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# Expansion Due To Compression Tests With Rapid Heating Rate For RIA Situations

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## Abstract

This paper presents an assessment of the thermo-mechanical behavior of non-irradiated Cold-Worked Stress Relieved (CWSR) Zircaloy-4 nuclear fuel cladding, the first of the three containment barriers for the radioactive matter, under thermo-mechanical loading conditions representative of the first phase of a Reactivity Initiated Accident (RIA) in a nuclear power reactor. During this type of accident, the zirconium alloy fuel cladding tubes may be subjected to Pellet-Cladding Mechanical Interaction (PCMI) due to the thermal expansion of the pellet. Experimental data from past research reactor programs simulating RIAs have shown that the cladding experiences a strain rate of more than  $1 \text{ s}^{-1}$ , a heating rate of up to  $1000 \text{ }^{\circ}\text{C.s}^{-1}$ , and a variable multiaxial load path. In this study, different kinds of Expansion Due to Compression (EDC) tests with varying strain biaxiality ( $\epsilon_{zz}/\epsilon_{\theta\theta}$ ) conditions have been performed in order to study the evolution of the hoop strain at failure. The cladding was heated by a Joule effect heating method in order to produce heating rates greater than  $150 \text{ }^{\circ}\text{C.s}^{-1}$ . The heating method consists of passing an electric current through a heating element inside a ductile metallic pellet, which in turn is inserted inside the cladding. The electric current heats the pellet, which then heats the cladding via conduction. Once the temperature of the cladding reaches  $500^{\circ}\text{C}$ , the heating element and the pellet are compressed by two rigid pistons. As the pellet is compressed and expands in diameter, a hoop strain is imposed on the cladding specimen. To vary the biaxiality, the ends of the sample are either free or fixed. During the tests, the strain field in the sample is measured using a Digital Image Correlation (DIC) technique, and the temperature field is characterized using a thermal camera and thermocouples.

## Introduction

The core of a Pressurized Water Reactor (PWR) in a nuclear power plant is made up of fuel assemblies that include fuel pellets stacked inside zirconium alloy cladding tubes, the first of the three containment barriers for the radioactive matter. The postulated Reactivity Initiated Accident consists of a sudden and uncontrolled RCCA ejection, which results in a rapid local increase in reactor power. The evaluation of the behavior of the nuclear reactor includes the study of the mechanical behavior of the cladding in this situation. The rapid increase in power under the RIA leads to nearly adiabatic heating of the fuel pellets, which immediately deform by thermal expansion (1). This causes, during the first phase of the accident, a multiaxial thermomechanical loading on the cladding characterized by a strain biaxiality ratio ( $\epsilon_{zz}/\epsilon_{\theta\theta}$ ) between plane-strain (no axial strain in the cladding tube) and equal-biaxial tension (equal tensile strains in the hoop and axial directions) (2), a cladding tube heating rate of up to  $10^3 \text{ }^{\circ}\text{C.s}^{-1}$ , temperatures of up to  $600^{\circ}\text{C}$  (3-4), and a hoop strain rate on the order of  $1. \text{ s}^{-1}$  (1).

To accurately reproduce the accident, a laboratory test should provide an appropriate strain rate with a displacement-controlled load, at the relevant test temperature and heating rate, and with appropriate strain biaxiality. The biaxiality of the strain components, the strain rate, and the heating rate can have an important effect on the fracture strain of the material. Experiments have shown that the hoop strain at fracture tends to decrease as the strain biaxiality ratio increases (5). The effect of strain rate and heating rate on ductility has been reviewed by Yeuh et al (6) on hydrided and irradiated Zy-2 using flat and cladding C-clip sample geometries. The test results have shown that rapid heating leads to lower ductility than slow heating conditions, and ductility is smaller for larger loading rates.

The objective of the current study is to develop a new rapid heating method applied to Expansion Due to Compression (EDC) tests and to evaluate the effect of biaxiality on the strain at fracture for high heating rates. Two types of EDC tests were used. The first one consists of placing a pellet-shaped cylindrical device inside a sample of fuel cladding (7). The device is compressed axially, causing it to expand in diameter, and thereby creating a hoop strain in the cladding sample. During this type of free-end EDC test, the sample shrinks axially as it expands in diameter, and the stress and strain biaxiality achieved are close to uniaxial hoop tension. In the second configuration, a fixture prevents the sample from retracting axially (8). This end restraining fixture prevents any change in length of the sample, so the strain biaxiality is much more representative than that

of a free-end test. In this study, the tests are performed at 500°C with strain rates on the order of  $1. s^{-1}$ . The strain field in each sample is measured by a 3-dimensional DIC (Digital Image Correlation) technique.

