Electromagnetic Energy Transmission in Magnetic Pulse Welding of Al/Cu Sheets using 1, 3, 4 and 6 Turn Flat Coils

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Abstract A high pulse current from a capacitor bank is discharged through an insulated flat coil for magnetic pulse welding of sheets. The sheets (Al/Cu) with a gap are overlapped and fixed on the coil. Electromagnetic coupling exists between the coil and the Al sheet near the coil. This study shows the transmission efficiency of the electromagnetic energy which move from the bank to the coil by using equivalent discharge circuits. The welding is carried out by the energy that moved to the coil. Since the efficiency improves as the equivalent coil inductance increases, the 6 turn flat coil is most effective compared to other coils with fewer turns. The efficiency of the 1, 3, 4 and 6 turn flat coils was calculated based on the welding experiments.

Keywords Electromagnetic energy, Energy transmission, Magnetic pulse welding, Flat coil, Discharge circuit, Equivalent circuit, Electrical connection, Al/Cu

1. Introduction

In recent years, the necessity of welding aluminum (Al) to copper (Cu) for electrical connection is increasing [1]. However, this welding is not easy from the difference in physical quantities such as melting point. For this reason, a brittle intermetallic compound which is not suitable for the welding occurs at the welded interface [2]. There are few efficient and excellent welding methods for Al/Cu sheets (or plates).

Magnetic pulse welding belongs to solid-state welding, among which it belongs to an impact welding group similar to explosive welding. This welding of Al/Cu sheets has the greatest advantage that the formation of the brittle intermetallic compound is avoided. The welded interface of Al/Cu sheets shows wavy interface morphology like explosive welding [3-10]. The microstructure of the interface has been studied in detail and the high quality magnetic pulse welds (Al/Cu) have been obtained [5-10]. Welding type is lap welding where impact electromagnetic energy (actually, a physical quantity called work by electromagnetic force) is used.

Its technique is based on discharging the high pulse current from the capacitor bank through the single-turn or multi-turn flat coil to produce electromagnetic forces. The Al/Cu sheets with the gap are overlapped and fixed on the coil. The Al sheet near the coil is electromagnetically coupled with the coil. When the pulse current flows through the coil, a magnetic flux (B) is suddenly generated under the Al sheet and penetrates into the sheet. Numerous micro-closed eddy currents flow through the Al sheet to hinder its further penetration. 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. As a result, strong electromagnetic forces (or magnetic pressure) act on the Al sheet. This sheet is accelerated and collides with the Cu sheet and both are welded. At this time, the electromagnetic energy transferred from the bank to the coil is used. If the energy transmission efficiency is good, the welding can be done with the small bank energy.

The author welded Al/Cu sheets using the multi-turn flat coil [11-15]. The use of the multi-turn coil is known to reduce the high pulse current for the welding. In addition, this use will cause more energy to move to the coil. The transmission efficiency using the equivalent discharge circuit electromagnetically coupled with the Al sheet has been calculated for the single-turn coil [16,17].

This paper also shows the transmission efficiency using

the same equivalent discharge circuit [15-17]. It is shown that the efficiency becomes considerably good, if the equivalent coil inductance increases in comparison with other inductance of the discharge circuit. The efficiency was calculated based on the experiments using the 1, 3, 4 and 6 turn flat coils.

2. Experimental apparatus and materials

Figure 1 shows a block diagram of an experimental apparatus for the welding Al/Cu sheets using the 6 turn coil, for example. The discharge circuit consisted of the capacitor bank, a discharge switch, the coil and low inductance transmission lines. Figure 2 shows the appearance of the discharge circuit for photography. The capacitor bank (capacitance C=24 μ F) consisted of four capacitors of 6 μ F in parallel. The capacitance was chosen to be relatively small, to use with 1 to 6 turn coils. The residual inductance of the bank was 0.01 µH. 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. Al/Cu sheets having the gap were fixed on the coil. When the switch was closed and discharged, the damped oscillating current flowed through the coil. The welding process was completed by one shot of the discharge. Discharge current waveforms were observed as shown in Fig. 1.

The 6 turn coil was made by six insulated E-shaped Cu alloy plates (0.3 mm thick) shown in Fig. 3. A narrow central part of each plate was 5 mm wide and 110 mm long. The plates were piled up with the same width. Four places on the lower side of each plate were soldered for electrical connection. The total thickness of the 6 turn coil was approximately 3 mm including insulators between each plate. The insulators were polyimide of 0.1- 0.2 mm thick. After these connections, insulation and fixation, the discharge current can flow through each central part for 6 turns.

