# Interfacial Observation of Parallel Seam Welded-Aluminum Sheets by Magnetic Pulse Welding Method with Collision between Metal Jets\*

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This paper describes the parallel seam welding of aluminum sheets by a magnetic pulse welding method with a flat one-turn coil. The coil has a narrow central part and this part has two parallel upper parts. A discharge current from a capacitor bank flows along these parts. A magnetic flux having two high-density peaks is suddenly generated around these parts. The flux intersects the sheets which are overlapped on the coil. The resulting eddy currents are induced in the sheets, applying two parallel strong electromagnetic forces to them. The sheets with a gap collide with each other at high speed on two parallel places, and are welded. In this time, four metal jets occur just ahead of the collision front and four weld zones are made. Two metal jets occurring in the inside collide if the experimental conditions are suitable. The interfaces of such parallel seam welded-aluminum sheets are observed by an optical microscope. Two inside weld zones are connected to each other with a small cavity.

Key Words: Interfacial observation, Pressure welding, Magnetic pulse welding, Seam welding, Aluminum sheet, Metal jet

### 1. Introduction

Magnetic pulse welding (MPW) is an impact welding process where a high speed collision of metal work-pieces makes a weld using electromagnetic forces. For a long time, MPW method has been used for welding tubular work-pieces<sup>1-4</sup>). Recently, a considerable number of papers on MPW of flat work-piece have been reported<sup>5-15</sup>). General configurations consist of a lap joint of similar or dissimilar sheet metals<sup>5-7</sup>) and length scales of 10~100 cm<sup>8</sup>). The mechanism and features of MPW are considerably well known including interfacial microstructure <sup>9-12</sup>).

At the high-speed collision, metal jets are emitted in the welding interface of sheet metals. Two metal jets emitted from the joint of Al-Al sheets were directly observed by a high-speed video camera in our experiments<sup>13,14)</sup>. The jets emitted brilliant lights in the air. The length of the observed lights was  $1\sim2mm$ . The weld interface was cleaned by the emission of metal jets. Usually the sheet metals join in two narrow seam-weld zones and a middle clearance (non-weld zone)<sup>5, 6, 9,10)</sup>. Two metal jets do not collide with each other. If the MPW with collision between metal jets is carried out by parallel seam welding, we can increase seam-weld zones widely with a small cavity<sup>15</sup>).

The interface formed by such parallel seam welding has not been observed in others now. In this paper, we observe and confirm the increase of seam-weld zone width using the coil of new structure for such welding.

#### 2. Experimental procedures

#### 2.1 MPW method for parallel seam welding

Fig. 1 is an illustration of the flat one-turn coil for the parallel seam welding. A discharge current from the capacitor bank flows into the narrow central part of the coil and flows out from the wide outside parts. Two high-density currents pass through the two parallel upper parts of the central part. These parts form of a narrow groove. The groove width *w* is called parallel distance.

Two Al sheets with a gap are fixed on the coil with a thin insulator as shown in Fig. 2 (cross section view). When the discharge current flows into the two upper parts, a magnetic flux which has two high-density peaks is suddenly generated around



**Fig. 1** Flat one-turn coil for parallel seam welding.

Groove width w



Fig. 2 Fixation of coil and Al sheets (cross section view).

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the two upper parts. The flux intersects the lower sheet (flyer sheet) and eddy currents are induced electromagnetically in the skin of the flyer sheet. Two parallel strong electromagnetic forces f act on the flyer sheet. This sheet is accelerated upward and collides with the upper target sheet at two initial collision places as shown in Fig. 3. These collision places move along the surface of the target sheet and four metal jets are emitted. Two metal jets occurring in the inside collide if the experimental conditions are suitable. Two sheets will be welded in two parallel with the MPW method accompanied by collision between metal jets.

The details of the electromagnetic force (or magnetic pressure) are shown elsewhere  $^{5-7)}$ .

# 2.2 Experimental apparatus and materials

The discharge system consisted of the capacitor bank, a discharge switch, the flat one-turn coil and others as shown in Fig. 4. The capacitor bank (capacitance  $C=24\mu$ F) consisted of four capacitors of  $6\mu$ F in parallel to reduce internal (or residual) inductance. The charged energy *E* of the bank was less than 2kJ. The bank was connected to the discharge switch and the coil by low inductance transmission lines. Therefore, approximately 60% of charged energy *E* moved to the coil as magnetic energy<sup>8</sup>. Al sheets were insulated in a DC manner from the coil, but there was electromagnetic coupling between them. We can say that the Al flyer sheet is accelerated by the magnetic energy moving to the coil and collides with the target sheet.

The coil was mainly made by Cu-Cr alloy E-shaped flat board (3mm thick). The narrow central part (100mm long, 7, 8mm wide, 3mm thick) of the coil had the groove (width w=1.0, 2.0mm, depth d= 0.5, 1.0, 1.5mm) such as Fig.1. Aluminum sheets were A1050, 70mm long, 100mm wide and 0.2mm thick. Two sheets were overlapped 50mm in length with the gap and fixed on the coil with the insulator (polyimide of 0.1mm thick) such as Fig.2. The gap distance (or stand-off distance) was 0.5mm.

