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Experiment and Numerical Analysis of Deformation and Collision Behavior during Al/Cu Magnetic Pulse Welding

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Abstract –To investigate high-speed deformation and collision behavior during Al/Cu magnetic pulse welding, experiment and numerical analysis were performed. An Al plate and a Cu plate were used for a flyer plate and a parent plate, respectively. Charging energy stored in a capacitor and a gap between the plates were changed in the range from 1.0 kJ to 6.0 kJ and from 1.0 mm to 2.5 mm, respectively. The charging energy from 4.0 kJ to 6.0 kJ were available to weld them with the gap from 1.5 mm to 2.5 mm. In contrast, when the charging energy of 3.0 kJ was used, the welding was achieved at the gap in 2.0 mm and 2.5 mm. Numerical analysis of deformation behavior revealed that the Al flyer plate deforms like a cantilever beam. The initial collision velocity increased with increasing the charging energy and the gap of plates. Whereas, the initial collision angle increased with only increasing the gap of plates and it did not depend on the charging energy. As the collision progressed, the collision velocity decreased and the collision angle increased.

Keywords: magnetic pulse welding, deformation behavior, collision behavior, aluminum, copper

1. Introduction

Copper is used in wide range of industry fields because of the electrical conductivity and thermal conductivity. However, the matter of increasing costs and weight occurs when the most of the product is made from copper. Therefore, it is desirable to partially replace copper with aluminum. In order to replace copper with aluminum, dissimilar-metal welding of aluminum and copper was required. When fusion welding is applied to Al/Cu welding, thick and brittle intermetallic compound (IMC) layers such as Al_2Cu, AlCu, Al_4Cu_9 and $AlCu_4$[1] are produced along the welding interface and the layer formation usually results in low joint strength. Therefore, solid-state welding is assumed to be one solution which prevents the formation of IMC layer. Magnetic pulse welding is classified as the solid-state welding, and is a kind of impact welding method [2]. High-speed oblique collision between multiple metals makes strong welding interface. The magnetic pulse welding is normally completed in the order of microseconds with a negligible temperature increase. This welding process can be applied to wide material combinations which are different in physical and mechanical properties such as melting point, thermal expansion coefficient and hardness [3-6]. The welding interface in the magnetic pulse welded joint exhibits a characteristic wavy form. Such the wavy interface is also observed in the joint fabricated by other impact welding methods such as explosive welding [7-9] and water jet welding [10].

In order to understand the mechanism of the magnetic pulse welding, reports of explosive welding which is a classical impact welding method were referred. In explosive welding, it is known that collision velocity and collision angle are important factors for achieving the welding [10]. To estimate the collision velocity and collision angle in magnetic pulse welding, it is necessary to understand the deformation and collision behavior which occurs in the order of microseconds. In the present study, magnetic pulse welding process was simulated using numerical analysis, and the collision velocity and collision angle which achieve a sound welding were accurately estimated by combining the results of the numerical analysis with the experimental results.

2. Experimental Procedure and Numerical Analysis

2.1. Principle of magnetic pulse welding and welding condition

Figure 1(a) shows a schematic diagram of discharge circuit. The circuit consists of a capacitor for a supply of electrical energy, a discharge gap switch and a one-turn coil. The two plates are placed above the coil with a little gap. The plate near the coil is termed the "flyer plate" and the plate above it, which is fixed firmly in place, is referred to as the "parent plate". When the capacitor is charged and gap switch is closed, a discharge pulse is released to the coil. Figure 1(b) shows a close-up around the coil. When the discharge pulse runs through the coil from the capacitor, it induces high-density magnetic flux around the coil. The generated magnetic flux lines intersect with the flyer plate, and then in accordance with Lentz's law, eddy currents are excited in the surface of the flyer plate adjacent to the coil. In according to Fleming's left-hand rule, the eddy current and the magnetic flux induce an electromagnetic force upward. The electromagnetic force drives the flyer plate toward the parent plate at a high velocity and the flyer plate is welded to the parent plate.

