XRD RESIDUAL STRESS MEASUREMENTS ON ALLOY 600 PRESSURIZER HEATER SLEEVE MOCKUPS

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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 two Alloy 600 heater sleeve mockups. Surface residual stresses ranged from 340 to 690 MPa. For the most part, the residual stresses decreased with increasing depth below the surface. For the heater sleeve mockups, the percent cold work (i.e. true plastic strain) and yield strength as a function of depth were determined. As a result of pre-reaming and welding the heater sleeves, the amount of plastic strain and yield strength increased to a nominal depth of 0.025 cm. The true plastic strain and yield strength decreased with increasing depth below the surface.

INTRODUCTION

Several of the pressurizer nozzles and heater sleeves 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 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 presence of a tensile stress of at least 275.8 MPa must exist (2). Residual stresses from a pre-installation reaming operation were originally judged to be the key parameter causing the failures, but residual stress measurements on a leaking sleeve removed from CC-2 indicated that the residual stresses present in the reamed area some distance from the J-weld were low tensile or compressive. These stresses were judged not to be sufficient to cause PWSCC even in a material with a susceptible microstructure exposed to the pressurizer environment.

The major objective of this paper was to benchmark the residual stresses present in pressurizer heater sleeves. This paper presents the results of an experimental program using Alloy 600 heater sleeve weld mockups to determine the location and magnitude of residual stresses in these mockups.

MOCKUP FABRICATION

C-E prepared two Alloy 600 heater sleeve mockups (mockups #8 and #9). To the extent possible, fabrication procedures, materials and geometries for the heater sleeve mockups closely duplicated those in the field. The Alloy 600 heater sleeve material was prepared from decontaminated sleeves from the CC-2 pressurizer. The heater sleeves had a yield strength of 434.4 MPa and a reamed portion (reamed area length is approximately 2.54 cm for each heater sleeve). The two mockups were prepared from the reamed portion of the sleeves. The base material for the two heater sleeve mockups was SA-533B reactor vessel archive material. The base material blocks were first machined to the appropriate dimensions (length, width, height and angle). After the basic machining was completed, the SA-533B blocks were weld clad with Alloy 82 (ERNICr-3) using the procedures for weld cladding field units. After cladding, the appropriate size holes were drilled into each mockup, the J-groove weld preps were made

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and the J-groove weld between the heater sleeve OD and the cladding of each mockup was completed using a manual tungsten-inert gas welding procedure with Alloy 82 filler metal. For the heater sleeve mockup descriptions refer to Figure 1.

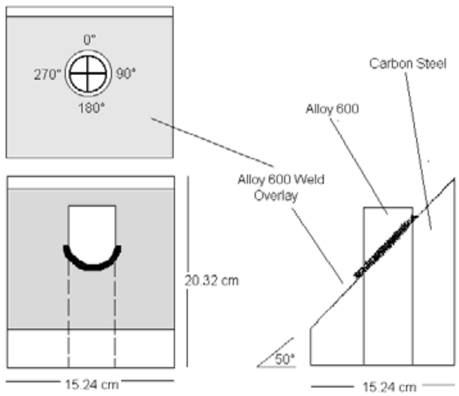

Fig 1 - Alloy 600 Heater Sleeve in the Pressurizer Head (50°).

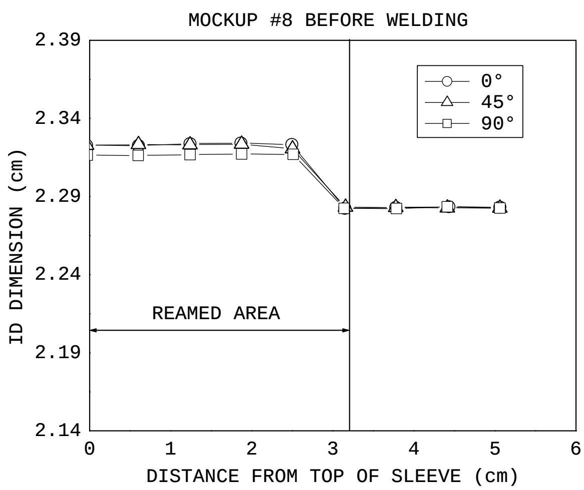

Fig. 2 - ID measurements in reamed heater sleeve #8, high side of weld, before welding.

