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Étude du comportement viscoplastique du dioxyde d'uranium par essai de compression uniaxial à pression partielle d'oxygène contrôlée et simulation du dispositif associée.

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T. Helfer, J.B. Parise, P. Garcia, C. Introini. Étude du comportement viscoplastique du dioxyde d'uranium par essai de compression uniaxial à pression partielle d'oxygène contrôlée et simulation du dispositif associée.. *Materiaux* 2018, Nov 2018, Strasbourg, France. cea-02339459

HAL Id: cea-02339459

<https://cea.hal.science/cea-02339459v1>

Submitted on 27 Nov 2019

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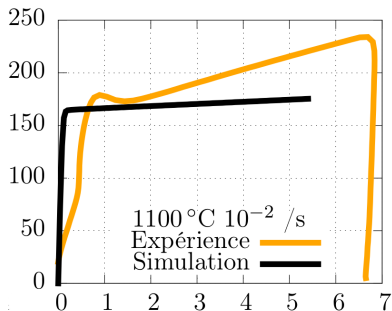


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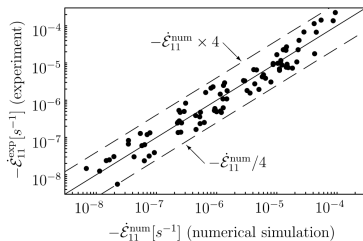
Étude du comportement viscoplastique du dioxyde d'uranium par essai de compression uniaxial à pression partielle d'oxygène contrôlée et simulation du dispositif associée.

Matériaux 2018 | THOMAS HELFER, JEAN-BAPTISTE PARISE, INTROINI CLÉMENT, PHILIPPE GARCIA

20/11/2018



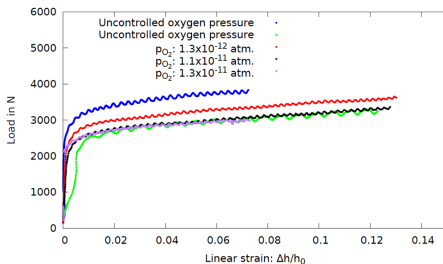
Salvo et al. (2016)



Monerie et al. (2003)

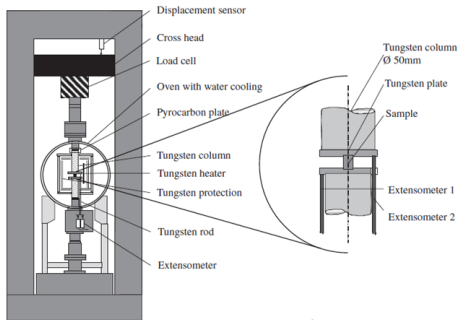
- Current identification of UO_2 viscoplastic behaviours can still be significantly improved.
 - Significant experimental dispersion that must be reduced.
 - Modelling of tests must be made more accurate and must include a finer description of the experimental device :
 - Consistent finite strain constitutive equations.
 - Identification must be made on the whole stress or strain history.

Effect of the oxygen partial pressure on creep tests



- Results of uniaxial compressive tests at constant crosshead speed test ($20 \mu m/min$) at $1500^\circ C$ on samples with identical pellet geometry and microstructure.
- Most studies so far did not control this parameter :
 - **A first order contribution to the experimental dispersion**
 - In a W furnace under “pure” Ar/H₂, oxygen pressures (which should be of the order of 10^{-14} atm at $1500^\circ C$) may vary depending upon :
 - Impurities in the gas phase (e.g. State of oxidation of W)
 - Time left for system to equilibrate

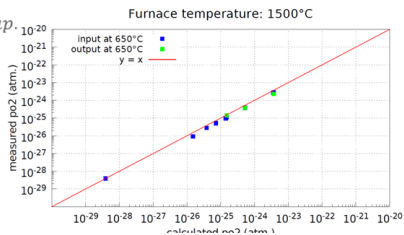
Device



- Buffering insured by $H_2 + \frac{1}{2} O_2 \rightleftharpoons H_2O_{vap}$.
- p_{O_2} controlled by YSZ oxygen pump

- Buffering checked by
 - Output=input
 - Experimental value=calculated value

- Compression testing
 - 100 kN frame equipped with W $\sim 1700^\circ\text{C}$ furnace & *-in situ* extensometers
 - Originally all tests carried out under Ar/H₂
- System equipped with O₂ & H₂O probes, up/down stream



Finite strain constitutive equations

- Kinematic based on the Hencky lagrangian strain :

$$\underline{\epsilon}_{\log}^{to} = \frac{1}{2} \log (\underline{\mathbf{C}}) = \log (\underline{\mathbf{U}}) = \frac{1}{2} \log \left(\underset{\sim}{\mathbf{F}} \cdot \underset{\sim}{\mathbf{F}} \right)$$

Note : $\underline{\mathbf{F}}$: deformation gradient, $\underline{\mathbf{C}}$: right Cauchy tensor, $\underline{\mathbf{U}}$: stretch tensor

- The dual stress $\underline{\mathbf{T}}$ is defined as the work conjugate of $\underline{\epsilon}_{\log}^{to}$:

$$J \underline{\sigma} : \underline{\mathbf{D}} = \underline{\tau} : \underline{\mathbf{D}} = \underline{\mathbf{S}} : \dot{\underline{\epsilon}}_{GL}^{to} = \underline{\mathbf{T}} : \dot{\underline{\epsilon}}_{\log}^{to}$$

