LAMBDA Technologies Group

Diffraction Notes

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ENHANCING NUCLEAR REACTOR LONGEVITY: CONTROLLING RESIDUAL STRESS AND COLD WORK IN TRADITIONAL AND MODULAR SYSTEMS

ADDRESSING THE NEED FOR ENERGY THROUGH NUCLEAR POWER

Over the past two decades, electricity demand in the United States has stayed relatively stable, but it is now rising as technology companies accelerate the development of advanced artificial intelligence systems. As both the U.S. and countries worldwide ramp up efforts to secure reliable, low-carbon energy sources, nuclear power is attracting renewed interest. Today's nuclear options include not only traditional large-scale power plants, but also newer modular and micro nuclear reactor technologies. These smaller reactors address some of the challenges of conventional plants—such as high upfront costs, lengthy construction periods, and site limitations—by offering compact, factory-built units that can be quickly deployed and easily scaled to fit a variety of energy needs. Their reduced size makes them suitable for locations where large plants are not feasible, such as remote communities, smaller power grids, or areas with limited infrastructure. They also present an opportunity to convert aging fossil fuel sites into sources of clean, emissions-free electricity.

ENHANCED SAFETY AND LONGEVITY THROUGH MATERIAL CONTROL

Regardless of the reactor size and type, reactor fabrication requires machining, welding, and fit-up of high temperature corrosion resistance alloy components. Alloys, including austenitic stainless steels and nickel-base 600 and 690, used for nuclear reactors are highly sensitive to cold working and weld shrinkage and can often be left in a state of high tensile residual stress. Uncontrolled tensile residual stresses introduced during fabrication and assembly can combine with operational stresses to exceed critical thresholds, leading to stress corrosion cracking (SCC), fatigue failure, or distortion in high-radiation environments. Accurate measurement and control of residual stresses and cold work are critical for ensuring the structural integrity and longevity of nuclear reactor components.

Strategically introducing beneficial residual stresses and controlled cold work enhances safety and performance in nuclear systems. Compressive residual stresses, induced via mechanical surface treatments, counteract operational tensile stresses, significantly improving fatigue resistance and SCC immunity. This creates a safe state where even damaged components resist crack propagation under cyclic loads.

EXAMPLES OF RESIDUAL STRESS AND COLD WORK IN REACTOR COMPONENTS

Lambda has significant experience in measurement and optimization of residual stress and cold working in nuclear applications. Measurements have been conducted on a variety of nickel-base alloys, austenitic stainless steels, cobalt-base alloys, and zirconium alloys.

Below are examples of residual stress measurements collected on expanded steam generator tube joints, U-bend tubing, and heater sleeve mockups.

Roller Expanded Tube-to-Tubesheet Mockup:

A tube-to-tubesheet expanded joint is a critical mechanical connection in nuclear reactor steam generators that secures the thin-walled tubes, which carry the primary coolant to the thicker tubesheet. Expansion is usually achieved mechanically by plastically deforming the tube so it tightly fits into the tubesheet hole.

Sometimes, expansion is combined with welding for additional strength and leak tightness. The expansion process induces high residual stresses, especially in the transition region between the expanded and unexpanded tube. When coupled with water chemistry typical in nuclear environments, these stresses can drive SCC on the primary and secondary side of the tube.

Examination of tube-to-tubesheet steam generator tubing sections removed from the Davis-Besse Nuclear Power Station identified significant axial primary water stress corrosion cracking (PWSCC). Residual stress and cold work evaluations demonstrated that rerolling after stress relief raised both residual stress and cold work levels, thereby increasing the tube's susceptibility to cracking. A subset of the residual stress results is presented in Figure 1, together with a schematic of a tube-to-tubesheet mockup. The measurements revealed high tensile residual stresses within the expansion transition zone. Additional details of this program are provided in the full paper.

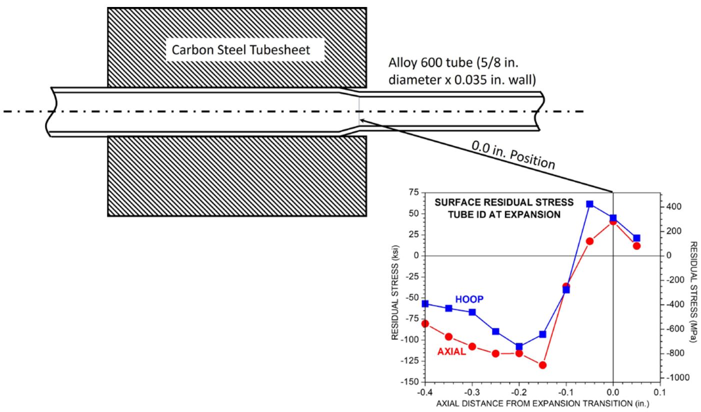

Figure 1: Schematic of Roller Expanded Mockup With Surface Residual Stress on ID of Expanded Tube Revealing High Tensile Residual Stresses in Expansion Transition Region

U-Bend Tubing:

U-bend tubes are essential components in nuclear reactor systems, serving as the primary heat transfer surfaces within steam generators of Pressurized Water Reactors (PWRs) and similar designs. Their inverted U-shape allows reactor coolant to flow up one leg and return down the other, efficiently transferring heat from the hot primary coolant to the cooler secondary water, generating the steam required to drive turbines.

