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supérieure \_\_\_\_\_  
paris-saclay \_\_\_\_\_



# STUDY OF THE TENSILE ANISOTROPY OF EXTRUDED ODS STEEL TUBES USING NOTCHED RINGS

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## GEN IV Sodium Fast Reactors

- More sustainable fuel cycle
- Improved safety
- Reduced waste production

Higher burnup leading to more severe fuel cladding solicitations

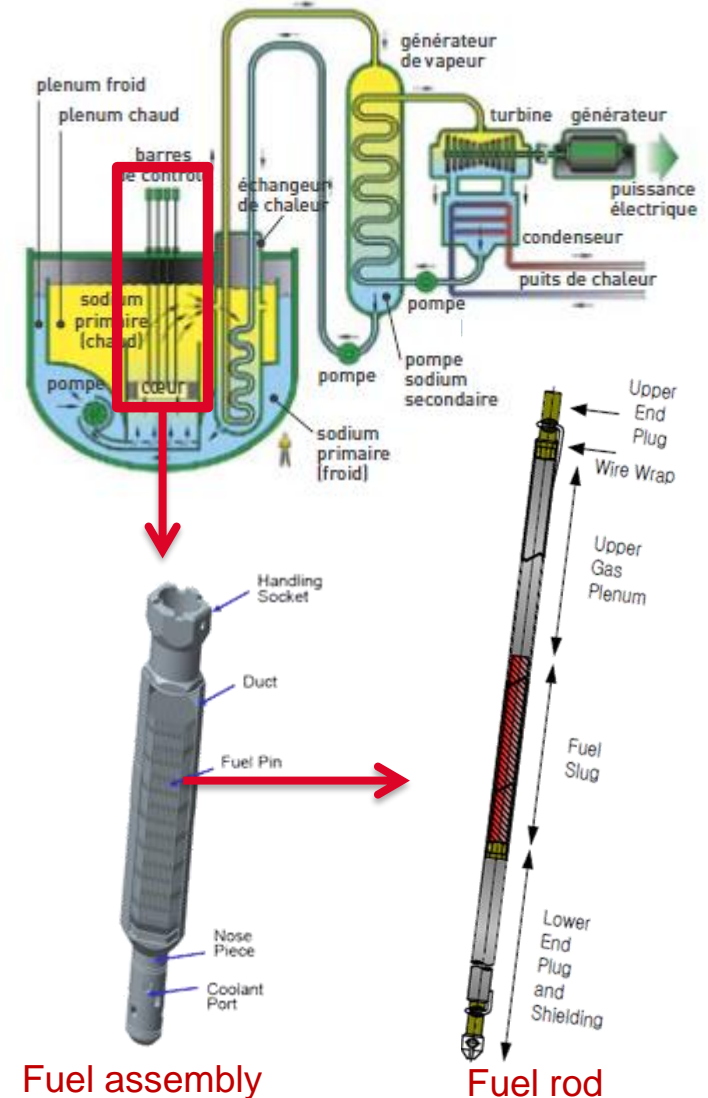
- Temperature: 400-650°C
- Internal pressure: 120 bars (max at life end)
- Irradiation: 100-200 dpa
- Sodium environment effects

### ➤ Oxide Dispersion Strengthened (ODS) steel

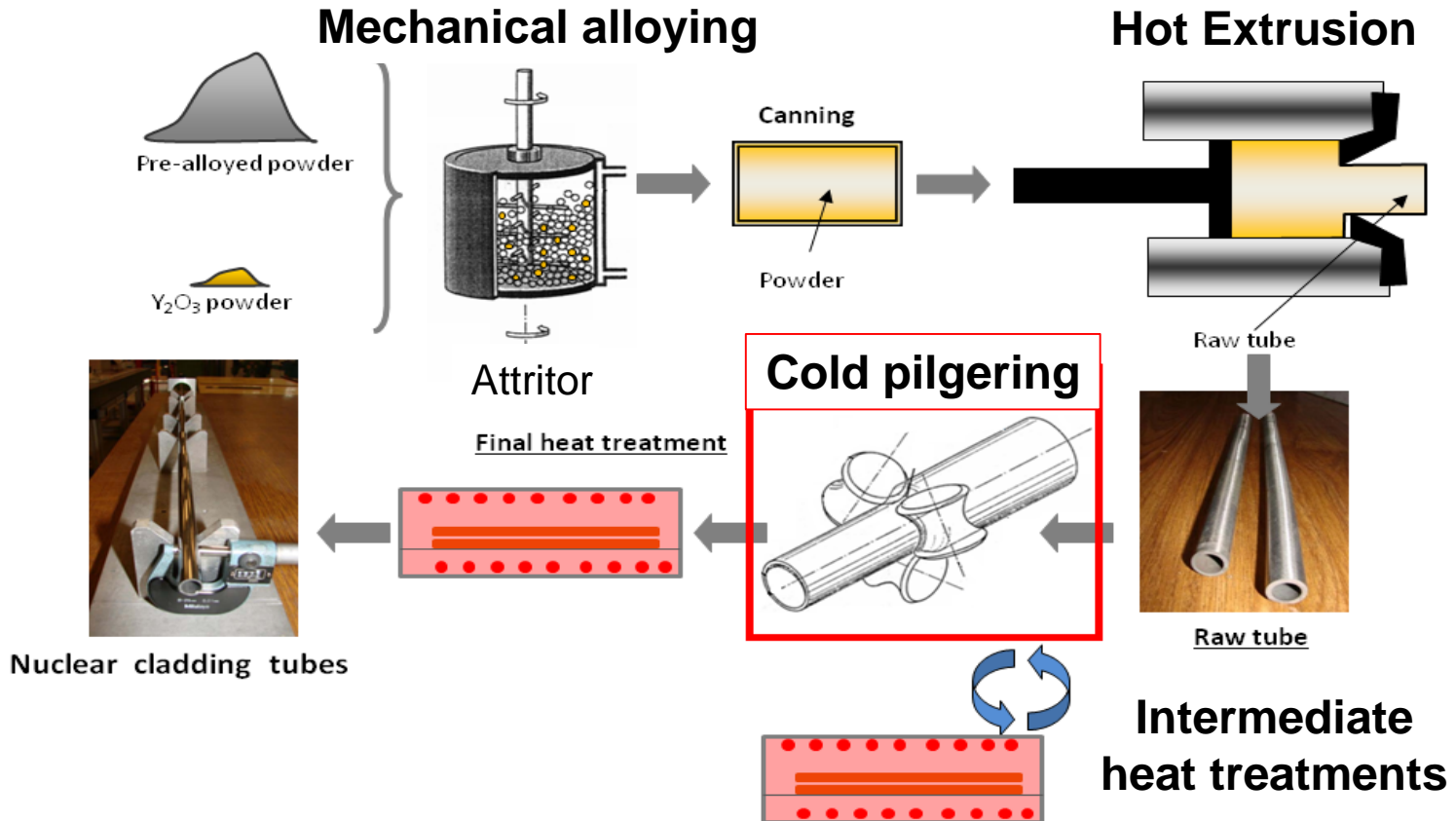
Good candidate material thanks to:

- high resistance to thermal creep
- Low irradiation swelling

[CLEFS CEA n°55, 2007]



[Kim et. Al., 2013]



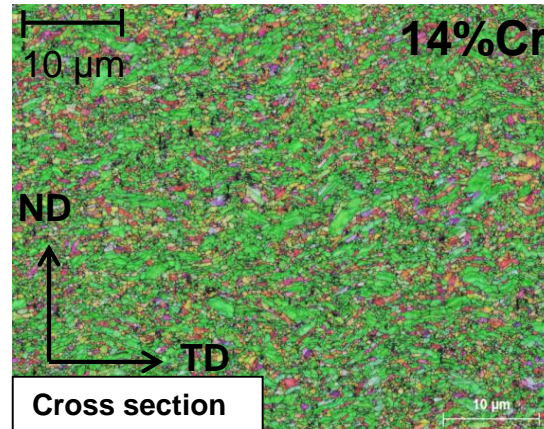
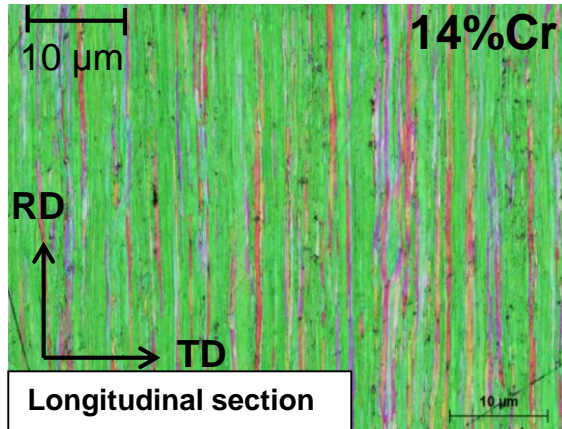
- Studied material : **tube**
- Process introducing **anisotropic microstructure**

