

Impulse Magnetic Pressure Seam Welding of Aluminum and Copper Sheets

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Abstract

The present paper describes a new seam welding technique and its experimental results. When an impulse current from an energy-stored capacitor bank passes through a flat one-turn coil, a high-density magnetic flux is suddenly generated in the coil. Eddy currents are induced inside the overlapped ends of Al-Cu, Al-Al or Cu-Cu sheets (thickness 0.5 or 1.0 mm) placed in the coil. The ends can be joined both by the Joule heat generated in them and by the magnetic pressure applied onto them. A bank energy required for seam-welding an area 5 mm×100 mm is less than 4 kJ.

1. Introduction

Spot welding method is conventionally used for welding aluminum sheets. In this method, a high current passes almost instantaneously between electrodes pressed on each side of the overlapped ends of two aluminum sheets being welded to make a spot joint by resistance heating (Joule effect). Although the seam welding of aluminum sheets is possible by continuous spot welding with roller electrodes, only a few reports have been made on the application of seam welding for aluminum sheets. The reason is that the heating effect on aluminum is low due to its higher electrical and thermal conductivities compared with those of steel and the lifetime of electrode used in cyclical welding of aluminum sheets is short due to severer alloy-yielding fusion. It is the same with the seam welding of aluminum and copper sheets or copper sheets.

We propose a new method of seam welding which is applicable for aluminum or copper sheets. In our method with a special coil instead of electrodes, sheet-materials with higher electrical conductivity such as Al or Cu undergo better heating effect and can be joined by instantaneous resistance heating without applying high mechanical pressure. In this paper are also reported our experiments of the seam welding of Al-Cu, Al-Al or Cu-Cu sheets 100 mm long.

2. Principle of Welding

The principle of the welding method proposed by us is shown in figure 1 : cross section view of two metal (Al and Cu for example) sheets and a coil with a magnetic field (magnetic flux density B).

When a high-density flux is suddenly generated on both sides of the overlapped parts of two metal sheets and penetrates into them, eddy currents (current density i) pass

through them hindering its further penetration. As a result, an electromagnetic force $i \times B$ acts in the direction that presses the two parts together. The eddy currents i are given by equation (1) and the magnetic pressure p equivalent to the electromagnetic force by equation (2), where κ , μ , τ stand for the electrical conductivity, magnetic permeability and thickness of metal sheet respectively, B and B_0 for the magnetic flux density

on the outsides of the two parts and their contacting surfaces respectively, and $\delta = \sqrt{2/\omega \kappa \mu}$ means the depth of the skin effect, where ω stands for the angular frequency of the changing field.

$$\text{rot } i = -\kappa (\partial B / \partial t) \quad (1)$$

$$p = (B^2 - B_0^2) / 2\mu = (B^2 / 2\mu) [1 - \exp(-2\tau/\delta)] \quad (2)$$

The overlapped ends through which flow eddy currents are heated by Joule heat i^2/κ . As is evident from equation (1), the higher the electrical conductivity κ of a material is, the more the eddy currents flow in it and the more efficiently a large amount of Joule heat is generated. With increasing of the electrical conductivity, the depth of the skin effect decreases, resulting in increasing the magnetic pressure p in accordance with equation (2). Consequently our method is applicable to welding metal sheets with higher electrical conductivity such as Al or Cu. Since eddy currents pass through such materials for a duration of 10 to 100 μ s, the thermal effect by this welding method is also lower compared to that in the conventional resistance welding method.

When the density, rise time, duration and range of magnetic flux are suitably chosen in this method, both spot welding and seam welding can be used for joining an overlap of Al-Cu, Al-Al or Cu-Cu sheets. Two metal sheets even with a minute gap between them can be joined by our method.

3. Experimental Apparatus

Figures 2 show general outlines of the impulse magnetic pressure seam welding apparatus proposed by us, 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 which can generate a high-density magnetic flux in the coil area.

