# Magnetic Pulse Welding (MPW) Method for Dissimilar Sheet Metal Joints

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## Abstract

The magnetic pulse welding (MPW) is a cold weld process of conductive metals to the similar or dissimilar material combination. 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 weld. In the most of the previous paper and research report the conventional MPW method was introduced for the tubular or cylindrical components. On the other hand, only a few papers on MPW of sheet work-piece have been reported. This paper describes a novel MPW technique for dissimilar sheet metal joints and its experimental results. In our experiments, the MPW formation in the dissimilar joining of Aluminum/*Fe* (SPCC), Aluminum/*Ti* and Aluminum/*Mg* (AZ91D) were investigated.

## 1. Introduction

One of the most difficult problems a welding engineer faces is to decide how to weld dissimilar metals together. Certain processes like laser welding, friction stir welding, magnetic pulse welding and inertia welding can be used effectively to solve many dissimilar metal welding problems. There are also several transition joints that can be used to affect the bridge from such difficult to join combinations as aluminum to steel. Diffusion bonding and adhesive bonding are other workable alternatives.

The magnetic pulse welding (MPW) is one of the reliable methods that can be used for the dissimilar metal joints. The magnetic pulse welding is solid-state joining process of conductive metals such as aluminum, brass, or copper to steel, titanium, stainless, aluminum, magnesium copper and most other metals. 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. As current is applied to the coil, a high-density magnetic flux is created around the coil, and as a result eddy currents is created in the parts. The eddy currents oppose the magnetic field in the coil and a repulsive force is created. This force can drives 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 aluminum 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 flat one-turn coil instead of the solenoidal coil. This coil consisted of upper and lower H-shape plates and the overlapped sheet workpieces 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 workpieces and as a result the sheet metals were welded in the seam state. The magnetic flux lines produced by this type of coil was shown in Figure 1. In this method, eddy currents which flowing in both sheets are considerably different, when dissimilar sheets metals like *Al/Fe* sheets are welded. And also the thickness of the work-pieces was limited by the space between two H-shape plates. Therefore, the welding of dissimilar sheet metals was difficult, and any contrivance or improvement was needed. These experimental results and welding characteristics for several samples such as *Al-Al* [4], *Al-Cu* and *Al-Fe* [5] were reported in our previous papers.

In our present experiment, a new coil was designed to improve the welding characteristics of dissimilar sheet metals, which can be used in application ranging from short and small part to the large and long work-piece with higher weld quality. This paper describes MPW formation in the dissimilar joining of Aluminum/*Fe*, Aluminum/*Ti* and Aluminum/*Mg* (AZ91D).

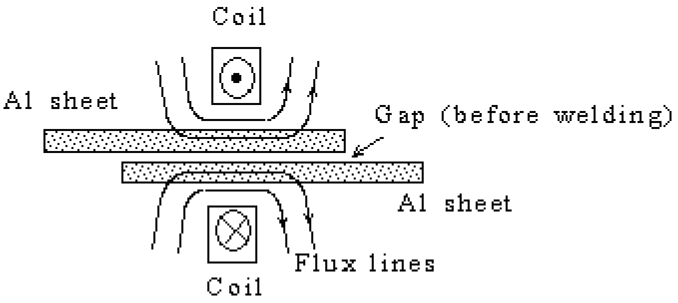


**Fig.1** Magnetic flux lines produced by one-turn coil (cross section view)

## 2. Principle of Welding

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 under the *Al* sheet and penetrates into *Al/Fe* sheets, 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 *Fe* 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.

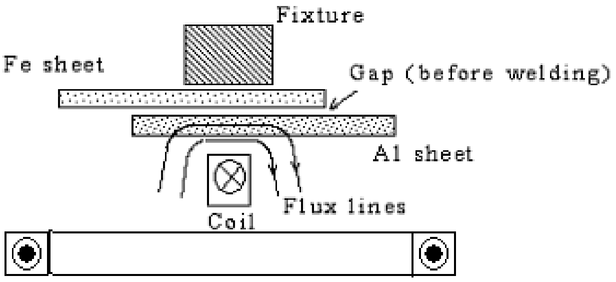


**Fig.2** Principle of the MPW for welding of *Al/Fe* sheets sample (cross section view)

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

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

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

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 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 our method is applicable to welding metal sheets with higher electrical conductivity such as aluminum and cupper to dissimilar sheet metal. As eddy current pass through the sheets in a short duration of about 50 μs, the sheets themselves do not get so hot. 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. When current density, rise time, duration and the range of magnetic flux are optimized in this experimental setup, both spot welding and seam welding can be used for joining aluminum or copper sheet to dissimilar sheet metal.

