MEASUREMENT OF RESIDUAL STRESSES IN ALLOY 600 PRESSURIZER PENETRATIONS

J. F. Hall, J. P. Molkenthin (ABB-CE), P. S. Prevéy (Lambda Research),
R. S. Pathania (EPRI)

ABSTRACT

Alloy 600 penetrations in several pressurized water reactors have experienced primary water stress corrosion cracking near the partial penetration J-welds between the Alloy 600 and the cladding on the inside diameter of the components. The microstructure and tensile properties indicated that the Alloy 600 was susceptible to primary water stress corrosion cracking (PWSCC) providing that a high tensile stress (applied + residual) was present.

The residual stress distributions at the inside diameter surface and at different depths below the surface were measured in Alloy 600 nozzle and heater sleeve mockups. Surface residual stresses on the nozzle mockup ranged from -350 to +830 MPa. For the heater sleeve mockup, the surface residual stresses ranged from -330 to +525 MPa. In the areas of high tensile residual stress, for the most part, the residual stresses decreased with increasing depth below the surface. For the nozzle and heater sleeve mockups, the percent cold work and yield strength as a function of depth were determined.

INTRODUCTION

Several of the pressurizer heater sleeves and nozzles in Calvert Cliffs Unit 2 (CC-2) developed primary coolant leaks during the 1989 refueling outage, as evidenced by the presence of boric acid deposits on the pressurizer around some of the Alloy 600 nozzles and heater sleeves (1). A destructive examination of leaking CC-2 nozzles and heater sleeves determined that the leakage was the result of throughwall intergranular stress corrosion cracks near the J-groove partial penetration weld between the sleeves/nozzles and the Alloy 600 pressurizer head. The microstructure and tensile properties indicated that the Alloy 600 was susceptible to primary water stress corrosion cracking (PWSCC) providing that a high tensile stress (applied + residual) and an aggressive environment were present.

The major objective of this project was to bench mark the residual stresses present in pressurizer nozzles and heater sleeves. For this paper we will discuss the residual stress results in two mockups.

MOCKUP FABRICATION

We prepared one Alloy 600 heater sleeve mockup (mockup #8) and one Alloy 600 nozzle mockup (mockup #2). To the extent possible, materials, fabrication procedures, and geometries for the nozzle and heater sleeve mockups closely duplicated those in the field (2). The Alloy 600 heater sleeve material (SB-167) was prepared from decontaminated sleeves from the CC-2 pressurizer. The heater sleeve had a yield strength of 434.4 MPa and a reamed portion (reamed area length is about 2.54 cm for the sleeve). The mockup was prepared from the reamed portion of the sleeve. The Alloy 600 nozzle (SB-166) was fabricated from 482.7 MPa bar stock. For the heater sleeve and nozzle mockup descriptions refer to Figures 1 and 2.

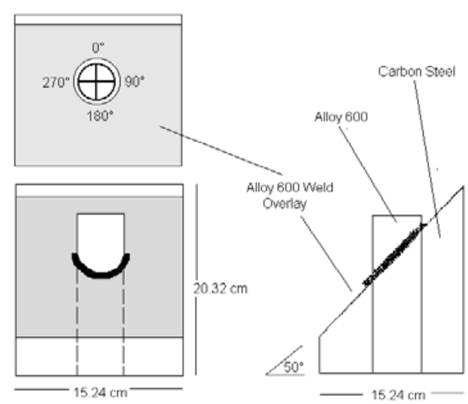

Fig 1 - Alloy 600 Heater Sleeve in the Pressurizer Head (50°).

Conference on the Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors, 12-16 Sept. 1994. Paris: Societe Francaise d'Energie Nucleare (SFEN).

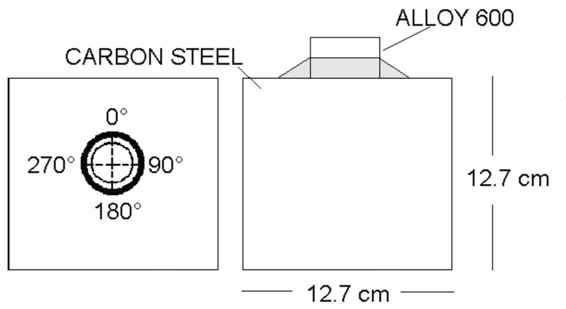

Fig 2 - Alloy 600 Nozzle in the Pressurizer Head (90°).

