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Modified ring tensile testing and a new method for fracture toughness testing of irradiated cladding

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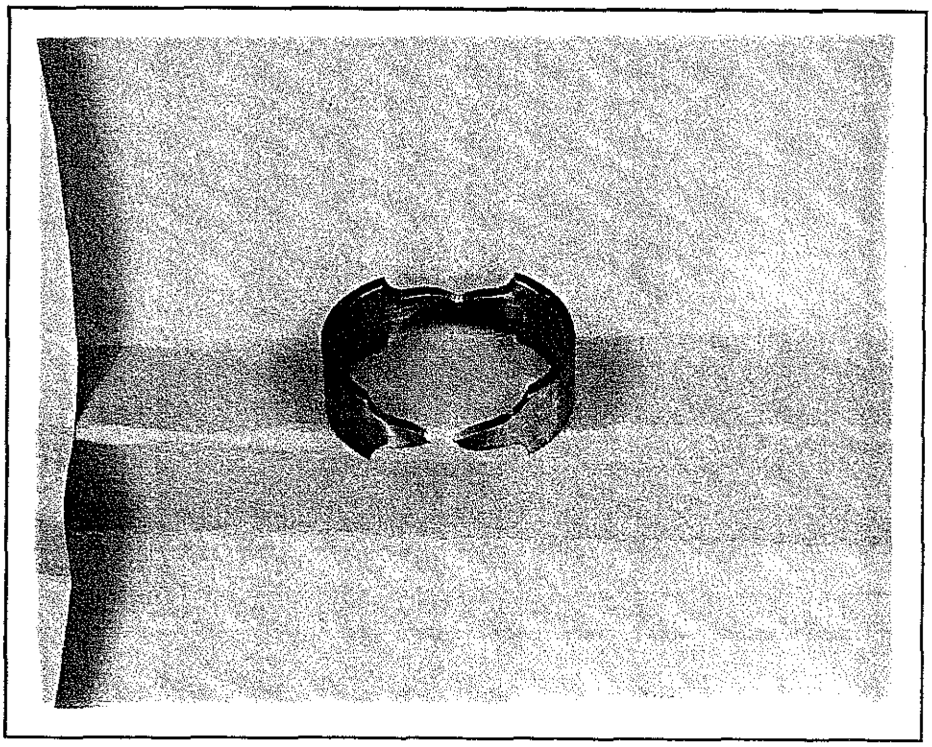

Studsvik Material

1996-05-10

Modified ring tensile testing and a new method for fracture toughness testing of irradiated cladding

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Abstract

Two test techniques for evaluation of the mechanical properties of irradiated fuel cladding are presented in this paper.

Ring tensile testing was used at Studsvik in the early 70's. It was recently independently invented and developed by Arsene and Bai at Ecole Centrale Paris, France, on the basis of a three-dimensional finite element method analysis. The modified ring tensile testing technique provides an almost uniform stress distribution in the notched part of the ring specimen. It also allows to deduce the hoop strain in the gauge length from the global displacement. The hoop stress in the notched part is proportional to the global force.

A new method for fracture toughness testing uses the concept of fracture mechanics for thin-walled cladding. Axially notched ring specimens can be tested in a way similar to what is used for compact tension specimens. J-integral values for irradiated cladding can be obtained.

Both techniques are presently used at Studsvik Material AB.

Background

Degradation of the mechanical properties of zirconium alloy cladding due to irradiation hardening combined with hydrogen embrittlement at high burn-up levels of the fuel are the reasons why attention has been paid to find appropriate techniques for testing of the cladding. This paper presents two new mechanical testing techniques suitable for this purpose.

In the early 70's there was a need at Studsvik for standardized determination of the strength and the ductility of irradiated cladding tubes [1]. Different test techniques and sample geometries were evaluated during the development of standardized procedures. The ring expansion testing and the ring tensile testing methods were the two most used test methods for evaluation of the strength and the ductility in the circumferential direction. Attempts were done by Anevi to refine these test methods and to compare the results [2]. The ring expansion testing showed a too large scatter of the stress values. The ring tensile testing showed promising results with the sample geometry shown in Figure 1a. Both a half cylinder loading fixture (Figure 1b) and a fixture having a distance element (Figure 1c) were tested. The fixture having a distance element gave the best results.

