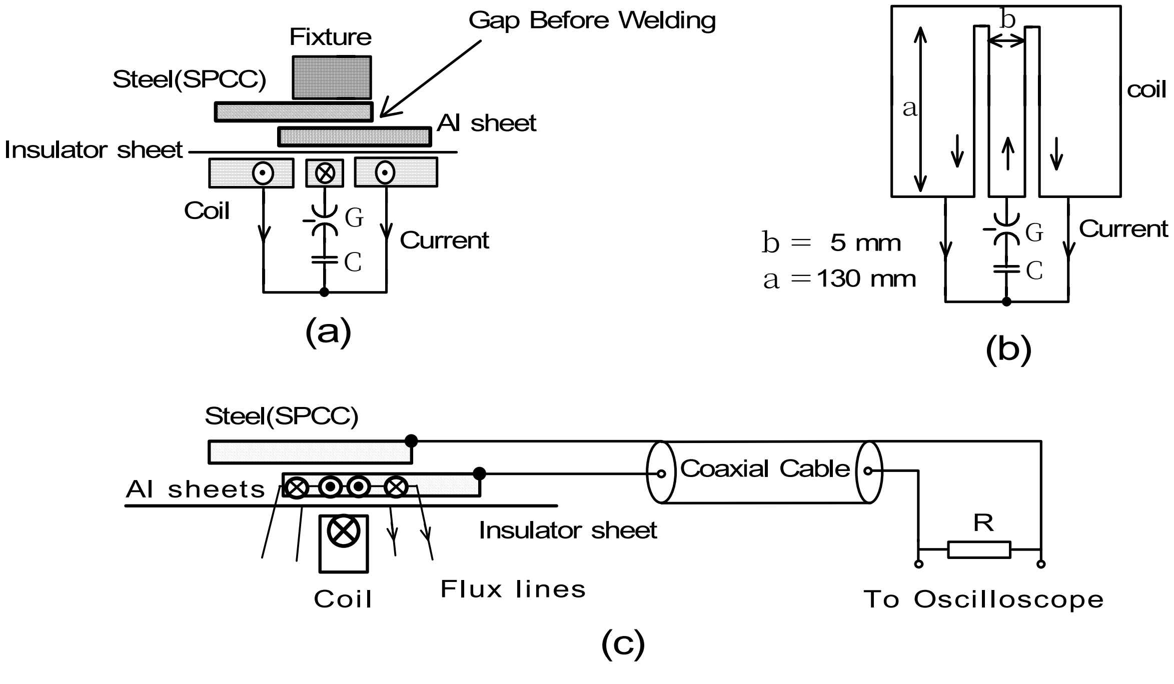


**Figure 3 — General outlines of apparatus: (a) cross-section view of the coil containing lap of *Al*/Steel (SPCC) sheets and discharge circuit (b) plan view of coil with discharge circuit (c) collision speed measurement. C: The Capacitor bank and G: Gap switch**

The capacitor bank that drives the discharge system of MPW device consists of two capacitor of 100µF/10kV in parallel. The inductance of the bank capacitor is 0.02 µH and it is connected to the gap-switch and one-turn coil by a low inductance transmission line. The circuit is designed to keep the inductance as low as possible to carry-out a fast welding. The flat E-shaped one-turn coil was made by Cr-Cu alloy. The coil thickness is 2mm and the inductance of the coil is 0.04µH. The block diagram of the discharge system is shown in

Figure 4. When the gap switch is closed, an impulse discharge current from the capacitor bank (C) passes through the coil and the MPW process is started.

