Journal of Nuclear Materials 446 (2014) 27–37

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Methodology for mechanical property testing of fuel cladding using an expanding plug wedge test

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ARTICLE INFO

Article history:
Received 12 July 2013
Accepted 20 November 2013
Available online 27 November 2013

ABSTRACT

An analysis is presented to determine the stress–strain response of ring-shaped test specimen subjected to internal pressurization using a radially expanding plug. Previous work has been reviewed using this test method to determine the residual ductility of irradiated nuclear fuel cladding and highlight the role of several parameters on the distribution of stresses and the mode of failure. It is shown that bulging effect, which had previously not been accounted for, has a significant effect on the distribution of stresses and mode of failure. The new analysis provides guidelines for optimizing specimen geometry and loading conditions and a means for determining the hoop stress σ_θ in the ring-shaped test specimen using a scaling factor, χ-factor, to convert the ring load F_{ring} into hoop stress σ_θ, and is written as $\sigma_\theta = \chi \frac{F_{ring}}{tl}$, where t is the clad thickness and l is the clad length. The predicted stress–strain curves were found to agree well with experimental results for alloy Zr-4 over 10% strain.

1. Introduction and background

Fuel and cladding must be examined to verify the performance of fuel rods and to produce data that can be used for fuel qualification. One of the essential examinations is the mechanical properties test. In a hot-cell environment, conventional tensile testing might not be convenient due to complexities associated with specimen preparation and testing. Hendrich et al. [1,2] invented an expanding plug test method and applied it in post irradiation examination for the Fissile Materials Disposition Program to assess for the performance of fuel rods contained in mixed oxide lead test assemblies. The advantages of the method are the simplicity of using the test component assembly in the hot cell and the direct measurement of specimen strain. It was also found that cladding strength can be determined from the test results.

It is important to understand the thin-walled pressurized cylinder model on which the expanding plug method is based. If the cylinder walls are thin and the ratio of the thickness to the internal diameter is less than about 1/20, then it can be treated as a thin-walled vessel [3–5]. The three principal stresses in the shell are circumferential or hoop stress, longitudinal stress, and radial stress. For a thin-walled cylinder, it may be assumed that the hoop and longitudinal stresses are constant across the thickness. The radial stress is small and can be neglected. As shown in Fig. 1, the hoop stress can be described as

$$\sigma_\theta = \frac{F}{tl} \tag{1}$$

where F is the force exerted circumferentially on an area of the cylinder wall that has a thickness t and an length l.

Using the Young–Laplace equation, the hoop stress created by an internal pressure in a thin-walled cylindrical pressure vessel can be estimated as

$$\sigma_\theta = \frac{Pr}{t} \tag{2}$$

where P is the internal pressure, t is the wall thickness, and r is the inside radius of the cylinder.

When the cylinder to be studied has an r/t ratio of less than 20, the thin-walled cylinder equations are no longer valid. Between inside and outside surfaces, stresses can vary significantly and shear stress through the cross section can no longer be neglected. Estimation of stress and strain becomes much more complicated.

A simple test method using expanded plug approach to estimate circumferential mechanical properties of tubular materials [1,2] was developed recently, as shown in Fig. 2. This method is designed for testing fuel rod cladding ductility in a hot cell by utilizing an expandable plug to stretch a small ring of the irradiated cladding material. The basic approach of this test method is that an axial compressive load is applied to a cylindrical plug of polyurethane (or other materials) fitted inside a short ring of the test material to radially expand the specimen. Three measurements are made: total applied load, amount of plug compression, and radial expansion of the specimen. The radial expansion of the specimen is used to calculate the circumferential strain accrued during the test.

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0022-3115/$ - see front matter
http://dx.doi.org/10.1016/j.jnucmat.2013.11.026

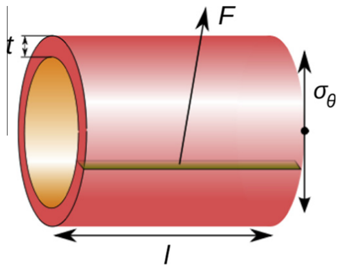

Fig. 1. Circumferential stress of a cylinder.

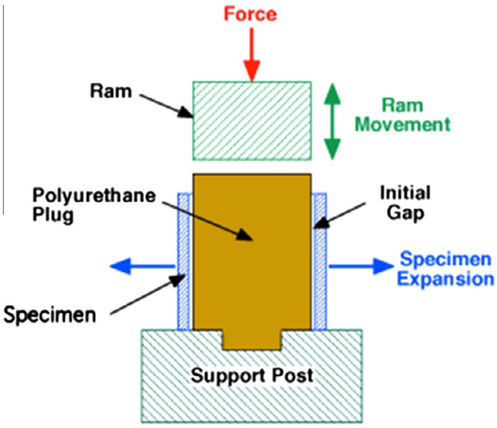

Fig. 2. Schematic of expanding plug test [2].

