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Letters

Material flow visualization during friction stir welding using high-speed X-ray imaging



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ABSTRACT

This study employs high-speed X-ray imaging to capture the process dynamics during FSW in-situ, using a high-intensity X-ray beam to image a 2 mm \times 2 mm area at 20,000 frames per second. The friction stir (FS) tool made of H13 tool steel with threads and 3-flats on the probe was used in an aluminum 6061-T6 workpiece. The process parameters employed result in a fully consolidated weldment without any observable sub-surface voids. The density changes captured by the high-intensity X-ray beam show the formation and filling of cavities in the wake of the tool three times per rotation.

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1. Introduction

Friction stir welding (FSW) is a solid-state joining process consisting of a non-consumable rotating tool plunging into two metallic workpieces and traversing along the joint line, mechanically intermixing the two workpiece materials [1]. The solid-state nature of the process combined with grain-refinement due to intense plastic deformation of the material provides distinct mechanical and corrosion advantages over traditional fusion-based joining methods. Significant research has been published across literature focusing on the FSW of Aluminum alloys [2,3]. Intermittent material flow has been significantly discussed in the literature for FSW. Researchers began providing substantial evidence that the formation of "onion rings" stems from the intermittent extrusion of the material around the tool probe. The intermittency is observed in the form of banded features within the cross-sectional view of the welds in the welding plane at a distance equivalent to the tool's advance per revolution [4]. Several researchers have articulated material flow hypothesis based on opening and filling of cavity once per revolution in the wake of the tool probe [5,6]. Several methods, including microstructural examination [7], NDE testing [8], measuring dynamic process forces [9], numerical modeling [10], etc., have been used in the literature to represent material

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flow during FSW. Prior work using X-ray imaging has relied on tracer particles that enabled the observation of bulk material flow and the calculation of strain rates [11]. However, no published study performs an *in-situ* dynamic visualization of the material flow with density change (i.e., cavity/void opening and closing) around the FS tool. Through this study, the authors demonstrate the novel use of high-intensity high-speed X-ray imaging to visualize the material flow dynamics within one tool revolution during friction stir welding.

2. Experimental setup

FSW was performed on a 3-axis CNC mill (HAAS TM-1). 16-mm-wide aluminum 6061-T6 workpieces were used and placed on a mild steel backing plate. The FSW tool was made out of H13 tool steel, consisting of an 11.5-mm-diameter concave shoulder and a 4-mm-long probe, tapered from 6 mm at the shoulder to 4.5 mm at the tip. The tool had three flats spaced 120° apart and was threaded with a 1 mm pitch and constant thread depth of 0.625 mm. The addition of threads promotes material stirring, and flats allow for an increased local deformation and turbulent flow of the plasticized material, leading to a reduction in process forces and torques [12]. All welds were performed at a 3° travel angle, with a commanded plunge depth of 0.8 mm, spindle speed of 1200 RPM (counterclockwise), and traverse speed of 240 mm/min. The welds were 80 mm long. These conditions result in a fully

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consolidated weld. In this apparatus, the rotating tool is fixed in the X-Y plane, while the workpiece traverses in the Y-axis during the process. High-speed X-ray imaging was performed at the Advanced Photon Source (APS), Argonne National Laboratory using the 32-ID-B beamline. The FSW setup (i.e., entire 3-axis CNC mill) was placed inside the beamline hutch. The X-ray beam is generated using a 1.8 cm period undulator yielding a quasi-single peak (1st harmonic) at \sim 24 keV energy and a bandwidth of 5–7 %. A pair of slits were used to define the size of the X-ray beam, generating a 2 mm \times 2 mm imaging window. A downstream detection system is used to convert the X-ray signal to visible light via a scintillator (LuAG: Ce, 100 µm) which is captured using a high-speed camera (Photron FastCam SA-Z 2100K) equipped with a 10X objective (Mitutoyo) at 20,000 frames per second. The images were taken approximately halfway (40 mm) into the weld to ensure a steady-state regimen. 3000 frames were recorded for each measurement, capturing 0.15 s or 0.6 mm of the linear weld. Since the FS tool advances 0.2 mm/rev, the video captures three full rotations of the probe in the workpiece. A schematic illustration of the experimental setup is provided in Fig. 1.

