Fabrication of 2000 Series Aluminum Alloy Lap Joint Sheets by Magnetic Pulse Welding and Their Interfacial Microstructure Observations

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Lap joint sheets of 2017-T3/2017-T3 and 2024-T3/2024-T3 were fabricated by magnetic pulse welding (MPW). Tensile shear tests were performed on the welded sheet, and a good lap joint was achieved at a discharge energy more than 3.0 kJ for both lap joint sheets. Weld interface showed wavy morphology when bonding at an adequate amount of discharge energy. Weld width of the lap joint sheets tend to increase with increasing of discharge energy. Collision speed calculated based on collision time was 211 m/s and estimated 1.5 GPa of the collision pressure at discharge energy of 3.5 kJ. SEM and EDS results showed that the weld interface exhibited no significant contrast of intermediate layer and oxides. A Metal jet was observed as aggregates of fine particles with size of less than 100 nm at the outside of bonded area. From TEM observation at the bonding interface, Al phases between flyer and parent sheets had direct contact without the intervention of the oxide, and localized melting was not recognized. From these obtained results, good lap joint is attributed to true-contact of Al phases, an increase of weld width, the anchor effect, and work hardening at weld interface. [doi:10.2320/matertrans.L-M2017821]

Keywords: magnetic pulse welding, aluminum alloy, microstructure, interface

1. Introduction

The 2000 series aluminum alloy is classified as a difficult material to join via conventional fusion welding method such as TIG and MIG welding due to the weak properties of the joint section from using these suggested joining methods. Generally, the joining of this type of aluminum is by means of mechanical joining such as rivet and screws. However, the joining can also be made by taking advantage of the electron beam method which reduces the heat affected zone, thus narrowing the soft, weak joining areas. In recent years, solid-state welding are getting more attention for the joining of heat-treatable aluminum alloy. Solid-state welding such as friction stir welding which utilizes frictional heat and plastic flow is an excellent joining method to join various aluminum alloy series such as the 5000, 6000 series and also the high strength aluminum alloys such as the 2000 and 7000 series. Since the invention of TWI in 1991, continuous research and development have been done and the technology have been applied to various transportation equipment like aircraft and railway vehicles. Currently, research on structure formation resulted from frictional heat and plastic flow caused by the rotation of the tool, along with the mechanism are being conducted progressively.

On the other hand, magnetic pulse welding (MPW) is known as one of solid-state welding technique. Utilizing electromagnetic force, MPW is suitable for high electrical conductive metals such as Cu and Al because large eddy current can be induced which is essential to generate large electromagnetic force during the joining process. In 1960, a patent was published on the moulding and joining of metal tubes, and the joining of the circular tubes by mechanical fastening and compaction was reported. Later, Aizawa proposed an electromagnetic seam joining method using a flat one-turn coil with a simple structure and a higher mechanical strength than the conventional coil. It was reported that Al sheet with thickness of 0.3 mm was stacked up to a thickness of 50 mm was successfully join together at a discharge energy of 1.6 kJ by this method. MPW utilizes electromagnetic shock whereby the flyer sheet is abruptly exposed to magnetic flux which then drives the flyer sheet to the parent sheet colliding at a very high velocity, thus joining is achieved. This method of solid-state welding is similar to impact welding such as those in explosive welding. Good joining strength is achieved in both methods of welding and wavy morphology can be observed at the welding interface. This wavy morphology formation process is similar to those observed at the joint interface produced by the impact force from explosive welding, and this phenomenon is attributed to the hydrodynamic instability of the material at high pressure and high speed deformation. It was reported that this phenomenon is related to the Karman vortex and Helmholtz instability. However, this matter is still open to discussions. In explosive welding, the collision speed can be adjusted according to the amount of explosives set before the welding process with the collision speed is approximately several hundreds to 1000 m/s or more (collision pressure is 10 GPa and above), making it possible to perform large surface area joining for various metal sheets. On the other hand, MPW is also an impact welding which uses electromagnetic force, but at smaller scale as compared to explosive welding and produces a weaker seam welded materials.

