



Feasibility of Friction Stir Welding for Sealing the Roller-Expanded Heat Exchanger Tube-To-Tubesheet Joints

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Abstract

In expanded-welded tube-to-tubesheet joints, where welds separate the two transfer fluids, tungsten inert gas (TIG), welding is preferred traditionally. A non-conventional novel technique for sealing the roller-expanded joints using friction stir welding (FSW) instead of TIG welding is proposed. FSW was effective with up to 8% expanded tube-to-tubesheet joints. The minimum leak path of 4%, 8%, and 12% expanded and welded joints were 0.74mm, 1.34mm and 0.32mm, respectively. Grains were refined at the stir zone due to dynamic recrystallization and at the expanded zone due to compressive stress imparted by rollers. The results proved that the FSW is a promising technique for producing quality sealed joints.

Keywords: Aluminium; Friction stir welding; Heat exchanger; Tube; Tubesheet.

Received: 27 March 2024; Revised: 05 June 2024; Accepted: 14 June 2024.

Article type: Research article.

1. Introduction

Leakproof tube-to-tubesheet welds (TTW) are essential for avoiding mixing shell-and-tube heat exchanger fluids.^[1] Currently, tube-to-tubesheet joints are fabricated using tube expansion, seal and strength welding.^[2] The tungsten inert gas (TIG) welding process is mainly used to manufacture welded or expanded-welded tube-to-tubesheet joints (TTJ). The TTWs are classified as strength weld and seal weld whereas the former exhibits high tube pull-out strength compared to the latter. The welds prevent the mixing of the transfer fluids, and the minimum distance of separation of transfer fluids is influenced by the weld penetration. This least distance of separation is the minimum leak path (MLP). The leakage at the TTJs due to cracks or erosion causes catastrophic damage, ceasing the functioning of the heat exchangers. The major drawback of TIG welding is the formation of residual stresses and residually stressed weldments act as the region of crack initiation and propagation.^[3] Plant shutdowns for repairing the heat exchangers result in huge financial loss.^[4] As an

alternative method, the feasibility of using friction stir welding (FSW) instead of TIG for hybrid expanded-welded TTJ conditions is proposed and evaluated. FSW is proven suitable for high-strength steel and polymers-based tube-to-plate configurations. Moreover, authors have proved the capability of FSW for producing tube-to-tubesheet joints with high leak path using Al alloys.^[5] With this proven capability of FSW, a study of FSW on roller expanded (RE) joints is highly demanding. FSW is challenging plastically deformed materials more than undeformed materials. Therefore, ductile and low melting-point aluminum alloys are chosen to verify the success of the proposed technique. The proposed technique is promising for heat exchanger and boiler applications.

2. Materials and methods

AA 6061-T6 tubes and AA 6061-T6 tubesheets were coupons for manufacturing roller expanded-FSW welded joints. Tubes were 18mm outer diameter and 2.5mm wall thickness. A tubesheet hole of 18mm was cut on 52x40x30 mm tubesheet blocks. The tube-to-tubesheet configuration was flush joint where the end face of the tube aligned with the tubesheet face. Three sets of roller-expanded TTJs at 4%, 8% and 12% (light to heavy expansion ranges) expansion percentages were initially fabricated using Elliott ELC110220 electric torque controller, 99 series electric rolling motor, and three roll-standard reach expander with flush collar (Fig 1a). The tubes were rolled for a roller length of 22mm. After the roller expansion process, the friction stir welding is performed using a vertical milling machine (Fig 1f). A fixture was developed

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for holding the tube and tubesheet (Fig. 1c) and FSW was performed using a tool made of H13 tool steel (Fig. 1b) on the roller-expanded joints (Fig. 1d). Instead of the pin in a conventional FSW tool, the projected cylindrical portion from the shoulder is used only for alignment of tool-to-tube/tubesheet assembly. The FSW is merely performed using the tool shoulder. The rotational speed and plunge depth were 1600rpm and 0.3mm.^[5] The composition of coupons, the FSW tool, and expansion percentage calculations have been added to the repository.^[6] The sectioned samples were ground using SiC papers (P80 to P1200) and polished using an alumina-water solution. Etchant (10ml HF+90ml distilled H₂O) was swabbed using cotton buds to reveal the microstructures in an optical microscope (Make: Motic Panthera TEC MAT).