3. Results and discussion

Fig. 2 shows a selection of frames from a series of 333 frames capturing 1/3rd rotation (120°) of the probe. Five frames at 0 ms, 4 ms, 8 ms, 12 ms, and 16 ms are shown in Fig. 2. In the figure, 't' represents the relative time from the first reference frame and 'θ' represents the probe rotation from the reference frame. Since the FS tool has 3-flats, during the 1/3rd rotation of the probe, we observe a complete interaction of one flat with the material. The X-rays capture density changes occurring at the trailing edge of the probe. Due to the X-ray beam's 2 mm \times 2 mm image window, the focus has been to observe the probe-driven material. The complete video of one full rotation of the tool probe in the workpiece material during FSW can be found in the supplementary material.

According to the flow-partitioning model presented by Arbegast et al. [5], later articulated by Boldsaikhan et al. [6], within one revolution, a cavity opens as the tool moves forward at the trailing edge of the probe due to a stress barrier preventing initial material movement. As the cavity size increases, the stress barrier holding the shear layer of the material decreases until it is released and

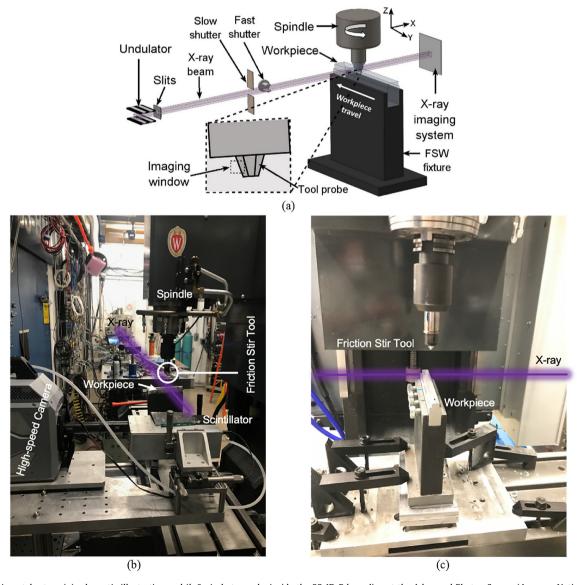


Fig. 1. Experimental setup: (a) schematic illustration and (b & c) photographs inside the 32-ID-B beamline at the Advanced Photon Source (Argonne National Laboratory).

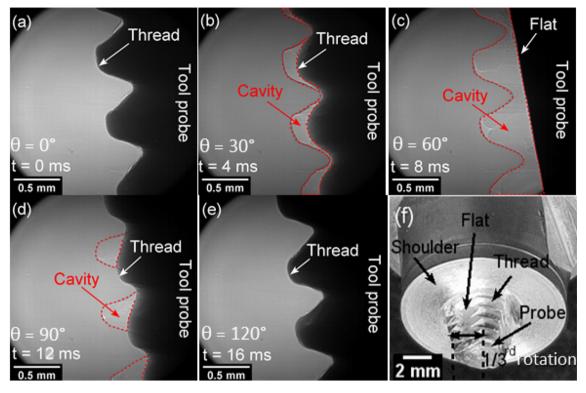


Fig. 2. (a-e) High-speed X-ray image frames showing material flow within 1/3rd rotation of the FSW tool and (f) FSW tool used in the study. The cavity is represented by the red outlined regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

extruded into the cavity. Thus, the periodic opening and filling of the cavity occurs once per revolution in the wake of the probe.

