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Residual stresses in indian pressurised heavy water reactor rolled joints

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ABSTRACT

Evaluation of residual stresses in rolled joints of PHWR primary coolant components such as pressure tube, liner tube and sparger tube is carried out by combined experimental and analytical methods. While the linear elastic theory is shown to be adequate to assess the residual stresses in pressure tube and liner tube, deformation plasticity theory with monotonic loading assumption is shown to be effective for assessing residual stresses in nonlinear range for sparger tube. The assumptions of the analysis are validated by strain data and elastoplastic stresses. It is demonstrated that low tensile residual stresses are developed in these rolled joints which are not significant from the point of view of flaw propagation and delayed hydride cracking.

1 INTRODUCTION

Studies on residual stresses in Indian Pressurised Heavy Water Reactor (PHWR) components have been a continuing research and development activity. Rolled joints are commonly used in PHWRs to join tubular components to tube sheets or end- fittings. Pressure tube, liner tube and sparger tube are three such components employing rolled joints for their attachments. The information on residual stresses in these rolled joints have been generated for assuring their satisfactory long term performance from the consideration of flaw propagation due to cyclic loads, delayed hydride cracking (DHC) and stress relaxation in the rolled joints leading to leakage. The pressure tube rolled joints have been modified from low clearance joints for Zircaloy-2 tubes to nearly zero clearance rolled joints for Zr-2.5% Nb tubes. Stainless steel (AISI 410 grade) liner tubes are used as a part of the end fitting assembly of the coolant channels. These tubes are joined to the martensitic stainless steel (AISI 403 grade) end-fitting assembly through rolled joints. Recently a development work has been carried out to install Zircaloy 2 sparger tubes to serve as moderator inlet to the core with rolled joints in the SS 304 L calandria tube sheet. This arrangement gives uniform moderator flow and eliminates the need for routing moderator inlet piping through the inaccessible region of the calandria vault.

The present paper brings out combined experimental and analytical case studies of residual stress analysis for different rolled joint designs of pressure tube, liner tube and sparger tube. For the measurement of residual stresses in Zircaloy 2/ Zr- 2.5% Nb pressure tube, a combination of machining operations such as sleeve removal, slit cutting and hole drilling technique are used on the test assemblies which are instrumented with strain gauges. Three categories of safety concerns are addressed in this study. In the first category the concern is to control the level of tensile residual stresses in Zircaloy 2/ Zr-2.5% Nb pressure tubes to avoid on set of DHC mechanism near the rolled joint region of the pressure tube. In this case the end fitting of relatively high strength material undergoes only a minor plastic deformation. Linear elastic theory is used to predict the residual stresses in this case. It is demonstrated that the compressive stresses on account of contact pressure developed between pressure tube and end-fitting assembly are dominant over stresses developed due to local plastic deformation by rolling. This feature results in a very low level of tensile residual stresses. The second category of concern is relevant for liner tubes. In this case it is shown through measurements that the tensile residual stresses are again local in nature and are of low magnitude compared to the yield strength of SS grade 410 liner tube material. The third class of problem is that of the Zircaloy 2 sparger tube rolled in SS 304L calandria side tube sheet. Here the concern is to check the level of tensile residual stresses in tube sheet during and after completion of rolling. Measurements on test assemblies have been carried out to check the level of residual stresses. In this case the tube sheet undergoes significant plastic deformation and due to contact type of rolling load the tube sheet remains in compressive state of stress. Evaluation of residual stresses in this case was carried out by development of an algorithm based on monotonic deformation plasticity theory with isotropic strain hardening assumptions to convert the measured strains to stresses. The present study demonstrates that due to rolling the tube sheet remains in compressive state of residual stress which will not allow any crack propagation in tube sheet.

