EXTERNAL GLASS PEENING OF ZIRCALOY CALANDRIA TUBES TO INCREASE THE CRITICAL HEAT FLUX

R.W.L. Fong, C.E. Coleman, T. Nitheanandan, V.D. Kroeger, R.G. Moyer, D.B. Sanderson
Atomic Energy of Canada Limited, Canada

J.H. Root, and R.B. Rogge
National Research Council, Canada

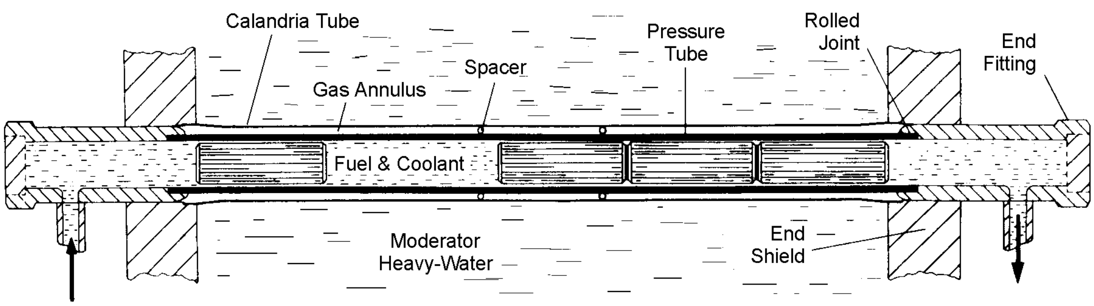
ABSTRACT

Glass-peening the outside surfaces of Zircaloy calandria tubes increases the nucleation sites available for boiling heat transfer and has been demonstrated to enhance the critical heat flux (CHF) in pool-boiling experiments. The objective of this study is to optimise the heat transfer enhancement by glass peening while ensuring that the microstructure of the peened tube is acceptable for reactor use. Pool boiling tests were done using small Zircaloy tubes with as-received ("smooth") surfaces and variously-peened surfaces, to evaluate two peening parameters, glass-bead size and the coverage of peened surface. Our results showed that the maximum enhancement of CHF (by 60% compared with as-received tubes) was obtained using a glass-bead size of 90-125 µm with a coverage of 100%. The CHF enhancement was found to be insensitive to glass-bead size over a wide range (from 60-90 µm to 125-180 µm). Using a fixed glass-bead size of 125-180 µm to evaluate the influence of peening coverage, the maximum effect on the CHF response was obtained with a coverage of 100%. The microstructures of the peened tubes were evaluated using light microscopy, X-ray and neutron diffraction, and mechanical tests. After peening, the microstructure in the sub-surface layer (~30 µm) consisted of deformed α-Zr grains and the crystallographic texture of the grains changed slightly. After stress-relieving at 500°C for 1 h, some re-crystallisation had occurred and the residual strains remaining in the tube were low. The tensile and burst properties of glass-peened and stress-relieved tubes were similar to as-received tubes. The microstructures introduced by peening and stress-relieving were judged to have little effect on creep and growth behaviour. Since there are no deleterious consequences of the glass-peening treatment, the peened and stress-relieved tubes are found to be acceptable for reactor use.

INTRODUCTION

In the fuel channel of a CANDU® reactor, the calandria tube surrounds the hot pressure tube and isolates it from the cool heavy-water moderator (Figure 1). The calandria tubes, made of annealed Zircaloy-2, are 6-m long and have an inside diameter of 130 mm and a wall thickness of 1.4 mm. Normally the operating conditions of the calandria tubes are not severe - the neutron flux is about 75% that experienced by the pressure tubes, the tensile stresses are low, and the temperature of normal operation is about 70°C.

Figure 1. Schematic diagram of a CANDU fuel channel.



In certain postulated loss-of-coolant accidents, the pressure tube may overheat and balloon into contact with the moderator-cooled calandria tube. Upon contact, heat stored in the pressure tube would be rapidly transferred to the calandria tube and into the moderator water. The sudden transfer of heat through the calandria tube to the moderator could exceed the critical heat flux at which point film boiling (dryout) occurs on the outer surface of the calandria tube. Nucleate boiling, rather than film boiling at the outer surface of the calandria tube is required to keep the calandria tube temperatures low (<150°C).

