Numerical Study of Joining Process in Magnetic Pressure Seam Welding †

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Abstract

The magnetic pressure seam welding is one of the candidate methods to join thin sheet multifunctional materials. In this research, to examine the mechanism of magnetic pressure welding from a dynamic viewpoint, numerical simulation of the impact was carried out by using a commercial Euler-Lagrange coupling software MSC.Dytran (MSC.Software) as a first step of the computational studies, where the joint between Fe and Al was employed according to the previous experimental researches. From the serial numerical results, it was found that the increase of temperature at the joint interface was not enough to melt Al or Fe in the range of collision velocity and angle studied in this report. Also, it was revealed that the very large mean stress occurring at the interface which could be considered as the pressure at joint interface and Al moved with high velocity along the interface. Moreover, it was found that there were two patterns of plastic strain distribution near the joint interface depending on the collision velocity and collision angle. Finally, it can be concluded that the plastic strain pattern might be related to the success of magnetic pressure seam welding.

KEY WORDS: (Magnetic Pressure Seam Welding) (Collision Velocity) (Collision Angle) (Euler-Lagrange Coupling Analysis) (Finite Element Method)

1. Introduction

There have been strong demands to join multifunctional materials to other materials without any functional defects in the multifunctional materials for propagating their use. The ordinary physical joining methods using heat sources such as arc welding, laser welding and electron beam welding cause microstructural changes at the joint interface[1,2] and largely affect the original feature of the multifunctional materials. In order to overcome this problem, several joining methods have been proposed, which are, for examples, diffusion bonding[3], explosive bonding[4], friction welding[5], magnetic pulse welding and so on.

Recently, Aizawa et al. developed a seam welding technique called "magnetic pressure seam welding" as one of the species of magnetic pulse welding[6]. In this joining method, a thin plate of a material with a high electric conductivity is suddenly subjected to a high density magnetic field and magnetic forces cause the plate to impact a parent plate. Then, a seam is created between the two plates due to this impact. Although the large impact is applied at the interface between dissimilar materials, the temperature of the joint is close to room temperature and any superior material properties of these dissimilar materials seem to be preserved. So, the magnetic pressure seam welding is considered as one of the best candidate methods to join dissimilar thin sheet materials of multifunctional materials and other materials.

Experimental investigations of the conditions necessary for successful joining, microstructural observations of the joint interface and mechanical evaluation of the joints were reported in the previous studies[7-10]. However, the mechanism of this joining process is still not well understood and appropriate joining conditions have been decided from experimental considerations. The final target of this research is to examine the mechanism of the magnetic pressure seam welding from a dynamic viewpoint and to reveal the appropriate joining conditions theoretically. So, in this report, numerical simulation of the impact was carried

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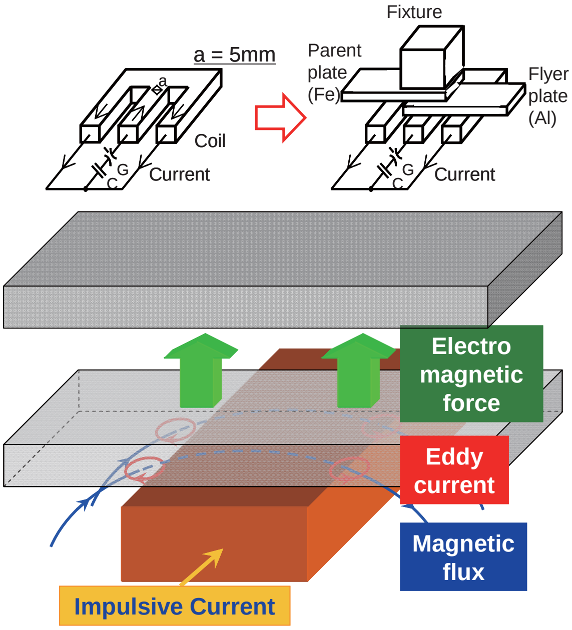


Fig. 1 Schematic illustration of magnetic pressure seam welding.

out by using commercial Euler-Lagrange coupling software MSC.Dytran (MSC.Software)[11] as a first step of the computational examination of the magnetic pressure seam welding.

