Primary Water Stress Corrosion Cracking (PWSCC) in Bimetal Nuclear Pipe Welds – Analysis Considerations

by

F. W. (Bud) Brust – Battelle Columbus
Paul Scott – Battelle Columbus

ABSTRACT

There have been incidents recently where cracking has been observed in the bi-metallic welds that join the hot leg to the reactor pressure vessel nozzle. The hot leg pipes are typically large diameter, thick wall pipes. Typically, an inconel weld metal is used to join the ferritic pressure vessel steel to the stainless steel pipe. The cracking, mainly confined to the inconel weld metal, is caused by corrosion mechanisms. Tensile weld residual stresses, in addition to service loads, contribute to PWSCC (Primary Water Stress Corrosion Cracking) crack growth. In addition to the large diameter hot leg pipe, cracking in other piping components of different sizes has been observed. For instance, surge lines and spray line cracking has been observed that has been attributed to this degradation mechanism. Here we present some models which are used to predict the PWSCC behavior in nuclear piping. This includes weld model solutions of bimetal pipe welds along with an example calculation of PWSCC crack growth in a hot leg. Risk based considerations are also discussed. Three dimensional effects are considered here as well.

INTRODUCTION

PWSCC is an issue that has received attention in the nuclear power industry of late. The purpose of this paper is to study the cracking behavior in bimetallic welds of the type used in the VC Summer plant and other typical bimetal pipe joints in PWR plants. The results of an investigation of some of the causes of PWSCC in the bimetallic piping are also addressed here. First, the weld process is modeled for several bimetal pipe welds. This modeling includes buttering of the pressure vessel nozzle with inconel 182 followed by post weld heat treat of the nozzle. After the heat treat, which significantly reduces the residual stresses caused by buttering, the weld passes joining the nozzle to the stainless steel pipe are deposited. This is followed by a hydro-test (at room temperature) and then service loads are applied. All of the above processes are included in the fabrication model. The importance of including all of the history of fabrication in the analysis is clearly shown. Weld repairs can adversely affect the residual stress distribution in bimetal pipe and repair cases are considered here as well. Here the focus is on surge line size pipe. Reference [1] considered different pipe sizes as well as probabilistic effects.

WELD ANALYSIS PROCEDURE

Most computational weld models which are available commercially are mathematics and physics based models. The following is a description of the VFT^{TM} (Reference [2]) code, but other codes are similar (VFT^{TM} is commercially available now). There are two main analysis modules, the thermal model and the structural model, that make up the weld process simulation models. The thermal model (CTSP) was developed based on superposition of complicated closed form analytical expressions and developed heat source theories. CTSP is very rapid and is used for large problems. Numerical thermal solutions based on a modification of Goldak theory are also used. The numerical solutions were used here since the analyses were made for axis-symmetric pipe welds. It is generally accepted that axis-symmetric analyses of girth welded pipe welds tend to produce conservative residual stress predictions compared with full three dimensional solutions. The structural model (UMAT) was developed based on ABAQUS commercial finite element codes by implementing a special materials module, which includes a constitutive law that permits stress relief due to weld melting/re-melting effects, strain hardening effects, large deformation mechanisms, rapid weld metal deposition features, phase transformation plasticity (based on the Leblond model [Ref. 3]), etc. It is noted that experience clearly suggests that uncoupled thermal/structural solutions for weld problems is accurate in all weld models. Many more details of the VFT code, with many example solutions can be found in References [4 – 7] and in the many references therein.