To promote nucleate boiling, the outer surface of the calandria tube is roughened using glass-bead peening. Calandria tubes having a glass-peened outer surface have been tested and shown to have better heat transfer characteristics in pool boiling conditions than "smooth" (un-peened) tubes [1]. The objective in this study is to optimise the enhancement of CHF by peening while ensuring that the microstructures of the tubes are acceptable for reactor use. Two peening parameters, glass-bead size and the coverage of the peened surface, were studied. Pool-boiling experiments were performed on small Zircaloy tubes with various peening treatments to determine the influence of surface features on the critical heat flux. During peening, compressive deformation processes introduce local changes in the microstructure below the peened surface. However, after peening the tube is given a stress-relief heat-treatment as part of the normal production requirement. The microstructures of peened tubes have been examined using light microscopy and X-ray and neutron diffraction techniques, and mechanical tests to evaluate whether the tensile and burst properties of the tube would be affected by the peening treatment.

EXPERIMENTAL

Glass-Peened Zircaloy Tube Samples

The outside surfaces of Zircaloy tube samples each having 19.4 mm O.D. x 0.76 mm wall thickness x 450 mm length, were glass-peened using industrial equipment. The peened tube samples were produced at a fixed peening intensity but using different sizes of glass beads and coverage of the peened surface. The typical surface topologies of the as-peened tube samples (Figure 2), along with samples that were not peened (i.e. having an as-received "smooth" surface) were tested in pool-boiling conditions to determine the effect of glass-peening on increasing the critical heat flux.

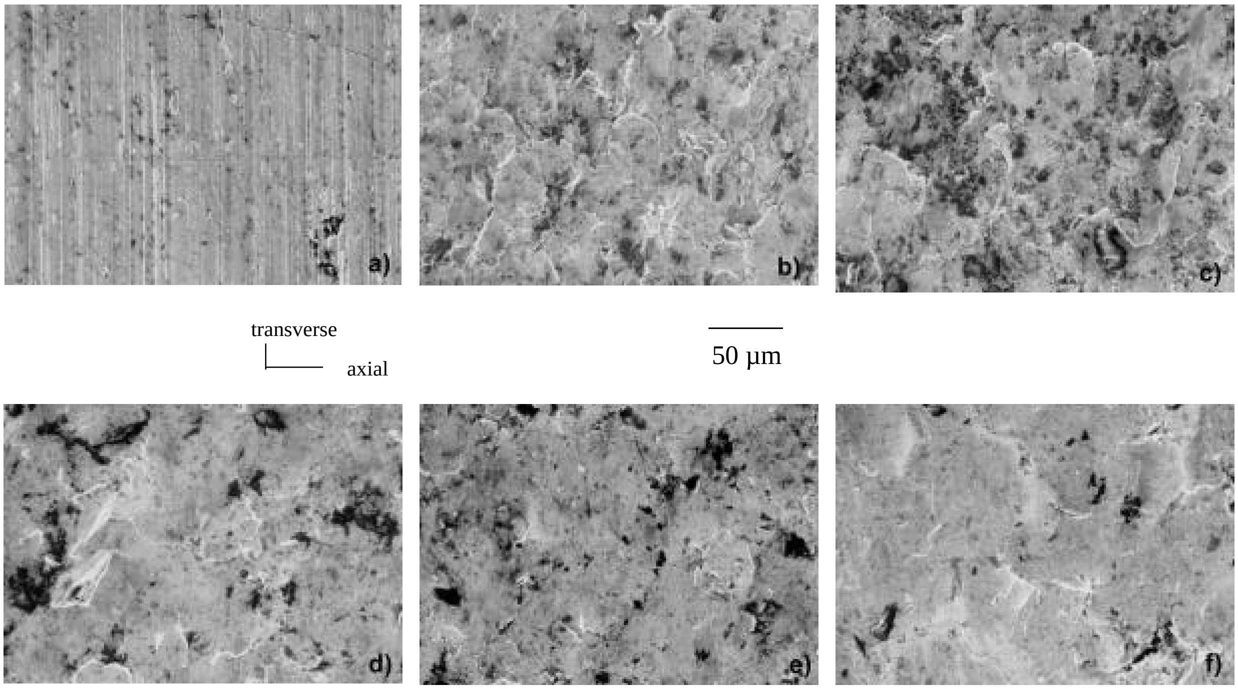


Figure 2. Comparison of surface topology of as-received and variously-peened tubes:

a) Not peened (as-received "smooth" surface),
b) Peened: 60-90 µm beads / 100% coverage,
c) Peened: 90-125 µm beads / 100% coverage,
d) Peened: 125-180 µm beads / 100% coverage,
e) Peened: 180-210 µm beads / 100% coverage,
f) Peened: 125-180 µm beads / 80% coverage.

Pool Boiling Tests

Pool-boiling tests were performed on the tube samples in a tank of water at 100°C, Figure 3. A water temperature of 100°C was chosen to minimise the temperature variation of the water surrounding the tube during the tests. Two voltage-lead taps were spot-welded on the outside surface of each tube at a spacing of 300 mm. A direct current was applied to the sample to raise the temperature of the metal while the boiling events were observed and recorded. A "spike-power ramp" procedure was chosen to apply the current to the tube sample, since this condition simulates the transient heat transfer condition that occurs when a hot pressure tube balloons into contact with its calandria tube. In this procedure the power was ramped at a rate of about 75 kW/s to the set point using a special switching circuit. This set point was steadily increased in each successive power ramp until dryout was observed on the tube sample. Once dryout was observed, the set point power was lowered and the procedure repeated at least seven times. For each occurrence of film boiling, the critical heat flux of the tube is calculated using the expression:

$$CHF = P/(\pi DL)$$

where, CHF denotes the critical heat flux, in kW/m^2, P is the power at which film boiling occurs (based on measured current times the voltage drop across the taps) in kW, D is the outside diameter of the tube sample and L is the distance between the voltage taps, both in m. The CHF values for glass-peened tube samples were compared with those for samples that were not peened (i.e. smooth) to determine the CHF enhancement:

$$\text{CHF enhancement} = \text{CHF}_{\text{peened}} / \text{CHF}_{\text{smooth}}$$

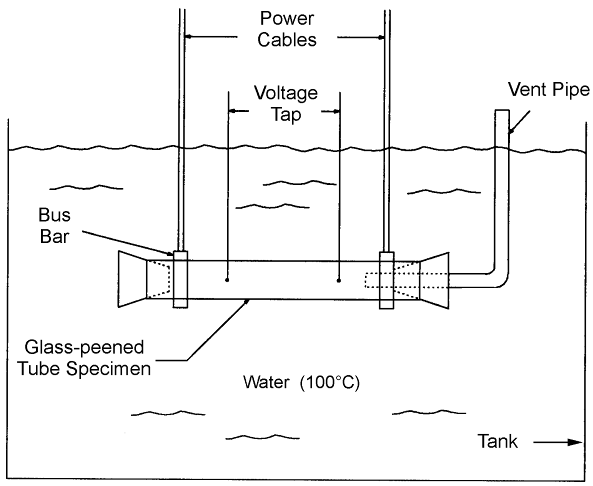


Figure 3.

Schematic diagram of experimental setup for pool boiling tests.

Metallography

The microstructures of glass-peened Zircaloy tubes in the as-peened condition and after a stress relief heat-treatment of 500°C for 1 h, were examined using standard light microscopy. X-ray diffraction was used to examine the local changes in crystallographic texture on the peened surface. The state of residual strain near and below the peened surface of the tubes was measured using X-ray line broadening and neutron diffraction techniques. The results were evaluated to determine whether the peened and stress-relieved microstructures are acceptable for reactor use.

Mechanical Tests

Mechanical tests on the peened and stress-relieved tubes were performed in duplicate to obtain tensile and burst properties for comparison with the tubes that were not peened. The results were evaluated to determine whether the properties of the tube would be affected by the peening treatment.

