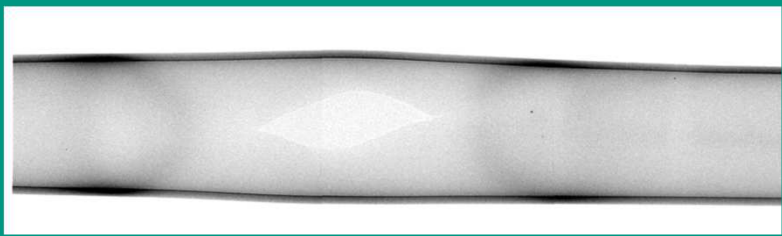
Karlsruhe Institute of Technology

Which Resolution can be achieved in Praxis in Neutron Imaging Experiments? - A General View

M. Grosse, N. Kardjilov

KIT / Institute for Applied Materials / Program NUSAFE

Helmholtz Centre Berlin



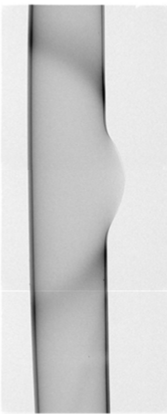
Outline

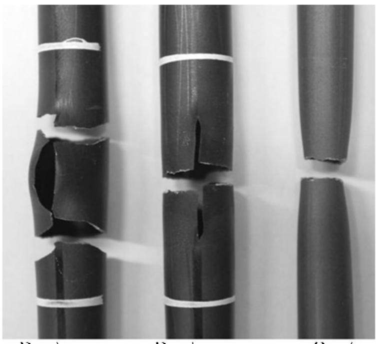
- Introduction
- Theoretical view on NI resolution
- Application on the systems Zr – H and ZrO_2 - ZrN
- Conclusions

Introduction

Hydrogen in Zircaloy

Hydrogen enrichments in nuclear fuel cladding tubes made of Zircaloy after loss of coolant accident simulation



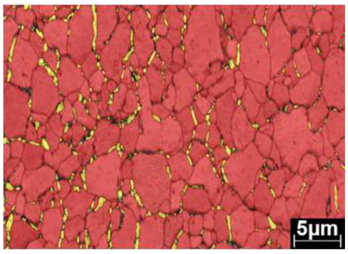


Rupture near to the burst opening due to hydrogen enrichment	Rupture across the burst opening due to stress concentration	Rupture near the end plugs after necking