A general procedure was developed to determine the circumferential stress in the expanding ring specimen is described in Ref. [1,2]; where the load and radial expansion data from the ring tests can be converted into material stress–strain curves to examine mechanical properties, such as Young's modulus, yield strength, and strain-hardening characteristics.

In nuclear engineering and design, intensive research is focusing on material characterization of fuel cladding. Among the vast literature, Nilsson et al. [6] and Kim et al. [7] did a similar investigation on fuel cladding using ring specimens. Nilsson et al. presented an assessment of the segmented expanding mandrel (SEM) test for material properties and a structural integrity assessment of nuclear fuel claddings. The loading is induced by expanding segments placed inside a cladding tube to simulate cracked fuel that expands thermally. The test is appropriate for assessing the effects of defects and microstructure on ductility.

Kim et al. evaluated the hoop-directional mechanical properties comprising strength (i.e., yield strength and ultimate tensile strength) as well as mechanical ductility (i.e., uniform elongation and total elongation) of un-irradiated and high burn-up Zircaloy-4 and characterized their fracture behaviors. Kim et al. also investigated the effect of friction between the loading pins and the test specimen and the effect of various lubricants to determine the lubricant for this ring tensile testing.

This paper is organized into two main parts: (i) using FEA to evaluate the existing expanding plug method and (ii) to develop a modified expansion expanding plug wedge testing protocol to improve its performance and to achieve more uniform loading conditions. The hyperelastic material properties of the polyurethane plug were taken into consideration in FEA. The estimated stress and strain distributions from FEA were validated by tensile test data and compared with mechanical properties generated from ring expansion clad testing data. The FEA simulations revealed the limitations of the current expanding plug method and provided important guidance for the second stage of the study.

To overcome these limitations, a significant effort was dedicated to improve the test design. Systematic studies were conducted by investigating the effect of several parameters, including geometric design, selection of expanding plug material, and designing new parts for the testing system. An expanding plug wedge test was developed to reconcile the potential nonconservatism inherent in the current expanding plug test.

2. Evaluation of current expanding plug method

2.1. FEA of room-temperature ring expansion clad testing

As described above, a test method was developed for room-temperature circumferential tensile testing of nuclear fuel cladding in a hot cell. The method involves radially expanding a ring specimen of the test material by axially compressing a cylindrical plug of polyurethane fitted inside the specimen.

A 3D FEM model of the ring expanding plug clad testing system was developed with a hyperelastic material model for a polyurethane plug, as shown in Fig. 3. To permit direct comparison to existing test data and to validate simulation results, the material selected for the ring specimen was Zircaloy-4 (Zr-4). Polyurethane material was used for the expanding plug. High-strength steel was used for the ram and the support post. The simulated dimensions of the ring were length, 7.112 mm (0.28 in.); outer diameter (OD), 9.398 mm (0.37 in.); and inner diameter (ID), 8.240 mm (0.326 in.). The simulated dimensions of the plug were length, 7.518 mm (0.296 in.); and plug diameter, 5.905 mm (0.325 in.). Hence the initial gap in Fig. 3 between the ring specimen and the expanding plug was 0.013 mm (0.0005 in.).

A cylindrical coordinate is employed in FEA model. As illustrated in Fig. 3, R represents the radial direction of the ring; θ is the hoop direction of the ring and Z is the axial direction of the ring. Pressure load was applied to the top of the ram in the Z direction, while the bottom surface of the support post was constrained in six degrees of freedom (DOF). A general contact was defined as being between the outer surface of the cylindrical expansion plug and the inner surface of the ring specimen. The load was 4626 N for testing an unirradiated Zr-4 ring specimen at room temperature.

The material properties of components simulated in the system model in Fig. 3 are listed in Table 1. Fig. 4 illustrates the engineering stress–strain curve for unirradiated Zr-4 cladding generated from an uniaxial tensile test data [8]. The ultimate strength of unirradiated Zr-4 cladding is 514 MPa. Strain hardening data were generated on the basis of tensile test data in Fig. 4 and provided to the FEA model as plastic material behavior of Zr-4 during the ring expansion test simulation. Polyurethane material has hyperelastic characteristic and was simulated with hyperelastic Yeoh form [9] in FEA.

FEA result shown in Fig. 5 reveals the stress status at the end of the loading process, when a polyurethane plug was slightly pressed into the ring specimen, and the ring barreling at the middle section. The von Mises stress distribution in the cladding is not uniform, and the maximum stress occurred in the cladding within the whole test system.

Fig. 6 shows the radial dilatation distribution in the cladding along the gage section. The radial dilatation is equal to the ring radial displacement U1 divided by the outer radius of the ring. Radial strain shows highly nonuniform distribution. Maximum strain occurs at the ring bulged-out section. Compared with the test of the unirradiated Zr-4 ring specimen at room temperature, shown in Fig. 7, the FEA simulation reveals a very similar deformation shape.

In the ring expanding plug clad testing [1,2], the increase in specimen diameter was continuously monitored and recorded by