In the present study, a magnetic pulse system (Bmax, MP 12.5/25, capacitance of a capacitor: 40 μF) was used for performing magnetic pulse welding. A pure aluminum (A1050, hereafter Al) and a copper (C1100, hereafter Cu) plates were used as the flyer plate and parent plate, respectively. Before welding, both plates were rinsed in acetone with an ultrasonic cleaner and then dried well. The coil is made of Cu-Cr-Zr alloy and the cross-sectional shape is trapezoidal (length of upper surface: 3.0 mm). The flyer plate was fixed by overlapping the upper surface of the coil with a width of 3.0 mm, and then the parent plate was set with a little gap over the flyer plate. The charging energy and the gap between the plates were changed in the range from 1.0 kJ to 6.0 kJ and from 1.0 mm to 2.5 mm, respectively.

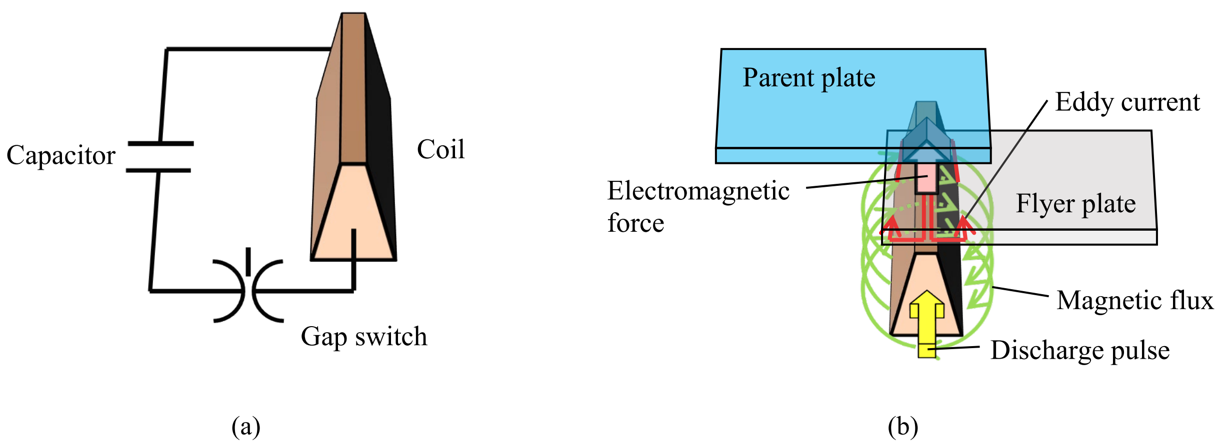
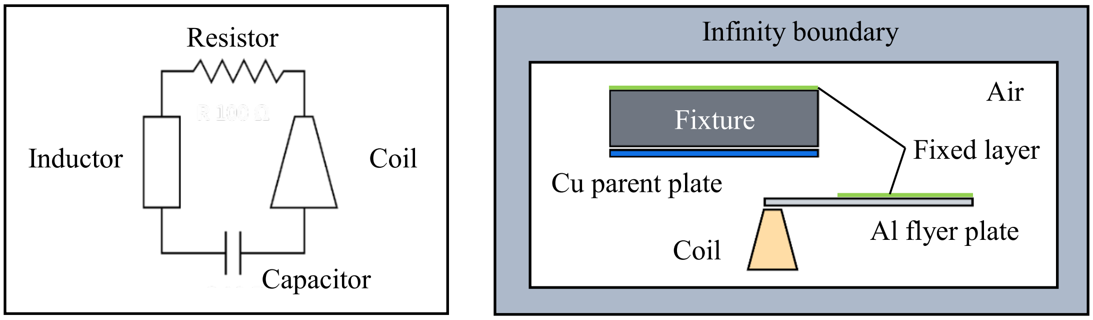


Fig.1 Schematic diagrams of principle of magnetic pulse welding.
(a) Discharge circuit. (b) Induction of electromagnetic force.

2.2. Numerical analysis of deformation and collision behavior

The deformation of the flyer plate by electromagnetic force was simulated by using ANSYS Mechanical Ansys Parametric Design Language (APDL). APDL uses finite element method (FEM) to reproduce situations. Figure 2 shows the FEM model used. Table 1 shows mechanical properties of Al and Cu plates used for the numerical analysis. The coils in Figs. 2(a) and 2(b) were coupled. Figure 2(a) shows a FEM circuit which computes the current running through the coil. After the computing of the current, magnetic flux generated around the coil was calculated with the FEM model shown in Fig. 2(b). Then, the induced electromagnetic force was estimated, and deformation of the flyer plate was reproduced. The collision velocity and collision angle at the collision point were monitored from time to time from the moment of the initial collision between the flyer plate and the parent plate.



