Magnetic Pulse Welding Conditions for High-Tensile Steel of 1 GPa Class and 6061-T6 Aluminum Alloy Sheets*1

Takaomi Ito1+2, Shunichi Kitta1 and Keigo Okagawa2

1Department of Mechanical Engineering, Chiba University, Chiba 263-8522, Japan
2Department of Electrical and Electronic Engineering, Tokyo Metropolitan College of Industrial Technology, Tokyo 140-0011, Japan

The 6061-T6 sheet and the DP 780 steel sheet were joined under the condition with the gap length d of 1.17 to 1.42 mm and discharge energy W of 3.0 kJ. The impact speed ranged from 430 to 460 m/s. The weld width showed a tendency to increase due to the increase of the collision speed. However, when the gap length exceeds 1.59 mm (impact speed of >460 m/s), the weld width became narrow. Considering that the electromagnetic force continues to apply on the flyer sheet after collides with the fixed sheet, it is desirable to perform the welding in a time shorter than the time \( t_m \) when the collision time reaches the maximum current value. Therefore, the collision time is considered to be one of the factors that affect the welding condition. As a result of experiments in consideration of above conditions, it was possible to achieve a strong lap joint of the 6061-T6 sheet and the DP 980 steel sheet, although the welding condition was limited as compared with the case of the DP 780 steel sheet. Thus, sound lap joint between 6061-T6 sheet and high-tensile steel sheet with 1 GPa class was achieved by magnetic pulse welding.

Keywords: magnetic pulse welding, 6061-T6, DP980 steel, microstructure, interface

1. Introduction

In recent years, weight reduction of transportation equipment, such as automobiles, railway vehicles, and airplanes, has attracted increasing attention as a means to prevent global warming. The amount of CO₂ emitted by driving a car is proportional to the weight of the vehicle body, regardless of the driving method. Therefore, reducing the body weight is one of the key requirements for reducing CO₂ emissions, and efforts are being devoted to reducing the body weight of cars.¹ One of the most promising efforts to reduce the body weight of a car is the utilization of high tensile steel (590–1400 MPa) in automobile parts.²⁻⁴ Using high strength steel sheets in the car body, collision safety is improved, and weight reduction is achieved by reducing the sheet thickness. Although it is believed that weight reduction will continue in the future by utilizing high tensile steel sheets in a comprehensive manner, there are limits to reducing the sheet thickness without affecting the rigidity of the members. When it is necessary to reduce the weight by 30% or more compared to the current level, multi materials that partially use an aluminum alloy (hereafter referred to as Al alloy) should be considered. In this case, a dissimilar metal welding technology for steel and Al alloys becomes indispensable.⁵

In the case of dissimilar metal welding, the solid state welding method has attracted attention due to the fact that brittle intermetallic compounds are formed at the bonding interface in the fusion welding method, and high bonding strength tends to be difficult to obtain. Numerous different solid state welding methods have been considered, including friction stir welding,⁶⁻⁷ friction welding,⁸⁻⁹ explosive welding,¹⁰ diffusion bonding,¹¹ roll bonding,¹² stud junction,¹³ and mechanical joining methods.¹⁴⁻¹⁵ Magnetic pulse welding (MPW) is also a type of solid state welding.¹⁶ Up to now, MPW has been applied to welding between similar metals, such as industrial pure aluminum sheets,¹⁷ Cu sheets,¹⁸ and 2000-series Al alloy sheets,¹⁹ as well as to welding between dissimilar metals, including industrial pure aluminum sheets and Cu sheets,²⁰ and 6000-series Al alloy sheets and steel sheets.²¹ In any case, under appropriate welding conditions, a wavy pattern can be observed from the welding interface in a good bonding state as in the case of explosive welding, and it is known that an intermediate layer is partially formed at the welding interface between dissimilar metals.²₀,²¹ When a good welding state is achieved, it is possible to obtain a strongly joined sheet that does not break on the welded area but rather on the base metal that has a low strength. Based on the literature background, we reported in a previous work that joining a 6061-T6 sheet with a dual phase DP 590 steel sheet by colliding the flyer sheet with the fixed sheet at a higher collision speed can be achieved by tuning the discharge energy and gap length between the fixed and flyer sheets.²₂ The use of high tensile steel for automobile bodies is steadily progressing, and it is predicted that by 2025 1 GPa class super high tensile steel sheets with a tensile strength of 980 MPa or more will be used extensively.²³

