Effect of Welding Parameters on Weld Formation and Mechanical Properties in Dissimilar Al Alloy Joints by FSW

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The dissimilar Al alloys, 5052 and 5J32, were joined by friction stir welding (FSW) technique under several welding conditions, including material arrangement. The tool rotation speeds were 1000 and 1500 rpm, and the welding speeds were varied within the range from 100 to 400 mm/min. At a tool rotation speed of 1000 rpm, all joints with the 5052 on the advancing side exhibited better properties than those with the opposite arrangement. When the 5J32 was placed on the advancing side, defect-free welds were obtained under all welding conditions. However, when the 5J32 was placed on the retreating side with a rotation speed of 1500 rpm, some defects were detected below the top surface of the retreating side. Furthermore, fractographs of the defects indicated an evidence of liquation cracking during FSW. The experimental results showed that the weld formation and mechanical properties depended upon the material arrangement as well as the conventional welding parameters. [doi:10.2320/matertrans.M2010032]

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1. Introduction

Recently, vehicle weights have been increasing due to improvements in collision safety, drivability, comfortability and mounting of various devices. Meanwhile, automobiles have to meet more stringent regulations against exhaust emissions, including carbon dioxide and NOx emissions, to protect the environment. Therefore, weight reduction has become a major focus in the automotive industry.¹) Aluminum alloys are an effective material for reducing vehicle weight and thereby increasing fuel efficiency. Moreover, the use of tailor welded blanks (TWBs) has increased rapidly, which consists of two or more sheets of different thicknesses, grades, and surface treatments joined together and then formed to create a part with optimal properties.²) Various joining methods, including spot welding, laser welding and self piercing riveting (SPR), have been applied to join the aluminum alloys but many problems occurred such as strength reduction, defect formation and weight increase.

Recently, friction stir welding (FSW) has been identified as an adequate joining technology that can be used in the joining of aluminum alloys, including similar and dissimilar alloys, while offering versatility, environmental friendliness and energy efficiency. Since The Welding Institute (TWI) of the United Kingdom developed FSW in 1991, it has primarily been applied to aluminum alloys. Among numerous aluminum alloys, the 5xxx (Al-Mg) and 6xxx (Al-Mg-Si) series alloys have been predominantly used for automotive parts, especially inner and outer body panels, respectively. 5052 and 5J32 alloys are widely used for the inner panel of doors. 5J32 is the alloy code number of Kobe steel, which corresponds to the 5023 designation by the aluminum association, and it contains less impurities compared with 5023.¹) This alloy has a superior formability to 5052 alloy but very expensive, so this is only used for the parts that require good formability. Therefore, joining of these two alloys is necessary for the fabrication of the inner panel with low cost.

In the early stage, few studies on the FSW of dissimilar aluminum alloys were undertaken, and most of these were focused on material flow visualization rather than the characterization of various properties.³–⁶) Recently, many studies have been conducted to establish the optimum parameters for FSW of dissimilar aluminum alloys and to identify their microstructures, mechanical properties and defect formations. It is important to note that for FSW of dissimilar materials, additional parameters, such as material arrangement and position of tool plunge with respect to the weld center line, need to be considered, as well as general parameters such as tool geometry, rotation speed, and welding speed. Because material flows and thermal hysteresis differ between the advancing and retreating sides, so material arrangement and tool plunge position exert a significant effect on weld formation.

For FSW of dissimilar materials having different strength, Larsson et al. initially proposed that the softer material should be placed on the advancing side of the weld to produce better welds,⁷) and many researchers have subsequently reported similar results.⁸,⁹) However, some researchers reported that superior welds obtained when the harder material was placed on the advancing side¹⁰) or that the material arrangement did not affect the weld property.¹¹) Therefore, we investigated the effect of welding parameters, including material arrangement, on weld formation and mechanical properties in dissimilar 5052-5J32 alloy joints produced by FSW and suggested the possibility of liquation cracking during FSW.