Before and after fabricating mockups #8 and #9, the inside diameter of the heater sleeves were measured over a distance of 2.54 cm on either side of the anticipated weld location. Measurements were made every 0.635 cm starting at the top of each heater sleeve extending 5.08 cm into each sleeve. This was done by making silicone molds of the ID of each heater sleeve. Inside diameter measurements were taken at 0° (i.e. high side of weld), 45°, and 90°, moving in the clockwise direction around each sleeve using Starrett dial calipers, with a range of 0 to 15.24 cm and calibrations traceable to National Institute of Standards and Technology (NIST) Standards. These measurements were used to quantify the distortion produced by welding.

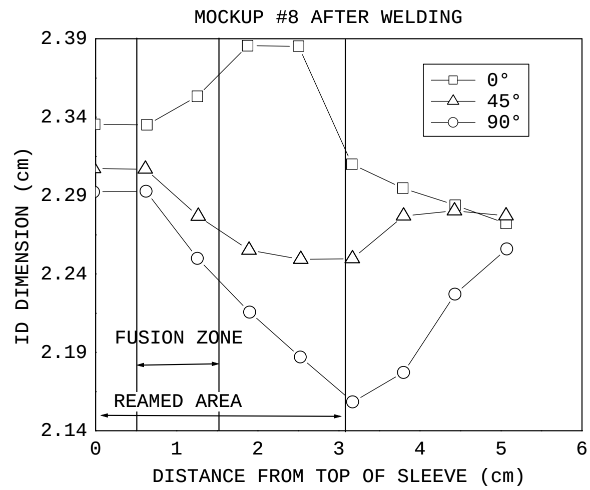

Fig. 3 - ID measurements in reamed heater sleeve #8, high side of weld, after welding.

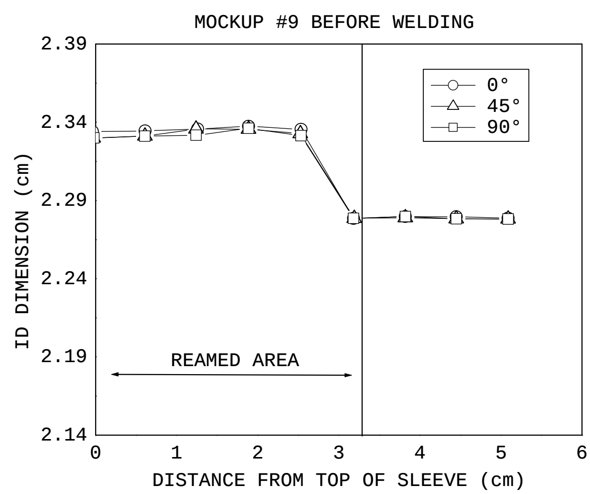

Fig. 4 - ID measurements in reamed heater sleeve #9, high side of weld, before welding.

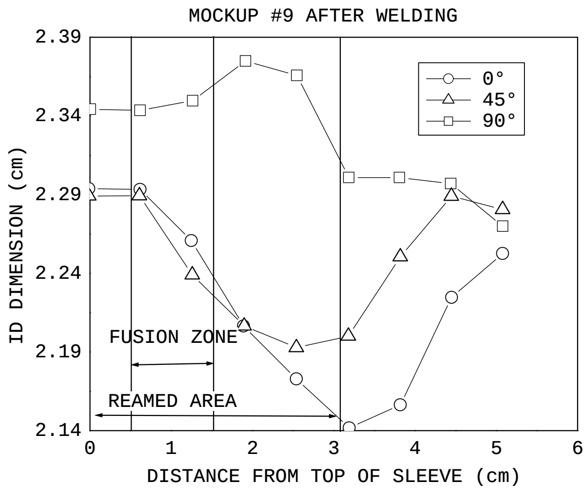

Fig. 5 - ID measurements in reamed heater sleeve #9, high side of weld, after welding.

