Simulation and Experimental Analysis of Metal Jet Emission and Weld Interface Morphology in Impact Welding*1

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Metal jet emission and weld interface formation in impact welding were investigated for similar- and dissimilar-metal lap joints. Numerical simulation of oblique collision between metal plates was performed using smoothed particle hydrodynamics (SPH) method for various plate thicknesses, collision velocities, and collision angles. Metal jet emission and formation of the characteristic wavy weld interface in impact welding were reproduced successfully. The composition of the metal jet was governed by the degree of relative density difference between two metals. When the density difference was large, such as Al/Cu and Al/Ni lap joints, the metal jet was mainly composed of the metal component with lower density, Al. On the other hand, when the density difference was small or zero, such as for Cu/Ni and Al/Al lap joints, the metal jet was composed of both metal components. Several types of lap joints were fabricated by magnetic pulse welding (MPW). Metal jets emitted from Al/Cu and Cu/Al lap joints were collected, and their components were analyzed by X-ray diffraction. The microstructure of the weld interface was also examined. The experimental results were in good agreement with the simulation results.

Keywords: impact welding, interface morphology, metal jet, magnetic pulse welding, smoothed particle hydrodynamics

1. Introduction

Impact welding is one of the solid-state welding methods. There are several impact welding methods, including explosive welding,1) gas gun welding,2) magnetic pulse welding,3–5) and water jet welding.6) The impact welding methods are suitable for a wide variety of combinations of similar and dissimilar metals. Welding is achieved in a few microseconds. It is known that when metal plates collide with each other obliquely at high speed, such as several hundreds of meters per second, the surface layer of the plates are emitted as a metal jet. The metal jet emission results in formation of a refreshed cleaned surface on each plate. Application of high pressure at the collision point promotes strong metallic bonding of the atoms on the refreshed surfaces. It is known that the interface of an impact welded lap joint exhibits a characteristic wavy morphology.1–4)

These processes have been studied theoretically.5–7) In numerical analysis, we can freely choose the welding parameters, such as collision velocity, collision angle, metal combination, and shape of the plate. Generally, the numerical analysis is performed by using the Lagrangian method and the Euler method. However, it is difficult to reproduce the phenomena of wavy interface formation and metal jet emission. This is because those numerical methods cannot cope with heavy deformation at the collision interface and require an extremely small and infeasible mesh size in order to reproduce the detailed morphological change at the interface. Therefore, a mesh-less method has attracted much attention in this research field. The smoothed particle hydrodynamics (SPH) method is one such mesh-less analysis method. In the SPH method, particles are defined as interpolated points of physical quantities. Each particle moves without deforming itself during analysis. The diameter of a particle is defined as smoothed length $R$. The physical quantity of the particle is calculated in the next cycle in reference to neighboring particles inside a circle of radius $2R$.

In this research, the deformation behavior of metal plates in oblique collisions was simulated by using the SPH method. The emission behavior of the metal jet and the resultant interface morphology were investigated. In addition, several types of lap joints were fabricated by magnetic pulse welding and the emitted metal jet was collected. The chemical composition of the metal jet and the interface morphology were compared with simulation results.

2. Numerical Simulation

2.1 Analytic model

Numerical simulation was performed by using the hydrodynamic code AUTODYN. Figure 1 shows a schematic illustration of the oblique method analytic model. A flyer plate is inclined $\alpha$ degrees with respect to a parent plate and given the initial velocity of $V_i$ throughout the plate. The underside of the parent plate was fixed. In the present study,
we used a hybrid model consisting of two different solvers. The area that could suffer heavy deformation by collision was modeled by SPH. A Lagrange solver was used for other regions. The boundary between SPH and Lagrange solver regions was connected by using a join function. In this model, the collision velocity and the collision angle could be controlled freely and independently.

The Mie-Grüneisen of the shock Hugoniot equation of state and the Steinberg-Guinan strength were used in this study. Physical, chemical, and mechanical parameters of the materials were selected from the built-in material library of AUTODYN and from values reported by Steinberg.8) The length of the plate perpendicular to the plane was assumed to be infinite, since the symmetry system was 2D planar.

