Effect of weld line shape on material flow during friction stir welding of aluminum and steel

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Abstract. The effect of weld line shape on material flow during the friction stir welding of aluminum and steel was investigated. The material flow velocity was evaluated with simulated experiments using plasticine as the simulant material. The validity of the simulated experiments was verified by the marker material experiments on aluminum. The circumferential velocity of material around the probe increased with the depth from the weld surface. The effect is significant in cases where the advancing side is located on the outside of curve and those with higher curvature. Thus, there is an influence of weld line shape on material flow.

1. Introduction
Friction stir welding (FSW) is solid-state welding technique in which frictional heating and plastic material flow are induced by a welding tool. It is useful for welding aluminum alloys and is typically applied in the automotive and high-speed railway industries. The FSW of aluminum and steel can achieve high joining efficiency because of the thin intermetallic compound layer (less than 1μm thick) that forms at the weld interface [1-6]. Recently, this method has received attention in the production of hybrid structure components for transportation vehicles, which balances the cost and the structural strength.

Control of material flow behavior is important in FSW to achieve high joining efficiencies. However, the process window for welds between aluminum and steel is smaller than that for welds between aluminum alloys. The material flow changes with welding conditions (welding speed, rotation speed, tool shape, and weld shape) and can generate defects in the weld under unfavorable material flow conditions. Material flow in the FSW of aluminum and steel is different from that of aluminum alloys because of the existence of the rigid steel wall at the weld interface and the weld-shape effect on the material flow and joining efficiency [7]. Thus, material flow during the FSW of aluminum and steel needs to be investigated further. Material flow during FSW has been studied using microstructural observations, X-ray techniques, simulated experiments with simulant materials, and numerical simulation. However, the details of material flow have not been established yet.

Material flow observations made using marker materials or simulant materials are an effective way to understand the material flow visually [8-11]. In this study, the effect of weld line shape on material flow was investigated by evaluating the material flow velocity quantitatively. This simulated experiment was conducted using plasticine as the simulant material. The validity of the simulation was verified by microstructure observations of aluminum with a marker material.
2. Experimental procedure

2.1. FSW between aluminum and steel with 2D weld line

The arrangements of the test pieces for the 2D weld line are shown in Figure 1(a). The weld line shape included both straight and curved segments with 30 and 50 mm radii. The thickness of test pieces was 6 mm. The welding tool was composed of a shoulder 20 mm in diameter and a probe with an M4 left-hand screw 4 mm in length, as shown in Figure 1(b). The rotating tool probe is plunged into a test piece on the retreating side (RS) that is made of A6063 or plasticine, as shown in Table 1. In all of the experiments, steel (S45C) was placed on the advancing side (AS).

The rotating tool moves along the weld line, slightly grinds the steel surface on AS, and stirs a test piece on the RS. To understand the effect of curvature, three types of weld were fabricated, as shown in Figure 2. As for the curve weld line, we need to consider the curvature and arrangement of the test piece. Straight welding is considered as having an infinite radius of curvature ($R = \infty$), as shown in Figure 2(a). Curved welds with a negative radius of curvature ($R < 0$) are defined as having the AS located on the outside of the curve, as shown in Figure 2(b), and curved welds with a positive radius of curvature ($R > 0$) are defined as having the AS located on the inside of curve, as shown in Figure 2(c).

![Figure 1](image1.png)

**Figure 1.** Schematic drawing of the material flow observation experiment for FSW of steel and aluminum.

| Test piece (AS) | S45C (t6mm) |
|----------------|-------------|
| Test piece (RS) | A6063 (t6mm) | plasticine (t6mm) |
| Marker material | Straight welding | aluminum oxide (6μm) | plasticine (1mm width) |
| | Curve welding | pure aluminum (Ø0.3mm) | |

**Table 1.** Test piece and marker materials and geometries.
Figure 2. Schematic of material flow observation experiments on the FSW of steel and aluminum. The arrows indicate the tool rotation and movement.

In order to visualize the material flow, marker materials, as shown in Table 1, were embedded in the test pieces. In case of straight welds, an aluminum oxide layer was fabricated by a plasma electrolytic oxidation process. A thin aluminum plate was inserted between the marker material and steel for the arrangement of the marker. However, in the curve welding case, it is difficult to fabricate a thin, curved aluminum plate. In this case, vertical holes were drilled along the marker line, and pure aluminum wires were embedded into the holes. Also, different colors of plasticine were layered for the simulated weld experiment. Marker materials were embedded at the tool center position, as shown in Figure 2. The welding tool stopped at the A-A plane and withdrew from the test piece. Material flow around the exit hole of the probe was observed by cutting the weld horizontally at 1, 2, and 3 mm depths from the weld surface. In case of aluminum on the RS, the horizontal cross section was ground and etched with Keller’s reagent for marker material observations. The welding conditions are summarized in Table 2.

| Test piece (RS) | Plasticine |
|----------------|------------|
| A6063          |            |

Table 2. Welding conditions.

| Test piece (RS) | A6063 | Plasticine |
|----------------|-------|------------|
| Straight Welding | No defect | No defect |
| Rotation speed (min⁻¹) | 2000 | 500 |
| Welding speed (mm/min) | 800 | 1100 |
| Curvature radius R (mm) | ∞ (straight), -50, -30, 30, 50 |

2.2. Material flow velocity
Schmidt et al. proposed an evaluation method for the material flow velocity around the tool probe by using a trace of marker material layer [8]. However, it is difficult to introduce marker material layer in FSW because of the difference in properties between aluminum and the marker material. Thus, the material flow velocity was evaluated using the simulated experiments with the simulant materials. A viscoplastic material, plasticine, has been used in the simulated experiment of the metal forming process. Liechty et al. discussed the applicability of plasticine to these simulated FSW experiments [9, 10, 11]. The material flow was observed by using different colored plasticine. Plasticine (Van Aken Int., Inc.) was used as the simulant material, as shown in Table 1, and the circumferential velocity of material flow around the probe was evaluated. Figure 3 shows the model for the velocity evaluation; the derived equation is given by
where $S_{\theta_1-\theta_2}$ is the measured distance of marker (mm), $U$ is the welding speed (mm/min), $W_t$ is the width of marker material (mm), $\rho_{\text{pixel}}$ is the pixel density (pixel/mm$^2$), and $M_{\theta_1-\theta_2}$ is the number of pixels for measuring the distance.

