NEUTRON RESIDUAL STRESS MAPPING OF REPAIRED SPENT NUCLEAR FUEL WELDED STAINLESS-STEEL CANISTERS

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Abstract: *Stress corrosion cracking (SCC) caused by atmospheric deposition and deliquescence of aggressive compounds such as chloride-containing salts or oxidized sulfur species may pose a potential issue to the extended service life of spent nuclear fuel (SNF) storage canisters. When a chemically susceptible material is exposed to a hostile environment (e.g., coastal salt air) for a sufficient length of time, SCC may occur at locations on the canister which have undergone high tensile residual stress. These locations are often found in weld zones and the heat-affected zones (HAZ) of welded joints. Ideally, these cracks could be repaired by traditional fusion welding techniques, but the highly localized heat input of the repair welding may introduce additional high tensile residual stress and could increase the risk for future SCCs. This paper presents the results of neutron residual stress mapping of as-welded and repaired stainless steel specimens. The as-welded specimens were provided by Sandia National Laboratories from a canister mock-up manufactured using procedures similar to those used for actual canister production. ASME-qualified gas-tungsten arc welding (GTAW) was used to repair the specimens, and post-repair residual stresses were measured using neutron diffraction at the Oak Ridge National Laboratory (ORNL) High Flux Isotope Reactor (HFIR). As-welded and repaired specimen residual stress distributions are evaluated and compared. Significant residual stress profiles were identified from the received as-welded longitudinal weld sample. The generated residual stress profile from neutron diffraction is similar to that of the Sandia residual stress data obtained from deep-hole drilling. The GTAW-repaired specimen showed a notable redistribution in residual stresses and even introduced compressive stresses when compared with the as-welded condition. It appears that groove excavation and the well-controlled GTAW heat input resulted in a stress relief/annealing effect on the metal. The results of this comparison are expected to be used to guide improvements in future repair welding techniques.*

I. INTRODUCTION

Spent nuclear fuel (SNF) canisters are being used for longer periods than initially anticipated, and some of these canisters may become vulnerable to chloride-induced stress corrosion cracking (CISCC) over time. Thus, it is very important to develop, qualify, and demonstrate repair techniques and assess canister material properties and their impact on corrosion to ensure long-term safe storage.

For CISCC to initiate, residual tensile stresses must be of a sufficiently large magnitude. Of specific interest are fusion zones (FZ) and heat-affected regions associated with the welds on the canisters, since the welding process modifies the microstructure of the stainless steel and its resistance to localized corrosion. Further, welding may introduce high tensile residual stresses that can drive the initiation and growth of cracks that may potentially lead to a loss of the canister confinement boundary. High radiation levels, limited access, and space constraints make in situ repairs very challenging and necessitate the development of remotely operated systems for real-time repair. To address this challenge, Oak Ridge National Laboratory (ORNL) researchers are developing a Mobile Examination and Remediation Fixture (MERF) that exploits remote gas-tungsten arc welding (GTAW) to remove and repair cracks from canister surface, if needed[1]. The MERF can reduce the dose rate to operators, minimize repair costs, and ensure the long-term safety of SNF canisters.

Neutron diffraction was performed on the Neutron Residual Stress Mapping Facility (NRSF2) at ORNL's High Flux Isotope Reactor (HFIR) to assess the effect of the new remote repair technique. The NRSF2[2] exploits the large penetration depth of neutrons to measure residual stresses deep within a material by detecting the change in the diffraction pattern of an incident neutron beam, a technique known as "neutron diffraction". In fact, neutron diffraction is the only nondestructive method that can provide a 3-D mapping of residual stress in a material.

The measurements at NRSF2 provided an accurate mapping of residual stresses of an as-welded and repaired specimen. The specimen was provided by Sandia National Laboratories from a mock-up canister representative of actual spent nuclear fuel canisters[3]. Notably, the nondestructive neutrons showed significant residual tensile stress near the longitudinal weld of the canister before repair, in agreement with the results of a destructive test at Sandia National Laboratories that drilled deep holes in the material and likewise found stress to be highest at the weld seam. However, residual stresses after repair were found to be lower than expected, a significant result that paves the way for remote repair of canisters using ORNL's GTAW procedure.

II. APPROACH

Residual stress is generated in metal structures as a result of irregular elastic–plastic deformation during processes such as welding, heat treatment, and mechanical processing. The residual stress distribution can be measured by destructive or nondestructive methods. Destructive methods include shallow and deep hole drilling that typically provide localized variable depth measurements. Nondestructive methods include X-ray or neutron diffraction. Due to sample thickness, X-ray diffraction can only penetration a few µm. In addition, we wanted to avoid any damage to the specimen in order to use it for repair demonstration and subsequent residual stress measurements. For these reasons, neutron diffraction was selected as it is this only technique that can provide a 3-D mapping of residual stresses without damaging the sample.

