MRP and US Industry Developments for Stress Analysis of Nickel Base Alloy Components

Open Meeting on Stress Analysis in Nickel-Base Alloy Component Structures

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Overview

- Summary of industry activities on stress analysis and fracture mechanics evaluations of Ni base materials
- Welding residual stress analysis model validation
- Additional specific topics of interest
  - Piping butt welds and weld overlays
  - Alloy 52/152/52M construction-related weld flaws
  - Fracture mechanics evaluations of circumferential flaws in nozzle penetrations

Industry Activities on Stress Analysis
Background

- Since 2001, stress and fracture mechanics analyses have played key roles in industry activities regarding PWSCC of Ni base alloy components
  - Safety assessments of RCS components
    - RPV top and bottom head
    - Pressurizer
    - Piping butt weldments
  - Inspection activities
    - Demonstrate sufficient coverage per EA-03-009
    - Presumed flaws in nozzle regions masked from coverage
  - Repair evaluations
    - Presumed remnant flaw following repair

Industry Activities on Stress Analysis
Safety Assessments

- Welding residual stress analysis in combination with fracture mechanics calculations form inputs to industry safety assessments on PWSCC
- RPV closure head and bottom head safety assessments
  - Risk of nozzle ejection due to circumferential cracking
    - Resid stress plus Newman-Raju for calculated crack tip SIF, input to CGR
  - Risk of excessive wastage resulting from leakage due to axial cracking
    - Crack opening displacement calculated from welding residual stress model
    - Resid stress plus Newman-Raju for calculated crack tip SIF, input to CGR

Industry Activities on Stress Analysis
Safety Assessments

- Pressurizer heater sleeve JCO
  - Circumferentially oriented cracking in heater sleeve found in 2003
  - Justification for Continued Operation considered crack growth rate of a circumferential flaw beyond weld
    - Fracture mechanics included stress redistribution with crack growth
    - Response to RAIs provided in-depth discussion on justification for fracture mechanics methodology
- Butt weldment safety assessment
  - Resid stress plus Newman-Raju for calculated crack tip SIF, input to CGR

Industry Activities on Stress Analysis

Inspection Activities

- Plants set inspection coverage requirements based on EA-03-009
  - Welding residual stress analysis used to determine location of 20 ksi stress contour relative to weld elevation
  - ASME Code Case N-729 adoption for inspection coverage
- Flaw evaluations for small flaws or limited regions masked from inspection coverage
  - Flaw evaluations typically performed using welding residual stresses plus Newman-Raju fracture mechanics
  - Acceptable methods described in Appendix I to N-729
  - Requires relief request since EA-03-009 is not met

Industry Activities on Stress Analysis

Repair Evaluations

- Nozzle repair evaluations typically include Section XI evaluations of a remnant flaw
  - Half nozzle weld repair leaves original J-groove weld and/or lower nozzle piece
  - Inlay and/or overlay repairs leave flaw in place, in nozzle and/or in weld
  - Section XI calculations performed using welding residual stress in presence of operating transients
  - Flaws in weld hypothesized to be entire planar extent of weld region
    - Welds not inspected, high dose to grind out original weld material
  - Calculated crack tip SIF for flaw (including residual stress) typically high relative to K_{Ia} or K_{Ic}
- Relief request required to perform EPFM evaluation of flaw in head
  - Code Case N-749 in process to replicate methods commonly used for EPFM evaluation

Welding Residual Stress Model Validation
General Model Background

- Independent welding residual stress models have been developed by many industry and regulatory consultants
- DEI model originally developed in 1990 to simulate J-groove attachment welds of pressurizer heater sleeves
  - Expanded to include other nozzle penetrations with J-groove welds since 1991
  - Expanded to butt welds in 1995 (stainless steel) and 1997 (Ni base alloys)
  - Expanded to various nozzle repair methodologies since 2002
- Consistent analysis methodology has been used since initial development of welding residual stress model
  - Thermal model simulates weld heating and cooling using idealized target temperatures for weld center and HAZ
  - Structural model uses temperatures from thermal model to simulate thermal expansion followed by weld strengthening with cooling