2 RESIDUAL STRESSES IN PRESSURE TUBES

The pressure tubes of Zircaloy 2 and Zr-2.5% Nb are installed in end-fittings by rolling the inside surface of pressure tubes to cause plastic deformation against a rigid end-fitting of stainless steel AISI 403 grade (fig.1). An optimum level of plastic deformation is imparted to the tube material during the tube rolling operation so as to firmly secure the tubes to get a leakproof joint along with a high pull out strength. However, excessive tensile residual stresses could be detrimental due to increased susceptibilities to DHC in the local areas close to the rolled joint. Cases of failure of Zr- 2.5% Nb pressure tubes due to tensile residual stresses have been reported earlier [1]. In Indian PHWRs development of pressure tube rolled joints have been successively carried out to achieve adequate contact pressure without any appreciable plastic deformation of the end fittings.

Evaluation of residual stresses in test assemblies of Zircaloy-2 and Zr-2.5% Nb pressure tubes rolled to a short piece of end-fitting was carried out through a sequence of sleeve removal, slit cutting and hole drilling methods (fig.2). Measurements were performed on the inside and outside surfaces of pressure tube with the help of normal strain rosettes and hole drilling type strain rosettes [2]. A typical layout of strain rosettes of hole drilling type is shown in fig.3. The strain data thus obtained is indicative of overall residual stresses due to contact pressure developed between the sleeve and the tube alongwith the local stresses developed on account of rolling operation. The strain data were collected after sleeve removal, slit cutting and finally during the hole drilling operation by inserting an air driven turbine cutter tool through the slit to drill a small hole (1.59 mm nominal dia) at the centre of the strain rosette. In the following paragraph residual stress data derived from measurement on a nearly zero clearance rolled joint of Zr-2.5% Nb pressure tube of 500 MWe PHWR design is described.

The distribution of stresses along the pressure tube axis due to contact pressure obtained during sleeve removal is shown in fig.4. Overall bending stresses obtained by slit cutting method are shown in fig.5. The combined residual stresses due to sleeve removal and slit cutting are shown in fig.6. It may be noticed that the dominant stresses in rolled portion are compressive and overall bending stresses in unrolled portion of tube are of very small magnitude. This indicates that the rolling tool is well within the end-fitting and insignificant tensile stresses due to hydrostatic component of load are developed in the tube.

Local surface stresses in the tube are obtained by hole drilling and the distribution of these stresses are shown in fig.7. This measurement gives the local tensile stresses in unrolled portion of the tube. It indicates that the tensile stresses are developed during rolling process due to multiple lobes emerging under the local roller forces. Table 1 shows the total residual stress picture and its orientation with respect to the longitudinal axis by combining stresses due to all the three operations namely sleeve removal, slit cutting and hole drilling. In the table circumferential and axial stresses are also shown. Fig.8 shows the distribution of the total residual stresses and the maximum tensile stress of 208 MPa is noticed. The dominant stresses are compressive and are governed by contact pressure.

Similar studies were also carried out on rolled joints of Zircaloy-2 pressure tube with end-fitting test assemblies with high clearance joint design. In this case measurements on both outside and inside surfaces of pressure tube were taken up and it was shown that the maximum tensile stresses on outside surface in rolled portion is 517 MPa and 621 MPa on the two specimens respectively while on inside surface it is of the order of 558 Mpa (table2). Measurements made for Zircaloy-2 and Zr-2.5% Nb tubes at a few other locations along the circumference indicated that stresses vary within 12-15% and hence it may be concluded that the tube is not subjected to any torque during the rolling operation. This is clear from the orientation of principal stresses which are nearly axial and circumferential (fig 9) as shown in table 1 for Zr-2.5% Nb tube experiment.

From the above two studies it is demonstrated that Zr- 2.5% Nb pressure tube with low clearance joint results into low level of tensile residual stresses. All the new 220 MWe and 500 MWe PHWR plants in India have been designed with Zr-2.5% Nb pressure tubes with interference fit rolled joints. This will result in still lower level of tensile residual stresses. Thus the total tensile stresses will be dominated by operating stresses and there will be no appreciable change in applied stress intensity due to residual stresses in a good rolled joint design.