Previously, it was reported that successful joining of similar metals (Al-Al and Cu-Cu), as well as dissimilar metals such al Fe-Al and Cu-Al have been fabricated by MPW. Joining for practical materials have also been attempted, such as the joining of 6000 series aluminum alloy and SPCC where good bonding is achieved, and the details on the structure of the bonding interface have been reported. However, in MPW, there are many reports on similar joining of pure metals. There have been few reports on the joining of practical materials used in industries, and the joining of

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2000 series aluminum alloys have not been reported. Therefore, the present study examined the joining of 2017-T3/2017-T3 and 2024-T3/2024-T3 sheets fabricated by MPW. The joining characteristics and the structure of the joining interface were also investigated.

2. Experimental Procedure

2.1 Fabrication of magnetic pulse welded lap joint sheet

Figure 1 shows a schematic diagram of MPW circuit. As shown in the figure, two metal sheets are set above the coil with a gap in between. The metal sheet near the coil is called "flyer sheet" and the metal sheet above it is called "parent sheet". In this state, the capacitor which is the power supply, is charged with electrical energy (voltage $V$). When the gap switch is closed, an impulse current is discharged from the capacitor and flows through the coil. The electrical energy from the charged capacitor is one of the welding conditions in the process and it is referred to as discharge energy ($W$). $W$ is expressed by the eq. (2.1) whereby $C$ is the capacitance of the capacitor, and $V$ is the applied voltage.

$$W = \frac{1}{2} CV^2$$  \hspace{1cm} (2.1)

In this experiment, $C$ was kept at 400 μF. When the impulse current from the charged capacitor flows into the coil, a high density magnetic flux is generated around the central position of the coil which penetrates the flyer sheet. Eddy current is induced in the flyer sheet to hinder the penetration of the generated magnetic flux. The generated eddy current and high-density magnetic flux induce an electromagnetic force which then drives the flyer sheet into the parent sheet at high velocity, thus colliding together. Since electromagnetic force is proportional to the density of eddy current, metal sheets with high electrical conductivity is preferable to generate large drive force. The joining process can be done efficiently by adjusting the magnitude of the magnetic flux and change of time. In this research, in order to identify the collision time between both metal sheets, lead wire was attached to the edge of both metal sheets to measure the pulse signal when both the metal sheet were in contact during collision. The pulse signal was measured using an oscilloscope. Details on the measurement of the collision time can be referred to the report from Okagawa et al. \(^{19}\)

2017-T3 sheet and 2024-T3 sheet from the 2000 series Al alloy both with dimension of $100 \times 80 \times 1.0 \text{ mm}^3$ were used in the present study. Table 1 shows the chemical composition of 2017-T3 and 2024-T3 sheets used for this experiment. Similar lap joint sheets were fabricated using both types of Al sheets with discharge energy ranged from 1.5 to 3.5 kJ. Figure 2(a) and Fig. 2(b) show the macroscopic appearance of the cross-section of the lap joint sheet produced by MPW. During the welding process, electromagnetic force drives and deforms the flyer sheet as shown in the figure.

2.2 Mechanical properties of magnetic pulse welded lap joint sheet

Bonding strength was evaluated by conducting tensile shear test using Instron type universal testing machine. The test piece were cut out by slicing the welded sheet according to the requirements in JIS 13 B (reduced to 1/2 its original size) using wire-cut electrical discharge machine. The cross-head speed was kept constant at 1.0 mm/min. In addition, in order to provide pure shearing stress to the welded joint during the tensile test, auxiliary plate was fixed together at the joint. Figure 3 shows the appearance of the test piece before the tensile shear test (left side) and the test piece after the test (right side). Base metal fracture indicates strong bonding, whereas peeling at the welded joint indicates weak bonding. Micro-hardness test around the joint interface was also performed using micro-Vickers hardness test machine with indentation load of 3 gf.

