Study of the tensile anisotropy of extruded ODS steel tubes using notched rings

Thibaud Jaumier, Sébastien Vincent, Ludovic Vincent, Rodrigue Desmorat

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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 sollicitations

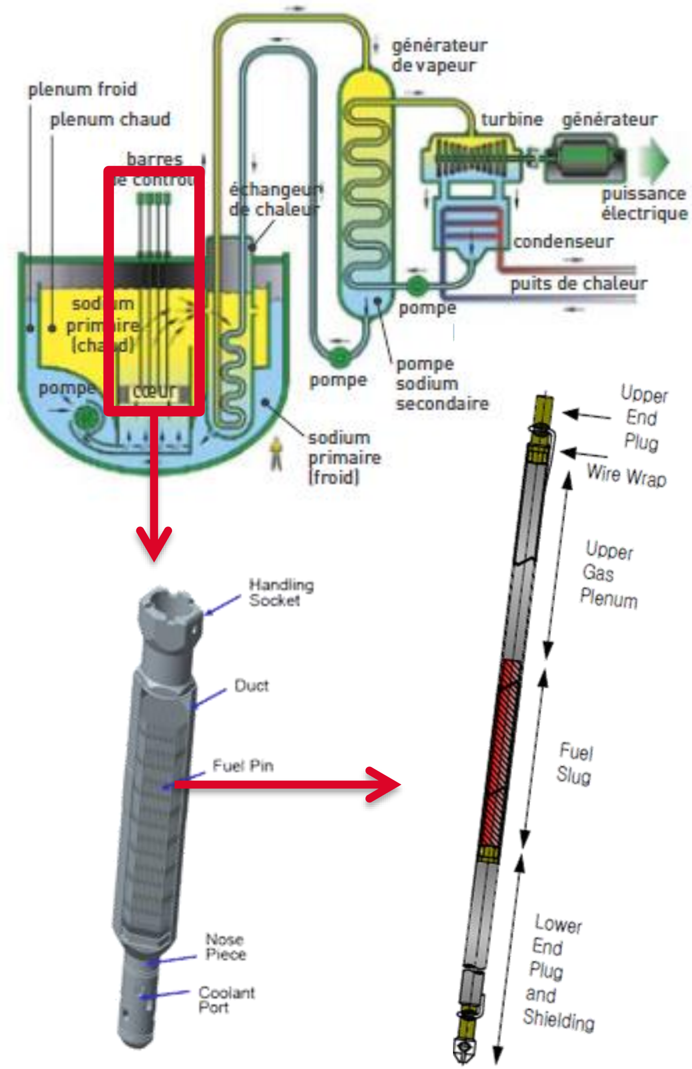
- Temperature: 400-650°C
- Internal pressure: 120 bars (max at life end)
- Irradiation: 100-200 dpa
- Sodium environment effects

➢ **Oxide Dispersion Strengthened (ODS) steel**

Good candidate material thanks to:

- high resistance to thermal creep
- Low irradiation swelling

[CLEFS CEA n°55, 2007]



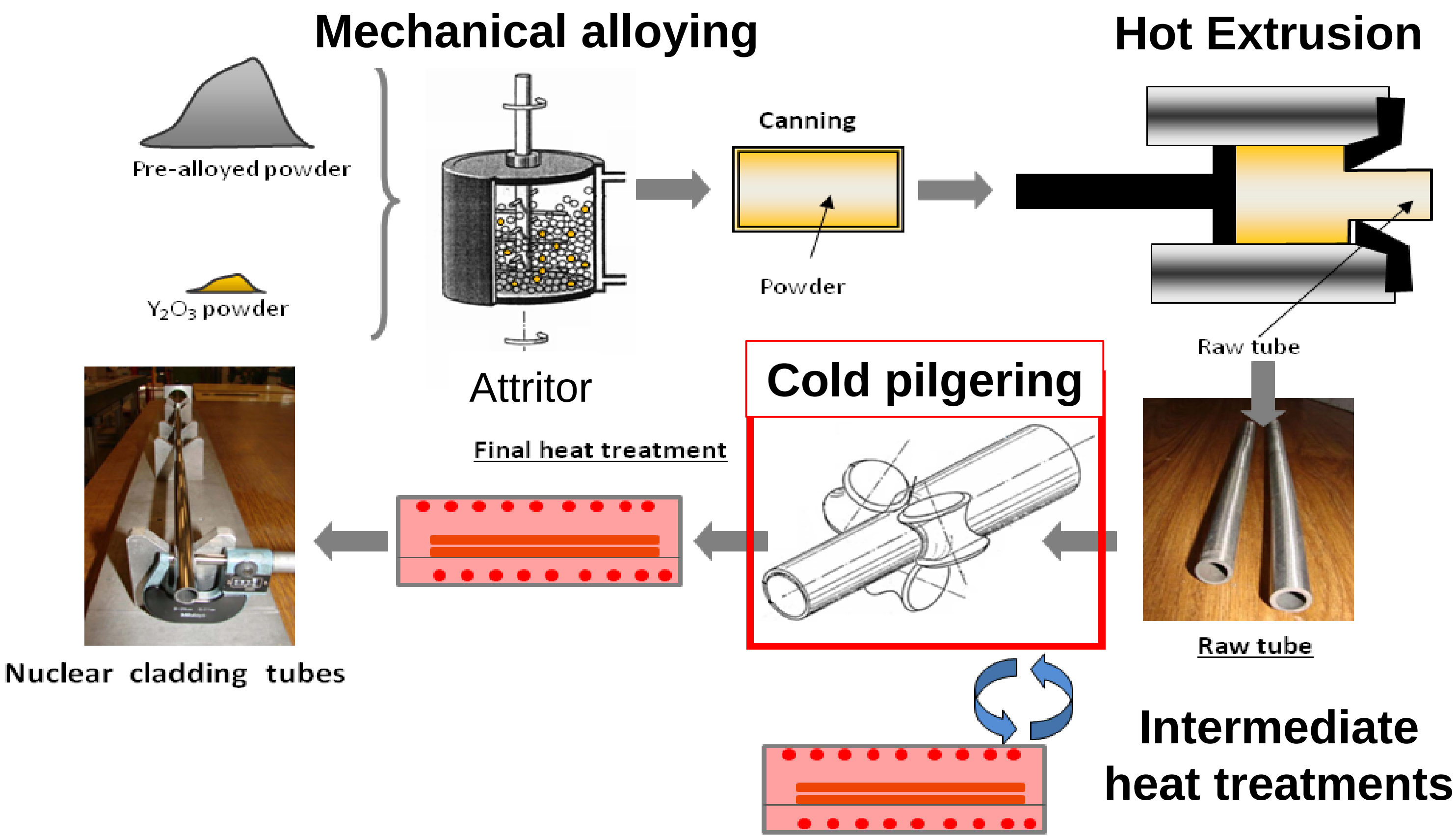
Fuel assembly

Fuel rod

[Kim et. Al., 2013]

ODS STEEL TUBE MANUFACTURING

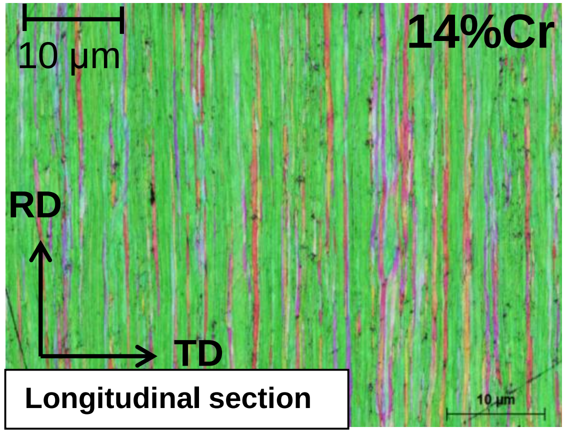
[MINOS 2012]

