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Characterization of plastic deformation and material flow in ultrasonic vibration enhanced friction stir welding

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Material flow and plastic deformation in ultrasonic vibration enhanced friction stir welding are visualized by employing a special marker material and welding procedure. Based on the results, three methods are developed to evaluate the volume of deformed material, the material flow velocity and the strain/strain rate, and the effect of ultrasonic vibration on the plastic deformation and material flow around the tool is characterized.

Keywords: Friction stir welding; Ultrasonic vibration; Plastic deformation; Material flow; Strain rate

It has been generally accepted that, by superimposing ultrasonic vibration on plastic deformation of metal the measured forming load can be reduced significantly [1,2]. This provides ultrasonic vibration enhanced friction stir welding (UVeFSW) an obvious edge over the thermally aided friction stir welding (FSW) processes in partially resolving the high welding load requirement and tool wear in FSW [3]. In UVeFSW, ultrasonic vibration is transmitted directly into the localized area of workpiece near and ahead of the rotating tool by a vibration tool head (Fig. 1a), which has been detailed in [3]. It has tremendous application potential in welding high strength and high hardness materials [3]. However, with the physics of material flow in FSW yet to be fully understood, exploring its behavior in UVeFSW is a great challenge. Previous investigations with tracers [4] and marker material (MM) [5–7] have partially described the material flow in FSW, but the results could be erroneous due to the large gradients in material density/plasticity of the base material and tracers/MM. Numerical models [8–11] can describe the material flow quantitatively. However, they have not been verified by experiments completely.

In this study, nominal 0.2 mm thick 1060 Al foil was used as MM and tool “sudden stop action” (the tool lost power suddenly and was pulled out instantaneously) was adopted to “freeze” the transient material flow around the pin. Material flow was observed around the horizontal cross-sections of exit hole (EH) by optical microscope. Based on the observed results, three methods were developed to evaluate the volume of deformed material around the pin, the material flow velocity and the strain/strain rate in FSW and UVeFSW. The welding conditions were identical for FSW and UVeFSW. Rolled plates of 3 mm thick 2024Al-T4 were butt welded by placing the MM in their faying surface. The welding speed, rotation speed, and plunge depth were 80 mm/min, 600 rpm and 0.1 mm, respectively. Length of conical tool pin with smooth surface is 2.66 mm. Diameters of tool shoulder, pin top and root are 10 mm, 3 mm and 4 mm, respectively. The tool tilt angle is 2.5°. In UVeFSW, the vibration tool head like a horn with a hemispheric endpoint (diameter 8 mm) was traversed 20 mm ahead of the tool. The oscillation was a longitudinal wave with 40° deviating from the workpiece plane and amplitude of 40 μm. The ultrasonic frequency and output power were 20 kHz and 300 W, respectively. The efficiency of coupling from the transducer into the workpiece is 83%. Horizontal cross-sections of weld specimens with EH were cut at various depths (z), polished and etched with Keller’s reagent. Figure 1b shows a coordinate system with its origin at the center of EH on the top surface. MM distributions in FSW and UVeFSW on the horizontal planes at $z = 0.5$ mm and $z = 1.5$ mm are shown in Figure 1c–f. Since the MM is inserted in the faying surface between two plates, the MM indicates a stream line entering in front of the pin which then flows around the retreating side of the pin [6]. At $z = 0.5$ mm plane, the material flow is continuous and laminar; while at $z = 1.5$ mm plane, it presents typical periodic arc-shaped textures, thus is non-continuous. The continuous flow zone (upper one third of weld) is driven by the shoulder and defined as shoulder-affected zone (SAZ) and the non-continuous flow zone (lower two thirds of weld) is driven by the pin and defined as pin-affected zone (PAZ) [5].

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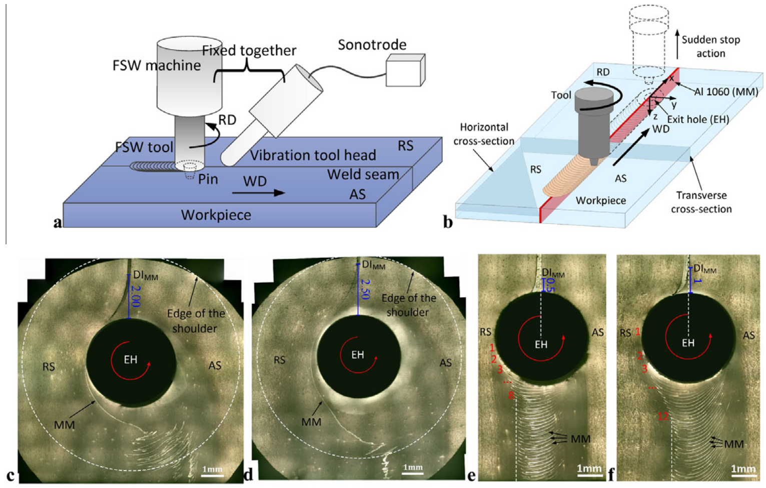

Figure 1. Experiment details: (a) Schematic of UVeFSW; (b) Schematic of MM (mark material) configuration and welding procedure; Distribution of MM on horizontal planes around the EH (exit hole) at $z = 0.5$ mm ((c) FSW (d) UVeFSW) and $z = 1.5$ mm ((e) FSW (f) UVeFSW).

