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In-situ material flow pattern around probe during friction stir welding of austenitic stainless steel

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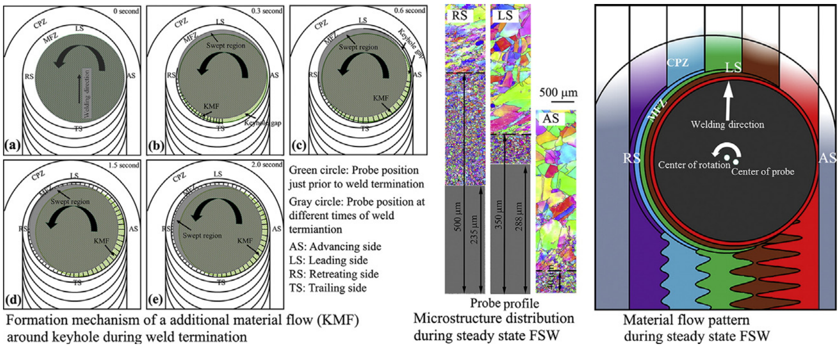
HIGHLIGHTS

- The probe route as well as the material flow around the keyhole during weld termination were tracked.
- The in-situ microstructure distribution and material flow during FSW were analyzed and presented.
- The formation mechanism of compression zone (CPZ) and material flow zone (MFZ) were clarified.
- A material flow model was established to describe the in-situ material flow during FSW.

GRAPHICAL ABSTRACT



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ABSTRACT

The probe route as well as the material flow around the keyhole during weld termination were tracked and used to determine the probe position just prior to weld termination. This approach enables analysis of in-situ microstructure distribution and the nature of material flow during friction stir welding (FSW). A FSW flow model was established. During steady state FSW, the material at the advancing side (AS) recrystallized rapidly when it was swept by the hot rotating probe. The recrystallized grains were driven to rotate around the probe along the tool rotation direction, forming the material flow zone (MFZ). As the base material approached the probe, it was compressed initially, forming a compression zone (CPZ) mainly consisted of coarse deformed grains. When the coarse deformed grain in CPZ collided with the hot material in the MFZ, it recrystallized and added into the MFZ, thickening the MFZ ahead of the probe. During FSW, the material intersecting the path of probe was displaced to rotate around the probe and then deposited behind the probe at roughly the same transverse position as its initial position.

1. Introduction

Friction stir welding (FSW) is an innovative solid-state joining process in which a non-consumable tool is used to 'stir' the joint materials to produce a high quality joint with a fine microstructure and superior mechanical properties [1–5]. FSW is considered to be one of the most significant welding techniques to emerge in the past two and a half decades. Although FSW was initially developed for joining low melting point metals, such as Al, and Mg alloys [6–9], research in FSW of steels has grown with the development of effective welding tools.

A complete understanding of the material flow and microstructure evolution during FSW process is a key element in understanding the

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development of weld defects, and post-weld microstructure and properties. Although some researchers have investigated the material flow behavior during FSW, the existing theories are still inconclusive and often contradictory. This is because the material flow during FSW is complicated, varies with workpiece material and welding parameters, and cannot be observed directly.

Marker insert technique has been used to track the material flow during FSW. For example, Colligan [10] embedded steel shots with a diameter of 0.38 mm along the welding path of aluminum alloys and showed the shot distribution with the aid of X-ray tomography after suddenly stopping the forward motion of the welding tool. Morisada et al. [11,12] showed the three-dimensional flow pattern of a 0.3 mm spherical tungsten tracer during FSW using two pairs of X-ray transmission real time imaging systems. Although all experiments clearly indicate that weld material is displaced around the welding tool, there are some concerns in that the tracers of vastly different density than the matrix may not properly represent the actual material flow.

As foreign material with similar density and thermomechanical properties as the base material but with other composition is selected as tracer, the tracer and base material will deform and flow in a similar manner. Reynolds [13] has used Al alloy 5454 sheet as a marker material for FSW of Al alloy 2195. After a comparison of the initial and final positions of the marker, they deduced that the FSW process can be roughly described as an in situ extrusion process wherein the tool shoulder, the weld back plate and the cold base metal outside the weld zone form an ‘extrusion chamber’ which moves relative to the workpiece. Schmidt et al. [14] insert copper strip as marker material for FSW of Al alloy 2024. The distribution of the copper around the probe and in the weld region was recorded by X-ray and computer tomography (CT) techniques. Based on experimental and simulation results, Schmidt et al. considered that the flow zone during FSW process consisted of rotation zone, transition zone and deflection zone from the probe surface to the base material. Each zone was closely related to its corresponding flow pattern.