3 RESIDUAL STRESSES IN LINER TUBE

Liner tube of stainless steel grade AISI 410 is rolled to the end-fitting and acts as a transition between pressure tube and primary heat transport feeders (fig.1). Residual stress evaluation in liner tube is of interest to ensure its performance for cyclic load and proper leak tightness. In the present study residual stresses were determined during and after the rolling for a wall thickness reduction of 12 %. Table 3 shows the strains and calculated stresses during and after the rolling operation on the tube OD. The maximum residual tensile stress of 221 MPa in the liner tube is noticed in circumferential direction after the completion of rolling. The maximum tensile stress of 485 MPa is developed during the rolling process when the tool is located inside the tube. The longitudinal stresses are compressive and both the peak stresses decay rapidly within a distance of 38 to 43 mm from the sleeve edge.

4 RESIDUAL STRESSES IN SPARGER TUBE

The earlier two examples of residual stress analysis were based on linear elastic theory. Zircaloy 2, Zr-2.5% Nb and SS 410 have yield stress comparable to the end fitting sleeve material and D/t ratio is small. This results in very low level of tensile stresses compared to the yield strength of tube material and the sleeve remains in nearly elastic state. For rolled joints with large D/t ratio such as calandria tube and sparger tube, the tube is first rolled in the tube sheet and subsequently an insert is rolled to achieve adequate strength as shown in fig.10. In this case the tube sheet of stainless steel grade AISI SS 304 L is comparatively ductile and has lower yield strength. Here the concern is to check the level of residual stresses in tube sheet during and after the completion of rolling.

Experiments on two test assemblies of Zircaloy 2 sparger tube rolled into stainless steel 304L sleeve were carried out from zero nip to a maximum of 12% wall thickness reduction in steps of 2%. Subsequently inserts were put and further rolling was carried out from zero nip to 10% wall thickness reduction in the first experiment and 8% wall thickness reduction in the second experiment. The strain data were collected at 69 mm, 77 mm and 85 mm from centre line of sleeve on diametrically opposite locations. The two strain data were within 10% of difference which demonstrates the accuracy of data collected. The repeatability of strain data was also confirmed on two experimental sets (set I & set II) well within a limit of 10%.

Peak strain values in the range of 1.4% to 1.5% were noted. In order to obtain stresses from the measured strains a computer program ROSEPL was developed for the determination of elasto-plastic stresses from recorded strain data based on Von Mises flow rule and isotropic strain hardening criteria [3,4]. This is based on deformation plasticity theory since the strains during rolling and after completion of rolling for a particular level of wall thickness reduction did not differ significantly. A simplified assumption of monotonic loading is therefore adequate. Table 5 shows the stress distribution in tube sheet for the two experiments(set I & set II) before and after the rolling operation. The maximum circumferential tensile stress of 119 MPa at a distance of 24 mm from sleeve ID is observed. Near the sleeve ID surface these stresses are compressive. After completion of rolling the maximum residual tensile stress is 65 MPa at a distance of 24 mm from the sleeve surface.

It is concluded from the above study that the contact load developed due to rolling of ductile tube sheet of SS 304L results in high compressive stresses near the sleeve surface which are balanced by a tensile stress field of lower magnitude over a wide distance [5]. These experiments were done in sleeve of 190 mm ID and with large solid material surrounding the bore in actual tube sheets the overall state of compression will be significant. This study demonstrates the adequacy of rolled joints and no flaw will be initiated during rolling operation.

5 CONCLUSIONS

In this paper evaluation of residual stresses for rolled joints on Zircaloy 2 and Zr-2.5% Nb pressure tubes, SS410 linear tube have been made and it is shown that the tensile stresses in tubes near the sleeve edge is within elastic limit. For large D/t ratio tubes such as sparger tube the dominant elastoplastic stresses in tube sheet are compressive. Evaluation of these stresses have been carried out using deformation based plasticity theory. The monotonic loading assumption has been validated with the stresses evaluated during and after the rolling. This study is helpful to assess the feasibility of rolling tubes for repair or re-engineering work of old plants. Flaw propagation or onset of DHC mechanism is unlikely on account of low level of residual tensile stresses for PHWR tubular rolled joints.

