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On pull out strength of Calandria tube rolled joint

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ABSTRACT: The results of elevated temperature (125°C) tensile pulling of calandria tube-tube sheet rolled joints of pressurized heavy water reactors are described. The maximum stress values attained by the calandria tube test pieces at 125°C are considerably higher than those are expected during normal reactor operation. There is no significant deterioration in the helium leak rates after tensile pulling. Microstructural evidences presented suggest that the entire rolled joint participates in supporting the load at all stages of tensile deformation.

1 INTRODUCTION

Calandria tubes in Pressurized Heavy Water Reactors (PHWRs) envelop the pressure tubes and are joined at both the ends to the tube sheets by a special sandwich rolled joint (Fig.1). The main purpose of these tubes is to provide an annular gas/air gap to separate hot pressure tube from relatively cold heavy water moderator which is at temperatures below 100°C (Cooper 1982). As these tubes form a part of the in-core components, neutron economy consideration dictates the selection of zirconium alloys. Usually, thin walled (thickness≈1.24mm) seam welded Zircaloy-2 tubes are used in the fully annealed condition. Calandria tube sheets are made of AISI 304L stainless steel and contain grooves in the inner wall. An insert, made of AISI 410 stainless steel, containing matching lands is also used in making this joint. The joining process involves rolling of the bell mouth portion of the Zircaloy calandria tube between the calandria tube sheet bore and the insert. During rolling insert expands causing flow of tube material into the grooves. A residual contact pressure develops between the calandria tube and the insert and also between the tube and the tube sheet. This residual contact pressure ensures leak tightness of the joint.

During reactor operation, the joint gets heated due to nuclear radiation as well as heat transfer from the primary coolant system. The temperature of the joint is governed by the moderator which acts as coolant for the joint. In addition, the joint is subjected to stresses which arise from various sources such as pressure of the moderator, bending load arising due to buoyancy and garter spring reaction forces. The residual contact pressure tends to relax at higher temperatures because of the differential thermal expansion of the materials involved in the rolled joint. In PHWRs, the joint presently operates at an estimated temperature of 95°C and is performing satisfactorily. The main functional requirement of this joint is to provide adequate leak tightness. Recently, modification has been suggested in terms of flow distribution of the moderator. The suggested modification is expected to cause local rise in temperature of the components of the joint at some locations. An increase in

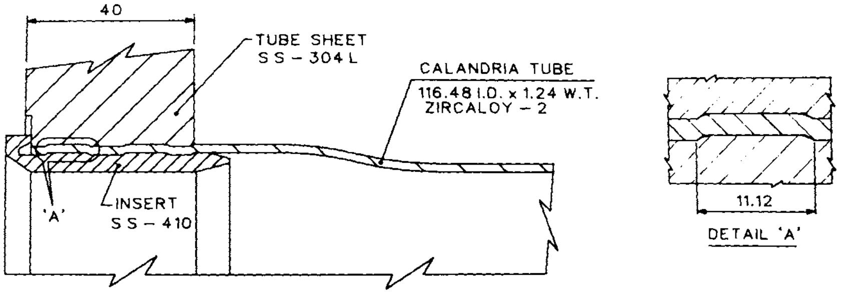

Figure 1. Details of calandria tube rolled joint. All dimensions are in mm.