2. Modeling for Analysis

2.1 Magnetic pressure seam welding

Figure 1 shows the principle of the magnetic pressure seam welding. An electrical discharge circuit is applied in the present welding. The circuit consists of a power supply, a capacitor, a discharge gap switch and a one-turn flat coil. A plate called “flyer plate” is set over the coil. A thin film is inserted between them as an insulator. Another plate called “parent plate” is placed so that it overlaps the flyer plate with a little gap. The parent plate is fixed firmly using a fixture. When an impulse current from the bank passes through the coil, a high density magnetic flux is suddenly generated around the coil. The generated high density magnetic flux lines intersect the overlapped area of the plates. Eddy currents are induced in this area, in particular, in a very surface layer of the flyer plate. Eddy currents flow in an opposite direction to the impulse current in the coil. The high density magnetic flux and the generated eddy currents induce an electro-magnetic force upward. This force drives a part of the flyer plate to the parent plate with an extremely high speed (150 - 500 m/s)[12].

2.2 Whole model for magnetic pressure seam welding

In the previous studies of the joint between Fe and Al using this joining process, the metal jet, whose

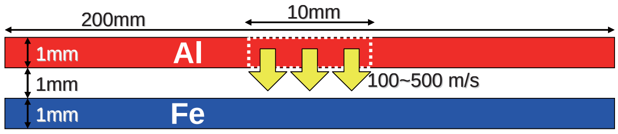


Fig. 2 Schematic illustration of whole model for magnetic pressure seam welding.

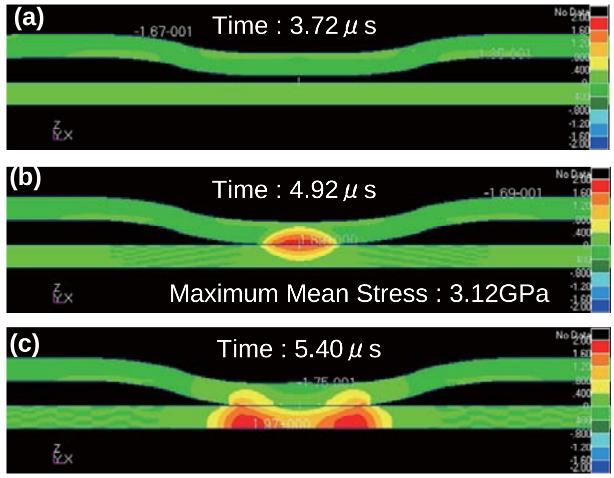


Fig. 3 Deformations and mean stress distributions of magnetic pressure seam welding (collision velocity : 200 m/s).

Table 1 Material properties used for numerical analyses.

	Fe	Al
Young’s Modulus (GPa)	206	70.3
Yield Stress (MPa)	500	200
Density (kg/m^3)	7.87 x 10^3	2.70 x 10^3
Poisson’s Ratio	0.3	0.345
Linear Expansion Coefficient (1/K)	1.18 x 10^{-5}	2.39 x 10^{-5}
Shear Modulus (GPa)	79.2	26.0
Specific Heat (J/kg･K)	440	900
Melting Point (K)	1808	933

composition was mainly Al, was observed[12]. So, Fe and Al were modeled by a Lagrange and an Euler model, respectively. In order to examine collision behavior in this process roughly, the whole plates of Fe and Al (200^{L} x 1^{T} mm) were simulated as two dimensional plain strain problem as shown in **Fig. 2**, where the minimum element size was 100 x 100 μm^2 and total number of elements and nodes was 13240 and 29172, respectively. An initial gap between the plates was set to 1 mm and an initial velocity was applied to the center part of the flyer plate (Al), whose length was assumed to be 10 mm. **Table 1** shows mechanical and thermal properties used in this research. According to the experimental results[12], initial velocity in this computation was varied in the range from 100 to 500 m/s. **Figure 3** shows typical computational results of the collision behavior of the whole plates of Fe

