Transactions of the Korean Nuclear Society Spring Meeting
Gyeongju, Korea, May 29-30, 2008

Ductility and Fracture Toughness Test Techniques of Irradiated Cladding in a Hot Cell

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1. Introduction

Nuclear fuel cladding supports the fuel pellets and prevents their escape to the passing coolant of fission products, especially fission product gases. Operating conditions involving longer cycles and a higher burnup can degrade the mechanical properties of a cladding. Such changes appear as losses in ductility and fracture toughness due to oxidation, neutron irradiation and hydrogen uptake during a service. These are the essential properties governing the fuel reliability and the operational safety under a normal operation as well as transient conditions. Ductility and fracture toughness of a cladding are also the key considerations in evaluating the design and performance of a fuel rod at a high burnup. The present paper represents an attempt at briefly reviewing a selection of these mechanical test techniques aimed at evaluating the in-service ductility and fracture toughness degradation of an irradiated fuel cladding.

2. Ductility Test Techniques

The ductility of cladding has been evaluated by using the following PIE techniques; the ring and longitudinal tensile test, the ring compression test, the expansion-due –to-compression test and so on. Some of the techniques used to examine the ductility of irradiated cladding in a hot cell are described. The grip and specimen handling tools should be designed for use in a hot cell. The ductility is evaluated as an elongation, a strain and a strain energy obtained from the test.

2.1 Ring Tensile Test

Ductility in the hoop direction of a cladding has been examined by many researchers [1~2]. The notched ring specimen is designed to limit a deformation within the gage section and to maximize a uniformity of strain distribution at the gage section. The two half-cylinders are designed such that a constant specimen curvature is maintained during deformation. The ring specimen is placed around two half-cylinders which are attached to the grip, and is pulled apart as shown in Fig. 1. To minimize the friction between half-cylinder and specimen, the contact surface is lubricated by using the graphite lubricant (Model P-37, Molykote Co.)[1]. Uniform and total elongations can be determined from the hoop stress-hoop strain curve.

2.2 Longitudinal Tensile Test

To evaluate the constitutive properties of a cladding in the longitudinal direction, several kinds of specimens have been developed [3~4]. The dogbone tube specimen is designed with a small cross-sectional area and, thus a low load capacity to accommodate Swagelok fittings or pin without slippage between the specimen and the grip. The grip should be designed such that no slippage at the gripping section occurs during the testing in Fig. 2. From the stress-strain curves, the elongations in the longitudinal direction are obtained.

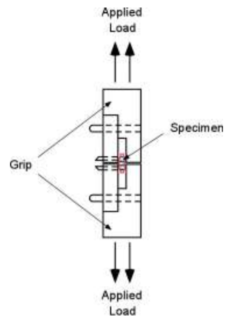

Fig. 1 Ring tensile test

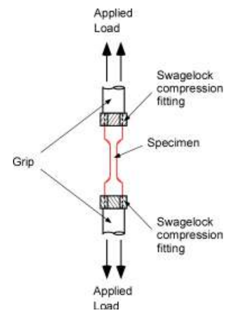

Fig. 2 Longitudinal tensile test

2.3 Ring Compression Test

For safety analyses under LOCA condition, the ring compression test has been done [5]. This test method was used to develop fuel safety criteria for Zircaloy cladding addressed in NRC, 10 CFR 50.46, and allows to perform the comparative analysis of results obtained by different researchers for this cladding materials and other cladding alloys. The cladding segment is compressed by using the upper and lower platen grips as shown in Fig. 3. The absorbed energy and the displacement at failure are calculated from the load-displacement data.

2.4 Expansion-due-to-compression(EDC) Test

The EDC test is a high strain rate mechanical testing technique using a soft mandrel (polymer pellet). This technique has been developed to simulate the pellet-cladding mechanical interaction (PCMI) loadings of the cladding during RIA [6]. Specimen is expanded as a polymer pellet is rapidly compressed in universal testing machine as shown in Fig. 4. The hoop strain at failure and the critical strain energy density defined as the area under load-displacement curve are obtained.

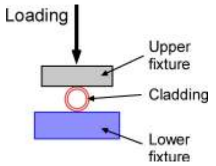

Fig. 3 Ring compression test

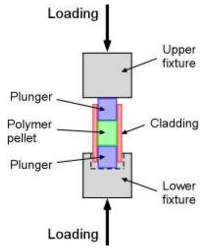

Fig. 4 EDC test

3. Fracture Toughness Test Techniques

An axial through-wall defect caused by debris fretting, manufacturing flaws or pellet-cladding interaction (PCI) cracks can occur in a cladding during service. However, the usual fracture mechanics tests are not well suited to measuring the fracture toughness of tubular materials such as a fuel cladding. Several methods can be used to evaluate the resistance to crack propagation in the axial direction. The grip or fixture can be easily handled by the manipulator equipped at a hot cell. The crack extension measurement and the fracture surface observation should be done by using the special apparatus designed for use in a hot cell.

