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Journal of Nuclear Materials 352 (2006) 116–125

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Crack resistance curves determination of tube cladding material

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Abstract

Zirconium based alloys have been in use as fuel cladding material in light water reactors since many years. As claddings change their mechanical properties during service, it is essential for the assessment of mechanical integrity to provide parameters for potential rupture behaviour. Usually, fracture mechanics parameters like the fracture toughness K_{IC} or, for high plastic strains, the J-integral based elastic–plastic fracture toughness J_{IC} are employed. In claddings with a very small wall thickness the determination of toughness needs the extension of the J-concept beyond limits of standards. In the paper a new method based on the traditional J approach is presented. Crack resistance curves (J–R curves) were created for unirradiated thin walled Zircaloy-4 and aluminium cladding tube pieces at room temperature using the single sample method. The procedure of creating sharp fatigue starter cracks with respect to optical recording was optimized. It is shown that the chosen test method is appropriate for the determination of complete J–R curves including the values $J_{0.2}$ (J at 0.2 mm crack length), J_m (J corresponding to the maximum load) and the slope of the curve.

PACS: 62.20.Mk; 81.40.Lm; 81.40.Np; 81.70.Bt

1. Introduction

A manufactured component is, a-priori, expected to be defect-free. But in practice any material of a component may contain flaws or flaws can be created during special operational conditions. The question is whether such a flaw can expand into a crack and whether this crack is going to propagate. Especially for Zircaloy components in a nuclear environment eventually the question of safe operation or handling of the component arises. For normal operational conditions in a nuclear power plant axial split of Zircaloy cladding tubes or the behaviour of cracks in other thin walled components as spacers/grids may be a concern. For the period after service, during transportation (vibrations, shocks), intermediate dry storage (delayed hydride cracking, stress corrosion cracking) or final storage [1] fracture toughness properties of fuel cladding can become relevant.

The use of fracture mechanics technology for reactor Zircaloy issues has been limited in the past. This is partly due to a lack of regulatory emphasis on cladding failure as a safety issue [2] and to the fact that much of the standard fracture mechanics methodology does not apply to standard light water reactor (LWR) bundle component geometries. The use of fracture mechanics to predict the behaviour of cracks or defects is increasing. Papers at recent international conferences have illustrated fracture

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doi:10.1016/j.jnucmat.2006.02.045

mechanics techniques for analysing crack propagation in failed Zircaloy tubing [3–5]. And for many years, leak-before-break criteria and critical crack lengths in CANDU-type reactor (CANada Deuterium Uranium) pressure tubes have been analysed using fracture toughness methodology [6].

The strict methodology of LEFM usually does not apply to geometries (particularly thicknesses) of interest to reactor components. The plastic zone sizes of zirconium alloys are too large. For example: In order to satisfy the criteria of ASTM Standard E399 [7] for valid fracture toughness K_{IC} determination for a only roughly expected $K_{IC} = 55$ MPa m$^{1/2}$ and a yield stress of 600 MPa for irradiated Zircaloy at 573 K, the thickness of the tested samples must exceed a value of about 21 mm. This is many times the thickness of cladding, grid, channel, etc., components. For unirradiated Zircaloy the required thickness would be even larger.

To accommodate soft material the *J*-integral is frequently applied. As commonly used, '*J*' is related to the amount of work (dissipative energy, both elastic and plastic) per unit crack surface area required to extend a crack. But, it is strictly valid only in the case where the crack grows in an elastic material. Its use, however, has been extended [8,9] to include elastic–plastic materials like Zircaloy or for small radioactive samples of nuclear application relevant steels [10]. But even the less stringent size requirements for the applicability of the *J*-integral are not met theoretically by thin walled claddings. This work attempts to find a *J*-type approach to define mechanical quantities of claddings which allow a prediction of the fracture behaviour of cladding material with different toughness. In analogy to the conventional fracture mechanics approach such quantities should be as far as possible independent from specimen geometry to allow their application to components and realistic crack geometries.

2. Experimental

2.1. Material

The experiments were carried out with samples fabricated from the aluminium alloy Al-7050 and cold-worked stress relieved (SRA) Zircaloy-4. Cold-worked SRA Zircaloy was selected because it shows a lower tendency to very early crack blunting compared to re-crystallized Zircaloy. The aluminium alloy which exhibits significant lower fracture toughness was chosen because of comparison reasons.

2.2. Sample geometry

Our approach was based on the following criteria:

- In order to have a well defined starting point we have chosen a specimen geometry, which basis is well characterized under valid stress intensity factor *K* and *J* conditions.
- With respect to later testing of service exposed cladding material the geometry should also allow easy manipulator handling.
- All parameters reported for established *K* and *J* testing should be measurable.

Fracture mechanics samples can be of bending type or of tension type. Typical bending type samples are the compact tension (CT) specimen and the single edge notched (SEN) bending sample [11]. Well known tension type samples are the single or double edge notched tension (SENT, DENT) samples or the centre notched panel (CN). Because of our approach criteria, basically a pipe type tensile version was chosen.

Fig. 1 shows the tested different notched samples and the influence of their geometries and pre-cracking on the failure behaviour. To use an optimal sample form for generating well defined starter cracks by fatigue and to have a situation as close as possible to a potential real crack in a cladding tube, various tube sample geometries and the geometries' influence on the pre-cracking procedure were tested. The wall thickness of the samples B is 0.6 mm, the width W is 12.5 mm and the notch length l is dependent on the cutting process. The two edge notches on the front side of the DENT-like ring sample are cut with a wire saw, the holes of the samples which we designate CHT (central hole tension) and CLHT (central long hole tension) are drilled and the notch of the CNT (central notch tension) sample is cut by spark erosion. All hole and notch types are situated at the sample front side. The notch lengths and sizes respectively are about 0.8–1.0 mm (DENT), 1.1 mm in diameter (CHT), 1.2 mm × 3.2 mm (CLHT) and 0.4 mm × 1.8 mm (CNT).

2.3. Experimental equipment

The samples were tested on an electro-mechanical Schenck testing machine at room temperature in air. We used the 'one sample method'. Crack lengths and strain were recorded optically with a