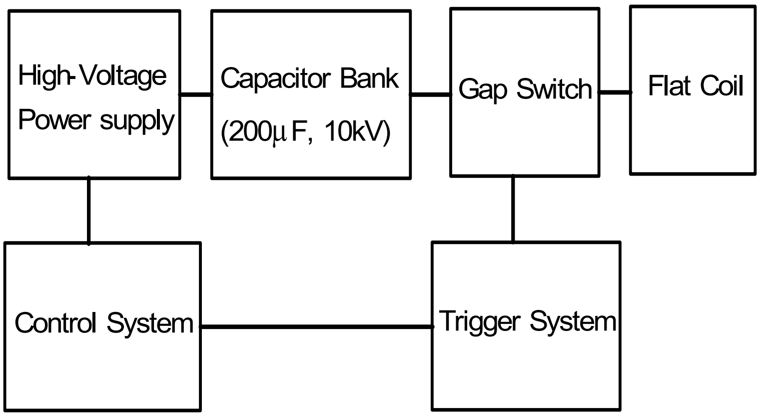


**Figure 4 — The block diagram of the discharge system**

Aluminium alloy (A1050, A2017, A3004, A5182, A5052, A6016, and A7075) and Steel (SPCC) sheets were prepared to carry out the weld testing. The characteristics parameter of the aluminium alloy and SPCC steel, which are used in our experiment are shown in Table 2.

**Table 2 — The Aluminium Alloy and SPCC Steel Characteristics**

| Sample Specification | A1050 | A2017 | A3004 | A5182 | A5052 | A6016 | A7075 | SPCC |
|---|---|---|---|---|---|---|---|---|
| Conductivity [IACS%] | 61 | 49 | 41 | 33 | 35 | 53 | 45 | 13 |
| Tensile strength [MPa] | 165 | 187 | 255 | 360 | 290 | 212 | 292 | 350 |

The size of all samples was 100 mm long, 100 mm wide with thickness of 1.0mm. The contact surface between two samples were polished and cleaned-up by abrasives and methanol. The insulating sheets with 0.1mm and 1mm thick are loaded between the coil surface and the overlapped ends of the work-pieces sheet. It should be notice here that the more conductive metal works as a base metal (*Al* sheet is the base metal in our experiment) and the main eddy current appears in base metal. The coil is clamped with the fixture during the welding operation. After welding the welded sample was divided to 10 pieces for tensile shearing strength test, optical-micrograph and SEM image observation (Figure 5).

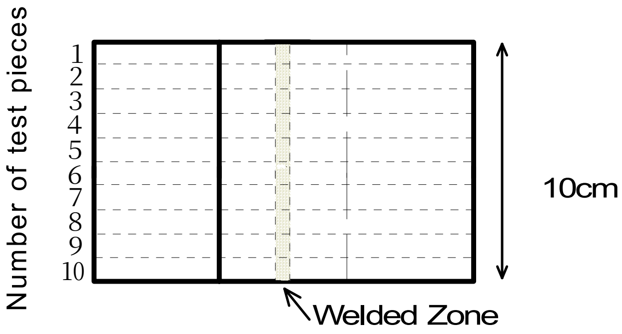
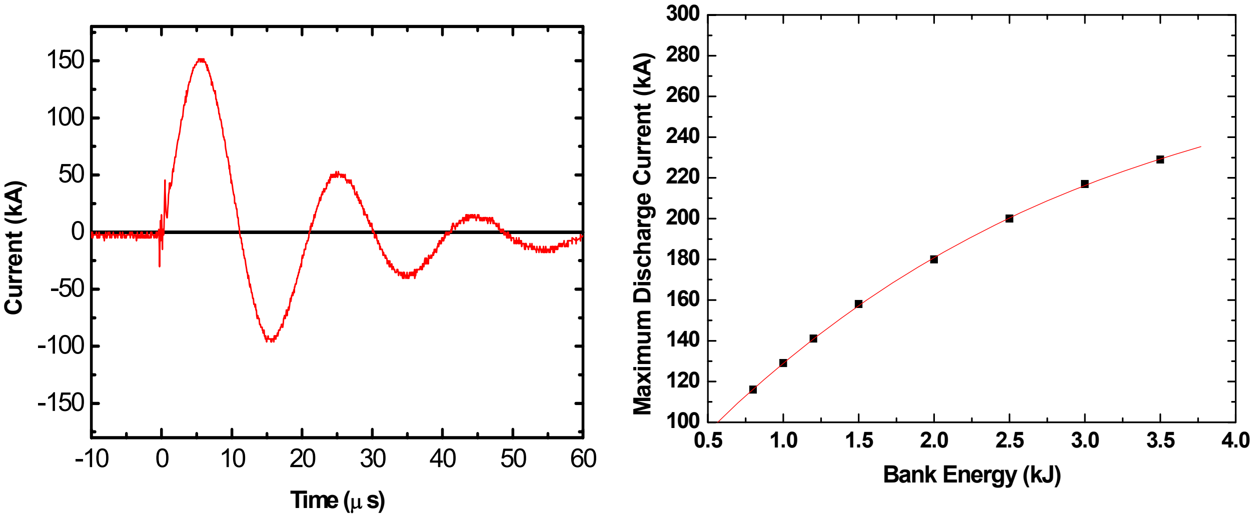