The discharge current and a collision time were measured by the same way as our previous paper<sup>7</sup>).

#### 3. Experimental results and discussion

## 3.1 Discharge current and collision speed

Typical discharge current and collision time signals are shown in Fig. 5. The damping and oscillating current flows through the coil for duration of about  $30\mu$ s. In measurement the oscillating period was  $7.3\mu$ s, and so the skin depth was 0.22 mm for the Al sheet. The maximum discharge current was about 200kA. The sheets collided in around the time for the maximum current and



Fig. 3 Illustration just after collision (Emission of metal jets).



Fig. 4 Block diagram of discharge system.



Fig. 5 Typical discharge current and collision time signals.

after  $1.8\mu s$  from the start of the current. The collision speed when the sheets collided was calculated to be approximately 600m/s.

#### 3.2 Appearance of parallel seam welded sheets

Fig. 6 shows a typical appearance of parallel seam welded sheets taken from the flyer sheet side. A part of the flyer sheet deformed toward the target sheet along the narrow central part. The weld zones were in the deformed region which was 100mm in length to the longitudinal (or seam) direction and about 10mm in width direction as shown in Fig.6. This width was nearly equal to the central part width of the coil. The welded sheets were cut with several places and polished for optical interfacial observations.

# 3.3 Interfacial observation

# 3.3.1 In the case of *w*=1.0mm and *d*=1.5mm

Fig. 7 and Fig. 8 show cross sectional appearances of joining



Fig. 6 Appearance of seam welded Al-Al sheets.

interfaces of the deformed region for the groove width w=1.0mm and the depth d=1.5mm. The upper side is the target sheet and the lower the flyer sheet. Four weld zones marked by arrows ( $\downarrow$ ) are observed in Figs. 7 and 8. The welding was not attained completely throughout the deformed region. There were clearances or a small cavity between each weld zone. The clearances to be seen in Fig. 8 are clearer than those of Fig. 7. The inside weld zones were increased, connected and unified including the cavity. This state was similar along the seam welding direction as shown in Figs. 7 and 8. Fig. 9 shows enlarged micrographs for the center of joining interface of Fig. 7. The width of the cavity was about  $0.1 \sim 0.2$ mm.

# 3.3.2 In the case of *w*=2.0mm and *d*=0.5~1.5mm

Fig. 10 shows the groove depth (d) dependence on the interface for w=2.0mm. Four weld zones ( $\downarrow$ ) are seen in each photograph. There is the cavity in the case of d=0.5 and 1.0mm. The cavity is not seen for d=1.5mm. Influence of the groove depth (d) strongly appeared in this case. Fig. 11 shows enlarged micrographs for the center of joining interface of Fig. 10. The width of the cavity is about  $0.1 \sim 0.2$ mm.



Fig. 7 Cross sectional appearances of joining interface of seam welded Al-Al sheets (*E*=1.4kJ, *w*=1.0mm and *d*=1.5mm). Places (a) and (b) of observation are places (a) and (b) of Fig. 6, respectively.



**Fig. 8** Cross sectional appearances of joining interface of seam welded Al-Al sheets (*E*=1.8kJ, *w*=1.0mm and *d*=1.5mm). Places (a) and (b) of observation are places (a) and (b) of Fig. 6, respectively.



Fig. 9 Optical micrographs of center of Fig. 7 (a) and (b), (E=1.4kJ, w=1.0mm and d=1.5mm).



Fig. 11 Optical micrographs of center of Fig.10 (*E*=1.6kJ and *w*=2.0mm).

0.1mm

As the discharge energy E decreased, the inside weld zones of the interface became harder to be connected and unified as shown in Fig.12. However, four weld zones marked by  $(\downarrow)$  were observed and the inside weld zones were wider than the outside.

# **3.4 Discussion**

Four weld zones marked by arrows  $(\downarrow)$  were not observed at two initial collision places. These zones observed at the places slightly away from the initial collision places. It was suggested from the experimental results that the sheets could collided obliquely at these zones and be welded. The angle of the oblique collision influences the welding greatly<sup>14)</sup>. The collision angle in the inside must have changed by the width (w) and the depth (d).

The following contents may explain the increase, connection and unification of the weld zones in the inside.

(1) We were able to choose the better collision angle in the inside. (2) If four metal jets are emitted near to each other and two inside metal jets collide, the neighborhood of this collision may become a high temperature and a high pressure state. This is possible by our experiments.

#### 4. Conclusions

The parallel seam welding experiments of aluminum sheets were carried out using the flat one-turn coil. The interfaces of the



Fig. 12 Cross sectional appearances of joining interface of seam welded Al-Al sheets (w=2.0mm and d=0.5mm).

welded-sheets were observed. The conclusions are as follows.

(1) Four weld zones appeared for discharge energy  $E=1.0\sim1.8$ kJ. (2) Inside weld zones were increased, connected and unified including the small cavity for the width w=1 and 2mm if the depth (*d*) and energy (*E*) are suitable as shown in Figs. 10 and 12. (3) The observed interfaces were similar along the seam welding direction as shown in Figs. 7 and 8.

(4) The MPW method with collision between metal jets will be effective for aluminum sheet welding.

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