Effect of gap on FSW joint formation and development of friction powder processing

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A gap between two materials is a critical problem for friction stir welding (FSW). It is generated by a mismatch at the interface between two materials and causes defects and porosities due to the lack of material in the joint. In this study, friction powder processing (FPP) is proposed to solve this problem. Metal powder is first added to the gap between and then the FSW is performed. The effect of the gap width on the joint properties was first investigated, and the FPP feasibility was then assessed by adding pure Al powder to the gap between A1050-H24 plates. In addition, the mechanical properties and microstructures were investigated when adding a dissimilar powder, such as Cu powder, to the gap between Al plates. When using pure Al powder, the formation of defects is prevented. When using pure Cu powder, Al_2Cu precipitates were formed in the stir zone, and consequently, the hardness significantly increased.

Keywords: Friction powder processing, Friction stir welding, Aluminium, Copper, Powder, Gap

Introduction

Friction stir welding (FSW) is a novel and attractive joining technique, which has several advantages because it is a solid state process.[1–3] Accordingly, FSW has been applied to many industrial structures such as rail cars, marine vessels and automobiles.[4] Before FSW, a small interface gap between the two materials was required. A mismatch at the interface between two materials generally causes the gap, which is a critical problem because a tool is plunged into the interface between the two materials during FSW. The gap easily causes defects and porosities due to insufficient material and plastic flow. As a result, the mechanical properties of the joint significantly decrease. In particular, when large structures, such as rail cars, are produced, a gap is easily generated. To prevent the gap from being generated, highly accurate plates have to be manufactured and an advanced extrusion technique is then required.

In order to solve this problem easily, the authors developed the friction powder processing (FPP). FPP is based on the principle of FSW or friction stir processing (FSP). For FPP, the FSP is performed after powder with a controlled composition is placed in the gap between the two materials. FPP has three advantages. The first is that the metal powder serves as a filler metal to fill the gap. The second is that it can be applied to curved or complicated shape structures. The third is that a partially alloyed material is fabricated by adding a dissimilar metal powder. Chuang *et al.* performed the FSP for thin foil specimens stacked as a sandwich to form an intermetallic compound.[5] Hsu *et al.* performed the FSP for several sintered materials to form composite materials.[6–8] Mishra *et al.* and Morisada *et al.* reported that a metal matrix composite was fabricated by introducing ceramic particles, carbon nanotubes or fullerenes into a matrix via FSP.[9–13]

In this study, an aluminium alloy was used as the base material. First, the effect of the gap width on the mechanical properties was investigated. Next, pure Al powder (89 μm average grain diameter) and pure Cu powder (106 μm average grain diameter) were used as the filler metal. When using pure Al powder as the filler metal, the effect of the oxide film on the mechanical properties was investigated. When using pure Cu powder, the effect of the precipitation hardening on the mechanical properties was investigated.

Experimental procedure

Five millimetre thick A1050-H24 plates, with the nominal chemical composition of Al–0·06Si–0·34Fe–0·02Cu (in wt-%), were used as the base material in order to investigate the effect of the gap width on the joint properties. A gap was intentionally formed by placing 1, 2 or 3 mm thick shims between the two A1050-H24 plates. In order to investigate the effect of the metal powder type, Al powder (average: 89 μm) or Cu powder (average: 106 μm) was used. The Al or Cu powder was placed in the gap between the two plates before the FSW was performed, as shown in Fig. 1. The A1050-H24 plate was 5 mm thick. The FSW tool made of SKD61 has a columnar shape (ϕ15) with a threaded probe (M6). In order to prevent the powder from flying off and to increase the filling rate of the powder, the FSW was first performed with only the shoulder (0mm probe length). Next, the probe (4·5 mm) was then inserted into the gap filled with the powder. If necessary,

