An approach towards a high fidelity imaging the local material behaviour of Friction Stir Welded (FSW) 304 stainless steel joints

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Abstract

Friction Stir Welded (FSW) 304 austenitic stainless steel (SS) joints are studied using optical microscopy to obtain the grain morphology in the weld region. High-resolution 2D-Digital image correlation (DIC) is used to assess the local strain response within the elastic limit across the weld surface. The full-field data obtained from the DIC is linked with the micrographs to classify the local material behaviour of the FSW zones. To understand the strain localizations across the weld nugget X-ray CT is used to confirm the weld geometry and also to evaluate the internal weld defects. Thus high-resolution DIC data combined with the microscopy techniques aids in establishing a core structure-property relationship of the FSW zones.

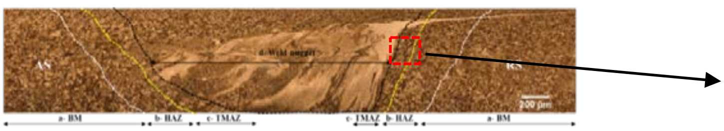
Keywords: Stainless steel (SS), Friction Stir Welding (FSW), Optical microscopy, Digital Image Correlation (DIC)

1. Introduction

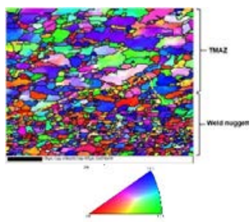
Friction Stir Welding (FSW) is a solid-state welding process that does not involve any bulk melting of the base materials and the joining is achieved by the frictional heat and plastic work rate produced by a rotating and traversing non-consumable tool. This high plastic deformation and frictional heat are responsible for the generation of recrystallized ultrafine grains in the weld nugget, making the weld nugget stronger compared to the parent material. In the present investigation, 2 mm thick 304 austenitic stainless steel (SS) sheets were welded in the butt weld-configuration using the FSW process. SS-SS joints have major applications in the power generating structures due to high mechanical strength and corrosion resistance characteristics of the SS. As the different weld zones in the vicinity of the FSW weld such as Heat Affected Zone (HAZ), TMAZ (Thermo-Mechanical Affected Zone), SZ or weld nugget (Stir Zone), and BM (Base Material) have distinct microstructural characteristics, the local mechanical behaviour of these zones also vary. Therefore to assess the local strains across these zones with a high degree of confidence, High-Resolution (HR) 2D-DIC data is linked with optical micrographs to unambiguously identify the local properties of the FSW (SS-SS) weld zones.

2. Microstructure of the FSW (SS-SS) joint- along the weld cross-section

For the microscopy analysis, the specimen was polished using a standard polishing procedure and then etched with the ferric chloride solution for 10 sec. The microstructure was observed using an Olympus BX51optical microscope at a magnification of 200x. For the EBSD (Electron backscattered diffraction) analysis, a JEOL 6500F field-emission gun scanning electron microscope (FEG-SEM) with HKL Nordlys detector was used at an accelerating voltage of 20 kV and probe current of 17 nA. Fig. 1a shows the sequentially stitched optical micrographs along the cross-section of the FSW (SS-SS) joint. In addition to the weld nugget (d), the FSW (SS-SS) weld exhibits three local weld zones such as: (a) BM, (b) HAZ, (c) TMAZ along the advancing and retreating sides of the weld.



(a)



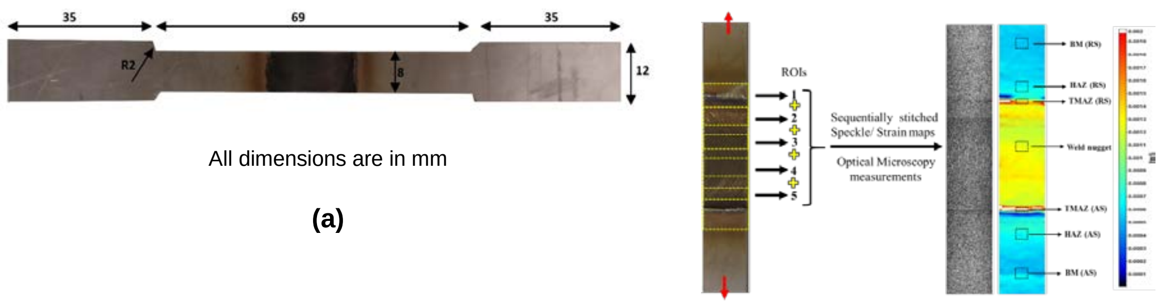
(b)