In this study, after clarifying appropriate welding conditions for DP 780 steel sheets and 6061-T6 sheets via MPW, the two sheets were joined, and the welding conditions were examined. The joining characteristics were evaluated through a tensile shear test for the lap joint sheet. Furthermore, the microstructure of the welded interface in the lap joint sheet was imaged using an electron microscope, and the formation of the interface structure was analyzed.

2. Experimental Methods

2.1 Preparation of the magnetic pulse-welded sheet and evaluation of the strength of the lap joint sheet

In the lap joining of sheets via MPW, the fixed sheet and flyer sheet that need to be joined on a coil are installed with a gap. The electric energy stored in the capacitor is one of the

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*²Corresponding author, E-mail: itoi@faculty.chiba-u.jp
joining conditions and is expressed as the discharge energy \( W \). When a large pulse current flows through the coil, a high density magnetic flux is generated around the center of the coil. When the magnetic flux crosses the flyer sheet, an eddy current is induced in the flyer sheet so as to prevent the magnetic flux from entering it. Here, the induced eddy current and high density magnetic flux interact to generate an upward electromagnetic force inside the flyer sheet. The flyer sheet to which the electromagnetic force is applied is deformed, collides at high speed, and is joined to the fixed sheet in a seam shape. Since the eddy current is larger for a metal having a higher conductivity, an Al alloy with higher conductivity is used as the flyer sheet in joining the steel sheet and the Al alloy sheet. A chromium copper flat E-shaped one-turn coil was used as the coil. The capacity of the capacitor was 400 \( \mu \)F and the frequency was 33 kHz.\(^{24}\)

As test metals, either a 6061-O sheet or a 6061-T6 sheet was used as the flyer sheet. On the other hand, either a DP780 steel (JSC780Y) sheet or a DP980 steel (JSC980Y) sheet was used as the fixed sheet. JSC steel is a type of DP steel having a two-phase structure consisting of ferrite and martensite phases which exhibit a tensile strength of 780 and 980 MPa, respectively. The dimensions of the Al alloy sheets and steel sheets were \(80 \times 100 \times 1.0\) mm\(^3\), and each sheet was lap-joined perpendicular to the rolling direction. Table 1 shows the chemical components of the 6061-T6 sheet. The components are the same as those of the 6061-O sheet. Table 2 shows the chemical composition of the DP780 and DP980 steel sheets. Table 3 shows the tensile properties and hardness values of the 6061-O sheet, 6061-T6 sheet, DP780 steel sheet, and DP980 steel sheet used in this experiment.

The experiment was performed by adjusting the discharge energy \( W \) from 0.5 to 3.0 kJ and adjusting the gap length \( d \) from 0.38 to 5.22 mm. Figure 1(a) shows the lap joint between the 6061-T6 sheet and the DP780 steel sheet (hereafter, the joined sheet is designated as the 6061-T6/DP780 steel sheet), and Fig. 1(b) shows the corresponding cross-sectional view.

The bonding strength of the lap joint sheet was evaluated at room temperature via a tensile shear test using an Instron universal testing machine. A test piece of JIS13B (1/2 reduction) was prepared from the lap joint sheet using a wire electric discharge machine. The tensile shear test was performed at a constant crosshead speed of 1.0 mm/min parallel to the rolling direction of the sheet. The tensile shear test was performed after fixing the auxiliary sheet together with the test piece when fixing the joint, so that a shear force acts on the joint. Figure 1(c) shows the tensile shear test specimen and its conditions before and after the shear test, whereas Fig. 1(d) illustrates a schematic diagram of the joining process.