RESULTS

Figure 4 shows the relative increases in CHF of Zircaloy tubes with glass-peening treatments for the same coverage (100%) compared with tubes that were not peened. The maximum increase (~ 60%) in CHF was obtained from the surface that was peened using 90-125 µm size beads. Furthermore, the results indicate that there is a large range of bead sizes (from 60-90 µm to 125-180 µm) that gave similar increases in CHF near the maximum. Using a fixed glass-bead size (125-180 µm) for peening, the maximum effect on the CHF response was obtained with a coverage of 100% (Figure 5).

Figure 6 shows the microstructures of an as-peened Zircaloy tube (glass-bead size of 90-125 µm with a coverage of 100%) and one that was peened and stress-relieved at 500°C for 1 h. In the as-peened tube, the microstructure consisted of a highly deformed grain structure extending to a depth of ~30 µm. Beyond this depth there were some grains with a twinned structure. However, when the peened tube was stress-relieved at 500°C for 1 h as part of the normal tube manufacturing procedure, some re-crystallisation had occurred, indicating that the stress-relief heat-treatment was effective.

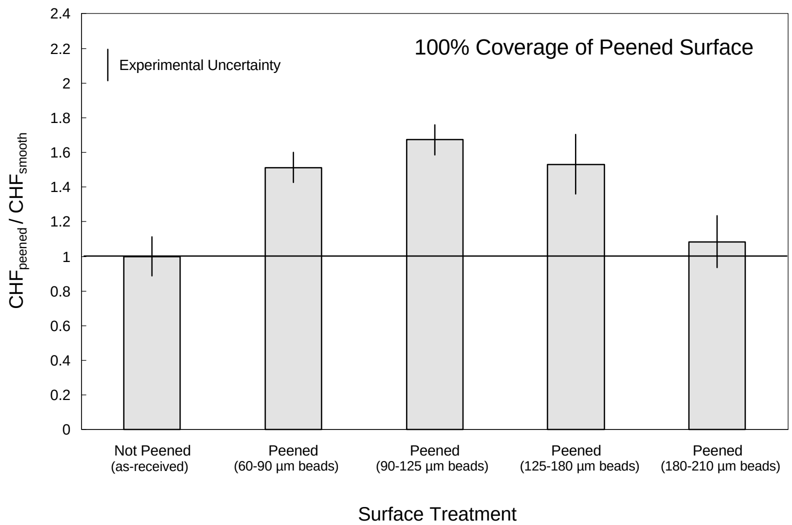


Figure 4.

Effect of glass-peening with different bead sizes on relative increase in CHF.

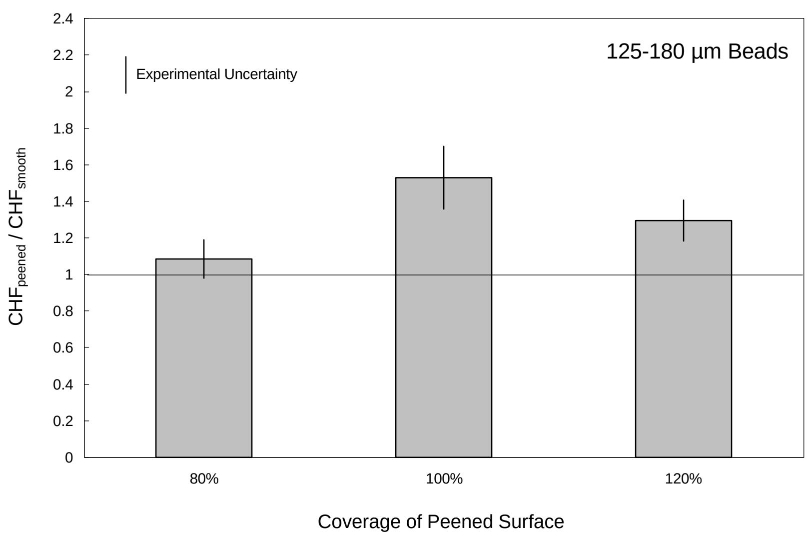


Figure 5.

Effect of glass-peening coverage on relative increase in CHF.