![Fig. 1](image1.jpg)  
**Fig. 1** Schematic of the magnetic pulse welding (MPW) process.

![Table 1](image2.jpg)  
**Table 1** Chemical compositions of the 2017-T3 and the 2024-T3 aluminum alloys (mass%).

<table>
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<th></th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mg</th>
<th>Mn</th>
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<td>0.5</td>
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<td>4.9</td>
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<td>1.8</td>
<td>0.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>

![Fig. 2](image3.jpg)  
(a) Macroscopic appearance of a 2024-T3/2024-T3 lap joint sheet fabricated by MPW. (b) Cross-sectional view of a lap joint sheet.
2.3 Interface microstructure of magnetic pulse welded lap joint sheet

Microstructural observation was performed at the cross-section of the joint interface, perpendicular the direction of the seam. Etching was conducted after surface polishing, where the specimen were chemically etched in a mixed solution of 50 ml distilled water, 2 ml of hydrofluoric acid (HF), and 2 ml of nitric acid (HNO₃). Microstructural observation was carried out using optical microscopy, scanning electron microscopy (SEM: H6600) and transmission electron microscopy (TEM: JEM2100F). For TEM specimens preparation, the joint area was cut into the dimensions of $2.7 \text{ mm} \times 1.0 \text{ mm} \times 1.0 \text{ mm}$ and then grinded to a thickness of $100 \mu\text{m}$. The specimens were then thinned by using the ion slicer. The first stage milling was performed at accelerating voltage of 6.0 kV with ion source tilt angle of 4.0°. This was then followed by second stage milling at accelerating voltage of 5.0 kV, which was gradually decreased to 1.5 kV to finish the process.

3. Results and Discussion

3.1 Joint characteristic of magnetic pulse welded lap joint sheet

Tensile shear test was conducted on 2017-T3/2017-T3 and 2024-T3/2024-T3 lap joint sheets at room temperature. The test results and the relationship between the fracture load and discharge energy are shown in the Fig. 4(a) and Fig. 4(b) respectively. At $W = 1.7 \text{ kJ}$, the joining was not achieved on both samples, and the joint were peeled during the slicing process to produce tensile test piece using the wire-cut electrical discharge machine. Therefore, tensile shear test was performed for lap joint sheet produced at $W = 2.0$ to 3.5 kJ. Joint peeling samples are indicated by white-coloured bars, and base metal fractured samples are indicated by black-coloured bars respectively. As shown in the figure, the fracture loads of 2017-T3/2017-T3 and 2024-T3/2024-T3 lap joint sheets are 2.6 kN and 2.7 kN respectively, indicated by the solid lines. Fracture load increases as discharge energy for to join both samples increases. For 2017-T3/2017-T3 lap joint sheet welded at $W = 2.0$ to 2.8 kJ, joint peeling occurred at fracture load of 1.7 kN to 2.5 kN. Similarly, for 2024-T3/2024-T3 lap joint sheet welded at $W = 2.0$ to 2.8 kJ, joint peeling occurred at fracture load of 1.6 kN to 2.7 kN. Both samples showed a tendency of increasing fracture load as discharge energy increases. On the other hand, at $W = 3.0$ and 3.5 kJ, both samples experienced base metal fracture with a fracture load of 95% and above of the base metal respectively. From the above results, lap joining of 2017-T3/2017-T3 and 2024-T3/2024-T3 sheets by MPW is possible and strong bonding is achieved as samples experienced base metal fracture when welded at discharge energy of 3.0 kJ and above.