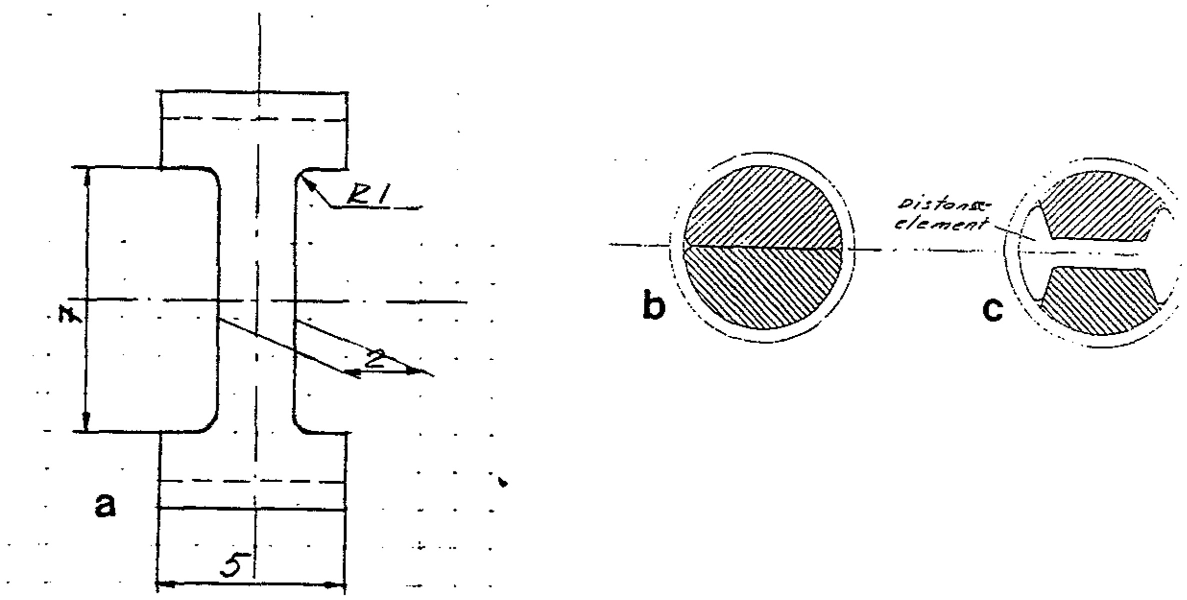

Figure 1
a) Old sample geometry for notched ring tensile testing [2], and **b)** old loading fixtures with half cylinders [1], and with **c)** a distance element. [1]

Nevertheless, the ring tensile testing has not been used since 1974 since a plane strain condition, regarded to exist in a fuel rod during service, could not be reproduced for such a test configuration. Burst testing with a fixed sample length was introduced and supposed to give a fairly good plain strain condition.

In the early 90´s the increased burn-up levels of the fuel introduced a need to examine the mechanical properties of heavy hydrided cladding.

The ring tensile testing, using a notched ring and a test configuration with a central part (another name for the distance element described above), was independently invented and developed in 1995 by Arsene and Bai [3]. A three-dimensional elastoplastic Finite Element Modeling (FEM) was used to optimize the specimen configuration and the test parameters. The modified ring tensile testing technique has been adopted for hot-cell testing of irradiated cladding at Studsvik Material AB.

A problem connected to the life of fuel rods is the risk for secondary defects, like axial splits, in the fuel rod cladding. An evaluation of the suceptibility of irradiated hydrided cladding to axial cracking was needed. However, the techniques known could not provide acceptable conditions for fracture mechanics testing of actual cladding. A new loading mode and test method for evaluation of the fracture toughness of thin-walled tubular materials have been presented by Grigoriev et al [4, 5].