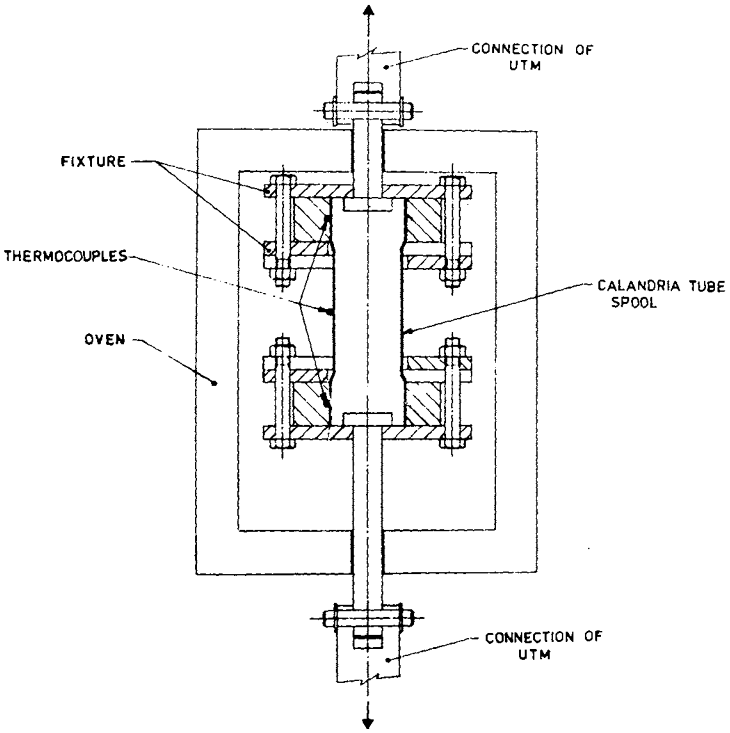

Figure 2. Schematic drawing of the pull out test arrangement.

temperature over that prevailing at the joints would relax the residual contact pressure further and as a consequence leak tightness of the joint may suffer. Estimation based on theoretical calculations using simplified elastic approach showed that the contact pressure between the components may become negligible at temperatures above 100°C. Thus doubt persists among the designers and regulatory authorities about whether or not sufficient testing and analyses have been performed to ensure adequate leak tightness of this joint at anticipated temperatures. In order to supplement the estimated value of the contact pressure of the assembly at temperatures above 100°C for assessing the leak tightness the pull out strength and leak tightness have been experimentally measured. In this investigation pull out tests have been carried out at 125°C corresponding to an upper bound analysis (≈115°C) plus a design margin (10°C).

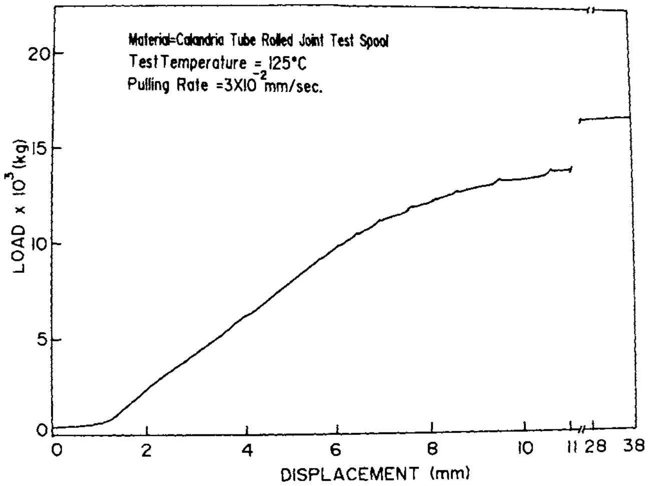

Figure 3. A typical load-displacement plot obtained during the pull out test.

2 EXPERIMENTAL

Short calandria tube spools were used for making test pieces of calandria tube rolled joints adopting an identical procedure as involved in the manufacture of the actual joints. Tube sheets were joined at both the ends of the calandria tube. The average length of the calandria tube between the two joints of the test piece was 200mm. Helium leak rate tests were initially performed on all the test pieces after subjecting to ten thermal cycles in the temperature range of room temperature to 125°C. A servo-hydraulic testing machine of 25 ton capacity was used for applying tensile load on the test pieces. An oven was used to heat the test pieces along with tie rods, connectors and other attachments of the load string. The details of this assembly are shown in Fig.2. Chromel-alumel thermocouples were placed at three different locations along the axis of the test piece. The test assembly was soaked for 2 hours at the desired temperature before commencement of the test. A pulling rate of $3.0X10^{-2}$ mm/sec was employed and test pieces were pulled to a displacement level where either a specified load was reached or the wall thickness of the calandria tube started showing localized thinning (necking). The test pieces were then unloaded and subjected to helium leak test. Detailed metallographic investigation was carried out on small sections taken from various locations (deformed region, weld region, rolled joint area, etc.) of the test spools after the tensile pulling. For the purpose of comparison, small sections for metallographic investigation were also taken from a test piece which was not subjected to pull out test.

3 RESULTS AND DISCUSSION

A typical load-displacement test record is shown in Fig.3. It is seen that the load initially increased linearly with displacement followed by a work hardening region. The load recorded at yielding varied from 12 to 13 tons for the test pieces pulled. The load continued to increase till the end of the test. No major load drop was noticed that could be associated with pull out or slippage of the tube from the joint. All the test pieces exhibited necking in the central portion of the calandria tube.