3.1 Pin-loading Tension (PLT) Test

The PLT test was develop for an evaluation of the fracture toughness of thin-walled tubular materials [7]. A tubular specimen with pre-crack is subjected to Mode I loading similar to the pin-loading of a compact tension (CT) specimen as shown in Fig. 5. To continuously measure the crack extension during the test, DCPD method was used. Calculations of the J-integral are made from load vs. load-line displacement curves as used in the procedures of ASTM Standard E 1820. Crack initiation toughness, $J_{0.2}$, J-integral at maximum load, J_{max}, and crack growth resistance, dJ/da values are obtained.

3.2 Vallecitos Embedded Charpy (VEC) Test

The VEC test has been developed to measure fracture properties of thin-walled Zircaloy cladding [8]. The segment of cladding is inserted into the VEC fixture to form a bend bar with the same dimensions as a Charpy specimen (10x10x55 mm) in Fig. 6. The VEC specimen is treated as a standard 3-point bend fracture toughness specimen. Assuming the crack initiation coincided with the point of maximum load (J_{max}), the values of J_{max} is converted to a convenience value of K (K_{Jmax}).

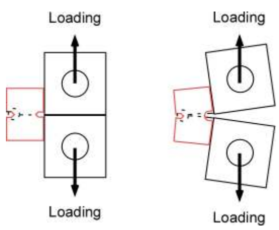

Fig. 5 PLT test

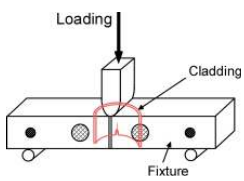

Fig. 6 VEC test

4. Conclusions

Ductility and fracture toughness test techniques for a fuel cladding are reviewed for developing an evaluation method for its integrity in service. Ductility and fracture toughness of a cladding are reduced through the mechanisms of oxidation, hydriding and irradiation damage. Loss in ductility is evaluated by the ring tensile test, the ring compression test, the expansion-due-to-compression test in the hoop direction, and by the longitudinal tensile test in the axial direction. The fracture toughness, as a measure of a crack growth resistance, is determined by using the PLT and the VEC test techniques. For the evaluation of the ductility and fracture toughness of an irradiated cladding in a hot cell, the most useful test techniques will be selected by taking into account the handling and manufacturing conditions of the specimen in our hot cell.

REFERENCES

[1] R. S. Daum, S. Majumda, H. Tsai, T. S. Bray, D. A. Koss, A. T. Motta, and M. C. Billone, Mechanical Property Testing of Irradiated Zircaloy Cladding Under Reactor Transient Conditions, ASTM STP 1418, pp. 195-210, 2002.
[2] D. S. Kim, Y. S. Choo, S. B. Ahn, W. S. Song, B. O. Yoo, S. J. Baik, K. H. Kim, K. W. Hong and S. K. Kim, "Modified Ring Tensile Test Technique for Fuel Cladding in Hot Cell," Abstracts of Proceedings of the Korean Nuclear Society Spring Meeting, Gyeongju, Korea, pp. 370, 2004.
[3] M. Balourdet and C. Bernaudat, Tensile Properties of Irradiated Zircaloy 4 Cladding Submitted to Fast Transient Loading, Proceedings of the CSNI Specialist Meeting on Transient Behaviour of High Burnup Fuel - Session IV, Cadarache Sept. 12-14, pp. 417, 1995.
[4] M. Balourdet, C. Bernaudat, V. Basini and N. Hourdequin, The Prometra Programme: Assessment of Mechanical Properties of Zircaloy 4 Fuel Cladding During an RIA, Transactions of the 15th International Conference on Structural Mechanics in Reactor Technology(SMiRT-15), Seoul, Korea, August 15-20, pp. II-485, 1999.
[5] J. H. Kim, M. H. Lee, B. K. Choi, and Y. H. Jeong, Failure Behavior of Zircaloy-4 Cladding after Oxidation and Water Quench, Journal of Nuclear Materials, Vol. 362, pp. 36-45, 2007.
[6] V. Grigoriev, R. Jakobsson, and D. Schrire, Temperature Effect on BWR Cladding Failure under Mechanically Simulated RIA Conditions, JAERI-Conf 2002-009, pp. 97-162, 2002.
[7] V. Grigoriev, B. Josefsson, and B. Rosborg, Fracture Toughness of Zircaloy Cladding Tubes, ASTM STP 1295, pp. 431-447, 1996.
[8] K. Edsinger, J. H. Davies, and R. B. Adamson, Degraded Fuel Cladding Fractography and Fracture Behavior, ASTM STP 1354, pp. 316-339, 2000.