In Fig. 2, as the tool rotates, a cavity begins to form in the wake of the probe (Fig. 2-b). Since the imaging system captures density changes, the cavities are seen as a lighter shade of gray compared to the darker gray, which represents the aluminum being present through the full thickness of the workpiece. The maximum volume of cavity formation is observed across the flats on the tool probe as the probe rotates to 60° in the material (Fig. 2-c). As the rotation continues, the material forged by the trailing threads begins to close the cavity (Fig. 2-d). With the tool probe's complete 120° or 1/3rd rotation, the forged material fills the cavity (Fig. 2-e). The cavities mimic the thread profile present on the tool probe, a phenomenon postulated in previous literature [13]. The cavity formation around the tool is not uniform since the manufactured threads are not perfect. Additionally, the tool has runout due to manufacturing and assembly tolerances. The tool runout leads to one thread dominating the material flow compared to the others [4]. The authors observed the flow patterns corresponding to probe

and shoulder-driven flows in the cross-sectional views of the stir zone. In the probe-driven flow, they observed a layered pattern, suggesting the space created in the trailing edge of the weld cavity is periodically filled, and the cavity mimics the probe profile.

In contrast to the general idea of the opening and filling of cavities in the wake of the probe, once per rotation of the tool probe with 3-flats and threads, this phenomenon is observed three times per rotation corresponding to the individual flats, as seen in Fig. 3. This potentially explains the formation of a new set of jagged bands within the periodic banded structures observed in the longitudinal cross-section of the weld that corresponds to the tool's advance per revolution. These additional bands were seen with the introduction of 3–5 flats in the tool probe [14].

Fig. 4 shows the various cross-sections for the FSW specimen examined in this study. The fully consolidated weld zone shown by the dynamic imaging (high-speed X-ray imaging) can be confirmed. The Y-Z-plane (Fig. 4b-c) shows the banded microstructures, which are believed to be a consequence of the periodic opening and filling of a cavity within the tool revolution. In this

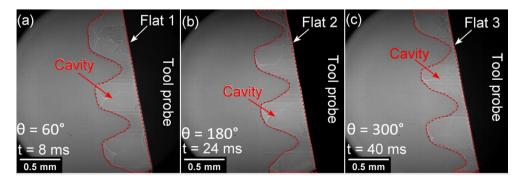


Fig. 3. (a-c): High-speed X-ray image frames showing cavity formation across the three flats in the tool probe per rotation of the tool. The cavity is represented by the red outlined regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

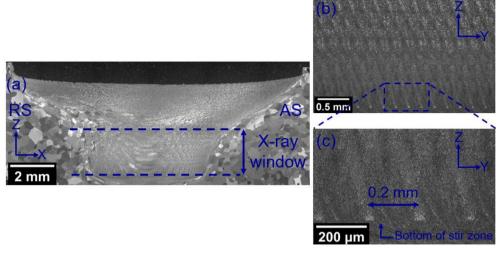


Fig. 4. Cross-sections of friction stir weld imaged in this study (a) X-Z-plane showing the stir zone width, (b) Y-Z-plane showing bands associated with intermittent material flow, (c) magnified view of Y-Z-plane near the bottom of the stir zone.

example, it is observed that the primary band features are separated by 0.2 mm, which is equivalent to the distance the tool advances per revolution.

4. Conclusions

FSW of aluminum 6061-T6 workpiece was performed using an H13 tool steel probe, consisting of threads and 3-flats. The experiments were conducted with a high-intensity X-ray beam while capturing the process flow dynamics through a high-speed camera. The following hypothesis was proven: "intermittent formation and filling of a cavity, once per revolution, at the trailing edge of the friction stir tool, is an inherent part of friction stir welding and processing of aluminum alloys." It was shown that this periodic opening and filling of the cavity happens for processing parameters that produce a fully consolidated weld, as was used in this study. A novel observation from the study is that for a tool with three flats and threads, the opening and filling of cavities occurred once per 1/3rd rotation of the probe.

The shear flow patterns can potentially be observed through dynamic imaging, which would further provide an improved understanding of the microstructural transformations during FSW. The strain rates generated during FSW influence the plastic flow patterns, including the dynamic viscosity of the deformed material [15]. Literature has shown the direct correlation of the plastic flow with dynamic recrystallization and texture evolution in the nugget zone [16]. Moving forward, this methodology will be applied to understanding the changes in process dynamics in processing conditions that produce sub-surface voids, along with the impact of process parameters and tool profiles on the material flow during FSW.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mfglet.2022.08.016.