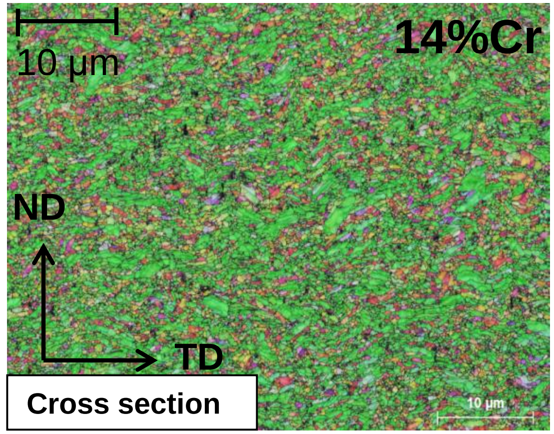


- Studied material **: tube**
- Process introducing **anisotropic microstrucure**

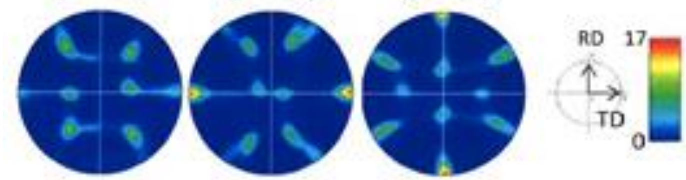
Ferritic **14%Cr** ODS steel $Fe\text{-}14Cr\text{-}1W\text{-}0.3Ti\text{-}0.25Y_2O_3$

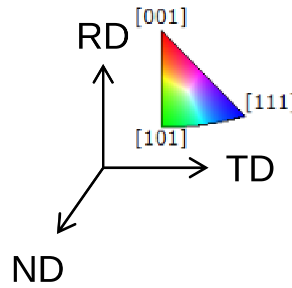
Martensitic **9%Cr** ODS steel $Fe\text{-}9Cr\text{-}1W\text{-}0.3Ti\text{-}0.25Y_2O_3$





L section pole figures





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

MATERIALS STUDIED

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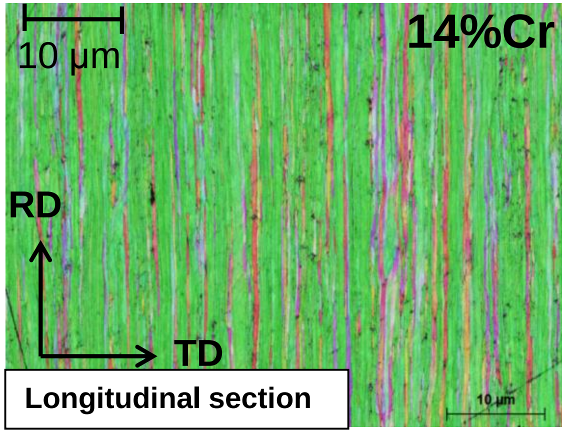
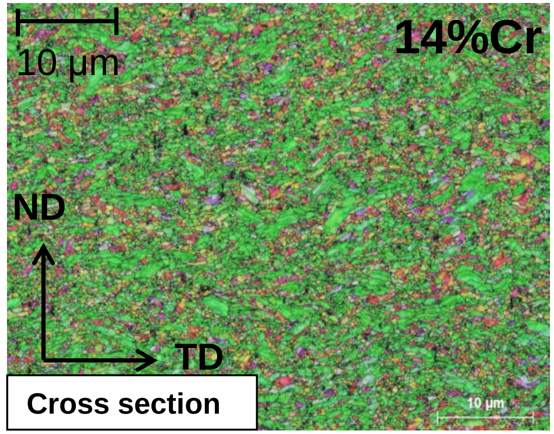
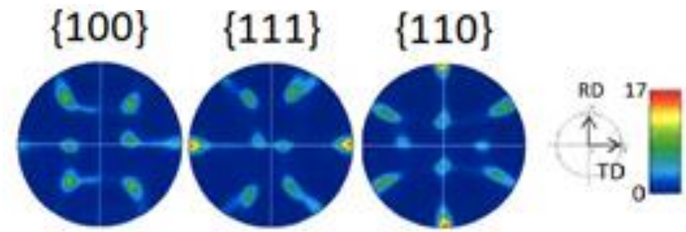
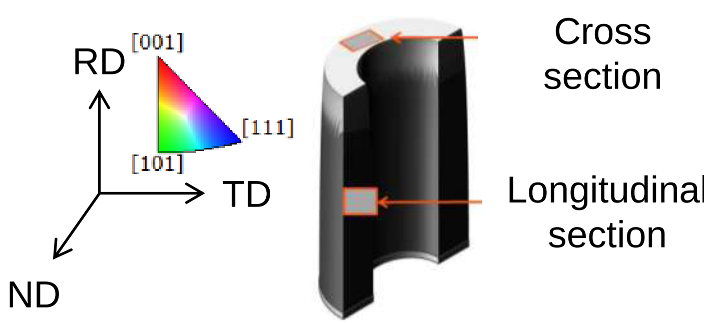


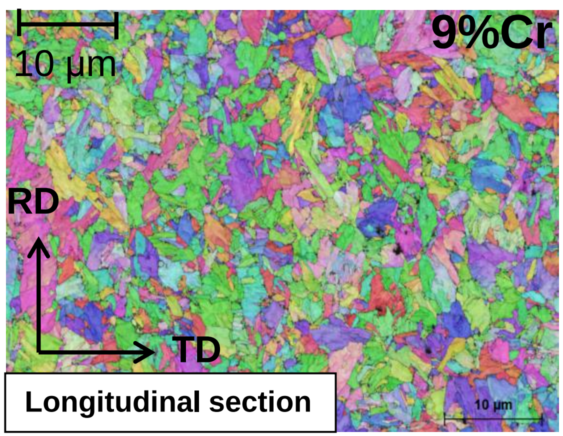


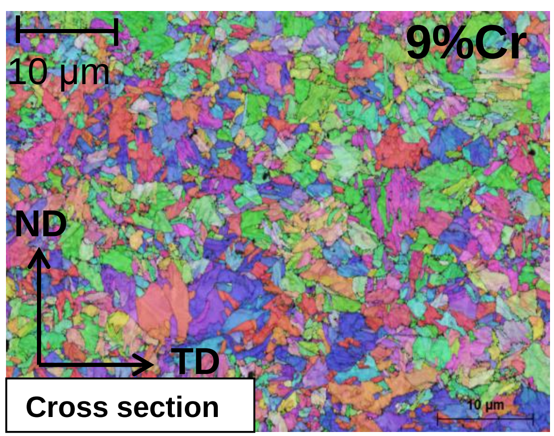
L section pole figures



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







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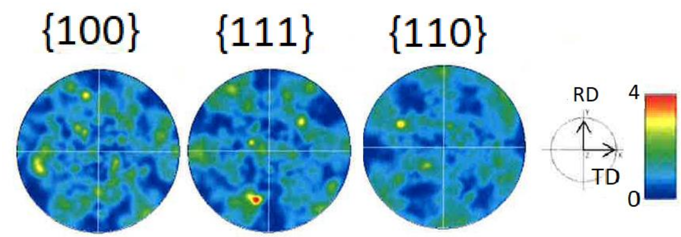