Ferritic 14%Cr ODS steel

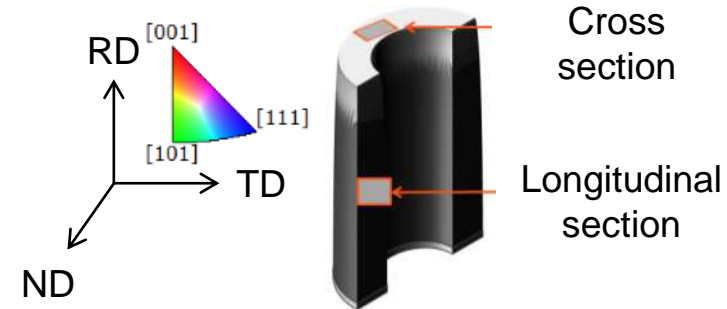
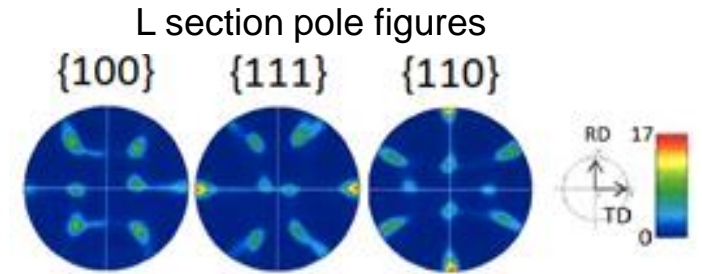
Fe-14Cr-1W-0.3Ti-0.25Y<sub>2</sub>O<sub>3</sub>

Martensitic 9%Cr ODS steel

Fe-9Cr-1W-0.3Ti-0.25Y<sub>2</sub>O<sub>3</sub>



- **Elongated grains parallel to the rolling direction and strong texture**

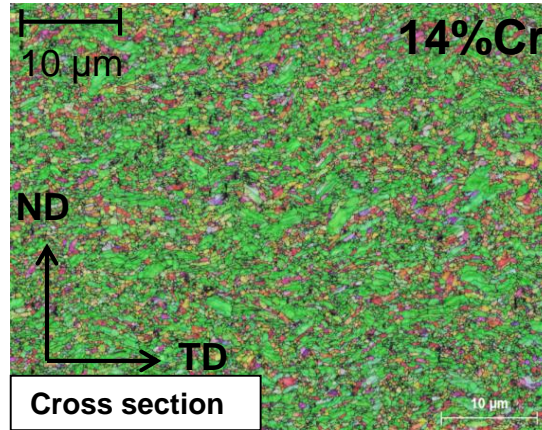
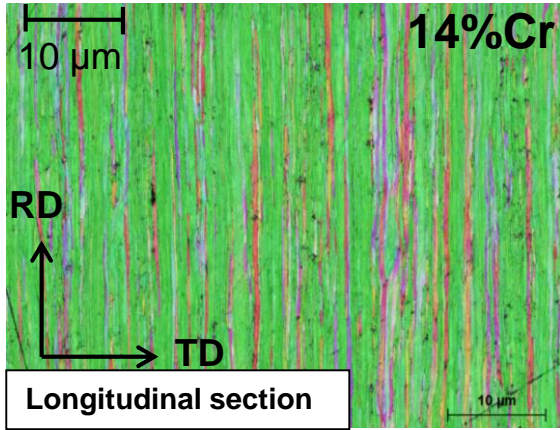


Ferritic 14%Cr ODS steel

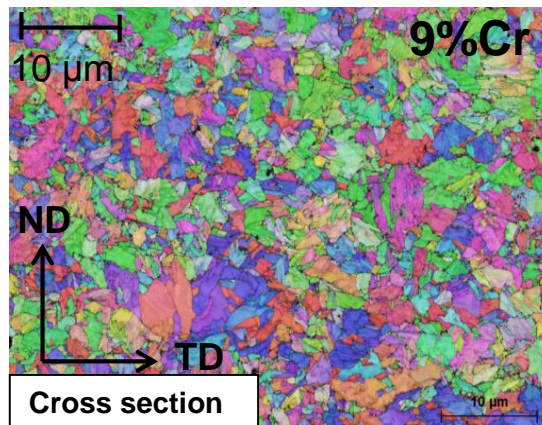
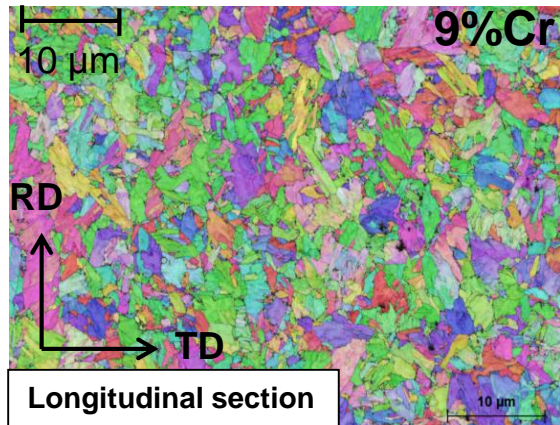
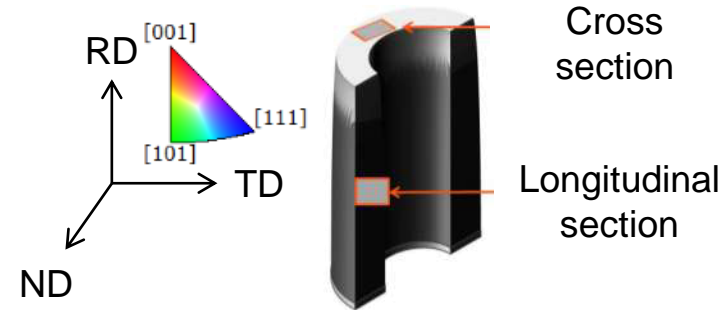
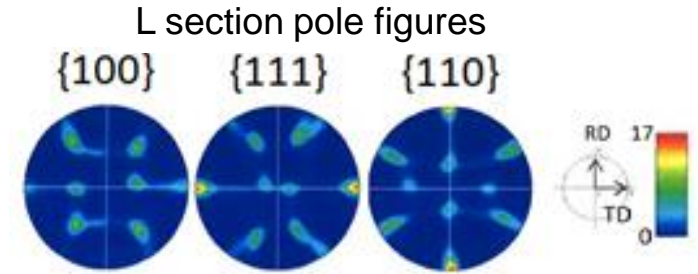
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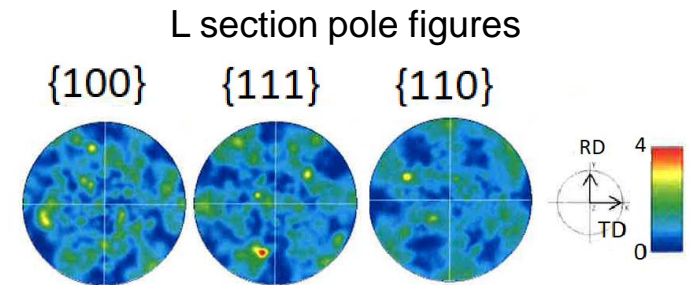
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➤ Elongated grains parallel to the rolling direction and strong texture



➤ Equiaxed grains with no specific texture



## □ Main objectives

- Testing the longitudinal and hoop properties of the tubes
- Through tensile, uniaxial and internal pressure creep tests
- In order to predict the lifetime of fuel cladding

# TILE AND RING TENSILE SPECIMENS

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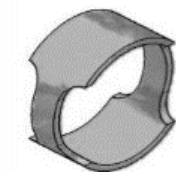
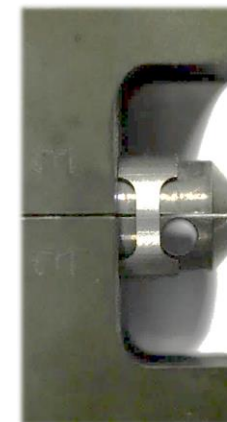
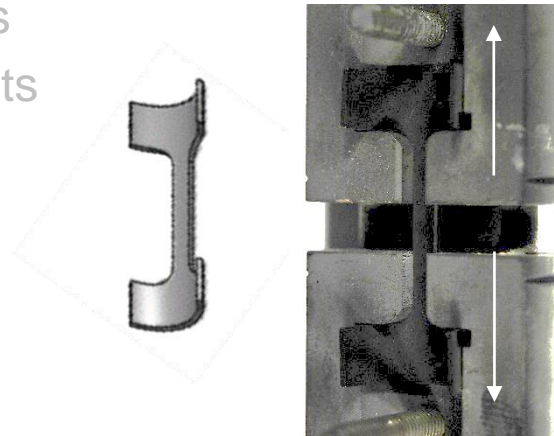
## □ Tensile properties: 2 specimen geometries