### Table 1 Chemical composition of the 6061-T6 sheet. (mass%)  

|   | Si   | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Al  |
|---|------|-----|-----|-----|-----|-----|-----|-----|
| 6061-T6 | 0.40~0.8 | 0.7       | 0.15~0.40 | 0.15 | 0.8~1.2 | 0.04~0.35 | 0.25 | Bal. |

### Table 2 Chemical compositions of the DP780 and the DP980 steel sheets. (mass%)  

|   | C  | Mn | Si | Fe |
|---|----|----|----|----|
| DP780 steel | 0.06 | 2.2 | 1.00 | Bal. |
| DP980 steel | 0.08 | 3.1 | 0.20 | 0.02 | Bal. |

### Table 3 Mechanical properties of the 6061-O, the 6061-T6, the DP780 steel and the DP980 steel sheets.  

|   | 0.2% proof stress [MPa] | Maximum stress [MPa] | HV0.5 | Elongation [%] |
|---|-------------------------|----------------------|-------|---------------|
| 6061-O | 41 | 121 | 37 | 25 |
| 6061-T6 | 280 | 305 | 115 | 10 |
| DP780 steel | 504* | 863 | 318 | 18 |
| DP980 steel | 665* | 1071 | 324 | 12 |

*Yield stress
tensile shear test specimen. In the figure, the grip area is indicated by the hatch pattern, and the distance between the grip areas is 46 mm. For a low bonding strength, the test piece was found to peel off in the bonding regions, whereas, for a high bonding strength, the base metal (6061-T6 sheet) was broken.

2.2 Collision time measurement and collision speed calculation

The collision time was measured using a 6061-O sheet and a 6061-T6 sheet as flyer sheets, setting $W$ to 2.0–3.0 kJ and changing $d$ from 0.38 to 5.22 mm. As an example, Fig. 2 shows the discharge current (upper curve) and collision time signal (lower curve) measured using an oscilloscope. In this case, the flyer sheet is a 6061-T6 sheet, and the discharge energy and gap length are $W = 3.0$ kJ and $d = 1.17$ mm, respectively. The discharge current oscillates and attenuates after reaching the maximum current ($I_{\text{max}}$) of 280 kA at time $t_m$. Times $t_0$ and $T$ denote the first zero current time and period which are 15.16 and 30.7 µs, respectively. The time during which the discharge current flows is as short as ~70 µs. Since the deformation of the flyer sheet starts when the discharge current flows through the coil, the collision time represents the time it takes for the collision time signal to increase when the rise time $t$ of the discharge current is set to zero. The distance between the solid lines on the horizontal axis is denoted as $t_c$. As described above, this measurement system is a continuous time measurement method and can accurately measure a collision time of several microseconds. During the measurement of the collision time in the MPW technique, the time required for the flyer sheet to reach the fixed sheet is measured, so that the collision speed does not depend on the mechanical properties of the fixed sheet.

2.3 Observation of the interfacial microstructure of the magnetic pulse-welded sheet

The microstructure of the weld interface was imaged for a cross section perpendicular to the seam direction of the joint. The microstructure was observed using a scanning electron microscope (SEM, JSM6510). The crystal orientation analysis via the electron backscatter diffraction (EBSD) method was performed using the AZteckHKL EBSD analysis software produced by OXFORD. In addition, elemental analysis was performed using an energy dispersive spectrometer built into the SEM.

3. Results and Discussion

3.1 Impact velocity changes upon increasing the discharge energy and gap length

Figure 3(a) shows the relationship between the collision time and gap length for the 6061-O and 6061-T6 sheets. Symbols “•” and “△” are used to denote a discharge energy of 2.0 kJ, whereas the “○” symbol corresponds to a discharge energy of 3.0 kJ. In each case, it can be seen that the longer the gap length, the longer the collision time. Furthermore, the collision time is longer for the 6061-T6 sheet than for the 6061-O sheet, as the former has a higher hardness value. In addition, it can be seen that, for the same 6061-T6 sheet, the larger the $W$, the shorter the collision time. Figure 3(b) shows the relationship between the collision speed of the two sheets and the gap length. The collision velocity can be obtained by fitting the gap length as a function of the collision time with a fourth-order polynomial and by subsequently differentiating the obtained equation with respect to time.