Figure 2 (a) is a plan 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 plan view of the lower H-plate, (d) a longitudinal section view (along the circuit) around the narrow middle portions (horizontal lines of H) of the coil containing the overlapped ends of two metal sheets with the discharge circuit, (e) a cross section view of the middle portions of the coil (containing

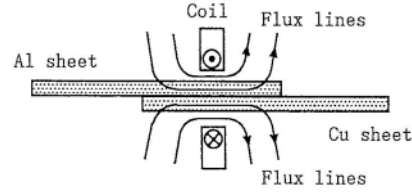


Fig. 1 Al and Cu sheets with coil and magnetic flux lines (cross section view)

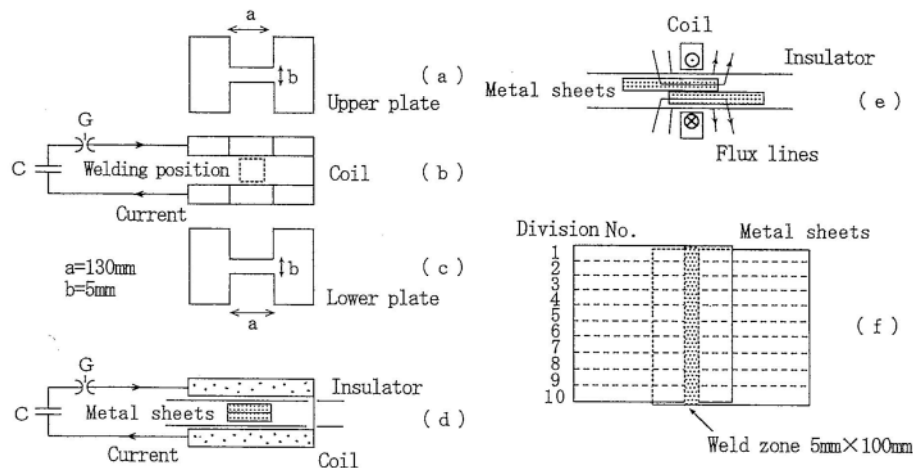


Fig. 2 General outlines of apparatus: (a) and (c) plan views of coil plates, (b) side view of coil with discharge circuit, (d) longitudinal section view of middle of coil containing lap of metal sheets with discharge circuit, (e) cross section view of middle of coil and magnetic flux lines, (f) plan view of seam-welded metal sheets.

two sheets) and a magnetic flux, and (f) a plan view of the welded metal sheets (the dotted line shows a dividing line for tests).

When the gap switch is closed, an impulse discharge current from the capacitor bank (C) passes through the coil, then a high-density magnetic flux appears around the narrow middle 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, applying magnetic pressure to them from the opposite middle portions of the coil plates.

The bank capacities used for the experiments are 200 and 400 μ F. The one-turn coil of inductance 0.06 μ H is 200 mm long and 21 to 23 mm thick, comprised of two H-plates of Cr-Cu 10 mm thick each. Aluminum (A1050) and copper (C1100) sheets are 100 mm long, 100 mm wide and 0.5 or 1.0 mm thick. The overlapped ends of the two sheets with insulating material 0.1 mm thick are loaded between the H-plates, as shown in figure 2 (d) and (e), after polishing with abrasives and degreasing with alcohol-containing cloth and so on. Both the plates of the coil are clamped with a fixture during the welding operation.

4. Experimental Results

4.1 Discharge Current and Flux Density

An example of the current waveforms obtained at $C = 200 \mu$ F is shown in figure 3. A damping and oscillating current flows through a one-turn coil for a duration of about 50 μ s. The oscillating period was measured 23 μ s. The depth of skin effect was calculated 0.39 mm for Al sheet and 0.32 mm for Cu sheet, and the maximum current about 190 kA at 2.1

kJ.

It is assumed that the discharge current (190 kA) flows uniformly on the inside surfaces of the middle portions of the coil. Under this condition, the maximum magnetic flux density is estimated about 41 T, while the maximum magnetic pressure is calculated about 630 MPa from equation (2).

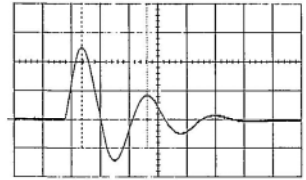


Fig. 3 Waveform of discharge current at 2.1 kJ discharge energy ($C = 200 \mu F$), 79 kA/div. $10 \mu s$ /div.