**Figure 5 — Divided region of the welded sample for shearing tensile test, optical micrograph and SEM image observation.**

## 3 Experimental Results and Discussion

### 3.1 Discharge Current and Flux Density

A typical current waveform is shown in Figure 6(a). This current signal was obtained at 1.4 kJ discharge (200μF/3.8kV) by using a magnetic probe. The current signal shows that a damping and oscillating current flows through a one-turn coil for the duration of about 50μs and the oscillating period is about 22μs. The maximum current was measured about 150kA at 1.4kJ bank energy discharge. The relation between the bank energy and discharge current in our system is shown in Figure 6(b).



**(a)** **(b)**

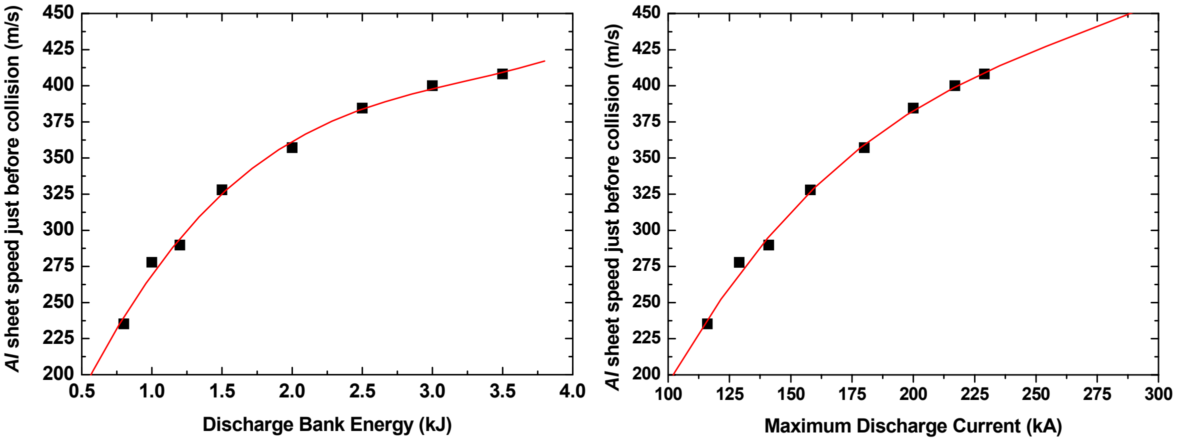
**Figure 6 — (a) Typical current signal at 1.4 kJ discharge (200μF/3.8kV) and (b) Bank energy vs. maximum discharge current.**

If the discharge current flows uniformly on the surfaces of the middle portions of the coil, then the depth of skin effect ( $\delta = \sqrt{2/\omega\kappa\mu}$ ) was calculated 0.38 mm for *Al* sheet and under this condition, the maximum magnetic flux density is estimated about 20T, while the maximum magnetic pressure is calculated about 150 MPa from equation (2).

### 3.2 Collision Speed Measurement

In order to measure the collision speed of the aluminium sheet just before welding, very simple circuit is prepared to measure the time travelling of the base metal in gap distance which is exist between two work pieces before welding. The circuit is consists of a coaxial cable and matching resistance (Figure 3(c)) [7].