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The tool-to-workpiece angle was 3:1 which the ratio of probe diameter to depth is approximately larger shoulder and probe than those of conventional tools, of 12 mm and probe length of 1.45 mm. This tool has a slightly advancing side and 5052 on the retreating side of the tool. ‘AS5J32-RS5052’ indicates the joint with 5J32 on the retreating side of the tool. In the AS5052-RS5J32 joints, zigzag shapes were observed in the weld zone, which indicated that the weld zone was not fully mixed, such as cold welding, with all welding conditions. In addition, only a very limited amount of the material around the tool probe was stirred from 5052 on the retreating side was restricted by 5J32 which to the difficulty of the plastic flow, so that the material flow AS5052 toward AS5J32. These phenomena were attributed amount of the material around the tool probe was stirred from various welding conditions. In the figure, the left and right sides of the weld center are consistent with the retreating and advancing sides, respectively, and the dashed lines indicate the width of the tool probe and weld centerline. 5052 and 5J32 Al alloys appeared to be white and dark, respectively, because of the different etching reaction of each material. As shown in this figure, dissimilar 5052-5J32 alloy sheets were successfully welded by varying the welding parameters, and no superficial defects were detected by macroscopic observation except in the AS5052-RS5J32 joints with a rotation speed of 1500 rpm. Closed lines in Fig. 1 indicate the position of defects and Fig. 2 shows the shapes of defects in the AS5052-RS5J32 joints with a rotation speed of 1500rpm. Under these conditions, most defects were detected below the top surface of the retreating side.

In the AS5J32-RS5052 joints, i.e., when the 5J32 aluminum alloy was placed on the advancing side, zigzag shapes were observed in the weld zone, which indicated that the weld zone was not fully mixed, such as cold welding, with all welding conditions. In addition, only a very limited amount of the material around the tool probe was stirred from AS5052 toward AS5J32. These phenomena were attributed to the difficulty of the plastic flow, so that the material flow of 5052 on the retreating side was restricted by 5J32 which is harder than 5052.

In the AS5052-RS5J32 joints, zigzag shapes were observed in the weld zone at 1000 rpm, while vortex-like lamellar structures were produced at 1500 rpm. The interface between the SZ and the base material was very distinct on the advancing side of the tool but relatively unclear on the retreating side of the tool. The formation of the vortex-like lamellar structure was attributed to the sufficient plastic flow resulting from the higher heat input and strain at 1500 rpm. In general, heat input and maximum temperature increase with increasing tool rotation speed at a constant welding speed and decrease with increasing welding speed at a constant tool rotation speed.12,13 Thus, a large amount of 5J32 on the retreating side was stirred toward the advancing side. This was consistent with the previously reported observation that was performed under similar material arrangements.14

### 3.2 Hardness profiles

The hardness value of the unaffected base materials were obtained in ranges of 70–73 Hv for 5052 and 72–80 Hv for 5J32. Figures 3 and 4 show the microhardness profiles of the cross-section along two different depths (about 0.5 mm

### 3. Result and Discussion

#### 3.1 Metallographic analyses

Figure 1 shows the cross-sectional images of the welds from various welding conditions. In the figure, the left and right sides of the weld center are consistent with the retreating and advancing sides, respectively, and the dashed lines indicate the width of the tool probe and weld centerline. 5052 and 5J32 Al alloys appeared to be white and dark, respectively, because of the different etching reaction of each material. As shown in this figure, dissimilar 5052-5J32 alloy sheets were successfully welded by varying the welding parameters, and no superficial defects were detected by macroscopic observation except in the AS5052-RS5J32 joints with a rotation speed of 1500 rpm. Closed lines in Fig. 1 indicate the position of defects and Fig. 2 shows the shapes of defects in the AS5052-RS5J32 joints with a rotation speed of 1500rpm. Under these conditions, most defects were detected below the top surface of the retreating side.

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### 2. Experimental Procedure

The base materials used were 5052 aluminum alloy (Al-Mg) and 5J32 aluminum alloy (Al-Mg-Cu) rolled sheets with a thickness of 1.5 mm and 1.6 mm, respectively. The chemical compositions and mechanical properties of the base materials are listed in Tables 1 and 2.

The dissimilar 5052-5J32 joints were produced perpendicularly to the rolling direction by employing various welding parameters such as material arrangement, rotation speed, and welding speed, as described in Table 3. In this table, “AS5J32-RS5052” indicates the joint with 5J32 on the advancing side and 5052 on the retreating side of the tool.

A left-handed threaded tool of the following dimensions was used: a probe diameter of 3.8 mm, shoulder diameter of 12 mm and probe length of 1.45 mm. This tool has a slightly larger shoulder and probe than those of conventional tools, of which the ratio of probe diameter to depth is approximately 1:1. The tool-to-workpiece angle was 3° from the vertical axis of the welds. The 0.1-mm thickness difference between the two materials was small enough to neglect the effect of the tilting sideways. The tool was rotated in the clockwise axis of the welds. The 0.1-mm thickness difference between the two materials was small enough to neglect the effect of the tilting sideways. The tool was rotated in the clockwise direction and the workpieces were tightly fixed to the backing plate.