In the measurement of the collision time, the discharge current and collision time signal (AC waveform) of the measurement circuit appearing immediately after the flyer sheet and fixed sheet come into contact with each other are simultaneously measured with an oscilloscope. The deformation of the flyer sheet starts after the discharge current flows through the coil. Therefore, the collision time can be accurately obtained by measuring the time difference from the collision time signal using the start time of the discharge current at the time of contact with the fixed sheet as the reference time. The details of the measurement of the collision time of MPW have been described in a report by
Okagawa et al.24) The collision speed increases with the increase of the gap length. It can be seen that the collision speeds are 531 m/s for the 6061-T6 sheet (\(W = 3.0\, \text{kJ}, d = 3.11\, \text{mm}\)), 456 m/s for the 6061-O sheet (\(W = 2.0\, \text{kJ}, d = 3.11\, \text{mm}\)), and 384 m/s for the 6061-T6 sheet (\(W = 2.0\, \text{kJ}, d = 2.04\, \text{mm}\)); these collision speeds decrease after reaching the maximum value. From this result, it can be seen that, when the same type of the 6061 flyer sheet is used, the collision speed increases when \(W\) is large. In addition, it can be seen that the collision speed is higher for the same \(W\) value, because the sheet with a lower hardness value has a smaller deformation resistance than the sheet with a higher hardness value. The reason why the collision speed decreases after reaching the maximum value is due to the fact that, if the gap length is too wide, the amount of deformation of the flyer sheet increases, causing work hardening. In addition, the reduction of the collision speed can be attributed to the decrease of the influence of the electromagnetic force as the flyer sheet exits the coil.

Based on the above results, a welding experiment able to achieve a higher collision speed was performed with \(W = 3.0\, \text{kJ}\).

### 3.2 Influence of the gap length on the welding characteristics of the 6061-T6/DP780 steel sheet

Figure 4(a) shows the relationship between the fracture load and gap length of the 6061-T6/DP780 steel sheet for \(W = 3.0\, \text{kJ}\). The sample where the joint was peeled off is shown in white, whereas the sample whose base metal was fractured is shown in black and exhibits the maximum load. In the figure, the breaking load of the 6061-T6 sheet is indicated by a solid line. Welding was possible with \(d\) from 1.00 to 1.59 mm and was impossible when \(d\) exceeded 1.59 mm. A tensile shear test was performed on a lap joint sheet prepared with \(d = 1.00–1.59\, \text{mm}\). For \(d = 1.00\, \text{mm}\), the joint peeled off at 0.8 kN; however, for \(d = 1.17–1.42\, \text{mm}\), the base metal fracture occurred in the 6061-T6 sheet. Furthermore, for \(d\) reaching 1.59 mm, the joint peeled off at 0.4 kN. From the above results, it can be inferred that \(d = 1.17–1.42\, \text{mm}\) is an appropriate joining condition and that a strong joining sheet causing the base metal fracture for the 6061-T6/DP780 steel sheet can be obtained. Figure 4(b) displays the relationship between the collision speed and gap length for the 6061-T6 sheet. In this figure, \(W = 3.0\, \text{kJ}\) as in the joining condition. The range of collision speeds in the production of the lap joint sheet in which the base metal is fractured is indicated by a dashed line. The collision speed under appropriate welding conditions with \(d = 1.17–1.42\, \text{mm}\) ranges from 430 to 459 m/s. The collision speed increases to 479 m/s for \(d = 1.59\, \text{mm}\) and to 531 m/s for \(d = 3.11\, \text{mm}\), but the lap joint sheet is peeled off or unwelded. That is, it is not possible to determine the bonding strength nor the possibility of welding the lap joint sheet based only on the collision speed. In order to obtain a strong bonding that fractures at the base metal, it is desirable to use a high collision speed for joining the 2024-T3 sheet with the 7075-T6 sheet and for welding the 6061-T6 sheet with the DP590 steel sheet with high tensile strength. Increasing the collision speed means increasing the collision pressure. However, from Figs. 4(a) and 4(b), it can be seen that, in the case of the 6061-T6/DP780 steel sheet, even if the collision speed increases, the lap joint sheets are peeled off or unwelded; thus, it is necessary to consider other factors in the welding conditions.