(a) (b)

Fig. 2 (a) FEM circuit and (b) FEM model used for numerical analysis.

Table 1 Mechanical properties of Al and Cu plates used for numerical analysis.

Mechanical property	A1050 (Al)	C1100 (Cu)	Air
Density [kg/m^3]	2707	8940	-
Young's modulus [GPa]	70.3	120	-
Poisson's ratio	0.33	0.33	-
Electrical resistivity [Ωm]	2.65×10^{-8}	1.68×10^{-8}	-
Relative permeability	1	1	1

3. Results and Discussion

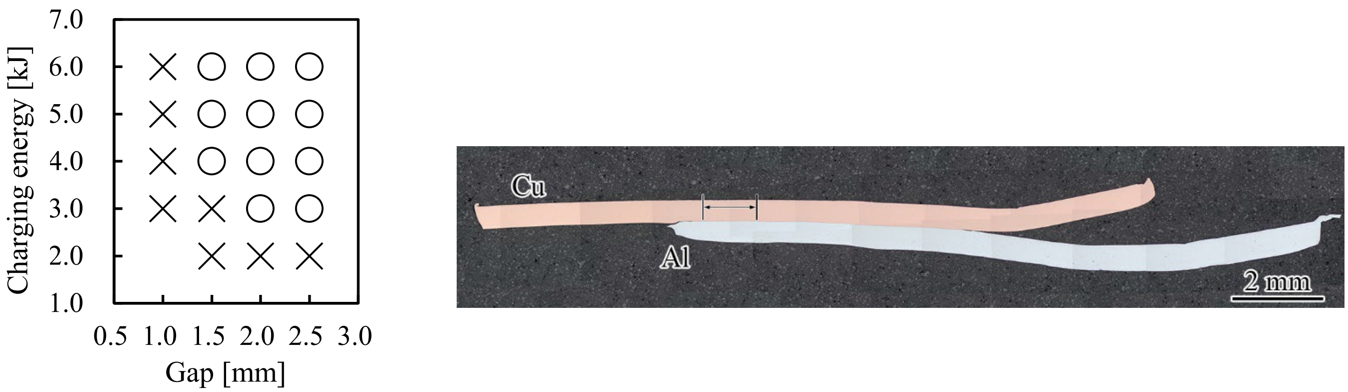
3.1. Investigation of weldable charging energy and gap between plates by welding experiment

Figure 3(a) shows experimental results of Al/Cu welding. An open circle and cross mark indicate the success and failure of welding, respectively. It was differed by combination of the charging energy and the gap between the plates. The charging energy from 4.0 kJ to 6.0 kJ were available to weld them with the gap from 1.5 mm to 2.5 mm. In contrast, when the charging energy of 3.0 kJ was used, the welding was achieved at the gap of 2.0 mm and 2.5 mm.

Figure 3(b) shows an optical micrograph of cross section of the area where the Al plate was pressed into the Cu plate in the joint formed with charging energy of 6.0 kJ and the gap between the plates of 1.5 mm. The Al plate was deformed toward the Cu plate and they were partially welded as indicated by arrow in Fig. 3(b). In any welding condition, no welding was observed at the interface corresponding to the vicinity of the Al tip, and the welded area was formed at next to the unwelded area. The widths of the unwelded area and the welded area ranged from 250 μm to 700 μm and 500 μm to 2400 μm, respectively. The width of the welded area tended to be shorter the larger the gap.