### 2.2 Analytic conditions

The analysis was conducted for two basic conditions as shown in Table 1. In the first case, the plate thickness was fixed to be 1.0 mm, except for the flyer plates of Cu/Al and Ni/Al lap joint, and the collision velocity and collision angle were varied. In the second case, the effects of plate thickness and collision velocity were examined for a fixed collision angle. The SPH region was set to be 100–300 μm in thickness. The smoothed length was decided according to plate size, since the number of the particles was limited. The effect of the mutual positions of the plates was also examined by replacing the flyer plate with the parent plate.

### 3. Experimental Procedures

#### 3.1 Magnetic pulse welding

In magnetic pulse welding, welding is achieved by driving the flyer plate to the parent plate.3,4) Figure 2 shows a schematic illustration of the discharge circuit of the apparatus. The discharge circuit consists of a capacitor, a discharge gap switch, and a one-turn flat coil. When a discharge pulse is released to the coil, high-density magnetic flux is induced around the coil. The magnetic flux intersects with the flyer plate and generates eddy currents according to Lentz’s law. The magnetic flux and the generated eddy currents produce electromagnetic force upward, as described by Fleming’s left-hand rule. The collision behavior in magnetic pulse welding was investigated by using a high-speed video camera.5) It was found that the central region of the flyer plate bulged radially and collided with the parent plate. The metal jet emission was also recorded clearly by the video camera.

#### 3.2 Materials and welding conditions for magnetic pulse welding

Pure aluminum (Al), pure copper (Cu), and pure magnesium (Mg) were used for the flyer and parent plates. Al (flyer plate)/Al (parent plate), Al/Cu, Cu/Al, Al/Mg, and Mg/Al lap joints were fabricated. The dimensions of the Al and Mg plates were 50 mm (width) × 100 mm (length) × 1.0 mm (thickness) for the flyer plate, and 10 mm × 100 mm × 1.0 mm for the parent plate. For Cu, the flyer plate was 50 mm × 100 mm × 0.3 mm, and the parent plate was 10 mm × 100 mm × 1.2 mm. Before welding, the plates were rinsed in acetone with an ultrasonic cleaner. The initial gap between the flyer and the parent plate was set to be 2.0 mm. The discharge energy was 2.5 kJ. Glass plates were inserted between the spacers to collect the metal jet emitted during the welding process.

#### 3.3 Microstructural observation of weld interface

The lap joints were cut perpendicular to the seam direction, and the cross section including the weld interface was polished. The microstructure was observed by optical microscopy and scanning electron microscopy.

#### 3.4 Analysis of metal jet composition

The metal jets collected during magnetic pulse welding of Al/Cu and Cu/Al were analyzed by X-ray diffraction. Analysis was conducted using a Cu target at an operating voltage of 35 kV and current of 300 mA. The scanning span was 20–80° with a step size of 0.015° and a speed of 0.5°/min.

### 4. Results and Discussion

#### 4.1 Interface morphology

Figure 3(a) shows the cross section of the weld interface of the magnetic pulse welded Al/Mg lap joint. Figure 3(b) shows a backscattered electron image of area “B” in (a). The
weld interface exhibits a clear wavy form which is characteristic of impact welded lap joints.\textsuperscript{1–4} It should be noted that the wavelength and amplitude of the interfacial wave changed gradually along the welding direction. This is attributed to the collision angle between the flyer plate and the parent plate gradually changing during magnetic pulse welding in the present setup, as confirmed in a previous work by the present authors.\textsuperscript{3}

Figure 4 shows the interface morphology obtained from the simulation. Three different patterns, namely, straight, wavy, and vortical, were obtained depending on the collision conditions. Under the constant collision angle conditions, the interface morphology changed from straight to wavy to vortical with increasing collision velocity. Figure 5 shows the interface morphology of the magnetic pulse welded Al/Cu and Cu/Al plates. The three patterns mentioned above were observed at the weld interface.