- Tile specimens for the longitudinal properties
- Notched ring specimens for the hoop properties

The ring test is non-standard [1-4], known to be dependent on :

- Load configuration
- Friction
- Length to width gauge ratio

Tile specimen



Ring specimen



# TILE AND RING TENSILE SPECIMENS

## □ Main objectives

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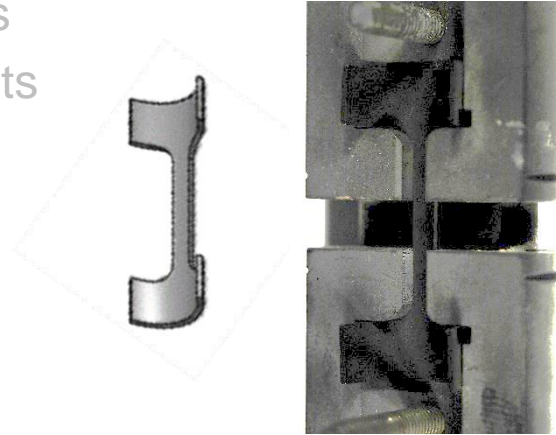
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The ring test is non-standard [1-4], known to be dependent on :

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Tile specimen



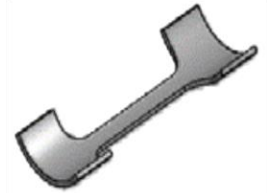
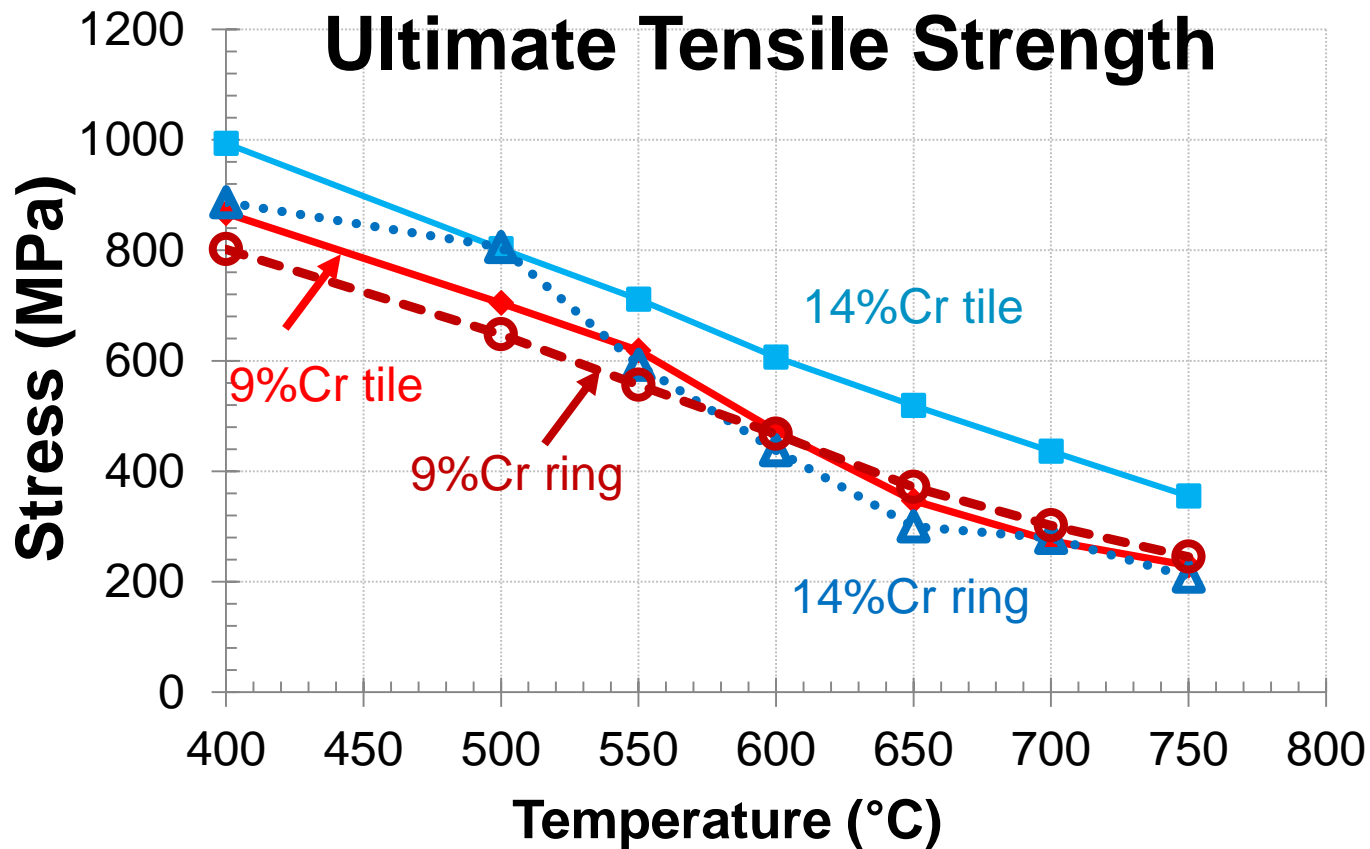
Ring specimen

➤ In order to properly study material anisotropies, the **effect of the specimen geometry** must be analysed

# TENSILE TESTS



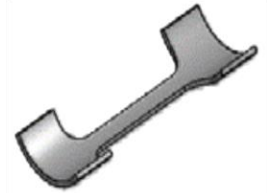
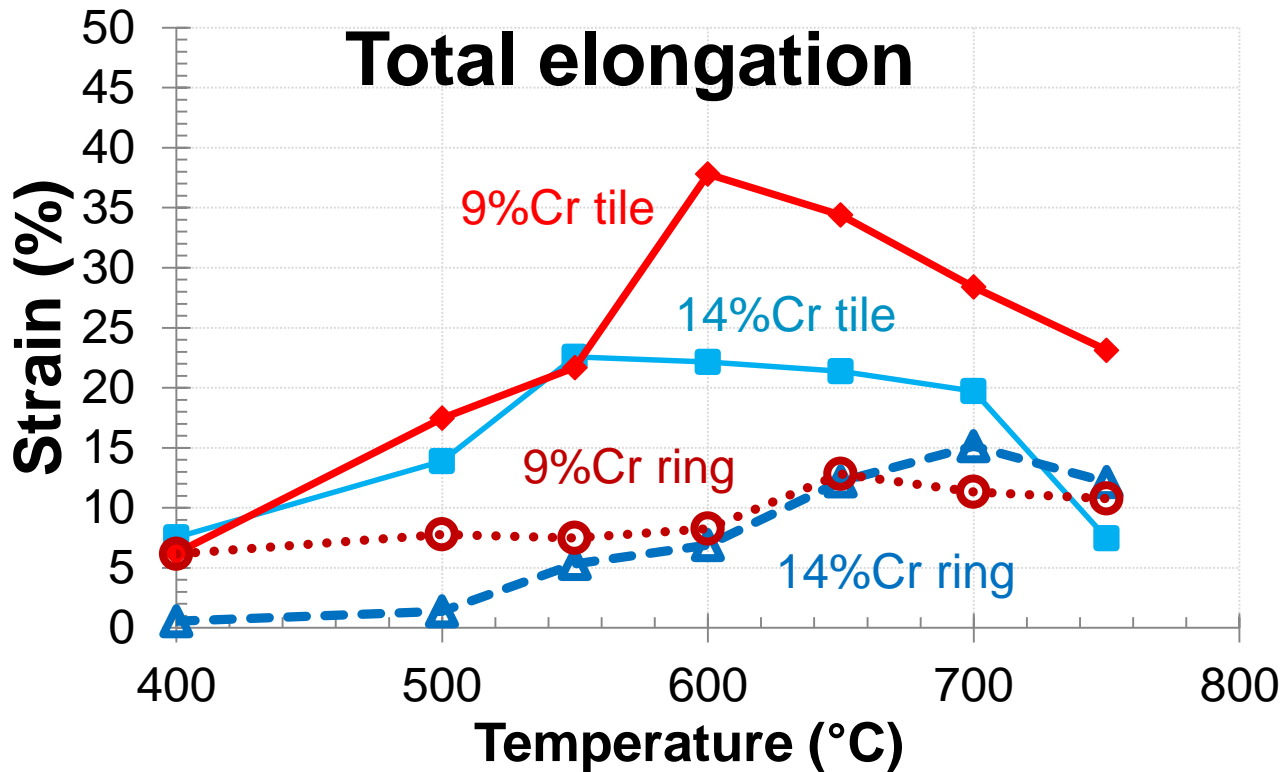
# TEST RESULTS – ENGINEERING CURVES