PIPE GEOMETRY

Most bi-material welds consist of welding a ferritic pressure vessel steel nozzle to a stainless steel pipe with a Nickel alloy weld metal. The geometry used for the surge line analysis was obtained from the literature and represents a typical PWR surge line. Many pipe geometries can be found in service and the residual stresses do vary significantly between the different pipes. As is typical of bimetallic welds that were used in nuclear power plants, the ferritic nozzle steel (A516 Grade 70 here but often A508) is first buttered with Alloy 182/82 weld metal and stress heat treated before making the weld. The heat treat consists of heating the nozzle to 593 C (1,100 F) and holding for four hours. The corresponding stress relaxation is modeled via a creep algorithm within the material user routine. After the weld has cooled to room temperature, a hydro-test is modeled. The hydro-test load consists of applying an internal pressure of 1.4 times the normal operating pressure of 15.5 MPa (2,250 psi), i.e., 21.7 MPa (3,150 psi), and then releasing. Because the surge line geometry is very thick, the hydro-test does little to alter the weld induced residual stresses. The weld residual stresses are the operating temperature residual stresses (324 C [615 F] for the bimetal welds and 288 C [550 F] for the stainless steel pipe). The geometry used for the surge line analysis has an inner radius of 128 mm (5.03 inches), an outer radius of 170 mm (6.68 inches) with a wall thickness of 42 mm (1.65 inches). The mean radius to thickness ratio (R_m/t) for the surge line is 3.5. This geometry is a rather thick pipe which leads to complicated weld residual stress patterns.

MATERIALS

The PRO-LOCA code (References [8-10]) is a probabilistic code which is being developed to permit risk informed predictions of loss of coolant accidents given certain inputs. For probabilistic predictions of primary water stress corrosion cracking (PWSCC), the weld residual stresses for the mean, plus two sigma, and minus two sigma material property data are required. For weld residual stress analyses, the material properties are required at temperatures that range from room temperature to melting. Here we only consider the mean properties (see [1] for probabilistic considerations). The temperature dependent material properties used for all three materials in the bimetal weld can be found in [1] and [10].

RESULTS OF BIMETAL WELD SURGE LINE ANALYSIS

One of the key drivers in PWSCC crack growth are tensile weld residual stresses. These tensile stresses react with the water chemistry and temperature to cause crack growth. For bimetal welds in pressurized water reactors (PWRs), primary water stress corrosion cracking (PWSCC) is a major concern. Referring to Figure 3, PWSCC crack growth in the Alloy 182/82 weld material or buttering material is the main concern. In terms of PWSCC, stress solutions were developed for the butter material and the weld metal itself since the PWSCC crack growth constants may differ in these regions because of the way the weld metal is deposited in buttering compared with the butt weld. Recall that the butter material is post weld heat treated prior to welding which may affect the microstructure and thus the PWSCC growth rates. Moreover, if a fluid path exists to the ferritic steel (A516 Grade 70 here), which may occur if the cladding is damaged or if PWSCC grows through the butter material, corrosion growth in the nozzle is possible. In the heat affected zone (HAZ) of the stainless steel (Figure 1), stress corrosion cracking is possible as well. The PRO-LOCA computer code is being developed to be as general as possible. As such, stress solutions were developed for all potential stress corrosion crack growth paths in all materials. Here, however, we focus on the inconel weld material. Results in other materials can be found in Reference [10].

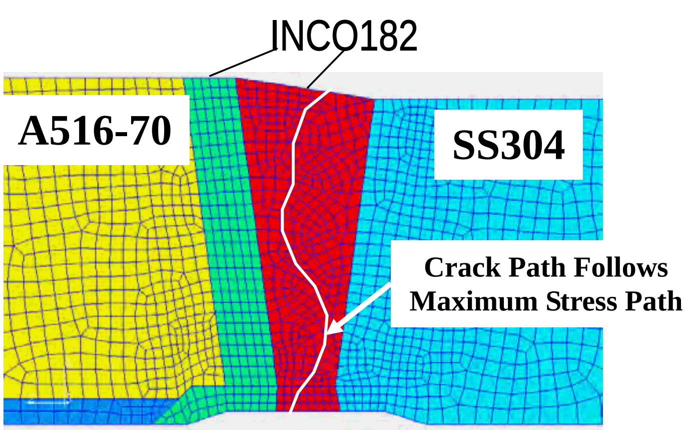

Figure 1 Crack path following maximum stress in

In summary, weld residual stress solutions were developed for the (1) butter and (2) weld material (both axial and hoop residual stresses) for circumferential and axial crack growth predictions. In addition, weld residual stresses were tabulated in the A516 Grade 70 nozzle material adjacent to the butter region (axial stresses) and in the HAZ region of the stainless steel. This permits all potential forms of stress corrosion cracking to be considered in bimetal welds.