- ➢ **Equiaxed grains with no specific texture**

CHARACTERIZING TUBES

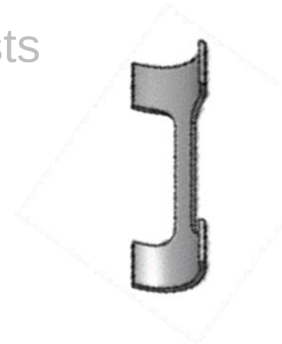
- Main objectives
  - Testing the longitudinal and hoop properties of the tubes
  - Through tensile, uniaxial and internal pressure creep tests
  - In order to predict the lifetime of fuel cladding

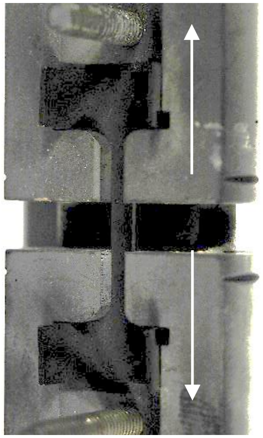
TILE AND RING TENSILE SPECIMENS

- ❑ 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

- ❑ **Tensile** properties: **2 specimen geometries**
  - ➢ Tile specimens for the longitudinal properties
  - ➢ Notched ring specimens for the hoop properties

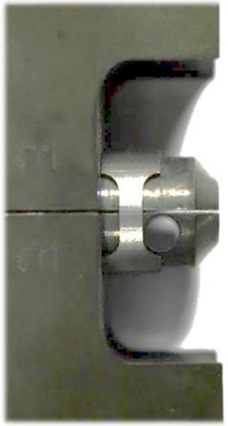
Tile specimen

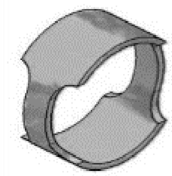




The ring test is non-standard [1-4], know to be dependent on :

- Load configuration
- Friction
- Length to width gauge ratio





Ring specimen

TILE AND RING TENSILE SPECIMENS

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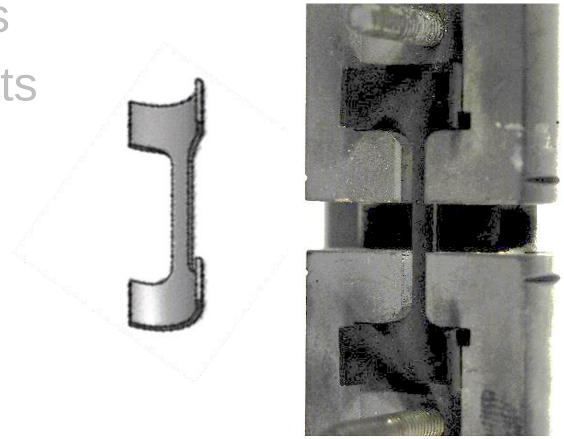
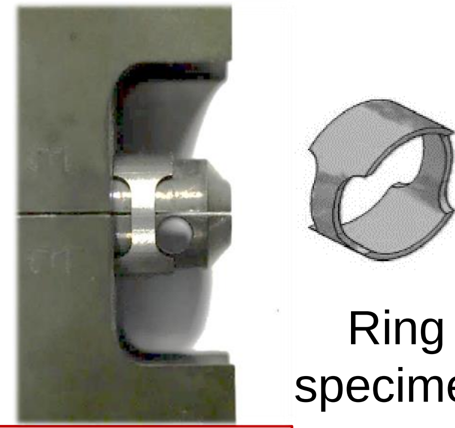
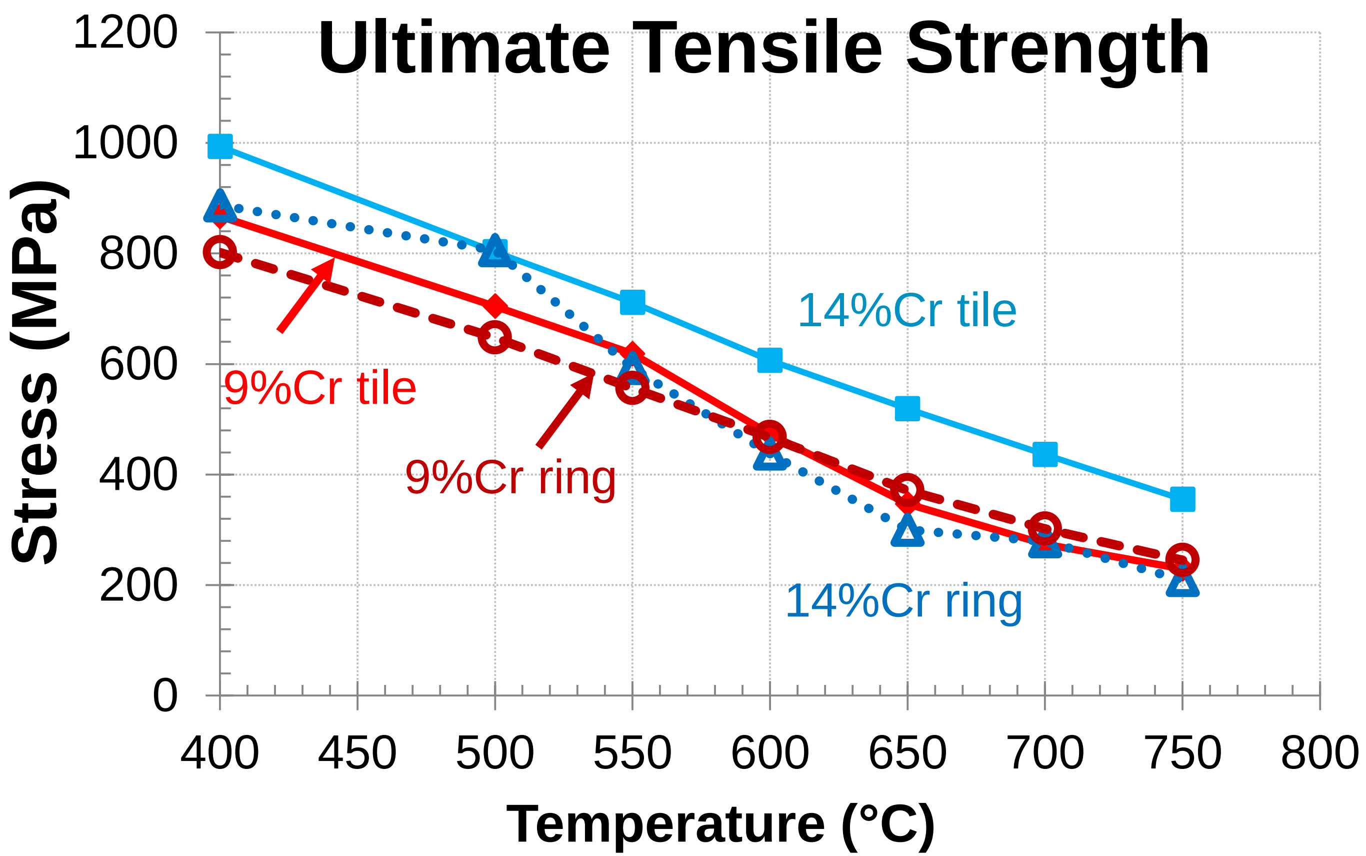