6 REFERENCE

1. Perryman ECW (1978)- "Pickering Pressure Tube Cracking Experience", *Nuclear Energy*, 17 No.2 pp 95-105
2. Khan MA, Charan JJ, Singh RK, Kushwaha HS, (1991) "Residual Stress Measurement in 500 MWe PHWR Zr-2.5% Nb Pressure Tube Rolled Joint, Task1081"
3. Mendelson A (1983) *Plasticity: Theory and Application*, Krieger Publishing.
4. Owen DRJ, Hinton E, (1980) *Finite Element in Plasticity: Theory and Practice*, Pineridge Press, Swansea, UK.
5. Khan MA, Charan JJ, Singh RK, Kushwaha HS,(1991) "Report on Strain Measurement on Rolled Joint on MAPS Sparger Tube, Annexure-IC".

Table 1 Residual Stresses (inside surface) Distribution in 500 MWe PHWR Zr-2.5% Nb Pressure Tube Rolled Joint with Low Clearance Joint.

Strain Gauge No.	Principal Stress -1 (MPa)	Principal Stress -2 (MPa)	Reference Angle (Degrees)	Circumferential-Stress (MPa)	Longitudinal-Stress (MPa)
1	-6.4	-56.7	11.3	-11.8	-46.4
2	-8.0	-43.7	25.1	-43.7	-8.0
3	71.5	37.0	10.2	52.5	56.0
4	208.0	-3.1	7.6	197.0	8.2
5	167.0	-504.0	9.8	-494.0	87.9
6	-19.7	-596.0	-0.4	-519.0	-96.6
7	77.6	-462.0	2.4	-229.0	-156.0
8	71.6	-343.0	-3.9	-165.0	-126.0

Table 2 Maximum Tensile Residual Stresses in Zircaloy 2 Pressure Tube Rolled Joint Assemblies with High clearance Joint.

Rolled portion out side surface	517-621 MPa
Unrolled Portion inside surface	558 MPa

Table 3 Micro Strains and Stresses (MPa) in Liner tube of 500 MW PHWR during and after Rolling (12% Wall Reduction)

B1 - B8 denote strain gauge nos. a= axial direction, c= circumferential direction

Strain Gauge No.	Micro-strain (During Rolling)	Stresses (During Rolling)	Micro-strain (After Rolling)	Stresses (After Rolling)
B1 a	-3194	-481.0	-1953	-316.8
c	3210	485.5	1612	221.2
B2 a	-1659	-307.0	-1641	-308.5
c	784	61.7	700	44.8
B3 a	-969	-203.4	-1197	-248.6
c	85	-44.4	146	-46.0
B4 a	-378	-83.0	-392	-89.5
c	-23	-29.4	-77	-42.0
B5 a	-143	-35.2	-65	-19.4
c	-68	-23.9	-84	-22.3
B6 a	71	18.7	25	5.5
c	52	15.8	02	2.0
B7 a	17	6.0	14	4.9
c	36	8.9	29	7.2
B8 a	-08	-0.20	-16	-2.5
c	25	4.9	15	2.2

Table 4 Residual Stresses (MPa) in Sparger Tube Sleeve Based on Elasto-Plastic Theory