Fig. 1 (a) Sequentially stitched optical micrographs of the FSW (SS-SS) weld cross-section, (b) EBSD grain orientation map of the region located in (a)

As a consequence of the plastic deformation during the FSW process, the weld nugget contains finely recrystallized sub-micron grains in a classical ‘onion ring structure’ in the form of intercalated lamellae produced by the frictional heat interlinked with the tool traverse and rotating motion that occurs during the FSW process. The ultrafine equiaxed recrystallized grains which densely populate the FSW weld nugget cannot be resolved by optical microscopy due to limitations in magnification and spatial resolution. To resolve the ultrafine grains in the weld nugget, the SEM-EBSD technique was applied in the location close to the TMAZ-weld nugget interface and its corresponding grain orientation map is shown in Fig. 1b, which reveals the microstructural gradients across the TMAZ/weld nugget and the ultrafine recrystallized equiaxed grains in the weld nugget. Furthermore, a clear boundary between TMAZ (elongated grains) and the weld nugget (fine grains) is also evidenced in the EBSD micrograph.

3. HR-2D-DIC analysis

To establish the local structure-property relationship in all the local weld zones, HR 2D-DIC was conducted on a standard tensile specimen as shown in Fig. 2a to investigate the full-field strain distributions on the surface of the FSW (SS-SS) weld. All the tests were performed within the elastic range in a Instron-8800 servohydraulic test machine equipped with 5 kN load cell at a displacement rate of 0.5 mm/min. The fine black speckled pattern required for the HR 2D-DIC analysis was created using an airbrush kit on a white painted background specimen. The HR DIC system consists of 16 MP LaVision CCD camera having a spatial resolution of 4904 x 3280 pixels fitted with a Canon MP-E 65 mm focal length macro lens enabling images to be captured with a spatial resolution of 307 pixel/mm. All the recorded images were processed using DaVis 8.3.1 (Subset Size: 120 x 120 pixel, Step Size: 30) to evaluate the deformation field and full-field strain maps in the local weld zones. As the high magnification optics always limits the ROI, the total area of ROI (50 x 8 mm) was partitioned into five individual ROIs (as shown in Fig. 2b) during the DIC experimental trials. The processed strain maps obtained from the individual ROIs at the same load were sequentially stitched using the Image-J grid stitching algorithm to visualize the full-field strain across the whole ROI. Fig. 2c shows the stitched strain maps (ε_{yy}) evaluated along the weld surface at 2 kN. From this strain map, it is noted that both base materials (AS and RS) have more uniform strain distributions. However, the weld nugget is highly strained compared to the base material. Furthermore, the strain concentration spots are clearly observed along the boundaries of the weld nugget. These strain concentrations achieved within the nominal elastic loading regime are considered to be associated with the weld geometry and internal weld defects of the FSW. To reveal the weld zones from the map, the local DIC data was aided with optical microscopy measurements and the zones were located as shown in Fig. 2c.



(a) **(b)** **(c)**

Fig. 2 (a) FSW (SS-SS) tensile specimen, (b) 2D-DIC ROIs and (c) 2D-DIC strain maps at 2 kN along the weld surface

4. Conclusion and Future Work

HR 2D-DIC was conducted on the FSW (SS-SS) weld surface and the local full-field strain distribution was obtained. Through a rich microscopy characterization techniques, the local strains were mapped to their corresponding weld zones without any approximations. However, to deal with the inconsistency in the DIC strain maps, X-ray CT analysis will be required to account for local geometry variations and also to locate any internal weld defects.