Ring specimen

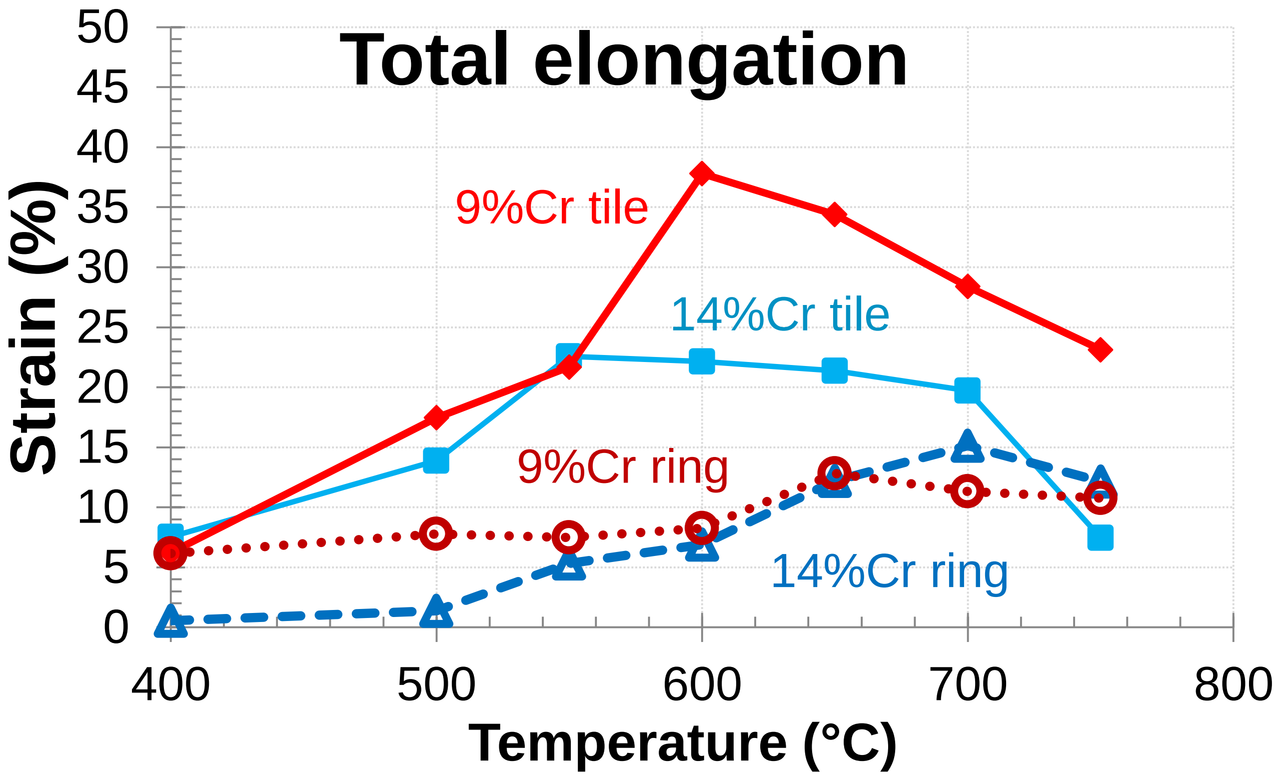
➢ In order to properly study material anisotropies, the **effect of the specimen geometry** must be analysed

TENSILE TESTS



Tested at 7.10^{-4} 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



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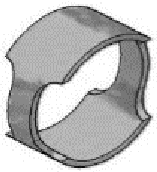
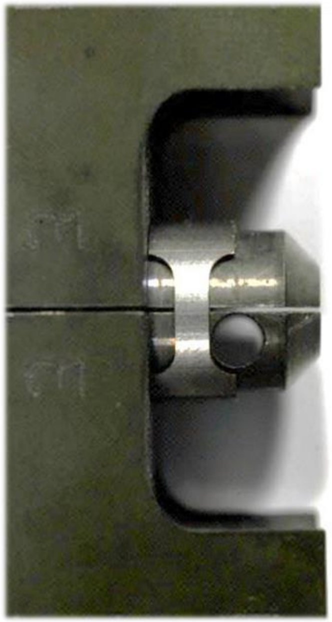
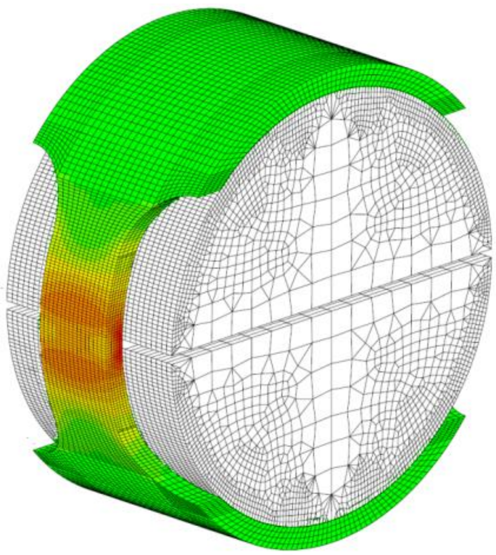


- In the 400-750°C range, both 9%Cr and 14%Cr show anisotropic total elongation
- As the 9%Cr mechanical behaviour is considered to be isotropic, specimen geometry is a potential cause to investigate -> modelisation





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

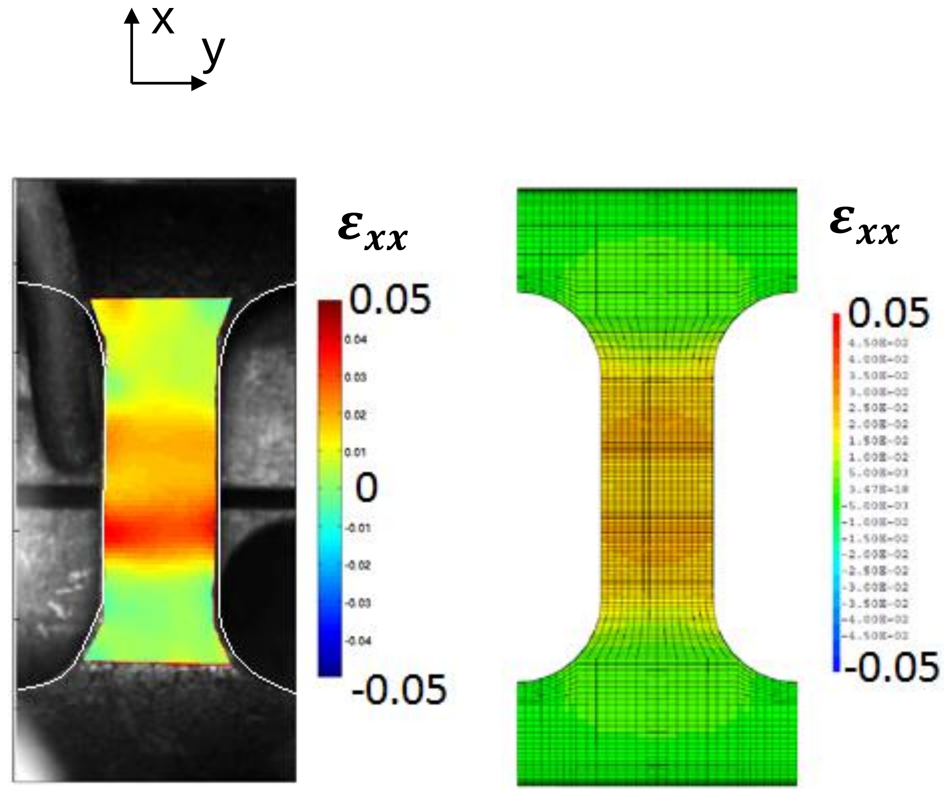
A continuum damage mechanics approach (Lemaitre-Chaboche) was used.

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.