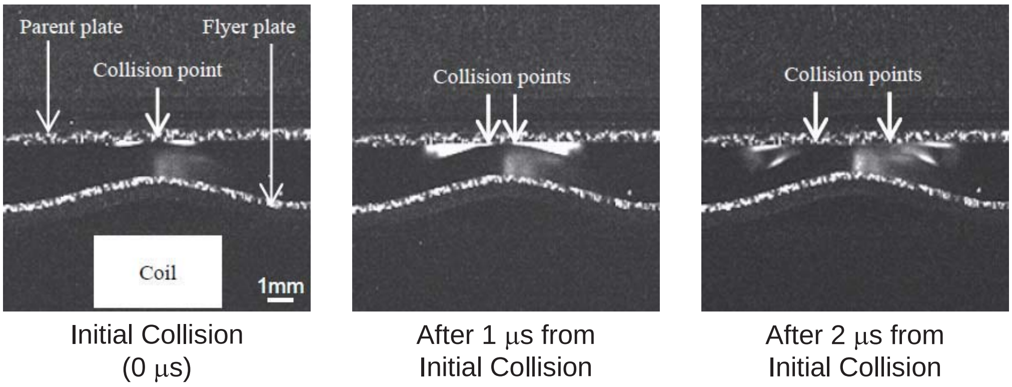
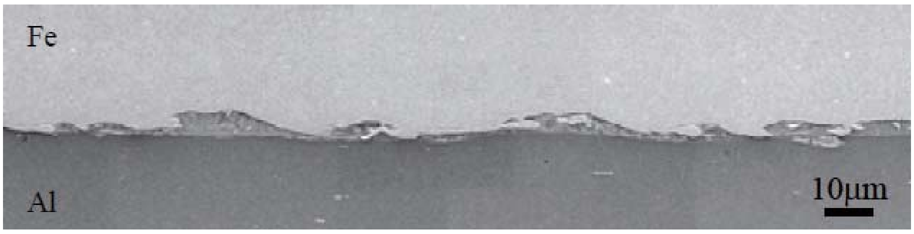


Fig. 4 High-speed photographs during collision process in magnetic pressure seam welding[10].

(a) Optical micrograph



(b) SEM-BEI micrograph

Fig. 5 High-speed photographs during collision process in magnetic pressure seam welding[10].

and Al, where the initial velocity was 200 m/s and the distributions of mean stress are represented. As shown in Fig. 3(b), the Al plate collided with the Fe at the center of the plate and a very large mean stress occurred. Also, after further 0.5 µs, the collision point moved along the surface of Fe plate. These behaviors have good agreements with the experimental results shown in **Fig. 4** which was recorded by a high speed camera[10,12]. Moreover, from these computational results for the whole plates, it was found that the collision angle at the contact point between Al and Fe plate was monotonically increased after the first collision.

2.3 Partial model for magnetic pressure seam welding

Since a wavy morphology was observed at the joint interface of the magnetic pressure seam welding and the cycle of wave is near 100 µm[7-10] as shown in **Fig. 5**, more fine meshes have to be used for examining the joint mechanism precisely. So, a part of two plates was modeled for the precise analysis as shown in **Fig. 6**, where not only the collision speed but also the collision angle was varied in the range from 100 to 500 m/s and 0.5 to 10 degree, respectively according to the experimental and the previous numerical results. A minimum element size was 1.5 x 1.5 µm^2, and the total number of elements and nodes was 281445 and 566956, respectively. The properties used for the partial model were the same as those in the previous computations for the whole components.

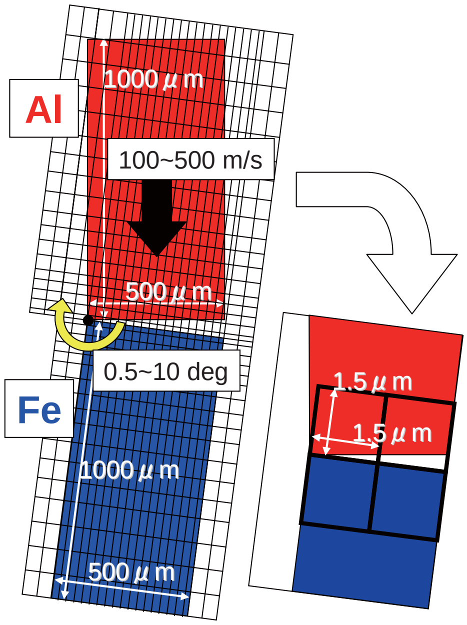


Fig. 6 Schematic illustration of partial model for magnetic pressure seam welding.

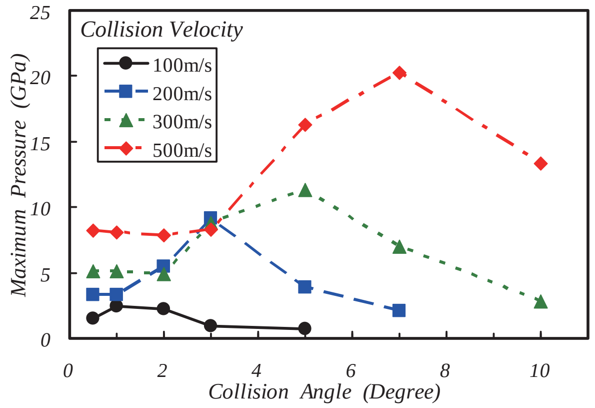


Fig. 7 Effect of collision velocity and collision angle on maximum pressure.

