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A new procedure to calculate the constitutive equation of nuclear fuel cladding from ring compression tests

F.J. Gómez Sánchez [a, *], M.A. Martin Rengel [b], J. Ruiz-Hervias [b]

[a] Advanced Material Simulation, S.L, Spain
[b] Departamento de Ciencia de Materiales, E.T.S.I. Caminos, Canales y Puertos (Universidad Politecnica de Madrid), C/Profesor Aranguren SN, Madrid 280840, Spain

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ABSTRACT

The geometry of the nuclear fuel cladding (thin-walled tube) makes it difficult to obtain its hoop mechanical properties.

A new procedure is devised to obtain the constitutive equation of nuclear fuel cladding along the hoop direction from ring compression tests. The method combines experimental results, finite element simulations and an original iterative algorithm to adjust the experimental data. The process is successfully applied to unirradiated pre-hydrided ZIRLO nuclear fuel cladding, tested at three temperatures (20, 135 and 300 °C) with hydrogen contents (0, 150, 250, 500, 1200 and 2000 ppm). The stress-strain curves were obtained for each configuration with an excellent agreement between the numerical results (based on back calculation of the obtained constitutive equation) and the experimental data.

The stress-strain curves calculated show that the mechanical properties do not depend strongly on hydrogen concentration, only a small ductility decrease with the hydrogen concentration was observed. The cladding shows a light strain hardening which is similar for the samples tested at 20 and 135 °C and does not depend on the hydrogen concentration. However, at 300 °C, the samples with the highest hydrogen concentrations (1200 and 2000 ppm) present a behavior that is close to an elastic-perfectly plastic material.

1. Introduction

Nuclear fuel cladding constitutes the barrier for the actual fuel and all products created during the fuel operation in the reactor. This cladding is a thin-walled tube made of zirconium alloys due to their low neutron absorption, corrosion resistance and good mechanical properties under reactor conditions. During the operation of light water nuclear reactors, the oxidation reaction that takes place at the outer cladding surface produces hydrogen which is absorbed and diffuses into the cladding. As a consequence, zirconium hydrides will be formed when the solubility limit is reached. These zirconium hydrides may reduce the mechanical properties of the fuel cladding and embrittle it (Arséne and Bai, 1996; Arséne, 1997; Martín-Rengel, 2009; Martin-Rengel et al., 2012; Martín-Rengel et al., 2009; Bertolino et al., 2003; Grange, 1998). To guarantee the safety and structural integrity, it is necessary to know the mechanical properties in the presence of hydrides (the stress-strain curve) and the fracture toughness for the temperatures and hydrogen contents of interest. Due to the manufacturing process, the nuclear fuel cladding is anisotropic (Linga and Charit, 2006). The geometry of the fuel cladding (thin-walled tubes) makes it difficult to obtain the mechanical properties along the hoop direction. While in the literature it is possible to find some mechanical tests to obtain these properties (Martín-Rengel, 2009; Desquines et al., 2005), none of them produces an uniaxial stress in the hoop direction.

Traditionally, the ring tensile test is one of the most employed to calculate the stress-strain curve in the hoop direction. The initial test consisted of applying a force from the inner surface of the sample cladding sample by means of two half cylinders. Arsene and Bai modified the experimental device to avoid bending of the sample during the test (Arséne and Bai, 1996; Arséne, 1997). Using such a device, M.A. Martin Rengel et al. (Martin-Rengel et al., 2012) recently proposed a novel numerical method to determine the mechanical properties of the cladding. The method, different from

* Corresponding author.
E-mail addresses: javier.gomez@amsimulation.com (F.J. Gómez Sánchez), mamartin@mater.upm.es (M.A. Martin Rengel).

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the traditional ones, is valid beyond small strains, considers non-linear geometry and does not require universal curves.

The ring tensile test presents two important experimental difficulties: the samples need a relatively complex machining (a really important factor when the test is performed with irradiated samples) and the results are affected by some parameters difficult to measure, such as the friction coefficient and the gap between the sample and the load device.

Alternatively, the ring compression test (RCT) could be employed to obtain the stress-strain plastic curve. Recently, it was used as a ductility screen test and as a simulation of pinch-type loading that may occur during cask transport accident (Billone et al., 2013). Previous works may be found in the literature, that use the RCT to calculate the mechanical properties of the tubes (Mahmoud, 2003; Reddy and Reid, 1979, 1980). Such a test presents several important advantages over traditional tests, such as ring tensile tests. It is both simple to perform and easy to carry out in terms of the machining of the samples. Such features are of significant importance when working with irradiated cladding.

The method proposed in this work is used to calculate the plastic stress-strain curve in the hoop direction from the RCT by an inverse analysis procedure that provides the curve that best reproduces the experimental results. The method is applied to ZIRLO nuclear fuel cladding with hydrogen contents of 0 (as-received samples), 150, 250, 500, 1200 and 2000 ppm, with the tests being performed at 20, 135 and 300 °C.