Tested at  $7.10^{-4} \text{ s}^{-1}$



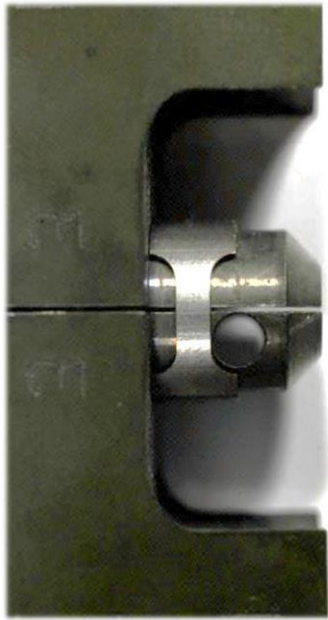
- In the 400-750°C range, the 14%Cr tube is significantly more resistant in the L direction
- For the 9%Cr tube, both directions are almost equivalent



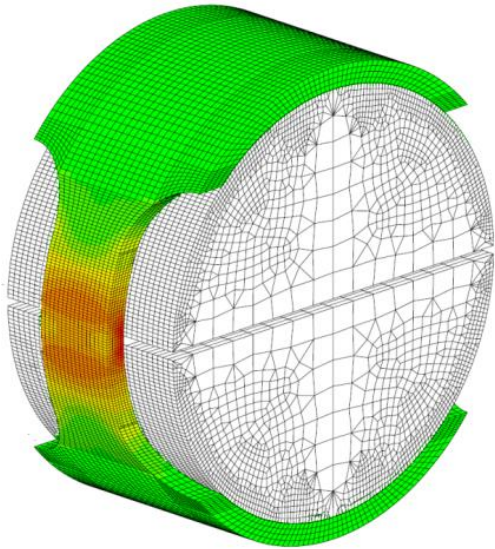
Tested at  
 $7.10^{-4} \text{ s}^{-1}$



- In the 400-750°C range, both 9%Cr and 14%Cr show anisotropic total elongation
- As the 9%Cr mechanical behaviour is considered to be isotropic, specimen geometry is a potential cause to investigate -> modelisation



## CONSTITUTIVE MODELLING AND FE SIMULATION



## Choices for mechanical behaviour and damage laws

Tensile and creep tests suggest the following:

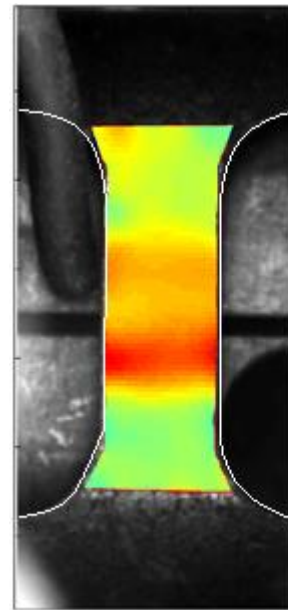
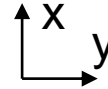
- ❑ 9%Cr tube: isotropic (viscoplastic) behaviour, anisotropic damage (to account for varying crack orientations)
- ❑ 14%Cr tube: anisotropic (viscoplastic) behaviour, anisotropic damage

A continuum damage mechanics approach (Lemaitre-Chaboche) was used.

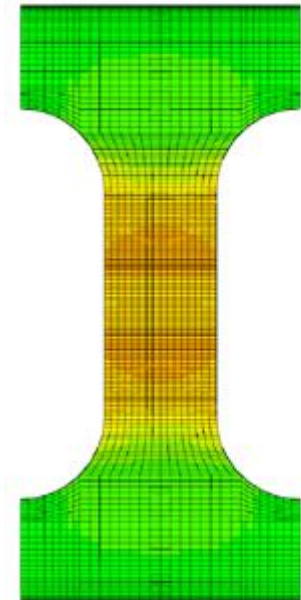
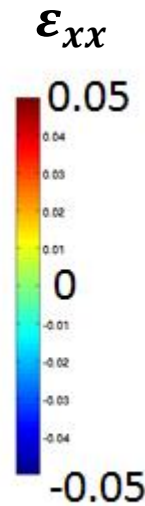
The following simulations work focus on the **tensile test** for the **9%Cr tube at 650°C**.

Understanding of the ring specimen influence on the overall behaviour will permit the proper analysis of the 14%Cr tube material anisotropies.

- Friction plays an important role and has to be estimated, lacking experimental means to evaluate it
- Digital Image Correlation is used to obtain displacement/strain fields on the outer surface of the gauge section of the ring
- Using a simple elastoplastic model the strain fields are compared for different friction coefficients.
- A value is chosen according to the best similarities (**friction coefficient =0.1**)



Strain from DIC



Simulated strain



Elasticity coupled  
with anisotropic  
damage

[Lemaitre et. al, 2000]

$$\begin{aligned}\boldsymbol{\varepsilon}^e &= \frac{1}{2G} (\mathbf{H}\boldsymbol{\sigma}'\mathbf{H})' + \frac{1}{9K} (g(\mathbf{H})\langle \text{tr } \boldsymbol{\sigma} \rangle_+ + \langle \text{tr } \boldsymbol{\sigma} \rangle_-) \mathbb{1} \\ \tilde{\boldsymbol{\sigma}} &= [\mathbf{H}\boldsymbol{\sigma}'\mathbf{H}]' + \frac{1}{3} (g(\mathbf{H})\langle \text{tr } \boldsymbol{\sigma} \rangle_+ + \langle \text{tr } \boldsymbol{\sigma} \rangle_-) \mathbb{1} \\ \tilde{\boldsymbol{\sigma}} &= \mathbb{E} : \boldsymbol{\varepsilon}^e\end{aligned}$$

$\tilde{\boldsymbol{\sigma}}$ : Effective stress

$\mathbf{D}$ : Damage 2<sup>nd</sup> order tensor

$\eta$ : hydrostatic sensitivity parameter

$K$ : bulk modulus

$G$ : shear modulus

$$\mathbf{H} = (\mathbf{1} - \mathbf{D})^{\frac{-1}{2}}$$

$$g(\mathbf{H}) = (1 - \eta) + \eta \left( \frac{1}{10} (\text{tr}(\mathbf{H}))^2 + \frac{1}{30} \text{tr}(\mathbf{H})^2 \right)$$

[Desmorat et. al, 2017]

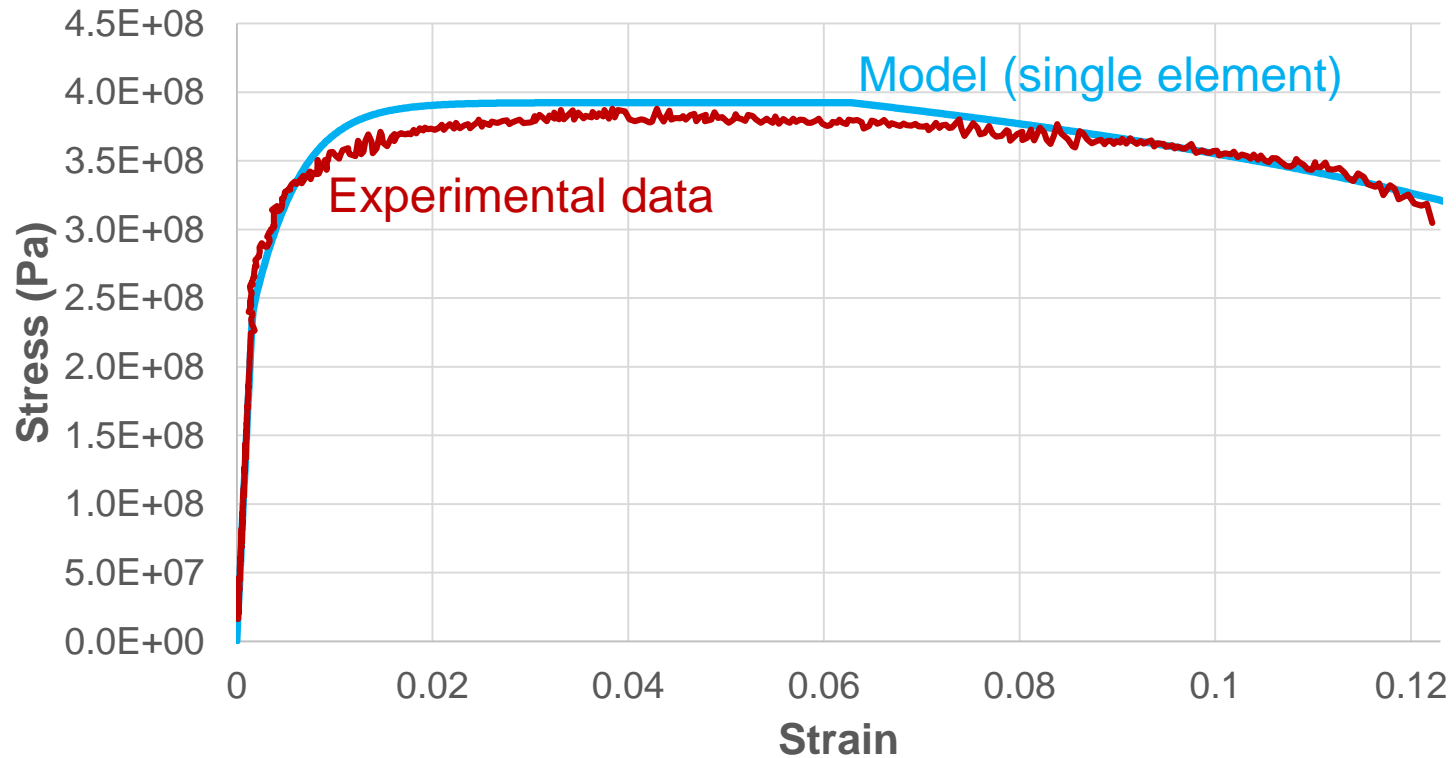
➤ **Anisotropic damage**, crack opening/closing phenomenon  
on hydrostatic stress  $\tilde{\boldsymbol{\sigma}}_H$