The specimen was cut from a full-size mock-up stainless-steel (304/304L certified) canister developed by Sandia National Laboratories[3]. Specimen dimensions are 200 mm × 74.7 mm × 16.1 mm. The specimen has a double-V longitudinal weld fabricated using submerged-arc welding. The as-welded specimen is shown in Fig. 1.

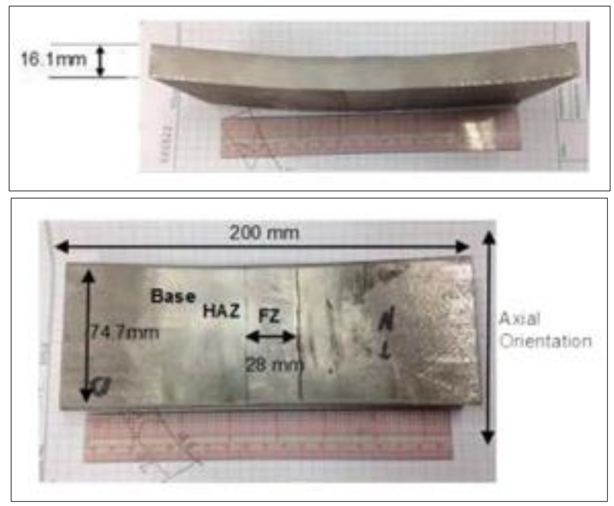
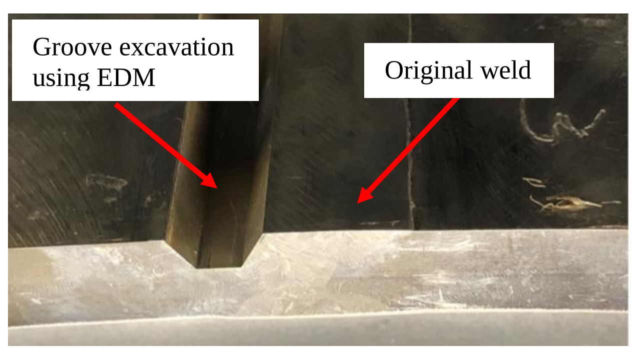


Fig. 1. Main dimensions of specimen used for residual stress measurements.

The as-welded specimen was first sent to NRSF2 for residual stress measurements. Then, a groove was excavated using electro-discharge machining (EDM) to simulate crack removal and the weld metal was deposited using GTAW to simulate a remote repair (Figs. 2 and 3). Once the repair weld was inspected and passed ASME-required tests, the specimen was sent again to NRSF2 for a second residual stress measurement.



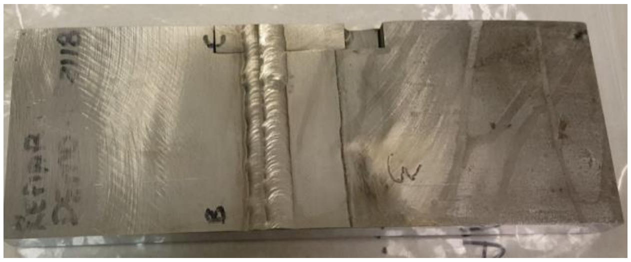


Fig. 2. Groove excavation (top) and repaired specimen (bottom). The GTAW welding passes next to original weld can be easily distinguished.