After the FSW process, the joints were cross sectioned perpendicular to the welding direction for metallographic analyses and hardness measurements. The cross sections were polished with a standard technique, etched with Keller’s etchant and observed by optical microscopy (OM). The hardness profiles were measured in the stir zone (SZ), thermo-mechanically affected zone (TMAZ), heat affected zone (HAZ) and base material using a Vickers micro-hardness tester (mvk-H1100) with a 300gf load for 10 seconds and a 0.4 mm spacing between the Vickers indents.

| Table 1 Chemical compositions of the base materials (mass%). |
|-----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Materials       | Mg    | Cu    | Si    | Fe    | Mn    | Zn    | Cr    | Ti    | Al    |
| 5052-H34        | 2.51  | 0.28  | 0.34  | 0.16  | 0.08  | 0.15  | 0.02  | 0.02  | Bal.  |
| 5J32-T4         | 5.68  | 0.20  | 0.11  | 0.09  | 0.01  | 0.03  | —     | 0.02  | Bal.  |

| Table 2 Mechanical properties of the base materials. |
|-----------------|-------|-------|-------|-------|
| Materials       | Tensile Strength, (MPa) | Yield Strength, (MPa) | Elongation, (%) |
| 5052-H34        | 234   | 176   | 11    |
| 5J32-T4         | 298   | 137   | 38    |

| Table 3 Welding parameters. |
|-----------------|-------|-------|
| Material Arrangement | Rotation speed, Revolution/min | Welding speed, mm/min |
| AS5J32-RS5052   | 1000  | 100, 200, 300, 400 |
| AS5J32-RS5052   | 1500  | 100, 200, 300, 400 |
| AS5052-RS5J32   | 1000  | 100, 200, 300, 400 |
| AS5052-RS5J32   | 1500  | 100, 200, 300, 400 |

Transverse tensile specimens were machined from the welds according to the ASTM-E8 standard, so that the weld centerline was positioned in the middle of the specimen gage length. Tensile tests were performed with a crosshead speed of 2 mm/min on an Instron-type test machine at room temperature. Moreover, fractographic observations were conducted by scanning electron microscopy (SEM).
and 1.0 mm from the top surface) under various welding conditions. Figure 3 shows the 5J32 Al alloy placed on the advancing side and Fig. 4 the reverse case.

Aluminum alloys are classified into precipitation-hardenable alloys and solid-solution-hardenable alloys, and it was reported that the softening of the welds did not occur during FSW for the solid-solution-hardenable alloys.\textsuperscript{15,16} For the AS5J32-RS5052 joints in Fig. 3, the hardness values of the SZ were slightly higher than those of the 5J32 base materials. The 5052 alloy of the retreating side exhibited slightly lower hardness than the 5052 base material.

These hardness results were attributed to grain refinement, dynamic recrystallization\textsuperscript{17,18} and dislocation tanglement in 5J32 and the annealing effect on 5052 due to the heat generated during FSW.\textsuperscript{15} In all conditions, the lowest hardness value was measured in the HAZ/TMAZ of 5052 and the highest value was measured in the 5J32 region. However, the values did not deviate largely from those of the

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**Fig. 1** Effects of material arrangements and welding conditions on weld zone shape.

**Fig. 2** Shapes of defects in the AS5052-RS5J32 joints with a rotation speed of 1500 rpm.
base materials. Furthermore, the hardness values which were sharply changed, were greatly affected by the measuring point of the hardness indenter. The 5052 and 5J32 alloys were not fully mixed and hence were easily distinguished by their color, as shown in Fig. 3. When the measuring points were in 5J32 region, higher hardness values were obtained than those of the 5052 region. For the AS5052-RS5J32 joints in Fig. 4, the hardness values were gradually changed along the horizontal line, which was attributed to the vortex-like lamellar structure of the SZ.

3.3 Tensile properties and fracture analysis

Figure 5 illustrates the results of the tensile test under various welding conditions. The dashed lines indicate the tensile strength and elongation obtained from the 5052 base material. For the joints with a rotation speed of 1000 rpm, the tensile strength and elongation were slightly varied according to the welding speed. The average tensile strength approached approximately ~90% of that of the 5052 alloy, regardless of the material arrangement, but the tensile strengths of the AS5052-RS5J32 joints were slightly higher than those of the AS5J32-RS5052 joint. This is consistent that for the solid-solution-hardened aluminum alloys, such as 5XXX series, FSW did not result in softening of the welds,\(^{15}\) the locations of the two dissimilar alloys exerted a significant effect on the resultant weld quality, and the low strength material should be placed on the advancing side to produce better welds.\(^{19}\)

However, the elongation was decreased compared with that of the 5052 alloy for both material arrangements. It should be noted that the elongation obtained in the transverse tensile test of the FSW weld using large specimens represents an average strain over the gage length including various zones.\(^{3}\) Therefore, the reduction of elongation does not indicate softening of the 5052 alloy.

