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Experimental and numerical studies of material flow during welding by friction stirring†

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KEY WORDS: (Friction Stir Welding) (Material flow) (High speed video camera) (PIV) (FEM model)

1. Introduction

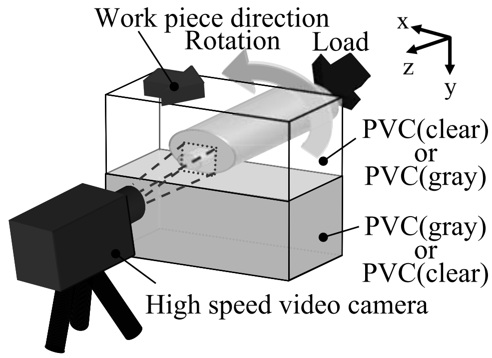
Friction stir welding (FSW) is a solid state welding process invented and patented by TWI in 1991 [1]. The weld joint is produced by plastic flow of material induced by friction between a tool and work pieces, and controlled by rotating speed of the tool, welding speed, axial force and the tool shape etc. As qualitative analysis of material flow, metallic insert material is set in the position of weld metal before FSW [2]. In case of dissimilar metals welding, the material flow was evaluated by X-ray computed tomography [3]. Additionally, direct observation of material flow was conducted by using transparent poly-vinyl chloride (PVC) as simulation experiments of welding between aluminum alloys [4]. However, it is difficult to evaluate the material flow quantitatively during welding.

In this study, quantitative measurement and calculation of the material flow around the tool pin during welding were investigated. As simulation experiments of welding between aluminum alloys, the material flow of welding between PVC was measured by particle image velocimetry (PIV) method with high speed video camera. Also, the material flow during welding was numerically simulated by plastic forming software DEFORM-3D. From these studies, direction and velocity of the material flow during welding around tool pin were estimated.

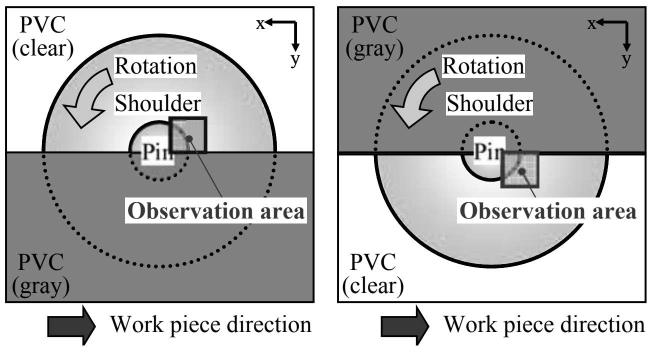
2. Direct observation of material flow during welding

Welding experiments were performed by a machining center (Enshu S400). The welding tool was composed with a shoulder, which was made of tool steel with ϕ20mm in diameter, and pin, which was made from WC-Co cemented carbide with a screw shape and ϕ5mm in diameter and 4.0mm in length on the top. In this study, transparent PVC (clear) and PVC (gray) were welded as simulation experiment of welding between aluminum alloys. PVC (clear) and PVC (gray) were both 20mm in width, 50mm in length and 20mm in thickness. **Figure 1** shows the arrangement of weld materials and movement of the tool. The tool is plunged into the interface between PVC (clear) and PVC (gray) and moves along the weld line. The rotating speed was 750rpm and the revolution pitch was 0.2mm/r. Material flow during welding was observed with a high speed video camera (Photron FASTCAM SA5). The material flows at advancing side (AS) and retreating side (RS) of the pin were observed from the tool bottom.

Particle image velocimetry (PIV) is an optical method of fluid visualization. It is used to obtain instantaneous velocity measurements. In this study, material flow during welding was measured with PIV method, and the analysis conditions were shown in **Table 1**.



(a) Schematic view of welding experiment.



(b)AS view. (c)RS view.

Fig. 1 Experimental set up for direct observation of FSW.

Table 1 Observation and PIV analysis conditions.

Shutter speed (frame/s)	1,000
Analysis image number	400
Interval of analysis image (s)	0.001
Scanning area (mm^2)	3.4

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3. Numerical model for FSW

In this study, the commercial FEM software DEFORM-3D™ was used for welding simulation. This software is a Lagrangian implicit code designed for metal forming processes. The workpiece was single-block continuum model (PVC), used in order to avoid contact instabilities due to the intermittent contact at the sheet-sheet and sheet-tool interfaces. The workpieces were meshed with about 100,000 tetrahedral linear elements. The tool was modeled as rigid body (WC-Co cemented carbide) and meshed for velocity analysis with about 3,700 tetrahedral elements. These assumption are reasonable as the yield strength of the workpiece is significantly lower than the yield strength of the rotating tool. Following thermal characteristics of PVC were used in this simulation: thermal conductivity k=0.17 (W/mK), and thermal capacity c=1.95 (N/(mm^{2}K)). These assumption linearizes the finite element formation for temperature analysis and results in better convergence [5]. A rigid-viscoplastic temperature and strain rate dependent material model is employed

$$\bar{\sigma} = c\left(\bar{\varepsilon}\right)^n \left(\dot{\bar{\varepsilon}}\right)^m + y \qquad (1)$$

Where c =7.791, n =1.987, m =-0.116 and y =20.052 (MPa) are material constants determined by a numerical regression based on experimental data [6].