MEASUREMENT PROCEDURE

A combination of mechanical (strain gage) and X-ray diffraction (XRD) techniques were used to measure residual stresses resulting from the fabrication process of the Alloy 600 nozzle and heater sleeve mockups (3).

Residual stress measurements were obtained in mockup #2 and the high side (0° sector) of mockup #8. Measurements were made at the surface and at different depths below the surface for both mockups (2).

The percent cold work as a function of depth for the nozzle and heater sleeve material in mockups #2 and #8 was calculated from the diffraction peak widths based upon the empirical relationship between peak width and known levels of true plastic strain (4). The percent cold work levels are reported as scalar quantities and represent the true plastic strain required to produce the diffraction peak width measured, based upon the empirical relationship.

Because the percent cold work was defined as the amount of true plastic strain, the yield strength as a function of depth for the nozzle/heater sleeve material in mockups #2 and #8 could be estimated using the true stress-strain curves shown in Figures 3 and 4.

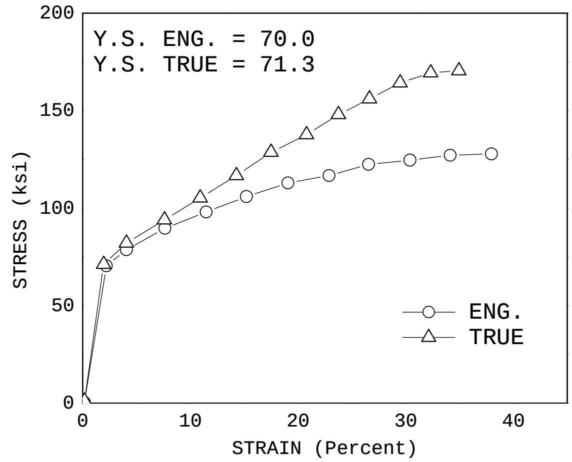

Fig 3 - Engineering and True Stress-Strain Curves For Alloy 600 Nozzle Material.

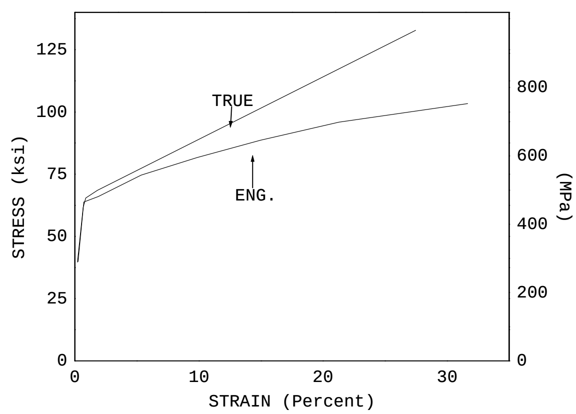

Fig 4 - Engineering and True Stress-Strain Curves for Alloy 600 Heater Sleeve Material.

RESULTS

Results from the residual stress measurements obtained in mockups #2 and #8 are presented in Figures 5 through 8. All residual stresses reported are referenced from the top of the steel encasement.

The XRD residual stress measurements for the high strength nozzle (248.2 MPa) at 90° are presented in Figures 5 and 6. For the most part, the surface residual stresses in both the axial and hoop directions were high in tension. The surface hoop residual stress in the fusion zone was +250 MPa, in the HAZ below the weld +830 MPa, and in the base metal 3.93 cm below the weld was approximately +780 MPa. Surface axial residual stress in the fusion zone was compressive (-350 MPa) and tensile in the HAZ below the weld (+620 MPa). At most locations measured, a decrease in residual stress was seen with increasing depth below the surface.

Figures 7 and 8 present the residual stress measurements for the heater sleeve mockup (434.4 MPa yield strength) at 50°. For this mockup, the surface residual stresses in both the axial and hoop directions ranged from relatively high tension to compression. The surface hoop residual stress in the HAZ below the weld was about +520 MPa tensile, and decreased in magnitude with increasing distance from the weld. In the base metal remote from the weld a compressive surface residual stress of approximately -130 MPa was measured. The surface axial residual stress in the HAZ below the weld was approximately +320 MPa tensile, and decreased in magnitude with increasing distance from the weld. The same was true above the weld. For the most part, a decrease in residual stresses below the surface was evident, although in some cases increases were observed.