3. Results and discussions

3.1 Minimum leak path

The shortest distance between the two transfer fluids across the weld is termed MLP. Fig. 2 shows the macro-images of roller expanded-FSWed coupons. Effective stirring-based material coalescence was evident in the 4% and 8% expanded coupons followed by FSW. 12% expanded tubes were excessively deformed at the expanded zone, causing high resistance to the FSW plunging tool. This led to high plunging

force, excessive milling bed vibration, and poor-quality welds. Therefore, FSW on heavy roller expanded (12% expansion percentage) TTJs is not recommended. The higher the expansion percentage, the higher the wall thinning. After tube wall thinning at expanded zones, the final inner diameters were 13.205mm, 13.395mm and 13.605mm for ~4%, 8% and 12% expansion percentages, respectively. Due to tube wall thinning at the expanded zone, the tube was axially elongated out (protruded) from the tubesheet surface by 0.39mm, 0.89mm, and 1.16mm at 4%, 8%, and 12% expansion percentages. The maximum protrusion at 12% expansion due to severe thinning at the expanded zone is anticipated to resist the plunging tool. The MLPs are 0.742mm, 1.347mm and 0.323mm for 4%, 8% and 12% expanded, followed by FSW specimens. Achieving sufficient MLP (1.347mm) and quality joints strongly suggest that the technique is suitable for manufacturing heat exchangers. The adherence of softened aluminum material to the tool caused material removal from the inner tube region, considerably reducing the leak path in 4% expanded-FSW specimens. The absence of softened metal-to-FSW tool adherence in 8% condition resulted in the highest leak path. Even though the friction stir welding failed at 12% condition, a small fusion zone was developed, and henceforth, the leak path was minimal.