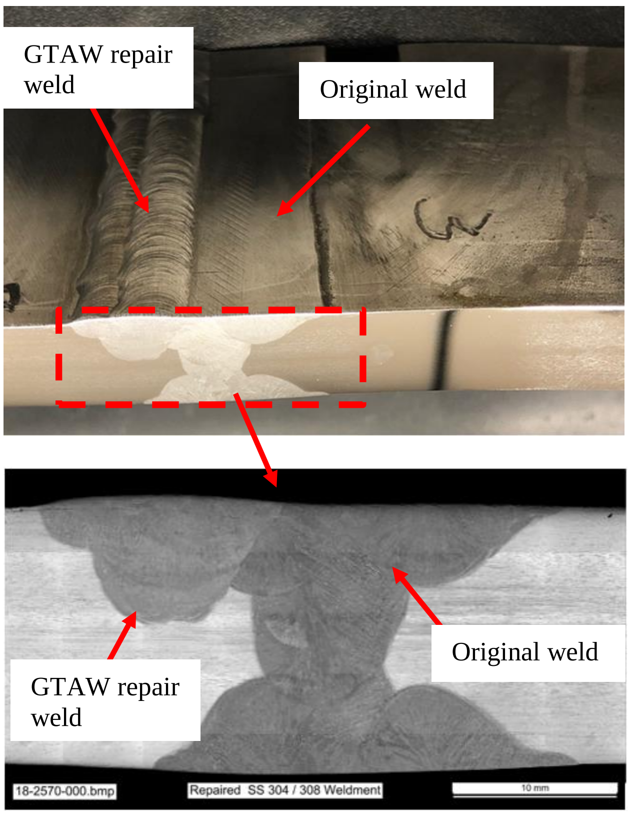


Fig. 3. Repair welding detail (top). Micrograph of specimen where repair and original welding microstructure is revealed (bottom).

III. NEUTRON RESIDUAL STRESS MAPPING MEASUREMENTS

To benchmark the residual stress profile within the received weldment, a nondestructive evaluation using neutron diffraction for determining the residual stress profile within the weld plate was carried out. The NRSF2 highest flux research instrument and support at the HFIR facility provide a unique capability and a state-of-the-art knowledge base for materials science research on measuring strains and strain gradients in materials. A 2θ goniometer with large XYZ/Ω mapping stages and a seven-detector array were provided at NRSF2, as illustrated in Fig. 4. The NRSF2 setup has multiple wavelengths for different materials and can conduct measurements of strains for multiple lattice planes. A 25kN linear electric actuator load frame allows in situ neutron measurement under tensile or/and compressive load. The experiment was completed after 5 days of neutron beam time. In order to increase the strain mapping resolution, five trace lines through the weld sample thickness, shown in Fig. 5, were scanned sequentially by neutron beam. Thus, a longer beam time was required for each targeted position, in order to achieve better resolution of residual strain mapping within the targeted base metal, heat-affect zones (HAZ), and FZ zones.

Neutron beam scanning was performed along five contours at the middle plane of the weldment, as shown in Fig. 6.

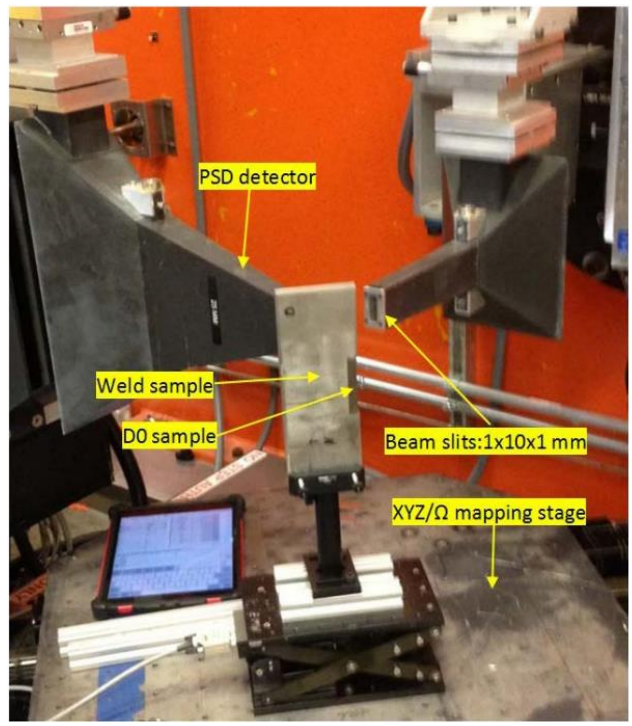


Fig. 4. NRSF2 experimental setup with weld specimen in place.

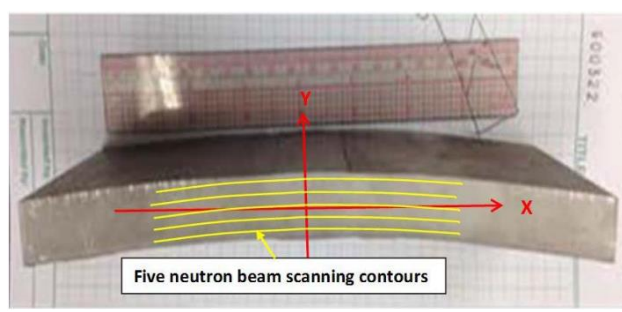


Fig. 5. A schematic of the neutron beam scanning contours at the middle plane throughout the thickness of the weldment.