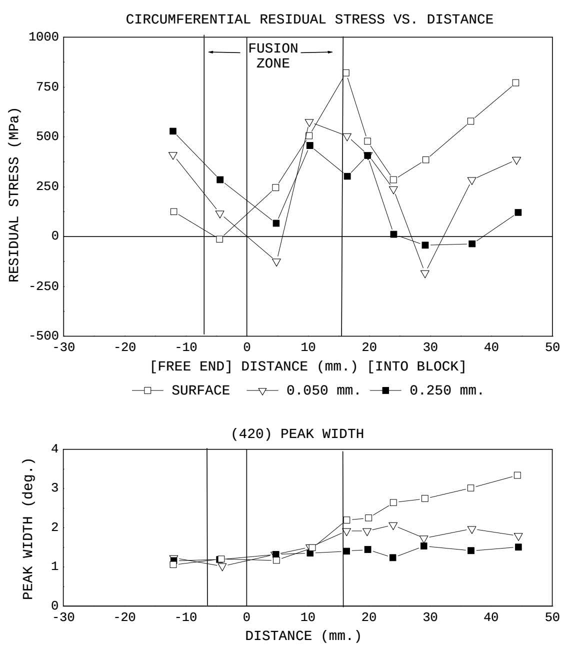

Fig 5 - Hoop Residual Stress in Nozzle Mockup #2, ID.

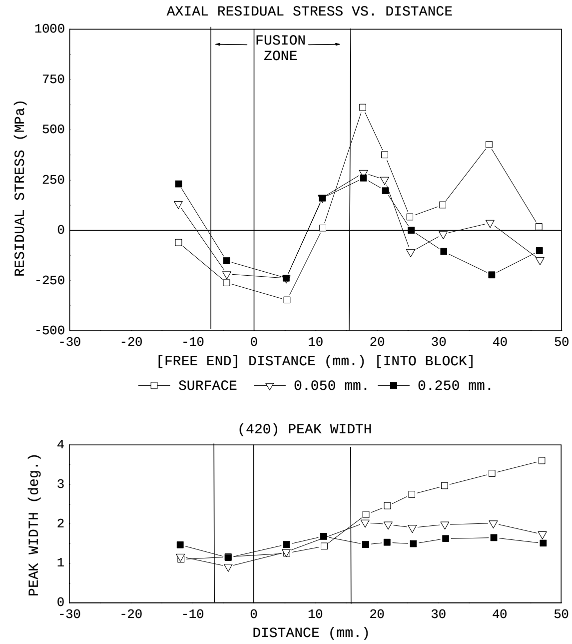

Fig 6 - Axial Residual Stress in Nozzle Mockup #2, ID.