Figures 2 through 5 are graphs of the inside diameter dimensions versus distance from the top of the sleeve (cm) for mockups #8 and #9. The figures include graphs of inside diameter dimensions before and after welding mockups #8 and #9, respectively. As a result of welding, the high (0° sector) and low (180° sector) sides of the weld were put into tension and 90° to the high and low sides of the weld were placed into compression, for both mockups. The maximum ovalization (Dmax-Dmin) observed for mockups #8 and #9 was approximately 0.191 cm and 0.185 cm, respectively, at a distance of approximately 2.54 cm from the top of each sleeve. For both mockups the maximum ovalization was observed in the fusion zone of the weld. This is similar to the 0.145-0.211 cm ovality measured in 45° CRDM nozzles (3).

MEASUREMENT PROCEDURE

X-ray diffraction (XRD) was used to measure residual stresses resulting from the fabrication process of the Alloy 600 heater sleeve mockups #8 and #9. Locations at which XRD measurements were taken included:

a) the fusion zone
b) the heat affected zone (HAZ)
c) the base metal adjacent to the HAZ
d) the base metal remote from the weld

Sectioning of the Alloy 600 mockups was necessary prior to x-ray diffraction residual stress measurements to provide access for the incident and x-ray beams. As part of the procedure, prior to sectioning, strain gages were applied at a location centered on the weld at the 0° (high side) and 180° (low side) positions on mockups #8 and #9. A series of six Micromeasurement type EA-06-062TT-120 biaxial strain gages spanned a distance of approximately 2.54 cm over the weld area (3). As a result, strain relaxation caused by sectioning was obtained as a function of distance from the weld centerline for each direction (axial and hoop). The total strain relaxation which occurred as a result of sectioning was recorded after the sectioning process was complete. The hoop and axial strains were then used to calculate the residual stress relaxation at any point between the end gages assuming a linear stress gradient between strain gage grids. These strain relaxations were used to correct the X-ray diffraction residual stress measurements performed on the sectioned mockups to determine the magnitude of the total residual stress when the mockup was whole.

X-ray diffraction residual stress measurements were made by means of the two angle sine-squared Ψ technique in accordance with specification SAE J784a, employing the diffraction of copper K-alpha radiation from the (420) planes of the face centered cubic (FCC) structure of the Alloy 600 (4). The diffraction peak angular positions at each of the Ψ tilts used for measurements were determined from the position of the K-alpha 1 diffraction peak. This peak was separated from the K-alpha doublet by employing a Pearson VII function peak profile in the high back-reflection region (4).

The value of the elastic constant that was required to calculate the macroscopic residual stress from lattice strain measured normal to the (420) planes of Alloy 600 had been previously determined in accordance with ASTM E1426-91. This determination had been made by loading a rectangular beam in four-point bending to different stress levels and then measuring the resultant change in the spacing of the (420) planes caused by the stress (5).

Residual stress measurements were obtained in the high side (0° sector) of mockups #8 and #9. The first set of measurements (hoop and axial) were obtained on the ID surface of both Alloy 600 heater sleeve mockups. These measurements allowed development of a traverse of surface residual stress along the ID of a mockup over a known distance.

Subsurface measurements were obtained after electropolishing each heater sleeve ID to a desired depth within the area of the first set of measurements. The exact depth was 0.005 cm. This depth was within the cold worked layer of the sleeve (cold working as a result of pre-installment reaming) for comparison with a similar depth in the non-reamed area. Residual stress measurements were obtained at the same locations as those examined on the surface in both the hoop and axial directions in the ID of mockups #8 and #9.