4. Results and Discussion

Figure 2 shows the material flow of the weld with high speed video camera and analysis of PIV at AS and RS. **Figure 3** shows FEM analysis of material flow. From PIV and FEM analysis, material flow was observed different type of flow direction at RS and RS. At RS, direction of the material flow (Flow2) was corresponded to the tool rotation. However, material flow (Flow1) at AS was in the reverse direction of the tool rotation. The material flow from AS to RS passed behind the pin.

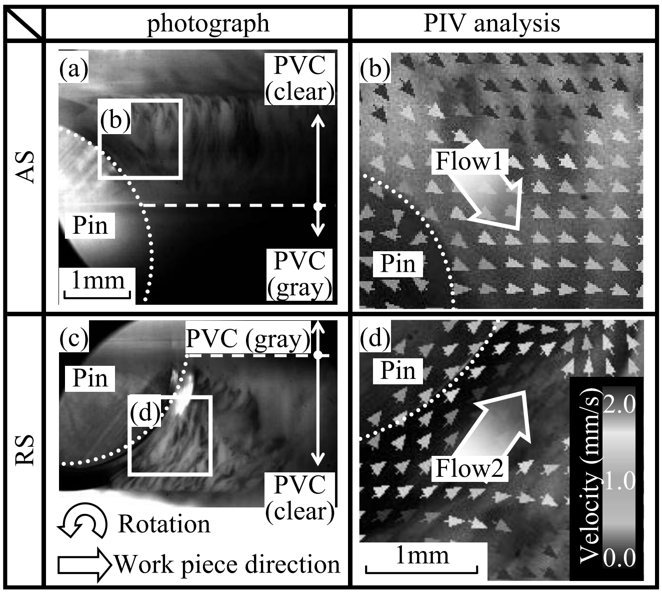

Fig. 2 Material flow of weld with high speed video camera and analysis of PIV.

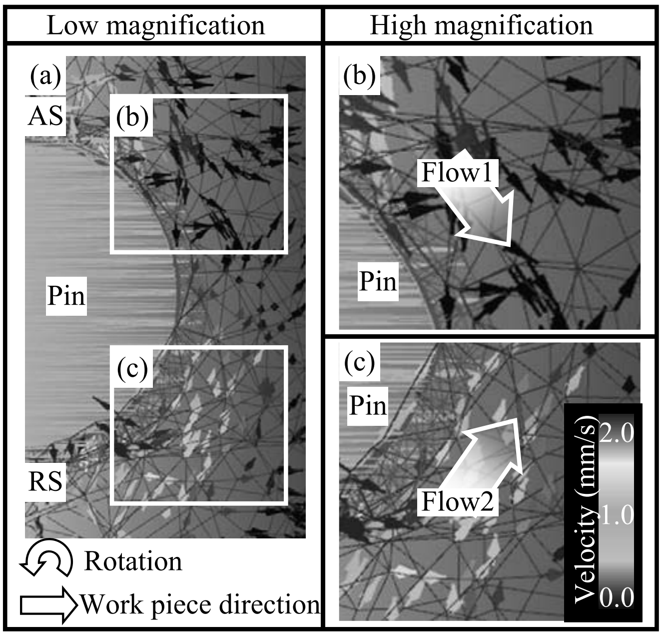

Fig. 3 FEM analysis of material flow.

Figure 4 shows measured and calculated results of material flow velocities by PIV and FEM analysis during welding. The material flow velocities of PIV analysis ranges from about 2 to 20 mm/s at AS. The material flow velocities of PIV analysis ranges from 1 to 5 mm/s at RS. These are similar tendencies that of FEM analysis. Additionally, both velocities of PIV and FEM at AS are faster than that flow at RS.

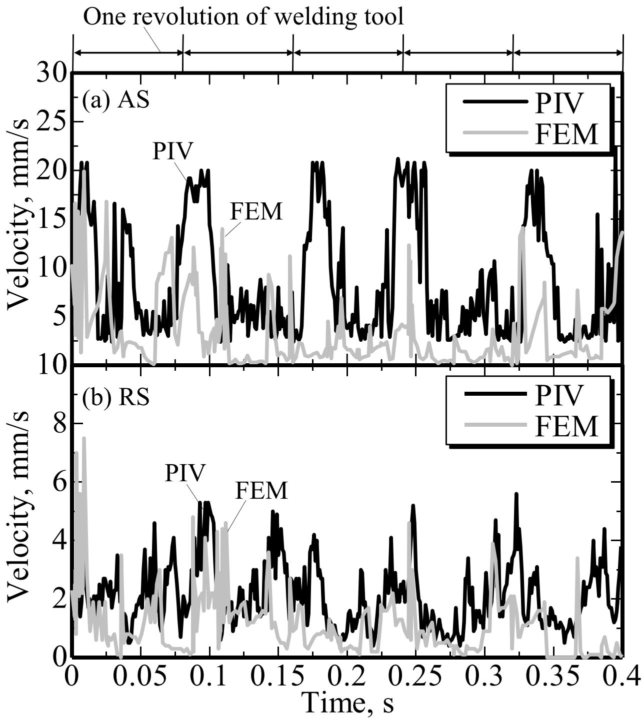

Fig. 4 Measured and calculated results of material flow velocities by PIV and FEM analysis during welding. Analysis area is Fig. 2, (b), (d) and Fig. 3, (b), (c).

5. Conclusions

Material flow by friction string during welding was investigated with experimental and numerical studies. Following results were obtained.

1. Material flow at RS corresponded to the rotating direction of the tool. However, material flow at AS was in the reverse direction of the tool rotation. The material flow from AS to RS passed behind the pin.
2. From PIV and FEM analysis, material flow velocities at AS are faster than that at RS.

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