The modified ring tensile testing and the new method for fracture toughness testing are described in more detail below.

Modified ring tensile testing

The main shortcoming with the earlier used ring tensile testing techniques, with configurations shown in Figure 2, was that bending moments develop in the two mid sections. This problem was still present even when using a notched ring or turning the notched zone away from the central position (Figure 2c). Thus, Arsene and Bai [3] used three dimensional FEM to analyze the stress and strain distribution in the ring, to optimize the ring tensile testing system, to investigate the effect of friction between the ring specimen and the fixture, and to derive a master curve for interpretation of the load-displacement curve.

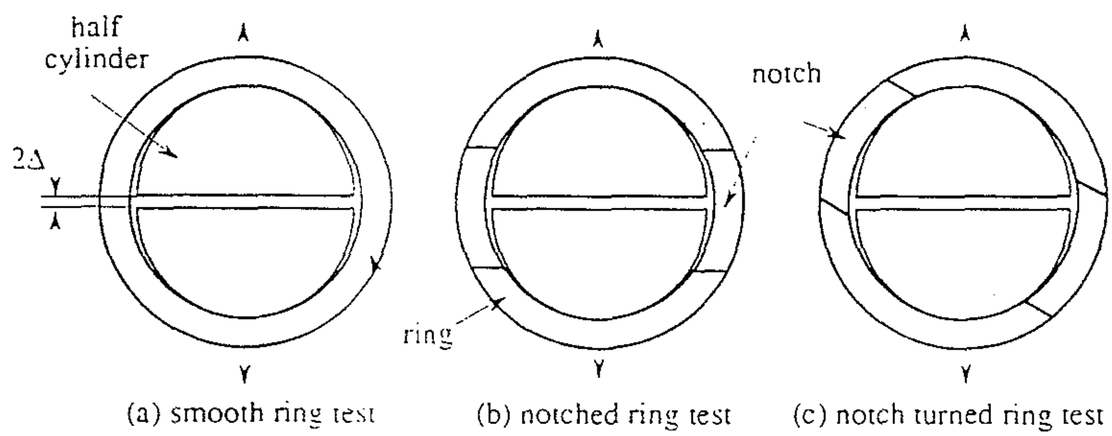

Figure 2
Different ring tensile testing configurations with smooth or notched ring specimens. **a)** Smooth specimen, **b)** notched specimen, and **c)** notched and turned specimen. [3]

The modified ring tensile testing system and the notched ring specimen are shown in Figure 3. In order to reduce the bending moment a central piece was introduced similar to that of Anevi [2]. In order to obtain a uniform uniaxial stress distribution, the notched zone should be in contact with the central piece. The height of the notched zone h_1 should be slightly smaller than that of the central piece h_2. On the other hand h_2 should be as large as possible because it is desirable to have a large gauge length. A good compromise for h_1/h_2 was found to be 5/6. Also the notch radius r_n is of importance. Three-dimentional FEM analysis has shown that the stress concentration K_t, the maximum stress in the notch over the average stress, increases from 1,16 to 1,35 when the ratio r_n/b (b is the notch thickness) decreases from 1 to 0,5. A suggested value of the ratio r_n/b was 3/4.