## 2. Experimental methods

The samples used in this study were non-irradiated Cold-Worked Stress Relieved (CWSR) Zircaloy-4 fuel cladding tubes. The length, the outer diameter and the wall thickness of the sample are 27 mm, 9.5 mm, and 0.57 mm, respectively. The pellet inside the sample is made of pure aluminum and has a length of 14 mm and a diameter of 8.28 mm. The heating element is made of titanium alloy TA6V and has a length of 14.5 mm and a diameter of 3 mm.

### 2.1 EDC test with rapid heating

The method consists of passing an electrical current through a heating element that is press-fit inside the pellet, which in turn is inserted inside the cladding. The current passing through the heating element is converted into heat, which is then transferred to the pellet and to the cladding by conduction. Fig. 1(a) presents a schematic illustration of the test.

Finite element simulations with CAST3M were performed to identify the appropriate materials for the heating element and media. The choice was based on the electrical and thermal conductivities, the heat capacity and the electrical resistivity for the heating element and the mechanical behavior at 500 ° C for the pellet. Several materials were tested for the heating element, before choosing the titanium alloy TA6V for its high electrical resistivity and high melting temperature. Different TA6V diameters were tested to increase the electrical resistance, experimental problems of fitting were encountered for small diameters. For the pellet, pure aluminum was used because it is soft and ductile at 500°C and has a low specific heat capacity and a high thermal conductivity, so it can heat quickly.

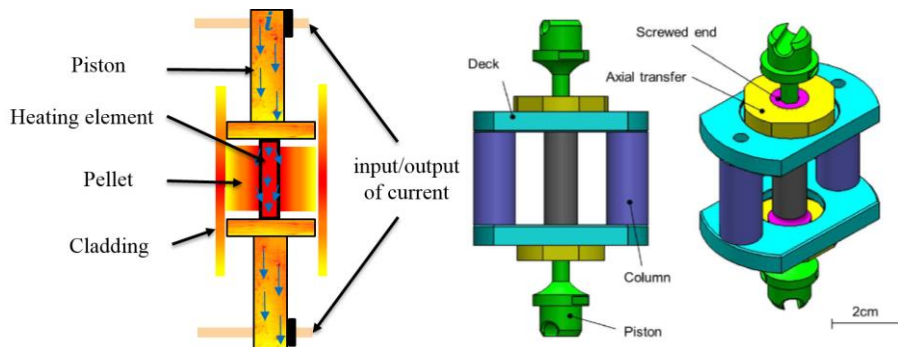


Fig. 1 EDC test with fast heating (a), fixed-end EDC test geometry (b)

Once the temperature of the cladding reaches 500°C, the heating element and the pellet are compressed by two rigid pistons. The axial compression causes the pellet to expand in diameter, thereby creating a hoop strain in the cladding. This type of test reproduces the loading mode of the accident, in which the expanding fuel pellet imposes a displacement-controlled strain on the fuel cladding. The tests can be performed at strain rates of the same order of magnitude as those experienced by the cladding during a RIA, typically  $1. s^{-1}$ . The EDC tests also load the cladding homogeneously in the gauge section and give conclusive results regarding crack profile (7). During these tests, the stress and the strain biaxiality achieved depend of the boundary conditions applied in the beginning of the test. Two EDC configurations are tested with different values of biaxiality. The first configuration, named free-end EDC, produces a state of nearly plane-stress in the sample, accompanied by a compressive axial strain. The stress and strain biaxiality achieved in the free-end EDC test is close to uniaxial hoop tension. The second configuration, named fixed-end EDC, produces a state of nearly plane-strain loading, in which the sample length is fixed Fig. 1(b).

### 2.2 Measurements

All the tests were performed on a MTS hydraulic tensile testing machine equipped with a 25 kN load cell. In this test, samples were heated to 500°C using a direct current and loaded mechanically using a cross-head speed of 28 mm/s, inducing a hoop strain in the sample with a strain rate on the order of  $1. s^{-1}$ . Temperatures were measured with thermocouples and a thermal camera, and the strain field was measured by a 3-dimensional DIC technique. All experiments were performed in air. The load, specimen hoop and axial strains and specimen temperature were recorded every 10 millisecond (100 Hz frequency).

