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Multimodal setups for the study of fresh Zircaloy-4 claddings under simulated thermal-mechanical RIA conditions

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Abstract — The research aims at characterizing the thermal-mechanical behavior of fresh Zircaloy-4 claddings under simulated Reactivity Initiated Accident (RIA) loading. The loading is characterized by a very high heating rate ($>1000^{\circ}\text{C/s}$) while the claddings are internally pressurized (10-100 bars). The temperature can exceed the allotropic phase transformation of Zircaloy-4 which occurs in the vicinity of 812°C for a quasistatic loading. A 2-step identification procedure is proposed to understand the effect of thermal-metallurgical couplings during the out of equilibrium phase transformation on the viscoplastic and fracture behavior of the cladding. First, the dilatometry machine GLEEBLE-3500 is used to better understand the thermal kinetic impact on the allotropic phase transformation. Then, the semi-integral test bench ELLIE is used to simulate thermal-mechanical RIA conditions.

Keywords — High heating rates, RIA, Zircaloy-4, NIRT, 3D-DIC

Introduction A Reactivity Initiated Accident is one of the design basis accidents which are studied for Pressurized Water Reactors. It is due to the inadvertent ejection of a control rod which leads to a sudden increase of the cladding temperature with heat rates which can exceed 1000°C/s and reach more than 900°C . It can be split up in two steps: the Pellet Clad Mechanical Interaction (PCMI) and the post-Departure from Nucleate Boiling (DNB).

The PCMI results from the high temperature increase in the fuel pellets which induces its brutal expansion along with the cladding remaining at low temperature during a short period. It imposes a biaxial strain-controlled mechanical loading between the cladding and the pellet. After this, the coolant may start to evaporate. It leads to a high degradation of the heat transfer between the coolant and the cladding and induces the previously mentioned cladding temperature increase. The temperature increase, combined with the filling gas pressure and the fission gas release, results in an internal pressure of several tens of bars. The loading mode moves to a pressure-controlled one. Two kinds of experimental tests are performed on Zircaloy-4 samples to better understand thermal-metallurgical behavior of claddings during the post-DNB phase.

Phase transformation analysis In order to study the allotropic phase transformation ($\alpha \rightarrow \beta$) on Zircaloy-4 cladding, the GLEEBLE-3500 machine is used. Free dilatometry tests are performed on Zircaloy samples under secondary vacuum with heat rates varying from 1 to 2800°C/s . Hoop thermal strain is first measured using an optical dilatometer. A high speed camera Phantom V710 is also used during the tests to perform contour detection [1] and Near InfraRed Thermography (NIRT) [2].

Semi-integral creep tests The experimental setup ELLIE showed in Figure 1 is used to perform creep tests on Zircaloy-4 claddings [2]. Initially the specimen is internally pressurized. Then a thermal transient is applied up to 1000°C/s using a 30kW induction device until the temperature reaches the set point. The temperature is then hold until the specimen bursts. During the experiment, Argon is flushed inside the enclosure to avoid oxidation and mirage effects. The thermal data are measured with a frequency of 1000

fps by NIRT method. The kinematics data are obtained using a 3D-DIC algorithm (using UFreckles software developed by J. Rethore). Due to the geometry device, standard calibration with calibration grids cannot be performed. This step is therefore performed by using the well-known geometry of the Zircaloy tubular sample [3]. In order to avoid radiation at high temperature two blue LED rings (see Figure 1) with a wavelength of 470nm are combined with the two 12 MPx CMOS cameras which have pass band filters at $\lambda=470\text{nm}$ [4]. Thus, a 3D kinematics field can be obtained with a frequency of 100 fps at temperature exceeding 900°C .

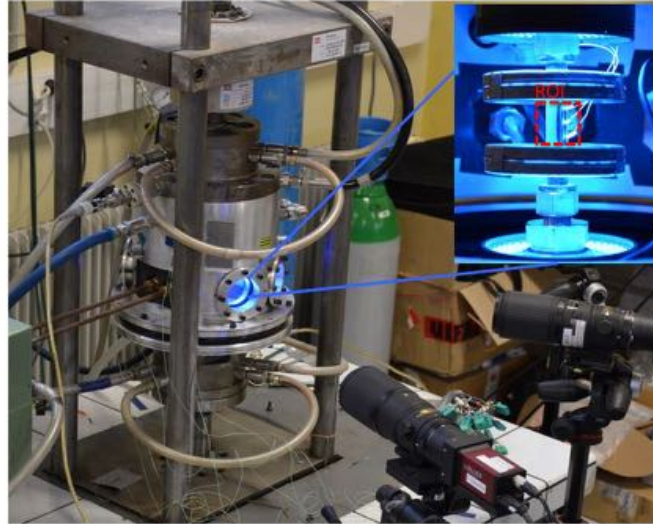


Figure 1: Experimental setup ELLIE [5]

Conclusion Two experimental setups have been used to simulate the loading of a RIA accident. Thermal and 3D kinematics fields are obtained with high frequency (1000 and 100 fps respectively). Combined to the phase transformation study, a power creep law, which takes into account the kinetic phase transformation, can be identified by a FEMU algorithm.

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