3.2 Interface morphology of magnetic pulse welded lap joint sheet

Figure 5 shows a SEM image of cross-sectional view of 2017-T3/2017-T3 lap joint sheet. The upper part is the parent sheet, and the lower part is the flyer sheet. Initially, the welding process starts from the center and progressed towards the outward section of the metal sheets. During the process, bonding between two metal sheets occurred at a certain range of collision angle and transition speed which then forms wavy morphology at the interface. Therefore, linear bonding occurs at the two positions corresponding to the width of the coil; on the right and left of the center line (indicated by dot-dash line as shown in the figure). Thereafter, these two positions are call the weld zone, and the weld width is the total width of both weld zones. Figure 6(a) and Fig. 6(b) show the optical microscope images of 2017-T3/2017-T3 lap joint sheet and 2024-T3/2024-T3 lap joint sheet respectively, fabricated at $W = 1.7 \text{ kJ}$. The left side is the center section of the sample, and the right side is the out-
er towards the edge of the welded sample. The weld width is shown by the solid line in the figure. The weld width in Fig. 6(a) is 0.63 mm, whereas the in Fig. 6(b) is 0.55 mm. On the other hand, samples welded at $W = 3.0$ kJ as shown in Fig. 6(c) and Fig. 6(d) are 2.24 mm and 1.97 mm respectively. From the results, both samples welded at a higher discharge energy exhibit longer weld width. In addition, when comparing the weld width of both samples, it can be clearly observed that the weld width of 2017-T3/2017-T3 lap joint sheet is much shorter than that of 2024-T3/2024-T3 lap joint sheet at any discharge energy. Figure 6(e) to 6(h) show the enlarged image of the bonding interface from Fig. 6(a) to 6(d) respectively. The dotted line represents the weld interface between two metal sheets. At $W = 1.7$ kJ (shown in Fig. 6(e) and Fig. 6(f)) the joint interface exhibits rather flat morphology. However, at $W = 3.0$ kJ (shown in Fig. 6(g) and Fig. 6(h)), wave pattern caused by plastic flow deformation during the joining process is observed at the joint interface. Additionally, the deformed Al grains along the joint interface can be observed. From engineering perspective, it can be considered that the surfaces of the metal sheets plastically deformed and anchor effect occurred at the interface. These characteristics at the joint interface contributes towards higher bonding strength and desirable joint interface structure.

3.3 Collision speed and weld width

Since the formation of the wavy morphology varies depending on the collision pressure and collision speed in which the flyer sheet collides to the parent sheet, it is important to investigate the collision speed to have a better understanding of this MPW process. Previously, Okagawa and Watanabe et al. have reported on the collision speed of pure aluminum sheet and pure copper sheet. However, there are still no studies on the lap joint of 2017-T3 or 2024-T3 sheets. Figure 7 shows the relationship of discharge energy, travelling velocity and collision time for both 2017-T3/2017-T3 and 2024-T3/2024-T3 lap joints when the gap is set to 1 mm. It is known that the travelling velocity gradually changes from the time the impulse current begins to flow in the coil during the MPW process. As the gap becomes larger, the velocity also increases. Despite the findings, it is still quite difficult to examine the exact velocity at the collision point. Therefore, the gap between the metal sheets (1 mm) is divided by the collision time, and this will become the average travelling velocity of this experiment. The collision pressure is calculated by the formula as shown in (3.1), where $\rho$ is the density, $V_p$ is the collision speed of the flyer sheet, $V_s$ is the sound speed of the flyer sheet.

$$P = \frac{1}{2} \rho V_p V_s$$

As shown in Fig. 7, it can be observed that both series of lap joints show shorter collision time and higher collision speed when discharge energy increases. At $W = 1.5$ kJ, the collision speed of 2024-T3/2024-T3 lap joint was 161 m/s, and
as the energy increases, the speed reaches 211 m/s at $W = 3.5$ kJ. It can be estimated that the collision pressure during the process was 1.1 GPa ($W = 1.5$ kJ) and 1.5 GPa ($W = 3.5$ kJ) respectively. The collision speed of 2024-T3/2024-T3 lap joint is not significantly different from 2017-T3/2017-T3 lap joint fabricated at any discharge energy used in the experiment. MPW is a linear seam welding, which exhibit a narrow bonding area as compared to those samples welded by explosive welding. However, the 2000 series Al lap joint sheets fabricated by MPW experienced base metal fracture during the tensile test, indicating that adequately strong bonding is achieved.