Detailed information on the experimental setup and original data files can be found in the mendeley dataset [17].

References

- [1] M.T.W. Friction stir butt welding. Int Patent No 1991;PCT/GB92/02203. https://cir.nii.ac.jp/crid/1570009751310225536.bib?lang=en.
- [2] Mishra RS, Ma ZY. Friction stir welding and processing. In Materials Science and Engineering R: Reports 2005; Vol. 50, Issues 1–2. https://doi.org/10.1016/j. mser.2005.07.001.
- [3] Threadgilll PL, Leonard AJ, Shercliff HR, Withers PJ. Friction stir welding of aluminium alloys. Int Mater Rev 2009;54(2):49–93. https://doi.org/10.1179/174328009X411136.
- [4] Franke D, Rudraraju S, Zinn M, Pfefferkorn FE. Understanding process force transients with application towards defect detection during friction stir welding of aluminum alloys. J Manuf Processes 2020;54:251–61. https://doi.org/10.1016/i.imapro.2020.03.003.
- [5] Arbegast WJ. A flow-partitioned deformation zone model for defect formation during friction stir welding. Scr Mater 2008;58(5):372-6. https://doi.org/10.1016/j.scriptamat.2007.10.031.
- [6] Boldsaikhan E, Burford DA, Gimenez Britos PJ. Effect of Plasticized Material Flow on the Tool Feedback Forces during Friction Stir Welding, In: Mishra R, Murray M, Sato Y, Hovanski Y, Verma R, editors. Friction Stir Welding and Proceesing VI, Wiley; 2011, p. 335-343.
- [7] Colligan K. Material flow behavior during friction welding of aluminum. Weld J 1999:75(7):229s-37s.
- [8] Rabi J, Balusamy T, Jawahar RR, Analysis of vibration signal responses on pre induced tunnel defects in friction stir welding using wavelet transform and empirical.
- [9] Shrivastava A, Pfefferkorn FE, Duffie NA, Ferrier NJ, Smith CB, Malukhin K, et al. Physics-based process model approach for detecting discontinuity during friction stir welding. Int J Advanced Manuf Technol 2015;79:604–15. https://doi.org/10.1007/s00170-015-6868-x.
- [10] Nandan RGGR, Roy GG, Lienert TJ, Debroy T. Three-dimensional heat and material flow during friction stir welding of mild steel. Acta Mater 2007;55

- [11] Morisada Y, Fujii H, Kawahito Y, Nakata K, Tanaka M. Three-dimensional visualization of material flow during friction stir welding by two pairs of X-ray transmission systems. Scr Mater 2011;65(12):1085–8.
- [12] Zhang YN, Cao X, Larose S, Wanjara P. Review of tools for friction stir welding and processing. Can Metall Q 2012;51(3):250–61.
- [13] Kumar KSVK, Kailas SV. The role of friction stir welding tool on material flow and weld formation. Mater Sci Eng, A 2008;485(1–2):367–74.
- [14] Schneider J, Brooke S, Nunes AC. Material flow modification in a FSW through introduction of flats. Metall Mater Trans B 2016;47(1):720–30.
- [15] Nandan R, Roy GG, Debroy T. Numerical simulation of three-dimensional heat transfer and plastic flow during friction stir welding. Metall Mater Trans A 2006;37(4):1247–59.
- [16] Schneider JA, Nunes AC. Characterization of plastic flow and resulting microtextures in a friction stir weld. Metall Mater Trans B 2004;35(4):777–83.
- [17] Pfefferkorn, Frank; Agiwal, Hemant; Ansari, Mo; Franke, Daniel; Faue, Patrick; Clark, Samuel; Fezzaa, Kamel; Rudraraju, Shiva; Zinn, Michael (2022), "High-Speed High-Energy X-ray Imaging of Friction Stir Welding 6061-T6 Aluminum Mfg Letters 2022", Mendeley Data, V1, https://doi.org/10.17632/4286rg7dps.1.