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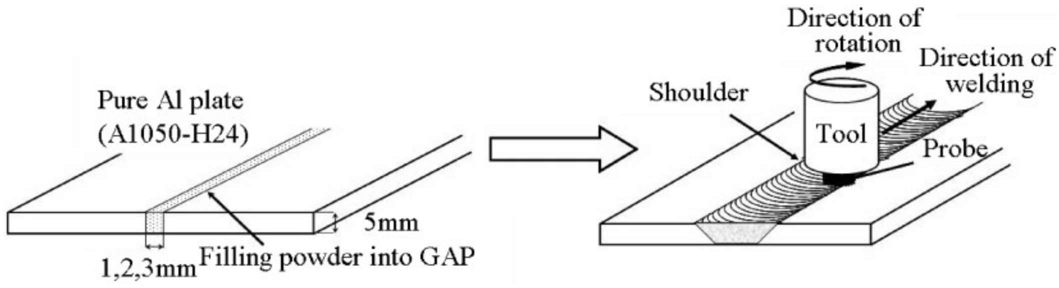


1 Schematic illustration of friction powder processing (FPP)

this process was repeated two times in order to investigate the effect of the number of processes. In this case, the FSW without the probe is not included in the number of processes. The tool travelled at 100 or 400 mm min^{-1} and rotated at 1500 rev min^{-1}. The tool was tilted by 3°.

The appearance of a cross-section was observed after polishing and etching with Keller's reagent. The hardness of the cross-section at a depth of 2·5 mm from the surface was measured using a Vickers hardness tester (Akashi HM-124) with a load of 245·2 mN. The specimens for the tensile test were prepared by cutting perpendicular to the welding direction. The tensile strength was measured using a universal testing machine (Instron 5500R) at the strain rate of 1·0 mm min^{-1}. The microstructure was investigated using a scanning electron microscope (Hitachi SU-70) in order to observe the defects and the dispersion of the powder in the stir zone. The specimens for the TEM observations were prepared by twin-jet electrolytic polishing in a solution with the mixed ratio of $HNO_3/CH_3OH=7:3$ at the temperature of −25°C. The transmission electron microscope (Hitachi H-800) was operated at 200 kV in order to observe the microstructure in more detail and identify the phases in the stir zone.