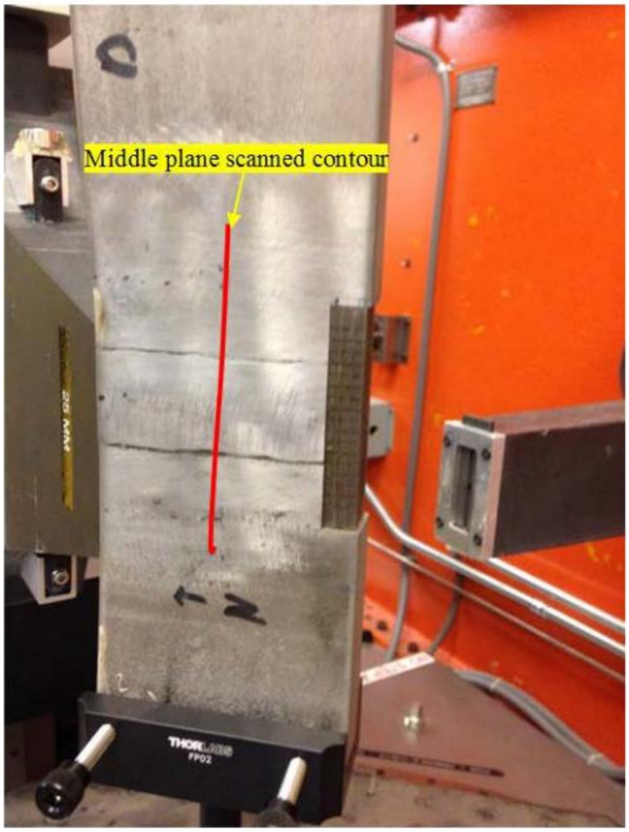


Fig. 6. Middle plane where neutron scanning occurred.

IV. RESIDUAL STRESS EVALUATION

Residual strains in X, Y, and Z directions along the five contours were measured. The measured strains in the radial direction were near zero. Thus, the plane strain condition was justified to calculate the weldment's strain and stress accordingly in the hoop and axial directions. The details of the test results for the hoop (circumferential) and axial (longitudinal) residual stresses profiles for as-welded and repaired specimens are shown in Figs. 7–10. In Figs. 9 and 10, the Sandia residual stress measurements (SNL, 2016) using deep hole drilling are shown for comparison.

It is observed that the maximum tensile residual stress for the as-welded specimen is 340 MPa. The maximum residual stress is located in FZ and oriented in the axial direction. It is also much higher than the yield stress of 200 MPa for the 304L. Based on Lincoln Electric[4], the yield stress and ultimate tensile strength for the 308/308L welding wire are 380 MPa and 565 MPa, respectively. Because of the local metallurgical process, weld zone material yielding strength may be higher than that of the 304L base metal and the 308L welding wire. The residual axial tensile stress also indicates that tensile stresses exist throughout the thickness of the weldment in the FZ.

The maximum hoop tensile residual stress has a value of 283 MPa and is located in FZ near the outer diameter surface. It also indicates that tensile stresses exist throughout the thickness of the weldment in FZ. The residual stress profiles estimated from ORNL neutron diffraction measurements and Sandia deep hole drilling approach are in good agreement, although there are differences in profile shape. This can be attributed to the fact that the received weldment sample was cut from the parent mockup canister wall, and a significant redistribution and relaxation of residual stress may have occurred during the cutting process.

For the repaired specimen, the maximum axial tensile residual stress has been increased by ~65 MPa to 406 MPa (from 340 MPa on the as-welded), and there is a shift in position. However, the full profile is not tensile through-thickness, and there are regions where compressive stresses have been introduced. Similarly, for the repaired hoop, residual stresses have been significantly reduced as compared with the as-welded residual stresses. This indicates that the repair could redistribute the stresses in a beneficial way.

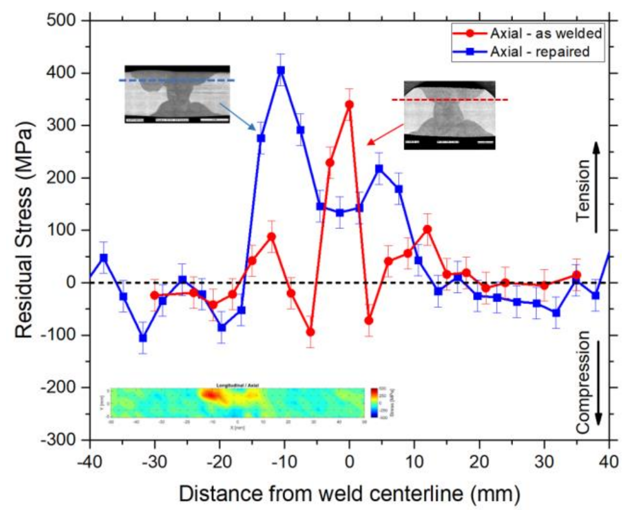


Fig. 7. Longitudinal/axial residual stress profiles perpendicular to the weld direction for as-welded and repaired specimen. The profile shown is located at the slice where the maximum stress is observed, ~3.3 mm from outer diameter surface. The contour map for repaired specimen is also shown.