ESTIMATION OF THE FRICTION COEFFICIENT

- 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**

CONSTITUTIVE MODELLING – 9%CR

Elasticity coupled with anisotropic damage [Lemaitre et. al, 2000]	$\boldsymbol{\varepsilon}^e = \frac{1}{2G}(\boldsymbol{H}\boldsymbol{\sigma}'\boldsymbol{H})' + \frac{1}{9K}(g(\boldsymbol{H})\langle tr\ \boldsymbol{\sigma}\rangle_+ + \langle tr\ \boldsymbol{\sigma}\rangle_-)\mathbb{1}$ $\tilde{\boldsymbol{\sigma}} = [\boldsymbol{H}\boldsymbol{\sigma}'\boldsymbol{H}]' + \frac{1}{3}(g(\boldsymbol{H})\langle tr\ \boldsymbol{\sigma}\rangle_+ + \langle tr\ \boldsymbol{\sigma}\rangle_-)\,\mathbb{1}$ $\tilde{\boldsymbol{\sigma}} = \mathbb{E}:\boldsymbol{\varepsilon}^e$

$\tilde{\boldsymbol{\sigma}}$: Effective stress
D: Damage 2nd order tensor
η: hydrostatic sensitivity parameter
K: bulk modulus
G: shear modulus

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

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

[Desmorat et. al, 2017]

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

CONSTITUTIVE MODELLING – 9%CR

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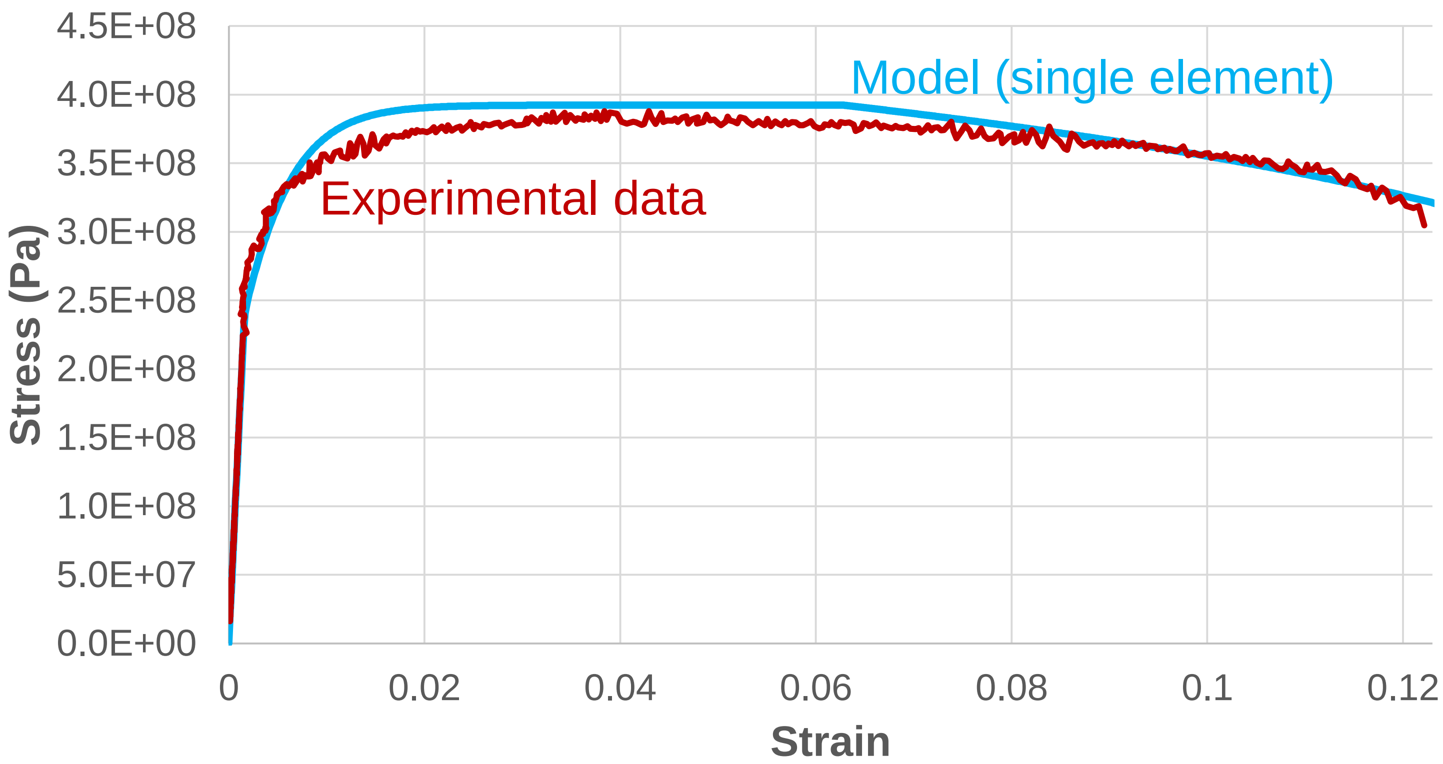
Viscoplastic law coupled with damage	Elasticity criterion $f = \widetilde{\boldsymbol{\sigma}}_{\boldsymbol{eq}} - R - \sigma_y$; $\varepsilon = \varepsilon^e + \varepsilon^p$ Isotropic hardening $R = R_\infty(1 - e^{-br})$; $\widetilde{\boldsymbol{\sigma}}_{\boldsymbol{eq}}$ Von Mises Flow rule: $\dot{\boldsymbol{e}}^p = \dot{\lambda}\frac{\partial f}{\partial \widetilde{\boldsymbol{\sigma}}} = \frac{3}{2}\dot{\lambda}\frac{\widetilde{\boldsymbol{\sigma}}'}{\widetilde{\boldsymbol{\sigma}}_{eq}}$ $\dot{\boldsymbol{\varepsilon}}^p = \dot{\lambda}\frac{\partial f}{\partial \boldsymbol{\sigma}} = [\boldsymbol{H}\dot{\boldsymbol{e}}^p\boldsymbol{H}]'$; $\dot{p} = \left(\frac{2}{3}\dot{\varepsilon}^p:\dot{\varepsilon}^p\right)^{1/2}$ Norton viscosity law $\dot{r} = -\dot{\lambda}\frac{\partial f}{\partial R} = \dot{\lambda} = \left\langle \frac{f}{K_N} \right\rangle_+^N$

- σ_y, : yield criterion
- R_∞, b : isotropic hardening parameters
- N, K_N : Norton parameters