When the impulse discharge current passes through the coil, a voltage is induced on the two work pieces by magnetic coupling between the coil and these work pieces. Just after the collision, the voltage appears at input terminals of the measuring circuit and that voltage signal can be detected by a digital oscilloscope. If we assume that the sheet movement is like a uniform acceleration motion, the collision speed just before welding can be estimated by using the time travelling and gap distance. The collision speed has a relation with the bank energy and the discharge current and the maximum collision speed can be obtained at the first maximum in the current signal. Therefore, by the fixing the appropriate gap distance between sample sheets the collision time can be nearly same as quarter period of the current signal. Figure 7 is shown the Al sheet speed just before collision vs. the maximum current and bank energy. After collision the temperature increases at the interface layer and the molten surface is produced during welding. This heat comes from several sources, such as the shock wave associated with impact and the energy expended in collision. Heat is also released by plastic deformation associated with jetting and ripples formation at the interface between the parts being welded.



**(a)** **(b)**

**Figure 7 — *Al* sheet speed just before collision vs. (a) Discharge Bank Energy and (b) Maximum Discharge Current**

### 3.3 Microstructure of Joined Interface

The width of the weld zone was nearly equal to the middle part of the coil (b=5 mm). The welded sheets were divided into ten test pieces with 10 mm wide as shown in Figure 5, and one longitudinal side of the division No.5 was polished for observing the joined interface. Several welded combination of Axxxx/Axxxx and Axxxx/SPCC-Steel were tested. For the similar work-pieces the joined interface was not so clear. However, in aluminium alloy and SPCC-Steel combination after etching and polishing, the interface layer were clearly seen against the base metals. Typical macrostructure of joined interface zone for A1050/A1050 and A1050/SPCC are shown in Figure 8. As a result of magnetic pulse welding a non-uniform wavy interface is visible for all welded samples. The wavy interfaces zone were formed with amplitudes as high as 20μm and width of 100μm. Figure 9 also shows the macrostructure of joined interface zone for A6016/SPCC combination.

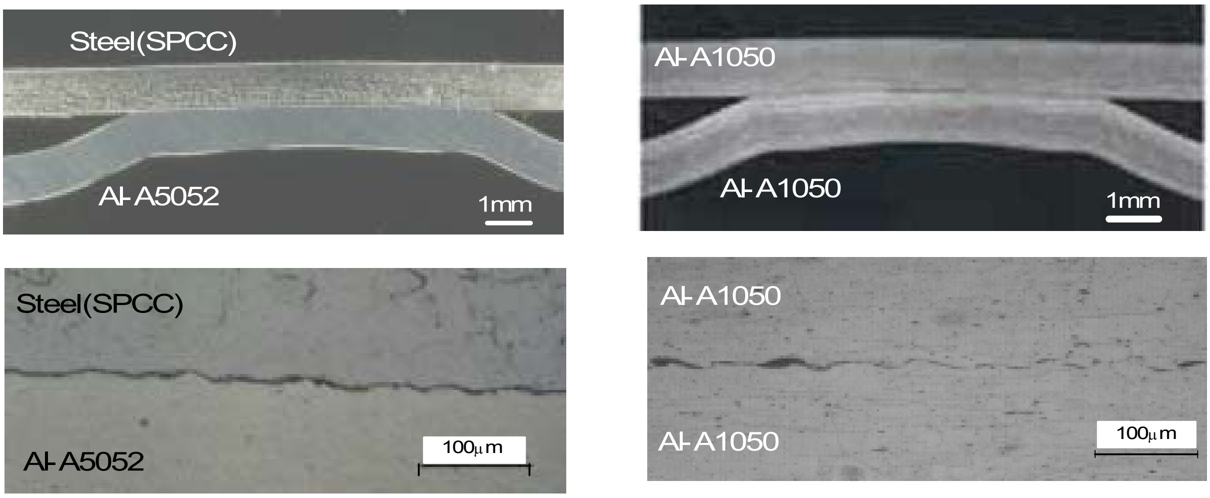
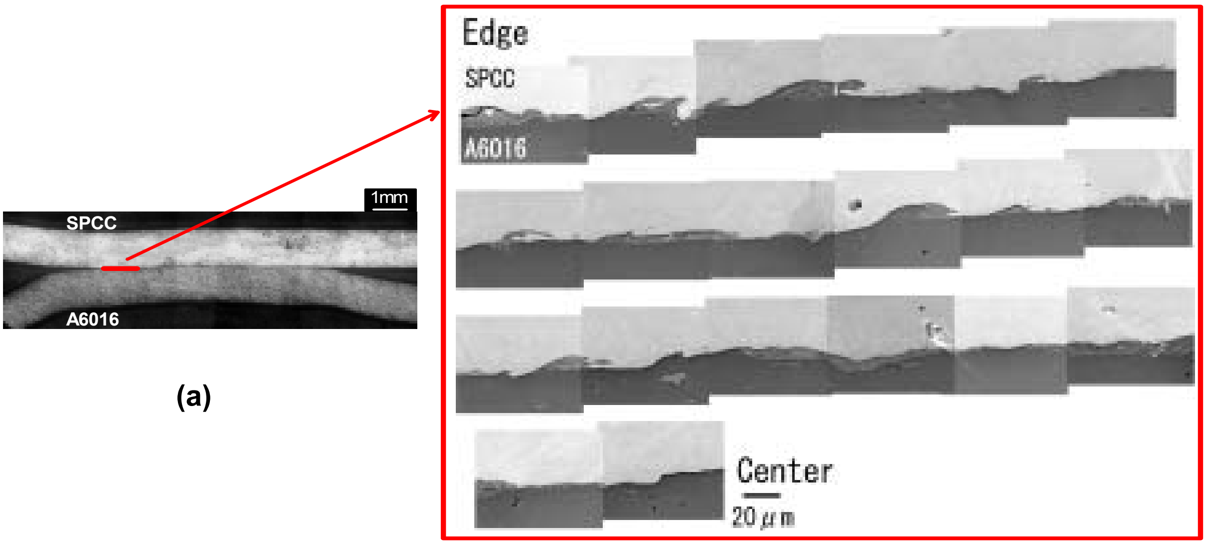