Table I summarizes the results of the mechanical testing before and after the pull out tests. It may be noted that the maximum load sustained by the test pieces before the

Table I : Details of Tensile Pulling and Helium Leak Rate Tests

Test No.	Maximum load sustained (Tons)	Helium Leak Rate x 10^{-7} (cc/sec) Before Pulling	After Pulling	Remarks
1	15.9	J1* 3400 J2* 820	-- --	Necking of calandria tube, no slippage at rolled joint
2	17.2	J1 20 J2 7.2	1.3 4	"
3	17.3	J1 0.44 J2 4.6	7.2 0.88	"
4	15.2	J1 4 J2 0.06	-- --	"
5	16.4	J1 100 J2 100	--	"

* J1, J2 corresponds to two joints of a test piece

test was terminated varied from 15.5 to 17 tons. These loads may be compared with the load that is expected in the joint from various sources. The maximum axial stress in the calandria tube is approximately 160 MPa (combined value for stresses due to axial load and bending moment) (Mahindru 1976). The axial load is computed to be 7 tons by considering the cross sectional area of the calandria tube. Thus the loads sustained during tensile pulling at 125°C are well above the load that arises during reactor operation. In fact, the computed axial load is even lower than the observed yielding loads of the test pieces which varied between 12 to 13 tons as mentioned earlier. Further, the loads sustained are higher than the load corresponding to the ultimate tensile strength of the calandria tube (at 125°C) which is calculated to be 14 tons.

The observed helium leak rates before and after the tensile pulling are comparable and are within the acceptable limits (Table I).

It is clear from the results of the preceding sections that the joints posses adequate strength up to 125°C and that the joints can withstand a load higher than that is required for introducing plastic instability in the calandria tube material. Further, the helium leak rate tests confirm that the integrity of the joint is maintained even after subjecting the joint to a much higher load than those expected at service conditions.

Metallographic investigation has been carried out primarily to identify features of slippage, plastic deformation(twin and slip) and local fracture, if any, and their distribution and density at various locations of the joint. Fig.4 is a composite metallograph which depicts microstructure of the bend section and straight portion (of the rolled joint) of calandria tube material before and after tensile pulling. The microstructure of straight portion of the joint before deformation corresponds to starting microstructure of the tube and reveals equiaxed grains which resulted from the annealing operation during the final stage of tube fabrication. The microstructure of the bend section after tensile pulling, on the other hand, reveals elongated grains within which a large number of lenticular twins can be seen. Twinning usually occurs during deformation of zirconium and its alloys at a temperature of about 100°C when deformation by slip is constrained or in the presence of multiaxial state of stress (Tenckhoff 1988). Microstructure of the bend portion after tensile pulling revealed features similar to those observed before the test. An estimation of the number density of twins showed a larger volume fraction in the latter case. Lenticular twins have also been observed in straight portions of the joint after tensile deformation but with a lesser frequency. However the equiaxed morphology of the original grain structure