CONSTITUTIVE MODELLING – 9%CR

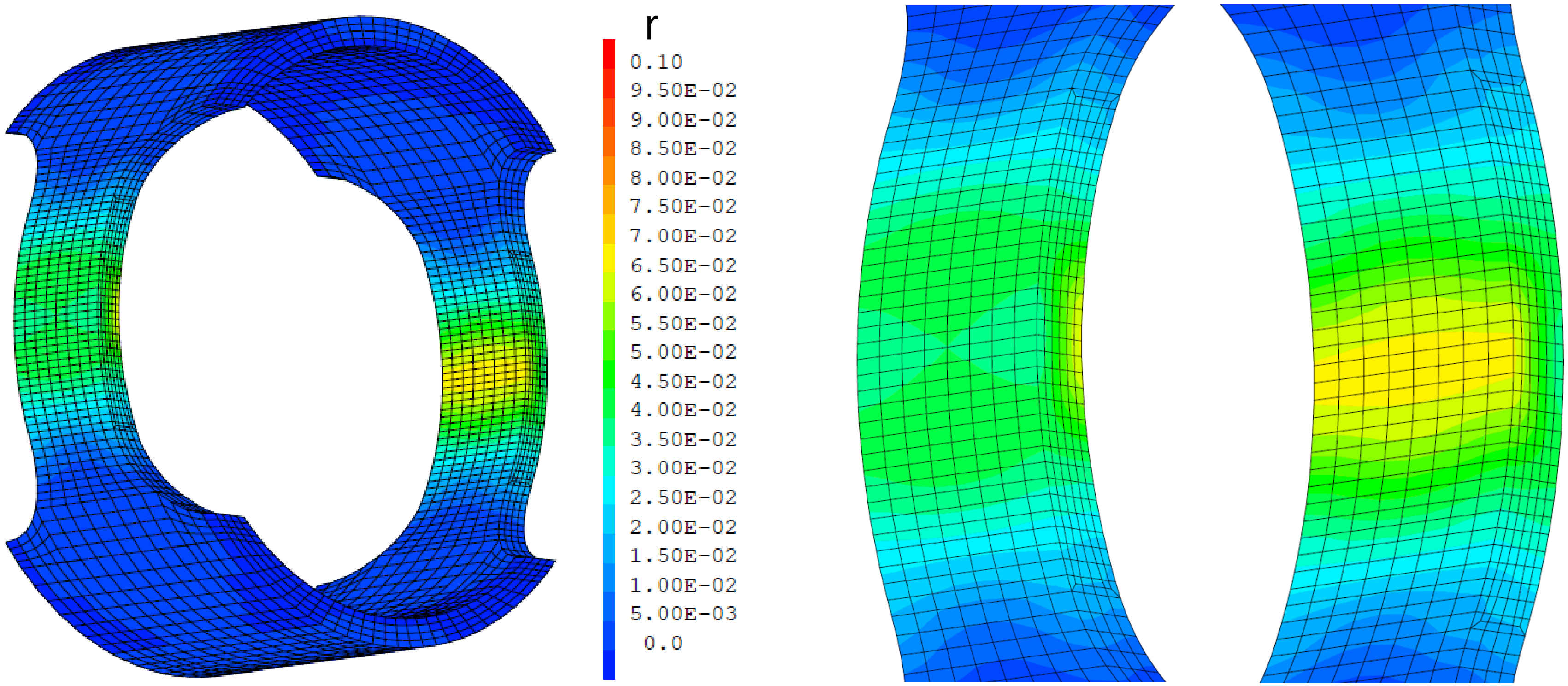
Elasticity coupled with anisotropic damage [Lemaitre et. al, 2000]	$$\boldsymbol{\varepsilon}^e = \frac{1}{2G}(\boldsymbol{H}\boldsymbol{\sigma}'\boldsymbol{H})' + \frac{1}{9K}(g(\boldsymbol{H})\langle tr\,\boldsymbol{\sigma}\rangle_+ + \langle tr\,\boldsymbol{\sigma}\rangle_-)\mathbb{1}$$ $$\widetilde{\boldsymbol{\sigma}}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