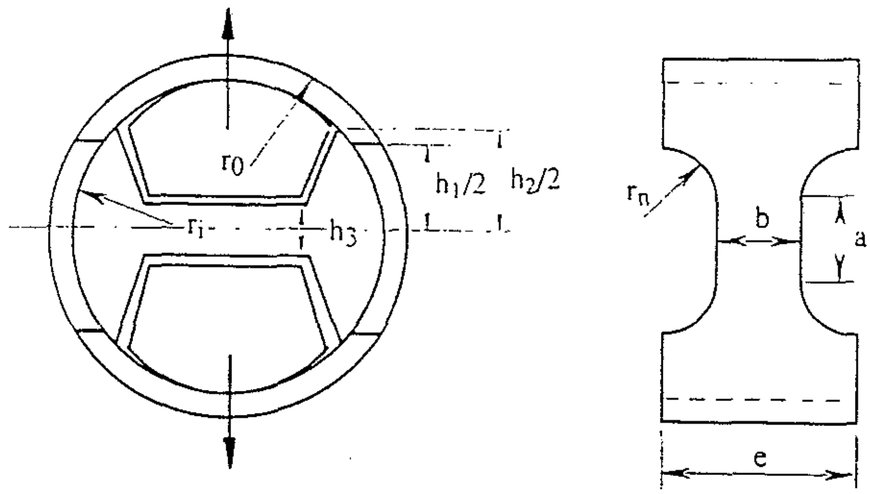

Figure 3
Modified ring tensile testing system and the notched ring specimen. [3]

Friction between the ring specimen and the fixture, as well as the clearance between the notch and the central piece and between the ring and the upper (or lower) cylinder has also been evaluated. The effect of the friction for normal friction coefficients was found to be less important for the results. However, the clearance is of more importance. If the clearance between the ring specimen and the upper cylindrical loading grip is too large the bending will be considerable, and a fracture can occur in the thicker part of the specimen, marked "e" in Figure 3. If the clearance is too small contact will be lost between the ring and the central piece prematurely during loading. The clearance between the notch region of the specimen and the central piece is of most importance in the very beginning of the testing. Afterwards the clearance will be zero. Optimal values of the clearance between the ring specimen and the central piece and between the ring specimen and the upper cylinder were found.

In order to obtain the mechanical characteristics of the material from the ring tensile testing, it is necessary to find the relation between the global force versus the displacement and the displacement versus the strain. The hoop stress is proportional to the global force, but the relation between the hoop strain and the displacement is not linear. Due to the non-linear relationship between the hoop strain and the displacement, a so-called master curve has been derived from the three-dimentional FEM. An example of the master curve is found in Figure 4. The curve can be divided into two straight parts with different proportionality coefficients. These coefficients mainly depend on the ring specimen and the fixture geometries, but also somewhat on the mechanical properties of the material.

Modified ring tensile testing has been performed of unirradiated and irradiated Zircaloy cladding with promising results. An example of a force-displacement curve from room temperature testing of an unirradiated Zircaloy cladding is shown in Figure 5a. A sample after testing at 300°C is shown in Figure 5b.

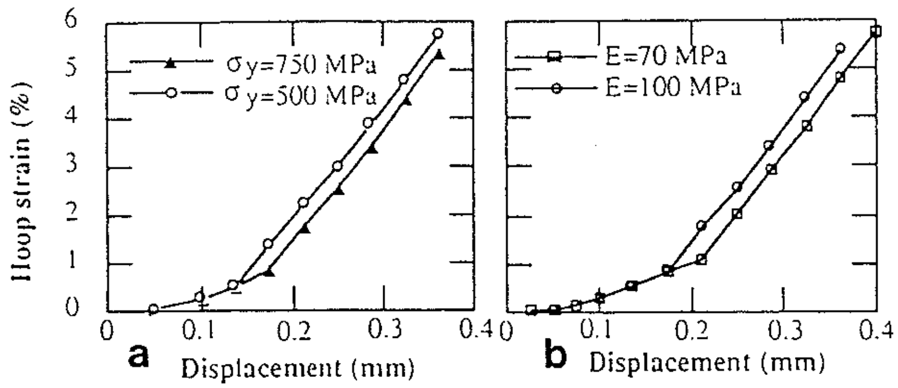

Figure 4
Master curve correlating the strain in the notched part of a ring specimen to the global displacement. **a)** Effect of the yield stress on the correlation. **b)** Effect of Youngs modulus on the correlation. [3]

