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Hydraulically Expanded Tube-to-Tubesheet Joints

To avoid stress corrosion cracking, a method of producing tube-to-tubesheet joints with low residual stresses was sought. Hydraulic expansion was found to be an acceptable method. In this paper, the experimental and theoretical work done to determine these stresses is presented. The area of interest is the transition region between the expanded and unexpanded sections of tubing. X-ray diffraction, stress corrosion cracking test and strain gaging were the prime measuring techniques used. Extensive use of finite element analysis was also made. In addition, the pull strength, length change, etc., of this type of joint were investigated.

Introduction

There are several techniques for expanding tubes into the tubesheets of steam generators and heat exchangers; all leave residual stresses in the tube wall. If these stresses are tensile and above 100 MPa, the tube is susceptible to stress corrosion cracking. Some steam generator manufacturers do a thermal stress-relief after expansion to reduce these high residual tensile stresses. However, situations arise where this is impractical if not impossible. The in-situ repair of steam generators in some CANDU nuclear power plants was such a situation. For this repair, an urgent program was carried out at the Chalk River Nuclear Laboratories (CRNL) to find a tube-to-tubesheet joint with low residual stresses.

According to the literature, there are three main techniques used for tube expansion; rolling, explosive forming, and hydraulic forming. Rolling is by far the most commonly used technique and unfortunately, the only one for which comprehensive residual stress measurements have been made. Tube expansion by rolling is a crushing process that hardens the material and distorts the grains. Hence, the residual stresses are high and there is a substantial tube elongation which may induce additional axial stress.

Explosive forming has been successfully used to expand tubes into tubesheets. This is done by detonating a carefully sized charge inside each tube causing it to deform and make contact with the tubesheet. Little is presently known on the residual stresses produced. This will be resolved by the continuing work at CRNL on tube-to-tubesheet joints.

Hydraulic forming is a relatively new method for attaching tubes to tubesheets in heat exchangers. It was developed by Balcke-Dürr AG of West Germany [1] and is now used by a number of other companies. Again very little was known about the residual stresses from this process. However, the accurate control of working pressure in hydraulic expansion suggests that the stress levels should be less than those produced by roller expansion.

From these preliminary investigations, it was concluded that only hydraulic expansion could produce a low-stress joint, and be developed in the time allocated for the in-situ steam generator repairs. This paper describes our experimental work on hydraulic-expanded joints, which included stress corrosion tests, X-ray diffraction and strain gauging. Also, the finite-element analysis done to show that hydraulic expansion does produce joints with acceptable stress levels is described.

Hydraulic-Expansion Tooling to Make Test Samples

Hydraulic expansion of tubes into tubesheets can be done by either the "bladder" or the "O-ring" technique. In the bladder technique (Canadian Patent 1152876), a bladder is inserted into the tube and then pressurized hydraulically to expand the tube. In the O-ring technique, a mandrel with two O-rings at appropriate locations (see Fig. 1) is inserted into the tube. Hydraulic pressure applied between the O-rings causes the tube in that region to expand. This was the technique used to produce the samples for our study.