The ID of mockups #8 (0° sector) and #9 (180° sector) were then electropolished to a total depth of 0.025 cm. XRD residual stress measurements were obtained at the same locations used for the 0.005 cm depth in both the hoop and axial directions in both mockups.

Mockup #8 was electropolished to depths of 0.051 cm and 0.127 cm and measurements were obtained at each depth at the same locations as those examined on the surface in both the hoop and axial directions.

To relate the peak widths to the amount of true plastic strain, a piece of Alloy 600 bar stock with a yield strength of 394.4 MPa was fabricated into a tensile test sample. The sample was machined in accordance with ASTM E-8 specifications, to give a 2.720 cm gage length. The sample was annealed at 1204° C for 15 minutes and shot peened using 230-H steel shot at an Almen intensity of 0.010A. The test sample was pulled in tension to 1% strain using a Baldwin Lima Hamilton Tensile Testing Machine. The (420) diffraction peak width was measured as a function of depth in the gage region (shot peened plus strained to 1%) and in the tab region (shot peened only) of the Alloy 600 tensile test sample. The empirical relationship between the (420) peak width and cold work (measured as true plastic strain) was calculated from the difference in peak width between the gage section and tab regions as a function of depth (6).

The percent cold work as a function of depth for the heater sleeve material in mockups #8 and #9 was calculated from the diffraction peak widths based upon the empirical relationship between peak width and known levels of true plastic strain. 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 strengths of the Alloy 600 heater sleeve material as a function of depth for mockups #8 and #9 could be estimated using the true stress-strain curve shown in Figure 6. The stress-strain curve was extrapolated for strains greater than 25 percent.

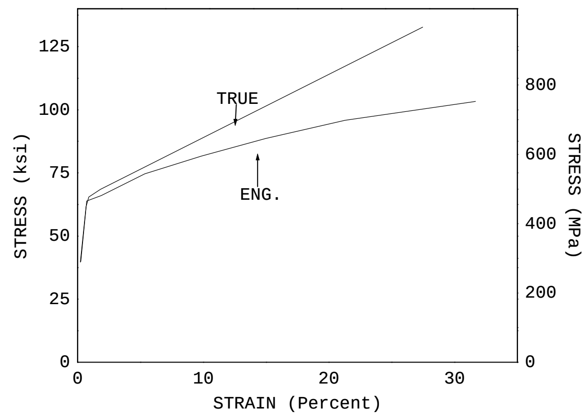

Fig. 6. - Engineering and true stress-strain curves for Alloy 600 heater sleeve material.

RESULTS

Results from the residual stress measurements obtained in mockups #8 and #9 are presented in Figures 7 through 10. All residual stresses reported are referenced from the top of the steel encasement.

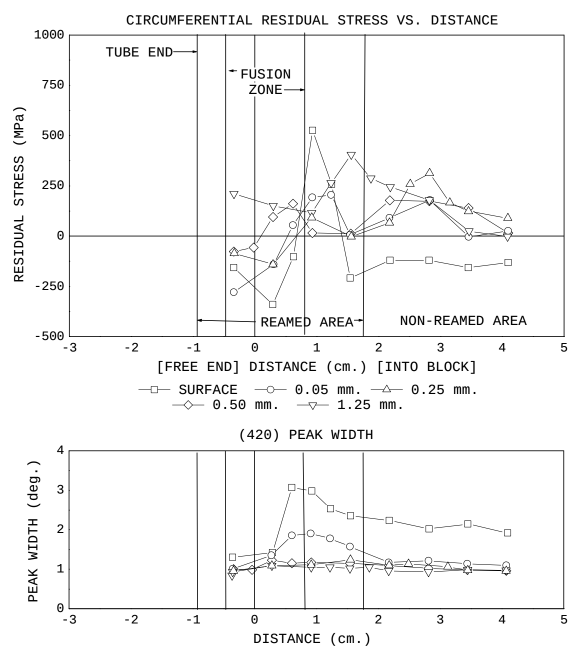

Fig 7 – Hoop residual stress in reamed heater sleeve #8, ID, high side of weld.