Figure 6 shows a schematic illustration of a typical welding window. The vertical axis represents collision velocity, and the horizontal axis represents collision angle. The weldable area and the corresponding weld interface morphology are indicated in the welding window. The shape of the welding window is almost equivalent for various types of similar- and dissimilar-lap joints. The relationship between collision angle and collision velocity in Cu/Cu explosive welding was examined by Jaramillo \textit{et al.} and they provided the welding window.\textsuperscript{9} What we can see from the welding window is as follows. For a fixed collision angle, as collision velocity increases, as shown by the dotted line Fig. 6(a), the interface morphology changes from straight to wavy. The vortical form is possibly the extreme of the wavy form. This corresponds to the simulation results shown in Fig. 4. For a low fixed collision velocity of 150 m/s, interface morphology was basically straight. On the other hand, for a high collision velocity of 400 m/s, interface morphology was wavy, but when the initial angle was low or high, such as 5° or 25°, straight interface morphology was observed. It is considered that interface morphology was straight outside weldability condition of the welding window in numerical simulation. On this basis, the simulation results corresponded to the theory of the welding window.

As mentioned above, the SPH method is useful in investigating the relationship between interface morphology and welding parameters such as collision angle and velocity. However, it is important that SPH particles are not hard spheres. In that case, they could overlap with each other. Then, it would be difficult to examine wavy morphology, such as wave length and amplitude, in a quantitative manner.

### 4.2 Composition of metal jet

Metal jet emission during impact welding was reproduced well by using the SPH method. Figure 7 shows the simulation results for the Al/Al lap joint. The initial angle was 15°, and the initial velocity was 400 m/s. The flyer plate collided with the parent plate, and then a metal jet was emitted from the collision point. The velocity of the metal jet was estimated about in the range of 1000–2000 m/s. It was also found that the amount of emitted metal jet increased with increasing collision velocity for a given collision angle.

The effect of plate thickness was also investigated for the Al/Cu and Cu/Al lap joints. Figures 8(a)–(f) show the simulation results of metal jet emission for various plate thicknesses. The initial angle was 15°, and initial velocity was 500 m/s. The increase in plate thickness was expected to increase the kinetic energy for collision. However, the composition of the metal jet (mostly Al) was not changed. Therefore, it is considered that metal jet composition was independent of plate thickness and position, but dependent on the chemical identity of the metal plate.

Figures 9(a)–(e) show the simulation results at the collision point for Al/Al, Al/Cu, Cu/Al, Al/Ni, Cu/Al lap joints. The initial angle was 25°, and the initial velocity was 400 m/s. The physical, chemical, and mechanical properties of four metals are presented in Table 2. The composition of the metal jet was classified well according to the density difference between the two metal plates. They could not be sorted by shear modulus or melting temperature. We found that when the density difference of the two metal plates was large, such as Al/Cu and Al/Ni lap joints, the metal jet was mainly composed of the lower density material. On the other hand, when the density difference was small or zero, such as for Cu/Ni and Al/Al lap joints, the metal jet was composed of both metals. Figures 10(a)–(f) show the simulation results at the collision point of Al/Mg lap joints. The initial velocity was fixed at 400 m/s, and the initial angles were 15° and 25°. In the case of Al/Mg and Mg/Al lap joints, metal jet components changed depending on the collision conditions.

Figure 11 shows X-ray diffraction patterns of the metal jet material collected during magnetic pulse welding of Al/Cu and Cu/Al. Glass plate was used as the collector. Regardless of the initial positions of the Al and Cu plates, the metal jet was mainly composed of Al. The experimental results were in good agreement with the simulation results.