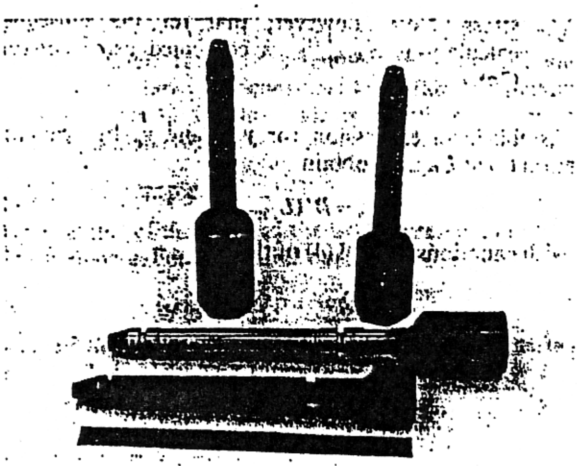

Fig. 1 Typical hydraulic expansion tooling

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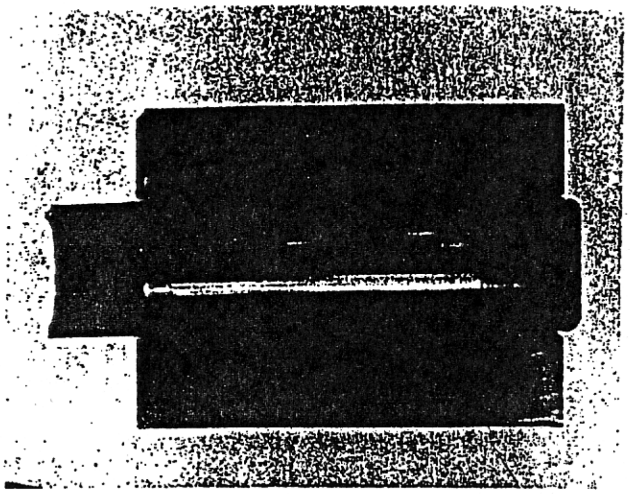


Fig. 2 Example of tube which had been expanded inside its sleeve

Stress Corrosion Tests

Stress corrosion tests can be used to locate and estimate the maximum tensile stresses at the surface of expanded tubes. Samples of the expanded joint are exposed to a corrosive environment for specific periods of time. If tensile stresses exist, cracks will form on the surface. The longer the test, the lower is the stress required to initiate cracking. Therefore, by timing the test until the first cracks are observed, and by comparing this time to that required to form cracks in calibration samples, the maximum stress in the sample can be deduced. The cracks that appear are normal to the direction of maximum stress at that point.

The time to produce these cracks depends on the choice of corrosive environments and the material under test. Austenitic stainless steel samples are very sensitive to boiling magnesium chloride and tests can be run in a few days. Unfortunately, this test does not work with Incoloy-800, the material of prime interest in this investigation. For Incoloy-800, boiling sodium hydroxide is normally used but this test takes 6 to 9 months to get results. Since the time available was short and because the stress levels in Type-304 stainless steel samples should be similar to those in Incoloy-800 samples, it was decided to do tests with both materials. The results of the Incoloy-800/sodium hydroxide test are not available for this paper.

The tests with the stainless steel consisted of exposing the samples to boiling magnesium chloride at 154°C for 24, 48 or 96 hours. In all, 27 samples plus a number of calibration samples stressed to known levels were tested. Twenty-one of the samples were produced by hydraulic expansion, 3 by roller expansion without stress relieving and 3 by roller expansion with subsequent stress relieving. After a macroscopic examination for cracks, each sample was sectioned longitudinally, as shown in Fig. 2. The tube sections were then removed and re-examined for cracks hidden by the sleeves.

Sections containing both ends of the expansion transition zones were metallographically examined for cracks. Longitudinal cracks were observed in 13 of the 21 hydraulically expanded tube samples. In 6 of these, the cracks extended under the sleeves. For some of the tube samples, the transition zone was well inside the sleeves, making it impossible to determine by macroexamination, where the longitudinal cracks ended relative to the expanded region.

Two transverse sections containing longitudinal cracks, one with the cracks ending under the sleeve, and the other with the cracking ending outside the sleeve, were ground down and photographed at measured intervals. At each interval the radius of the tube was calculated from 3 points on the outside tube diameter on each photomicrograph. This showed that both cracks ended in the transition zone.

Transverse cracks were also observed in 9 of the hydraulically expanded tube samples. These cracks were outboard of the end of the sleeves but within the transition zone. In 4 of the 9 samples the tube expansion had extended beyond the end of the sleeves, causing a bulge on the outside of the tube.

The 3 samples produced by roller-expansion without subsequent stress relieving contained transverse cracks (Fig. 2). No cracking was present in the roller-expanded tubes that had been stress relieved after expansion.

These results indicate that, the residual stresses in hydraulically expanded joints are higher than those present in rolled joints that have been stress relieved, but considerably lower than those in rolled joints that were not stress relieved. Using the calibration samples as reference it was deduced that the tensile residual stresses in the hydraulically expanded samples were less than 70 MPa. X-ray diffraction tests done on stainless steel samples since then, have confirmed this.

X-Ray Diffraction Stress Measurements

X-ray diffraction is a technique widely used for determining the surface stresses in crystalline materials. Because of this and its ability to produce results quickly, X-ray diffraction was used on the Incoloy-800 hydraulically-expanded samples. These measurements showed that hoop stresses are dominant. This agrees with the results from the stress corrosion tests which showed that most cracks were longitudinal, i.e., perpendicular to the plane of maximum stress. On the other hand, previous work had shown that axial stresses were dominant in rolled joints.