Figure 8(a) and (b) show the weld width result of both 2017-T3/2017-T3 and 2024-T3/2024-T3 lap joint sheets produced at the several discharge energies. □ indicates the weld width on the left side from the mid-section, △ indicates the weld width on the right side, and ○ indicates the total sum of weld widths of the right and left sides. From these figures, it can be observed that the weld width for the left side is substantially of the same length to the right side for both type of samples. Similarly, the weld width also increases as discharge energy increases. In addition, the weld width of 2017-T3/2017-T3 lap joint sheet is larger as compared to 2024-T3/2024-T3 lap joint sheet fabricated at the same discharge energy. This result is attributed to the fact that the 2024-T3 sheet has a relatively higher tensile strength as compared to 2017-T3 sheet. At the same discharge energy, the Al sheet with higher tensile strength exhibit smaller plastic deformation at the joint interface which then results in a smaller weld width. However, as the discharge energy exceeds 3.0 kJ, the increase of weld width becomes smaller. From Fig. 8(a), it can be clearly seen that the weld width for 2017-T3/2017-T3 lap joint sheet decreases despite the increase in discharge energy (above 3.0 kJ). The impact force from electromagnetic force and the joining mechanism of MPW is similar to those in explosive welding. In explosive welding, it is known that appropriate collision angle between the plates and the travelling speed at collision point are the factors which need to be satisfied to form a wavy morphology (a good joining state) at the joint interface. Accordingly, an increase in collision speed, also, the increase in travelling velocity at collision point due to the increase in discharge energy are the factors which influence the formation of the wavy morphology. As shown in Fig. 7, the collision speed increases as discharge energy increases. In other words, it is suggested that the joining at a collision speed which exceed more than the appropriate condition for the formation of the wavy morphology results in the smaller increase in weld width. From Fig. 7, the collision speed of 2024-T3/2024-T3 lap joint at discharge energy of 3.0 kJ and 3.5 kJ are 202 m/s and 211 m/s respectively, which have no significant difference. In this study, the collision speed is the average value in which it is different from the actual collision speed at the moment the flyer sheet collides with the parent sheet.

Watanabe et al. performed MPW at discharge energy of 2.5 kJ and recorded the process using high-speed video camera. Pure Al sheet was used as the flyer sheet and the moment of collision between the flyer sheet and parent sheet was observed. The collision speed estimated by Watanabe et al. was 250 m/s, which is twice higher than the average collision speed (130 m/s) investigated in the same method of present study. This difference is suggested to be due to electromagnetic force generated by the interaction of discharge current, magnetic flux and eddy current, which continues to accelerate the flyer sheet until discharge current disappears. The pure Al sheet and the Al alloy used in the present study have different electrical conductivity and mechanical properties. However, MPW process remains unchanged, thus, both material undergo the same process with the same tendency. In other words, when discharge energy is 3.0 kJ and 3.5 kJ, the difference in the actual collision speed...
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3.4 Microstructure of metal jet and joint interface