CONSTITUTIVE MODELLING – 9%CR 650°C



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

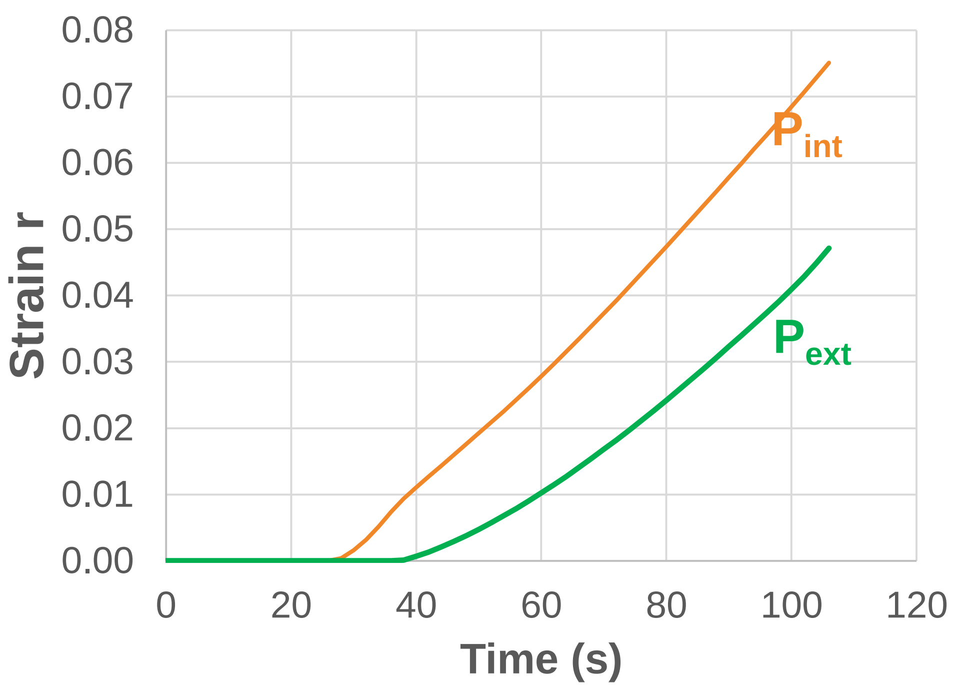
SIMULATION – 9%CR TENSILE TEST

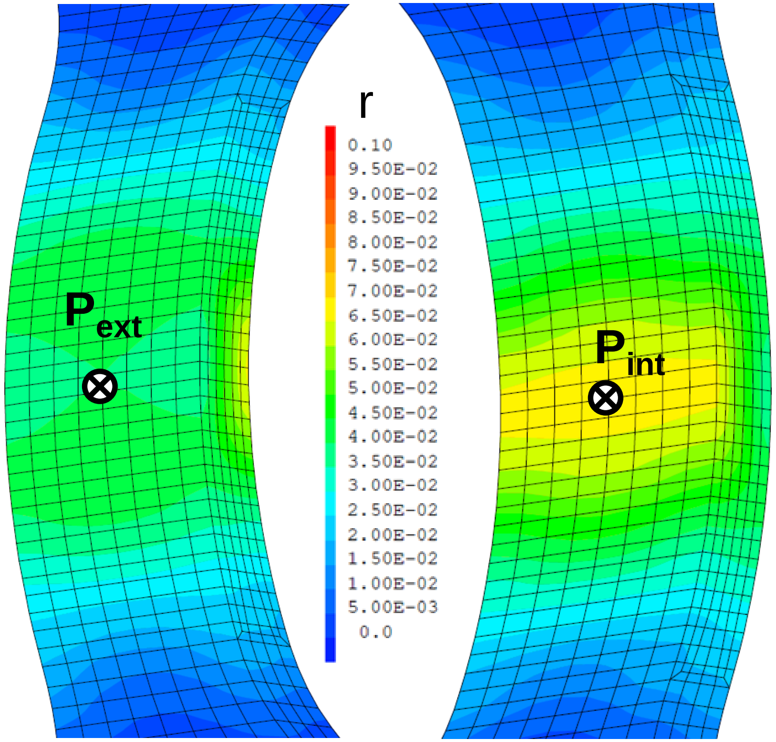


Accumulated plastic strain r

- Plastic strain is not homogeneous in the gauge section

SIMULATION – 9%CR TENSILE TEST

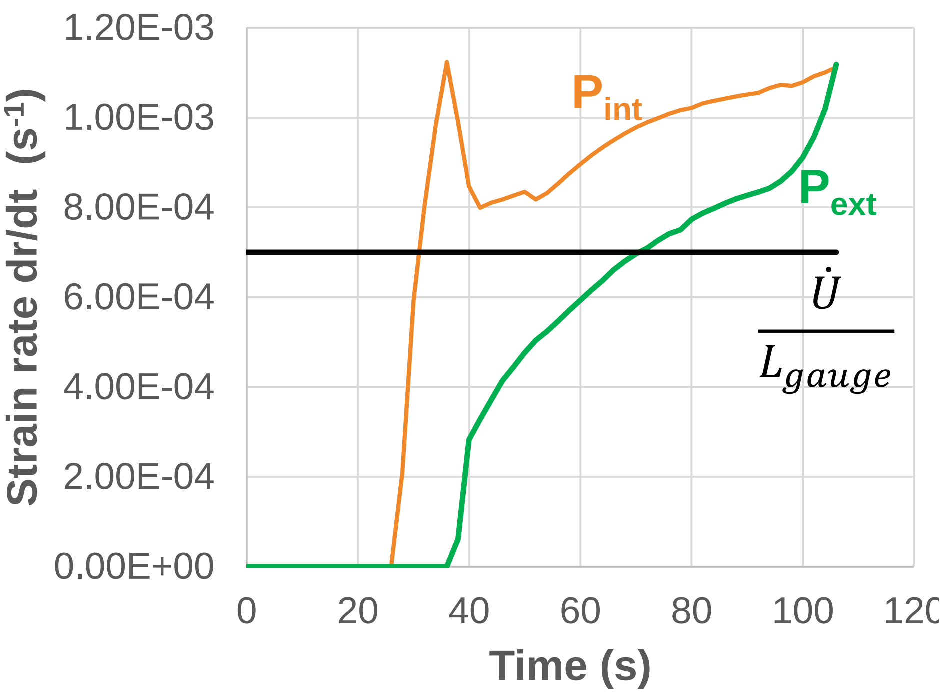


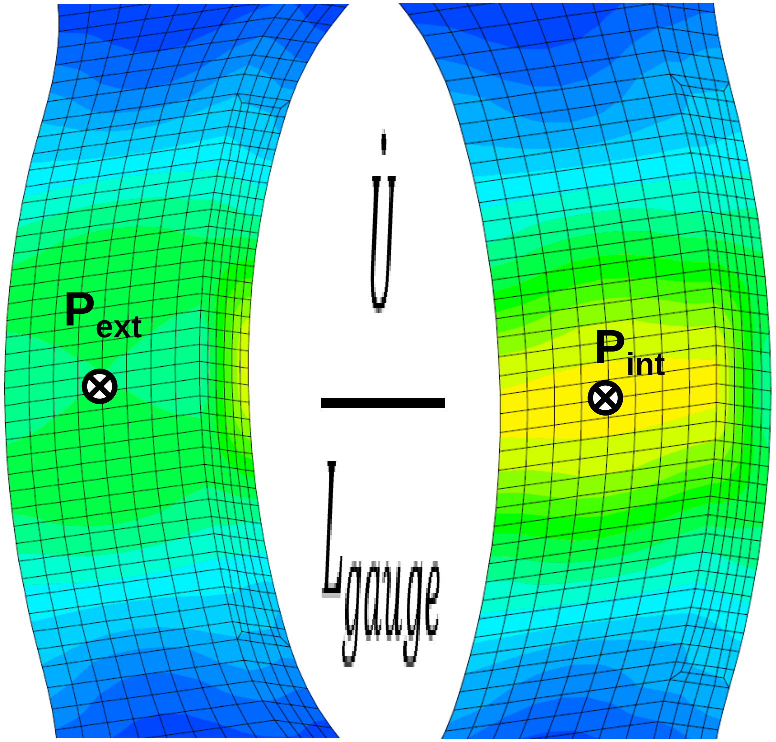


Accumulated plastic strain r

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

SIMULATION – 9%CR TENSILE TEST

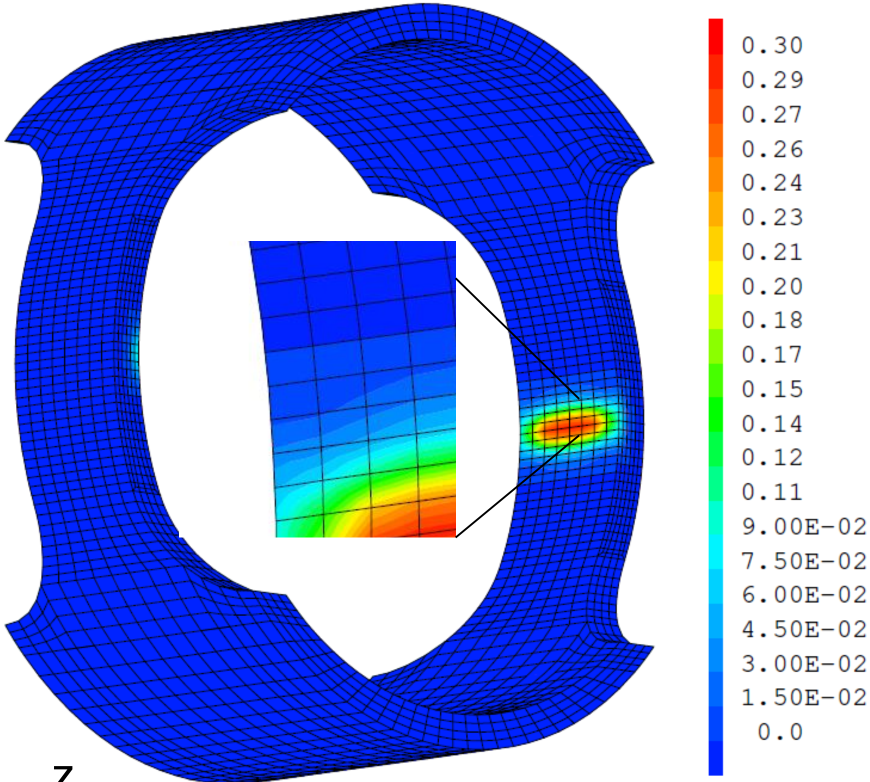


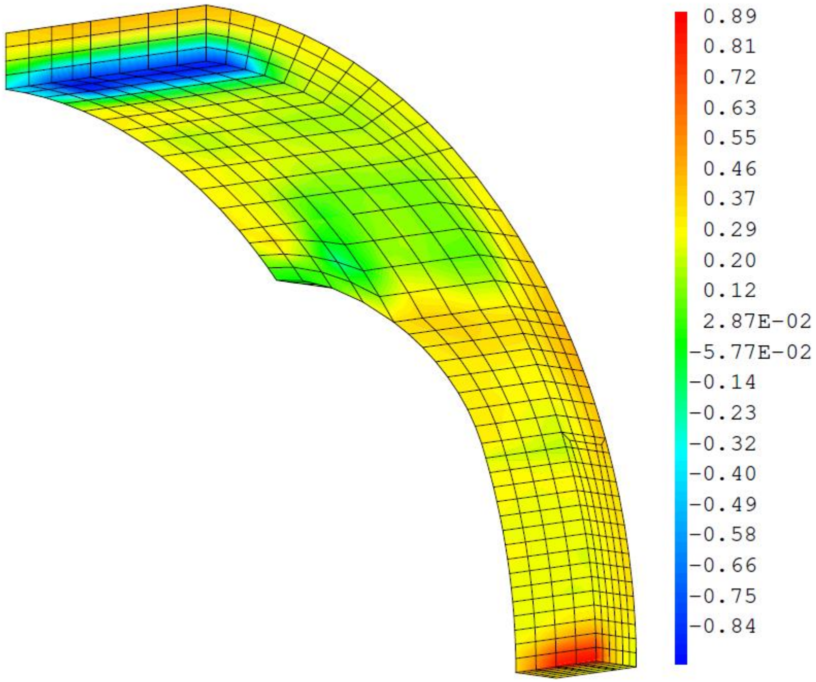


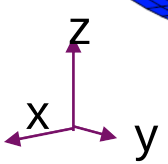
Accumulated plastic strain r

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

