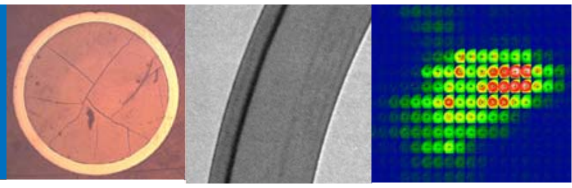

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Hydrogen diffusion in Zircaloy measured by high-resolution neutron imaging

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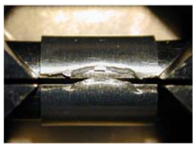
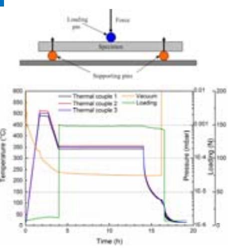
Motivations

- **Hydrogen** in Zircaloy **nuclear fuel claddings** can often be **non-uniform** risking the integrity of fuel rods during operation, intermediate dry storage, handling and transportation.
- PSI Neutron Microscope offers highest available **spatial resolution** to look into hydrogen field.



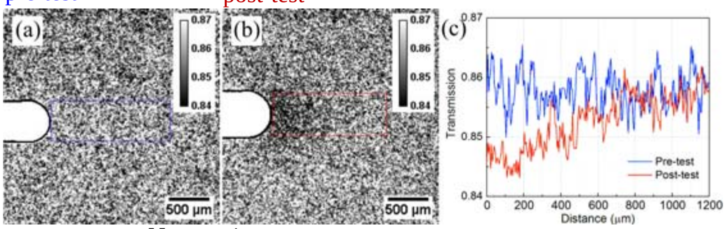
Stress-driven diffusion @BOA 2016

- Zry-4 plate, 4.5 mm, H ~600wppm
- 3-points bending
- H difffusion under stress, 10h at 350°C
- Exposure 30 s × 30
  FOV 2.5 mm × 2.5 mm



pre-test

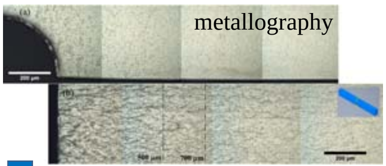
post-test

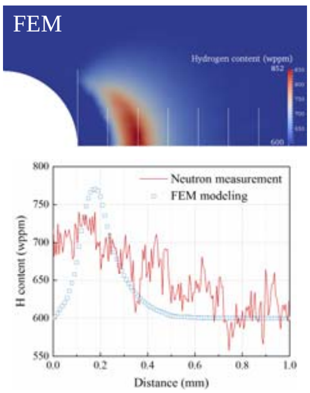


Neutron images

- H cont. gradient in 700 µm
- Max. elevation ~160 wppm
  at 100~200 µm off the notch

metallography





- Thermodynamics computation

second law $\frac{\partial}{\partial t}c^H + \underline{\nabla}.\underline{J}^H = 0$,

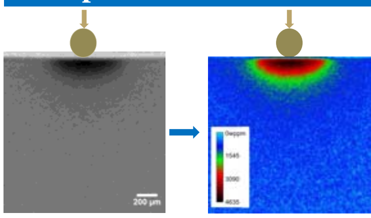
H flux $\underline{J}^H = -\frac{c^H D^H}{RT}\underline{\nabla}\mu^H$,

stress-dependent chemical potential

$$\mu^H(\sigma) = tr\underline{\underline{\sigma}}\left(\overline{V^H} - \overline{V^h}\right)$$

- Agreement in the area of the highest hydrogen concentration
- 50 wppm difference identified valid by modeling

Temperature-driven diffusion @BOA 2016

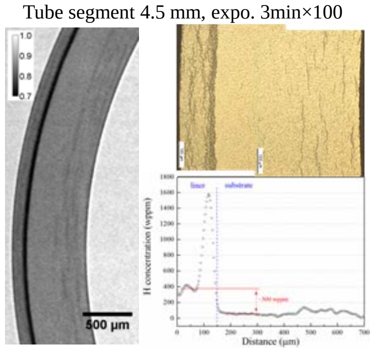


- Temerature gradient at the bending spot
- H accumulation up to 4000 wppm at the cold junction

Liner-induced diffusion @POLDI 2017

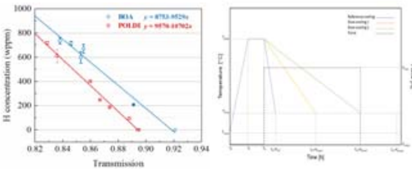
Cladding tubes used in Swiss LWRs normally have a **liner** which **always acts as a sink of hydrogen**. Quantification of hydrogen concentration in the liner and zirconium has never been achieved, which is of great interest both for the industry and scientific community.

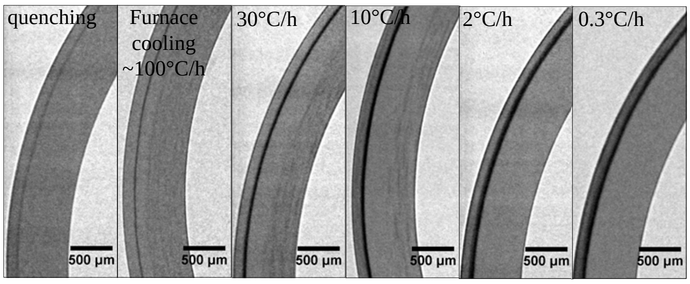
Tube segment 4.5 mm, expo. 3min×100



Highlights

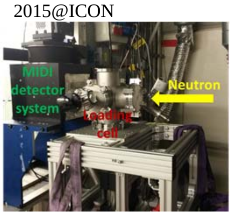
- **Visualization of single hydride**
- **Hydrogen gradient**
- **Effect of cooling rates**



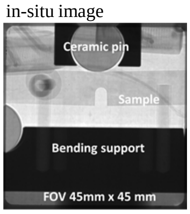


In-situ thermo-mechanical test

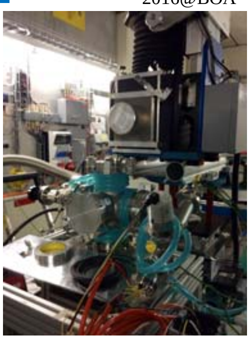
2015@ICON



in-situ image



2016@BOA



unsuccessful in-situ campaigns

- Spatial resolution limitation in 2015
- SINQ broke down in 2016…

Summary

- Hydrogen diffusion in various cases was quantified in a sub-10 µm scale by PSI Neutron Microscope.
- A combined approach of neutron imaging and finite element modeling helps to distinguish a valid measurement from experimental errors.
- An in-situ thermo-mechanical equipment was constructed specially for neutron imaging.

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