The PWSCC or SCC crack path will follow the maximum stress locations as the crack proceeds through the thickness of the pipe. This is illustrated in Figure 1 where a schematic of a crack growing through the Alloy 182/82 weld material is shown. As such, for each of the four locations (discussed in the previous paragraph) the maximum stress through the thickness is compiled. Because of this, axial stresses may not be balanced through the pipe thickness (as they should since the ends of the pipe are free for the weld

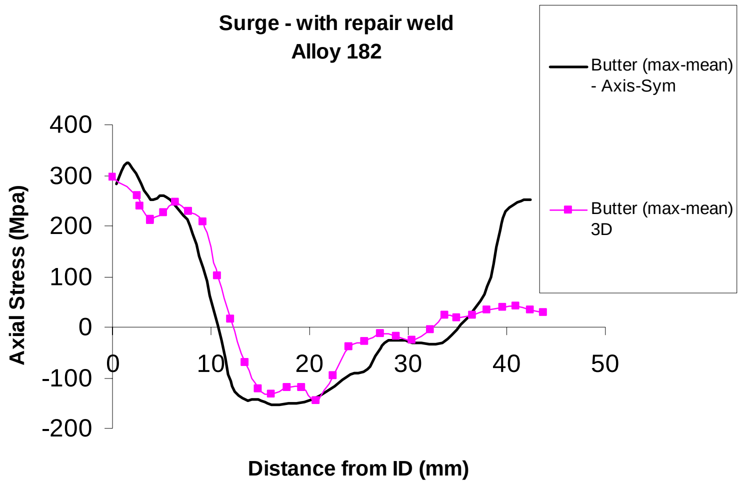

Figure 2 Surge Line Residual Stresses.

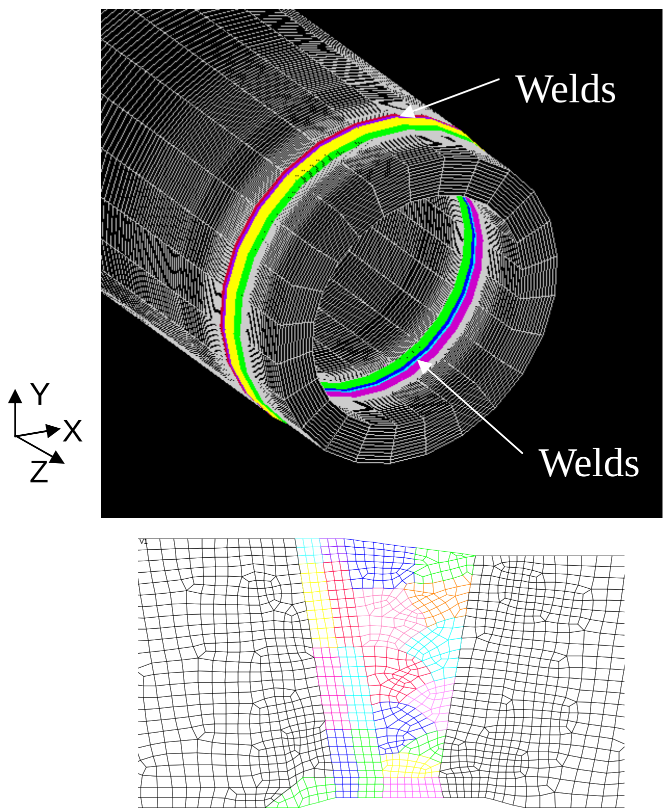

Figure 3 Bimetal Weld Geometry.

analysis). Keep this in mind when viewing the stress plots. Of course, the hoop stresses do not have to be self equilibrated.

In most cases, the bimetal welds in the larger diameter pipe were completed and then the inner diameter (ID) region was ground out (~15% of the wall thickness) and a weld bead re-deposited. It turns out that this repair weld typically increases the tensile residual stresses in the ground out region. This effect is especially detrimental in thick pipe such as in the surge line considered here. The effect of the ID repair weld is dramatic. The maximum tensile stresses near the ID are increased along with increasing the maximum value of compressive stresses near mid thickness. The tensile stresses are markedly increased near the inner surface for the weld repair case. This of course suggests that PWSCC and IGSCC growth rates will increase as well. The hoop stresses are also significantly increased by the ID repair weld. The stresses in the A516 Grade70 and the stresses in the Type 304 stainless steel material are also altered by the repair weld, but to a lesser extent.