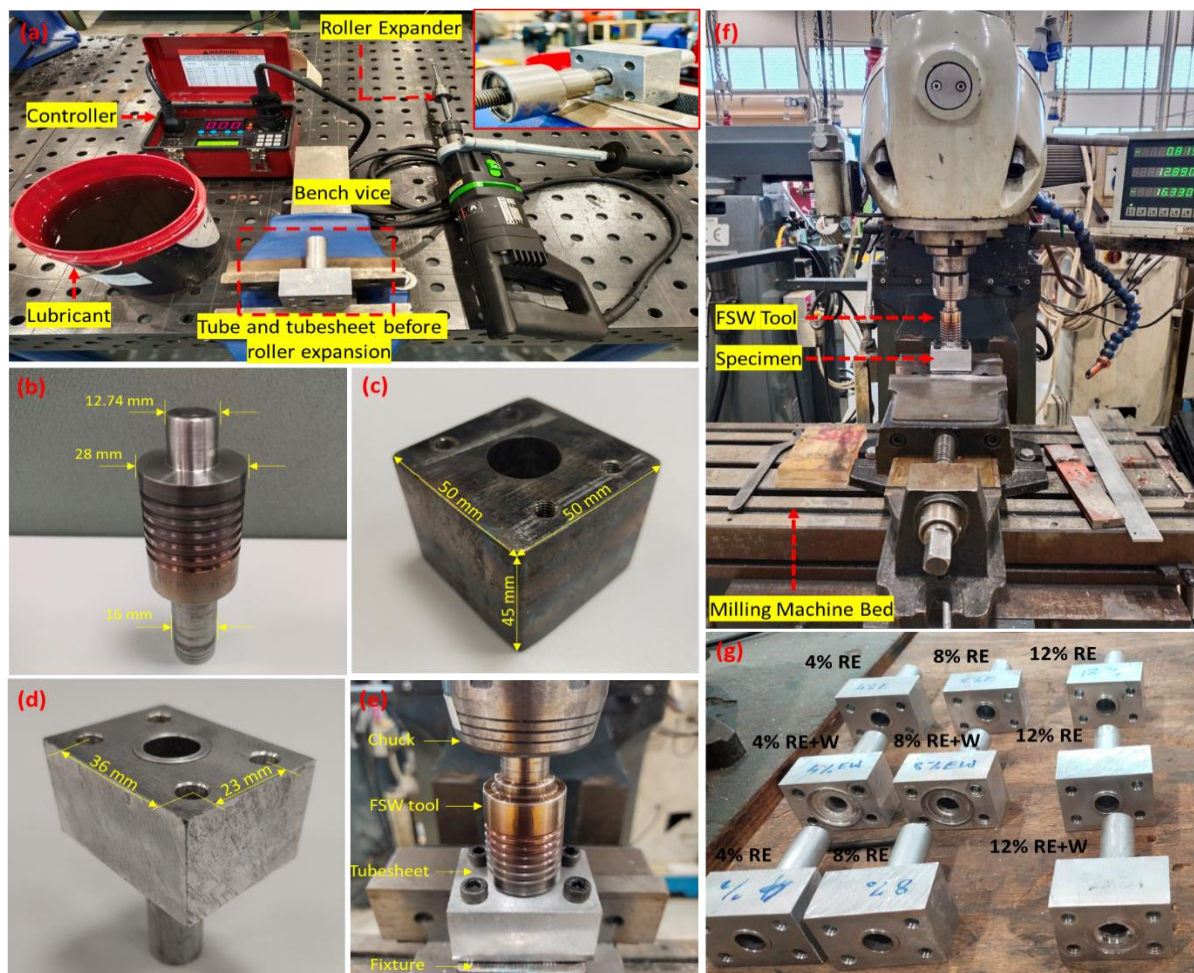


Fig. 1 Experimental setup and procedures. (a) Roller expansion setup; (b) FSW tool; (c) Fixture to hold tube-and-tubesheet; (d) Roller-expanded TTJ; (e) FSW process; (f) Vertical milling machine-based FSW setup; (g) Joints (RE and RE+FSW).

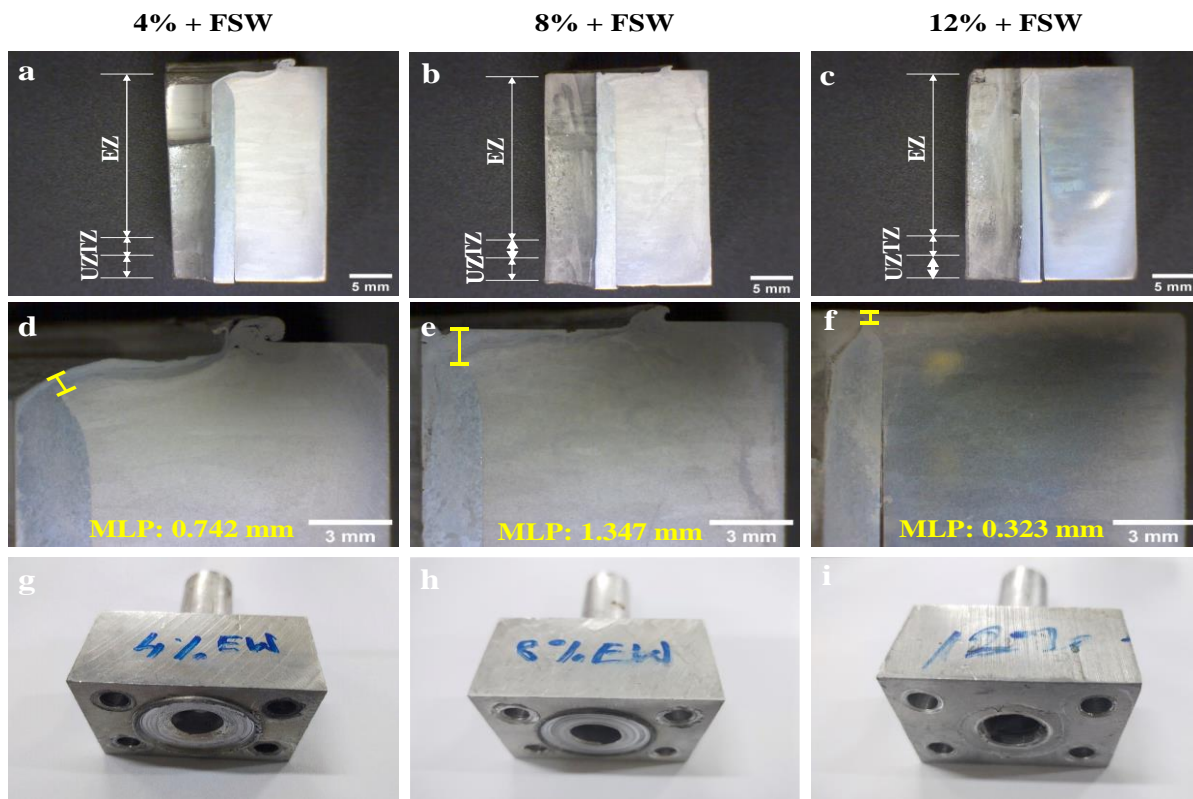


Fig. 2 Macro-images of hybrid welded-expanded joints at three conditions. (UZ: Unexpanded zone, TZ: Transition zone, EZ: Expanded zone).

