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► **To cite this version:**

Damien Campello, Nicolas Tardif, Marie-Christine Baietto, Michel Coret, Jean Desquines, et al..  
Thermo mechanical behaviour of fresh zircaloy-4 under LOCA conditions. PHOTOMECHANICS  
2015, May 2015, Delft, Netherlands. hal-01863134

**HAL Id: hal-01863134**

**<https://hal.science/hal-01863134>**

Submitted on 28 Aug 2018

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# THERMO MECHANICAL BEHAVIOR OF FRESH ZIRCALOY-4 UNDER LOCA CONDITIONS

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**ABSTRACT:** During a Loss of Coolant Accident in a Pressurized Water Reactor, a break on the reactor primary circuit leads to the quick water depressurization from 155 to almost 1 bar. The fast temperature drop of the fuel cladding from 320°C to 1200°C induces filling gas pressure increase. Thus, the pressure difference between the inner and outer tube surfaces grows, leading to important hoop stresses. Simultaneously, steam environment affects the creep behaviour of the cladding by oxidation and hydriding. Hydriding has several noticeable effects [1] on the creep behaviour of Zircaloy-4, creep rate decrease, embrittlement and shift of phase transition temperatures ( $\alpha \rightarrow \alpha + \beta$ ,  $\alpha + \beta \rightarrow \beta$ ) towards lower temperature. A custom experimental setup is used to study the macroscopic secondary creep behaviour of as-received and hydrided zircaloy-4 (cladding material) under a representative thermo-mechanical loading. The experimental matrix focuses on the following ranges, temperature between 700°C and 800°C (the phase transformation temperature of as-fabricated material is about 820°C), hoop stress in a range of 20 - 75 MPa and hydrogen content between 0 and 650 ppm. Experimental setup, post-treatment and preliminary results are here presented on as-received zircaloy-4 (Zr - 1,3 Sn - 0,2 Fe - 0,1 Cr).

## 1. EXPERIMENTAL SETUP

The experimental setup initially designed by N. Tardif et al. [2] has been suited for testing zircaloy cladding. Figure 1.a shows the device. The samples are 90 mm long, 0.57 mm thick and their outer radius is 4.75 mm. Argon gas is used for the test atmosphere and pressurizing the claddings. Due to the bottoming effect, a compressive force is set in order to produce a uniaxial stress state in the hoop direction. Induction device heats up the sample. The thermal distribution over the height is not uniform, even in the region of interest, between the two coils (Figure 1.a), which is 20 mm long.

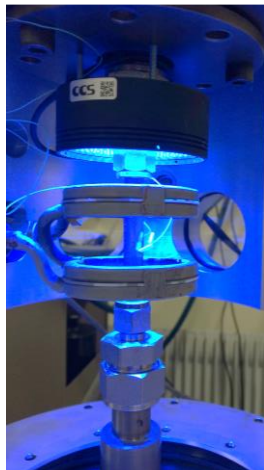


Figure 1.a



Figure 1.b

Region of interest (1.a), and entire experimental setup with cameras and LED rings (1.b).

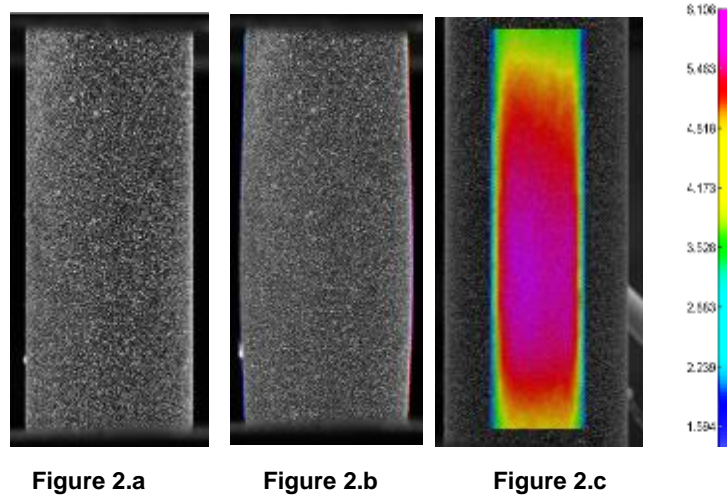
Experimental setup has been designed in order to get local temperature and kinematics data. As a matter of fact, the temperature acts a lot on the creep behaviour of alloys (especially at high temperature). An infrared camera gets the thermal field which is calibrated from the thermocouples data.