Data E=1.962E05 MPa, υ =0.3 , σ_y=233.87 MPa, H'=2528 MPa

	Experiment Set I				Experiment Set II			
Distance (mm) from Sleeve	During Rolling Radial	During Rolling Hoop	After Rolling Radial	After Rolling Hoop	During Rolling Radial	During Rolling Hoop	After Rolling Radial	After Rolling Hoop
8	-281.6	-56.3	-285.5	-66.4	-284.6	-57.7	-288.3	-70.5
	-282.5	-37.1	-285.7	-50.1	-276.5	-41.8	-279.3	-49.8
16	-227.5	20.3	-250.4	-26.5	-233.7	8.2	-255.7	-41.8
	-224.1	30.2	-238.8	2.8	-225.1	26.4	-245.2	-12.7
24	-132.1	64.3	-142.1	18.0	-133.7	77.4	-125.1	8.2
	-147.7	119.1	-151.3	65.3	-126.3	45.5	-125.5	1.6

Notes. (i) Two experiment sets I & II were done on test pieces from same batch of material for sleeve, tube & insert.

(ii) Two values of residual stresses on sleeve at 8 mm ,16 mm & 24 mm are at diametrically opposite locations as shown in fig 10.

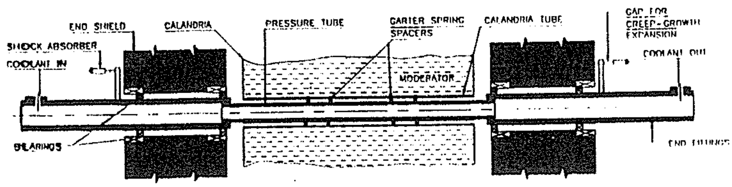

FIG. 1 SCHEMATIC OF COOLANT CHANNEL IN PHWR