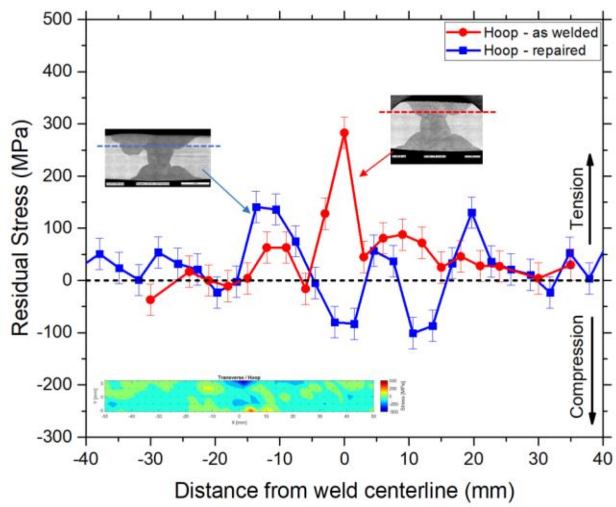


Fig. 8. Transverse/hoop residual stress profiles perpendicular to the weld direction for as-welded and repaired specimen. The profile shown is located at the slice where the maximum stress is observed, ~3.3 mm from outer diameter surface. The contour map for repaired specimen is also shown.

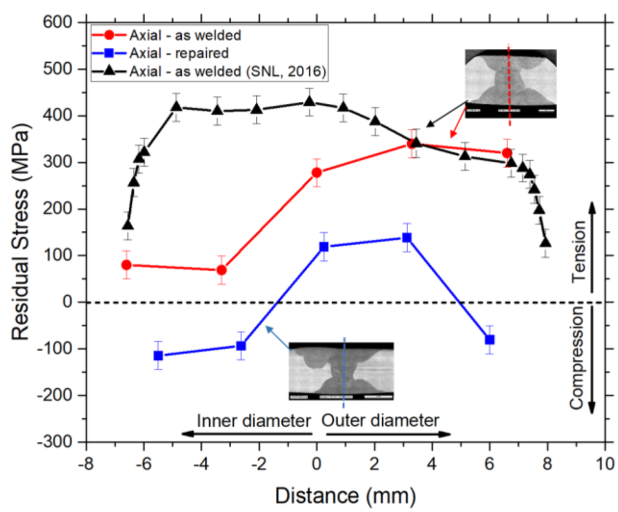


Fig. 9. Longitudinal/axial residual stress profiles through thickness (parallel to weld) for as-welded and repaired specimen. The profile shown is located at weld centerline.

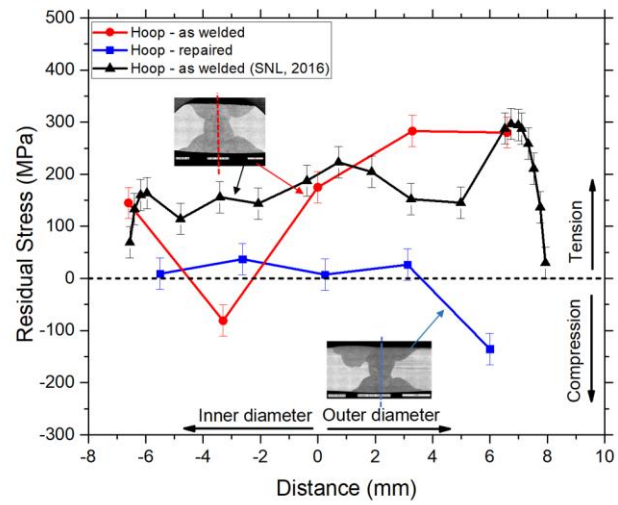


Fig. 10. Transverse/hoop residual stress profiles through thickness (parallel to weld) for as-welded and repaired specimen. The profile shown is located at weld centerline.

ACKNOWLEDGMENTS

This material is based upon work supported by the US Department of Energy, Office of Nuclear Energy, under contract number DE-AC05-00OR22725. A portion of this research used resources at the High Flux Isotope Reactor, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory. The authors would also like to thank Paris Cornwell for his technical assistance in the experiments, Charles Bryan from Sandia, who provided the specimen, and Doug Kyle who performed the repair welding.

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