The axial stresses for the surge line/pressurizer nozzle weld are shown in Figure 2 in the butter region. Figure 2 illustrates the residual stresses using an axis-symmetric solution and a full three dimensional solution. The three dimensional results are at a location 180 degrees from the start/stop location of the welds. The weld geometry for the surge line is shown in Figure 3. The assumption of axis-symmetry is rather good for locations away from start/stop locations but is drastically different near these locations.

Likewise, bimetal weld residual stresses were obtained for the other materials and implemented into the PRO-LOCA code, including the spray line (please see Ref. [1, 10] for details). We emphasize that the pipe weld procedures and geometries do vary significantly from plant to plant. As such, the solutions presented here are understood to be representative for a class of PWR bimetal pipe weld. For accurate PWSCC crack growth predictions, the actual pipe weld of concern should be modeled, including the precise details of all repairs. PWSCC growth in PWR bimetal pipe welds continues to be a concern in the worldwide nuclear industry.

During construction of nuclear piping systems in nuclear power plants, often repair welds were necessary if a weld defect was found. This was typically performed by grinding out the damaged region of the weld and then re-depositing the weld metal again. Figure 4 illustrates this procedure. Here, after deposition of the 9 butter passes (see bottom of Figure 3), and 11 weld passes, the 360-degree grinding operation is modeled (about 15% of the thickness is removed). Then two more passes are deposited. After this, the 90-degree repair is modeled as seen in Figure 4. A 26 % through the thickness amount of material is removed and re-deposited with 4 new passes. The repair here was designed such that the center of the 90-degree