Initial measurements with this technique indicated stress levels considerably above those deduced from the stress corrosion tests. This raised questions as to

- the applicability of stress corrosion cracking results obtained for stainless steel tubing to Incoloy-800 tubing, and
- the accuracy of x-ray diffraction on severely deformed tubing.

Since the material properties of Incoloy-800 and Type-304 stainless steel are nearly identical, it was argued that the stainless steel results should represent the stress levels in the Incoloy-800 joints. As for the accuracy of the X-ray diffraction technique, the literature indicates that it can give misleading results when used on plastically deformed bodies [2]. However, the literature also cites cases where the technique can be used on plastically deformed bodies [3].

Another possible reason for the discrepancy was the presence of a work-hardened layer on the surface of the Incoloy-800 tubing prior to expansion, due to surface grinding during manufacture. The stainless steel tubes were not surface ground. To check this theory, a number of samples made from Incoloy-800 tubing, that had the surface layer etched away, were tested by X-ray diffraction. The results confirmed this hypothesis.

In summary, the X-ray diffraction measurements showed that the surface tensile stresses in the Incoloy-800 tubes do not exceed 550 MPa and fall to 90 MPa 0.06 mm below the surface. This was confirmed by a finite element analysis, as described later.

Strain Gage Measurements

The use of strain gages to measure residual stresses in expanded tubes is normally considered difficult. Tube expansion techniques usually induce residual stresses with steep gradients, which implies small strain gages located close together. Our initial estimate of the stress gradient in this transition zone indicated that 3 or 4 gages installed over a

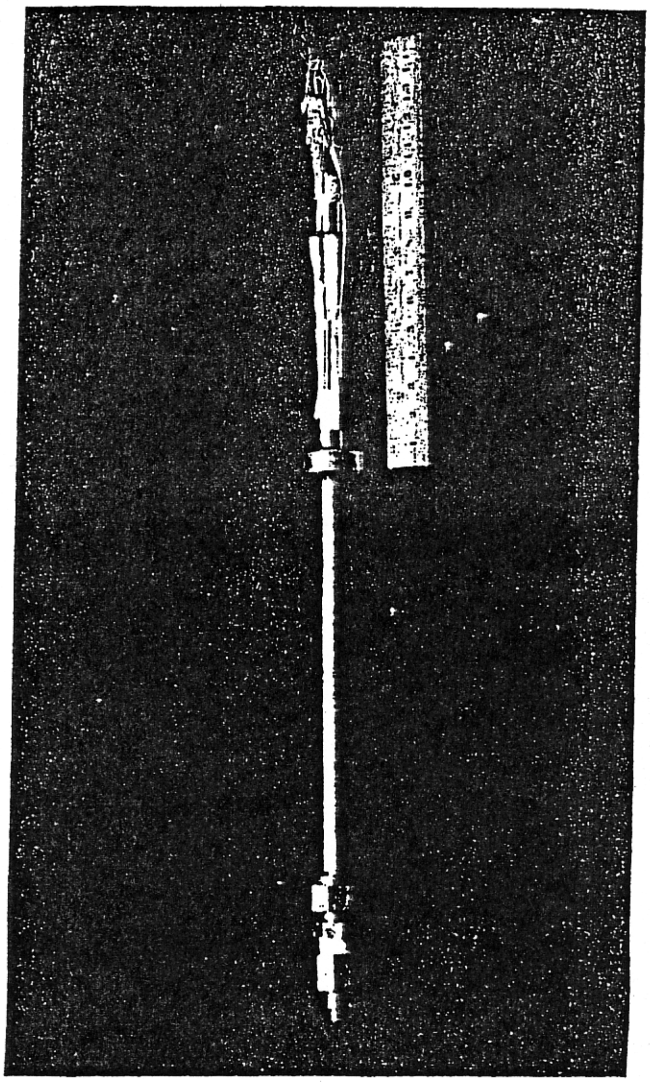
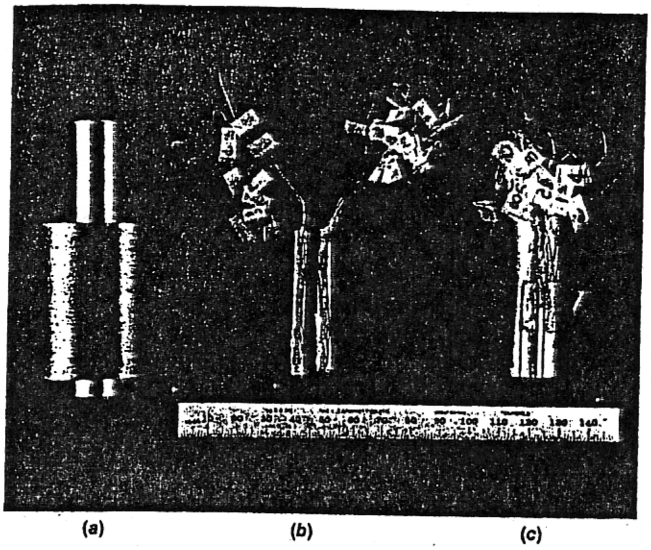