4.2 Joined Interface

Al-Cu sheets were seam-welded along the middle of the coil. The width of the weld zone was nearly equal to that of the middle ($b=5$ mm). The welded sheets were divided into ten test pieces 10 mm wide as shown in figure 2 (f), and one longitudinal side of the piece of division No. 5 was polished for observing the joined interface.

Figures 4 are the photographs of the longitudinal side of the piece No. 5 : figure 4 (a) is an optical-micrograph showing a general section view of the joined interface where are seen the sections of two welded seams and one clearance between them, figure 4 (b) an

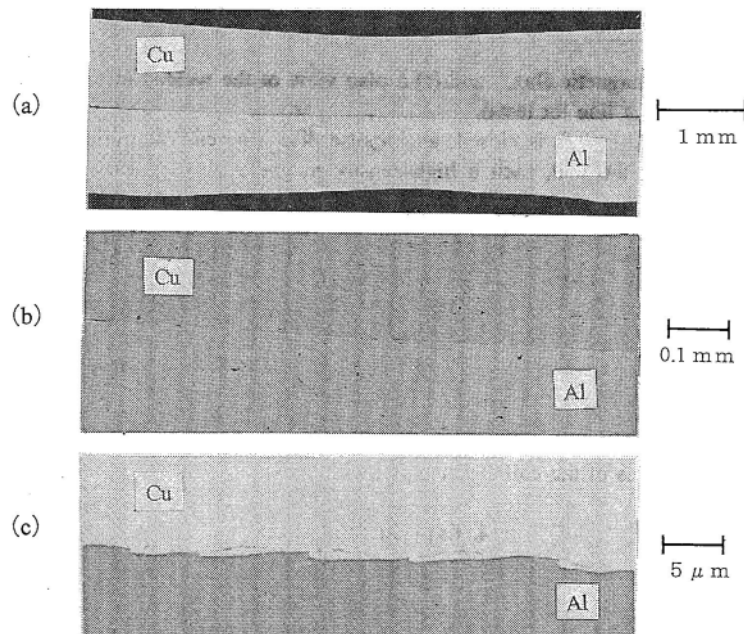


Fig. 4 Photographs of longitudinal side of piece (division No. 5): (a) optical-micrograph showing general section, (b) enlarged view of welded seam, (c) EPMA surface analysis of seam, (Al-Cu sheets thickness 1.0 mm each, discharge energy 2.6 kJ, $C = 400 \mu F$)

enlarged view of one seam in figure 4 (a), and figure 4 (c) an example of surface analysis of one seam by EPMA (electron probe micro-analyzer). No fusion is visible in figure 4 (b), while a wavy pattern visible in figure 4 (c).

Similar results were obtained from the experiments on Al-Al sheets and Cu-Cu sheets.

4.3 Shearing Tensile Strength

Tests were made for each divided piece to determine the maximum shearing tensile strength. The test results obtained for Al-Cu sheets 0.5 and 1.0 mm thick are shown in figure 5 and figure 6, where a mark \circ indicates the existence of a rupture of the non-welded parts (base metal rupture) and \bullet a separation of the weld zone. The shearing strength of the divisions No. 1 and No. 10 were less than that of the others. The results on Al-Al sheets and Cu-Cu sheets 0.5 mm thick are shown in figure 7 and figure 8 respectively. Ruptures appeared in sheets of any combination whenever welded at large discharge energy.