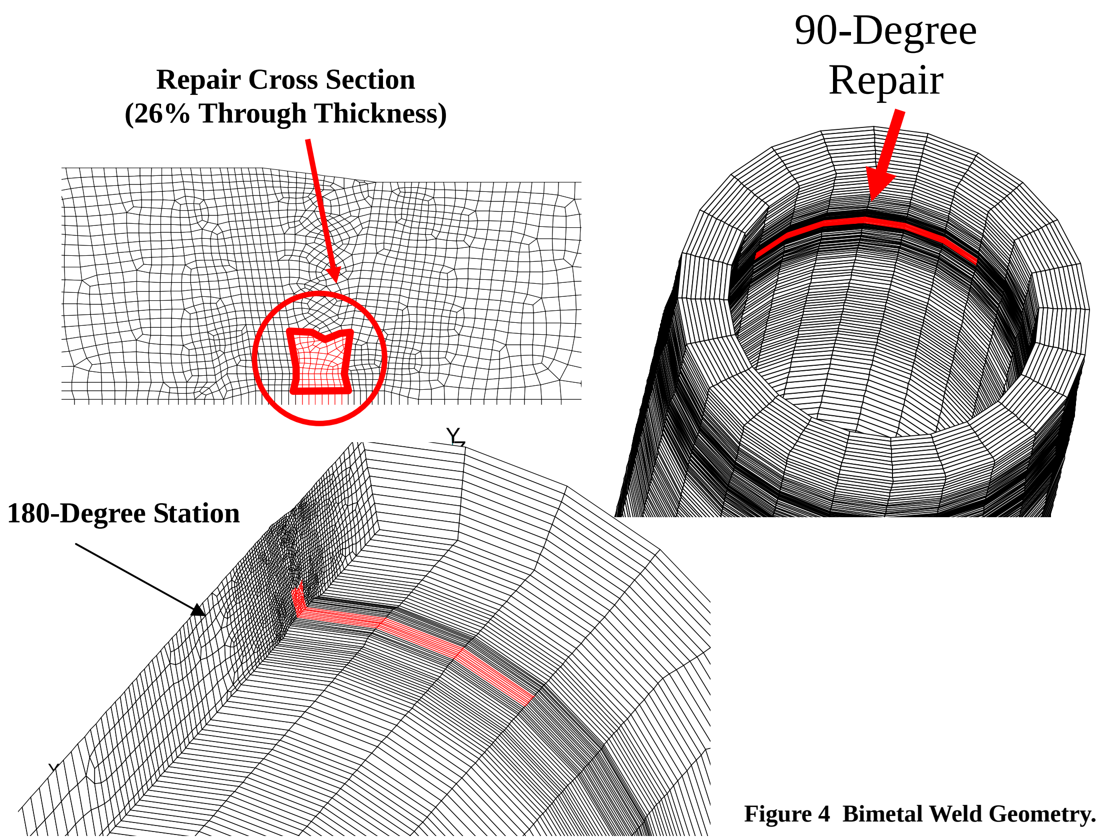

Figure 4 Bimetal Weld Geometry.

repair coincided 180 degrees from the original start/stop location of the pipe as seen in Figure 4. The effect of the repair is dramatic. Reference [11] showed repair effects on pipe weld also but shell elements were used and the results are not as accurate as these. The three dimensional solution had 55,000 elements and took four days to run on a two processor machine using ABAQUS. It is easy to restart the analysis after the first 22 welds and model different repair welds. This is ongoing and will be presented in the future.

Figure 5 shows the corresponding axial weld residual stresses in the pipe at a section at the center of the 90-degree repair. The white outline indicates the butter and weld boundaries. Also the pipe ID location is marked with white boundaries where one can see the bevel geometry. This was done to make it easier to see since this is a cross section of a three dimensional plot. It is clear that the weld residual stresses are strongly affected by the repair. Note that this is at the 324C operating temperature. Finally, Figure 6 illustrates the residual stress distribution in the butter for the axis-symmetric and 3D solution without the 90-degree repair, and the 3D solution with the 90-degree repair. The repair increases the depth of the tensile residual stresses but the magnitude is not increased significantly.

PRIMARY WATER STRESS CORROSION CRACK GROWTH ANALYSIS

With a library of weld residual stresses available, it is possible to make a probabilistic 'Loss of Coolant Accident' (LOCA) using the PRO-LOCA code ([8, 9]. The surge line solutions presented here are being implemented into PRO-LOCA. For the current version of the PRO-LOCA code, the Monte-Carlo simulation (MCS) procedure is used in predicting the probabilities. Monte-Carlo simulation is a numerical scheme which solves a statistical problem by generating multiple deterministic scenarios of a model by repeatedly sampling values from the probability distributions for the uncertain variables and observing what fraction of the scenarios satisfy a relevant performance function or functions. The method is useful for obtaining numerical solutions to problems that are too complicated to solve analytically and can be used for any number of random parameters.

In PRO-LOCA, only one critical location or node was analyzed during each run. For this code, one node consists of one circumferential section of the pipe at any location in the piping system. Note that longitudinal cracking is not analyzed by this version of PRO-LOCA. If the user required the leak probability for the entire system, individual runs for each location were required and the

3D Solution 180-Degree Location (After 90-Degree Repair)

3D Solution 180-Degree Location (No 90-Degree Repair)