Oxide exists on the surface of the metal is one of the factors that hinders the joining in both similar and dissimilar metals. Therefore, the removal of the oxides is desirable to obtain a clean virgin surface between both joining metals to form a good bonding. From the results of the present study, it was found that good bonding condition is achieved at $W = 3.0 \text{ kJ}$ for both 2017-T3/2017-T3 and 2024-T3/2024-T3 lap joint sheets. Additionally, wavy morphology was observed, but no clear formation of the oxide was detected at the joint interface. Therefore, in order to clarify the existence and dispersion condition of the oxides at the joint interface, microstructural observation was carried out using electron microscopy. Figure 10 shows (a) SEM image of joint interface of 204-T3/2024-T3 lap joint sheet; (b) EDS mapping of O, (c) Al, (d) Cu, and (e) Mg respectively at the same joint interface. From the EDS mapping result, the precipitates of 2 to 10 $\mu$m observed from the SEM image consists of Cu and Mg and EDS point analysis revealed that the precipitates is a MgCuAl$_2$ phase (Al - 23 at% Cu - 20 at% Mg). Similarly, CuAl$_2$ phase (Al - 31 at% Cu) was observed from 2017-T3/2017-T3 lap joint sheet. The joint interface is present at the central section, indicated by the arrow in the SEM image (Fig. 10(a)). However, as shown in the EDS mapping results (Al and O), there were no clear formation of oxide (Al$_2$O$_3$) present at the central section of the joint interface. In order to confirm the segregation of the oxide at different section of the joint interface, similar microstructure observation was conducted at the joint end (edge) of the joint interface. Figure 11 shows (a) SEM image and (b) EDS distribution analysis of O and (c) Al at the joint end of the joint interface. The section indicated by the arrow in the SEM image is the joint end, and on the left end towards the center indicated by the black contrast is the unbonded area. As shown in Fig. 11(b), the concentration distribution of O element can be clearly seen at the unbonded area, whereas the oxygen was not present at the bonded area (Fig. 10). The O element observed in the unbonded area is suggested to be due to the adhesion of the oxide film present on the surface of 2024-T3 sheet, or the product of the polishing agent where alumina (Al$_2$O$_3$) was used during sample preparation for microstructural observation. Therefore, from the SEM observation and EDS analysis results, it can be concluded that the amount of oxide is smaller at the joint interface as compared to the unbonded area of the lap joint sheet.

In explosive welding, the metal jet is discharged from the surface of the metal plate when colliding at high speed during the welding process. Turgutlu et al. observed flashes occurred in micro-seconds and recorded this phenomenon using X-ray photographs and framing cameras. On the other hand, in MPW, Watanabe et al. investigated the impact pressure bonding mechanism of pure Al sheet lap joint. From their findings, the collision angle of the flyer sheet with the parent sheet gradually increases from 0 degree at the center, and the wavy morphology also gradually changes along the joint interface. It was reported that a flash was observed, 1 micro-second after the initial collision between the two sheets, and this flash indicates that metal jet was discharged during the process. This means, the inclined collision between parent sheet and flyer sheet in MPW, (similarly in explosive welding), eliminates the oxide and contaminations on the surface of the metal sheet, thus producing clean metal surfaces suitable for bonding. This phenomenon is consistent with the results from SEM observation in this study. However, there were no examples of observing metal jets that has been discharged. Observation on the discharged
metal jet at the unbonded section near the joint end was conducted for 2017-T3/2017-T3 lap joint sheet (W = 3.0 kJ). Figure 12 shows SEM image and EDS mapping of the deposits observed at the unbonded section of the lap joint sheet. Aggregate of scattered fine particles were observed in the area surrounded by the white circle as shown in Fig. 12(a). The enlarged view of the aggregate particles is shown in Fig. 12(b). From the SEM image, it can be seen that the aggregate is composed of fine particles of about 100 nm or less. Analysis on these particles was carried out and compared with the composition of elements of 2017-T3 sheet as shown in Table 1. EDS mapping of (d) O, (e) Al, (f) Cu, (g) Si, conducted on the same area in SEM image (Fig. 12(c)). Al and Cu are distributed almost uniformly, but since the distribution of O and Si correspond with the particle and position as those in SEM image, the particles mainly consists of Al, Cu, Si and O which is also the elements composition contain in the 2017-T3 sheet. Therefore, the deposit is considered to be metal jet. From the above, the oxide film on the metal surface is eliminated by the inclined collision between the two sheets, and the fine particles of 100 nm or less is discharged as metal jet which leads to the successful metal-to-metal bonding. Therefore, in order to clarify the bonding state of the interface more detail, the structure of metal-to-metal bonding. In addition, cracks can be observed at the MgCuAl2 phase (indicated by the thin arrow) on the flyer sheet’s side, and this region is considered to be the joint interface. Figure 13(c) shows an enlarged image of the joint interface indicated by the white frame in the TEM image of Fig. 13(b). From the joint interface in the figure, fine oxide as observed in Fig. 12 was not present. The interface was also linear along the crystal grain and no trace of melting found suggesting that solid-state bonding occurred during the joining process. Additionally, the structure on the flyer sheet’s side below the interface, a contrast due to dislocation was observed indicating that strain accumulates near the joint interface. This result is consistent with the work hardening phenomenon in the vicinity of the joint interface, observed in Fig. 9. Figure 13(d) shows a high resolution TEM image of the joint interface. The Al phase of the lower side of the flyer sheet was observed with an incident beam along [110] direction. The figure also shows the results of EDS analysis with the beam narrowed down to about 3 nm for region A and B. EDS analysis results show that Al, Cu and Mg were detected from the regions A and B where the estimated compositions were Al-0.5at%Cu-1at%Mg and Al-1at%Cu-1at%Mg respectively. Both base metal were of Al phase. High resolution TEM image were taken, and it can be seen that the Al lattice is in direct contact at the joint interface where both Al phases are bonded to each other without interposing nano-sized oxides or contaminations. In other words, at the moment of collision between the two metal sheets during MPW, oxide films and contaminations were discharged as metal jets from the surface of the sheet and at the same time, the bonding of newly cleaned surfaces of Al phases is suggested to have occurred.