<p>Elasticity coupled with anisotropic damage</p> <p>[Lemaitre et. al, 2000]</p>	$\boldsymbol{\varepsilon}^e = \frac{1}{2G} (\mathbf{H}\boldsymbol{\sigma}'\mathbf{H})' + \frac{1}{9K} (g(\mathbf{H})\langle \text{tr } \boldsymbol{\sigma} \rangle_+ + \langle \text{tr } \boldsymbol{\sigma} \rangle_-) \mathbb{1}$ $\tilde{\boldsymbol{\sigma}} = [\mathbf{H}\boldsymbol{\sigma}'\mathbf{H}]' + \frac{1}{3} (g(\mathbf{H})\langle \text{tr } \boldsymbol{\sigma} \rangle_+ + \langle \text{tr } \boldsymbol{\sigma} \rangle_-)$ $\tilde{\boldsymbol{\sigma}} = \mathbb{E} : \boldsymbol{\varepsilon}^e$		
<p>Viscoplastic law coupled with damage</p>	<p>Elasticity criterion</p> <p>Isotropic hardening</p> <p>Flow rule</p> <p>Norton viscosity law</p>	$f = \tilde{\boldsymbol{\sigma}}_{eq} - R - \sigma_y$ $R = R_\infty (1 - e^{-br})$ $\dot{\boldsymbol{\varepsilon}}^p = \dot{\lambda} \frac{\partial f}{\partial \tilde{\boldsymbol{\sigma}}} = \frac{3}{2} \dot{\lambda} \frac{\tilde{\boldsymbol{\sigma}}'}{\tilde{\boldsymbol{\sigma}}_{eq}}$ $\dot{\boldsymbol{\varepsilon}}^p = \dot{\lambda} \frac{\partial f}{\partial \boldsymbol{\sigma}} = [\mathbf{H}\dot{\boldsymbol{\varepsilon}}^p\mathbf{H}]' \quad ; \quad \dot{p} = \left( \frac{2}{3} \dot{\boldsymbol{\varepsilon}}^p : \dot{\boldsymbol{\varepsilon}}^p \right)^{1/2}$ $\dot{r} = -\dot{\lambda} \frac{\partial f}{\partial R} = \dot{\lambda} = \left\langle \frac{f}{K_N} \right\rangle_+^N$	$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^p$ $\tilde{\boldsymbol{\sigma}}_{eq} \text{ Von Mises}$

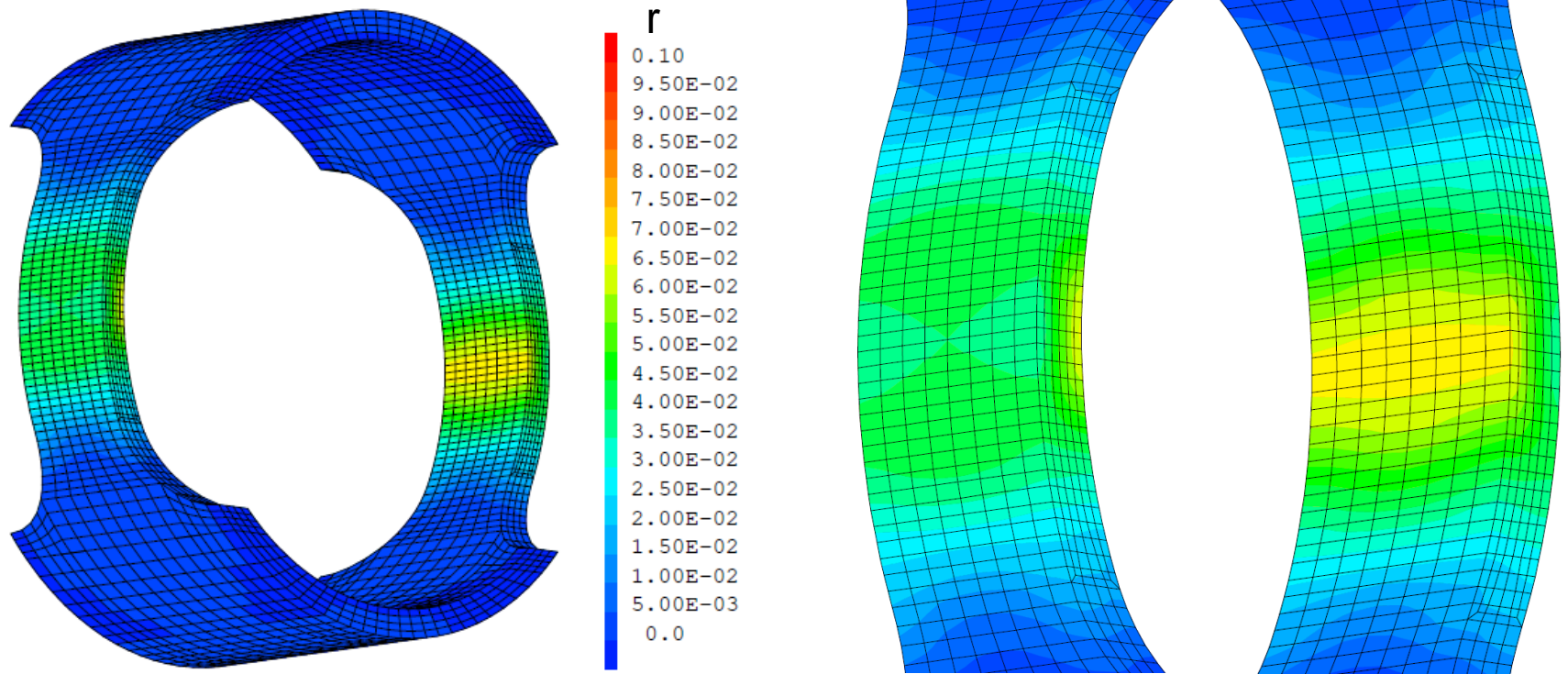
- $\sigma_y$ , : yield criterion
- $R_\infty$ ,  $b$  : isotropic hardening parameters
- $N$ ,  $K_N$  : Norton parameters