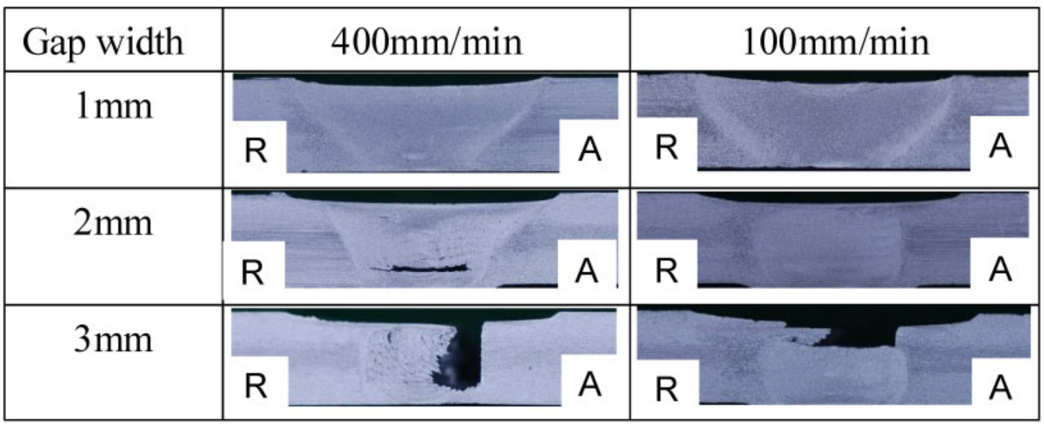
Results and discussion

FSW with gap

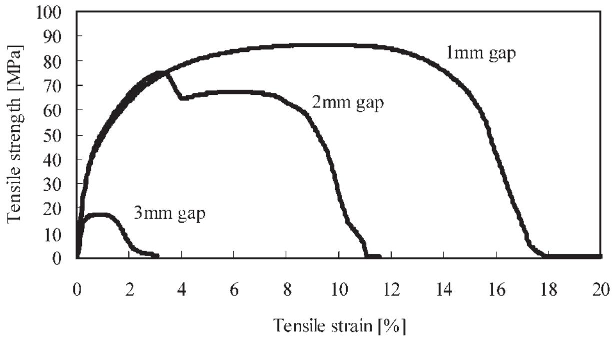
Figure 2 shows the effect of the gap distance on the appearances of the cross-sections of the joints obtained without any powder. In this case, the rotation speed was 1500 rev min^{-1}. The travelling speed of 400 mm min^{-1} is the same as the optimum conditions for joining A1050-H24 plates without any gap.[14] For 1 mm gap, no defect formed throughout the joint, because sufficient plastic flow enables the 1 mm gap to be completely filled. For the 2 mm gap, no surface defects appeared but internal defects formed. For the 3 mm gap, a large defect was formed from the surface to the bottom. It was a groove-like defect, which was generated on the advancing side.

It should be noted that the stir zone was smaller as the gap width became larger, because the gap decreases the heat input. Frigaard *et al.*[15] reported an equation for the relationship between the generated heat and various parameters during FSW. According to the equation, the heat input is proportional to the cube of the shoulder diameter. The contact area between the shoulder and the material surface has a significant effect on the heat input. When a gap exists, the contact area decreases and then a cavity or groove-like defects are easily caused due to the insufficient heat input.[16] Accordingly, FSW was performed with a higher heat input by decreasing the travelling speed from 400 to 100 mm min^{-1}. Under the higher heat input conditions, no internal defects were formed even for the 2 mm gap. However, when the gap was 3 mm, the lack of material could not be solved by the higher heat input.

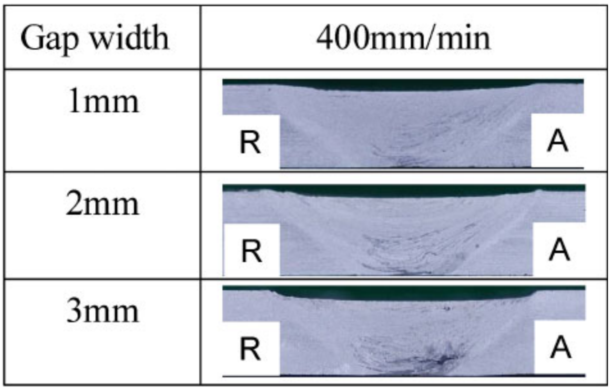
Figure 3 shows the effect of the gap width on the stress–strain curve of the joints obtained without powder at 400 mm min^{-1} and 1500 rev min^{-1}. Corresponding to the microstructure, there are no influences by the 1 mm gap. For the 2 mm gap, the tensile strength suddenly decreased before reaching the maximum tensile strength due to the tunnel hole defects. For the 3 mm gap, the sample was easily fractured due to lack of material. Thus, an increase in the heat input can effectively decrease the effect of the gap. However, a low welding speed is not practical in industrial applications. The thickness of the joints decreases when a large gap exists. In order to solve this problem, the authors have



2 Cross-section of joints obtained without powder at 400 and 100 mm min^{-1} (A: advancing side; R: retreating side)



3 Effect of gap width on stress–strain curve of joints obtained without powder at 400 mm min^{-1} and 1500 rev min^{-1}



4 Cross-sections of joints obtained with Al powder at 400 mm min^{-1} and 1500 rev min^{-1}

developed a new joining method, called FPP, using pure aluminium powder as the filler metal.

FPP with aluminium powder

Figure 4 shows cross-sections of the joints obtained after adding Al powder to the gap. The travelling speed and rotation speed were 400 mm min^{-1} and 1500 rev min^{-1} respectively. In this case, no significant defects were observed, because the Al powder served as a filler metal. However, after etching the specimen, many zigzag lines were observed on the advancing side after etching the specimen. As shown in Fig. 5, these zigzag lines were similar to a lazy S. Reynolds[17] has suggested that the lazy S is the remnants of the oxide layer at the interface. This indicates that the oxide film on the Al powder caused these zigzag lines in this case. It is also noted that the powder tended to segregate on the advancing side.