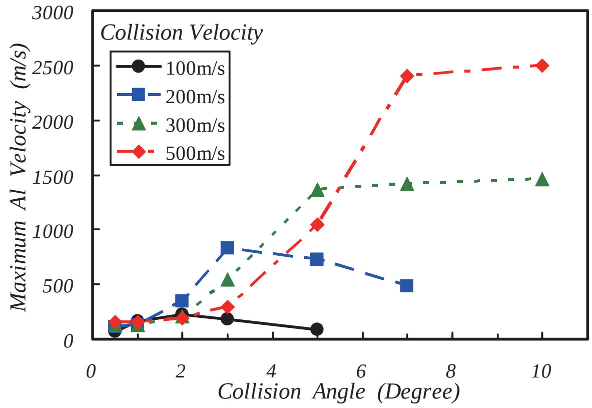


Fig. 8 Effect of collision velocity and collision angle on maximum Al velocity.

3. Results and Discussions

3.1 Temperature rise

One possible mechanism of the magnetic pressure seam welding seems to be an occurrence of local melting at the joint interface caused by large collision velocity. Since, in these numerical analyses, only the plastic strain would generate the temperature increment, the plastic strain occurring near the joint interface was examined. The maximum amount of plastic strain computed was in the range from 0.27 and 1.65. A total energy per unit volume caused by the plastic strain can be written by the product of yield stress σ_Y and plastic strain ε^p in the case without work hardening. So, the temperature rise can be written by the following equation,

$$\frac{\sigma_Y \cdot \varepsilon^p}{c \cdot \rho} \qquad (1)$$

Where c and ρ are the specific heat and the density. From the above equation, it is found that 1.0 plastic strain can generate a temperature rise of only 80.5 K for Al according to Table 1. So, a possible maximum temperature increment would be in the range from 22 to 132 K and any occurrence of local melting could not be considered because the melting temperature of Al is 933 K.

3.2 Pressure (mean stress)

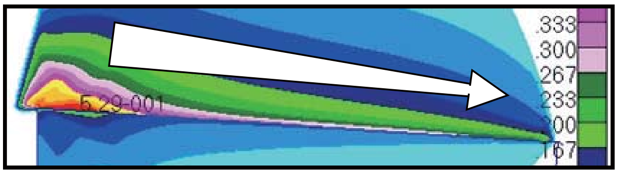
From the previous analyses using the whole model, it was found that a very large mean stress occurred at the collision point. This mean stress at the joint interface could be considered as a pressure at the joint surface. So, the influences of collision velocity and collision angle on the pressure were studied using the partial model. The same as the cases for the whole model, the pressure was locally applied at the joint interface and the point having the maximum pressure moved along the joint interface. **Figure 7** shows the effects of collision velocity and collision angle on the maximum pressure. From this figure, it was found that the maximum pressure was 5 and 100 times larger than the yield stress of Al and the higher collision velocity could mostly generate the higher maximum pressure at the same collision angle. Also, it was revealed that the maximum pressure of each collision velocity would have a maximum value at a different collision angle.

3.3 Al velocity parallel to interface

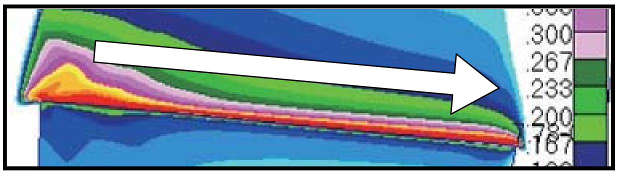
Since the metal jet whose composition was mainly Al was observed experimentally, the Al velocity parallel to the joint interface was examined. The influences of collision velocity and collision angle on maximum Al velocity at joint interface were summarized into **Fig. 8**. The maximum Al velocity sometimes exceeded the collision velocity and such high Al velocities might be caused by the local high pressure at the joint interface. So, it can be considered that the differences between collision velocity and maximum Al velocity might generate the metal jet of Al. From Fig. 8, it was also found that the maximum Al velocity increased with increasing the collision angle, and reached at a maximum value. Moreover, it was revealed that the maximum or saturated value of the maximum Al velocity at higher collision velocity occurred at a large collision angle.

3.4 Plastic strain distribution

Although the plastic strain occurring near the joint interface would be much smaller for generating the local melting, two types of plastic strain distribution were obtained in these serial computations by varying the collision velocity and collision angle. **Figs. 9(a)** and **(b)** were typical examples of the plastic strain distributions generated near the joint interface and the influences of collision velocity and collision angle on the plastic strain distributions were summarized into **Table 2**. As shown in



(a) Pattern A



(b) Pattern B

Fig. 9 Plastic strain distributions near joint interface.