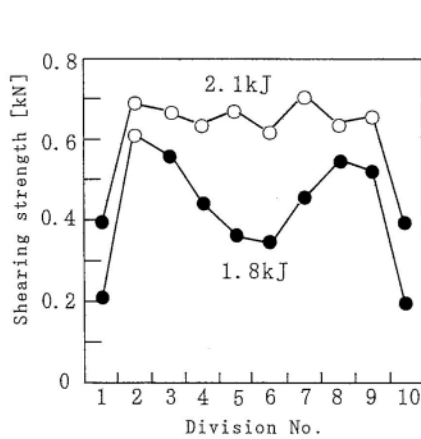


Fig. 5 Results of shearing tensile test for each division : \circ non-welded part rupture, \bullet weld zone separation (Al-Cu sheets thickness 0.5 mm each, $C = 200 \mu F$)

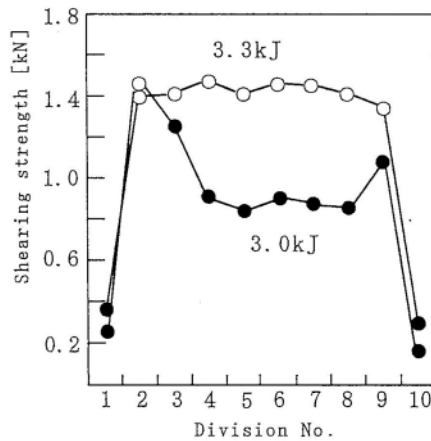


Fig. 6 Results of shearing tensile test for each division : \circ non-welded part rupture, \bullet weld zone separation (Al-Cu sheets thickness 1.0 mm each, $C = 400 \mu F$)

5. Discussion

We observed no clear fusion microscopically in the joined interfaces of aluminum and copper sheets obtained by our seam welding method. The thickness of the sheet was decreased in the seam welded zone about 10% as shown in figure 4 (a). 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 receive a strong impulse electromagnetic force (magnetic pressure).

A seam weld is visible on each end of the weld zone section in figure 4 (a). In our estimation based on the distribution of magnetic flux, the reason is that both the ends through which eddy currents flow intensively are more strongly heated, consequently receiving a stronger electromagnetic force than the middle.

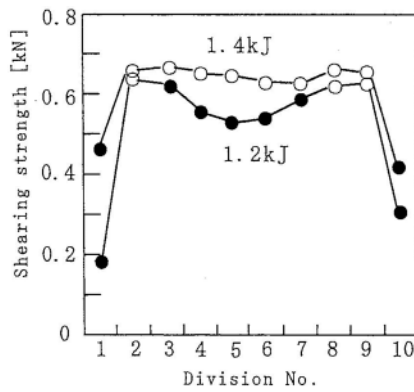


Fig. 7 Results of shearing tensile test for each division : ○ non-welded part rupture, ● weld zone separation (Al-Al sheets thickness 0.5 mm each, $C = 200 \mu F$)

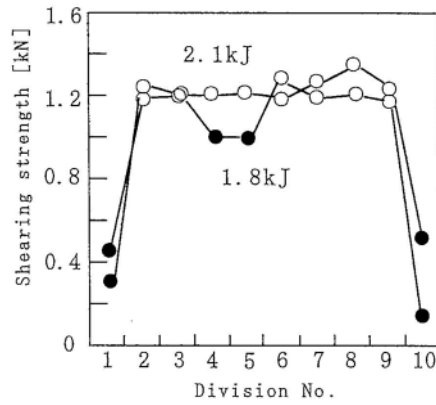


Fig. 8 Results of shearing tensile test for each division : ○ non-welded part rupture, ● weld zone separation (Cu-Cu sheets thickness 0.5 mm each, $C = 200 \mu F$)

We consider that the reason why two pieces (end divisions No. 1 and No. 10) have a less shearing strength than the others as shown in figure 5 to figure 8 is that the direction of eddy currents changes on both ends and consequently that of electromagnetic force also changes, which leads to weakening the component of the electromagnetic force in the direction of pressing the parts to be joined together.

6. Conclusion

We have proposed a new seam welding method which is applicable to aluminum or copper sheets. We have proved that it is possible to realize a 5 mm wide and 100 mm long seam-welded joint of Al-Cu, Al-Al or Cu-Cu 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-density magnetic flux impulsively intersect with this block. In the experiments, the energy of the capacitor bank required for the proposed seam-welding was 1.4 to 3.3 kJ and the maximum discharge current that flowed through the coil 157 to 214 kA.

Acknowledgments

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