Table 1 shows the ultimate tensile strength and the elongation of the joints obtained using Al powder at 400 mm min^{-1} and 1500 rev min^{-1}. After the first pass, for both the 1 and 2 mm gaps, the joints show a sufficient elongation and ductile fracture, although the

5 Image (SEM) of cross-section of joints with Al powder after etching (400 mm min^{-1} and 1500 rev min^{-1})

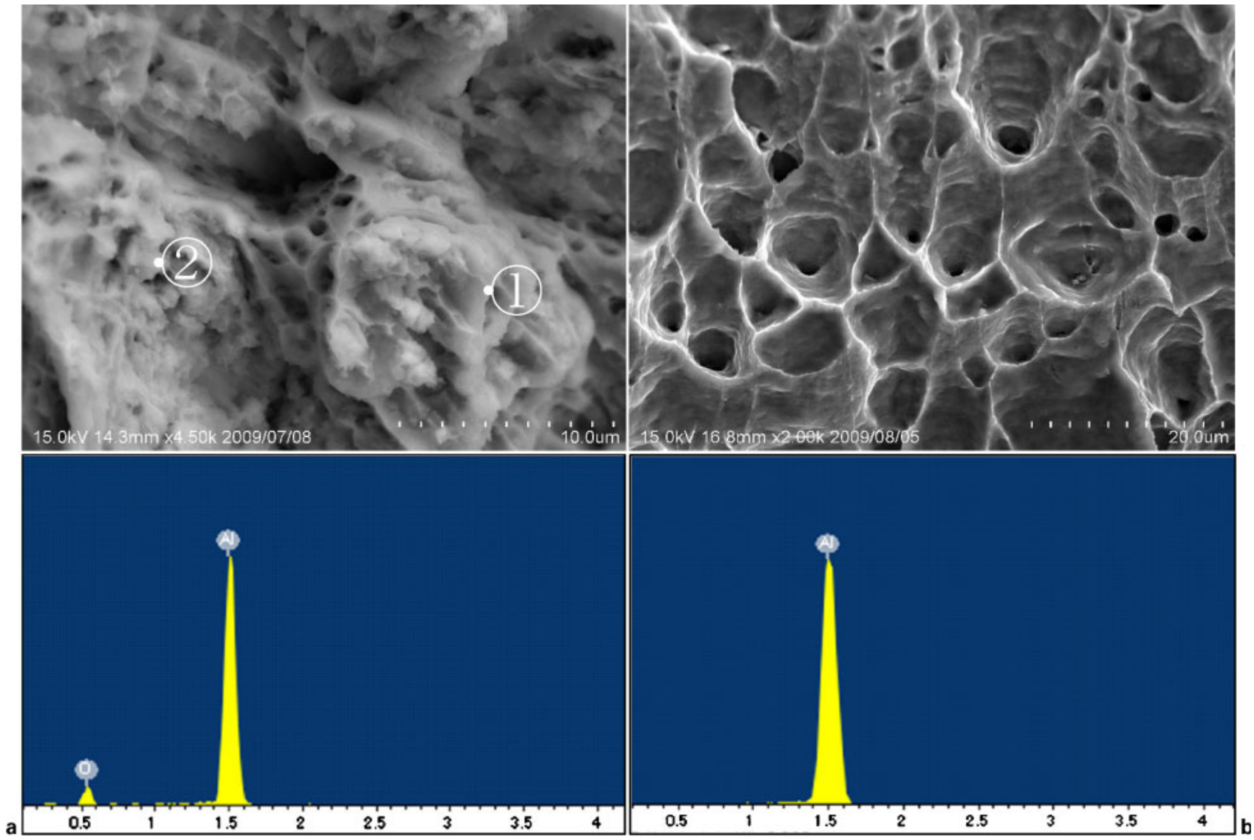
elongation slightly decreased from that of the base metal. For the 3 mm gap, the strain–stress curve was discontinuous and brittle fracture occurred. In order to enhance the joining of the Al powder with the Al matrix, the FPP process was repeated twice. Note that even for the 3 mm gap, ductile fracture occurred after the second pass while brittle fracture occurred after the first pass.