Both mockups were identical and the angle of the sleeves in these mockups was 50°. For mockup #8 (Figures 7 and 8) 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 approximately 524 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 131 MPa was measured. The surface axial residual stress in the HAZ below the weld was approximately 317 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. For mockup #8, the hoop and axial residual stresses were comparable in magnitude with higher stresses observed in the reamed portion of the sleeve.

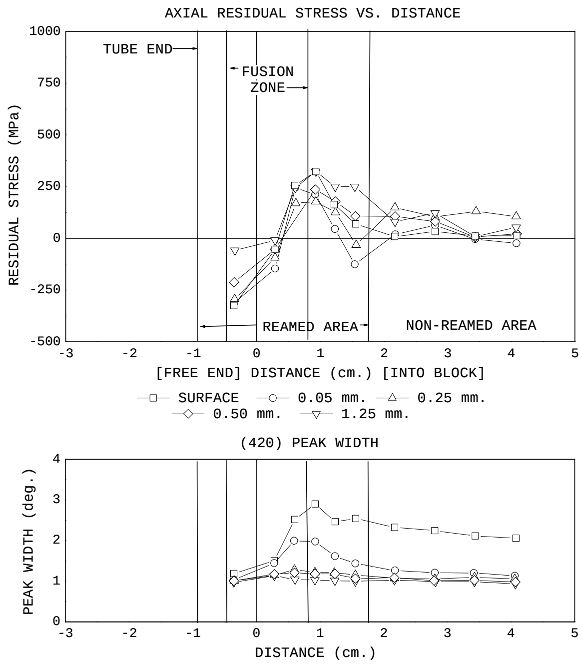

Fig. 8 - Axial residual stress in reamed heater sleeve, #8, ID, high side of weld.

For mockup #9 (Figures 9 and 10) the residual stresses on the surface and below the surface in both the hoop and axial directions also varied significantly, ranging from high tensile to compressive depending on the location and proximity of the weld. The surface hoop residual stress in the HAZ below the weld was approximately 620 MPa tensile, just below the HAZ 360 MPa tensile and in the base metal remote from the weld 54 MPa compressive. The surface axial residual stress in the HAZ below the weld was 638 MPa tensile, just below the HAZ 243 MPa tensile and in the base metal remote from the weld approximately 76 MPa tensile. A decrease in residual stresses below the surface was observed at these locations, although in some cases small increases were evident. For mockup #9, the hoop and axial residual stresses were comparable in magnitude with stresses in mockup #8. Similarly, stresses in the reamed portion of the heater sleeve were higher in magnitude compared to the non-reamed area.

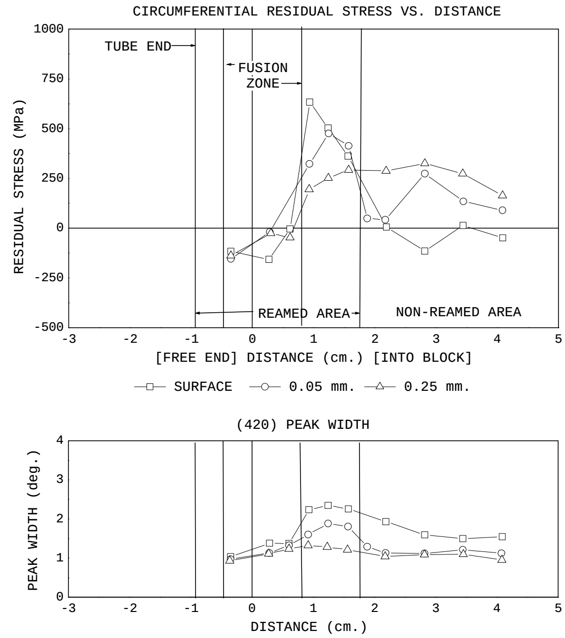

Fig. 9 - Hoop residual stress in reamed heater sleeve #9, ID, high side of weld.