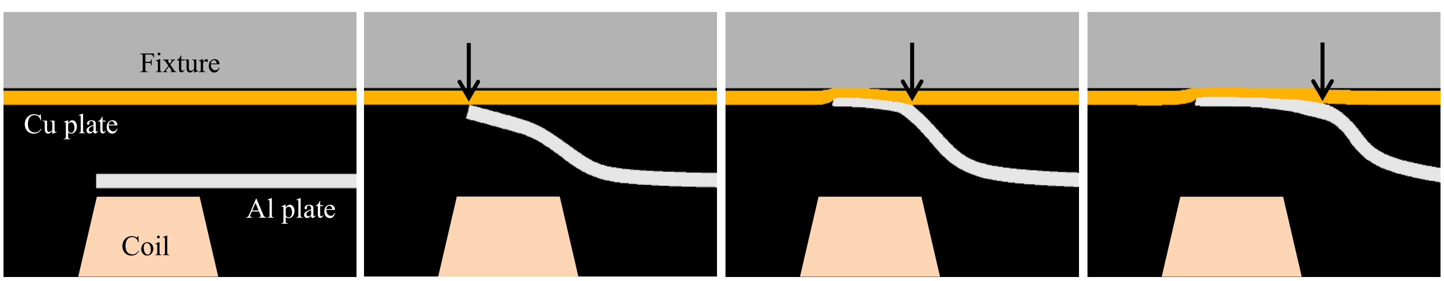
3.2. Deformation and collision behavior

Figure 4 shows the deformation and collision behavior reproduced by using the numerical analysis in Al/Cu welding. The tip of the Al flyer plate was lifted by electromagnetic force and the Al flyer plate deformed toward the Cu parent plate like a cantilever beam (Fig. 4(a) and 4(b)). Initial collision occurred between the tip of the Al flyer plate and the Cu parent plate (Fig. 4(b)), and the collision point indicated by arrow moved with increasing the collision angle (Fig. 4(b)-4(d)). The time from the discharge of current to the coil to the initial collision, t_I, shortened with increasing the charge energy or decreasing the gap between the plates. In the present condition of charging energy and gap between the plates, the t_I was estimated to be 7 ~ 12 microseconds. This time range almost corresponds to the time measured in the welding experiment[2,3]. Also, the collision in the welded area finished in 2 microseconds. Figure 4(d) shows the shapes of the Al and Cu plates after collision obtained by using FEM analysis. These shapes were similar to the experimentally oberved cross-sectional shape of the Al/Cu joint as shown in Fig. 3(b). This indicates that the present numerical analysis simulates the actual welding process well.



(a) (b)

Fig. 3 (a) Relationship among charging energy, gap between plates and weldability in Al/Cu welding.
(b) Optical micrograph of cross section of joint welded at charging energy of 6.0 kJ and gap between plates of 2.5 mm.



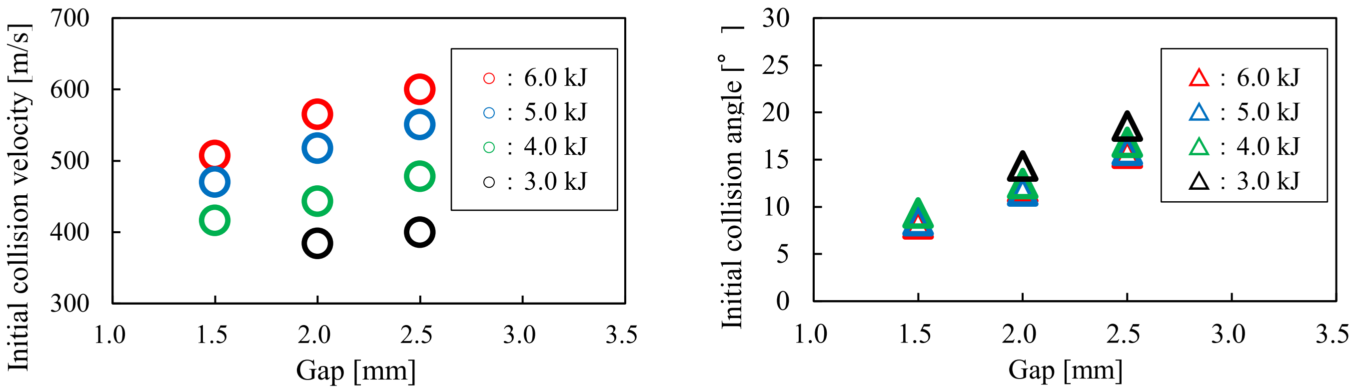
(a) (b) (c) (d)

Fig. 4 Deformation and collision behavior of the plates.
(a) Before welding. (b) Initial collision. (c) 2 μs after initial collision. (d) After welding.