3.2 Microstructures at the stirring zone and fusion zone

The stirring zone represents the region of contact interface between the tool-shoulder and the adjacent regions of tube and tubesheet. The fusion zone is the tube-tubesheet fused region. Fig. 3 shows specimens' material flow behaviour and microstructure characteristics with 4% and 8% tube expansion percentages followed by FSW. Material flow patterns were

visible at both the stirring zone and fusion zone as a result of mixing.^[7] The tube was softened due to prolonged exposure of contact prior to tool shoulder-to-tubesheet contact. The softened tube material was compressed and flowed towards the tubesheet by the mutual effect of plunging force and stirring action. Solidification in the final stage established an adequate coalescence between tube and tubesheet. Fine grains

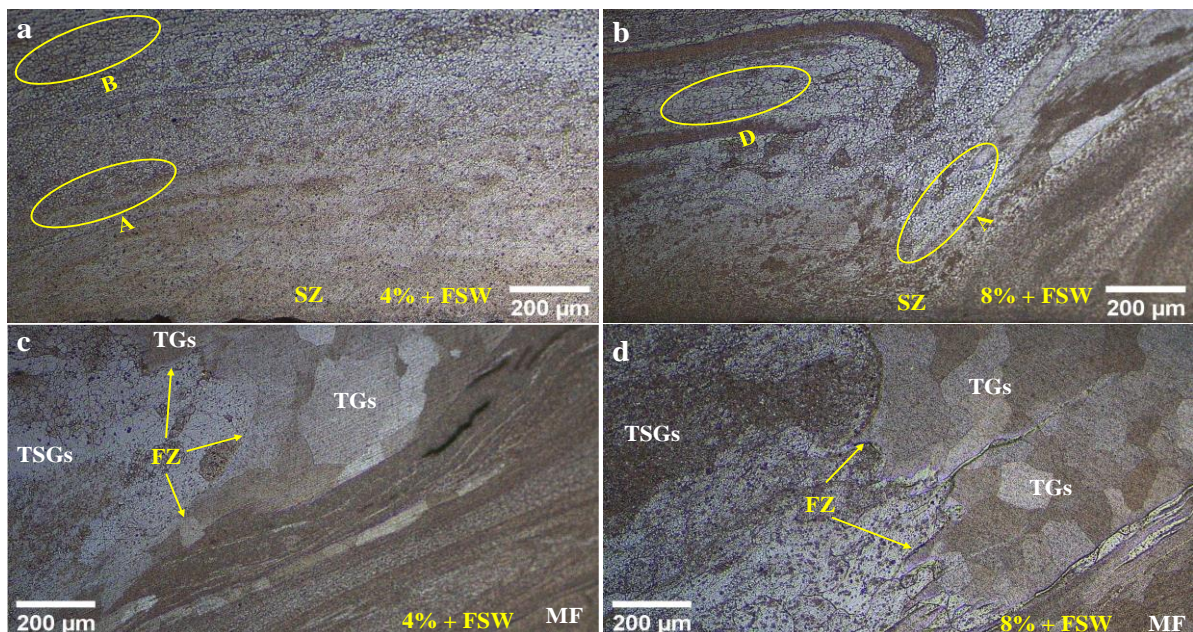


Fig. 3 Stir zone: (a) 4%+FSW; (b) 8%+FSW; Fusion zone: (c) 4%+FSW; (d) 8%+FSW. (MF: Material flow; TGs: Tube grains; TSGs: Tubesheet grains).