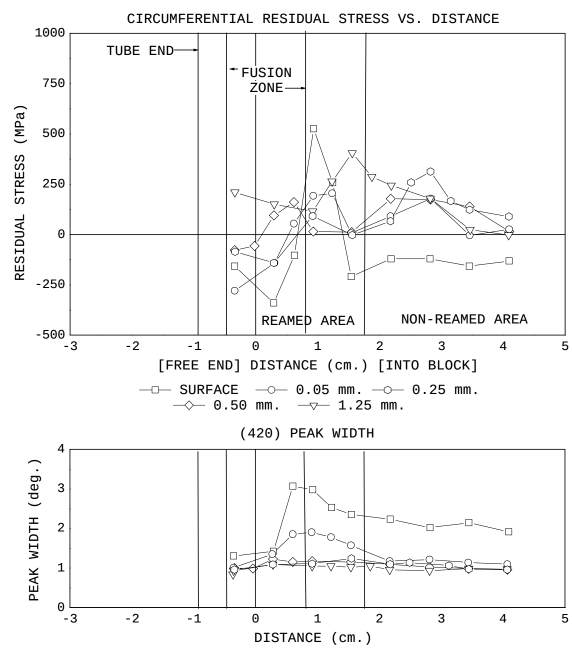

Fig 7 - Hoop Residual Stress in Heater Sleeve Mockup #8, ID, High Side of Weld

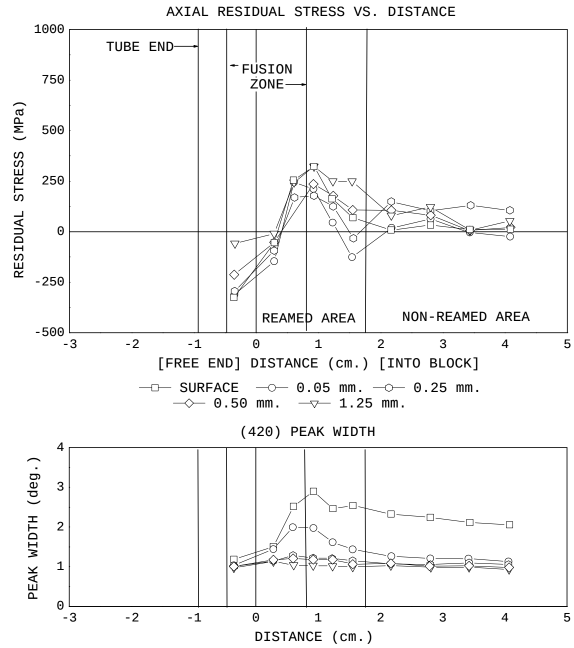

Fig 8 - Axial Residual in Heater Sleeve Mockup #8, ID, High Side of Weld

The percent cold work and yield strength levels as a function of depth for the nozzle and heater sleeve mockups are presented in Figures 9 through 12. All distances reported are referenced from the top of the steel encasement.

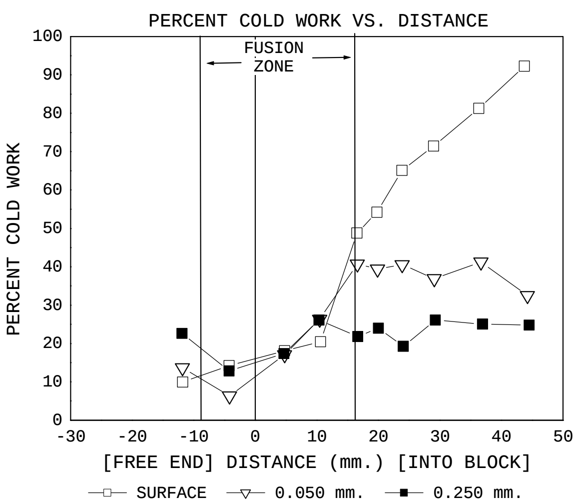

Fig 9 - Percent Cold Work in Nozzle Mockup #2, ID.

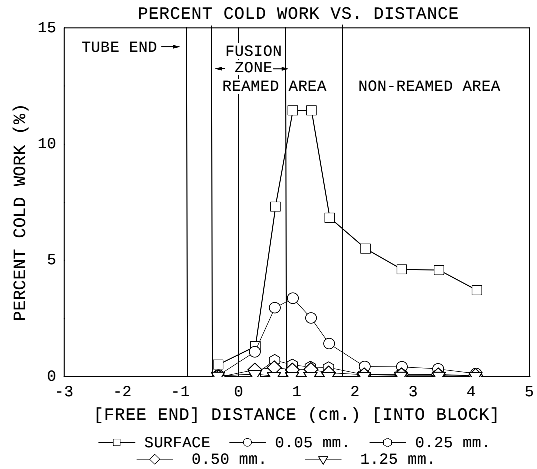

Fig 10 - Percent Cold Work Stress in Heater Sleeve Mockup #8, ID, High Side of the Weld.

The percent cold work data presented in Figures 9 and 10 show a decrease in cold work as the depth into the nozzle or sleeve is increased for mockups #2 and #8. For mockup #2 (i.e. nozzle mockup), percent cold work levels as high as 90% were seen on the surface at a distance of 3.93 cm below the weld. In the HAZ below the weld on nozzle mockup #2, a surface cold work level of 50% was present. The percent cold work levels decreased with increasing depth below the surface. The surface cold work levels for mockup #8 were 11.4% in both the HAZ below the weld and adjacent to the HAZ below the weld. At a depth of 0.025 cm below the surface of the heater sleeve mockup, the cold work was equivalent to the full annealed material (i.e. 0 percent).

