Effect of material flow on joint strength in activation spot joining of Al alloy and steel sheets

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Abstract. A new joining method for dissimilar metal sheets was developed where a rotated consumable rod of Al alloy is pressed onto an Al alloy sheet at the part overlapped with a mild steel sheet. The metal flow in the joining region is increased by the through-hole in the Al sheet and consumable Al rod. The rod creates the joint interface and pads out of the thinly joined parts through pressing. This produces a higher joint strength than that of conventional friction stir spot welding. Measurements of the joint interface showed the presence of a 5–10 nm thick amorphous layer consisting of Al and Mg oxides.

1. Introduction
In order to reduce CO₂ emissions and minimize energy and resource consumption, the automotive industry is increasingly being pressured to reduce the weight of vehicle bodies [1-2]. In order to do so, extending the application range of light metal materials such as Al alloys and high-tensile-strength materials is essential. In multi-material design, joints between dissimilar materials are unavoidable. When an aluminum alloy and steel are joined by conventional fusion joining such as resistance spot welding, brittle intermetallic compounds easily form at the joint interface [3-6]. In addition, the costs associated with mechanical joining methods such as riveting are high [7].

Hence, growing interest in friction stir spot welding to join metals in the solid phase without melting has recently led to its application to dissimilar joining (Al/Fe) [8]. However, achieving sufficient joint strength is of concern because of joint concavity, which tends to occur in correspondence with the tool shape, and the consequent reduction in sheet thickness [9]. Therefore, we propose using activation spot joining (ASJ) to maintain the joint thickness during the joining process and increase the joint strength; we report here on the joining of Al alloy and mild steel sheets using this method. We measured the static strength, interface morphology, and other properties of the resulting joint.

2. Experimental procedure
Friction-process equipment (owned by Kosei Aluminum Co., Ltd.) was used for the joining to control the rotational speed and tool position precisely. The chemical compositions of the workpiece materials are listed in table 1. As shown schematically in figure 1, ASJ was implemented using an Al alloy rod (A2017, 10 mm diameter) to maintain the joint thickness. The rod was pressed and rotated into an Al alloy sheet to simultaneously produce friction and an Al deposit. The deposit was removed after a
given holding time to complete the spot joint between the 1 mm thick Al alloy (A6061-T6) sheet and 0.8 mm thick mild steel (SPC270) sheet. The resulting joint strength was assessed in terms of the tensile shear strength (TSS) and cross tensile strength (CTS). The rotational speed $N$, plunge speed $v$, plunge depth PD, and hold time $t$ were varied in the ranges listed in Table 2 to determine the optimum process conditions. Through-holes with diameters of 0 (no hole), 5, 6, or 7 mm were drilled in the Al alloy sheet prior to joining to investigate the joint strengthening effect. The joint interface morphology was observed using transmission electron microscopy (TEM) and other analysis methods.

### Table 1. Chemical composition of workpiece materials (mass%).

| Material                  | Si   | Fe  | Cu  | Mn  | Mg   | Cr  | Zn  | Ti+Zr | C   | P   | S   | Al   |
|---------------------------|------|-----|-----|-----|------|-----|-----|-------|-----|-----|-----|------|
| Rod (A2017)               | 0.50 | <0.70 | 4.00 | 0.70 | 0.60 | <0.10 | <0.25 | <0.20 | -   | -   | -   | bal.  |
| Specimen (A6061)          | 0.59 | 0.38 | 0.26 | 0.03 | 0.96 | 0.25 | 0.02 | 0.04  | -   | -   | -   | bal.  |
| Specimen (SPC270)         | 0.002| bal. | 0.205| -   | -   | -   | 0.019| 0.0104| 0.005| -   | -   | bal.  |

### Figure 1. Schematic illustration of activation spot joining using friction surfacing.

### Table 2. Spot joining conditions.

|                  | $N$ (rpm) | 1000–3000 |
|------------------|-----------|-----------|
| Tool rotation    |           |           |
| Tool plunge speed| $v$ (mm/s)| 0.5       |
| Tool plunge depth| PD (mm)  | 0.8–1.4   |
| Hold time of tool| $t$ (s)  | 1, 2      |
| Through-hole diameter | dia. (mm) | 0, 5, 6, 7 |

### 3. Results and Discussion

Figure 2 shows the effect of the hole diameter on the joint strength. When the hole diameter was 5–7 mm, the TSS was 4–4.4 kN, which is twice the value of 2 kN for the joint with no through-hole. The TSS with holes was also higher than the value of 3.7 kN for the conventional joint strength as reported in the literature [8]. The CTS for a through-hole diameter of 7 mm was less than 1 kN.

Figure 3 shows the fractured steel and Al alloy sheet surfaces after TSS measurements for the case with the through-hole diameter of 7 mm. In all cases, interfacial fracture modes occurred with or without the through-hole. At the micrometer level, the fracture mode for the Al–steel joint was ductile fracture.

Figure 4(a) shows the cross-section of the joint interface with the 7 mm diameter through-hole. Regions of high elemental copper content were preferentially etched with Keller’s reagent. The elemental copper from the Al rod mixed into and permeated the Al sheet metal. As shown by the electron probe micro analyzer (EPMA) element mapping in figures 4(b)–(d), little or no copper was present near the surface of the steel sheet. This indicates that the Al rod did not contact the steel layer. Based on these results, we conclude that the Al sheet metal around the hole flowed into the center, closed the hole, and thus formed a joined layer with the surface of the steel sheet.
The inferred plastic flow behavior is presented in Figure 5, which shows the time-dependent change when the rod was pushed in.