Figure 6 shows the fracture surface morphology and EDX analysis results of the tensile test specimens obtained after the first pass (Fig. 6*a*) and the second pass (Fig. 6*b*) after adding Al powder to the 3 mm gap. After the first pass, agglutinated Al powders were observed at the fracture surface. After the second pass, on the other hand, dimple patterns, a feature of the ductile fracture, were observed. According to the EDX analysis results, after the first pass, the oxygen was detected on the fracture surface. The ratio of the oxygen content at points 1 and 2 were 30·5 and 28·3 at-% respectively. This indicates that the oxide film on the Al powder caused the brittle fracture. Using Al powder as the starting material was effective to fill the gap. However, control of the interfacial area between the matrix and the oxide film is required. Sato *et al.*[18,19] evaluated the behaviour of the surface oxide film and investigated the dispersion of the Al_2O_3 oxide layer from the initial butt surface during the stirring in the FSW process. They suggested that the distribution of Al_2O_3 oxide particles in the local region did not affect the mechanical properties, but agglutination of the oxide film often adversely affects the mechanical properties of the weld.[18–20] It is important to decrease the quantity of the oxide film on the original powder surface.

As mentioned before, to repeat the FPP twice is one way to solve this problem as shown in Table 1 and Fig. 6. After the second pass, a sound joint was successfully obtained even for the 3 mm gap. The second FPP pass is effective for not only combining

Table 1 Ultimate tensile strength and elongation of joints obtained after first and second passes at 400 mm min^{-1} and 1500 rev min^{-1} after adding Al powder

Gap width, mm	One-pass UTS, MPa/elongation, %	Two-pass UTS, MPa/elongation, %
0	85·0/12·2	
1	85·5/9·5	86·8/10·4
2	89·2/8·5	85·3/8·6
3	82·8/4·0	81·5/8·8



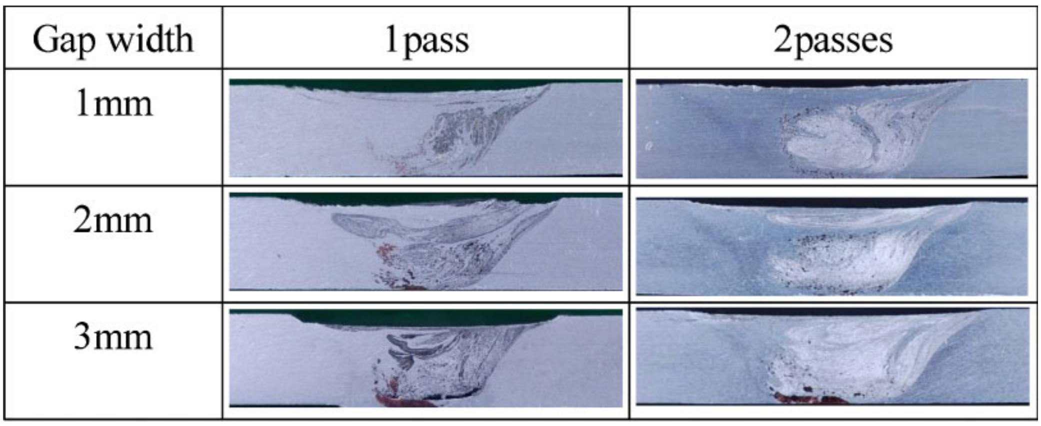
6 Fracture surface appearances and EDX analysis results of tensile test specimens obtained after *a* first pass and *b* second pass after adding Al powder to 3 mm gap

the Al powder with the Al matrix, but also dispersing the agglutinated oxide films. This phenomenon is similar to that in the multipass FSW/P in which homogeneous microstructures are generally obtained.[21]