The yield strength estimates presented in Figures 11 and 12 show a decrease, for the most part, in yield strength with increasing depth below the surface of the nozzle/heater sleeves. The highest yield strengths, on the order of 1850 and 690 MPa, occurred at the surface 3.93 cm below the weld and just below the fusion zone, respectively, in the nozzle and heater sleeve mockups. The yield strengths decreased to a minimum of 750 and 450 MPa, respectively, at a depth of 0.025 cm for the nozzle/heater sleeve mockups.

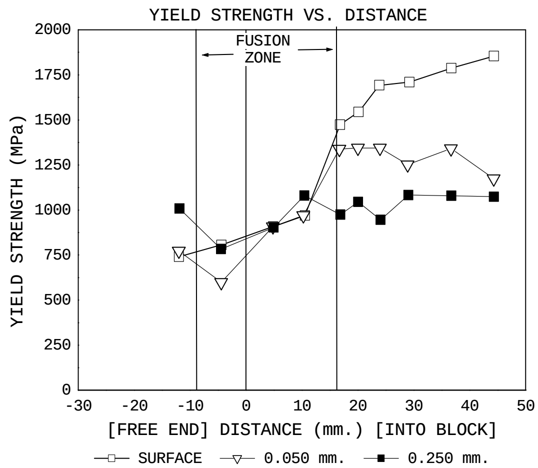

Fig 11 - Yield Strength in Nozzle Mockup #2, ID.

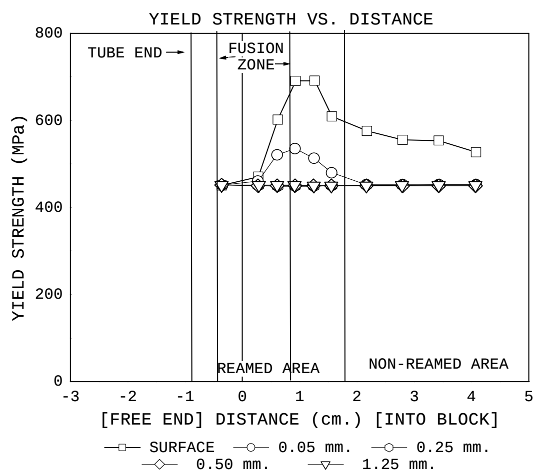

Fig 12 - Yield Strength in Heater Sleeve Mockup #8, ID, High Side of the Weld.

DISCUSSION

Examination of the residual stresses in the nozzle and heater sleeve mockups (Figures 5 through 8) showed that the J-weld produced high hoop and axial stresses in the mockups. These stresses contributed to PWSCC of nozzle and heater sleeve penetrations in the field.

The results of the XRD analysis of nozzle mockup #2 are presented in Figures 5 and 6. The hoop surface stress in the HAZ below the weld was about +830 MPa and decreased to approximately +300 MPa as deep as 0.025 cm below the surface. This +300 MPa tensile stress is not only sufficient to propagate SCC, but also could initiate it. Surface tensile stresses as high as +780 MPa were seen at a distance of 3.93 cm below the weld. These high surface residual stresses are a direct result of the combined effects of cold working the surface during machining followed by weld shrinkage. Thus, a source of stress sufficient to initiate and in some locations propagate PWSCC below the surface was present in the nozzle as a result of the cold work induced by machining and the J-weld process.

Figures 7 and 8 present the results of the heater sleeve mockup (i.e. #8, reamed sleeve at 50°). The surface residual stress in the hoop direction in the HAZ below the weld was about +520 MPa and decreased in magnitude with increasing distance from the weld. Below the surface, the residual hoop and axial stresses were reduced in most locations. In some locations the stresses went from tensile to compressive, whereas at other locations the opposite was evident. This observation suggests that there is significant variation in residual stress levels in welded heater sleeves due to the complex thermal and plastic strain distributions. It is possible that a crack could initiate on the surface and propagate in a direction depending on the stress levels at different locations and depths.