Figure 5(a) shows a cross-sectional backscattered electron (BE) image of a 6061-T6/DP780 steel joint sheet. The upper side is a fixed sheet (DP780 steel sheet) and the lower side is a flyer sheet (6061-T6 sheet). In MPW, after the flyer sheet collides with the fixed sheet, the collision point moves from...
the center line of the coil shown in the figure toward the joint end side, and the joint starts from a specific position. Therefore, the sheets are joined at two points on the left- and right-hand side of the figure, as indicated by the white line, almost symmetrically with respect to the center line. Hereafter, these two areas are referred to as the joint area, and the sum of their widths is referred to as the weld width. The BE images in Figs. 5(b)–5(d) show the prepared joint sheets with \( d = 1.05, 1.17, \) and 1.59 mm, respectively. The left-hand side of the figure corresponds to the center line side of the coil, whereas the right-hand side corresponds to the joint end side. Similar to explosive welding, joining is performed at a portion of the sheets where both the moving speed of the collision point and the collision angle between the fixed sheet and the flyer sheet satisfy the conditions of wavy interface welding. A wavy pattern is observed at the weld interface in Figs. 5(b)–5(d). In MPW, the angle between the fixed sheet and the flyer sheet increases continuously, so that the wavelength tends to increase from the center line toward the joint end. In the case of Fig. 5(b), as indicated by the arrows, it is about 10 \( \mu \text{m} \) near the coil and about 50 \( \mu \text{m} \) near the joint end. In addition, the formation of an intermediate layer is partially observed inside the wave front area (the flyer sheet side) from any of the weld interfaces. The weld widths of the joint sheets in Figs. 5(b)–5(d) are 1.05, 1.34, and 0.91 mm, respectively; thus, the weld width is the largest in Fig. 5(c), and the base metal was fractured upon performing the tensile shear test. Therefore, it can be concluded that the wider the weld width, the stronger the joint state.

Figure 6 shows the weld width of the joint sheets for different gap lengths. The “\( \circ \)”, “\( \Delta \)”, and “\( \ast \)” symbols indicate the weld width on the left-hand side from the center, the weld width on the right-hand side, and the total weld width. From this figure, it can be seen that the left and right weld widths are almost the same regardless of the gap length \( d \). Furthermore, it can be seen that the weld width exhibits the maximum value (2.92 mm) for \( d = 1.31 \) mm and becomes narrower for \( d > 1.31 \). In the figure, the range of gap lengths in the production of the joint sheet for which the base metal is fractured is indicated by a dashed line. From this result, it can be seen that a weld width of 2.38 mm or more is required to fracture the base metal. However, as can be observed from Fig. 5(d), when \( d \) is increased to 1.59 mm, the weld width becomes narrower. In other words, it can be seen that the weld width becomes narrower even though the welding is performed at a faster collision speed.

Figures 7(a) and 7(b) show the measurement results regarding the relationship between the discharge current and the collision time signal for \( d = 1.17 \) and \( d = 1.59 \) mm, respectively. From these figures, it can be seen that the time \( t_m \) for reaching the maximum current value is 6.28 and 6.20 \( \mu \text{s} \), respectively. The time at which the flyer sheet first collides with the fixed sheet (i.e., the collision time \( t_c \)) is 5.32 \( \mu \text{s} \) and 6.36 \( \mu \text{s} \), respectively, and becomes longer as the gap length increases. The collision times indicated by the arrows in Figs. 7(a) and 7(b) represent the times at which the flyer sheet reaches the fixed sheet, thus denoting the start times of the continuous collision of the flyer sheet. In addition, the start times of both collisions differ by about 1 \( \mu \text{s} \), and this difference collides before and after \( t_m \) (i.e., for \( t_c < t_m \) and \( t_c > t_m \)) when the weld start time reaches the maximum current value. The influence of collision timing on weldability was investigated in terms of the electromagnetic force. Figure 7(c) shows a schematic diagram of the time transition of the electromagnetic force generated in the flyer sheet. In the figure, \( t_c \approx t_m \) is indicated by a solid line, and the cases in which the start time \( t_c \) of the continuous collision is before and after \( t_m \) are indicated by arrows. From this figure, the case of \( t_c > t_m \) has a shorter pressure contact time when the two sheets are in contact with respect to the case of