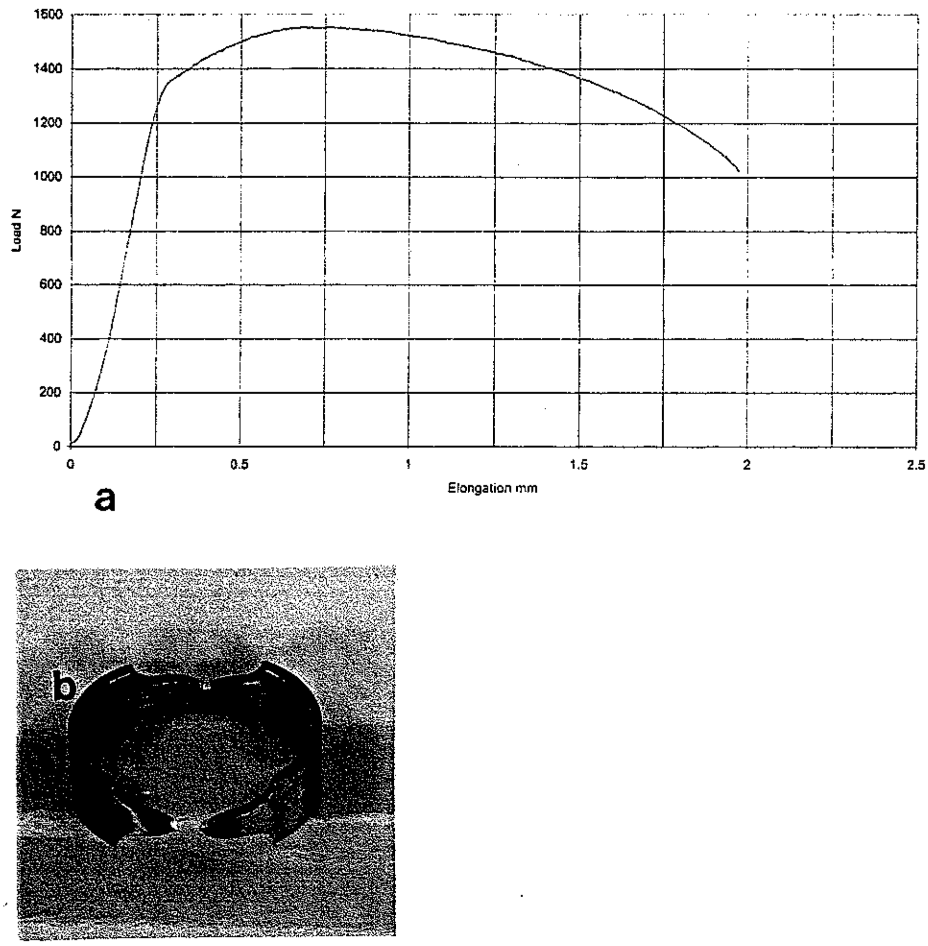

Figure 5
a) Load-displacement curve from room temperature testing of unirradiated Zircaloy cladding. **b)** Specimen after modified ring tensile testing at 300°C (2,3X).

Based on the three-dimentional FEM calculations, it has been concluded that modified ring tensile testing provides an almost uniform stress distribution in the notched part of the specimen. The method also allows to deduce the real stress-strain curve from the global force-displacement using a master curve.

A new method for fracture toughness testing

Determination of fracture mechanics parameters for irradiated fuel rod cladding requires the introduction of a sharp notch or crack in the specimen. The sharply notched thin-walled tubular specimen in Figure 6c is subjected to a mode of loading which is similar to the pin-loading (PL) of a compact tension (CT) specimen for fracture mechanics testing. Compared to uniaxial tension of the specimen the PL tension localizes the deformation and fracture processes to only a part of the specimen cross-section, compare Figures 6b and 6c. The small deformation zone in the specimen reduces both the load necessary for deformation and the elastic strains stored in the loading system thus eliminating the risk for spontaneous failure.