Fig. 3 Strain gage application tool ready to use



(a) (b) (c)

Fig. 4 (a) Typical hub, (b) stress-relieved strips ready for measuring gage location, and (c) stress-relieved tube with saw cuts

distance of only 2.5 mm would be required. Furthermore, this transition zone is relatively inaccessible, being mostly inside the sleeve used to simulate the tubesheet.

To carry out this part of the work a source of miniature strain gages was first found and a method to install them inside the tubes was developed. Installation was carried out after hydraulic expansion, to avoid damage to the gages. The strain gages used, came in strips of 10 gages, each with an active length of 0.7 mm. Three strips spaced at 120 deg were installed in each tube, one to measure axial strain and two to measure circumferential strain. By axially staggering the latter, greater resolution is obtained. To facilitate installation, each gage strip was prewired and mounted on a pad of silicone rubber. This pad acted as a backing that protected the wires and provided a flat surface to ensure uniform pressure during attachment of the gages.

The strain gage application tool, shown in Fig. 3, consists of a rubber bladder placed over a metal tube with one end closed and holes along its length.

Strips of strain gages were temporarily attached to the bladder and the application tool was positioned in the tube. Then the bladder was expanded at a pressure of 70 kPa. This allowed for proper bonding of the gages to the inside of the tube with an epoxy-type glue. A collar on the tool controlled the insertion depth and thus the axial location of the gages. A typical strain gage installation is shown on Fig. 4.

To measure the residual stresses in the tube, these stresses must be released. This was done by first cutting away the sleeve and then making axial cuts in the tube (see Fig. 4). These axial cuts were made with a pair of ganged slitting saws, spaced approximately 6.3 mm apart to avoid damaging the strain gages. Because of the small tube size (5/8 in. o.d.), the cut-out strip can be in segments of as much as 45 deg. Consequently, the flexural rigidity of this curved strip is greater than that of a flat strip and the axial residual stresses are not completely released. Where possible, the strip width was reduced by 1 to 1.5 mm, which changed the strain readings by up to 300×10^{-6}.

After the strain measurements were taken, the axial location of the gages was accurately measured relative to the transition zone. This provided the information necessary to calculate the residual stresses and obtain the stress distribution.

Although ideally the expansion process is axisymmetric, the strain gage measurements indicate that there can be large strain variations around the circumference. A variation of up to ± 50 percent is thought possible, which could indicate that the strain gage measurements are not very accurate. However, the strain gage results, as shown in Fig. 5, agree well with the results obtained by the other techniques used to determine residual stresses.

Finite Element Analysis

Description of Code. The code used to predict the residual stresses was the MARC[1] General Purpose Finite Element Program. MARC is a large code designed for linear and nonlinear analysis of structures in both static and dynamic regimes. For this work the tube-to-tubesheet system was modelled as a static, nonlinear elastic-plastic problem by using: 1) nonuniform material properties to accurately model the tube, the tubesheet and in some instances a hardened surface layer on the tube, 2) strain hardening to allow accurate tracking of the stress-strain state as the tube yields, 3) gap elements with zero stiffness when open, and with infinite stiffness when closed to model the initial tube/tubesheet clearance, 4) nonuniform pressure loading of a surface to simulate the actual hydraulic expansion technique, 5) an initial stress state in some runs, to simulate as-received tubing; and 6) step changes in model temperature

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[1] MARC Analysis Research Corporation of Palo Alto, Calif.

