Magnetic pulse welding method: Discharge current commutates to collision part of Al/Cu sheets

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Abstract In this report, magnetic pulse welding is started by rapidly flowing a damped oscillating discharge current from a capacitor bank through an insulated 5-turn flat coil. Overlapped Al/Cu sheets having a gap are fixed on the coil, and each sheet connects to both ends of the coil. When the current flows through the coil, a high density magnetic flux is applied to the Al sheet near the coil. The resulting eddy currents are induced in the Al sheet and electromagnetic forces act on the sheet. The Al sheet collides to the Cu sheet at high speed and both sheets will be welded. The discharge current is set to be nearly peak when both sheets collide. Both sheets also act as high-speed mechanical switch contacts and so the current flowing through the coil commutates to the short-circuit including the collision part of sheets. The coil current does not oscillate but gradually damps which is good for the discharge device. The results of Al/Cu sheets welding by this method have been reported.

Keywords Magnetic pulse welding, Mechanical switch, Sheet metal, Capacitor bank, Discharge current, Commutation

1. Introduction

In recent years, the necessity of welding aluminum (Al) to copper (Cu) for electrical connection is increasing. However, this welding is not easy from the difference in physical quantities such as melting point. There are few efficient and excellent methods of welding Al to Cu. Magnetic pulse welding is suitable for welding dissimilar sheet metals such as Al and Cu. This welding belongs to impact welding similar to explosive welding [1]. The weld interface of Al/Cu sheets (or plates) was observed in 2001 and showed a wavy interface morphology like explosion welding [2]. The microstructure of such a interface has been studied in detail and the high quality magnetic pulse welds (Al/Cu sheets) have been obtained [3-6].

Al/Cu sheets having the gap are overlapped and fixed on the single-turn or multi-turn flat coil. The Al sheet near the coil is electromagnetically coupled to the coil. When the discharge current flows through the coil, a magnetic flux is suddenly generated under the Al sheet and electromagnetic forces act on the sheet. This sheet is accelerated and collides with the Cu sheet and both sheets are welded. Such welding is efficient when colliding near the peak (maximum value) of the discharge current [7]. In addition, using the multi-turn coil is more efficient [8].

Since the resistance of the discharge circuit is low, the normal discharge current oscillates and gradually damps. If the

current direction changes and large amplitude oscillations continue, the voltage changes significantly. This is not good for discharge devices. In particular, it is important when using semiconductor discharge switches. In order to prevent the current from oscillating, it is sufficient to short the both ends of the multi-turn coil with a relatively low impedance circuit when the current reaches the peak [9-11].

In this report, the overlapped Al/Cu sheets are fixed on the 5-turn coil. Each sheet connects to both ends of the coil. The Al/Cu sheets act as high-speed mechanical switch contacts. When the discharge current is flowed through the coil and the sheets collide near the peak current, the current flowing through the coil is commutated to the short-circuit including the collision part of Al/Cu sheets and does not oscillate. Such a welding method and results have been reported. The sheets will be welded as before.

2. Related mathematical expressions [12-14]

When the magnetic flux (flux density **B**) is suddenly generated under the Al sheet which does not move and penetrates into the sheet, numerous micro-closed eddy currents (density \mathbf{i}) flowing in the Al sheet are given by Eq. (1). The electromagnetic force \mathbf{f} acting on unit volume of the Al sheet is given by Eq. (2). Many adjacent micro-closed eddy currents are canceled out for viewing, and so-called eddy currents flow in the direction opposite to the coil current. The magnetic flux generated between the coil and the Al sheet increases compared to the case without Al/Cu sheets. This increase is less than twice. The force f is difficult to measure and calculate. So, the magnetic pressure p acting on unit area of the Al sheet equivalent to the force f is given by Eq. (3). Numerous micro-closed induced electric fields E that generate numerous eddy currents are shown in Eq. (4).

rot
$$\mathbf{i} = -\kappa \left(\partial \mathbf{B} / \partial t \right)$$
 (1)
 $\mathbf{f} = \mathbf{i} \times \mathbf{B}$ (2)
 $p = \left(B o^2 - B i^2 \right) / 2 \mu$
 $= \left(B o^2 / 2 \mu \right) \left[1 - \exp \left(-2 \tau / \delta \right) \right]$ (3)