<p>Elasticity coupled with anisotropic damage</p> <p>[Lemaitre et. al, 2000]</p>	$\boldsymbol{\varepsilon}^e = \frac{1}{2G} (\mathbf{H}\boldsymbol{\sigma}'\mathbf{H})' + \frac{1}{9K} (g(\mathbf{H})\langle \text{tr } \boldsymbol{\sigma} \rangle_+ + \langle \text{tr } \boldsymbol{\sigma} \rangle_-) \mathbb{1}$ $\tilde{\boldsymbol{\sigma}} = [\mathbf{H}\boldsymbol{\sigma}'\mathbf{H}]' + \frac{1}{3} (g(\mathbf{H})\langle \text{tr } \boldsymbol{\sigma} \rangle_+ + \langle \text{tr } \boldsymbol{\sigma} \rangle_-) \mathbb{1}$ $\tilde{\boldsymbol{\sigma}} = \mathbb{E} : \boldsymbol{\varepsilon}^e$
<p>Viscoplastic law coupled with damage</p>	$f = \tilde{\boldsymbol{\sigma}}_{eq} - R - \sigma_y \quad \boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^p$ $R = R_\infty (1 - e^{-br})$ $\dot{\boldsymbol{\varepsilon}}^p = \dot{\lambda} \frac{\partial f}{\partial \tilde{\boldsymbol{\sigma}}} = \frac{3}{2} \dot{\lambda} \frac{\tilde{\boldsymbol{\sigma}}'}{\tilde{\boldsymbol{\sigma}}_{eq}}$ $\dot{\boldsymbol{\varepsilon}}^p = \dot{\lambda} \frac{\partial f}{\partial \boldsymbol{\sigma}} = [\mathbf{H}\dot{\boldsymbol{\varepsilon}}^p\mathbf{H}]' \quad ; \quad \dot{p} = \left( \frac{2}{3} \dot{\boldsymbol{\varepsilon}}^p : \dot{\boldsymbol{\varepsilon}}^p \right)^{1/2}$ $\dot{r} = -\dot{\lambda} \frac{\partial f}{\partial R} = \dot{\lambda} = \left\langle \frac{f}{K_N} \right\rangle_+^N$
<p>Damage law</p> <p><math>A, r_{threshold}</math> damage parameters</p> <p><math>\mathcal{H}</math> Heaviside function</p>	<p>Stress triaxiality function</p> $\frac{d}{dt} (\mathbf{H}^{-2}) = A \tilde{R}_v \mathcal{H}(r - r_{threshold}) \langle \dot{\boldsymbol{\varepsilon}}^p \rangle_+$ $\tilde{R}_v = \frac{2}{3} (1 + \nu) + 3(1 - 2\nu) \left\langle \frac{\tilde{\boldsymbol{\sigma}}_H}{\tilde{\boldsymbol{\sigma}}_{eq}} \right\rangle_+^2 \quad ; \quad \tilde{\boldsymbol{\sigma}}_H = \frac{1}{3} \text{tr}(\tilde{\boldsymbol{\sigma}})$



- Model parameters identified with ring test data on a single element

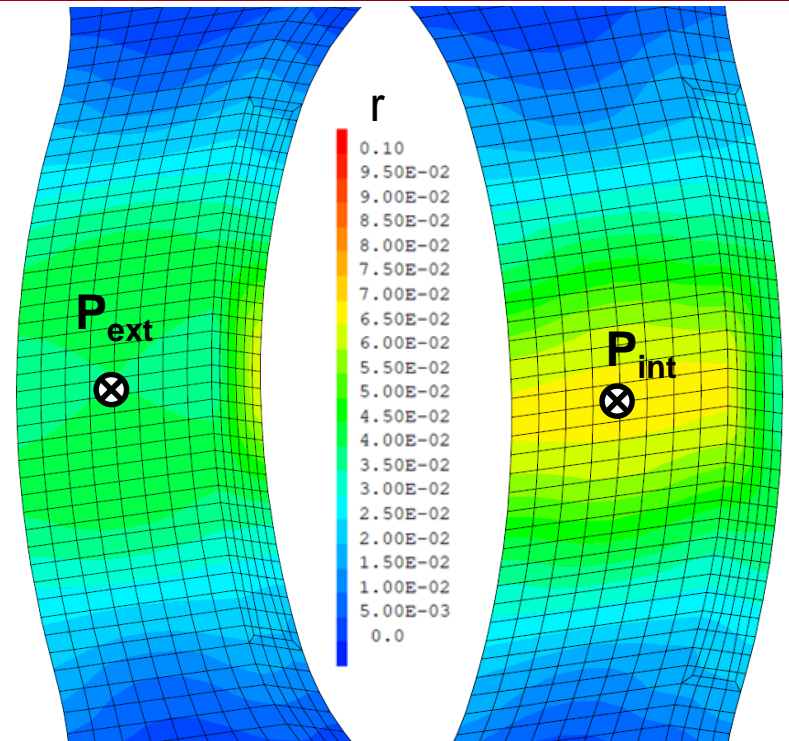
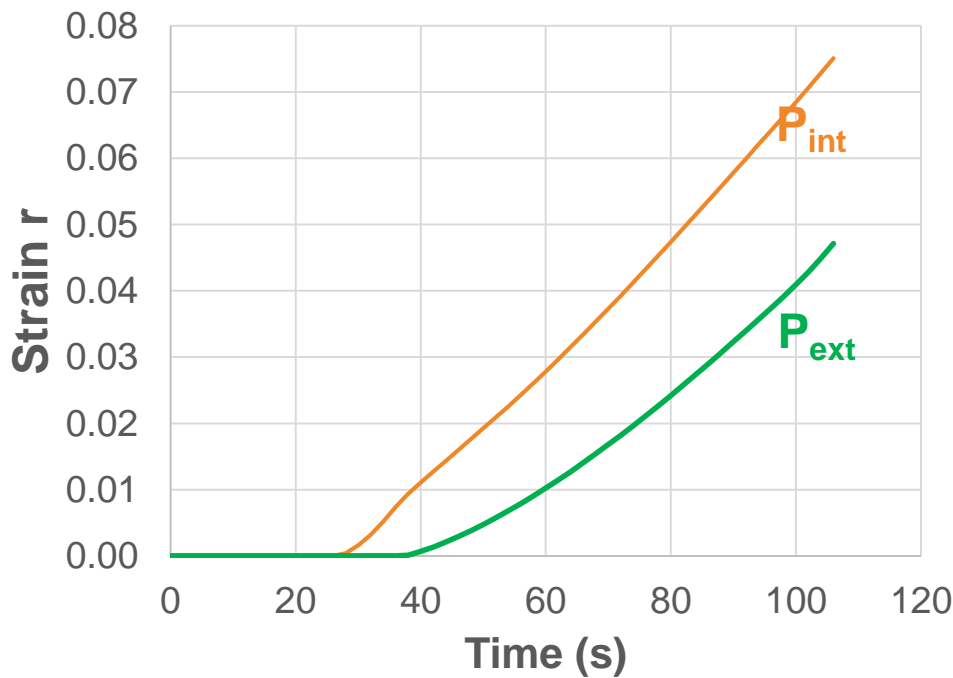
# SIMULATION – 9%CR TENSILE TEST



Accumulated plastic strain  $r$

- Plastic strain is not homogeneous in the gauge section

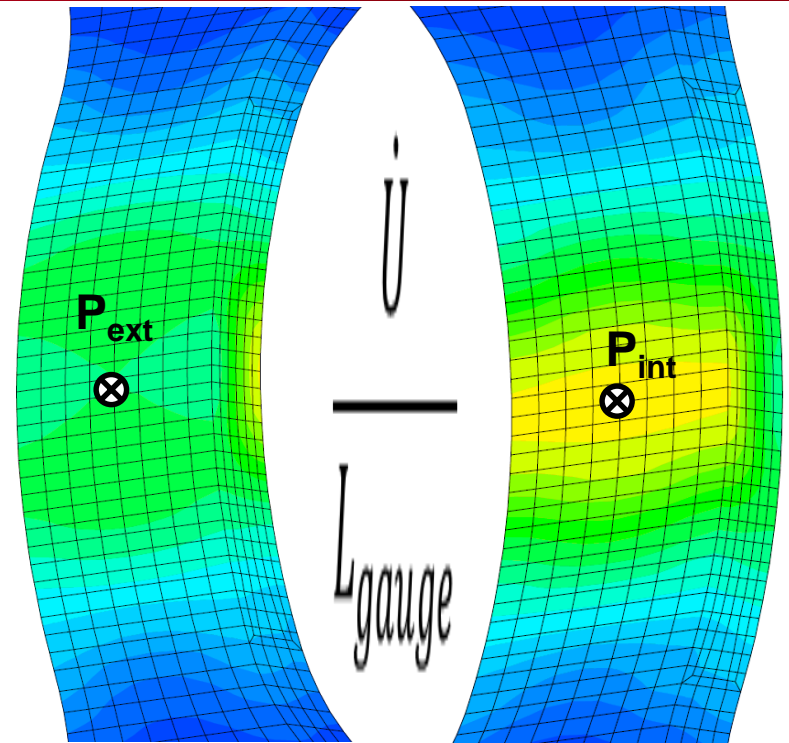
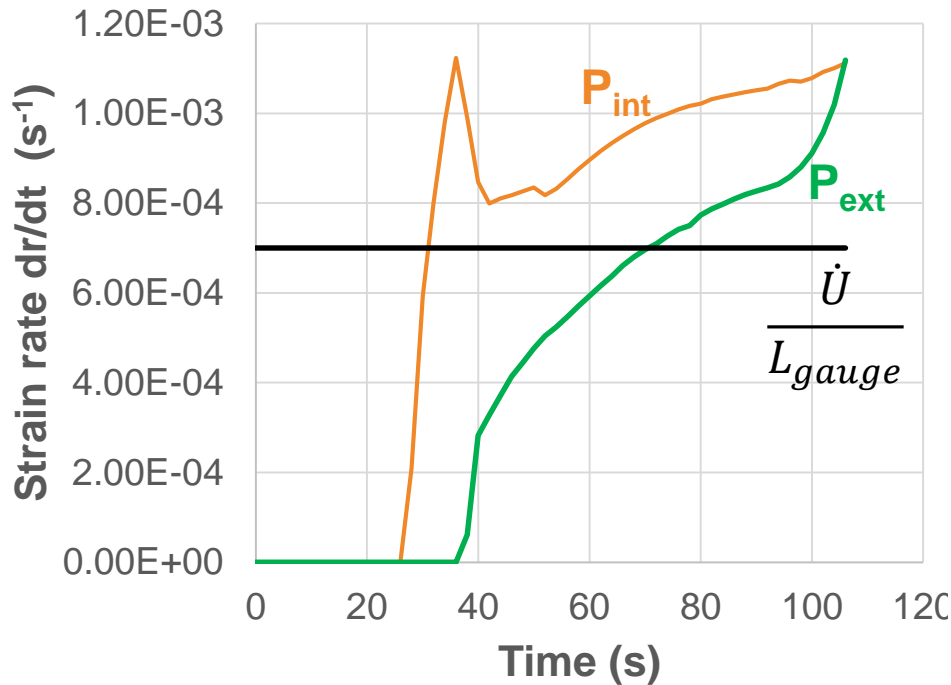
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Accumulated plastic strain  $r$