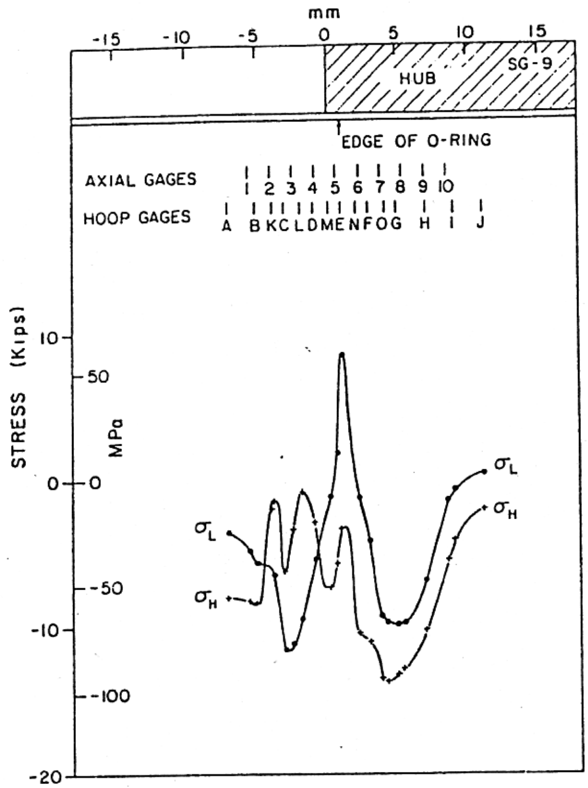

Fig. 5 Stresses calculated from strain gage measurements

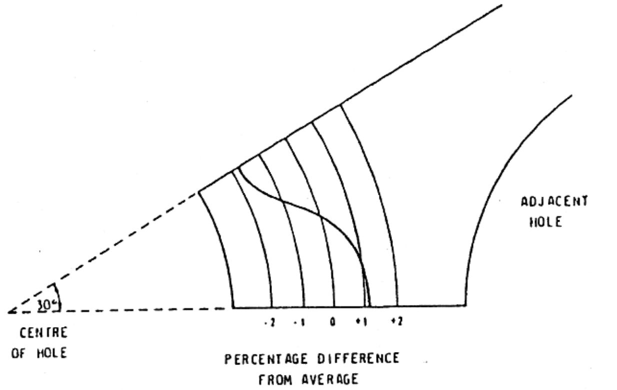

Fig. 6 Variation of tubesheet radial compliance around the tube hole perimeter

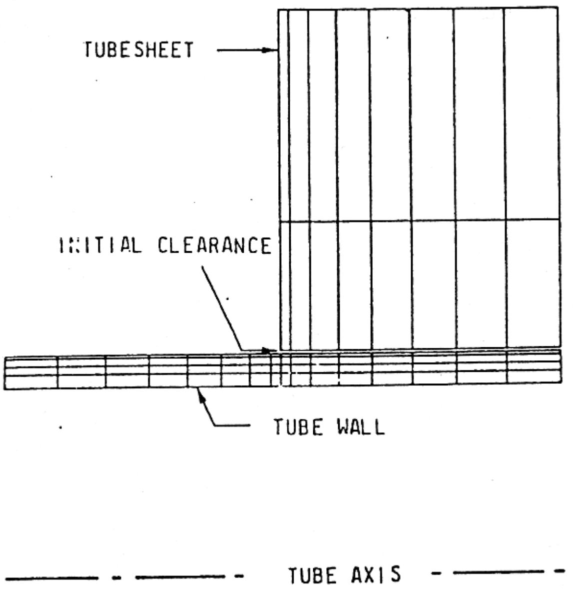

Fig. 7 Finite element model of a tube within a cylindrical sleeve

to determine the effect of temperature on the steady-state stress.

Tubesheet Compliance Analysis. The tube expansion models, both real and computer simulated, should be as realistic as possible. However, expense precludes the use of even a partial tubesheet to study the residual stresses in the tube transition zone. Thus, the tubesheet is modelled as an axisymmetric steel sleeve into which the tube is expanded. The MARC code was used to determine the error introduced by the assumption of axisymmetry and to find the equivalent wall thickness of the sleeve.