3.3. Initial collision velocity and initial collision angle

Relationship among initial collision velocity, charging energy and gap between the plates is shown in Fig. 5(a). The initial collision velocity increased with increasing the charging energy and the gap between the plates. Figure 5(b) shows relationship among initial collision angle, gap between plates, and charging energy. The initial collision angle increased with increasing the gap between the plates, but it did not change with the charging energy. The charging energy dependence and gap dependence of the collision velocity and collision angle were independent of the parent plate material, and similar tendency was observed for Al/Al welding and Al/Mg welding.

As shown in Fig. 4, in magnetic pulse welding, a flyer plate deforms like a cantilever beam by electromagnetic force through the gap between the plates toward a parent plate. The electromagnetic force is generated by indirect conversion from the charging energy. Therefore, in case of the constant gap between the plates, the higher charging energy is considered to lead the higher deformation rate of the flyer plate and result in the faster initial collision velocity. Also, the initial collision velocity increased with increasing the gap between the plates, as shown in Fig. 5(a). This is considered to indicate that the flyer plate is accelerating in the gap of 2.5 mm. The gap between the plates is positively correlated with the deformation distance of the flyer plate to the collision of the flyer plate and the parent plate. Since no change in the deformation shape of the flyer plate due to the charging energy or gap between the plates was observed, the collision angle increased with increasing the gap between the plates and it does not depend on the charging energy.



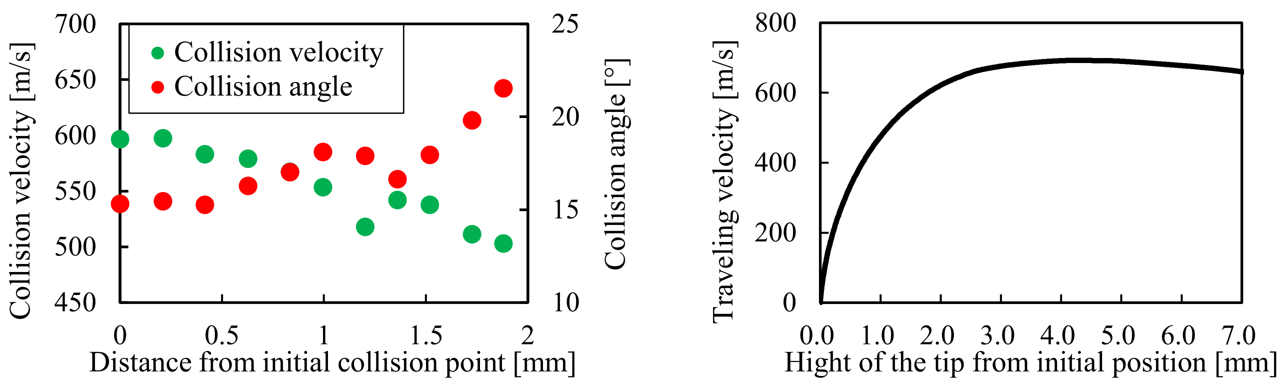
(a) (b)

Fig. 5 (a) Relationship among initial collision velocity, charging energy and gap between the plates.
(b) Relationship among initial collision angle, charging energy and gap between the plates.

3.4. Collision velocity and collision angle of flyer plate

In order to investigate collision velocity and collision angle during the collision at the welded area and unwelded area, experimental and analysis results were compared. Figure 6(a) shows the transition of collision velocity and collision angle with charging energy of 6.0 kJ and the gap between the plates of 2.5 mm simulated by FEM. As the collision progressed, the collision velocity decreased and the collision angle increased. This tendency of change in collision velocity and collision angle was similar regardless of the welding condition.

In order to investigate the traveling behavior of Al flyer plate in the gap of plates, the simulation was performed with a gap of 7.0 mm, larger than in the experiment. Figure 6(b) shows the traveling velocity of the tip of the Al flyer plate with charging energy of 6.0 kJ. The traveling velocity increased until the tip of the Al flyer plate was approximately 4.3 mm above the initial position, then slightly decreased. Therefore, within the range of weldable gaps in this study, the Al flyer plate continued to accelerate until it collided to the Cu parent plate.