### 4.3 Hump formation at collision point

Simulation results revealed that a hump was formed ahead of the collision point when initial angle was more than 20°. The hump is an area where the metal plate bulged at the collision point. In the present study, the hump was defined as

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**Table 2 Physical parameters for materials.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, ( \rho/\text{g cm}^{-3} )</th>
<th>Shear modulus, ( G/\text{GPa} )</th>
<th>Melting Temperature, ( T_m/°C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>2.69</td>
<td>27.1</td>
<td>660</td>
</tr>
<tr>
<td>Mg</td>
<td>1.78</td>
<td>16.5</td>
<td>650</td>
</tr>
<tr>
<td>Cu</td>
<td>8.96</td>
<td>47.7</td>
<td>1085</td>
</tr>
<tr>
<td>Ni</td>
<td>8.90</td>
<td>85.5</td>
<td>1455</td>
</tr>
</tbody>
</table>

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**Fig. 3** Cross section of the Al/Mg lap joint. (a) Optical micrograph of bulging region. (b) Backscattered electron image of the weld interface.
the height between two dotted lines “h” in Fig. 9(b). It seems that there is a relationship between hump formation and metal jet emission. It is considered that the formation of the hump is related to the movement direction of the collision point. The movement directions of collision point are shown by pink arrows in Figs. 9(a)–(e). In the case of the Al/Cu lap joint, the movement direction of collision point was shifted toward the Cu plate, and Al plate pulled to Cu plate. Then, a hump was formed on the Al plate. The metal jet was emitted along the Cu plate. Even if the flyer plate and the parent plate were interchanged, the same behavior was observed. These phenomena were common when the density difference between two metal plates was large. The metal jet emissions in explosive welding of various types of lap joints were observed by using the high-speed camera, following the procedure of Ishii et al. There has been no report on the composition of the metal jet. However, they showed that the metal jet was emitted including to the higher density metal plate side when the density difference between the two metal plates was large. This is in good agreement with the present simulation results. On the other hand, in the case of Al/Al and Cu/Ni lap joint, for which there is little or no
Fig. 8 Simulation results of metal jet emission for various plate thicknesses. Initial angle and initial velocity were fixed 15° and 500 m/s respectively. (a) 1 mmAl/1 mmCu (b) 1 mmCu/1 mmAl (c) 1 mmAl/1.5 mmCu (d) 1.5 mmCu/1 mmAl (e) 2 mmAl/0.3 mmCu (f) 0.3 mmCu/2 mmAl.

Fig. 9 Simulation results of metal jet emission and hump formation at the collision point. Initial angle was 25° and initial velocity was 400 m/s. (a) Al/Al (b) Al/Cu (c) Cu/Al (d) Al/Ni (e) Cu/Ni. The movement directions of collision points are also shown.

Fig. 10 Simulation results of metal jet emission of Al/Mg lap joints. Initial velocity is fixed 400 m/s (a) Initial angle is 15° (b) Initial angle is 25°.
density difference between plates, the movement direction of the collision point did not shift to one side. Two plates pulled each other equally and a hump was formed on both metal plates. A metal jet was emitted along the direction of bisector of the two metal plates. Bahrani proposed that the hump was formed ahead of the collision point due to the metal jet and the wavy interface was the result of continuous hump formation. In the present study, we could reproduce the hump formation successfully; however, further analysis is need in order to investigate whether or not the hump formation affects wavy interface formation.

5. Conclusions

Impact welding was investigated numerically and experimentally. The following findings were obtained.

(1) The metal jet emission and weld interface morphology were reproduced successfully by using the SPH method.

(2) Three patterns of interface morphology were obtained from the simulation; straight, wavy, and vortical. These morphological changes corresponded to those observed at magnetic pulse welded lap joint interfaces.

(3) The composition of the metal jet was governed by the relative density difference between the two metals to be welded. When the density difference was large, the metal jet was mainly composed of metal with lower density. On the other hand, when the density difference was small or zero, the metal jet was composed of both metals.

(4) The metal jet was collected during magnetic pulse welding of Al/Cu and Cu/Al. The metal jet was mainly composed of Al in both cases. The experimental results were in good agreement with the simulation results.

(5) Hump formation was observed ahead of the collision point. When the density difference of the two metal plates was large, a hump was formed on the lower density metal and the metal jet was emitted along high density metal. On the other hand, in the case of when the density difference was small or zero, humps were formed on both the flyer and parent plates and the metal jet was emitted along the direction of the bisector of the two metal plates.

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