The 1, 3 and 4 turn coils were made in the same way as the 6 turn coil. However, the thickness of each plate of 1, 3 and 4 turn coils was 3, 1 and 0.5 mm, respectively.

Details of experiment procedure using each coil and experimental results are given in others [11-14].

3. Discharge circuit and its equivalent circuit

If Al/Cu sheets are not on the coil, the discharge circuit



Fig. 1 Block diagram of experimental apparatus.



Fig. 2 Appearance of discharge circuit for photography.



Narrow central part



- Fig. 4 Capacitor discharge circuit (a) and its equivalent circuit (b) without Al/Cu sheets.
- *C* is bank capacitance. *Lr* is total equivalent residual inductance. *Lc* is coil inductance. *Rc* is coil resistance.
- R is total equivalent resistance.

with the switch closed is drawn like Fig. 4 (a) [15-17]. The discharge current (I) flows in the circuit. Here, C is the bank capacitance, Lc the coil inductance and Rc the coil resistance. There are both L_1 (inductance) and R_1 (resistance) in series with C in the bank. Similarly, in the discharge switch, there are L_2 and R_2 , and in the transmission lines, there are L_3 and R_3 . When we add up same elements, the equivalent circuit of Fig. 4 (a) is given like Fig. 4 (b). Lr and R are called the total equivalent residual inductance and the total equivalent the current (I) flowing from the bank has the same result in Fig. 4 (a) and (b).

If Al/Cu sheets are on the coil, the equivalent discharge circuit with the switch closed becomes like Fig. 5 (a). This circuit is composed of a primary side circuit including C and a secondary side circuit of the Al sheet, like two winding transformers. The coil inductance Lc couples electromagnetically with the Al sheet equivalent inductance Ls



- Fig. 5 Equivalent circuit (a) and its simplified equivalent circuit (b) with Al/Cu sheets.
- C is bank capacitance.
 Lr is total equivalent residual inductance.
 Lc is coil inductance.
 R is total equivalent resistance.
 Ls is Al sheet equivalent inductance.
 Rs is Al sheet equivalent resistance.
 M is mutual inductance between coil and Al sheet.
 Le is equivalent coil inductance.
 Re is total equivalent resistance.
 Le and Re were referred to primary side.

through mutual inductance M. Rs is the sheet equivalent resistance. Eddy currents flow in the sheet (the secondary side). All the secondary side quantities in Fig. 5 (a) can be referred to primary side, so the simplified equivalent circuit is given like Fig. 5 (b). Here, small quantities such as capacitive reactance between the coil and the sheet were ignored. *Le* is called the equivalent coil inductance and *Re* the total equivalent resistance. It can be said that the coil inductance *Lc* changes to *Le* when the sheet is on the coil and the welding is performed.

4. Transmission efficiency of energy

We explain the efficiency (or ratio) that the bank energy moves to the coil during the welding. Here, the simplified equivalent circuit (Fig. 5 (b)) is used. The bank energy charged by initial voltage V_{θ} is $(1/2) CV_{\theta}^2$ and stored as an electric field. We start the discharge of this energy at the time of t = 0.

$$\frac{1}{2}L_e I^2 = \frac{1}{2}CV_o^2 - \frac{1}{2}L_r I^2 - \int_0^{tm} R_e I^2 dt \tag{1}$$

$$\eta = \frac{\frac{1}{2}L_e I^2}{\frac{1}{2}CV_0^2} = \frac{L_e}{L_e + L_r} \left(1 - \frac{\int_0^{tm} R_e I^2 dt}{\frac{1}{2}CV_0^2} \right)$$
(2)

$$T_1 = 2 \pi \sqrt{(L_e + L_r) C}$$
(3)

$$T_2 = 2 \pi \sqrt{L_r C} \tag{4}$$

$$\eta = \frac{L_e}{L_e + L_r} \qquad \text{(Approximate expression)} \tag{5}$$

When the bank energy $(1/2) CV_0^2$ becomes zero at t = tm, the discharge current (*I*) flowing through the circuit reaches its peak (maximum value). The equivalent inductance *Le* has the energy of $(1/2) Le I^2$ given by Eq. (1) at t = tm. The term including *Re I*² is energy loss of the equivalent resistance. The energy of $(1/2) Le I^2$ is stored as a magnetic field around the coil, and $(1/2) Lr I^2$ is stored around the equivalent residual inductance. Such magnetic energies occur to all parts which the current flows through in this way. Since the Al sheet moves, the inductance *Le* increases (or is not constant). In addition, the energy $(1/2) Le I^2$ is partially used for the acceleration and the plastic deformation of the Al sheet. However, we assume that the energy $(1/2) Le I^2$ is constant for convenience.