Introduction

Hydrogen in Zircaloy

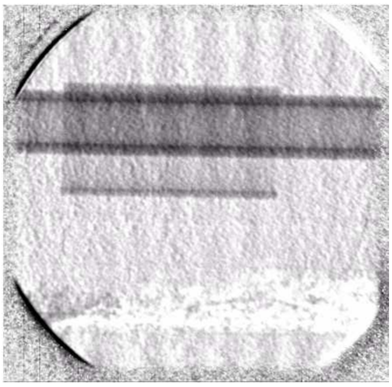
Delayed Hydride Cracking

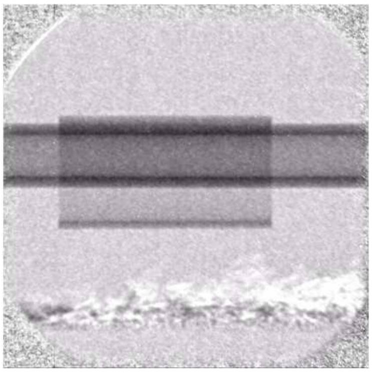


Σ(Zry-4) = 0.21 cm^{-1}
$\Sigma(ZrH_2)$ = 5.80 cm^{-1}
→ high n contrast

Introduction

ZrN in ZrO_2



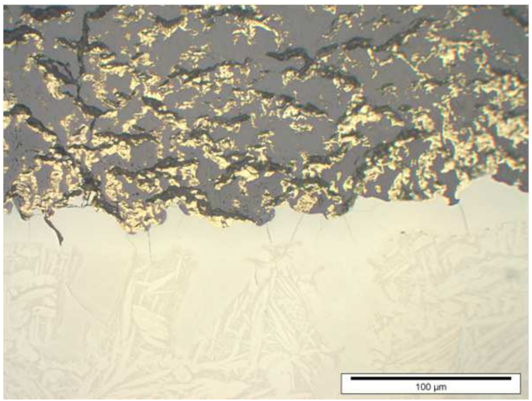


Zry-4, 900°C, 12 l/h Ar, 2 g/h H_2O

Zry-4, 900°C, 12 l/h Ar, 2 l/h H_2O + 10 l/h N_2

Introduction

ZrN in ZrO_2



$\Sigma(ZrO_2)$ = 0.44 cm^{-1}
$\Sigma(ZrN)$ = 0.81 cm^{-1}
→ low n contrast

Introduction

Can we investigate single ZrH_2 precipitates in Zry-4 or ZrN precipitates in ZrO_2 by means of neutron imaging (formation, re-distribution, re-orientation)?

Spatial resolution in the order of 1µm is needed!

Theoretical view

The object has to give a contrast to the matrix

$$\frac{|I_O - I_M|}{I_M} = |1-\exp(-(\Sigma_O-\Sigma_M)\,s_O)| > \frac{\sqrt{I_M+I_B}}{I_M-I_B}$$

The pixel size has to be smaller than the object size

$$s_{pixel} < s_O \qquad I \sim s_{pixel}^2$$

The collimation has to be good enough

$$L/d \geq l/s_O \qquad I \sim (L/d)^{-2}$$

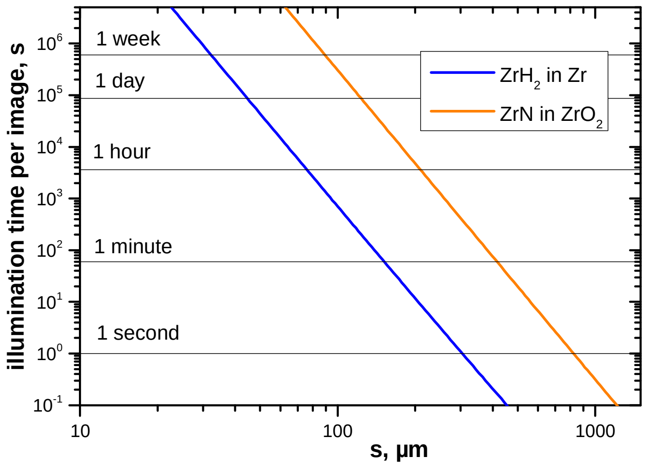
$$N_{projections} = \frac{\pi}{2}\,\frac{s_M}{s_O}$$

$$\Delta t = \frac{4\,l^2}{\phi_1(\Delta\lambda,\lambda)\,s_O^4\,(1-\exp(-\Delta\Sigma\,s_O))^2}$$

$$t = \frac{2\,\pi\,s_M\,l^2}{\phi_1\,s_O^5\,(1-\exp(-(\Sigma_O-\Sigma_M)\,s_O))^2}$$