## 3. Experimental Apparatus

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

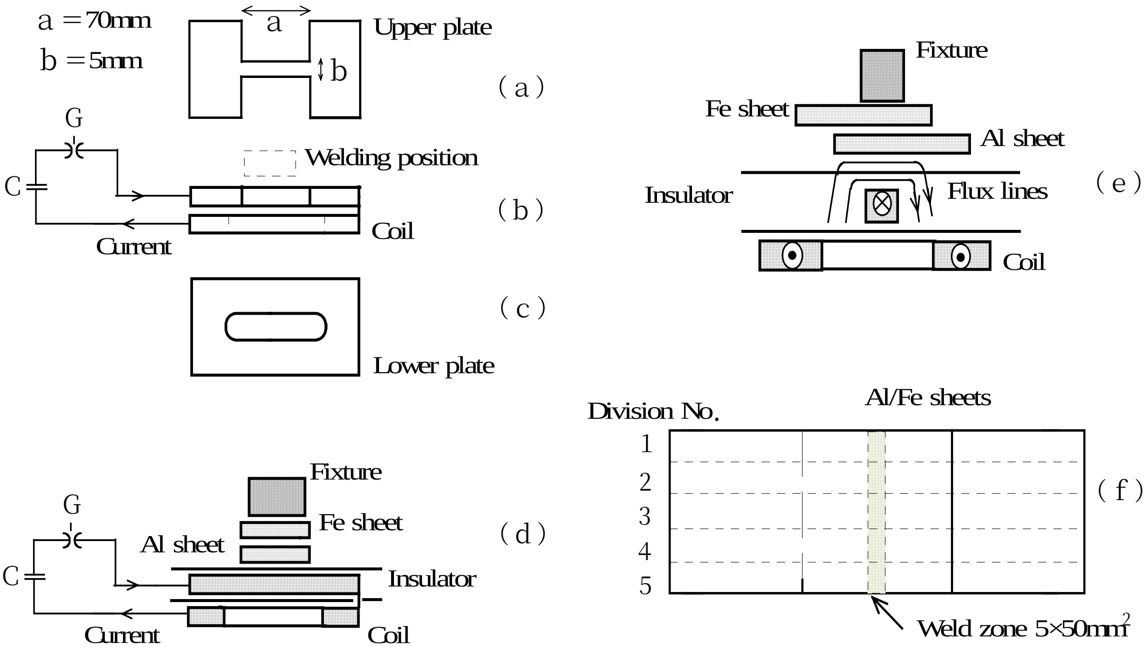


**Fig. 3** General outlines of apparatus: (a) and (c) up-side views of coil plates, (b) side view of coil with discharge circuit, (d) cross-section view of middle of coil containing lap of Al/Fe sheets with discharge circuit, (e) cross section view of middle of coil and magnetic flux lines, (f) up-side view of seam-welded Al/Fe sheets.

Figure 3 (a) is a up-side view of the upper H-shaped plate of the coil, (b) a side view of the coil with the discharge circuit (before loading sheets), (c) a up-side view of the lower rectangular plate with a hole, (d) a longitudinal section view (along the circuit) around the narrow middle portions (horizontal lines of H) of the upper coil containing the lapped *Al/Fe* sheets with the discharge circuit, (e) a cross section view of the middle portions of the coil (containing two sheets) and a magnetic flux, and (f) a plan view of the welded *Al/Fe* sheets (the dotted line shows a dividing line for tests).

A capacitor bank drives the discharge system of MPW device. The capacitor bank consists of two capacitor of 100 μF/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 one-turn coil was made by Cr-Cu alloy. The coil consists of upper and lower plate (Figure 3(a) and 3(c)). The thickness of each plate is 2mm and the inductance of the coil is 0.04 μH.

When the gap switch is closed, an impulse discharge current from the capacitor bank (C) passes through the coil, and then a high-density magnetic flux appears around the narrow middle of the upper H-shaped plate of the coil where a current concentrates. As shown in Figure 2 (e), this flux intersects the overlapped ends of the sheets and eddy currents flow through them, and as a result the magnetic pressure applies to them from the middle portion of the upper plate.

Aluminum (A1050), *Fe* (SPCC) and *Mg* (AZ91D) sheets were prepared to carry out the weld testing. All samples size were 100 mm long, 50 mm wide with thickness of 1.0 mm or 0.5mm. The contact surface between two samples were polished and cleaned-up by abrasives and methanol. The overlapped ends of the *Al*/*Fe* sheets with insulating material 0.1 mm thick are loaded between the upper plate and a fixture, as shown in Figure 2(d) and 2(e). 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 sheet.