- Plastic strain is not homogeneous in the gauge section
- Plastic strain varies through the thickness of the ring

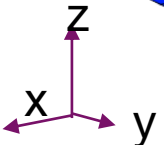
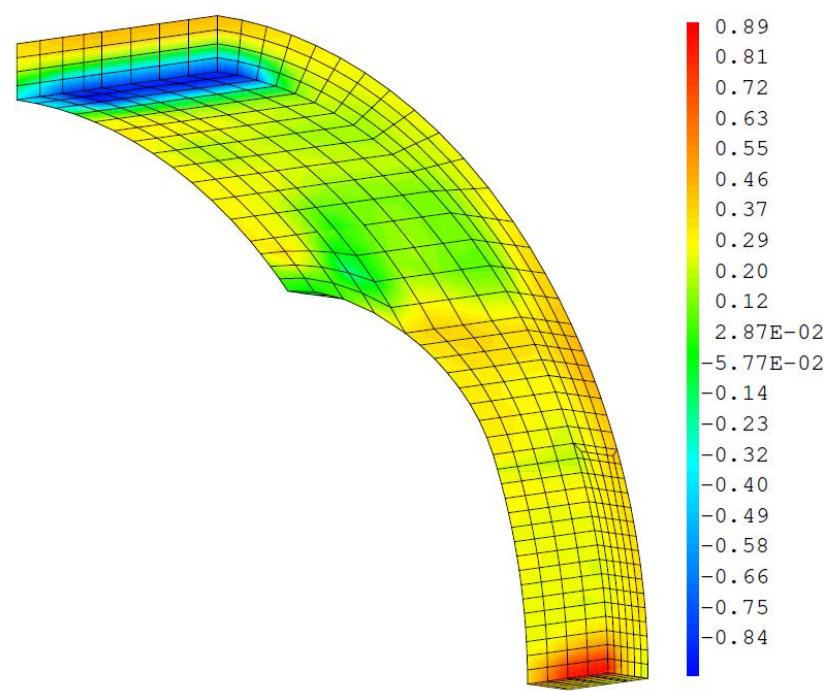
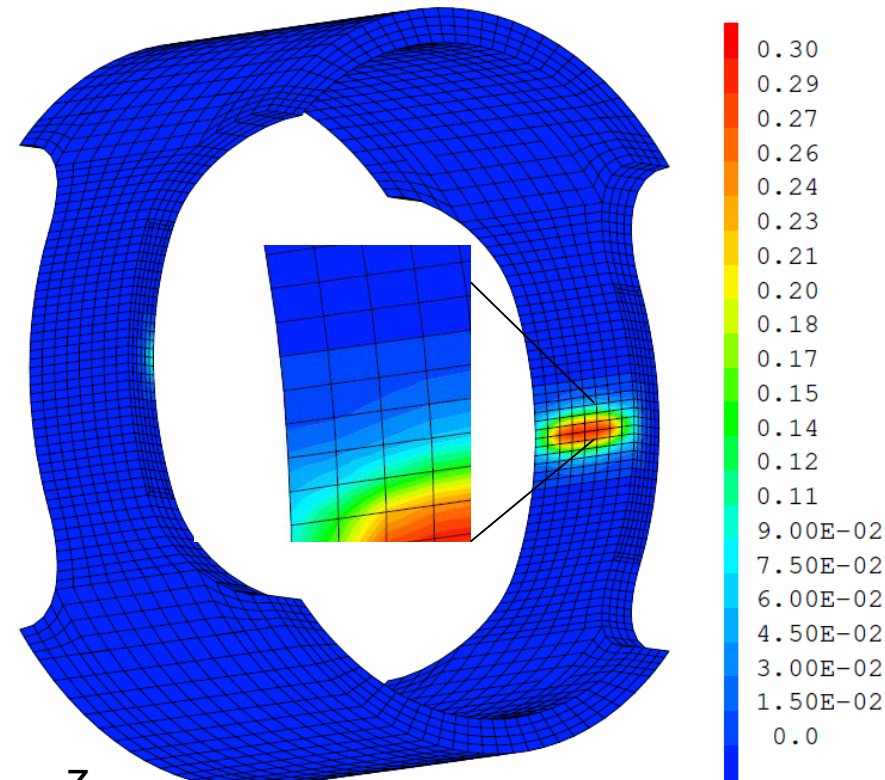
# SIMULATION – 9%CR TENSILE TEST



Accumulated plastic strain  $r$

- Plastic strain is not homogeneous in the gauge section
- Plastic strain varies through the thickness of the ring
- Plastic strain rate also varies through the thickness of the gauge section

# SIMULATION – 9%CR TENSILE TEST



Damage  $D_{zz}$

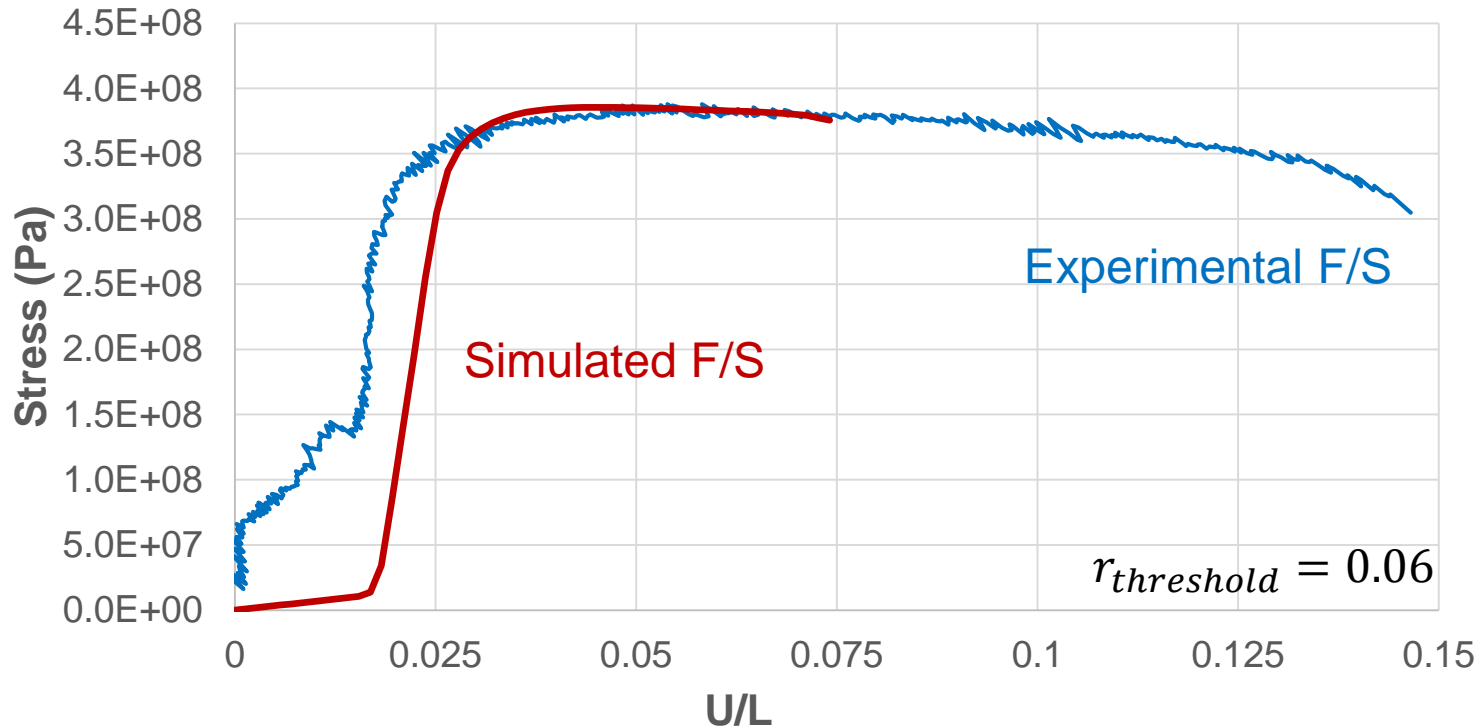
$$D = \begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{pmatrix}$$