**Figure 2.** Results of tensile strength test: (1) Al/Fe-TSS (3.7 kN) with tool diameter of 13 mm [8]; (2) Al/Fe-CTS (0.6 kN) with tool diameter of 10 mm [9].

**Figure 3.** Fractured steel and Al alloy surfaces after TSS measurements of hole with 7 mm diameter.
Figure 4. (a–c) Cross-sectional observations and (d) EPMA element mapping of joint interface. Hole diameter of 7 mm.

Figure 5. Inference of plastic flow behavior for activation spot joining.
To examine this inference, we performed a simulation using a simple model with a non-consumable steel rod, as shown in figure 6. The simulation was performed using the finite element method with the software FORGE for a 10 mm diameter rotating steel rod pressed down onto an Al alloy sheet with a 7 mm diameter through-hole. The simulation conditions are listed in table 3. Note that the non-consumable steel rod was a rigid body and that the Al alloy sheet was a viscoplastic body. We assumed no adhesion between the materials and $\mu = 0.3$.

Figure 7 shows the simulation and experimental results for the change in the through-hole morphology. As the plunge depth increased, the Al sheet metal tended to flow into the center and close the hole. This was because the material flowed towards areas where it was not restricted.

A simulation was also conducted without a hole; the results revealed key differences between the flow patterns with and without holes. In the simulation, we designated seven points on the Al sheet around the hole perimeter and traced their movement during the joining process with and without a hole, as shown in figure 8. The trajectory of point 6 (red line) was as expected. With the hole, it moved through three and a half revolutions. Without the hole, it stopped moving after one and a half revolutions. This clearly shows the effect of the through-hole on the generation of a dynamic plastic flow. The exposure of the newly formed Al surface at the interface was also evident.

![Simulation model for plastic flow.](image)

**Table 3. Simulation conditions.**

| Material                     | Condition                        |
|------------------------------|----------------------------------|
| Non-consumable steel rod     | Material model: rigid body       |
|                              | Initial temperature: 20 °C       |
|                              | Plunge depth: 0.8 mm             |
|                              | Plunge speed: 0.5 mm/s           |
|                              | Rotation: 1500 rpm               |
| Al alloy sheet               | Material model: viscoplastic body|
|                              | Deformation resistance database of comparable A6061 |
|                              | Initial temperature: 20 °C       |
| Boundary condition           | Coulomb friction: $\mu = 0.3$    |
|                              | Coefficient of heat transfer: 2 kW/m²·K |

![Experimental and simulation results of change in through-hole form.](image)
Figures 9(a) and (b) show the TEM imaging and energy-dispersive X-ray spectroscopy (EDS) element mapping of a joint interface with a 7 mm diameter through-hole. The results revealed the presence of both Mg and Al oxides at the interface, where they formed a 5–10 nm thick amorphous layer. The line analysis in figure 9(c) shows that Mg oxides in particular were deposited at the steel side of the interface.

Based on these results, we inferred the following model for the joining mechanism in the presence of a through-hole, as shown in figure 10: (1) The plastic flow increases the surface area of the Al sheet metal, which closes the hole. (2) A newly exposed Al surface forms, and Mg in the Al alloy sheet migrates to the surface. At the same time, the Al and Mg bond with oxygen on the steel surface. A more negative Gibbs free energy means a more easily oxidized element; thus, Mg, Al, and Fe were inferred to oxidize in that order. (3) This leads to a layer of oxidized Mg and Al and the eventual formation of the interface. Here, Mg and Al oxides were not considered to be present as connected films.

The applied load using the present method was investigated. The results are shown in figure 11. In this experiment, we varied the plunge depth of the consumable Al rod. When the plunge depth was 0.5 mm, the flow of the Al sheet metal from the hole periphery toward its center was quite evident. In this case, the actual plunge depth was a little less than 0.5 mm because of a growing consumable upset at the top of the Al rod (shown in figure 5).

These plots show the vertical load over the course of the joining process. With no through-hole (graph on right), the load rapidly increased to 8 kN in the initial stage. With the through-hole (graph on left), the load stopped rising at about 4 kN. Thus, using a hole reduces the applied load of the process.

4. Conclusions
Based on our results, the proposed method of Al/mild steel joining using a consumable Al rod demonstrates three major advantages:

- The metal flow in the joining region is increased by the through-hole in the Al sheet and consumable Al rod, which increases the joint strength compared to that achieved with existing methods. The TSS for the Al/mild steel joint was 4.4 kN (82 MPa).
- A 5–10 nm thick layer of Mg and Al amorphous oxides forms at the joint interface. The Mg in the Al appears to reduce the oxide film on the steel and contribute to interface activation.
- The applied load of this method is about half that used in existing methods.
Figure 9. (a) TEM imaging, (b) EDS element mapping, and (c) line analysis of joint interface.
Figure 10. Bonding model of interface for activation spot joining.

1. With hole initial load: 4 kN
2. Without hole initial load: 8 kN
3. Plastic flow (increasing Al surface area)

Newly exposed Al surface forms and Mg migrates to the surface

Al and Mg bond with the oxygen

This leads to a layer of oxidized Mg and Al

Figure 11. Comparison of changes in vertical load for joining process with and without hole.
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