(4)

Here, κ and μ are the electrical conductivity and magnetic permeability of the Al sheet, and B_0 and B i are the magnetic flux densities below and above the Al sheet, respectively. Further, τ is the thickness of the Al sheet and δ the skin depth where the magnetic flux penetrates into the sheet. The eddy currents flow according to Ohm's law ($\mathbf{i} = \kappa \mathbf{E}$), but when the Al sheet begins to move in the magnetic flux, another electric field is generated, reducing the total electric field and reducing eddy currents [14].

3. Experimental procedures

rot $\mathbf{E} = - \partial \mathbf{B} / \partial t$

Figure 1 is a sketch of the E-shaped 5-turn flat coil for this welding. The coil comprised five pieces of Cu alloy plates (0.5 mm thick) which were electrically insulated and were laminated as before [15,16]. The discharge current flowed into the narrow central part (120 mm long and 5 mm wide) of the plate No.1 upward and flowed out from the two wide outside parts downward. The divided currents joined at the lower parts of the plate No.1. The joined current flowed again into the central part of the plate No.2. The discharge current flowed through each central part in series and turned 5 degrees. Each central part of the plates was just piled up with the same width. A high density magnetic flux was generated around the central part as the 5-turn coil. The total thickness of the coil was about 3 mm including insulators between each plate.

Figure 2 shows the cross-section of Al/Cu sheets overlapped and fixed on the coil. Both sheets were connected to both ends of the coil, but connection plates were omitted in Fig. 2. The Al sheet was electromagnetically coupled to the









Fig. 3 Block diagram of experimental apparatus.

coil regardless of the connection. When the discharge current flowed through the coil, the electromagnetic forces (f) act on

the Al sheet and the Al/Cu sheets were welded .

Figure 3 shows a block diagram of an experimental apparatus using the 5-turn coil. The discharge circuit consisted of the capacitor bank, a discharge switch (spark gap switch), the coil and low inductance transmission lines. Figure 4 shows the appearance of the discharge circuit without the upper fixture. The capacitor bank (capacitance 50 μ F) consisted of two capacitors of 25 μ F in parallel. These bank, switch and coil were placed as close as possible to reduce the inductance of the transmission lines. The charged energy *E* of the bank was, for example, 0.6 kJ. The Al/Cu sheets were fixed on the coil, and each sheet connected to both ends of the coil using low inductance transmission lines remote from the central part.

After the discharge switch was closed, the damped oscillating current flowed through the discharge circuit along the dotted line. The current was set to be nearly peak when the sheets collided. The sheets worked for mechanical switch contacts. So, the current flowing through the coil commutated to the short-circuit including the collision part of Al/Cu sheets. And it continued to flow in the direction of the arrows.

The discharge current waveforms were observed using two small search coils (SC 1 and SC 2) as shown in Fig. 3. Each search coil electromagnetically coupled to the discharge circuit near each coil and detected a voltage signal proportional to the time derivative of each magnetic flux (B) near each coil. Each detected voltage signal was converted to a voltage signal indicating the current near each coil through a measurement circuit with an integrator. Each converted voltage signal of the current was observed with an oscilloscope as a current signal waveform. Each current amplitude value was easily calculated from the discharge condition or the conversion factor. Such a current signal waveform on the oscilloscope is called a current waveform (or simply current) for convenience.

The Al (A1050) and Cu (C1220) sheets were 70 mm long, 50 mm wide and 0.4 mm thick. The sheets were overlapped by 50 mm with the gap of 2 mm and fixed on the coil. The 2 mm gap was chosen not to break down with the voltage applied after the discharge.

4. Experimental results [17-19]

4.1 Current waveforms flowing to bank and coil

Typical current waveforms are shown in Fig. 5. The cur-



Fig. 4 Appearance of discharge circuit



Fig. 5 Current waveforms flowing to bank and coil (discharge energy E = 0.6 kJ).