The transmission efficiency (or ratio) η of the electromagnetic energy from the bank to the coil can be shown in Eq. (2) at t = tm. When all the bank energy moves to the coil (or *Le*), this efficiency becomes 1. Actually, it is less than 1 from Eq. (2). The efficiency at other time $(t \neq tm)$ is similar about the partial energy that is discharged by the bank, too. The methods to make better efficiency are as follows.

(1) We make the equivalent coil inductance Le greater than the residual inductance Lr.

(2) We lower the equivalent resistance Re.

(3) We perform the welding (i.e. the high speed collision) at near the time of t = tm with the first half oscillation (or half cycle) of the damped oscillating current.

5. Calculation of inductance and efficiency

We show the calculation method of the inductances (*Le* and *Lr*) in Fig. 5 (b) necessary to obtain the efficiency η . Because the total equivalent resistance *Re* is very small, relational expressions are given in Eq. (3) and Eq. (4). In these Equations, *T*₁ is a period (periodic time) of the oscillating current waveform when discharged to the coil having the sheet. Similarly, *T*₂ is a period of the waveform when we short-circuited the input and output terminals of the coil. Each period can be measured by an oscilloscope as shown in Fig. 1. The period *T*₁ is not constant and it increase slightly with time. Here, we use the average period *T*₁.

Usually, the welding process is over at the first half oscillation and the resistance *Re* is very small. The efficiency η can be obtained by the approximate expression of Eq. (5). Using Eq. (3) - Eq. (5) we can calculate the inductances *Le* and *Lr* and the efficiency η considerably well.

6. Calculation Results

Table 1 shows the calculation results of the equivalent inductance *Le*, the residual inductance *Lr* and the efficiency η for four kinds of coils. Since the inductance *Lr* of our discharge circuit was relatively small as 0.02 µH, each

Table 1. Approximate calculation results of inductances and energy transmission efficiency in simplified equivalent circuit using 1, 3, 4 and 6 turn coils. Bank capacitance $C=24 \mu F$, Total thickness of each coil is about 3 mm.

Number of coil turns	welding length [mm]	Inductance Le [µH]	Inductance Lr [µH]	efficiency η	Reference number
1	100	0.04	0.02	0.67	[14]
3	100	0.34	0.02	0.94	[11]
4	100	0.58	0.02	0.97	[14]
6	100	1.3	0.02	0.98	[12,13]

efficiency was calculated above 0.6. Of these, the 6 turn coil was the best efficiency. The experiments necessary for the calculation were carried out under the same conditions as possible using Al/Cu sheets. The high-speed collision of the sheets was near the time of t = tm. The seam-welding length of sheets was 100 mm. The central part length of the coil was approximately equal to the seam-welding length, or it was slightly long.

Relationship between the efficiency η and the residual inductance *Lr* are shown in Fig. 6 for the 1, 3 and 6 turn coils of Table 1. When the residual inductance *Lr* is bigger than approximately 0.2 µH, the use of the multi-turn coil may be necessary for the welding length of 100 mm. Otherwise, it is necessary to increase the bank's own energy considerably in order to increase the electromagnetic energy transferred to the coil for the welding.

7. Summary

This paper described the transmission efficiency η of the electromagnetic energy which move from the bank to the flat coil in magnetic pulse sheet-welding. Using the simplified equivalent discharge circuit, it was shown that the efficiency η became good, if the equivalent coil inductance *Le* increased as compared with the total equivalent residual inductance *Lr*. When the inductance *Lr* is large or can not be reduced, it is effective to use the multi-turn coil.

When using the multi-turn coil, other discharge circuit conditions such as bank capacity must be considered for the welding. The lifetime (or number of uses) of the 6 turn coil used for the welding is currently about 40 to 50 times [12, 13,15]. It is necessary to improve the multi-turn coil to prolong its lifetime.

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Fig. 6 Relationship between the efficiency η and the residual inductance *Lr* for 1, 3 and 6 turn coils.

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