For the joints with a rotation speed of 1500 rpm, the tensile strengths and elongations of the AS5J32-RS5052 joints were similar with those of joints obtained with a rotation speed of 1000 rpm. In contrast, they significantly decreased for the AS5052-RS5J32 joints. This is closely associated with some defects formed below a top surface of the retreating side.

As shown in Figs. 6 and 7, the specimens always fractured during transverse tensile testing within the shoulder diameter, and actual measurements of thickness before the testing showed that thicknesses of this region were almost uniform (e.g. weld center: 1.3xx~1.4xx mm, shoulder edge: 1.4xx mm). For example, in Fig. 6(b), 5052 side is thicker than 5J32, but the fracture occurred at 5052 side. Therefore, the 0.1-mm thickness difference between the base materials has no effect on the fracture locations. And most fractures occurred around HAZ or TMAZ on the 5052 side, except for
the AS5052-RS5J32 joints with a rotation speed of 1500 rpm. Therefore, to investigate the effect of defect formation on the tensile properties, the fracture surfaces of the tensile specimens were observed by SEM.

Figure 8 shows the fractographs of the tensile specimens for the AS5132-RS5052 joints. All fractures occurred on the 5052 side, and their fractographs presented typical ductile fracture surfaces with many dimples.

Figure 9 shows fractographs of the tensile specimens for the AS5052-RS5J32 joints. At a rotation speed of 1500 rpm, the fractures occurred at the 5J32 side. The fractographs show many protuberances which are somewhat similar to those of dendrites. These protuberances mean the existence of liquid among the grain boundaries and the evidence of resolidified material.28) The typical surface-resolidified material evident in these fractographs is indicative of liquation cracking during FSW.

In general, most aluminum alloys are susceptible to liquation cracking during conventional fusion welding because of their wide partial melting zone, large solidification shrinkage, large thermal contraction and residual intermetallic compounds.20) Many studies have investigated liquation or partial melting at HAZ during conventional fusion welding.21–23) However, few studies have focused on FSW and most of these were related to friction stir spot welding.24–26) These studies reported that liquation or partial melting during FSW occurred at the surface in direct contact with the tool shoulder and not at the interior of the weld zone or base materials. If liquation cracking occurs during FSW of specific Al alloys, it must be considered to control and choose welding parameters, such as shoulder dimension, backing material, cooling device, tool rotation speed, peak temperature and etc.

It was reported that maximum temperature within the weld zone was determined to be over 450~550°C, which is below the melting point of aluminum, and that the maximum temperature rise occurred at the top surface of weld zone.3) These temperatures are sufficiently high to melt various precipitates, such as Al₆Mg₅, Al₆CuMg₄, Al₂CuMg₂, remaining in aluminum matrix.27) Partial melting of the matrix
alone, however, is insufficient to cause liquation cracking, which therefore occurs when both partial melting and strain are applied simultaneously. Therefore, to identify the mechanism of liquation cracking during FSW, further study will be necessary, such as analysis of precipitates in base materials and weld zones, measurement of peak temperatures and strain rates during FSW.

4. Conclusions

(1) Dissimilar 5J32-5052 alloy sheets were successfully welded by varying the welding parameters, and no superficial defects were detected by macroscopic observation, except for the AS5052-RS5J32 joints with a rotation speed of 1500 rpm.

(2) When the 5J32 aluminum alloy was placed on the advancing side, zigzag shapes were observed in the weld zone under all welding conditions. These phenomena were attributed to the difficulty of the plastic flow, so the material flow of 5052 on the retreating side was restricted by 5J32 which is harder than 5052.

(3) When the 5052 aluminum alloy was placed on the advancing side, zigzag shapes were observed in the weld zone at 1000 rpm while vortex-like lamellar structures were produced at 1500 rpm. The formation of these vortex-like lamellar structures were attributed to the sufficient plastic flow resulting from the higher heat input and strain at 1500 rpm.

(4) The lowest hardness value was measured in the HAZ/TMAZ of 5052 and the highest value was measured in the 5J32 region. However, these values did not deviate largely from those of base materials.

(5) The average tensile strength approached approximately ~90% of that of the 5052 alloy, except for the AS5052-RS5J32 joints with a rotation speed of 1500 rpm.

(6) The reduced mechanical properties of the AS5052-RS5J32 joints with a rotation speed of 1500 rpm were closely associated with the defects formed by liquation or partial melting. Further study will be necessary to identify the mechanism of liquation cracking during FSW.

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