Based on the results in Figure 1c–f, the distance between the deformation initiation point on MM (DI_{MM}) and the EH wall would depend upon the cross-section depth (z) and process conditions. The thickness of the deformed material (d) in front of the pin can be described by $d = D - r$, where D is the distance between DI_{MM} and EH center, and r is the EH radius (Fig. 2a). Figure 2b shows the obvious reduction in r and D with increasing z. When z increases from 0.3 mm to 2.4 mm, D decreases from 4.3 mm to 1.7 mm in FSW while from 4.8 mm to 1.9 mm in UVeFSW. Figure 2c shows the variations in d with z. In FSW, d is larger in SAZ than in PAZ, whereas it decreases with z uniformly in UVeFSW. d in UVeFSW is larger by 0.21–0.67 mm than that in FSW at the same cross-sections. A larger value of d means a thicker layer of deformed material. If the layer of deformed material is integrated over the workpiece thickness, the volume of the deformed material will be obtained. Thus, the larger d means that ultrasonic vibration enlarges the volume of the deformed material around the pin.

Figure 3a shows the schematic of the continuous flow of material. Under pseudo-steady-state, the material flow around the pin is similar to a fluid flowing at an initial velocity (equal to welding speed) through a pipe which has the shape identical to the profile of MM distribution in Figure 1c and d. Though there exits vertical distortion in SAZ, it mainly appears on the advancing side of the EH rear, and is insignificant in contrast with horizontal flow [4]. Assuming the plastic aluminum alloy as incompressible, this problem can be regarded as one-dimensional incompressible fluid flow. The flow direction at any point in the pipe is tangential which meets the one-dimensional continuity equation, i.e., volume of the fluid flowing at any two cross-sections is equal at any instance. Figure 3b shows a schematic of one-dimensional flow through pipe. If the average fluid velocities are v_i and v_k at two random cross-sections S_i and S_k, the continuity equation is given by $S_i \cdot v_i = S_k \cdot v_k$. Similarly, the material flow in a thin layer dz in FSW, it can be given as $dz \cdot l_0 \cdot v_0 = dz \cdot l_i \cdot v_i$, simplifying to $v_i = v_0 \cdot l_0 / l_i$, where l_0 and v_0 are the initial width and velocity and, l_i and v_i are the width and velocity of the material on cross-section S_i respectively.

The flow velocities on $z = 0.5$ mm plane (Fig. 1c and d, where the material flow has better continuity and less vertical distortion) were measured using the above theory. Due to the continuity of flow, it is difficult and tedious to measure velocity at every position. Therefore, flow velocities were measured at every 0.5 mm along the welding direction. Figure 3c shows the positions where the widths of MM were measured using Image J software on the metallographs.

Figure 3d and e shows the measured and calculated flow velocities on $z = 0.5$ mm planes in FSW and UVeFSW respectively. It is clear that the material flow velocity in FSW increases slowly from the beginning to $x = 2$ mm, where the material approaches the pin surface. The velocity accelerates sharply from $x = 2$ mm to 0.5 mm, where the material is closest to the pin surface. The highest velocity measured is 25.9 mm/s, which is 20.1% of the pin surface linear velocity (on this cross-section, the pin diameter, 4.1 mm and the rotation speed, 600 rpm amount to a linear velocity, 128.8 mm/s), with a distance of 35 μm to the wall of the EH. It decelerates sharply from $x = 0.5$ mm to –0.5 mm, where the material starts diverging from the pin surface. It reduces further down the interval from $x = -0.5$ mm to $x = -2$ mm and is relatively stable at the rear side. From $x = -2$ mm, it gradually attains the initial value at the shoulder edge. In UVeFSW, the material flow velocity begins to accelerate sharply at $x = 3$ mm. At $x = 0.5$ mm plane, the maximum velocity measured is 11.7 mm/s at 0.261 mm from the pin surface. From $x = 0.5$ mm to $x = -3$ mm, the material moves away from the pin surface, and the velocity slows down gradually. From $x = -3$ mm to $x = -4$ mm, it is relatively stable before recovering to the initial velocity at the shoulder edge. The measured velocities in this study are of the same order of magnitudes as those reported earlier for 2xxx aluminum alloys in [6,8,11] from experimental investigation or numerical simulation. Especially, the experimentally estimated velocities of the MM in [6] are in close correspondence to those measured in this study.

Figure 3f and g shows the measuring schematic and the comparison of flow velocities in FSW and UVeFSW against the distance R (to the center of the EH). The velocities can be calculated by measuring the MM width at points where a concentric circle of the EH with a radius of R intersects the MM. It is clear that the velocity first increases slowly and then sharply with the decreasing R. The flow velocity in UVeFSW is obviously higher than that in FSW at the same R. At $R = 2.5$ mm, (i.e., 0.45 mm from