From the above results, it was found that when discharge
energy is 3.0 kJ or more, strong bonding can be achieved. The bonding is enough to fracture at base metal of the 2000 series Al alloy sheet. Results from the microstructure observation of the joint interface revealed that solid-state bonding occurred between the newly cleaned surfaces of the metal sheets due to the discharge of metal jet from the joint interface. Al phases were bonded to each other without oxide films and other contaminations in between the two phases. In addition to this, the anchor effect due to the formation of the wavy morphology and work hardening near the joint interface were also confirmed, and these factors contribute to the high bonding strength of the lap joint sheet.

4. Conclusion

(1) Successful similar metal joining of 2017-T3/2017-T3 and 2024-T3/2024-T3 lap joint sheets fabricated by MPW was possible at discharge energy of 1.7 kJ and above. Strong bonding, enough to fracture the base metal, could be attained at 3.0 kJ or more.

(2) The amplitude of the wavy morphology and the weld width of all the lap joint sheets increased with the increase of discharge energy. The weld width of 2017-T3/2017-T3 lap joint sheet was larger than that of 2024-T3/2024-T3 lap joint sheet, and the difference in the metal sheets tensile strength influences the change in the weld width.

(3) The collision speed increases as the discharge energy increases. The collision speed at discharge energy of 3.5 kJ for 2024-T3 sheet was 211 m/s, and from this speed, the collision pressure was estimated to be 1.5 GPa. The difference in collision speed due to the difference in tensile strength between 2017-T3 sheet and 2024-T3 sheet was small, and they were almost the same at the same amount of discharge energy.

(4) The hardness value in the vicinity of the joint interface was higher than that of the Al base metal, and work hardening occurred at the joint interface after MPW. (5) Results from SEM observation revealed that no oxide film was found at the joint interface of both 2017-T3/2017-T3 lap joint sheet and 2024-T3/2024-T3 lap joint sheet. Additionally, aggregates of fine particles of about 100 nm or less were observed from the unbonded region. These particles were mainly composed of Al, Si, Cu and O, and it was suggested to be metal jets discharged during the bonding process.

(6) Results from TEM observation revealed that the bonding interface is linear along the crystal grain and cannot be seen trace of melting. Al phases of both parent sheet and flyer sheet were in direct contact with each other at lattice level, joined together without oxides or other contaminations in between.

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