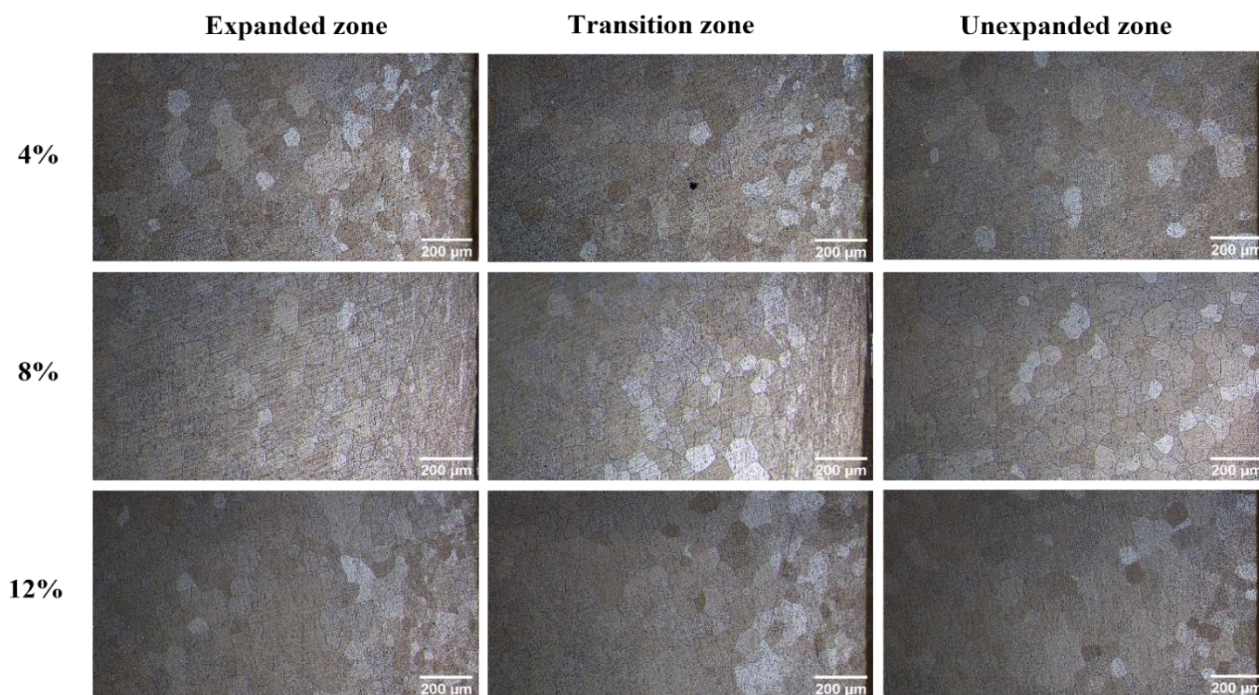


Fig. 4 Microstructures at expanded, transition and unexpanded zones of inner tube surfaces.

are formed at the stirring zone due to dynamic recrystallization.^[8,9] Grain sizes of $\sim 6.25\mu\text{m}$ are formed at locations A and C, whereas slightly coarser grains of size greater than $\sim 12.5\mu\text{m}$ are formed at locations B and D away from the stir zone in the tubesheet. Grains are coarsened at the fusion zone compared to the stir zone.

3.3 Microstructures at expanded, transition and unexpanded zones of inner tube edges

The tube expansion led to the formation of the expanded zone (EZ), unexpanded zone (UZ) and transition zone (TZ) (i.e., the slope between EZ and UZ) on tubes.^[10,11] The tube thickness reduced with the increase in the expansion percentages. As a result of the tube expansion process, the grains closer to the inner tube surface were significantly refined by the compressive forces exerted by the rollers (Fig. 4). The grains at the expanded zone are refined to $19.2\mu\text{m}$, $17.85\mu\text{m}$ and $13.15\mu\text{m}$ from a nominal grain size of $50\mu\text{m}$ for 4%, 8% and 12% expansion percentages, respectively. This intensive grain refinement is due to the dislocations resulting in the formation of several grain boundaries.^[12] Grain size reduction at the TZ, however, greater grain size than at the EZ and lesser than the UZ, indicated the influence of compressive stress at the expanded zone extended towards the transition zone, adjacent region of the expanded zone.^[13] The grains are unaffected at the unexpanded zone.

4. Conclusion

This work studied a developed cutting-edge technology for sealing the roller-expanded TTJs using the friction stir welding process. The major findings of the feasibility study are listed below.

- FSW is proven efficient for sealing the roller-expanded tubes up to 8% expansion.
- Wall-thinned tubes with severe plastic deformation at 12% roller expansion resisted the plunging tool, impeding the FSW process with considerable vibration of the milling machine bed, resulting in a poor weld.
- Fine grains $\sim 6.25\mu\text{m}$ are formed at the stirring zone due to dynamic recrystallization, whereas grain sizes of $\sim 12.5\mu\text{m}$ are observed at the tube-to-tubesheet fusion zone.
- The grain size close to inner tube edges reduced with the increase in the roller expansion percentage by the intense grain dislocations aided grain boundary formation.
- The tube expansion process affects microstructures at the transition and expanded zone.
- The disadvantage of the proposed technique is sticking the softened tube or tubesheet materials to the tool during the FSW, resulting in poor weld joints with the lowest MLP.
- In the future, FSwed TTJs should undergo the penetrant test and qualification procedures as in ASME section IX, TEMA, SAES, NBIC, and SES standards.

Acknowledgment

The project was funded by United Arab Emirates University (31N392) and Abu Dhabi University.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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