Triaxiality  $\frac{\sigma_h}{\sigma_{eq}} = \frac{1/3 * tr(\sigma)}{\sigma_{eq}}$

- Damage occurs first on the inside of the ring, at the center of the gauge length
- Damage location, linked to stress triaxiality, which is greater in the same area

➤ Fracture may occur earlier than what the macroscopic strain would suggest

# STRESS-STRAIN CURVE COMPARISON

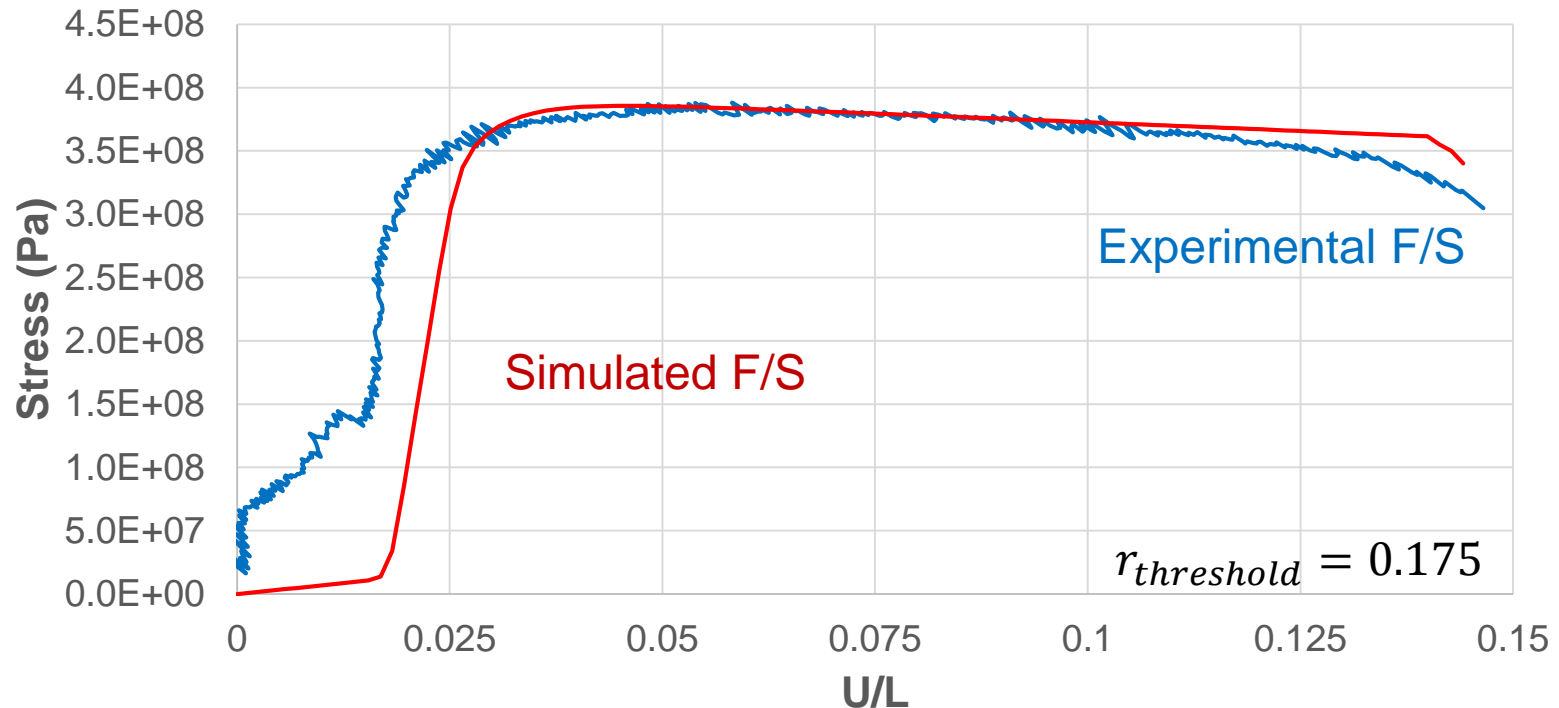


- For similar displacement, rupture occurs well before the experimental result
- Damage evolution is faster due to strain localization and high stress triaxiality

➤ **The criterion  $r_{threshold}$  for damage initiation has to be higher**



# STRESS-STRAIN CURVE COMPARISON



- Better prediction after  $r_{threshold} = 0.175$
- Adjusted  $r_{threshold} < 0.25$  tile specimen damage threshold
  - **Other possible parameters to change :  $\eta$ ,  $A$**  (ongoing work)
  - Higher threshold values incompatible with ring creep tests
  - Possible anisotropic damage mechanisms [Tanno et al.]

- The notched ring tensile specimen, in the load conditions chosen, introduces perceived anisotropy in raw test results (total elongation)
- Constitutive modelling and FE simulation of the ring tensile test analysis allow a more rigorous parameter identification
- Macroscopic values such as total elongation can be adjusted
- The understanding of geometry-dependent anisotropy enables the study of material-dependent anisotropy in the 14%Cr ODS steel tube

- **CLEFS CEA n°55, 2007**
- **Kim et. Al. 2013** : Sung ho Kim, J.H. Baek, J.H. Kim, C.B. Lee, « Fabrication and evaluation of SFR Cladding tubes », International Conference on Fast Reactors and related Fuel Cycles, Paris, France, 2013
- **MINOS 2012** : MINOS Workshop 2012, CEA-INSTN Saclay  
[www.materials.cea.fr/MINOS2012/Session1/DECARLANMINOS2012S1.pdf](http://www.materials.cea.fr/MINOS2012/Session1/DECARLANMINOS2012S1.pdf)
- **Desmorat et. al.** : R. Desmorat, B. Desmorat, M. Olive, B. Kolev, « Micromechanics based framework with second-order damage tensors », European Journal of Mechanics –A/Solids, V69, 2018, p88-98
- **Lemaitre et. al.** : J. Lemaitre, R. Desmorat, M. Sauzay, « Anisotropic damage law of evolution », European Journal of Mechanics – A/Solids, V19, issue 2, 2000, p187-208
- **Tanno et. al.** : T. Tanno, Y. Yano, H. Oka, S. Ohtsuka, T. Uwaba, T. Kaito, « Strength anisotropy of rolled 11Cr-ODS steel », Nuclear Materials and Energy, V9, 2016, p353-359
- **[1]** F. Nagase, T. Sugiyama, T. Fuketa, « Optimized ring tensile test method and hydrogen effect on mechanical properties of Zircaloy cladding in hoop direction », Journal of Nuclear Science and Technology, Vol.46,No.6, 2009, p545-552
- **[2]** C. Dick, Y. Korkolis, « Mechanics and full-field deformation study of ring hoop tension test », International Journal of Solids and Structures, V.51, 2014, p3042-3057
- **[3]** S. Arsene, J. Bai, « A new approach to measuring transverse properties of structural tubing by a ring test », Journal of Testing and Evaluation, JTEVA, Vol. 24, No. 6, 1996, p386-391
- **[4]** M.A. Martin-Rengel, F.J. Gomez Sanchez, J. Ruiz-Hervias, L. Caballero, A. Valiente, « Revisiting the method to obtain the mechanical properties of hydrided fuell cladding in the hoop direction », Journal of Nuclear Materials, 429, 2012, p276-283