(a) (b)

Fig. 6 (a) Position dependence of collision velocity and collision angle.
(b) Time variation of travelling velocity of the tip of Al flyer plate.

Figure 7 shows the relationship between collision velocity and collision angle which occurred in the area where the Al/Cu welding was achieved. It was found that the range of collision velocity and collision angle at which the welding was achieved is almost similar, even when the combination of the charge energy and gap between the plates is varied. This indicates that it is important to control the collision velocity and collision angle to achieve the welding in magnetic pulse welding as well as in explosive welding.

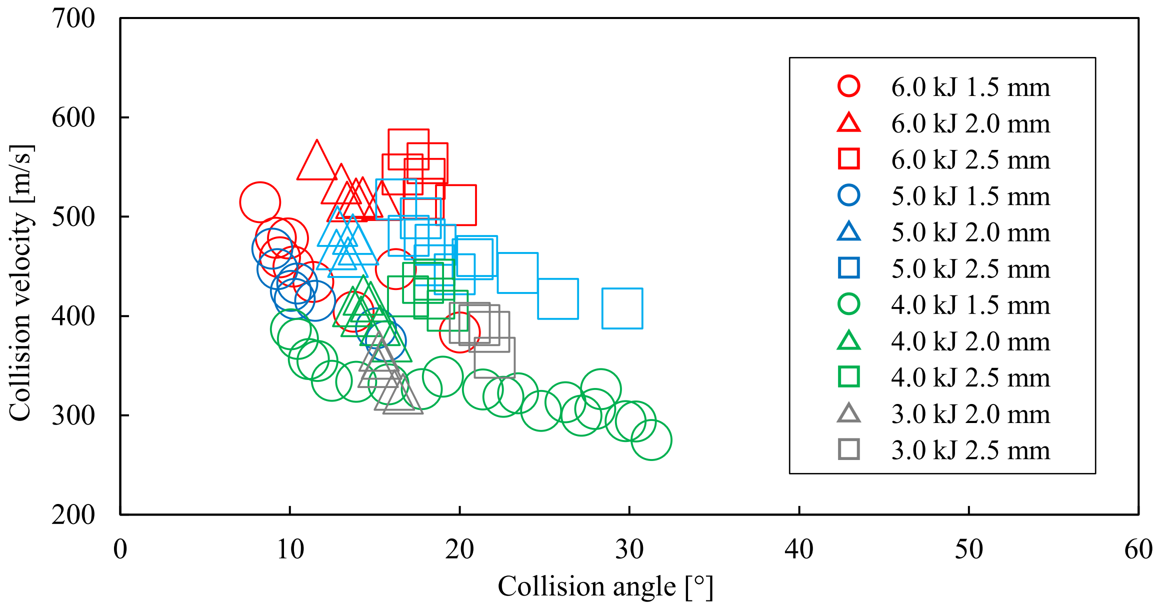


Fig. 7 Relationship between collision velocity and collision angle
which occurred in the area where the Al/Cu welding was achieved.

4. Conclusions

The deformation and collision behavior of the Al flyer plate and Cu parent plate during magnetic pulse welding process were analyzed by using experiment and numerical analysis. The obtained results are summarized as follows.

(1) Al flyer plate was lifted by electromagnetic force and the Al flyer plate deformed toward the Cu parent plate like a cantilever beam. Initial collision occurred between the tip of the Al flyer plate and the Cu parent plate, and then the collision point moved with increasing the collision angle.

(2) The initial collision velocity increased with increasing the charging energy and the gap between the plates. The initial collision angle increased with increasing the gap between the plates, but it did not change with the charging energy.

(3) As the collision progressed, the collision velocity decreased and the collision angle increased.

(4) The traveling velocity of the Al flyer plate increased up to the gap of 4.3 mm and then slightly decreased. This indicates that the Al flyer plate is accelerating in the range of gap where the welding was achieved in the present study.

(5) It was found that the range of collision velocity and collision angle at which the welding was achieved is almost similar, even when the combination of the charge energy and gap between the plates is varied. This indicates that it is important to control the collision velocity and collision angle to achieve the welding in magnetic pulse welding as well as in explosive welding.

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