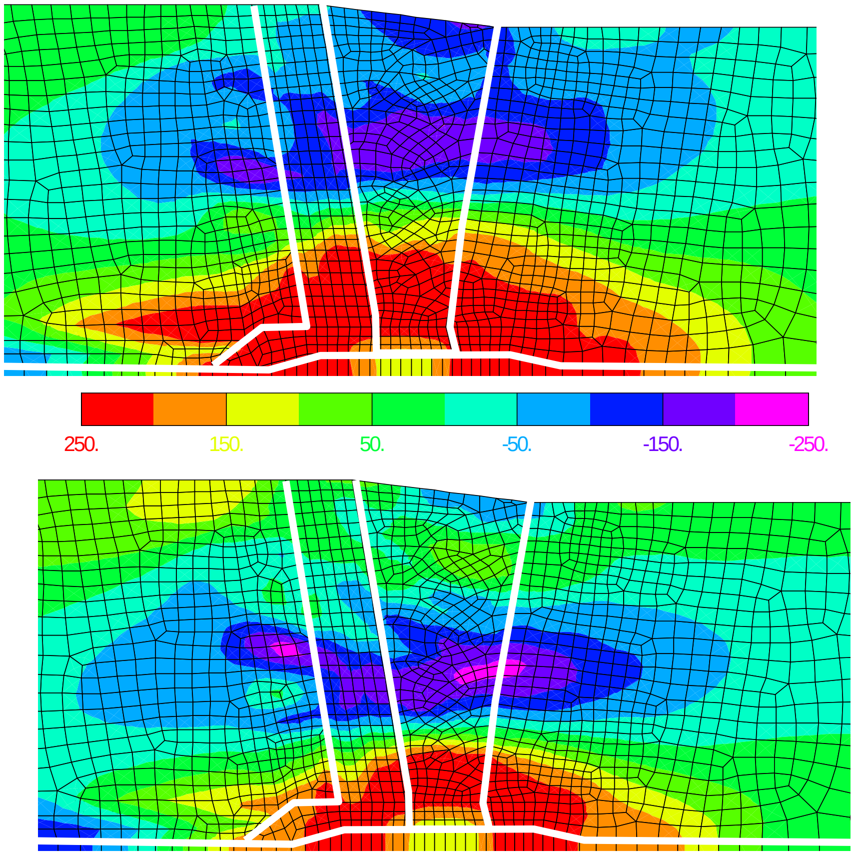

Figure 5. Axial Stresses – Welding 90-Degree Repair T = 324C

probabilities had to be summed to get the total system probability. Alternatively, the worst case location (either from a geometric, material, or load viewpoint) was analyzed, and the total system failure probability was conservatively estimated by multiplying the worst-case node failure probability by the number of girth welds in the system.

In all cases, the user is allowed to choose what type of plant was to be analyzed. The user has three choices for plant type: PWR, BWR, or BWR with hydrogen water chemistry. This choice not only helps define the system to be analyzed, but also sets the cracking mechanisms that would be active. Reference [1] illustrates some of these predictions (along with [10]) and some results are discussed with regard to the hot leg crack growth analysis here. In the following we provide an example of one type of analysis that is part of PRO-LOCA. It concerns the PWSCC crack growth of the VC Summer plant. As discussed above (and in Reference [5]), the leaking hot leg pipe in the VC Summer plant where the degradation mechanism of PWSCC in bimetal welds in PWR plants was first observed. This hot leg was somewhat unique in that it had a rather complex repair in the field. The weld process began and then a weld defect was discovered. The weld was subsequently ground partially and a ‘bridge’ was created about half way through the pipe thickness. Then the repair weld metal was deposited. However, it was unknown whether the weld metal was deposited on the inside of the pipe followed by welding on the outside, or vice-versa. Here we consider both cases. It will be seen that welding on the outside followed by completing the weld at the inner diameter is the worse case scenario.

The finite element alternating method (FEAM) was used to obtain stress intensity factors to perform the PWSCC analyses using the FRAC@ALT code (References [12-14]. FEAM is very convenient for obtaining mixed mode stress intensity factors in complex structures. Stress intensity factors were obtained for numerous crack sizes and shapes for cases of:

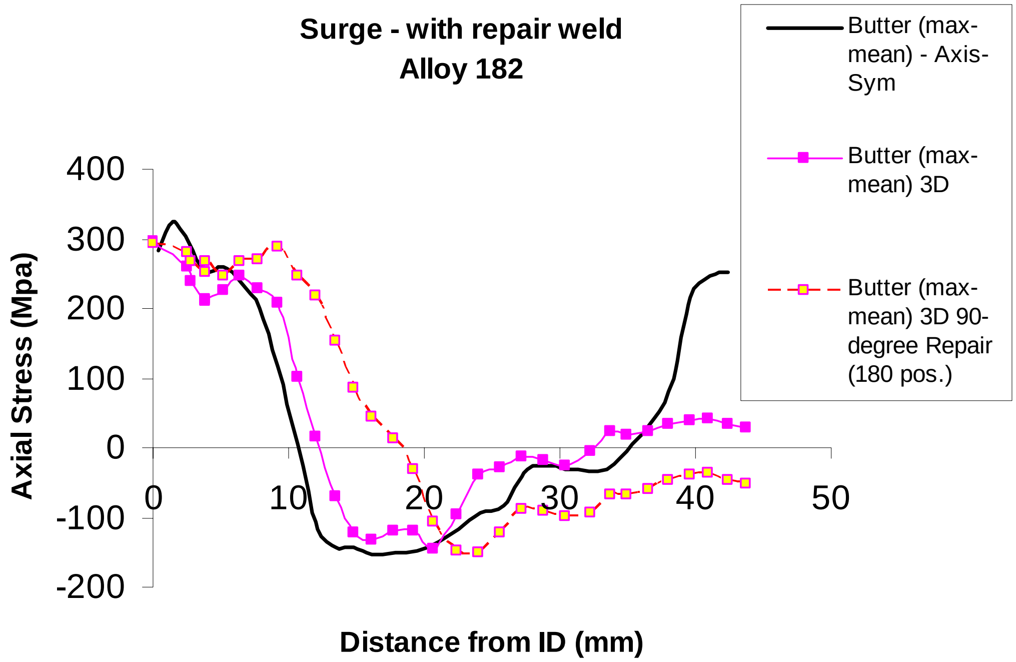

Figure 6. Axial Stresses – Welding Original 360 Grind and Repair (T = 324C)

FEAM properly accounts for stress redistribution as the cracks grow. As such, cracks that grow through a residual stress field that reach a compressive residual stress field (after stress re-distribution) can stop growing. Once stress intensity factors were available for many c/a, crack depth, for axial and circumferential cracks, etc., for about 200 different cases, PWSCC predictions were made. These values of K are then normalized by $a^{1/2}$, where 'a' is the crack depth. The tables of these normalized K values were used to model crack growth. The crack growth rate equation is taken from Reference [1]

PWSCC PREDICTIONS

Analyses of the residual stresses and PWSCC for the hot leg/RPV nozzle bimetal weld of the VC Summer plant were performed. The entire history of fabrication of the weld was included in the analysis, including inconel buttering, PWHT, weld deposition, weld grind-out and repair, hydro-testing, service temperature heat-up, and finally service loads. Some of the conclusions are described in the bullets below:

- The as fabricated *axial weld residual stresses* alternate sign as one proceeds from the ID to the OD of the pipe near the weld region. Tension to compression to tension back to compression axial residual stresses develop in the as fabricated pipe weld. The tensile stresses were highest at the ID for the case of the outside weld repair deposited first and finishing with the inside weld compared with the opposite case.
- Based on the PWSCC crack growth law from Reference [1] and the analysis results here, axial cracking should be confined to the weld region. Starting from a circular crack 5 mm in depth, the crack should break through the pipe wall within two years. The crack nucleation time is something that should be studied in more detail.
- PWSCC growth is attributed to aging in IN182 weld metal and is confined to the weld metal.
- Circumferential cracks should take about twice as long to become a through wall crack compared with axial cracks.
- Circumferential cracks will tend to grow longer than axial cracks. However, since service loads dominate circumferential cracks, they will slow their circumferential growth as they grow toward the bottom of the pipe. Here, by bottom of the pipe, it is understood to be the compressive bending stress region of the pipe. The service loads consist of thermal expansion mismatch, tension caused by 'end cap' pressure, and bending. The bending stresses caused by a bending moment are compressive 180 degrees from tension zone. Part through circumferential cracks that initiate in the tension zone and grow beyond the bending neutral axis may slow down as they approach the compressive bending stress zone. However, for non-fixed bending axes, where the tension zone changes, this may not be significant.
- PWSCC growth would be best considered using a risk based probabilistic approach using PRO-LOCA. The validity and accuracy of Equation 1, and the constants, is not known. More data is needed.

- Weld repairs alter pipe residual stress fields near the start/stop regions of the repairs. This may help slow down a growing stress corrosion crack

SUMMARY

This paper discussed the development of weld residual stresses in bimetal pipe welds in PWR nuclear plants. PWSCC has emerged as serious concern and remedial methods are currently being performed to eliminate this degradation mechanism. The PRO-LOCA code was discussed as a probabilistic fracture code used to predict LOCA frequencies. The library of weld residual stresses, some of which were discussed here, reside within PRO-LOCA. Finally, an example of PWSCC crack growth predictions were presented. This type of crack growth is modeled within PRO-LOCA.

