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Determination of strain rate in Friction Stir Welding by three-dimensional visualization of material flow using X-ray radiography

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Recrystallization, which is mainly caused by the induced strain, is one of the most important factors of Friction Stir Welding. In this study, strain and strain rate are directly obtained by the change in the material flow velocity which is observed by three-dimensional visualization of the material flow. The grain size of the pure aluminum in the stir zone estimated by the Zener–Hollomon parameter using the obtained strain rate shows good agreement with that observed by Electron Back-Scatter Diffraction mapping.

Keywords: Friction Stir Welding; X-ray radiography; Image analysis; Strain rate; Recrystallization

Much attention has recently been paid to Friction Stir Welding (FSW) because of the low distortion and excellent mechanical properties of the joint [1–4]. A rotating tool is inserted into the interface at the butt line of the metal plates and produces a highly plastically deformed zone. The metal plates are joined by the traveling of the rotating tool along the interface. Sever plastic deformation occurs and strain is induced in the stir zone (SZ). The interface of the two metal plates disappears by the material flow, and it is the main bonding mechanism of FSW. Generally, the SZ consists of recrystallized fine and equiaxed grains which are formed by the induced strain during the FSW [5–7]. Therefore, the recrystallization is one of the most important factors of FSW. It is well known that the recrystallized grain size can be estimated by the strain rate [8,9]. However, it is difficult to measure the strain rate accurately during the FSW because the various changes in the SZ cannot be observed directly using conventional methods. Therefore, determination of the strain rate is very important for estimating the microstructure in the SZ.

There are several reports related to the strain rate in the FSW. Chen et al. showed that the strain was ~3.5 and the strain rate was $\sim 85\ s^{-1}$ before entering into the thread space during the FSW with a simple threaded pin at 740 rpm [10]. Arora et al. indicated that the computed strains and strain rates were in ranges of −10 to 5 and -9 to $9\ s^{-1}$, respectively [11]. However, the obtained results are computed values based on a three-dimensional coupled viscoplastic flow and heat transfer model. The strain rate of $34.8 \pm 5.2\ s^{-1}$ was estimated for magnesium alloy (AZ31) during FSW by the experimentally verified finite element model [12]. If it can be obtained these values by a direct observation of the phenomenon, it should be very valuable to compare the other results.

In this study, the strain rate was directly calculated by the change in the material flow velocity. The material flow during the FSW was observed by the three-dimensional visualization process [13–15]. The material flow has been studied using various approaches such as the tracer method [16–20], analysis of the crystallographic texture in a weld [21], measuring the eutectic Si distribution [22]. However, it is impossible to know the material flow velocity using these approaches because the obtained results show only one part of the process. In this study, the material flow is three-dimensionally visualized using a 300 μm spherical tungsten tracer. The diameter of 300 μm is the smallest size of the tracer to detect the correct position by X-ray transmission image. One tungsten tracer was set at 1 mm from the top surface of the A1050 plate before the FSW. The three-dimensional material flow is obtained using the locus of the tungsten tracer observed by two pairs of X-ray transmission real-time imaging systems.

A pure aluminum (A1050) plate was used as the work-piece. The thickness of the work-piece and the back plate was 5 mm each. The unthreaded tool, which has a cylindrical shape (shoulder: ϕ 15.0 mm) with a probe (ϕ 6.0 mm, length: 1.9 mm), was used for the FSW. A2017 and Si_3N_4 were chosen for the materials of the back plate and the tool for the FSW, respectively. The X-rays can transmit through the work-piece, the back plate and the tool due to their low relative densities (Al: 2.7 g/cm^3, Si_3N_4: 3.4 g/cm^3). The two pairs of X-ray transmission

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real-time imaging systems were fixed to the perspective center in the middle of the stir zone [13]. Both lines of the X-rays passed through the horizontal A1050 plate at an angle of 30° each. The X-ray transmission images were recorded by two high-speed video cameras at a frame rate of 500 fps. These video cameras were synchronized to obtain a three-dimensional graph using the locus of the tracer observed by the two imaging intensifiers. The FSW was carried out in the positional control mode. The rotating rate was 1000 rpm. The travel rate of the tool and the tool tilt angle were 400 mm/min and 3°, respectively. The observed X-ray transmission images, and the shape of the material flow zone are described in detail elsewhere [13–15].