SIMULATION – 9%CR TENSILE TEST







Damage D_{zz}

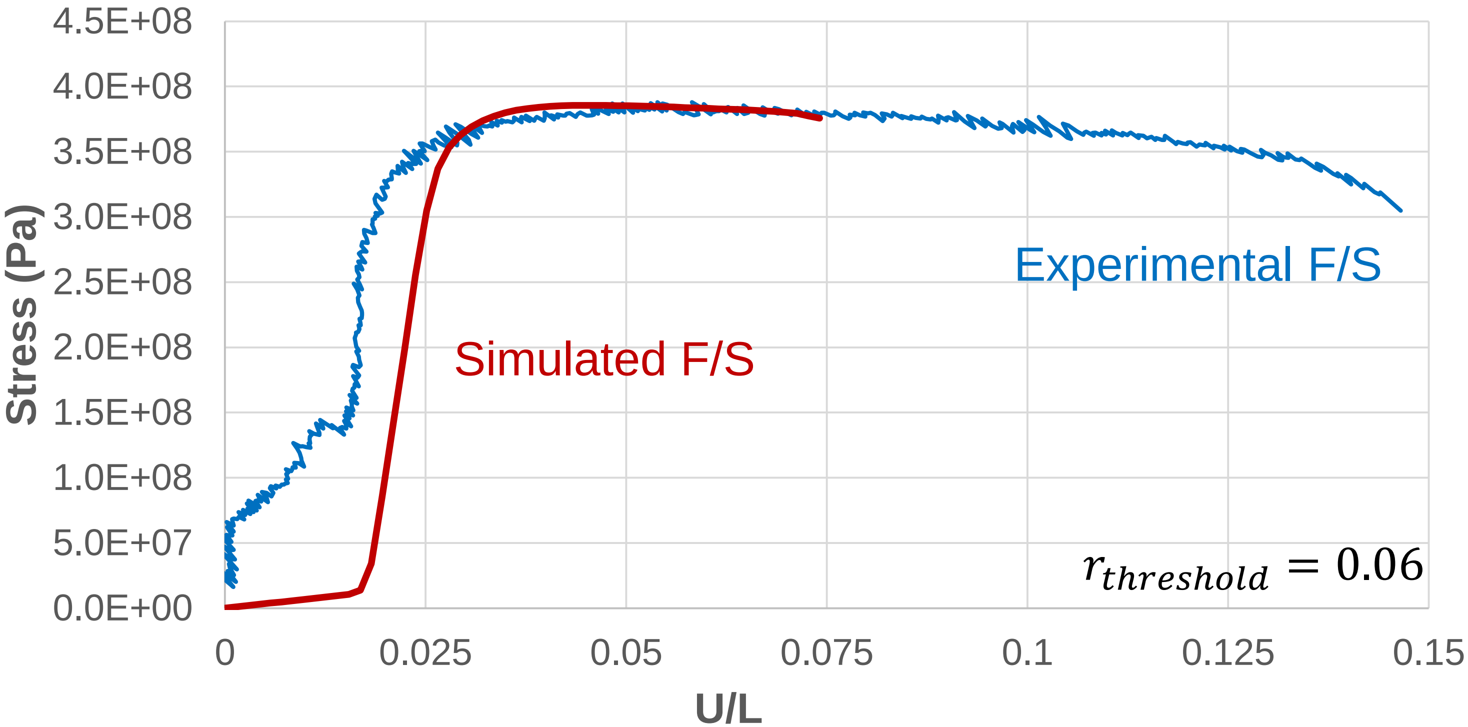
$$\boldsymbol{D} = \begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ & D_{yy} & D_{yz} \\ & & D_{zz} \end{pmatrix}$$

Triaxiality $\dfrac{\sigma_h}{\sigma_{eq}} = \dfrac{{}^1/_3 * tr(\boldsymbol{\sigma})}{\sigma_{eq}}$

- ➢ 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

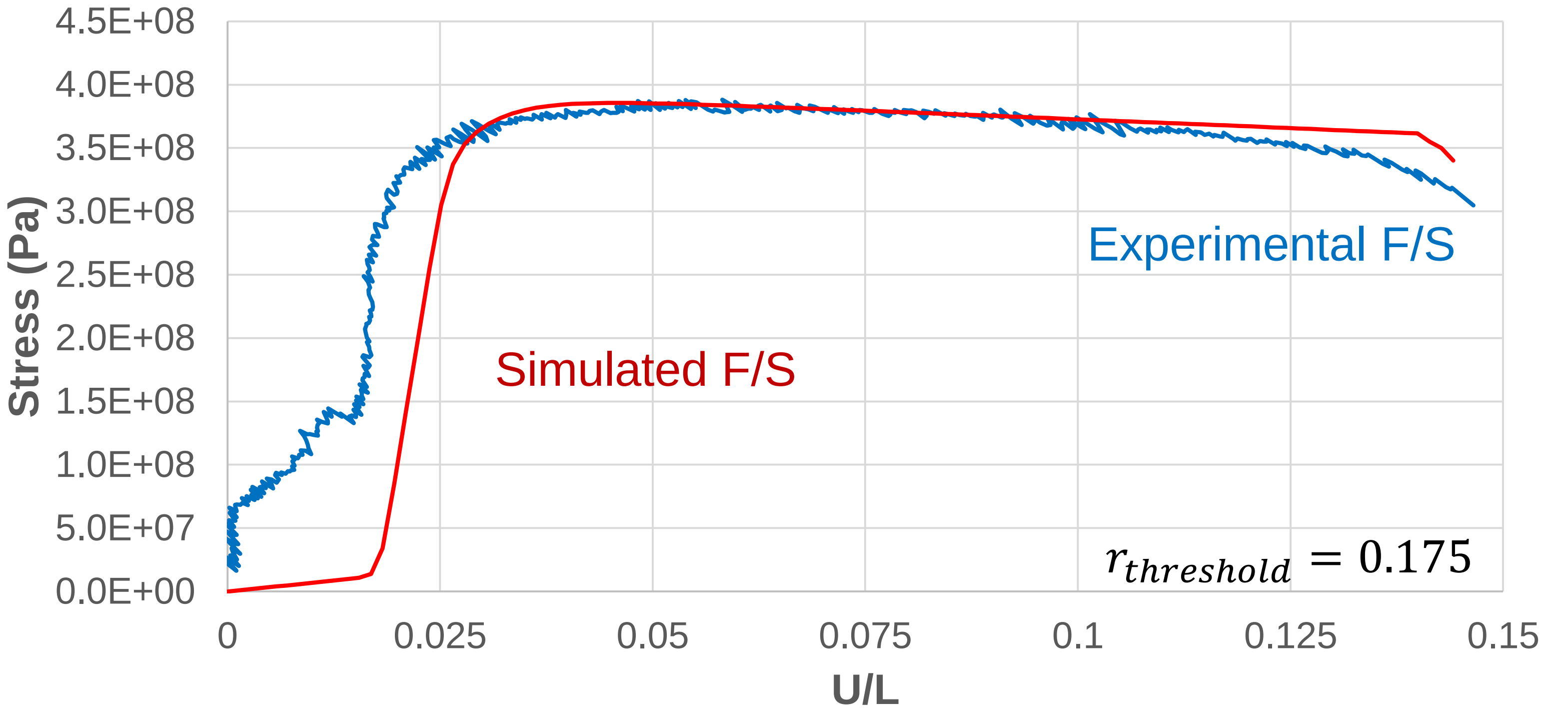
STRESS-STRAIN CURVE COMPARISON



- 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 : η, A** (ongoing work)
  - Higher threshold values incompatible with ring creep tests
  - Possible anisotropic damage mechanisms [Tanno et al.]

CONCLUSIONS

- 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

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