The coil is clamped with the fixture during the welding operation. *Al* sheets are similarly welded to *Ti* or *Mg* (AZ91D) sheet. Figure 4 shows another example of the flat one-turn coil composed of one plate. This coil uses for the long seam welding.

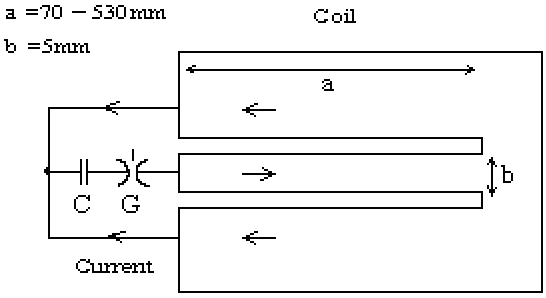


**Fig. 4** Plan view of another coil with discharge circuit

## 4. Results and Discussions

### 4.1 Discharge Current and Flux Density

A typical current waveform is shown in Figure 5. 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. This current signal was obtained at 1.2 kJ discharge (200 μF/3.5kV). The maximum current was measured about 150kA. If the discharge current flows uniformly on the surfaces of the middle portions of the upper plate (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).

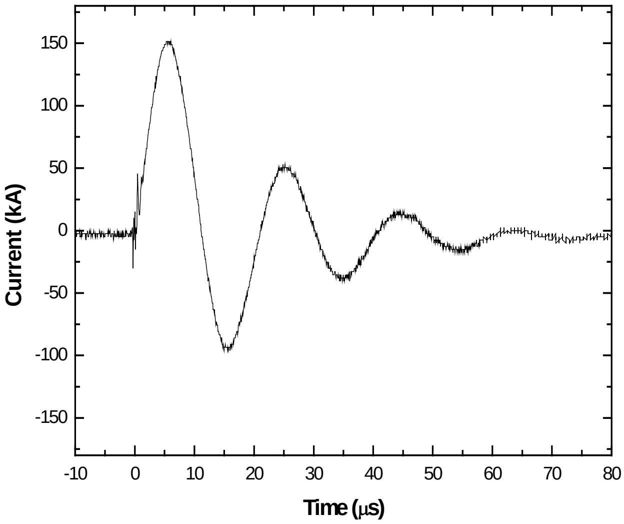
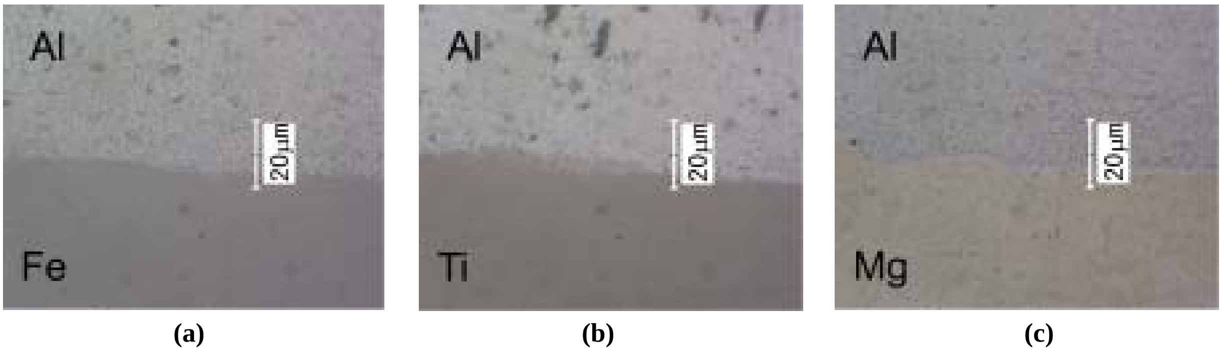


**Fig. 5** Typical current signal at 1.2 kJ discharge (200 μF/3.5kV).

## 4.2 Joined Interface

The samples were seam-welded along the middle of the coil. 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 five test pieces 10 mm wide as shown in Figure 2(f), and one longitudinal side of the piece of division No.3 was polished for observing the joined interface. Figures 6 are the optical-micrograph showing the joined interface of (a) *Al/Fe* sheets, (b) *Al/Ti* sheets and (c) *Al/Mg* sheets.