The material flow can also be deduced from the micro-textures since the deformation history can be recorded by the crystallographic distribution of the deformed material. Sato et al. [15] and Field et al. [16] have examined the micro-texture in FSW Al alloys using electron backscatter diffraction (EBSD) and found that the stir zone had a texture component with the {111} plan and <110> direction roughly parallel to the probe column surface and the pin rotation direction, respectively. The investigations on FSW of Mg alloys [17–19] showed that an intense (0002) basal plane texture surrounding the probe column surface was produced in the stir zone. For FSW of commercial pure Ti, the P-fiber texture with a pronounced $\{10\bar{1}0\}\langle 11\bar{2}0\rangle$ component which rotated from the retreating side (RS) to AS following the rotation of the shear direction across the stir zone were detected [20–22]. These observations indicated that the material flow during FSW mainly arose from the simple shear deformation around the probe. Because only the initial and final microstructure was examined, a full story about the material flow and microstructural evolution during FSW cannot be summarized from these fragments.

FSW keyholes have been made through ‘freezing’ the FSW process by the method of stopping the tool and immediately quenching the work piece (‘stop action’ technique) [18,23–25]. The microstructural investigation around the ‘frozen’ keyhole provided meaningful insights on the microstructure evolution and material flow. However, the rotating tool cannot be stopped instantly due to the inertia in the FSW system. The tool rotation as a result of inertia disturbing the material distribution around the probe. Additionally, probe shift caused by relaxation in the FSW system allowed the keyhole position to shift during weld termination, resulting in a keyhole microstructure that does not represent the in-situ material distribution during steady state FSW. In the experiment of Prangnell et al. [23], the tool rotation was stopped within 0.1 s after activating the emergency stop, a shift of probe occurred due to system relaxation is evident. This indicates that the material flow around the so called ‘frozen’ keyhole is not consistent with that around a probe during steady state FSW.

Because the FSW system relaxation and probe shift during weld termination cannot be totally avoid, a fundamental understanding about the system relaxation and what actually happed during the period from activation of weld termination to cessation of probe rotation is required. For this purpose, various techniques such as emergency weld termination, weld force monitoring, tracer technique and EBSD examinations were performed with great care in this study. The final objective is to present the in-situ material flow pattern during a steady state FSW.

2. Experimental details

Hot rolled commercial 304L austenitic stainless steels with a thickness of 12.7 mm were welded using the TTI-RM2 FSW machine. All welds were made polycrystalline cubic boron nitride (PCBN) convex-scrolled-shoulder-step-spiral (CS4) tools with a shoulder 25 mm in diameter and a frustum probe 9 mm in root diameter, 5 mm in tip diameter and 3.8 mm in length. The tool rotation rate, welding speed and downward force is 250 rpm, 100 mm/min (i.e. the workpiece traveled at a speed of 100 mm/min), and about 8 kN, respectively. A liquid cooled tool holder equipped with telemetry system was used. An argon shielding system was applied to minimize the workpiece surface oxidation. The temperature and the welding force in three dimensions were monitored during FSW.

One weld was terminated in a traditional way, i.e. reducing the welding speed to zero while maintaining tool rotation in its original speed and then extracting the rotating weld tool. The keyhole obtained at the end of this weld is identified as keyhole I. An emergency stop was used for another weld, i.e., terminating the workpiece travel and tool rotation as fast as the machine is capable. The probe remained in the workpiece after weld termination to reduce the system relaxation. The keyhole obtained at the end of this weld is identified as keyhole II. In order to reveal the material deposition during FSW, commercial 1008 low carbon steel slices were inserted in to the 304L austenite stainless steel as marker material and subjected to FSW as theses steels have similar thermal mechanical properties. Negligible temperature fluctuation was observed when the welding tool entered the region containing 1008 steel slices.

The workpiece travel was stopped within 0.01 s after activating welding termination for all the welding, resulting a longitudinal movement of <15 μm. Such a negligible shift was not considered in this study. For keyhole II, the tool rotation stopped completely 0.6 s after activating weld termination. To prevent significant grain growth, coolant was poured around the keyholes immediately after finishing FSW for all the welding. The keyholes were cooled to <200 °C within 10 s.

The samples for optical examinations were mechanical polished and then were electrolytic etched in a solution composing of 10 g oxalic acid and 100 ml distilled water. The EBSD samples were vibratory polished using 0.05 μm colloidal silica after a standard mechanical polishing. High resolution EBSD data were obtained at 20 kV at steps of 0.2 μm using FEI Helios Nanolab 600 with a TSL channel EBSD system. FEI Helios Nanolab 600 permitted more than one million EBSD data each hour and so that large-sized high-resolution EBSD maps were obtained in this study.

3. Results and analysis

3.1. Probe travel route during weld termination

The most accurate way to determine the system relaxation during weld termination is to evaluate the change of interaction forces between the workpiece material and the welding tool. Fig. 1 shows the forces on the probe during the process of welding and weld termination. For keyhole I (Fig. 1a and b), the downward force decreased to zero immediately after weld termination. The transverse and longitudinal forces turn negative first and then went back to zero 2 s after activation of weld termination. After activation of weld termination for keyhole II,