Fig. 6 Current waveforms flowing to bank and coil without commutation, (discharge energy E = 0.6 kJ).

rent flowing to the bank suddenly reduced its oscillation, and the current flowing to the coil flowed without oscillation. The current flowed through the coil for duration of about 100 μ s. The sheet collision and the current commutation occurred about 10 μ s after the start of current. The peak discharge current was 28 kA at the energy *E* of 0.6 kJ. The collision speed when the sheets collided was approximately 400 m/s.

For reference, Fig. 6 shows the current waveforms when the contact sheets are not connected to both ends of the coil (without the commutation). 4.2 Surface appearance and cross sectional observation

Figure 7 shows surface appearances of the welded Al/Cu sheets viewed from both sides. A part of the Al sheet was deformed toward the Cu sheet along the narrow central part, and the Cu sheet hardly was deformed. No trace of the discharge current commutation was found on both surfaces. The weld zones (usually two) were within the deformation area 50 mm long in the longitudinal direction and about 15 mm in the width direction. The welded sheet was cut and polished, and the cross section (interface) was observed (these were all done by a specialized company).

Figure 8 shows a cross sectional appearance of the welded Al/Cu sheets (or weld interface) at the deformed region. Two weld zones marked by arrows (\downarrow) and a middle clearance (non-weld zone) were seen in Fig. 8. The length of each weld zone was about 1 mm. The discharge current flowed through each weld zone after the sheet collision, but there were no melted and solidification parts like resistance spot welded nuggets (A possible reason is that when welding Al/Al sheets with thickness of 0.4 mm, the peak currents flowing through both are similar, but our flowing time is about 100 µs and about 1/100) [20]. Figure 9 is typical scanning electron microscope (SEM) images of the interface at two weld zones of Fig. 8. Wavy pattern morphology was seen in both weld zones. Such cross sectional appearance and wavy pattern were also seen when the E-shaped 6-turn coil was used without the commutation [15,16]. The occurrence of wavy patterns at the weld zones has been described in detail elsewhere [21].

4.3 Deformation of E-shaped coil plates

During the experiments, the 5-turn coil and the Al/Cu sheets were fixed at several points manually using thick and rigid fixing-plates from above and below as shown in Fig. 2. The lower fixing-plate (coil side) was an insulating plate and the upper fixing-plate was an insulated metal plate.

The experiments using the 5-turn same coil could be continued more than 100 times without any problems. The deformation of each coil plate became smaller than the previous deformation of 6-turn coil (A possible reason is that the deformation of each 5-turn coil plate (0.5 mm thick) became smaller than that of each 6-turn coil plate (0.3 mm thick) [15, 16].

In order to further reduce the deformation of each coil plate, it is preferable to fix the entire surface of both the coil



Fig. 7 Surface appearances of seam welded Al/Cu sheets.



Fig. 8 Cross-sectional appearance of Al/Cu sheets (E = 0.6 kJ).



Fig. 9 SEM images of weld interface in weld zones of Fig. 8.

and the sheets automatically and uniformly.

5. Summary

This welding method was started by rapidly flowing the damped oscillating discharge current from the capacitor bank through the 5-turn flat coil. Overlapped Al/Cu sheets having

the gap were fixed on the coil, and each sheet connected to both ends of the coil. The sheets collided at the peak discharge current. The current flowing through the coil commutated to the short-circuit including the collision part of both sheets, and the sheets could be welded as usual without melting or solidifying. The commutation current flowing to the coil did not oscillate. The current flowing to the bank also weakened its oscillation in a short time. The peak current in this case was 28 kA.

The above results are suitable for discharge devices. The semiconductor discharge switch has become easier to use. The life of the capacitor bank is also extended.

References

[1] A. Kapil, A. Shama: "Magnetic Pulse Welding: an efficient and environmentally friendly multi-material joining technique", Journal of Cleaner Production, Vol. 100, pp. 35-58, 2015.

[2] T. Aizawa, M. Yoshizawa: "Impulse magnetic pressure

seam welding of Aluminum and Copper sheets", Proc. 7th Int. Symp. of Japan welding Society, Kobe, Japan, pp. 295-300, 2001.