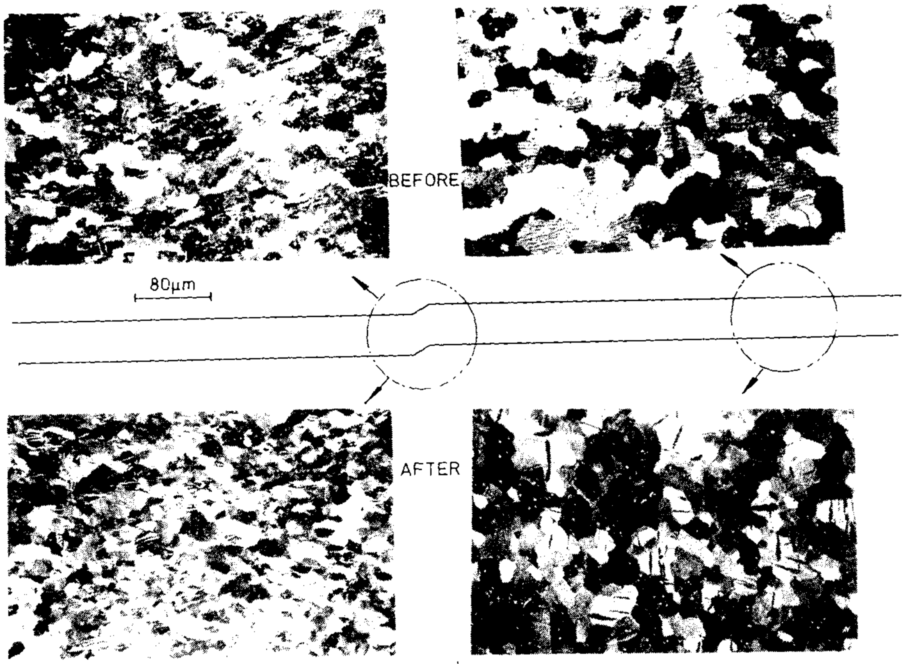

Figure 4. Schematic drawing of a section of the calandria tube from the rolled joint area and representative microstructures before and after the pull-out test.

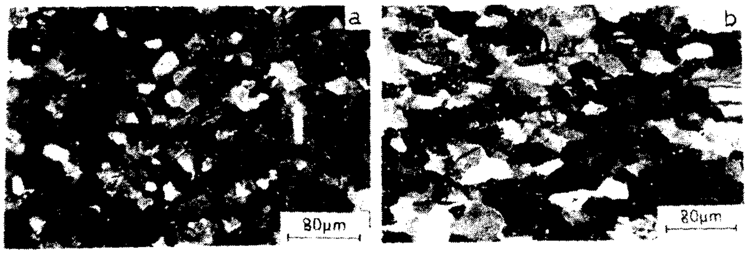

Figure 5. Microstructures of the calandria tube after the pull out test exhibiting (a) equiaxed grains far away from the neck region and (b) elongated grains at the neck region.

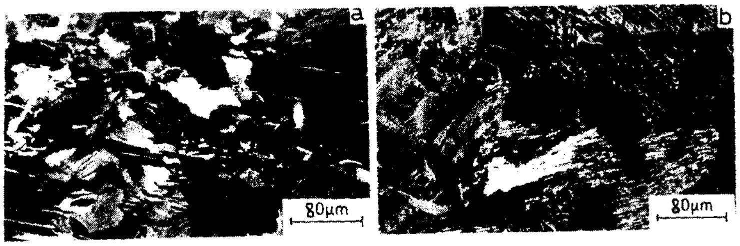

Figure 6. Micrographs taken from the neck region of the calandria tube corresponding to (a) the weld bead and (b) the interface between the weld and the base metal.

was preserved. The microstructural descriptions given above are typical of all the bend sections and their adjoining straight portions. The absence of elongated grains in the straight portions i.e. away from the bend sections confirms that there is no relative movement between the tube sheet and the calandria tube in the rolled joint. While the occurrence of lenticular twins in equiaxed grains in the straight portions points to the fact that deformation by slip is constrained at these locations because of the presence of multiaxial stress during tensile deformation. Thus it is clear that the applied load is shared by the bend sections as well as the straight portions as an integral component of the joint even at the maximum load sustained. It may be interesting to compare the microstructure of the central portion of the calandria tube where deformation is not constrained (Fig.5). The initial equiaxed grains (Fig.5(a)) become elongated (Fig.5(b)) in the direction of pulling and elongated grains are free of deformation twins. This is in contrast to that has been observed during constrained deformation as involved in the rolled joint areas. The total axial strain experienced by the test pieces during tensile pulling is estimated to be 20%. Even at this high level of deformation no sign of cracking or fracture has been noticed at any location. The microstructures of the most vulnerable regions like the weld bead (Fig.6(a)) and the interface between the weld and the base metal (Fig.6(b)) are free of microcracks. Thus the results of metallographic investigation further substantiate the observations of tensile pulling and leak detection tests.

4 CONCLUSIONS

On the basis of the present work following conclusions are drawn:

1. The maximum stress values attained by the calandria tube test pieces at the elevated temperature of 125°C are considerably higher than those are expected during normal reactor operation.
2. Metallographic observations indicate that the entire rolled joint participates in supporting the load at all stages of pulling at the test temperature. Further the residual contact stress in the radial direction persists to cause triaxiality condition and leak tightness in the joint area.
3. The heavily deformed microstructure remains confined to the bend portion only indicating that there is no relative movement between the tube sheet and calandria tube as well as calandria tube and the insert.

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