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Fracture mechanics analysis of Zircaloy-4 tubular samples after laboratory simulated LOCA transient

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ABSTRACT

This paper investigates the room temperature cladding embrittlement of Stress Relieved Annealed (SRA) Zircaloy-4 fuel cladding samples subjected to laboratory steam oxidation tests simulating Loss of Coolant Accident (LOCA) transients at 1 200 °C followed by water quenching. These high temperature oxidized tubes are mechanically tested using axial tensile samples with machined gage sections. Formerly performed studies suggested that Linear Elastic Fracture Mechanics (LEFM) could provide a good understanding of the sample failure process, including crack nucleation close to the oxidized surfaces followed by crack instability and sample failure at higher applied loads. However, it was found that when the applied stress intensity was calculated using solutions for plate material given in the Tada and Paris Handbook, with the cracks in the plate corresponding to a crack formed only on the cladding's outer surface – produced by oxidation on this surface alone – versus two opposing cracks formed on the cladding's inner and outer surfaces – produced by oxidation on both of these surfaces – the critical stress intensity was different between these two cases. It is shown here that for both of the foregoing configurations the same critical crack intensity values are obtained when the applied LEFM stress intensity values are calculated using three dimensional finite element modeling of the axial tensile samples. The critical stress intensity factors determined by this more accurate method – and calculated as a function of degree of surface oxidation and hydrogen content in the prior-β phase – could, thus be considered to be a true materials parameter correlating well with the experimentally determined effect of hydrogen content on the failure strength of the samples.

1. Introduction

The safety demonstration for LOCA in Pressurized Water Reactors (PWR) was substantially changed in France in recent years [1–2]. Regarding the brittle failure mode during the quenching phase, the requirement relies on sufficient fuel rod strength upon quenching taking into account an additional mechanical load. The pressurized thermal shock test results [3–7] performed at JAEA were intensively used to investigate the LOCA safety issues. These tests are integral tests activating complex phenomena including oxidation, creep, ballooning, burst and secondary hydriding. The JAEA tests, as illustrated in Fig. 1, showed the influence of hydrogen content on the cladding embrittlement. The degree of cladding embrittlement is evaluated using the Equivalent Cladding Reacted (ECR) criterion evaluated using the Baker-Just correlation [8] on the deformed geometry at the ballooning region. Due to the complexity of these test results, there is a need for simpler tests providing detailed understanding of the phenomena controlling the cladding material embrittlement.

Consequently, to simulate the influence of LOCA on Zircaloy-4, un-deformed tubular samples were systematically oxidized in a

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Nomenclature

a, a_i, a_o	crack depth, inner diameter crack depth, outer diameter crack depth
e	sample thickness
E	Young modulus
ECR	equivalent cladding reacted corresponding to the sample weight gain divided by its maximum value during the cladding oxidation during a loss of coolant accident
F, F_i, F_o	stress intensity factor, shape function averaged along the crack front, for inner diameter crack or outer diameter crack
FE	finite elements
F_z	axial load
[H]	hydrogen content
$[H]_\beta$	hydrogen content in the ex-β phase of the zirconium alloy
J	Rice integral
K_I	stress intensity factor
K_I^*	calculated parameter having K_I as a limit value under small displacement assumption
K_{IC}	material fracture toughness
LEFM	linear elastic fracture mechanics
LOCA	loss of coolant accident
PWR	pressurized water reactors
RIA	reactivity initiated accident
S_{gage}	gage section of the sample
SRA	stress relieved annealed
w	gage width of the sample
x	position along the crack front, 0 at symmetry and $\pm w/2$ at the intersection of the crack front with the sample surface
ν	Poisson ratio
$\sigma_{fracture}$	axial stress at fracture of the oxidized sample
σ_z	axial stress component
Φ_i, Φ_o	normalized shape function describing the evolution of the stress intensity factor along the crack front, at inner and outer diameter of the sample

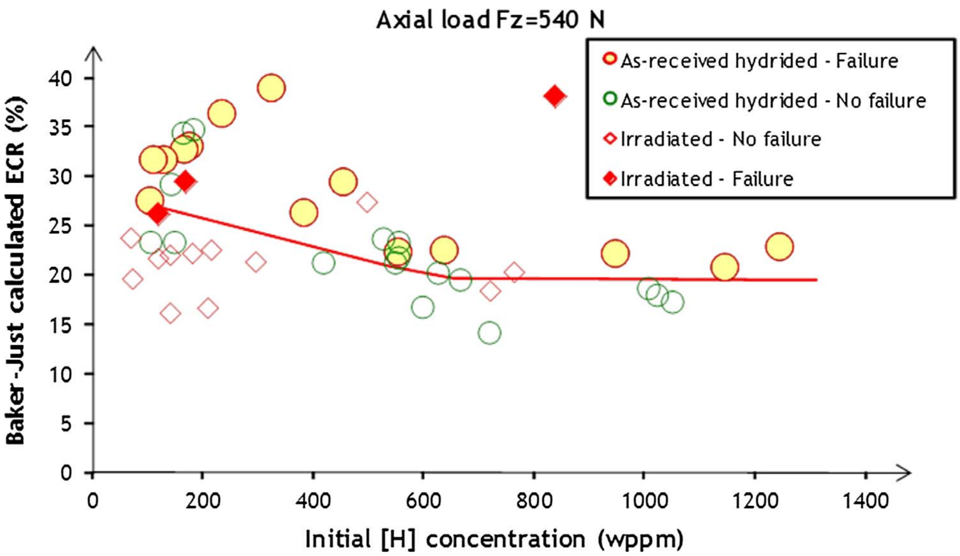

Fig. 1. Some JAEA pressurized thermal shock test results, with maximum applied load of 540 N on as-received, pre-hydrided samples and on irradiated rodlets. The red line corresponds to the lower limit of failed tests. The degree of cladding oxidation is evaluated using the Baker-Just correlation for ECR [3–7].

vertical furnace under steam environment at 1 200 °C after which they were quenched in a water bath. The samples were subsequently mechanically tested in order to fully characterize the level of material embrittlement. Different sample geometries were evaluated [9] having different mechanical responses depending on the type of oxidation: one-sided at the outer diameter or two-sided at both inner and outer surfaces of the cladding tubes. This study considers only test results obtained from axial tensile specimens as these types of tests provide acceptably simple boundary conditions for finite element modeling. The effect of hydrogen ([H]) content on the degree of embrittlement of these specimens is considered on the basis of the stress intensities evaluated with the finite element method since preliminary studies involving the present authors and others, based on the same sample geometry, confirmed that material embrittlement of the fuel cladding as observed after the pressurized thermal shock test results is strongly influenced by hydrogen content [10].

Elastic-plastic fracture mechanics was used by several laboratories for Reactivity Initiated Accident (RIA) studies to assess fuel cladding integrity [11–13] whilst the relevance of Linear Elastic Fracture Mechanics (LEFM) for modeling high temperature oxidized sample failures was evaluated in previous studies [9–10,14]. The incipient crack depth was associated with the cumulative depth of oxide layer and oxygen enriched α–Zr layer usually formed during LOCA transients. This assumption was experimentally confirmed at NSRC [15] from further results of the crack nucleation process. The Wu [15] experiments show that cracks form first in the oxygen enriched α-Zr layer during the oxidation phase and propagates, during the quenching under applied load, though the zirconia layer to