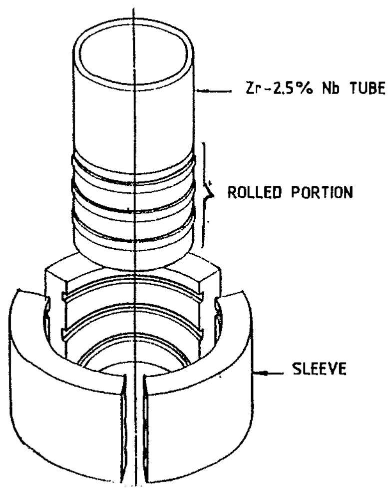

FIG. 2 Zr-2.5% NB TUBE
AFTER SLEAVE REMOVAL

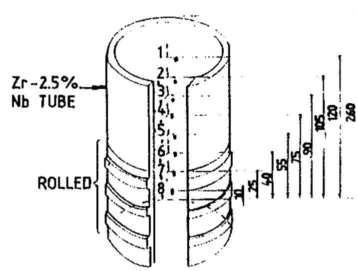

FIG. 3 STRAIN GAUGE LOCATION
IN PRESSURE TUBE

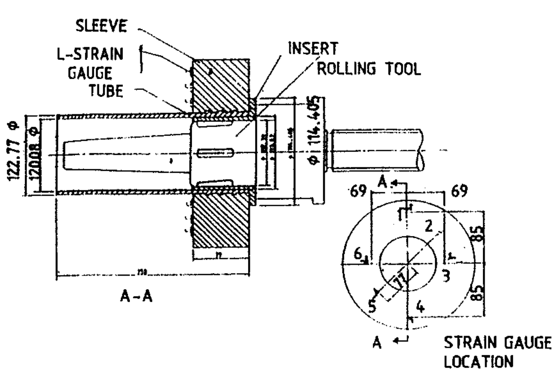

FIG. 10 ROLLING OF SPARGER TUBE

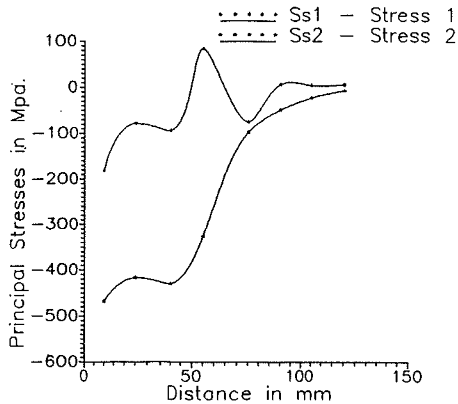

Fig. 4 : RESIDUAL STRESSES (SLEEVE REMOVAL) IN 500 MWe PHWR Zr 2.5% Nb TUBE

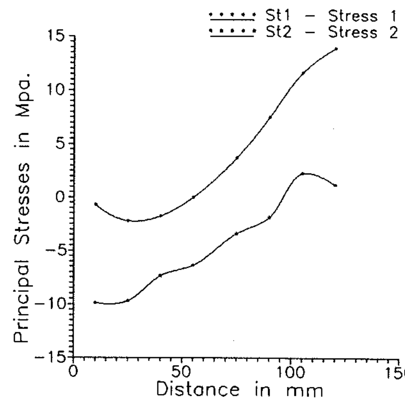

Fig. 5 : RESIDUAL STRESSES (SLIT CUTTING) IN 500 MWe PHWR Zr. 2.5% Nb TUBE

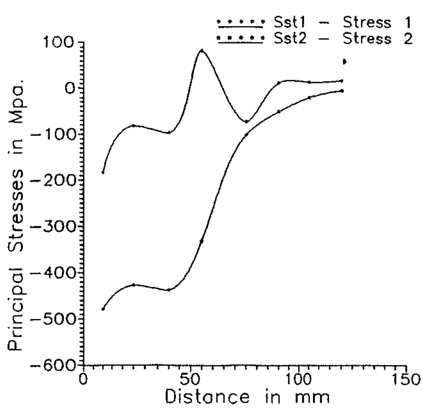

Fig. 6 RESIDUAL STRESSES (SLEEVE & SLIT CUT) IN 500 MWe PHWR Zr 2.5% Nb TUBE

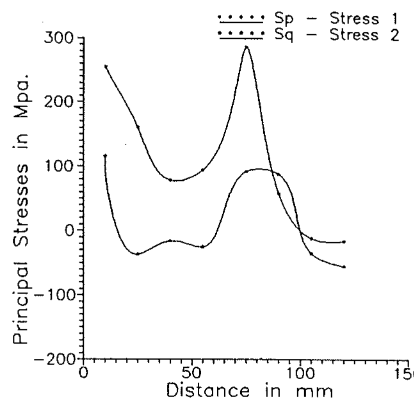

Fig. 7 : RESIDUAL STRESSES (HOLE DRILLING) IN 500 MWe PHWR Zr 2.5% Nb TUBE

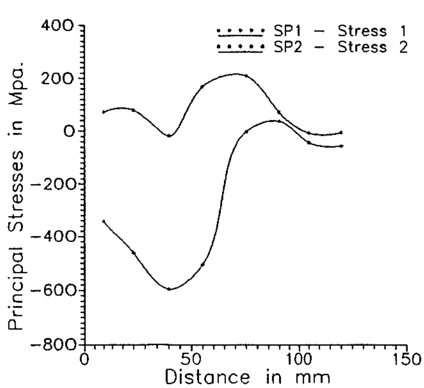

Fig. 8 : TOTAL RESIDUAL STRESS IN 500 MWe PHWR Zr 2.5% Nb TUBE

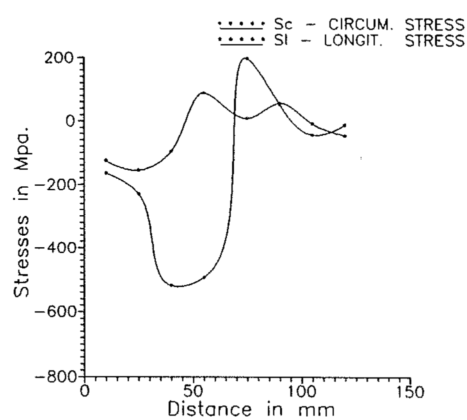

Fig. 9 : RESIDUAL STRESS IN 500 MWe PHWR Zr 2.5% Nb TUBE