**Figure 8 — Typical macrostructure of joined interface zone for A1050/A1050 and A5052/SPCC**



(a)

(b)

**Figure 9 — (a) Cross-section image of welded sample (the — zone is the observation area by SEM) (b) SEM image of joined interface for A6016/SPCC sample.**

The SEM image of A6016/SPCC also shows that the wavy morphology bond interface was formed in interface layer without any significant heat-affected zone (HAZ).

## 3.4 Tensile Shear Test

Welded samples were investigated on a standard tensile shear testing machine at test rate of 10mm/min. tensile shear test were made for each ten divided pieces to determine the maximum shearing tensile strength. The test results for *Al*/SPCC and Aluminium alloy combination are shown in Figure 10, where a mark (○) indicates the rupture of the non-welded area and (●) a rupture of the welded area. Based on the shearing strength test results, the tensile shear of divisions No. 1 and No. 10 were less than the others. However in other division the failures always occurred in the weaker metal and out-side of welded area.

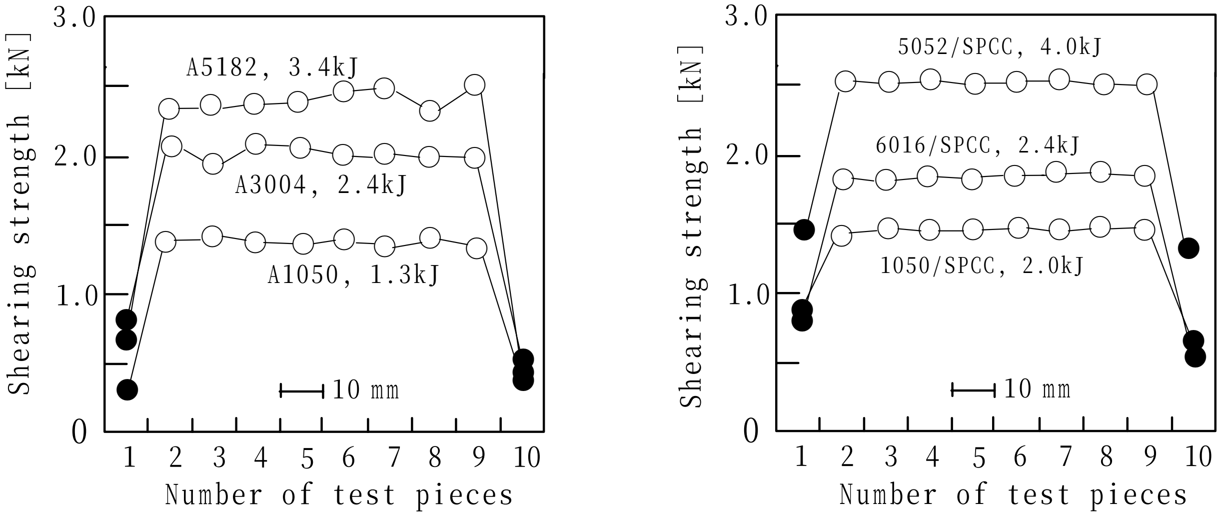
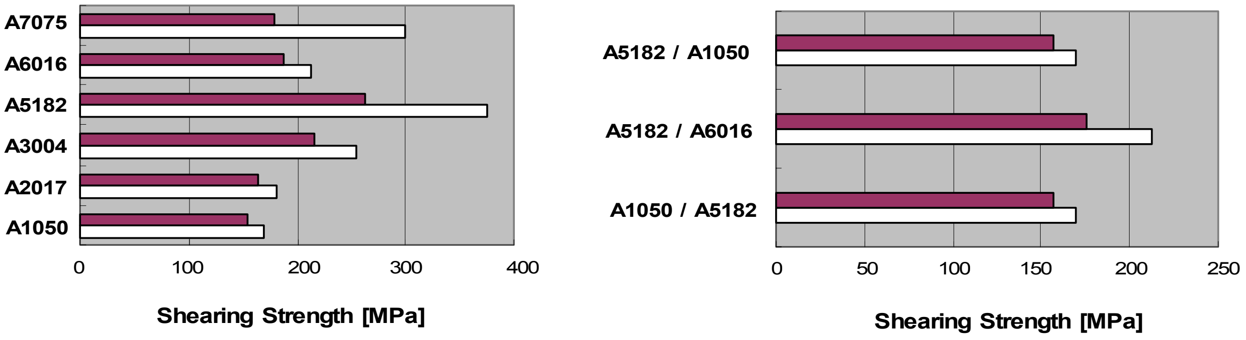


**Figure 10 — Distribution of tensile shearing strength for 10 divided pieces of welded sample (a): A1050, A3004 and A5182 sheets (b): A1050/SPCC, A5052/SPCC and A6016/SPCC sheets: ○rupture of non-welded area ●rupture of welded area.**

The comparison of the maximum tensile shearing strength for the same aluminium alloy combination and different aluminium alloy combination are shown in Figure 11. The result of the division No. 5 was used for this consideration.



(a) (b)

**Figure 11 — Comparison of the maximum tensile shearing strength for (a) the same aluminium alloy combination and (b) different aluminium alloy combination:**
**■rupture of welded area □rupture of non-welded area**

The comparison of the maximum tensile shearing for same alloy combination (see Figure 11(a)) shows that except of A5182/A5182 and A7075/A7075 combinations, the maximum tensile shearing for all other case is nearly same as a base metal tensile shearing strength. But for the different alloy combination (see Figure 11(b)), it can be pointed out that the welds are stronger than the weaker of the base metals so failure always occurred outside of welded zone for these combinations. These results would be expected for a solid-state bonding process.

### 3.5 Electron Probe Micro-Analysis (EPMA)

The result of EPMA for Fe and *Al* are illustrated in Figure 12 for SPCC to A1050. The EPMA profile for all combination (*Al*/SPCC) show a steep decrease in Fe concentration across the interface. The EPMA result shows that the 5µm wide transition layer is formed in the welding interface.