![Fig. 6 Relationship between weld width for the 6061-T6/DP 780 steel lap joint sheet prepared by various gap length.](image)

![Fig. 7 Wave forms of discharged current and collision time signals obtained (a) \( d = 1.17 \) mm, and (b) \( d = 1.59 \) mm, respectively. (c) Schematic image of electromagnetic force after collision times.](image)
\( t_c < t_m \) and is thus subjected to the impulse of the dark gray part shown in the figure. On the other hand, the case of \( t_c < t_m \) is subjected to the impulse of the light gray part of the figure in addition to the dark gray one. That is, under the welding condition of \( t_c < t_m \), the collision velocity is slightly slower, but the sheet is subjected to the action of a larger electromagnetic force from the coil. From Fig. 2, it can be seen that the maximum value of the discharge current is 280 kA when \( W = 3.0 \text{ kJ} \). It is difficult to quantitatively evaluate the effect of the electromagnetic force on the flyer sheet. However, since the electromagnetic force is proportional to the square of the discharge current, in the case of \( t_c < t_m \) the flyer sheet is affected by the integral electromagnetic force (i.e., the region including the maximum electromagnetic force) shown in light gray. It can thus be inferred that the electromagnetic force (light gray impulse) affects the weldability. From the results in Fig. 6, it can be observed that the weld width becomes wider when the action of the electromagnetic force continuously generated on the flyer sheet immediately after the first collision is sufficiently large in addition to the impact pressure caused by the collision speed. Therefore, the collision time is considered to be one of the main factors affecting welding in addition to the collision speed.

In a previous work, it was found that, even for MPW of the 6061-T6 sheet and the DP590 steel sheet, a strong bonding that fractures at the base metal was possible for \( W = 3.0 \text{ kJ} \) and \( d = 1.42 \text{ mm} \). Since in the present study it was possible to weld under the same conditions as those used in the abovementioned experiment, it can be inferred that both the electromagnetic force and the increase in collision speed influenced the measurements.

### 3.3 Preparation of the 6061-T6/DP980 steel joint sheet and observation of the interfacial microstructure

Based on the above results, a DP980 steel sheet and a 6061-T6 steel sheet with higher strength were joined. Figures 8(a) and 8(b) show the SEM images of the DP780 steel and the DP980 steel, respectively. The grain size of the DP780 steel is about 10–20 µm, but it can be seen that the grain size of the DP980 steel is smaller. Figures 8(c)–8(e) illustrate the image quality (IQ) map, phase map, and inverse pole figure (IPF) of the DP980 steel. From these measurements, the grain size was found to be about 1–5 µm and the ratio of \( \alpha \)-Fe to martensite was about 1:1. This ratio was almost the same for the DP780 steel.