The 12-sided symmetry of a triangular pitch tubesheet was exploited to reduce the model to a 30-deg wedge with its apex on a hole centerline. As shown in Fig. 6, the sides of the wedge were constrained to move radially to preserve symmetry. Whereas, the outer edge was either free or fixed, to bracket the true behavior. Pressure was applied to the inner surface of the hole and the model was allowed to find equilibrium. The movement of the nodes on the inner diameter of the tube was used to find both the tubesheet compliance and the nonuniformity around the circumference. The calculated asymmetry in radial compliance was small (see Fig. 6), so axisymmetry was assumed for all subsequent models.

Boundary Conditions, Loading and Material Properties. The chosen mesh, shown in Fig. 7, was a compromise between adequate resolution and program running cost. Several boundary conditions had to be applied to the mesh to minimize end effects and restrain rigid body movement.

For example, the right edge of both the tube and the tubesheet were not permitted any axial motion. This held the mesh in place axially and minimized frictional-force errors. The gap elements had no friction component, theoretically allowing sliding between the tube and tubesheet regardless of contact pressure. During expansion, the gap closes on the right first. Since most of the axial contraction occurs before contact, the absence of friction in the model should not significantly affect the results.

The left edge of the tube was restrained radially, making it somewhat stiffer than the actual case where the tube simply extends further to the left. This should yield conservative results. In any event, the restraint forces calculated by the program at this edge were very small, meaning that in the real case the movement would be small.

The model was loaded using a simulated hydraulic pressure. Radial forces were exerted along the inside surface of the tube corresponding to a given pressure. When the maximum pressure was reached, the forces were removed leaving residual stresses in the tube.

Several times during the project, better estimates of the mechanical properties were found in the literature or measured experimentally. This resulted in several program revisions. However, the tubesheet was always assumed to be of carbon steel with properties E (Young's modulus) $= 21 \times 10^4$ MPa, ν(Poisson's ratio) $= 0.3$ and α (coefficient of thermal expansion) $= 11.7 \times 10^{-6}\,^\circ\mathrm{C}^{-1}$.

The tube properties were $\nu = 0.34$, $E = 19.7 \times 10^4$, and $\alpha = 14.4 \times 10^{-6}\,^\circ\mathrm{C}^{-1}$.

Parameter Studies. Runs were done to determine the sensitivity of the residual stresses to various input parameters such as load and material properties. The base for comparison was an annealed tube pressurized to 248 MPa. Results were presented as plots of axial and hoop stress on the tube outer

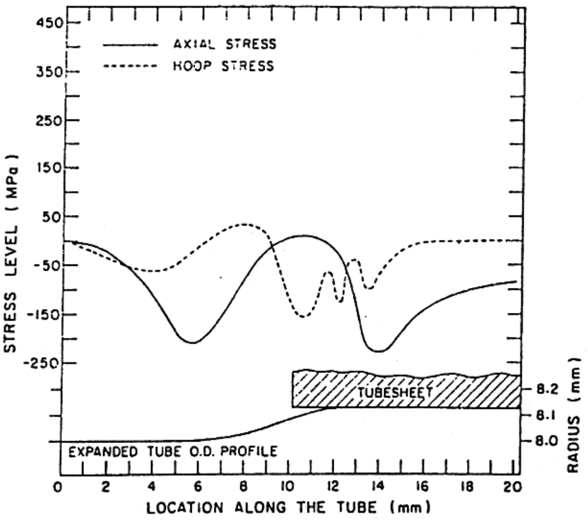

Fig. 8 Typical result showing curves drawn through the 48 calculated stresses on a horizontal subsurface plane of the tube

surface (the program actually calculates the stresses at a point 0.02 mm below the surface) against the axial position along the tube (see Fig. 8).

The effect of different expansion pressures on the axial residual stresses were calculated. With increased expansion pressure the curvature in the transition zone becomes sharper. However, the residual stresses are relatively insensitive to changes in the expansion pressure. At an expansion pressure of 138 MPa, the program predicted zero contact pressure between the tube and tubesheet (but negligible gap opening).

As mentioned earlier, the Incoloy-800 tubing had a work-hardened surface layer. To simulate this, the outside layer of tube mesh elements were given a higher yield strength. As expected, the calculated residual stresses in the hardened zone were higher because of this higher yield strength. However, this was only a surface effect and 0.2 mm below the surface, the stresses were comparable to or less than the "standard case."