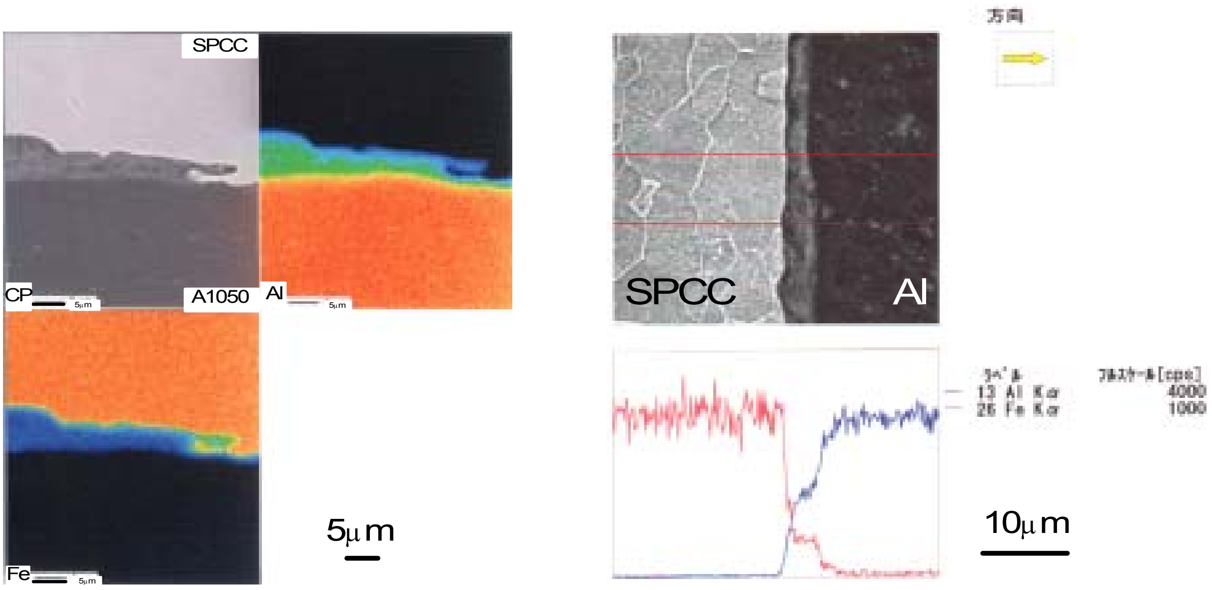
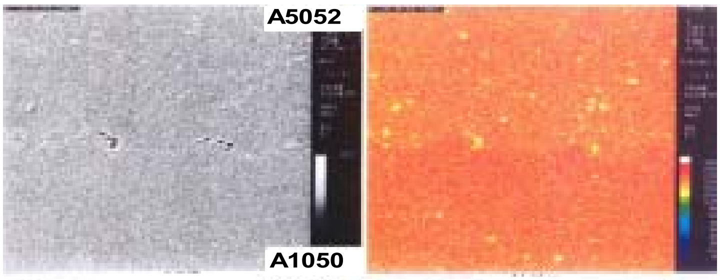


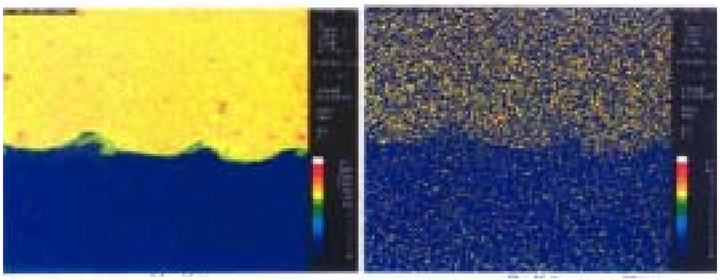
**Figure 12 — EPMA result for Fe and *Al* distribution across the SPCC- A1050 interface layer.**

Figure 13 shows the secondary electron images, obtained by scanning electron microscopy (SEM-SE) and also EPMA of *Al*, *Mg* and Cr in A1050/A5052 interface layer. The EPMA result for *Mg* clearly shows that a wavy bond interface was formed in welded zone.



SEM-SE Image

Al-Kα



Mg-Kα

Cr-Kα

**Figure 13 — SEM-SE image and EPMA result for *Al*, *Mg* and Cr distribution for A1050/A5052 sample.**

## 4 Conclusions

We can conclude that the solid-state weld quality achievable for most aluminium alloys and SPCC steel combination by using MPW method. Our experimental results show that the weld joint is always stronger than the weaker metal and in all tested combination a discontinuous or continuous pocket-type, wavy transition layer was formed without any significant heat-affected zone. The capability of our MPW method has been also examined for several other types of metals joint, such as T-joint, circular joint, long sheet sample (up to 500mm) successfully.

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