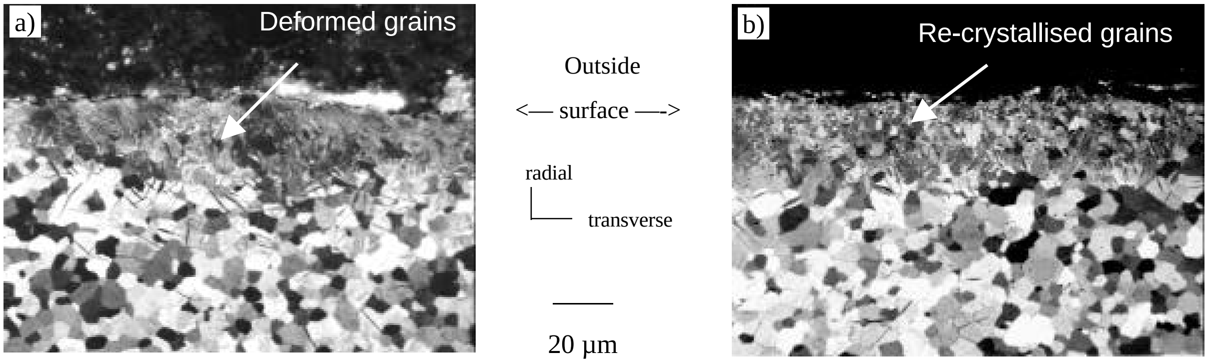


Figure 6. Micrographs Showing (A) As-Peened Tube with Deformed Grains Below the Peened Surface, And (B) Peened and Stress-Relieved Tube with Recrystallised Grains in the Peened Region.

The tensile and burst properties of peened and stress-relieved tubes are similar to the properties of calandria tubes that were not peened, Table 1.

Figure 7 shows a comparison of the crystallographic textures of the surfaces of as-received, as-peened, and peened and stress-relieved tubes measured by X-ray diffraction. The peened tubes were processed using 90-125 µm glass beads with a coverage of 100%. The texture data are represented in the form of inverse pole figures, and the resolved fraction (F_R) of the basal plane normals of the grains oriented in the radial direction of the tube is indicated beside the inverse pole figure. After peening the tube, the F_R value was reduced to 0.39 compared with a value of 0.59 for the tube that was not peened. When the peened tube was stress-relieved, the value for F_R remained similar to that of an as-peened tube.

Table 1. Comparison of tensile and burst properties of calandria tube materials.

	Tubes Not Peened	Tubes Peened* and Stress-Relieved
Transverse Tensile Properties at 25°C:		
0.2% Y.S. (MPa)	404	379
UTS (MPa)	509	513
Total Elongation (%)	31.3	31.7
Burst Properties at 170°C:		
Burst Strength (MPa)	536	539
Burst Strain (%)	1.5	1.3