Table 2 Effect of collision velocity and collision angle on pattern of plastic strain distribution.

Collision Angle	Collision Velocity			
	100 m/s	200 m/s	300 m/s	500 m/s
0.5 degree	A	A	A	A
1 degree	A	A	A	A
2 degree	B	A	A	A
3 degree	B	B	A	A
5 degree	B	B	B	A
7 degree	-	B	B	B
10 degree	-	-	B	B

Fig. 9(a) which is denoted as pattern A, when the collision angle is smaller and the collision velocity is larger, the plastic strain near the joint interface decreased toward the end. On the other hand, in the other cases, large plastic strain continued over the whole joint interface as shown in Fig. 9(b) which is denoted as pattern B.

This difference in plastic strain distribution seems to be related to the effects of collision velocity and collision angle on the pressure and the Al velocity as shown in **Figs. 10** and **11**. From these figures, it was found that, before the maximum pressure and the maximum Al velocity achieved the maximum, or almost saturated value, the plastic strain distribution became to be the pattern A. So, it can be considered that, in these cases, the movement of Al along the interface might be prevented by the continuous contact between Al and Fe although a relatively large pressure was occurred. While, in the other cases (pattern B), Al could move along the joint interface before the growth of new contact and then the maximum Al velocity achieved the maximum, or saturated value. Since it was reported that the appropriate collision velocity and collision angle should be needed to create the joint interface in the magnetic pressure seam welding from the previous experimental studies[10,12,13], the plastic strain distribution near the joint interface might be related to the success of magnetic pressure seam welding. Also, from Figs. 10 and 11, it may be seen that the higher collision velocity would need the higher collision angle in order to develop the plastic strain distribution like pattern B.

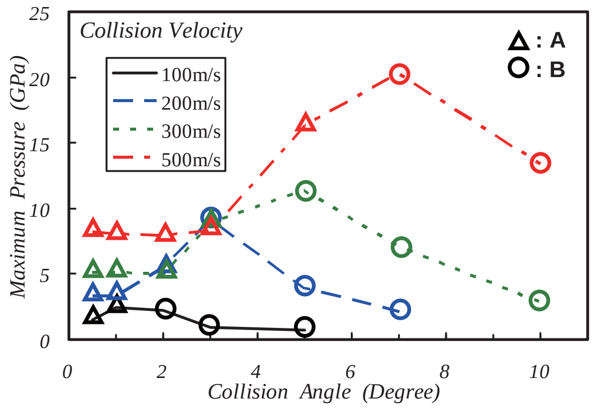


Fig. 10 Effect of maximum pressure on pattern of plastic strain distribution.

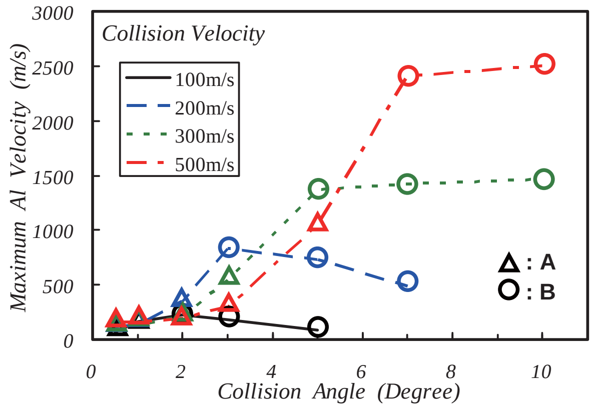


Fig. 11 Effect of maximum Al velocity on pattern of plastic strain distribution.

4. Conclusions

The magnetic pressure seam welding is one of the candidate methods to join thin sheet multifunctional materials. In this research, to examine the mechanism of magnetic pressure welding from a dynamic viewpoint, numerical simulation of the impact was carried out by using a commercial Euler-Lagrange coupling software MSC.Dytran (MSC.Software) as a first step of the computational studies, where the joint between Fe and Al was employed according to the previous experimental researches. The conclusions can be summarized as follows.

(1) The increase of temperature at the joint interface was not enough to melt Al or Fe in the range of collision velocity and angle studied in this report.

(2) The very large mean stress occurring at the interface could be considered as the pressure at the joint interface.

(3) Al moved with high velocity along the interface.

(4) There were two patterns of plastic strain distribution near the joint interface depending on the collision velocity and collision angle.
(5) The plastic strain pattern might be related to the success of magnetic pressure seam welding.

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