[3] M. Watanabe, S. Kumai, T. Aizawa: "Interfacial microstructure of magnetic pressure seam welded Al-Fe, Al-Ni and Al-Cu lap joints", Materials Science Forum, Vol. 519-521, pp. 1145-1150, 2006.

[4] Y. Zhang, S. Babu, C. Prothe, M. Blakely, J. Kwasegroch, M. LaHa, G. Daehn: "Application of high velocity impact welding at varied different length scales", Journal of Materials Processing Technology, Vol. 211, pp. 944-952, 2011.

[5] T. Itoi, A. B. Mohamad, R. Suzuki, K. Okagawa: "Microstructure evolution of a dissimilar junction interface between an Al sheet and a Ni-coated Cu sheet joined by magnetic pulse welding", Materials Characterization, Vol. 118, pp. 142-148, 2016.

[6] I. Kwee, K. Faes: "Interfacial Morphology and Mechanical Properties of Aluminium to Copper Sheet Joints by Electro-magnetic Pulse Welding", Key Engineering Materials, Vol. 710, pp. 109-114, 2016.

[7] K. Okagawa, T. Aizawa: "Effect of Gap and Characteristics on Seam Welding by Applying Magnetic Pressure", Journal of JSTP, Vol. 48, pp. 323-327, 2007. [8] T. Aizawa: "Electromagnetic Energy Transmission in Magnetic Pulse Welding of Al/Cu Sheets using 1, 3, 4 and 6 Turn Flat Coils", IEICE Technical Report, Vol. 117, No. 312, pp. 21-26, 2017.

[9] S. Kitagawa, K. Hirano: "Fast air gap crowbar switch decoupled by a low pressure gap", Rev. of Scientific Instrum., Vol. 46, No. 6, p.729-734, 1975.

[10] US Patent: "Crowbar switch", US3944887A, Publication, 1976.

[11] T. Aizawa: "Crowbar Switching System without Ripple Components in Load Current", Transactions on Institute of Electrical Engineers of Japan Vol. 102-B, No. 3, p.186, 1982.
[12] T. Aizawa: "Magnetic pressure seam welding method for aluminum sheets", Welding International, Vol. 17, pp. 929-9 33, 2003.

[13] T. Aizawa, M. Kashani, K. Okagawa: "Application of Magnetic Pulse Welding for Aluminum Alloys and SPCC Steel Sheet Joints", Welding Journal, Vol. 86, pp. 119s -124s, 2007.

[14] T. Aizawa, M. Kumagai, M. Matsuda: "Magnetic Pressure Seam Welding of Various Aluminum Alloy Sheets", IEICE Technical Report, Vol. 104, No. 574, pp. 7-12, 2004.

[15] T. Aizawa: "Magnetic Pulse Welding of Al/Cu Sheets using 6-Turn Flat Coil", Proc. of 10th Int. Conf. on Trends in Welding Research, Tokyo, Japan, pp. 964-967, 2016.

[16] T. Aizawa: "Magnetic Pulse Seam Welding of Al/Cu Sheets using 6-Turn Flat Coil", IEICE Technical Report, Vol. 116, No. 135, pp. 31-36, 2016.

[17] T. Aizawa: "Magnetic pulse welding method commutating discharge current to collision part of Al/Cu Sheets", IEICE Technical Report, Vol. 119, No. 84, pp. 1-6, 2019.

[18] T. Aizawa: "Magnetic pulse welding method commutating discharge current to collision part of Al/Cu Sheets (2nd Report)", IEICE Technical Report, Vol. 119, No. 234, pp. 1-6, 2019.

[19] T. Aizawa: "Magnetic pulse welding method: Discharge current commutates to collision part of Al/Cu sheets", IEICE Technical Report, Vol. 119, No. 294, pp. 1-4, 2019.

[20] T. Nakamura, T. Kobayashi, H. Morimoto: "Resistance Welding", 2nd Edition, SANPO PUBLICATIONS, INC, Tokyo, pp. 146-147, 1976, in Japanese.

[21] A. Ben-Artzy, A. Stern, N. Frage, V. Shribman, O. Sadot: "Wave formation mechanism in magnetic pulse welding", International Jounal of Impact Engineering, Vol.37, pp. 397-404, 2010.

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