*Using 90-125 µm glass beads with a 100% coverage

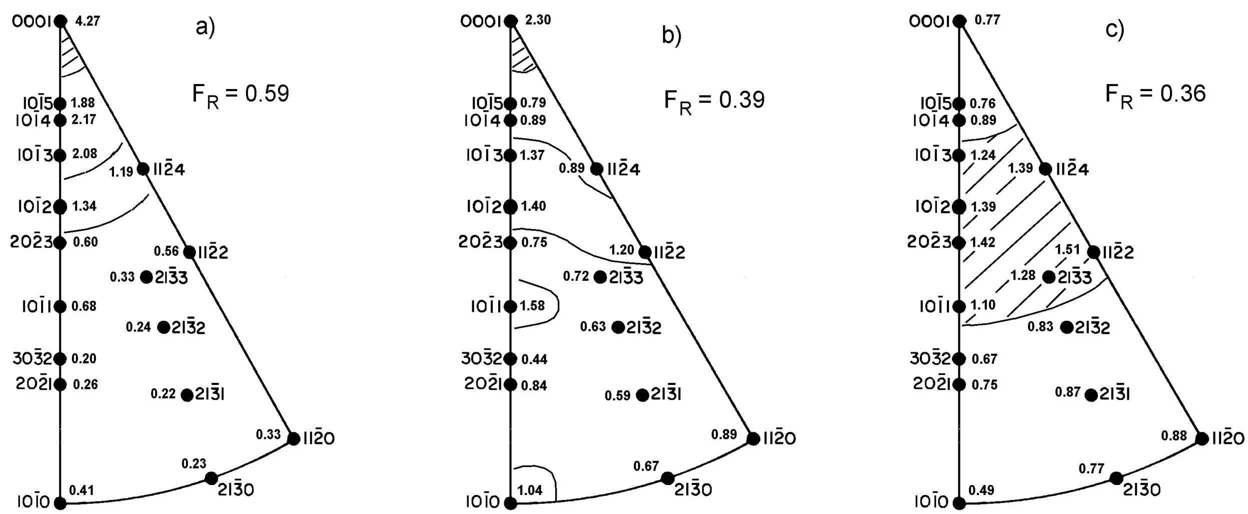


Figure 7.

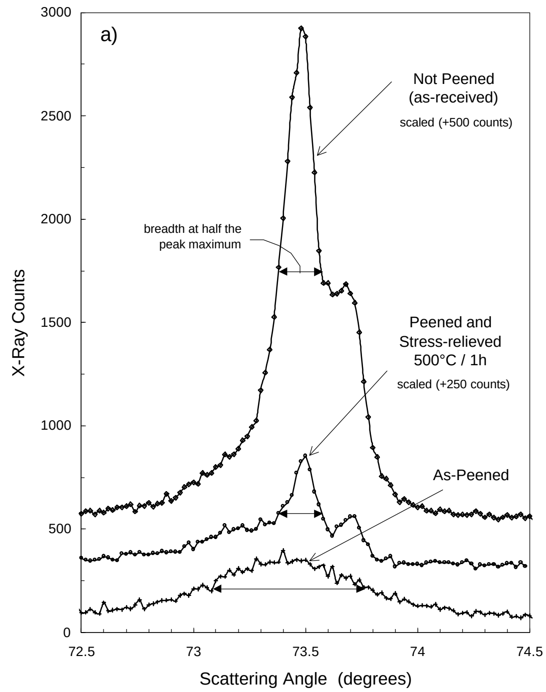
Inverse pole figure of grains on the tube surface with various conditions:

a) not peened, b) as-peened, and c) peened and stress-relieved at 500°C for 1h.

The resolved fraction, F_R, of the basal plane normals in the radial direction of the tube for each condition is indicated beside in the inverse pole figure.

The residual strains obtained from X-ray line broadening measurements are shown in Figures 8a and 8b. Figure 8a shows the changes in the breadth (width at half the peak intensity) of the diffraction profile reflected from the basal planes of α-Zr grains at the tube surface. The peak intensity of the peened tubes (as-peened and peened and stress-relieved condition) was reduced due to changes in the crystallographic texture of the grains on the surface of the tubes. The broader width of the profile indicates a larger amount of residual strain. A diffraction profile showing a sharp peak is indicative of a strain-free material, such as that seen in the tube that was not peened (Figure 8a). The results of breadth measurements obtained at various depths below the peened surface are plotted in Figure 8b. In the as-peened tube, the breadth is a maximum at the surface and decreased sharply below the surface and then leveled off in the interior of the tube wall. When the peened tube was stress-relieved at 500°C for 1 h, the line breadths were reduced to a level similar to that of an un-peened tube (Figure 8b), indicating that the heat-treatment was effective in removing the residual strains from the peened structure.

Figure 9 shows the residual strains obtained from neutron diffraction measurements. In the as-peened tube, the compressive residual strains were maximum in the peened region near the surface and then changed sharply to low tensile strains beyond the peened region. For the peened tube with a stress-relief heat-treatment of 500°C for 1 h, the residual strains were found to be low. These results confirm that the stress-relieving heat-treatment (500°C for 1 h) was effective in removing the high residual strains induced at the surface by the peening process.