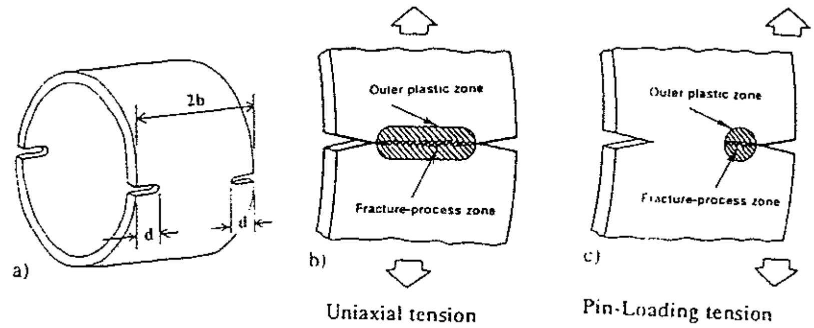

Figure 6
a) Configuration of an axially notched ring specimen. **b)** Notch tip deformation zones in a specimen under uniaxial tension, and **c)** under PL tension. [5]

The specimen for a PL tension test is easily prepared from either unirradiated or irradiated cladding. The specimen is approximately 1 cm long and contains notches as shown in Figure 6a. The proportions for the specimen dimensions d and 2b (see Figure 6a) are selected to prevent axial contraction in the deformed area, and to have the dimension 2b unchanged during testing.

A special fixture has been designed for the PL tension test. The fixture consists of two half cylinders. The design of the fixture for the PL tension testing can be seen in Figure 7. The clearance between the cylinder and the specimen should be minimal. The fixture halves, being loaded in tension through the pins, have the capability of mutual rotation around an axis determined by a small pin placed between the fixture halves at the outside end of the cylindrical holder (Figure 7b). The rotation of the fixture halves is similar to the rotation of CT specimen halves under loading, with only one difference: in the designed fixture the rotation axis does not change its position when the crack in the specimen is growing. The specimen and the fixture have closely interrelated configurations and, when combined, create an assembly characterized by the ratio W/a, see Figure 7c. In the assembly the four notches in the specimen should be positioned at the contact plane of the fixture halves. The notches on the back side of the specimen should coincide with the rotation axis of the fixture. Under PL tension testing, deformation takes mainly place at the notch tips at the front side of the specimen, nearest to the load line.

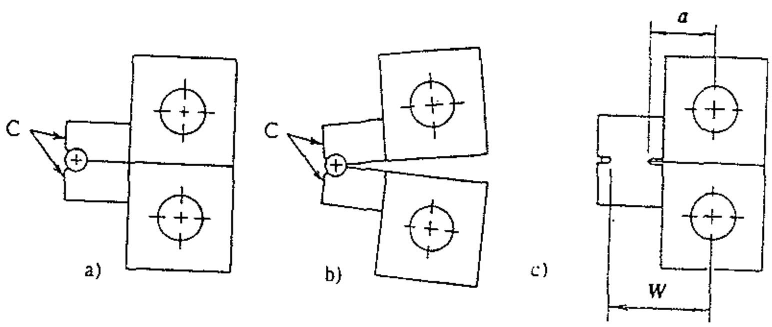

Figure 7
a) Pin-loading fixture design. **b)** Mutual rotation of the fixture halves. **c)** Specimen-fixture assembly before PL tension testing. [5]

During a PL tension test, the load applied to the specimen is recorded versus the load-line displacement. Load-displacements curves for three specimens of irradiated cladding (designated LK0, LK1, and LK2) and for one cold-worked unirradiated specimen (2C6) are shown as examples in Figure 8. The fracture toughness of the cladding is characterized by the J-integral value calculated at maximum load of the load-displacement curve. The J-integral is evaluated using the following equation developed for CT specimens: $J_I=\beta A_T/Bb_{o1}$ where A_T is the total area under the load versus load-line displacement curve, B is the specimen thickness, and b_o is the uncracked ligament length. For testing of CT specimens the coefficient β is connected to the position of the rotation center in the specimen and determines the uncracked ligament area subjected to the tensile stress. For the PL testing β=1 is chosen since the whole uncracked ligament is subjected to the tensile stress.