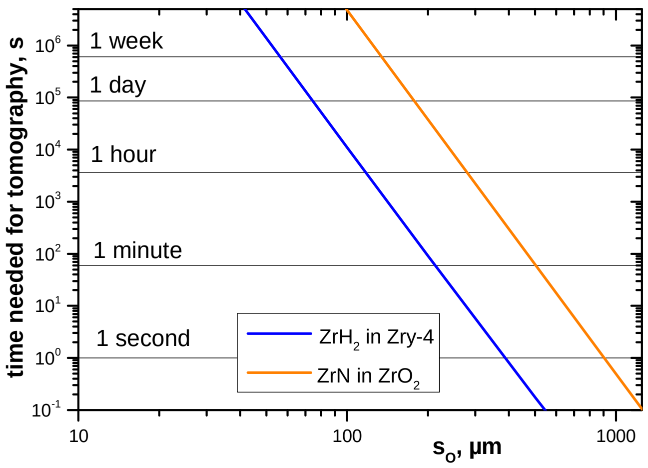
Application - Radiography

Model: single equiaxial object in homogeneous matrix



Application - Tomography

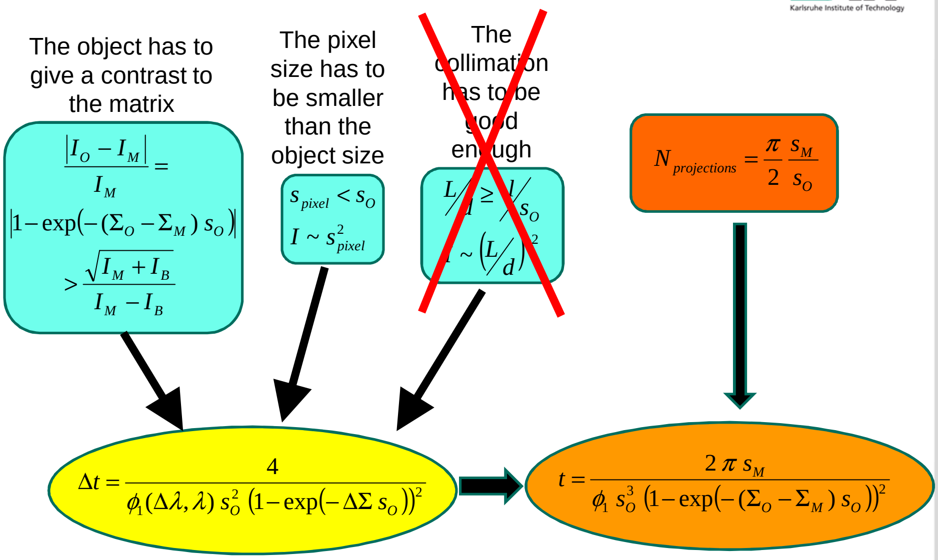
Model: single equiaxial object in homogeneous matrix



Remarks

- LiF based transmitter foils do not improve the situation compared to Gadox foils even the counts per pixel are higher.
- The analysis is valid for pinhole geometry. If neutron optics are applied the collimation condition can be deleted.

Theoretical view



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8th International Topical Meeting on Neutron Radiography, ITMNR-8
4-8 September 2016, Beijing, China

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Remarks

- LiF based transmitter foils do not improve the situation compared to Gadox foils even the counts per pixel are higher.
- The analysis is valid for pinhole geometry. If neutron optics are applied the collimation condition can be deleted
- The analysis is valid for equiaxial objects. Often rod- or disc-shaped objects or interfaces are of interest. In these cases the contrast depends on the neutron path length through the object.
- Often additional contrasts can be used (Frauenhofer diffraction, refraction, total reflexion, …). It would improve the situation.
- Increasing one component of the resolutions needs decreasing at least one other resolution component (e.g. strain imaging with $\Delta\lambda/\lambda<10^{-3}$)

Conclusions (1)

- Resolution in NI is a multidimensional ellipsoid surface depending on the differences in the total macroscopic neutron cross sections and the power of the source. At this surface the different resolution components can be varied.
- For pinhole camera setups the different dimensions of resolution are connected as following:
  - Time ~ spatial resolution $t \sim s_O^{-4}\left(1-\exp\left(-\Delta\Sigma\, s_O\right)\right)^{-2}$ (radiography)
    $t \sim s_O^{-5}\left(1-\exp\left(-\Delta\Sigma\, s_O\right)\right)^{-2}$ (tomography)
  - Time ~ wavelength resolution $t \sim \phi_1(\Delta\lambda, \lambda)^{-1}$
  - Time ~ contrast between the total neutron cross sections

$$t \sim \left(1-\exp\left(-\Delta\Sigma\, s_O\right)\right)^{-2}$$

Conclusions (2)

- Single objects of a size of 40 µm and 100 µm can be investigated by means of radiography in the systems ZrH_2 in Zry-4 and ZrN in ZrO_2, respectively, in realistic times.
- For tomography the limits are 60 and 150 µm, respectively.
- Wether single ZrN precipitates in ZrO_2 nor ZrH_2 precipitates in Zry can be investigated yet by means of neutron imaging methods.
- Much stronger neutron sources are needed for these investigations.

Thank you for your attention.

Questions?

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KIT – University of the State of Baden-Wuerttemberg and National Research Center of the Helmholtz Association
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