(a) (b) (c)

**Fig.6** Optical-micrograph picture of the joined interface: (a) *Al/Fe* sheets (b) *Al/Ti* sheets (c) *Al/Mg* sheets

No fusion and uneven interfaces are observed in Figures 6. Figures 7 shows the joined interface of (a) *Al/Fe* sheets, (b) *Al/Ti* sheets and (c) *Al/Mg* sheets, which were observed by a scanning electron microscope. A wavy interface is visible in Figure 7 for all welded samples. These wavy interfaces were produced with amplitudes as high as 10 μ m.

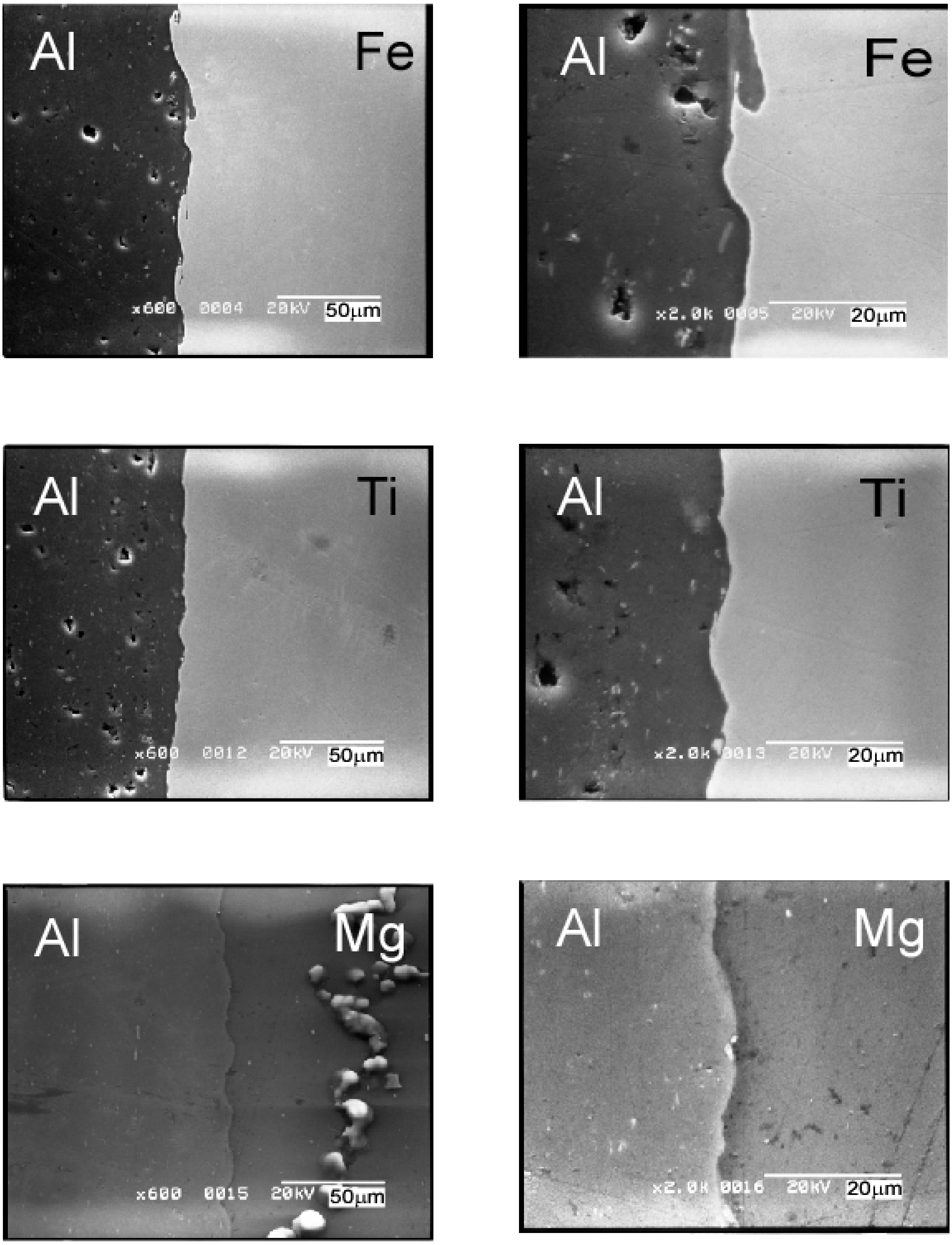
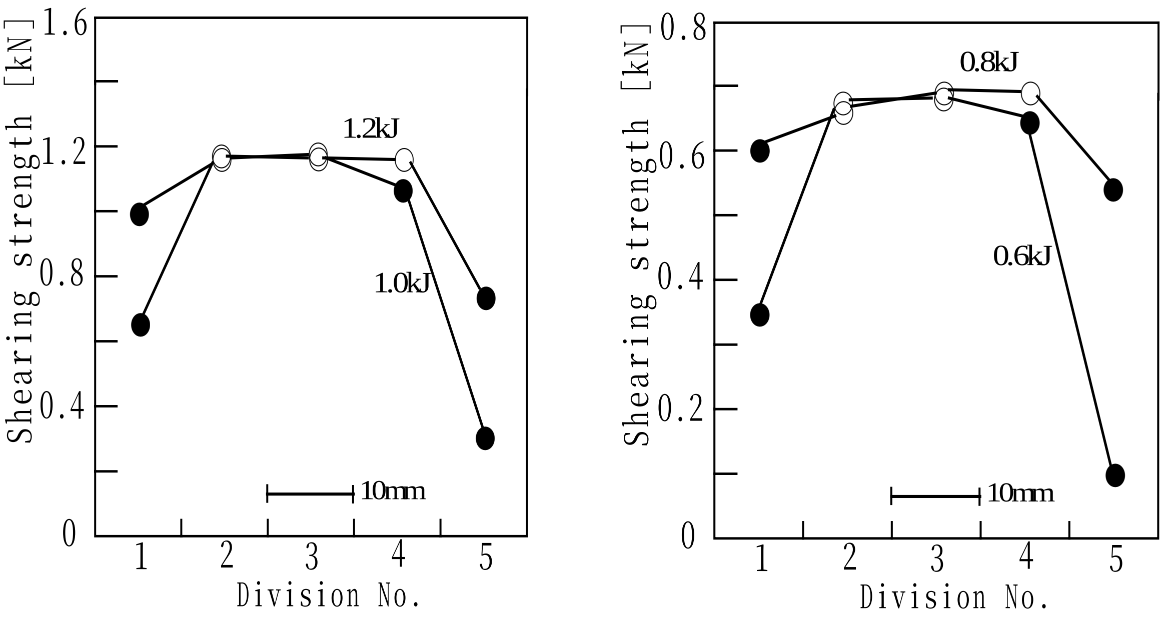