The coefficient of thermal expansion of the tube is 23 percent larger than that of the tubesheet. When the system was subjected to a uniform temperature increase, the tube tried to expand more than the tubesheet. Consequently, the surface stresses were significantly higher at reactor operating temperature (290°C) than at room temperature. It was also noted that the contact pressure between tube and tubesheet was lower after a thermal cycle, suggesting some degree of stress relieving.

Pull Strength and Dimensional Changes

Although the main objective of this investigation was to determine residual stresses, other parameters such as pull strength and dimensional changes were also measured and compared to rolled joints.

Pull strength is the axial force required to break the "bond" between the tube and sleeve. This was done on a tensile testing machine by straining the joints at a set rate while recording the load on a strip chart recorder. The pull strength was determined as the load at which this plot first deviated from a straight line. In most cases, this point was easily discernible.

During these tests the effects on pull strength of thermal cycling, joint temperature and of placing grooves in the sleeves were investigated. Of interest is the difference in frictional characteristics between cold and hot pull tests. Under cold conditions, the force increased to a maximum value and then dropped as the contact surface area was reduced. During hot conditions, the force had a repetitive saw-tooth pattern for many cycles. This is typical of "stick-slip" friction or galling.

To summarize the results, hydraulically expanded joints are: (*a*) weaker than rolled joints, (*b*) weakened by thermal cycling, (*c*) 15 times stronger at reactor operating temperature than at room temperature, and (*d*) 13 times stronger if expanded into a grooved tubesheet.

Dimensional measurements of the samples showed that: (*a*) during hydraulic expansion, the tube length shortened by approximately 6.47×10^{-3} mm/mm of expanded length, and (*b*) the tube wall thickness decreased approximately 2.5 percent.

Discussions

Each of the techniques used to measure residual stresses has certain advantages and disadvantages. Stress corrosion cracking tests give a good indication of the orientation of the principal stresses and with suitable calibration give approximate stress values. Unfortunately, tests on Incoloy-800 take 6 to 9 months to run and there is some question as to the applicability of short term tests done on Type-304 stainless steel.

X-ray diffraction has the advantage of measuring surface stresses directly. Its limitation is the difficulty in making measurements at the required location, i.e., under the sleeve. Also the X-ray beam size could mask some high-stress gradients.

Strain gage measurements have limitations similar to those of X-ray diffraction measurements. In addition, when strain gages are used, the material must be cut to release the strains elastically. Only when the residual strains are proportional to distance from the neutral axis are the resulting measurements accurate. If this is not the case, then some strain is not released and usually the predicted stress is too small. The advantage of using strain gages is that no sophisticated equipment is required.

Finite element analysis is very useful for prediction of both surface and through thickness stress distributions. It is also useful for studying the effect of parameters such as expansion pressure. Its main disadvantage is that it requires accurate values of the material properties. These are often difficult to find.

Incoloy-800 tubing, the material of interest in this investigation, has a cold-worked surface layer. The maximum tensile stress predicted for this layer was 550 MPa. This is based on the results of the finite element analysis and the X-ray diffraction measurements. Residual stresses of this magnitude are well above the acceptable limit of 100 MPa for stress corrosion cracking. However, the stress levels fall rapidly just below the surface. At a depth of 0.12 mm the stresses predicted by MARC did not exceed 50 MPa. Furthermore, the X-ray diffraction results indicated maximum tensile stresses of 90 MPa approximately 0.06 mm below the surface. Independently taken X-ray diffraction measurements at a depth of 0.08 mm were all compressive [4]. The magnesium chloride tests on strainless steel samples, which had no cold-worked layer, and the results of the strain gage measurements which were insensitive to the high surface stresses help to confirm these results.

Conclusions

1 Hydraulic expansion produces joints with residual stresses acceptable from a stress corrosion point of view.

2 There is reasonably good agreement between the different methods used to determine residual stresses.

3 Ground tubing should preferably be annealed or pickled to remove the work-hardened surface layer before expansion. The results show that annealed tubing produces joints with lower residual surface stresses.

4 The strain gage measurements indicate that although the expansion process is ideally axisymmetric there can be large variations in the stress around the tube.

5 The pull strength of hydraulically expanded joints are significantly less than rolled joints.

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