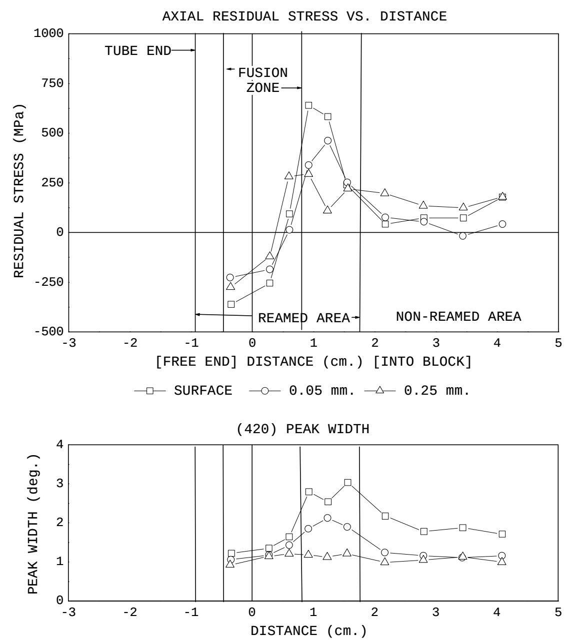

Fig. 10 - Axial residual stress in reamed heater sleeve #9, ID, high side of weld.

The percent cold work (i.e. true plastic strain) and yield strength levels as a function of depth for mockups #8 and #9 (0° sector) are presented in Figures 11 and 12. All distances reported are referenced from the top of the steel encasement.

The percent cold work data presented in Figures 11 and 12 show a decrease in cold work as the depth into the sleeve is increased for mockups #8 and #9. 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. For mockup #9, the surface cold work levels were 7.6% in the HAZ below the weld and 6.1% adjacent to the HAZ below the weld. At a depth of 0.025 cm below the surface of both mockups, the cold work was equivalent to the full annealed material (i.e. 0 percent).

The yield strength estimates presented in Figures 13 and 14 show a decrease in yield strength with increasing depth below the surface of the heater sleeves. The highest yield strengths, on the order of 690 MPa, occurred at the surface just below the fusion zone in both mockups. The yield strengths decreased to a minimum of 448 MPa at nominally 0.025 cm.

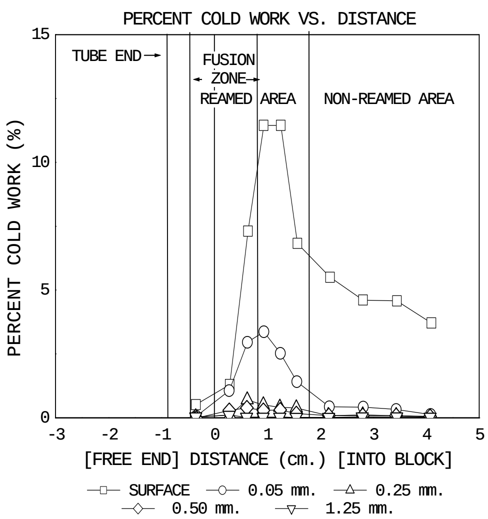

Fig. 11 -Percent cold work in reamed heater sleeve #8,D, high side of weld.