The J-integral, both the elastic and the plastic components, and the crack opening displacement have so far been successfully compared with different states of cladding tubes, both unirradiated and irradiated. Figure 9 shows as an example three irradiated specimens before PL tension testing and the fracture surfaces after testing at 300°C. The specimen were broken apart at room temperature. The resultant load-displacement curves for the specimens are shown in Figure 8. The results for these irradiated specimens and from other tests are described in Ref. 4 and 5.

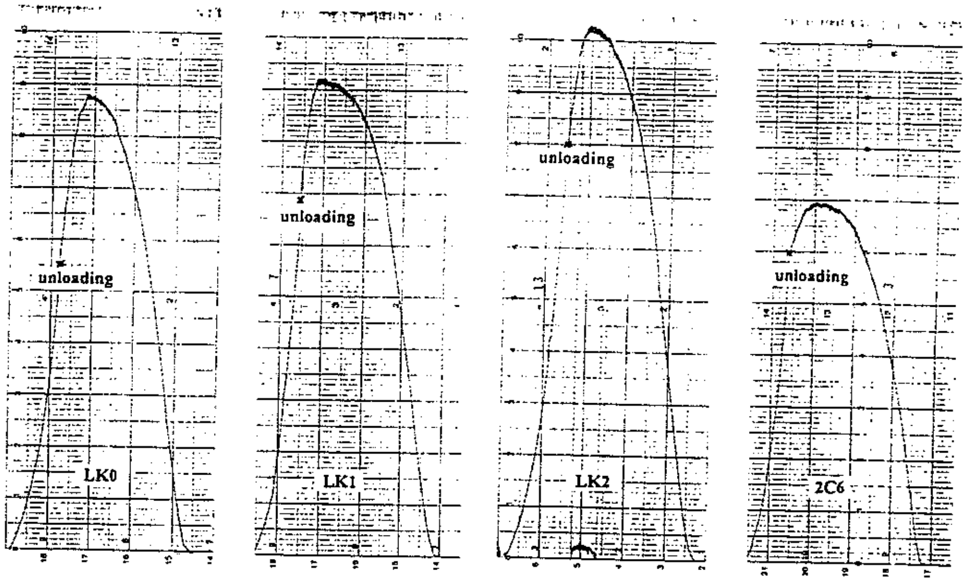

Figure 8
Load-displacement curves for specimens from irradiated cladding (LK0, LK1, and LK2, see Figure 9) and for a cold-worked unirradiated specimen (2C6). [5]