The high stresses seen on the surface of the nozzle/heater sleeves were possible because the machining of the nozzle and pre-reaming of the sleeves had cold worked the inside diameter of the nozzle/heater sleeves thereby increasing the yield strength of the surface layer. The cold working of the surface prior to welding allowed the nozzle/heater sleeves to support these high stresses.

The percent cold work and yield strength analysis for mockups #2 and #8 (Figures 9 through 12) showed that plastic deformation of the tube ID associated with machining, pre-reaming and welding the mockups increased the yield strength and the amount of cold work up to 0.025 cm below the surface.

For the nozzle mockup, the pre-installment machining, which cold worked the material of the ID surface, increased the yield strength of the material as deep as 0.025 cm. As a result of welding the nozzle into the steel encasement, the cold work layer (i.e. 0.025 cm deep) was annealed (i.e. approximately 0% cold work) within the weld zone. Upon cooling, the highly cold worked surface layers just below the fusion zone, which were not heated sufficiently to eliminate the cold work, are drawn into tension by the weld shrinkage. At a distance of 3.93 cm from the weld, the effects of welding were not evident.

For the heater sleeve mockup, an increase in yield strength and true plastic strain was also evident just below the fusion zone. This corresponds to the increases in residual stresses observed in these areas (i.e. just below the fusion zone).

As a result of increased yield strength, measured residual stresses in all areas are elastic (i.e. $\leq \sigma_{ys}$). The (420) diffraction peak width, shown in Figures 5 through 8, is a sensitive function of the chemistry, hardness and the degree to which the material has been cold worked. In work hardening materials, the diffraction peak width increases significantly as a result of an increase in the average microstrain and the reduced crystallite size produced by cold working. The diffraction peak width can be indicative of how the material may have been fabricated and to what depth it was plastically deformed. Examination of the peak widths for both the nozzle and heater sleeve material show the direct effects of machining, pre-reaming and welding. These effects vary from nozzle to nozzle or sleeve to sleeve and reflect the variation and complexity of the residual stress and cold work distributions which can result from the fabrication and welding processes. It can be concluded that the measured stresses are sufficient to initiate and at some locations propagate PWSCC in the pressurizer nozzle and heater sleeves as a result of the cold work induced by the combination of machining, pre-reaming and the J-weld process.

CONCLUSIONS

1. The J-weld induced a significant tensile residual stress in the ID of the Alloy 600 nozzle/heater sleeve, great enough to initiate PWSCC.

2. Machining of the Alloy 600 nozzle and pre-reaming of the heater sleeve increased the amount of cold work as a deep as 0.025 cm below the surface.

3. The J-weld residual stresses in the machined/pre-reamed area of the Alloy 600 nozzle/heater sleeve were high because of the presence of a cold worked layer on the ID surface.

4. The experimental measurements indicate that the residual stresses in actual Alloy 600 nozzles/heater sleeves are highly variable as a result of the fabrication and welding processes used.

5. The J-weld procedure used in welding the Alloy 600 nozzles/heater sleeves affects the amount of cold work to different depths below the surface.

6. Once cracks have initiated at the surface, the cracks will be driven by the subsurface residual stress distribution.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the funding of this work by the Electric Power Research Institute, under contract number RP3223-02.

REFERENCES

1. J. F. Hall, D. B. Scott, "Destructive Examination of Pressurizer Heater Sleeves from Calvert Cliffs Unit 2" (Report CE-NPSD-577, October 1989).
2. J. F. Hall, J. P. Molkenthin, P. S. Prevéy, "X-Ray Diffraction Residual Stress Measurements on Alloy 600 Pressurizer Nozzle and Heater Sleeve Mockups" (EPRI TR103104, December 1993).
3. J. F. Hall, J. P. Molkenthin, P. S. Prevéy, "XRD Residual Stress Measurements on Alloy 600 Pressurizer Mockups", Proceedings of the 6th Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, August, 1993, p. 855.
4. P. S. Prevéy, "The Measurement of Subsurface Residual Stress and Cold Work Distributions in Nickel Base Alloys, Residual Stress in Design, Process and Materials Selection, (ASM International, 1987), pp. 11-19.