XRD RESIDUAL STRESS MEASUREMENTS ON ALLOY 600 PRESSURIZER HEATER SLEEVE MOCKUPS

J. F. Hall, J. P. Molkenthin - ABB-Combustion Engineering Nuclear Power
Paul S. Prevéy – Lambda Research

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

Proceedings of the Sixth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors, 1993, TMS, ANS, NACE, San Diego, CA, pp. 855-861

cladding, the appropriate size holes were drilled into each mockup, the J-groove weld preps were made 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.

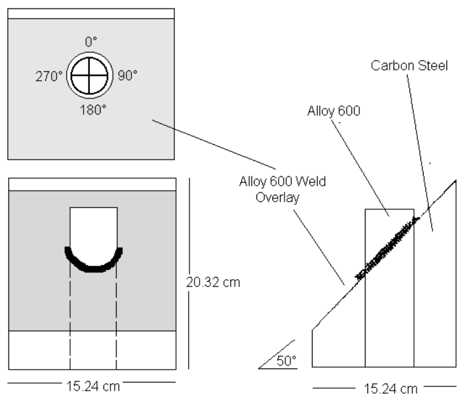

Fig 1 - Alloy 600 Heater Sleeve in the Pressurizer Head (50°).

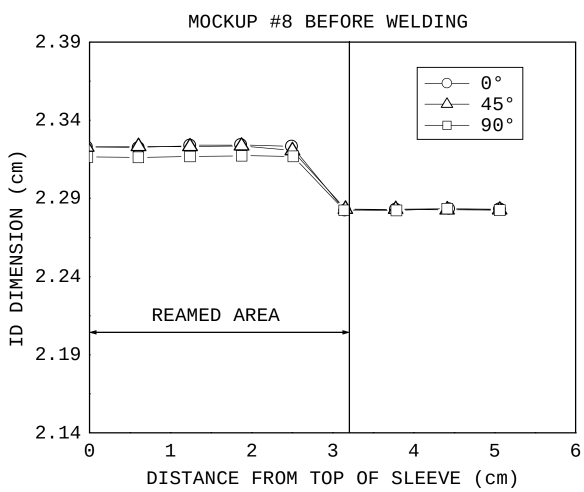

Fig. 2 - ID measurements in reamed heater sleeve #8, high side of weld, before welding.

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.

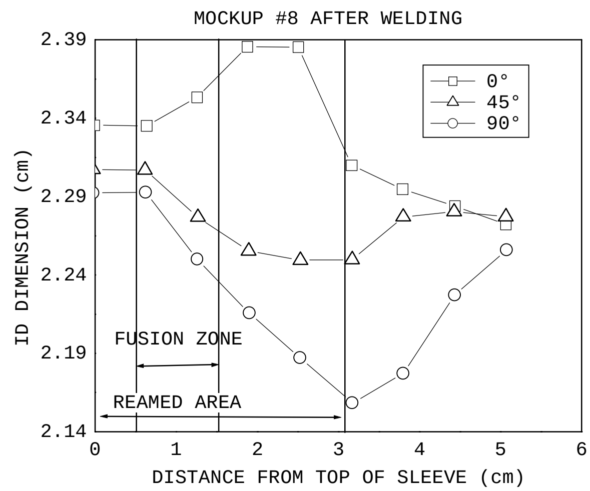

Fig. 3 - ID measurements in reamed heater sleeve #8, high side of weld, after welding.

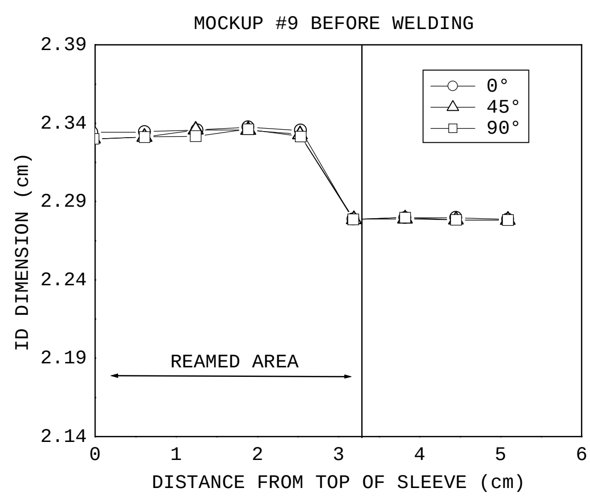

Fig. 4 - ID measurements in reamed heater sleeve #9, high side of weld, before welding.

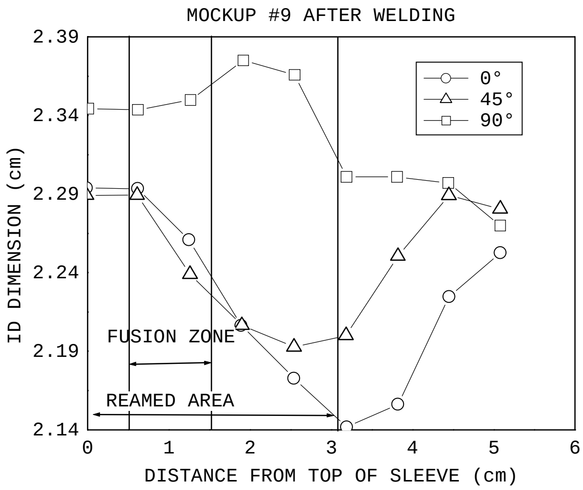

Fig. 5 - ID measurements in reamed heater sleeve #9, high side of weld, after welding.

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