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V_{\theta_1-\theta_2} = \frac{S_{\theta_1-\theta_2} \cdot U \cdot W_t \cdot \rho_{\text{pixel}}}{M_{\theta_1-\theta_2}},
\]  

(1)

3. Results and discussion

3.1. Straight welding

Figure 4 shows the material flow around the probe for straight welding without any defect. The marker materials are observed as a white line for aluminum and a dark strip for plasticine. Both of the marker materials flow toward the back of the probe and reach the weld interface. The distributed area of the marker materials increases with the depth from the surface. Both marker material movements show similar tendencies. From these images of the simulated experiment, the circumferential velocity of the marker material around the probe was evaluated. These velocities are 1212 mm/min at 1 mm depth from the surface and 1380 mm/min for 3 mm depth from the surface. As for the simulated experiment, the inlet velocity of material flow to the probe, i.e. welding speed, is 1100 mm/min and the circumferential velocity of the probe surface is 6280 mm/min. Although the circumferential velocity of the marker material is higher than the inlet velocity, the probe surface moves faster than the material and induces slip between the probe surface and flowing material. Also, the circumferential velocity of marker material at the bottom part is higher than that at the upper part. One reason for this is the difference in the slip condition caused by the difference in temperature around the probe. Another reason is the effect of the downward material flow produced by the probe screw [6].

Figure 5 shows the material flow around the probe for straight welding with defects. The defects are observed at middle and bottom part of the weld interface behind the probe on both aluminum and plasticine. From the marker material movements, this can be attributed to the lack of material flow behind the probe resulting from low heat input. From the simulated experiment, the circumferential velocities of the marker material are 150 mm/min at 1 mm depth from the surface, and 317 mm/min at 3 mm depth from the surface. As for the simulated experiment, the inlet velocity of material flow to the probe is 100 mm/min and the circumferential velocity of the probe surface is 2512 mm/min. The circumferential velocity of the marker material is close to the inlet velocity of material flow to the probe. However, the bottom part of material flow is higher than the inlet velocity. It is considered that the difference in slip condition and the effect of downward material flow by the probe screw produce this effect.
3.2. Curve welding

Figures 6 and 7 show the material flow at positive radius of curvature. The welding conditions were the “no defect” condition of straight welding, above. However, defects are observed at bottom part of the weld behind the probe for both radii. Furthermore, defects are observed at middle part of the weld in the plasticine. The circumferential velocities of marker material ranged from 1600 mm/min to 2200 mm/min. These values exceed the velocities of straight welding.
Figures 8 and 9 show the material flow at negative radius of curvature. The welding conditions were the “no defect” condition of straight welding, above. Defects are observed throughout the thickness at the –30 mm radius of curvature for both Al and plasticine. On the other hand, defects are observed in the bottom part of the weld at a –50 mm radius of curvature. From the trace of the marker material for plasticine, the material flow falls short of reaching the weld interface. The circumferential velocities of marker material ranged from 1700 mm/min to 2500 mm/min. The highest velocity was obtained on the bottom of the weld at a radius of curvature of 50 mm.

Figure 8. Material flow around the probe at –30 mm radius of curvature.

Figure 9. Material flow around the probe at –50 mm radius of curvature.

Figure 10 shows the circumferential velocity of marker material around the probe at various curvatures under the “no defect” condition of straight welding. The velocities increase with depth from the surface. The effect is significant at negative curvature and at higher absolute values of curvature (|R|). This is attributed to the effect of heat input and the travel distance of materials induced by the difference in weld line shape. The heat input depends on the contact area between the tool shoulder and aluminum, and this area differs with the weld line shape. From temperature measurements performed on the probe tip with a thermocouple for the welding of aluminum and steel, the temperature of each weld line at the point of observation is 698.6 K for positive curvature, 697.7 K for straight, and 699.1 K for negative curvature. These differences are small, and it is difficult to estimate the effect of heat input.

As for the travel distance of the marker material for welds with negative curvature, the marker material line in front of the tool curved toward the RS. This means that the marker material flows easily to the back side of the tool because of the short distance. As for the travel distance of marker material for welds with positive curvature, the marker material line in front of the tool curved toward the AS. This means that the marker material flows to the back side of the tool for long distances. The difference in travel distance affects to the volume of stirred aluminum and the overall material flow. Thus, the combined effect of heat input and travel distance affects the velocity difference in welds with different line shapes.
4. Conclusion
The effect of weld line shape on material flow during the friction stir welding of aluminum and steel was investigated using marker material experiments and simulated experiments. The validity of the simulated experiments using plasticine was verified by the marker material experiments using aluminum, and the material flow velocity was evaluated for these simulated experiments. The circumferential velocity of the marker material around the probe increased with the depth from the weld surface. The effect is significant at negative curvature and at higher absolute values of radius of curvature. Thus, there is an influence of the weld line shape on the material flow.

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