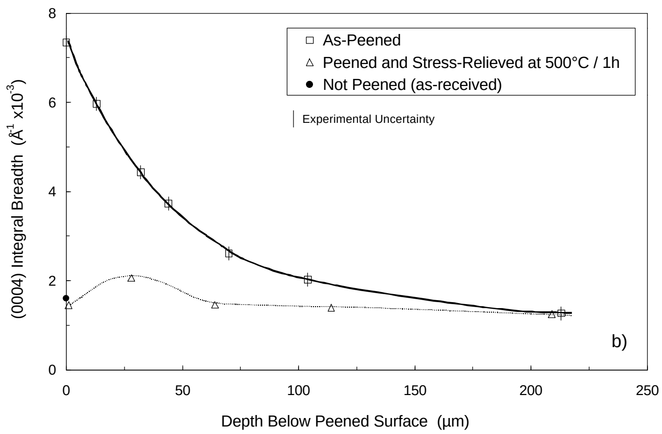


Figure 8.

a) X-ray diffraction profile reflected from basal (0004)

planes of Zircaloy-2 grains at the surface, and

b) Breadths of the diffraction profiles at various

depths below the surface.

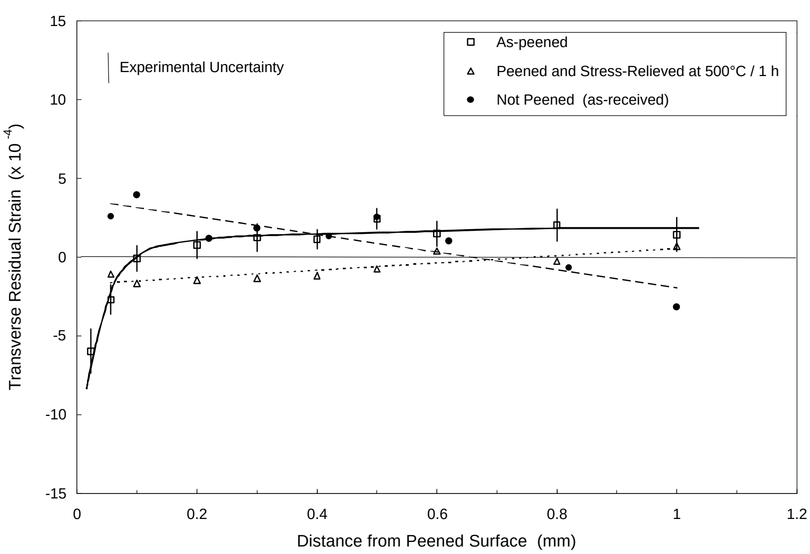


Figure 9.

Plot of residual strain as a function of distance from peened surface obtained from neutron diffraction.

DISCUSSION

Roughening the outside surfaces of CANDU calandria tubes by glass-bead peening has been shown to enhance the heat transfer characteristics in pool boiling experiments [1]. In this study to optimise the enhancement of CHF by glass-peening, using small Zircaloy tubes having variously glass-peened surfaces, our test results showed that the tubes roughened by glass-peening gave higher CHF values than tubes that were not peened (i.e. having an as-received, “smooth” surface). The results are consistent with other experimental studies conducted on samples with different surface modifications [2,3].

Previous work showed the importance of an appropriate size and distribution of nucleation sites (e.g. cavities) to form small vapour bubbles that would depart rapidly from the heated surface, thus increasing the CHF by avoiding coalescence of the bubbles on the surface [2]. For glass-peened surfaces, we attributed the enhancement of CHF to an increased density of nucleation sites such as small crevices produced by peening the surface (compare the numerous crevices represented by the dark features in Figures 2b to 2f with those in Figure 2a). A lower density of these features is produced when the surface is peened using a larger bead size (180-210 µm) for the same coverage of 100% (Figure 2e), and similarly, for a smaller bead size (125-180 µm) with a lesser amount of coverage (<100%) (Figure 2f). Although the micro-topology of glass-peened surfaces appeared to be different depending on the bead size and the coverage used for peening, the results from pool-boiling experiments showed that critical heat flux of all the peened tubes was enhanced compared with tubes that were not peened. An increase (by ~50%) in the CHF values was obtained from tubes peened using a large range of glass-bead sizes (60-180 µm); thus the enhancement in CHF is insensitive to bead size. The maximum enhancement of CHF was achieved for peened surfaces produced using 90-125 µm beads. For a fixed-size of glass beads, the maximum CHF enhancement was attained with a 100% coverage of the peened surface; this coverage is easily controlled by simply regulating the time of exposure of the peened surface during the peening operation.