**Fig.7** SEM image of the interface area for *Al/Fe* , *Al/Ti* and *Al/Mg*

### 4.3 Shearing Tensile Strength

Several tests were made for each divided piece to determine the maximum shearing tensile strength. The test results obtained for *Al/Fe* sheets 0.5 and 1.0 mm thick are shown in Figure 8, where a mark (○) indicates the existence of a rupture of the non-welded parts (for the *Al sheet*) and (●) a separation of the weld zone. The shearing strength of the divisions No. 1 and No. 5 were less than that of the others. The results of other sheets were nearly similar to *Al/Fe* sheets. Ruptures appeared in sheets of any combination whenever welded at large discharge energy.



(a) (b)

**Fig. 8** Results of shearing tensile test for each divided piece of Figure 3(f): (a) *Al/Fe* sheets thickness 1.0 mm; (b) *Al/Fe* sheets thickness 0.5 mm (○base metal rupture, ●interface rupture)

### 4.4 Discussion

We observed no clear fusion microscopically in the joined interfaces of aluminum and dissimilar sheets obtained by our seam welding method. The thickness of the sheet was decreased in the seam-welded zone about 10% as shown in previous paper. It is satisfactory to consider that such a weld zone is formed by solid-state welding when the parts are heated by eddy currents and receives a strong impulse electromagnetic force (magnetic pressure). We consider that the reason why two pieces (end divisions No. 1 and No. 5) have a less shearing strength than the others as shown in Figure 8 is that the direction of eddy currents changes on both ends and consequently that of electromagnetic force changes, which leads to weakening the component of the electromagnetic force in the direction of pressing the parts to be joined together. It is also explained by the penetration of magnetic flux from the side of overlapped sheets.

## 5. Conclusions

According to our experimental result, it can be concluded that the MPW method is applicable to dissimilar sheet metals with very good weld quality. We have proved that it is possible to realize a 5 mm wide and 50 mm long seam-welded joints of *Al/Fe*, *Al/ Ti* or *Al/Mg* sheets 0.5 or 1.0 mm thick each by loading their overlapped parts into a flat one-turn coil and then making a high magnetic flux density impulsively intersect with this block. In the experiments, the energy of the capacitor bank required for the proposed seam welding was 1 to 2 kJ and the maximum discharge current that flowed through the coil is 140 to 200 kA.

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