Figure 9 shows a cross-sectional BE image (on the right-hand side) of a 6061-T6/DP980 steel joint sheet (\( W = 3.0 \text{ kJ}, d = 1.17 \text{ mm} \)). The weld width was 1.38 mm for \( d = 1.17 \text{ mm} \) and 1.29 mm for \( d = 1.31 \text{ mm} \), thus very similar to the weld width of the 6061-T6/DP780 steel joint sheet. Similarly, from the weld interface, the formation of an intermediate layer was partially observed inside the wave crest. Figure 10 shows a photograph of a test piece of the 6061-T6/DP980 steel joint sheet (\( W = 3.0 \text{ kJ}, d = 1.17 \text{ mm} \)) after performing the tensile shear test. For \( W = 3.0 \text{ kJ} \) in the 6061-T6/DP980 steel joint sheet, in addition to the case of \( d = 1.17 \text{ mm} \) shown in the photo, the 6061-T6 sheet was capable of strong joints where the base metal fractures even for \( d = 1.31 \text{ mm} \). In other words, as in the case of welding between the 6061-T6 steel sheet and the DP780 steel sheet, good welding is possible when \( t_c < t_m \), which is consistent with the abovementioned considerations. However, since welding was not possible for \( d = 1.42 \text{ mm} \), the welding conditions were found to be stricter in this case than in the
case of welding between the 6061-T6 sheet and the DP780 steel sheet.

Figures 11(a) and 11(b) show enlarged images of the weld interface of the 6061-T6/DP780 steel joint sheet and the 6061-T6/DP980 steel joint sheet, respectively. A wavy pattern can be observed for both welding interfaces, and the 6061-T6 base metal seems to be entangled like a vortex by the plastic flow at the time of welding, which causes an anchor effect on the base metal. Figures 11(c) and 11(d) show enlarged images of each anchor areas. From the SEM images, it can be observed that the grains are elongated along the shape of the wave crest, and it can be seen that the grains of the DP780 steel sheet are smaller than the structure inside the base metal. On the other hand, it is difficult to identify microstructural changes in the DP 980 steel sheet because of the small grains.

Based on the above results, SEM imaging of the weld interface and crystal orientation analysis via EBSD were performed on the 6061-T6/DP980 steel joint sheet ($W = 3.0 \text{ kJ}, d = 1.17 \text{ mm}$). Figures 12(a)–12(f) present the SEM image, Fe map, Al map, IQ map, (e) IPF, and (f ) kernel average misorientation (KAM) map of the 6061-T6/DP980 steel joint sheet, respectively. From the SEM image, a wavy
pattern generated by the plastic flow as the fixed sheet and the flyer sheet collided with each other was observed at the weld interface. From the Fe and Al element maps of Figs. 12(b) and 12(c), the weld interface between the DP980 steel sheet and the 6061-T6 steel sheet can be clearly seen. In the figure, a region where both the Fe and Al elements are distributed inside the wave crest can be identified, and it can be seen that an intermediate layer of about 10 µm is formed in the sheet thickness direction. In the IQ map of Fig. 12(d), the region with low IQ values corresponds to the intermediate layer, suggesting that small grains were formed. The IPF in Fig. 12 also shows the boundary line (grain boundary) with an orientation difference between the grains of 15° or more. The region enclosed by a white line in the vicinity of the weld area corresponds to the region in which plastic flow occurred during the formation of the wavy pattern. Compared with the grain size of the base metal, it can be seen that the grains in this region are smaller, and grains of 1-µm size or less can be observed along the welding interface. The crystal orientation is random, and several works have reported grain refinement at such weld interfaces.20,23) This structure formation can be attributed to rapid solidification after local dissolution, or recrystallization by accumulation of strain near the interface due to impact deformation and subsequent heating. The KAM map in Fig. 12(f) shows the average value of the crystal orientation difference between adjacent pixels at each measurement point, indicating a distribution of misorientation values up to 5°. From the degree of strain accumulation shown in the KAM map, it is inferred that a relatively large amount of strain was introduced into the steel sheet side (the fixed sheet side) up to about 10 µm at the time of welding. As can be seen through comparison with Fig. 12(e), this region coincides with the region in which grains are of a smaller size.

It is considered that the wavy pattern observed at the weld interface is formed via the same mechanism as the wavy pattern observed at the weld interface using an impact force such as explosive welding.