Glass-bead peening the outer surface of the calandria tube produced a local change in the microstructure, and has little effect on the mechanical properties of the tube. Analyses from light microscopy showed the deformed grain structure to be limited to a sub-surface layer of about 30 µm. X-ray line broadening and neutron diffraction measurements of residual strains showed the effect of peening to be limited to a depth of about 100 µm below the surface. After peening, the grains in the sub-surface layer are deformed and contained compressive residual strains. When the peened tubes are given a stress-relieving heat-treatment of 500°C for 1 h, as part of normal tube manufacturing procedure, the grains in the peened region are re-crystallised and the residual strains remaining in the tube are reduced. The crystallographic texture of the grains on the surface changed slightly after peening, but remained the same following a stress-relief heat-treatment. Since the microstructures in the peened region (~30 µm) represents a small volume fraction (about 2%) of the calandria tube, the glass-peening treatment is expected to have little effect on the performance of tubes with respect to their creep and growth in reactor [4,5]. Thus we judged that the microstructures of a glass-peened and stress-relieved calandria tube to be acceptable for reactor use.

CONCLUSIONS

1. The maximum enhancement of CHF by glass-peening was obtained using a glass bead size of 90-125 µm with a coverage of 100%. The enhancement of CHF was found to be insensitive to a wide range of glass bead sizes (from 60-90 µm to 125-180 µm) for surfaces peened with 100% coverage.

2. Using a fixed-size of glass beads (125-180 µm) for peening the surface, the maximum effect on the CHF response was obtained with a coverage of 100%.

3. The peening treatment (using 90-125 µm glass beads with a 100% coverage) produced a deformed grain structure limited to a sub-surface layer about 30 µm, but after a stress-relief heat-treatment of

500°C for 1h (as part of the tube manufacturing requirement) some re-crystallisation had occurred and the residual strains remaining in the tube were low.

4. The peening treatment produced a slight change in the crystallographic texture at the surface that remained unchanged by the stress-relieved heat-treatment.
5. The tensile and burst properties of peened and stress-relieved tubes were similar to the properties of calandria tubes that were not peened.
6. Since the peened region represents a small volume fraction (~2%) of the calandria tube, we judged that the microstructural changes introduced by peening to have little effect on creep and growth response of the tube in reactor.

In summary, the CHF enhancement has been optimised and the microstructures of the peened and stress-relieved tubes were evaluated to be acceptable for reactor use.

REFERENCES

[1] C.E. Coleman, R.W.L. Fong, G.L. Doubt, T. Nitheanandan, and D.B. Sanderson, "Improving the Calandria Tubes for CANDU Reactors", Presented at 18th Annual Conference of the Canadian Nuclear Society, 1997, June 8-11, Toronto, Ontario, Canada. Publication is available in AECL-11815.

[2] J.M. Ramilison, P. Sadasivan, and J.H. Lienhard, "Surface Factors Influencing Burnout on Flat Heaters", ASME J. Heat Transfer, Vol. 114, pp. 287-290, 1992.

[3] P. O'Connor and S.M. You, "A Painting Technique to Enhance Pool Boiling Heat Transfer in Saturated FC-72", ASME J. Heat Transfer, Vol. 117, pp. 387-393, 1995.

[4] A.R. Causey and R.J. Klassen, private communications, November, 1997.

[5] R.J. Klassen, A.R. Causey, and N. Christodoulou, "Dependence of Irradiation Creep of Zircaloy-2 at 340 K on Microstructure", Proceedings of 5th International Conference on Creep of Materials, Lake Buena Vista, Florida, U.S.A., pp. 43-49, May 18-21, 1992.

ACKNOWLEDGEMENTS

The technical assistance from J.E. Winegar, R.M. Condie, A.J. Lockley (AECL Chalk River Laboratories), and R. Kaatz (AECL Whiteshell Laboratories), are much appreciated. Discussions with A.R. Causey, N. Christodoulou, and M. Griffiths (AECL Chalk River Laboratories) on creep and growth behaviour and X-ray line broadening are also appreciated.