2. Experimental

2.1. Material and testing

The material employed in this work was unirradiated ZIRLO cladding in stress-relieved condition (Sabol George, 2005). The cladding dimensions were 9.50 mm outer diameter and 0.57 wall thickness. The samples were cut in the shape of rings with a height of 10 mm.

Hydrogen was introduced in the samples by means of cathodic charging in a KOH aqueous solution. After this cathodic charging, the samples were heat treated (723 K for 7 h and then slowly cooled, 1.2 k/min). The hydrogen concentration was measured by using the inert gas fusion thermal conductivity detection method with a Horiba Jobin-Yvon hydrogen analyzer EMGA-621W. Samples for the RCT (rings with a height of 10 mm) with controlled amounts of hydrogen (0, 150, 250, 500, 1200 and 2000 ppm) were prepared for this process. The resulting hydride distribution was homogeneous through the cross-section, with hydrides being oriented along the hoop direction, as shown in Fig. 1. The diffraction patterns show that hydrides are δ-$ZrH_{1.66}$ (Martín-Rengel, 2009). Further details of the hydrogen charging procedure are given in (Martín-Rengel, 2009).

The RCTs were performed at 20, 135 and 300 °C with a universal testing machine. A resistance furnace was adapted to the universal testing machine to carry out the test at high temperature. The load was measured with a load cell of 5 kN capacity. Compression load was applied by means of two steel plates (plane and parallel), as shown in Fig. 2. Tests were carried out by applying a constant displacement rate of 0.5 mm/min.

2.2. Finite element model

A 2D finite model was prepared to simulate the RCT by assuming plane strain. Due to geometry and loading symmetries, only a quarter of the sample was employed. The commercial code ABAQUS v.6.11 (Abaqus, 2012) was used for calculations. The mesh is shown in Fig. 3. It should be noted that it is a semi-structured quadratic mesh, with eight-node quadrilaterals in the damage zone and the region where load is applied, and six-node triangles in the rest of the mesh. The minimum element size is 5 μm.

The load system was modeled as an analytical rigid surface that interacted with the top of the sample. A standard hard contact with 0.125 friction coefficient was placed between the two domains (Arséne and Bai, 1996). Non-linear geometry was considered in the calculations and material behavior was modeled as elastic-plastic and isotropic with the von Misses yield criterion (Arséne and Bai, 1996).

The elastic modulus was calculated by using the slope of the initial linear part of the load-displacement curve. The first initial elastic modulus E_i was modified through multiplying it by the experimental slope, S, and dividing it by the numerical, in an iterative way to get the best adjustment, (1). The new elastic modulus permitted the analysis to obtain good approximation of the initial load displacement curve.

$$E_{i+1} = E_i \times \left(\frac{S}{S_i}\right) \quad (1)$$

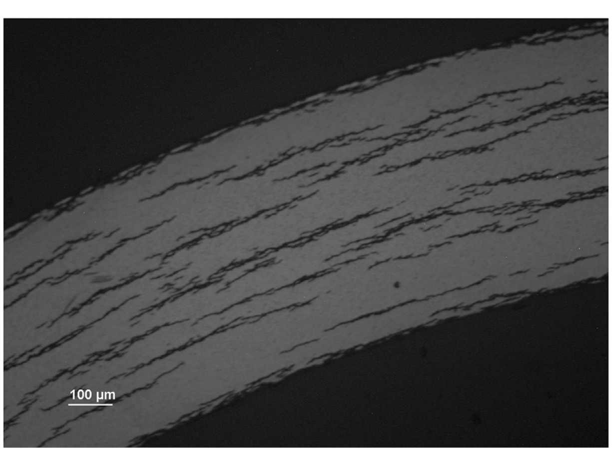

Fig. 1. Hydride distribution in a sample with 150 ppm of hydrogen.

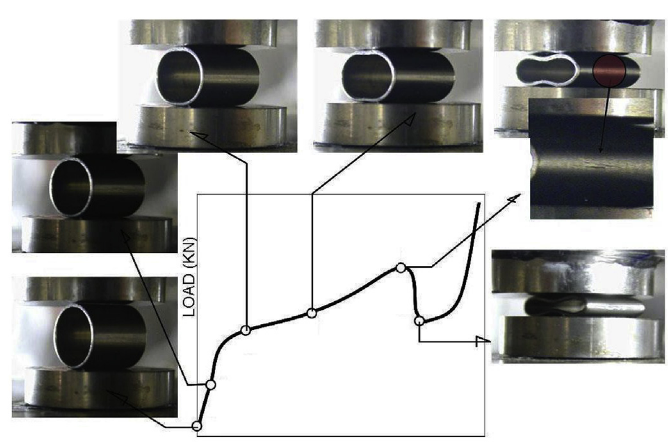

Fig. 2. Stages of the ring compression test.