Evaluation of Residual Stresses in Rotary Friction Welds Between Dissimilar Steels Using an Interlayer

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Abstract.
Dissimilar metal welding (DMW) is widely applied across critical industrial sectors but often faces significant challenges in conventional fusion welding due to the potential for metallurgical incompatibility and the formation of brittle intermetallic compounds (IMCs). Although solid-state methods like rotary friction welding (RFW) mitigate some of these issues, direct RFW of dissimilar steels can still induce elemental migration and create conditions under which brittle phases can form at the joint interface. To address these concerns, this study explores a novel approach in which a low-alloy steel interlayer is deposited onto both faying surfaces via arc welding prior to RFW. Solid, cylindrical RFW joints of dissimilar (low-alloy and low-carbon) steels were fabricated, and their residual stresses were evaluated using the contour method. Crucially, the magnitude of the residual stresses in the as-welded condition was significantly lower than that typically expected in traditional arc-welded joints. These findings demonstrate that RFW combined with a transitional interlayer offers a highly viable manufacturing solution for joining dissimilar metals while effectively minimizing detrimental residual stresses and enhancing structural integrity.

Keywords: Contour method; Dissimilar metal welding; Interlayer; Post-weld heat treatment; Residual stress; Rotary friction welding;

Introduction

Dissimilar metal welding, the process of joining dissimilar metals, is widely applied across various industrial sectors. It provides lightweight, durable joining solutions for specialized structures and has been extensively investigated in prior studies. Specifically, DMW is heavily utilized in the nuclear, offshore, oil and gas, and power generation sectors. Existing research has explored various dissimilar metal combinations, including dissimilar steels, steel-to-titanium alloys, titanium-to-aluminium alloys, and aluminium alloys-to-steel.
The conventional fusion welding of dissimilar metals can be challenging, owing to the melting and mixing of materials that may not be metallurgically compatible. Incompatibility can result from factors such as a large mismatch between the melting points of the materials being joined, or the propensity of the mixed liquid in the molten weld pool to form brittle intermetallic compounds. In recent years, several studies have explored solid-state welding methods, such as rotary friction welding, to join dissimilar metals. This approach mitigates some of the challenges associated with fusion welding and, in some cases, can yield improved mechanical properties in welded joints when compared to traditional arc welding techniques.
Although considerable research has been devoted to the RFW of dissimilar metals, some areas remain relatively unexplored. Evidently, few studies have investigated the potential for a transitional metal interlayer to enhance the overall performance of welded joints. For example, in the direct joining of dissimilar steels via conventional RFW, the migration of carbon and other alloying elements can result in the redistribution of local hardness across the components. Furthermore, differences between the intrinsic properties of the base metals, such as the linear thermal expansion coefficients (CTE), the high-temperature yield strengths, the thermal conductivities, the thermal diffusivities, or the phase transformation behaviour, could elevate levels of residual stress. Large residual stresses can in turn compromise the structural integrity of a component, either through the activation of degradation mechanisms such as stress-corrosion cracking or through a direct elevation in the risk of brittle fracture. However, the introduction of the same buttering interlayer via arc welding onto each of the faying surfaces of the base metal, prior to RFW, could mitigate many of these challenges.

Methodology and Experiments

The contour method was employed to map and evaluate the hoop stress profiles within the RFW joint. The experimental and numerical workflow consisted of three distinct phases.

- **Specimen Cutting:** The solid cylindrical RFW joint was precisely sectioned along the axial centre line using wire electric discharge machining (EDM). A fine brass wire and optimized cutting parameters were utilized to minimize cutting-induced artifacts and ensure a clean, symmetric relaxation of the internal residual stresses.
- **Surface Profile Measurement:** Following stress relaxation, the topographies of both resulting cut surfaces were digitized using a high-precision Coordinate Measuring Machine (CMM). The CMM captured fine-grid surface displacement data along the cutting plane, providing the raw deformation profile necessary for stress back-calculation.
- **Numerical Stress Reconstruction:** The digitised surface coordinates were processed and imported

into Abaqus for finite element grid generation and mesh optimisation. Subsequently, the pyCM program was implemented in conjunction with the CalculiX finite element solver. The experimental deformation profiles were applied as boundary conditions in a reversed elastic model to compute and reconstruct the full 2D hoop residual stress distribution across the weld zone.

Results and Discussion

The hoop residual stress distribution map is shown in Figure 1. From left to right of this figure is the F22 low-alloy steel and S355 low-carbon steel. The hoop residual stress distribution map reveals several key characteristics:

1. Outward from the RFW joint interface, the hoop stress shows a trend in which there is an initial increase followed by a subsequent decrease;
2. The peak hoop residual stresses occur at approximately 6 mm from the weld centre, with the maximum tensile stress within the weld zone reaching approximately 120 MPa;
3. With increasing distance from the weld interface, the residual stress levels gradually decline, transitioning from tensile to compressive stress, with the maximum compressive stress reaching approximately 100 MPa.

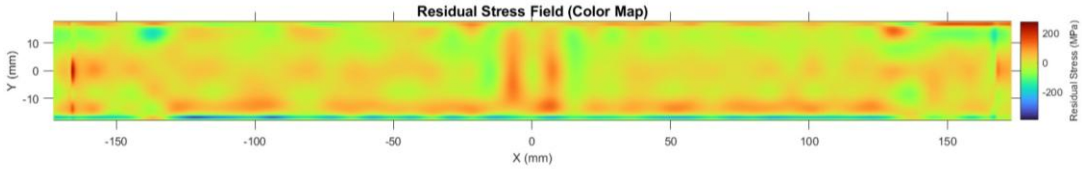

Figure 1. The distribution of hoop residual stress in the RFW joint.

The experimental results obtained from the contour method demonstrate that the residual stress distribution within the rotary friction welded joint satisfies the self-equilibrating characteristic[1]. Furthermore, the profile of the hoop residual stress aligns well with the anticipated M-shaped distribution for ferritic steels[2]. Within the weld centre zone (WCZ), known as the dynamic recrystallization zone (DRZ), the material experiences severe shear deformation and substantial heat generation during welding. This will result in the localised austenitisation of the steel and the development of a fine-grain microstructure. The decomposition of austenite upon subsequent cooling is associated with a dilatational strain that can offset the accumulation of thermal contraction strains, thereby leading to hoop residual stresses at a relatively low level near the weld centerline. Notably, the peak hoop residual stress (120 MPa) is still far below the material's yield strength (approximately 550 MPa). The low levels of residual stress state would improve both the mechanical performance and the fatigue strength of the welded joint [3].

Conclusion

This study demonstrates that RFW with a pre-buttered interlayer offers a highly viable and robust method for joining dissimilar steels. The integration of a low-alloy steel interlayer and RFW provides the possibility to form solid-state welded joints with low levels of residual stress when compared to traditional welding techniques. Future work will focus on optimizing the interlayer thickness and evaluating the variability in toughness across RFW joints.

References

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