ACKNOWLEDGMENTS

The authors would like to thank the US Nuclear Regulatory Commission for their support. Important and useful discussions with Drs. D. Rudland and G. Wilkowski of Engineering Mechanics Corporation are thankfully acknowledged.

REFERENCES

1. Brust, F. W., and Scott, P. M., "Weld Residual Stresses and Primary Water Stress Corrosion Cracking in Bimetal Nuclear Pipe Welds", Proceedings of the ASME PVP 2007/Creep 8 Conference, July 22 – 26, San Antonio, Texas, Paper PVP 2007-26297, 2007.
2. User Manual for VFT – Virtual Fabrication and Weld Modeling Software by Battelle Memorial Institute and Caterpillar Inc., February 2005.
3. Oh, J., and Brust, F. W., 'Phase Transformation Effects on Weld Distortion and Residual Stress Predictions', in Proceedings of PVP2005, 2005 ASME Pressure Vessels and Piping Division Conference, July 17-21, 2005, Denver, Colorado USA, In *Welding and Residual Stresses,* edited by O'Dowd, N., Brust, F. W., Keim, E., Sherry, A., and Dong, P.
4. Brust, F. W., Yang, Y. Y., Ezeilo, A., and McPherson, N., '*Weld Modeling of Thin Structures With VFT*', Proceedings of ASME Pressure Vessel and Piping Conference, San Diego, CA, July, 2004, in *Residual Stress, Fracture, and Stress Corrosion Cracking,* Principal Editor, Y. Y. Wang, 2004.
5. Brust, F. W., Scott, P. M., and Yang, Y., '*Weld Residual Stresses and Crack Growth in Bimetallic Pipe Welds,* Proceedings of SMIRT 17, Prague, Czech Republic, August, 2003.
6. P.Scott, R.Olson, J.Bockbrader, M.Wilson, B.Gruen, R.Morbitzer, Y.Yang, Williams , F. W. Brust, L.Fredette, N.Ghadiali, G.Wilkowski, D.Rudland, Z.Feng, R.Wolterman, 'The Battelle Integrity of Nuclear Piping (BINP) Program Final Report', NUREG/CR 6837, Volumes I and II, June, 2005.
7. Brust, F. W., and Dong, P., "Welding Residual Stresses and Effects on Fracture in Pressure Vessel and Piping Components: A Millennium Review and Beyond", Transactions of ASME, Journal Of Pressure Vessel Technology, Volume 122, No. 3, August 2000, pp329-339.
8. PRO-LOCA User Guide, prepared by Battelle and Engineering Mechanics Corporation of Columbus for the US NRC, 2006.
9. Scott, P.M., Brust, F. W., Rudland, D. R., and Wilkowski, G. M., MERIT Program, 'Overview of the MERIT (Maximizing Enhancements in Risk-Informed Technology) Program', in Proceedings of SMIRT-19, Toronto, Canada August 12-17, 2007.
10. Scott, P., Brust, F. W., Rudland, D., and Wilkowski, G. M., "PRO-LOCA code Development and Use", Internal Battelle Summary Report, March, 2006.
11. F. W. Brust, P. Dong, J. Zhang, "Influence of Residual Stresses and Weld Repairs on Pipe Fracture", Approximate Methods in the Design and Analysis of Pressure Vessels and Piping Components, W. J. Bees, Ed., PVP-Vol. 347, pp. 173-191, 1997.
12. P.Scott, R.Olson, J.Bockbrader, M.Wilson, B.Gruen, R.Morbitzer, Y.Yang, Williams , F. W. Brust, L.Fredette, N.Ghadiali, G.Wilkowski, D.Rudland, Z.Feng, R.Wolterman, 'The Battelle Integrity of Nuclear Piping (BINP) Program Final Report', NUREG/CR 6837, Volumes I and II, June, 2005.
13. FRAC@ALT© (FRacture Analysis Code via ALTernating method), Version 2.0, January, 2001, Battelle Memorial Institute.
14. Brust, F. W., 'The Importance of Material Fabrication History on Weld Durability and Fracture', ASTM STP 1417 *Fatigue and Fracture Mechanics: 33rd. Volume*, Summer, 2002.