These tubes are prone to several failure mechanisms due to their geometry, material condition, and demanding operating environment. A common concern is SCC, particularly at the U-bend apex and other regions where high residual stresses arise from bending and fabrication processes.

Residual stress measurements were performed using x-ray diffraction on the outer diameter of both straight and U-bend tubes. An example of the collected data is shown in Figure 2, with surface residual tensile stresses observed near the neutral axis and on the extrados of the bend. Additional technical details can be found in the full report.

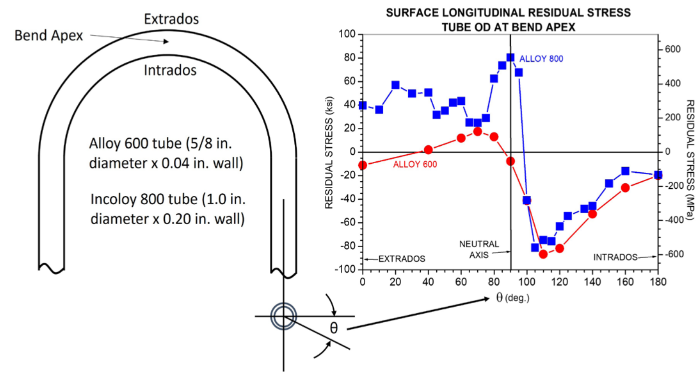

Figure 2: Schematic of U-bend Tubing with Surface Residual Stress on OD at Apex of Bend Showing High Tensile Residual Stress Near Neutral Axis

Alloy 600 J-Weld Penetration:

A J-weld (or J-groove weld) penetration refers to a partial-penetration weld configuration used to secure nozzles or tubes, particularly for control rod drive mechanisms (CRDMs) and instrumentation, to the upper head of a nuclear reactor pressure vessel. The weld derives its name from the J-shaped groove created at the point where the nozzle enters the vessel head. This geometry is designed to provide a robust mechanical attachment and maintain the integrity of the pressure boundary between the vessel and its penetrations. Alloy 600 and its welds (often using Alloy 82/182 filler) are susceptible to SCC, particularly at the interface exposed to hot, pressurized reactor water. Cracking can initiate at the weld root or heat affected zone (HAZ) and propagate, leading to leaks or compromising structural integrity.

Intergranular SCC was reported in a partial J-weld penetrations of Alloy 600 heater sleeves and pressurizer nozzles in nuclear pressure vessels. Early assessments showed that machining alone generated residual stresses well below the threshold required to initiate SCC. Mockup specimens were fabricated using Alloy 600 sleeves welded into steel blocks. These specimens were examined with mechanical strain gauging and x-ray diffraction to measure residual stresses and assess the degree of cold working on the inside diameter surface.

A subset of the residual stress results is shown in Figure 3. The investigation showed that the interaction between machining and weld shrinkage produces complex and highly localized distributions of residual stress and yield strength. These stress distributions were found to vary sharply with position, leading to small but critical regions of tensile residual stress. Such localized tensile zones increase susceptibility to intergranular SCC, demonstrating the importance of detailed residual stress characterization during fabrication. The full set of results can be found in the technical paper.

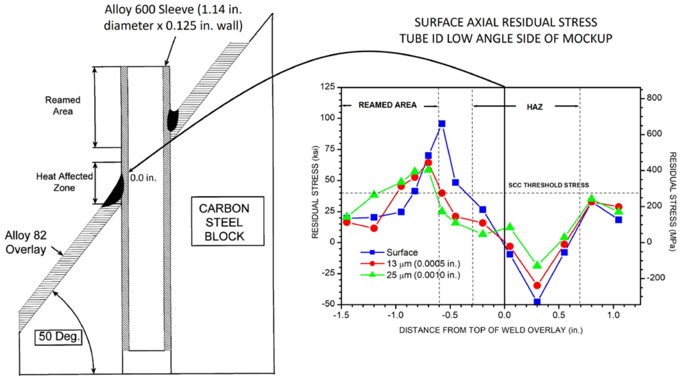

Figure 3: Schematic of J-weld Penetration with Surface and Subsurface Axial Residual Stress on ID Showing High Tensile Residual Stress Well Above the SCC Threshold

Lambda is ideally suited to measure, optimize, and develop surface treatments for modular reactors.

Lambda's comprehensive nuclear industry experience includes decades of collaboration with major utilities, national laboratories, and nuclear component manufacturers. Lambda's unique combination of world-class analytical capabilities, advanced surface treatment technologies, finite element modeling expertise, and deep understanding of nuclear material failure mechanisms, all backed by rigorous ISO 9001:2015 and AS9100 certifications, makes us the ideal technical partner for companies seeking to optimize residual stress fields, eliminate SCC risks, and develop novel surface enhancement solutions critical for the long-term reliability and safety of next-generation nuclear energy systems.