Various mechanisms have been proposed to explain the formation of wavy interfaces in explosive welding, such as the indentation mechanism, Kelvin–Helmholtz instability, Karman vortex streets, or shear instability due to large shear at the interface. The formation of these wavy interfaces is believed to be due to the hydrodynamic instability of the material during high pressure and high speed deformation, but its underlying mechanism has not yet been fully elucidated.25–27) In explosive welding, the collision speed is predominantly controlled by the amount of explosive, and a strong impact force can be obtained at a collision speed of 1000 m/s or more; thus, surface joining is possible for various metal sheets. On the other hand, MPW is a line-welding method that uses the electromagnetic force, which has a weaker impact than explosive welding. Since the shearing force is applied parallel to the weld interface of the joint sheet, the surfaces of the joint sheet are plastically deformed to produce an anchor effect, which is a preferable structure for improving the joint strength.22) From the above results, it was found that not only the 6061-T6/780 steel joint sheets but also the 6061-T6/DP980 steel joint sheets can be welded as well as the base metal (6061-T6) via MPW.

As for the welding conditions, a high collision speed is desirable. Therefore, as can be seen from Fig. 3(b), the coil and flyer sheet require a wide gap. However, considering the action of the electromagnetic force to which the joint sheet is subjected from the coil, it is desirable to have a narrow gap. In order to satisfy these contradictory welding conditions, it was found that the flyer sheet should collide with the fixed sheet at a high speed during all the time it takes for the discharge current to reach the maximum value. Therefore, in order to achieve good welding, it is necessary to control the collision time by adjusting the gap length \( d \) when the discharge energy \( W \) is constant. An accurate measurement of the collision time is important in examining the appropriate welding conditions, and the electrical measurement method used in this study was found to be effective. As the strength of the sheet steel increases, the range of the gap lengths that can be welded becomes narrower, and the joining conditions are limited. However, it was possible to weld a 6061-T6 sheet and a 1 GPa class high tensile steel sheet with a gap length that satisfies this condition.

4. Conclusions

The purpose of this study was to weld a 1 GPa class high tensile steel sheet and a 6061-T6 aluminum alloy sheet. The collision velocity related to the welding conditions was measured, and the influence of the electromagnetic force on the welding was explored. Additionally, the interfacial microstructure of the joint sheet was imaged and the joint mechanism was investigated. The results obtained can be summarized as follows:

(1) Upon increasing the gap length, the collision speed of the flyer sheet increased, reached a maximum value, and then decreased. When the same type of Al alloy sheet was used, the collision speed was found to be higher for a larger discharge energy and for the case in which the hardness value of the Al sheet was lower than that of the sheet above.

(2) In the joining of a 6061-T6 steel sheet with a DP780 steel sheet, when the discharge energy was 3.0 kJ, good welding was possible for a gap length of 1.17–1.42 mm. The collision velocity range under these conditions was 430–459 m/s.

(3) The weld width of the joint sheet tended to increase as the collision speed increased. However, with a gap length of 1.59 mm or more (i.e., a collision speed of 459 m/s or more), the weld width became narrower, and the joint sheet was peeled off after the tensile test. Thus, the welding conditions of a sheet with high tensile strength cannot be evaluated only based on the collision speed.

(4) Considering that the electromagnetic force continues to act on the flyer sheet even after the flyer sheet collides with the fixed sheet, the gap length needs to be adjusted so that the collision time of the flyer sheet becomes shorter than the time required to reach the maximum current value. Therefore, the collision time is considered to be one of the dominant factors affecting the joining conditions in addition to the collision speed.
Considering point (4), in the joining of the 6061-T6 steel sheet with the DP980 steel sheet, a good welding sheet of base metal fractures was obtained for a gap length in the range from 1.17 to 1.31 mm with a discharge energy of 3.0 kJ. The collision speed at this time was 430–446 m/s, and the gap length range of the welding was narrower than that obtained upon joining the 6061-T6 steel sheet with the DP780 steel sheet.

From SEM imaging, a wavy pattern was observed at the weld interface of each welding sheet, and an intermediate layer composed of Fe and Al was found to be formed discontinuously. It is considered that the base metals wound up like a vortex produced the anchor effect.

From the EBSD analysis results, it was found that plastic strain was accumulated at the weld interface of the 6061-T6/DP980 steel joint sheet and the grains were smaller than those inside the base metal.

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