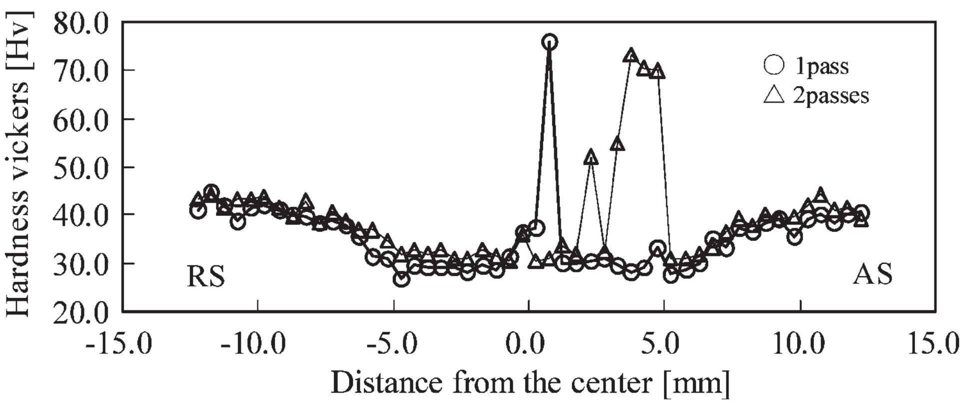
FPP with copper powder

For aluminium alloys, the temperature during the FSW generally reaches around 700 K. The Al–Cu system has a high solubility around this temperature according to the equilibrium phase diagram.[22] Accordingly, the authors thought that precipitation hardening can be expected during the FPP when Cu powder rather than Al powder is used. Figure 7 shows cross-sections of the joints obtained after adding the Cu powder. The travelling speed and rotation speed were 400 mm min^{-1} and 1500 rev min^{-1} respectively. No significant defects were observed, and it proved that Cu powder can also be effective for gap filling. However, the Cu powder was not uniformly distributed, but agglutinated on the advancing side.

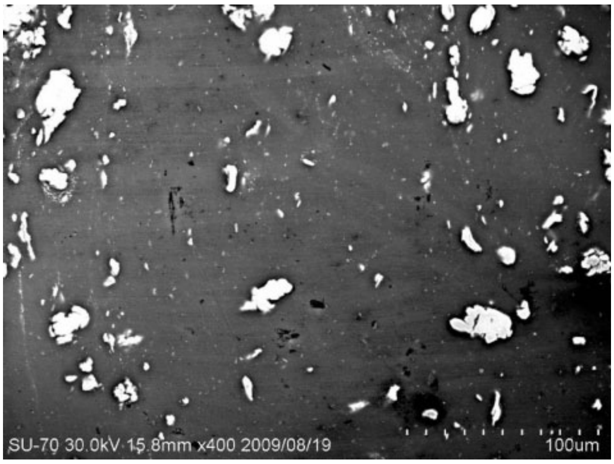
Figure 8 shows the hardness distribution after the first and second passes. The hardness values in the stir zone were not uniformly distributed in both cases, though the maximum hardness value in the stir zone approached ~75·1 HV. As shown in Fig. 9, the Cu particles were uniformly dispersed after the second pass. Thus, the second pass was effective for uniformly dispersing Cu particle in the stir zone. However, the hardness value in the stir zone had not uniformly increased, indicating that another strengthening mechanism exists. Figure 10



7 Cross-section of joints obtained after first and second passes at 400 mm min^{-1} and 1500 rev min^{-1} after adding Cu powder



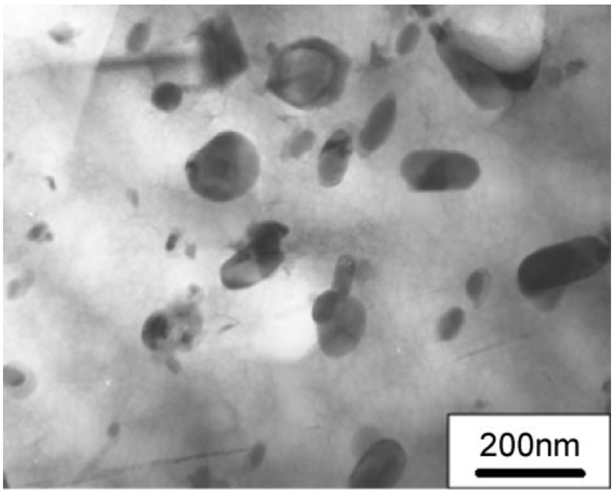
8 Hardness distribution in cross-section after second pass at 400 mm min^{-1} and 1500 rev min^{-1} with Cu powder added to 2 mm gap



9 Cu particle distribution in cross-section after second pass at 400 mm min^{-1} and 1500 rev min^{-1} with Cu powder added to 2 mm gap

shows the hardness distribution in the stir zone when the welding speed was decreased to 100 mm min^{-1}. High and uniform hardness values are obtained due to the sufficient heat input.