## 3 Experimental results

### 3.1 Heating rate

The left side of Figure 2 shows the temperature field measured by the thermal camera on the outer surface of the fixed-end EDC sample. At the end of heating phase and before applying the mechanical load, the temperature field is homogeneous in the gauge section of the cladding. The area in contact with the pellet is hotter than the ends of the specimen. The right side of Figure 2 compares the temperature measured by a thermocouple welded to the sample and that measured at the same point by the thermal camera. The target temperature of 500°C is reached after 2.5 seconds, i.e. a heating rate of 200 °C s<sup>-1</sup>. The difference between the thermocouple and the thermal camera measurements can be explained by the fact that the thermocouple measurement is slightly delayed due to the high heating rate.

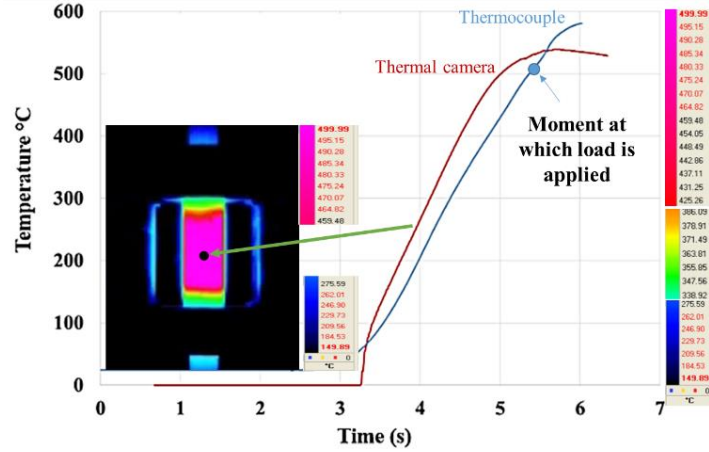


Fig. 2 experimentally measured temperature field and temperature-time curves

### 3.2 Hoop strain at failure

In the free-EDC test, the sample reached a hoop strain of 55% but did not rupture. In the fixed-end EDC test, the sample failed at a hoop strain of 26 % and an axial strain of 5 %. Figure 3 shows the path of the strain biaxiality as a function of the hoop strain  $\epsilon_{\theta\theta}$ . Photos of the final profiles of the free-end EDC test and fixed-end EDC test are illustrated next to each curve. It is found that the strain field is not perfectly axisymmetric, which is probably due to the fact that the media is very soft at 500°C, and it cannot maintain its barrel shape.

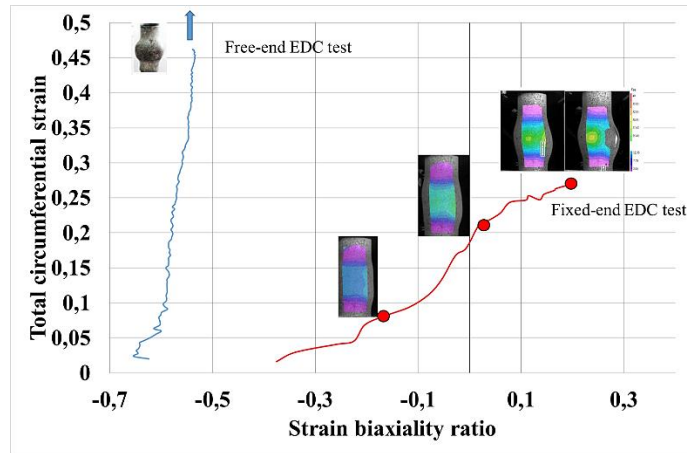


Fig. 3 Evolution of the hoop strain ( $\epsilon_{\theta\theta}$ ) as a function of the biaxiality of deformation ( $\epsilon_{zz} / \epsilon_{\theta\theta}$ ) for the free-end EDC and fixed-end EDC tests

## Conclusion

During a Reactivity-Initiated Accident (RIA), nuclear fuel cladding experiences a multiaxial loading state in which the Pellet-Cladding Mechanical Interaction (PCMI) produces a strain biaxiality ratio  $\varepsilon_{zz}/\varepsilon_{\theta\theta}$  of between 0 and 1, a strain rate of more than  $1 \text{ s}^{-1}$  and a heating rate of up to  $1000 \text{ }^{\circ}\text{C.s}^{-1}$ . This study investigates the effect of the strain biaxiality ratio, the strain rate and heating rate on the hoop strain at failure of CWSR Zircaloy-4 fuel cladding samples. A rapid heating method has been developed and validated. This method has been tested on a Free-end EDC and Fixed-end EDC geometry and shows that the hoop strain at failure tends to decrease as the strain biaxiality ratio increases.

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