Figure 1 shows the three-dimensional graph of the material flow and its two-dimensional graph on the WD-TD plane. WD and TD show the welding direction of the FSW and transverse direction of the A1050 plate, respectively. As shown in Figure 1(a) and (b), the tracer repeatedly rotated around the probe in a concentric circle. The result of the three-dimensional visualization of the material flow reveals that a flow zone of concentric circle with a relatively large diameter is formed around the probe. The vertical movement of the tracer (material flow) can be negligible under this FSW condition. The velocity of the tungsten tracer (V) can be directly calculated by the change in the coordinate for 0.002 s on the WD-TD plane as shown in Figure 1(c) using Eq. (1):

$$V = L/T \tag{1}$$

where L is the distance between the 2 plots and T is the transit time from one plot to the other plot. The obtained velocity can be considered as the material flow velocity because the material flow is a solid-state process and the tracer is small enough to show the material flow velocity. There was no significant difference in the velocity on all sides from the tool, and it increased with the increase in the distance from the center of the probe. Therefore, the velocity on the outer side was higher than that of the inner side in the stir zone. It is considered that the material flow was strongly affected by the shoulder rotation [13].

The strain rate can be easily calculated if the direction of the material flow is only tangential to the rotating tool as shown in Figure 1(d) using Eq. (2):

$$\dot{\varepsilon} = \frac{l_{n+1} - l_n}{l_n} \Big/ t \tag{2}$$

where l_n is the distance between the 2 plots and $_m$ is the velocity of the tracer between the 2 plots and t is the deformation time. l_n can be calculated using Eq. (3):

$$l_n = \frac{v_{m+1} - v_m}{\Delta t} \tag{3}$$

Figure 2 shows the velocity of the material flow during the FSW. The velocity was calculated by the data from one tracer because the locus of the tracer and the velocity at the same position were almost same in 3 times of the visualization. In the first rotation, the tracer started to move and its velocity sharply increased. The velocity then

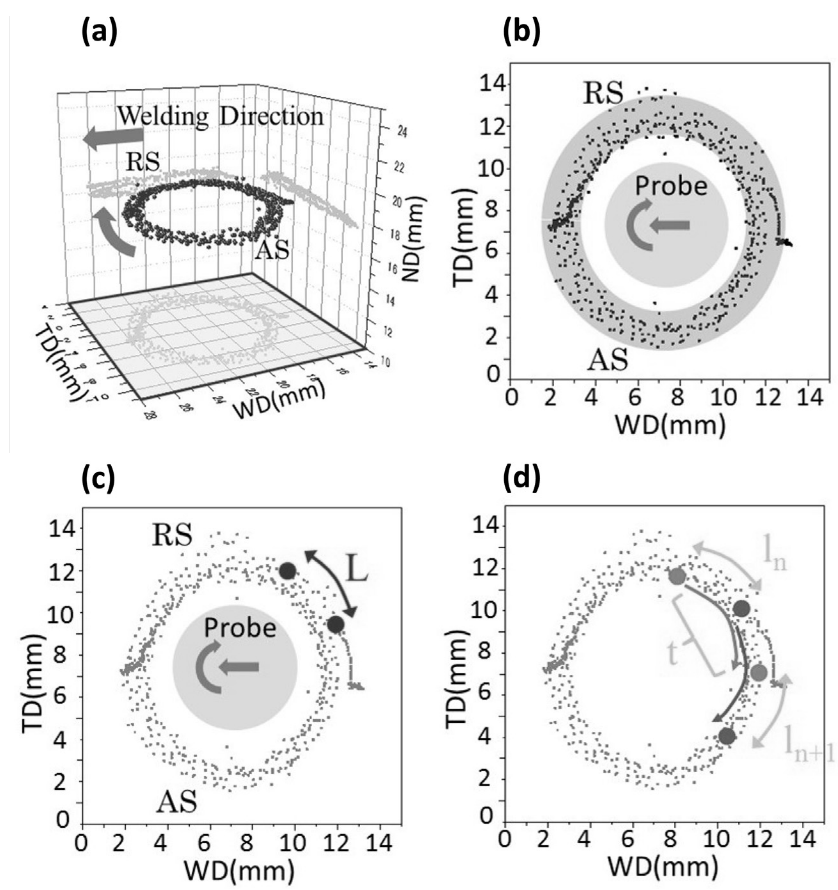

Figure 1. Locus of the tracer observed by the X-ray transmission real-time imaging systems. (a) three-dimensional image, (b) two-dimensional image on TD-WD plane (c) schematic drawing of calculation method for strain, (d) schematic drawing of calculation method for strain rate.