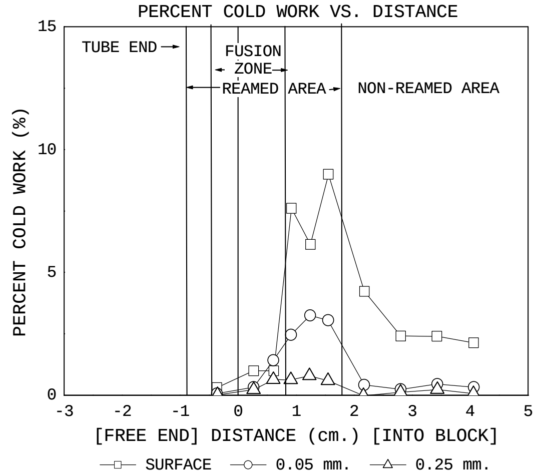

Fig. 12 - Percent cold work in reamed heater sleeve #9, ID, high side of weld.

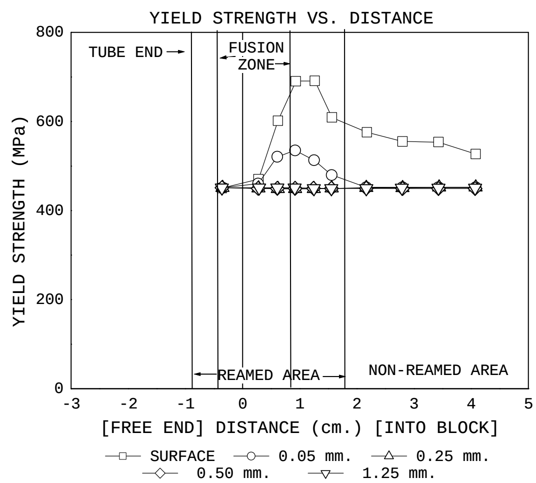

Fig. 13 - Yield strength in a reamed heater sleeve #8, ID, high side of weld.

DISCUSSION

Examination of the residual stresses in the eighth and ninth mockups (Figures 7 through 10) showed that the J-weld produced high hoop and axial stresses in the high (0° sector) side of the weld, sufficiently high enough to induce SCC without the addition of any operating stresses. For the two mockups (reamed heater sleeves at 50°), the surface stresses in the hoop direction in the HAZ below the weld were approximately 524 MPa and 627 MPa, respectively. These high stresses were possible only because the pre-reaming had cold worked the inside diameter of the heater sleeves thereby increasing the yield strength of the surface layer. The cold working of the surface prior to welding allowed the heater sleeves to support these high stresses. Below the cold worked 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. 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 percent cold work and yield strength analysis for mockups #8 and #9 showed that plastic deformation of the tube ID associated with welding the mockups further increased the amount of cold work (i.e. true plastic strain) up to 0.025 cm below the surface which in turn increased the yield strength of the heater sleeves, specifically just below the fusion zone. This agrees with 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 these areas are elastic (i.e. $\leq \sigma_{YS}$). The (420) diffraction peak width, shown in Figures 7 through 10, 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 crystalline 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. The peak widths for mockups #8 and #9 ranged from a maximum of approximately 3.0 degrees at the ID surface to a minimum of about 1.0 degrees at 0.025 cm below the surface in the reamed portion of the heater sleeves. For a non-welded heater sleeve the maximum peak width (3) in the reamed area of the heater sleeve was approximately 2.2 degrees on the ID surface. Thus, an increase in the amount of cold work (i.e. true plastic strain) was observed in the welded heater sleeves. It can be concluded that a source of stress sufficient to initiate and at some locations propagate PWSCC was present in the CC-2 pressurizer heater sleeves as a result of the cold work induced by 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 heater sleeves, great enough to initiate PWSCC.

2. Pre-reaming of the Alloy 600 heater sleeves increases the amount of cold work to a nominal depth of 0.025 cm below the surface.

3. The J-weld residual stresses in the pre-reamed area of the Alloy 600 heater sleeves were high because of the presence of a cold worked layer of material.

4. The experimental measurements indicate that the residual stresses in actual Alloy 600 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 heater sleeves increases the amount of cold work (i.e. true plastic strain) to a nominal depth of 0.025 cm below the surface.

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

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