Welding Residual Stress Model Validation

Model Background

- Welding residual stress calculations have been performed for a variety of Ni base alloy welds
- J-groove welds for a wide range of nozzle penetration types (e.g., CRDM, heater sleeve, etc.)
- Piping butt welds for sizes ranging from RPV outlet to 1-inch diameter nozzles
- All major nozzle repair types
  - Nozzle left in place (ID inlay, J-groove weld overlay)
  - Nozzle partially removed (internally or externally)
    - ID temper-bead half nozzle weld repair
    - Outer surface weld pad buildup with new J-groove weld attachment

Welding Residual Stress Model Validation
Key Reports

- *PWSCC of Alloy 600 Materials in PWR Primary System Penetrations*, EPRI TR-103696, July 1994.
  - Describes development of welding residual stress model properties
  - Compares model results to measured residual stresses from mockups
- *Evaluation of Crack Growth in BWR Nickel Base Austenitic Alloys in RPV Internals (BWRVIP-59),* EPRI TR-108710.
  - Shroud support welds examined (butt weld type geometries)
  - Model results compared to measured residual stresses from actual welds
- *Proceedings: 1992 EPRI Workshop on PWSCC of Alloy 600 in PWRs*. December 1993. EPRI TR-103345.
  - Overview of industry at a time when many models were being developed

Additional Topics of Interest

Butt Welds and Butt Weld Overlays

- Flaw indications of any size almost always requires a repair
  - Crack growth rates in weld material conservatively assumed to be 5 to 10 times higher than base metal
  - CGR plus stress distribution leads to predicted crack growth requiring a repair for even smaller flaw sizes
- Volume dilution of first layer of butt weld overlay typically leads to throwing away the first layer
- Evaluation of flaws in overlay repair
  - Currently no relief requests are allowed for flaws in the overlay
    - Prolongs plant outage to repair overlay flaws that would be acceptable using IWB-3600 Evaluation
  - Postulated flaws required in uninspectable volume masked by laminar flaw

Additional Topics of Interest

Butt Welds and Butt Weld Overlays

- An MRP-sponsored project on mockup of Preemptive Weld Overlay (PWOL) was completed in early 2006
  - Performed by Structural Integrity Associates
- This project included residual stress analysis and measurements, pre- and post-overlay, on a geometry resembling a PZR surge nozzle.
- The analytical-experimental comparisons found reasonable agreement
- A final EPRI report is in the publication process.

Additional Topics of Interest

Weld Flaws in Alloy 52/152

- As discussed in MRP-115 (Section A.7.2), recent investigations appear to provide convincing evidence that Alloy 82/182 weld defects (e.g. hot cracking) do NOT play a significant role in PWSCC initiation and propagation:
  - Mills and Brown observed extremely few hot cracks and ductility-dip cracks and concluded, therefore, that hot cracking and ductility-dip cracking had very little or no effect on CGRs.
  - Thomas et al. have performed detailed microscopic characterization work on cracked Alloy 182 samples from the Ringhals Unit 4 plant in Sweden showing no significant interaction between stress corrosion cracks and hot or ductility-dip cracks.
  - In a recent MRP-sponsored experimental program (MRP-107) using Alloy 182 weld material formed into pressurized test capsules, there was also reported no significant effect of hot or ductility-dip cracks on the PWSCC process.
  - These results are not surprising if one considers the fundamental differences in the current mechanistic understanding of PWSCC compared to the mechanisms of hot cracking and ductility-dip cracking.

Additional Topics of Interest

Weld Flaws in Alloy 52/152

- However, relatively large and sharp weld defects such as some weld lack of fusion regions may have the potential to promote PWSCC by creating a local stress concentrator and a high local crack tip stress intensity factor.
  - Lack of fusion areas at the weld wetted surface would be expected to be detected during pre-service NDE. Subsurface defects would necessarily have to become wetted by the primary coolant through some cracking process before they could grow via PWSCC.
  - It is possible that at least some of the cracking observed in Bottom Mounted Instrumentation nozzles at South Texas Project Unit 1 in 2003 may have been promoted through the wetting of subsurface weld lack of fusion areas.
- The conclusions regarding Alloy 82/182 may be applied to the concern for cracking in Alloy 52/152.

Additional Topics of Interest

Circumferential Flaws in Nozzles

- Comparison of DEI results with EMC2 and other results for inclined circ flaws in CRDM outer row nozzle