The kinematics fields are calculated by 2-D Digital Image Correlation [3] from optical full field measurements over the height of the specimen with an internal software developed at the LaMCoS. Image contours detection method [4] can also be used when viscoplastic hoop strains are too large for 2D-DIC.

To avoid radiation of the alloy and errors in the kinematics fields calculations [5], two blue LED rings ( $\lambda=470\text{nm}$ ) are combined with pass band filters centred on  $\lambda=470\text{ nm}$ . A black undercoating and a white speckle pattern are sprayed for the 2D-DIC. A black area is kept on the height in front of the infrared camera (high emissivity).

## 2. PRELIMINARY RESULTS

From the first tests, the temperature's distribution can be interrelate with the hoop strain state over the axial direction. Four cameras are distributed over the circumference and record pictures simultaneously: two of them are devoted to 2D-DIC, 1 to contours detection method and the last is consecrated to record what happens in the near infrared (Figure 2).



**Based on the reference image (2.a) the contours are determined (2.b) and the DIC can correlate up to 13% of hoop strain (2.c) at 800°C with a good agreement**

Thermal and kinematics fields are synchronized what leads to the identification of a multiplicative power-law describing the creep behavior of as-received zircaloy-4 fuel cladding:

$$\epsilon^{\text{creep}} = A \cdot \sigma_{VM}^n \cdot \frac{t^{m+1}}{m+1} \quad (1)$$

Where  $\epsilon^{\text{creep}}$  is the creep strain and A, m, n are three parameters depending on the temperature. Results are compared to the literature [6] in a validation purpose.

Infrared camera will provide a temperature field and the characterization of the multiplicative law could be effective for several temperature with a unique test, for a low strain state. These results will be presented in May with the characterization of the multiplicative law for an 800°C temperature.

## 3. REFERENCES

1. Brachet, J. Ch. and Portier, L. and Forgeron, Th. and Hivroz, J. and Hamon, D. and Guilbert, Th. (2002) Influence of hydrogen content on the  $\alpha / \beta$  phase transformation temperatures and on the thermal-mechanical behavior of Zy-4, 4 (ZrSnFeV), and M5 (ZrNbO) alloys during the first phase of LOCA transient. *Zr in the Nuclear Industry, 13th. Int. Symp.* 673-701.
2. Tardif, N. and Coret, M. and Combescure, A. (2011) Experimental study of the fracture kinetics of a tubular 16MnNiMo5 steel specimen under biaxial loading at 900 and 1000°C. Application to the rupture of a vessel bottom head during a core meltdown accident in a pressurized water reactor. *Nuclear Engineering and Design*, 241, pp. 755-766.
3. Sutton, M. A. and Wolters, W. J. and Peters, W. H. and Ranson, W. F. and McNeill, S. R. (1983) Determination of Displacement Using an Improved Digital Correlation Method. *Im Vis. Comp.*, vol.1, n°3, p.133-139.
4. Réthoré, J. and Francois, M. (2014) Curve and boundaries measurement using B-splines and virtual images. *Optics and Laser in Engineering*, 52, 145-155.
5. Pan, B. and Wu, D. and Wang, Z. and Xia, Y. (2011) High-temperature digital image correlation method for full-field deformation measurement at 1200 °C", *Measurement Science and Technology*, 22, 755-766.
6. Rosinger, H. E. and Bera P. C. and Clendening, W. R.(1979) The steady state creep of zircaloy-4 from 940 K to 1873 K. *Journal of Nuclear Materials*, 82, 286-297.