Figure 11 shows a TEM bright field image of the second pass joint at 100 mm min^{-1}. Many black precipitates were observed in the Al matrix. The SAED pattern of such particles corresponds to the Al_2Cu (a=6·067, b=6·067 and c=4·877) SAED pattern. Thus, these compounds are not the original powders or products due to the interfacial reactions, but are precipitates

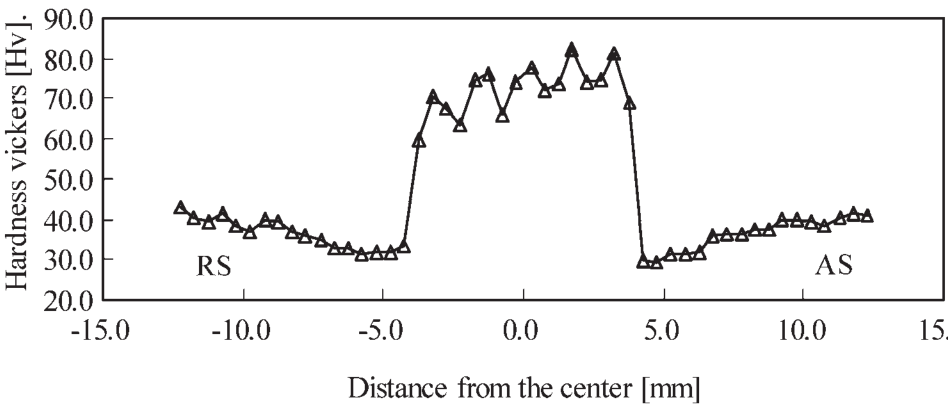


11 Image (TEM) at cross-section after second pass at 100 mm min^{-1} and 1500 rev min^{-1} with Cu powder added to 2 mm gap

of the Al_2Cu. Consequently, these intermetallic compounds were small and uniformly dispersed in the stir zone, which then uniformly increased the hardness value in the stir zone.

Conclusion

The effect of the gap width on the joint properties was first investigated. In addition, in order to solve the gap problem, FPP has been developed.



10 Hardness distribution in cross-section after second pass at 100 mm min^{-1} and 1500 rev min^{-1} with Cu powder added to 2 mm gap

The following conclusions were obtained from these results:

1. The type of defect is significantly affected by the gap width and the heat input. Under the same optimum conditions (1500 rev min^{-1} and 400 mm min^{-1}) for joining A1050-H24 plates without any gap, no defect was generated for a 1 mm gap. For a 2 mm gap, a tunnel hole was generated. For a 3 mm gap, a groove-like defect was generated.

2. Although the increase in the heat input is effective for decreasing the effect of the gap, the effect is limited. Adding powder to the gap significantly decreases the defect formation and enhances the mechanical properties of the joint (FPP).

3. When Al powder is used as the filler metal, the joints show a sufficient elongation and ductile fracture although the elongation was slightly decreased from that of the base metal.

4. A sound joint was successfully obtained even for the 3 mm gap when repeating the FPP twice. The second FPP pass is effective for not only combining the Al powder with the Al matrix, but also dispersing the agglutinated oxide films.

5. Cu powder can also be effective for gap filling. Under ordinary heat input conditions (1500 rev min^{-1} and 400 mm min^{-1}), the hardness value in the stir zone only partly increased even after the second pass. Under the higher heat input conditions (1500 rev min^{-1} and 100 mm min^{-1}), high and uniform hardness values are obtained due to many intermetallic compounds. These compounds are not original powders or products due to the interfacial reactions, but precipitates of the Al_2Cu.

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