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Magnetic Pulse Welding of Al/Cu Sheets Using 8-Turn Flat Coil

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Magnetic pulse welding of sheets is performed by rapidly discharging a large current from a capacitor bank to a flat coil. By increasing the number of coil turns, the current can be reduced. However, if the 8-turn coil of higher inductance is used, the current rise time will be longer. It may be difficult to efficiently weld sheets. In this paper, after charging the same two capacitors $(12 \,\mu\text{F})$ in parallel, they are discharged in series to reduce the bank capacity. The current rise time is improved, and efficient welding results will be obtained. The overlapped Al/Cu sheets with a gap are fixed on the coil. When the series discharge current flows through the coil, a high density magnetic flux rapidly generates around the coil and electromagnetic forces act on the Al sheet near the coil. This sheet collides with the Cu sheet at high speed and both sheets are welded. The bank energy and the parallel charging voltage required for welding are 0.70 kJ and 7.6 kV respectively, and the reduced peak discharge current is 21 kA. The interface of the welded sheets is observed.

Key Words: Magnetic pulse welding, Sheet welding, 8-turn flat coil, Discharge current, Parallel-charge, Series-discharge

1 Introduction

In recent years, the necessity of welding aluminum to copper for electrical connection is increasing¹⁾. 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 may occur at the welded interface²⁾. There are few efficient and excellent methods of welding Al to Cu.

Magnetic pulse welding belongs to impact welding similar to explosive welding^{3),4)}. When the impact occurs, metal jets are generated and the welding surface is cleaned⁵⁾. This welding is suitable for joining dissimilar metals. The welded interface of Al/Cu sheets shows wavy interface morphology and high quality welds have been obtained^{6)~9)}. The mechanism and features of such welding are considerably well known.

Technically, the large current is discharged rapidly from the capacitor bank to the flat coil. When using the E–

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Received: 2019/6/8 Accepted: 2020/1/31 shaped 1-turn coil and the bank capacity of 400 μ F, the peak discharge current required for Al/Cu sheets welding was over 150 kA^{6),8)}. The peak discharge current has been reduced to 25 kA by using the 6-turn coil and reducing the capacity to 24 μ F¹⁰⁾. Such capacity reduction will effectively reduce the rise time increase due to the increase in coil inductance. However, if we use the 8-turn coil of higher inductance, the current rise time will be longer. It may be difficult to weld Al/Cu sheets efficiently with the same energy and charging voltage.

In this paper, after charging the same two capacitors in parallel, they are discharged in series to reduce the bank capacity. It is also possible to reduce the discharge capacity without increasing the charging voltage with the same discharge energy. The current rise time is improved with almost the same energy and charging voltage as before. The sheets were efficiently impacted and welded near the peak of the discharge current as before^{10)~12)}. We will describe the results of magnetic pulse welding of Al/Cu sheets using the parallel-charge series discharge method and the 8–turn coil.

The purpose of this experiment is to reduce the welding discharge current. By using the coil of 8 turns or more and reducing the discharge current, easy-to-use semiconductor discharge switches can be used in the future.

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Fig. 1 Block diagram of parallel-charge seriesdischarge circuit.

2 Experimental procedure

The block diagram of the parallel-charge seriesdischarge circuit is shown in **Fig. 1**. The same two capacitors (each 12μ F) were charged in parallel and then they were discharged in series by triggering the same two spark gap discharge switches. The oscillating discharge current (*I*) flowed through the discharge circuit along the dotted line. The parallel charge voltage was 7.6 kV, and after series discharge, the capacity of the bank became 6μ F. The bank energy for charging and discharging was 0.70 kJ. During series discharge, the maximum voltage was about twice the charging voltage. Since this voltage was pulse and the generation time was about 100 μ s, it was easy to insulate.

The Al/Cu sheets with the gap were overlapped and fixed on the coil. The Al sheet near the coil was insulated in a DC manner from the coil, but there was electromagnetic coupling between them. When the series discharge current flowed through the coil, the magnetic flux (density B) was suddenly generated under the Al sheet and penetrates into the sheet. Eddy currents passed through the Al sheet to prevent further penetration. As a result, electromagnetic forces acted on the Al sheet (flyer sheet). This sheet was accelerated and collided with the Cu sheet and both sheets were welded.

Fig. 2 shows the appearance of the discharge circuit without the upper fixture etc. Each 12 μ F capacitor consisted of two parallel 6 μ F capacitors. The capacitors, the switches and the coil were placed as close as possible to reduce the inductance of the transmission lines. The welding process ended with one parallel charge and series discharge.





Fig. 2 Appearance of parallel-charge seriesdischarge circuit.



Fig. 3 Appearance of 8-turn flat coil.



Fig. 4 Appearance of eight E-shaped coil plates.