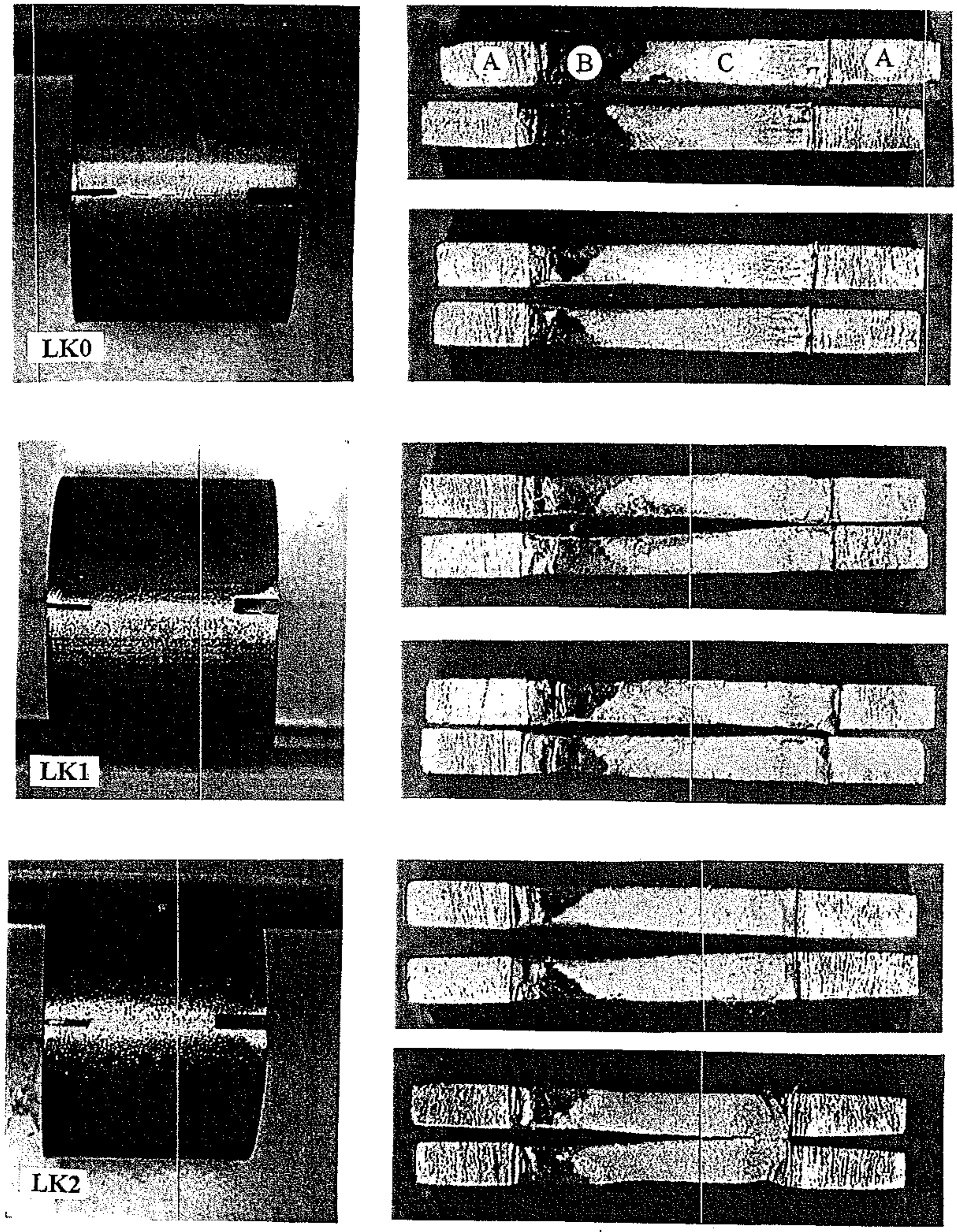

Figure 9
Irradiated specimens before PL tension testing and the fracture surfaces after testing. A = notch surfaces, B = high temperature fracture surfaces, C = room temperature fracture surfaces. [5]

Summary

Two experimental techniques are currently used at Studsvik Material AB for evaluation of the mechanical properties of irradiated fuel cladding. The modified ring tensile testing provides the relationship between the stress and strain in the circumferential direction of the cladding. The fracture toughness of the cladding, characterized by J-integral values, is evaluated by means of a new pin-loading tension test.

References

1 ANEVI, G
Aktiebolaget Atomenergi, Sweden, 1974 (TPM-MF-474, in Swedish).

2 ANEVI, G
Aktiebolaget Atomenergi, Sweden, 1973 (AP-MF-360, in Swedish).

3 ARSENE, S and BAI, J
"A new approach to measure transversal properties of tubing structures by a ring test.". To be published.

4 GRIGORIEV, V, JOSEFSSON, B, LIND, A and ROSBORG, B
A pin-loading tension test for evaluation of thin walled tubular materials.
Scripta Met. et Mat. **33** (1995) pp. 109-114.

5 GRIGORIEV, V, JOSEFSSON, B and ROSBORG, B
Fracture toughness of Zircaloy cladding tubes.
Presentation at the 11th Int Symp on Zirconium in the Nuclear Industry, September 11-14, 1995, Garmisch-Partenkirchen, Germany.