Fig. 3 shows the appearance of the 8-turn coil for photography without insulating sheets. When the discharge current flowed through the coil, the magnetic flux was generated around a narrow central part of the coil. The coil consisted of eight E-shaped Cu alloy plates shown in **Fig. 4**. The narrow central part of each plate was 5 mm wide and 110 mm long. The plates were piled up with the same

width. The lower 4 parts of each plate were soldered for electrical connection. Each plate was electrically insulated and the current flowed through the central part of each plate in series. The thickness of each plate was 0.3 mm. The total thickness of the coil including the insulating polyimide sheets and the air attached to them was 4 to 5 mm. The improved part of Fig. 4 will be described later.

The Al (A1050) and Cu (C1220) sheets were 100 mm long, 100 mm wide and 0.4 mm thick. The Al/Cu sheets were overlapped by 50 mm with the gap of 0.5 mm and fixed on the coil.

Discharge current signal and collision time signal were measured in the same way as in the previous paper¹⁰. The current measurement was performed using a current measurement small coil near the discharge circuit. This coil electromagnetically coupled to the discharge circuit and detected a voltage signal proportional to the time derivative of magnetic flux (\mathbf{B}) or discharge current (I). The detected voltage signal was converted to a voltage signal indicating the current (I) through a measurement circuit with an integrator. The converted voltage signal of the current (I) was observed with an oscilloscope as a current signal waveform. This 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 collision time signal was measured using two leads coming directly from the Al and Cu sheets. After the two sheets contacted (or collided), the voltage change that generated in the closed circuit including the contact sheets was observed with the oscilloscope through a measurement circuit with an isolation transformer.

Interface observations of the welded Al/Cu sheets were done by asking a professional company.

3 **Experimental results**

3.1 Discharge current and collision time signals

Typical discharge current and collision time signals are shown in Fig. 5. In both signal waveforms, large discharge noises occurred at the start of signals, and small noises occurred thereafter. The damping and oscillating current flowed through the 8-turn coil for duration of about 100 μ s. In measurement the oscillating period was $23 \,\mu s$. The inductance of the coil was about $2.2 \,\mu\text{H}$, which was about 55 times the inductance of the conventional 1-turn coil. When the discharge energy is 0.70 kJ, the peak discharge current is 21 kA and the peak magnetic flux (\mathbf{B}) is about 15 T. The sheets collided (or impacted) near the peak current and the

required time (collision time) was $4.0 \,\mu s$ after the start of the signals. The collision speed when the sheets collided was calculated roughly with 250 m/s. This speed was similar to the previous $paper^{10}$.

3.2 Surface appearance and side view

Fig. 6 shows a surface appearance of the welded Al/Cu sheets taken from the Al sheet side. A part of the Al sheet deformed toward the Cu sheet along the narrow central part. The weld zones (usually two seam welds) were in the deformed region with a length of 100 mm and a width of about 10 mm. Fig. 7 shows a side view of the welded



Fig. 5 Discharge current signal and collision time signal.

Deformed and seam weld zones





Deformed and seam weld zones



Fig. 7 Side view of welded Al/Cu sheets.

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Central part of coil (5 mm wide)

Fig. 8 Cross sectional appearance of welded Al/Cu sheets.



Fig. 9 SEM images of each weld zone.

sheets. The welding of the ends was not sufficient.

3.3 Interface observation

The sheets (each 0.4 mm thick) were cut perpendicular to the seam weld direction and polished for the interface observation. **Fig. 8** shows a cross-sectional appearance of the welded Al/Cu sheets. 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. These are almost the same as when using the previous 6-turn flat coil¹⁰). **Fig. 9** is SEM images of each weld zone. The welded interface exhibited wavy interface morphology similar to conventional magnetic pulse welding. Wavy interfaces are described in detail elsewhere¹³).

3.4 Deformation of coil plate

The experiments using the same coil could be continued about 60 times or more. The deformation of each coil plate became smaller than the previous deformation of 6-turn coil¹⁰⁾. The current through each plate of 8-turn coil was improved so as not to concentrate on the deformable area, as shown in **Fig. 10**. The current returning to the outside of the coil will flow away from the deformable region and the deformation will be improved. The improved parts of



Fig. 10 Schematic diagram of improved current flow.

each coil plate are shown in Fig. 4.

During the experiments, the coil and the Al/Cu sheets were fixed at several points manually using thick and rigid fixing-plates from above and below. The lower fixing-plate (coil side) was an insulating plate and the upper fixingplate was an insulated metal plate. The coil portion not covered by the sheets was also fixed by other fixing-plates. The coil pates were not fixed uniformly.

In order to further reduce the deformation of each coil plate, it is preferable to fix the entire surface of both the coil and the sheets automatically and uniformly.

4 Conclusion

This paper described the results of magnetic pulse welding of Al/Cu sheets, using the parallel-charge seriesdischarge capacitor bank and the 8-turn flat coil. The sheets were efficiently impacted and welded near the peak of the discharge current. The bank energy required for this welding was 0.70 kJ, the charging voltage of each capacitor was 7.6 kV, and the peak discharge current was 21 kA. The welded Al/Cu interface showed wavy interface morphology similar to conventional magnetic pulse welding.

Future work will need to reduce the deformation of coil plates and to increase the coil turns.

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