Note : in 1D, $\underline{\mathbf{T}}$ is the Kirchhoff stress $\underline{\tau}$

- Direct link between the trace of the Hencky strain and the change

of volume $\det \left(\underset{\sim}{\mathbf{F}} \right) = \exp \left(\text{tr} \left(\underline{\epsilon}_{\log}^{to} \right) \right)$

- **Standard viscoplastic behaviours' formalisms, based on an additive split of the total strain, can be re-used.**
- Implementation based on *Miehe at. al.*' work (Computer Methods in Applied Mechanics and Engineering, 2002)

- Viscoplasticity follows an associated Norton-Hoff law :

$$\dot{\underline{\epsilon}}_{\log}^{\text{vp}} = \dot{\rho} \underline{\mathbf{n}} \quad \text{with} \quad \dot{\rho} = \dot{\epsilon}_0 \left(\frac{(\underline{\mathbf{T}} - \underline{\mathbf{X}})_{eq}}{T_0} \right)^n \quad \text{and} \quad \underline{\mathbf{n}} = \frac{3 \operatorname{dev}(\underline{\mathbf{T}} - \underline{\mathbf{X}})}{2 (\underline{\mathbf{T}} - \underline{\mathbf{X}})_{eq}}$$

where A_{eq} and $\operatorname{dev}(A)$ denote respectively the von Mises norm and the deviatoric part of a tensor $\underline{\mathbf{A}}$

- Following Colin (Phd Thesis, 2004), kinematic hardening is described using the Armstrong-Frederick law (1966) :

$$\underline{\mathbf{X}} = \frac{2}{3} C \underline{\mathbf{a}} \quad \text{and} \quad \dot{\underline{\mathbf{a}}} = \dot{\rho} \underline{\mathbf{n}} - D \dot{\rho} \underline{\mathbf{a}}$$

- $\dot{\epsilon}_0$ is a function of the **temperature**, the **grain size** and **stoichiometry**.
- Numerical implementation using the open-source `MFfront` code generator (Helfer et al., 2015) <http://tfel.sourceforge.net>

The behaviour does not distinguish scattering and dislocation creep. Porosity evolution (Monerie et al.2006, Salvo et al.

2015) is not yet taken into account.

- Viscoplasticity follows an associated Norton-Hoff law :

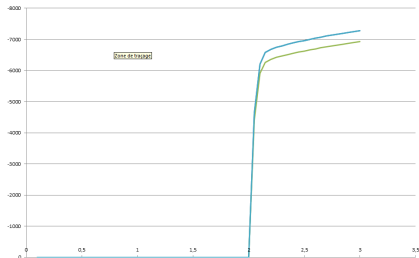
$$\dot{\underline{\epsilon}}_{\log}^{\text{vp}} = \dot{\rho} \underline{\mathbf{n}} \quad \text{with} \quad \dot{\rho} = \dot{\epsilon}_0 \left(\frac{(\underline{\mathbf{T}} - \underline{\mathbf{X}})_{\text{eq}}}{T_0} \right)^n \quad \text{and} \quad \underline{\mathbf{n}} = \frac{3 \operatorname{dev}(\underline{\mathbf{T}} - \underline{\mathbf{X}})}{2 (\underline{\mathbf{T}} - \underline{\mathbf{X}})_{\text{eq}}}$$

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- $\dot{\epsilon}_0$ is a function of the **temperature**, the **grain size** and **stoichiometry**.
- Numerical implementation using the open-source MFront code generator (Helfer et al., 2015) <http://tfel.sourceforge.net>

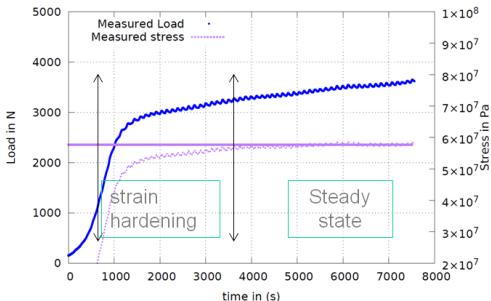


- The lagrangian approach implicitly introduces a reference state :
- The figures compares two computations of the same experiment :
 - The first one starts from room temperature. **Good approach**
 - The second one starts from the experiment temperature (with actualised geometry) **Incorrect approach.**
 - Up to 5 % error on the computed force. Can be higher in some cases.

Results

Macroscopic experimental data available and preliminary analysis

- *In situ* experimental data available: $h(t)$, load $F(t)$
- Vertical axis oriented downwards



- Initial phase: **combined response** of setup and apparent pellet hardening
- Second phase: linear increase in load

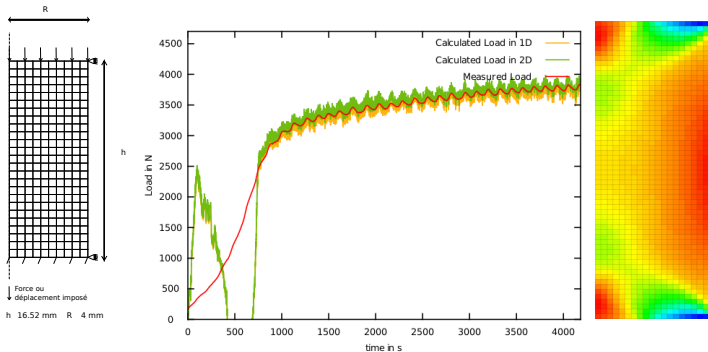
- Uniaxial hypothesis
- Creep occurs at constant volume: $S(t)h(t) = S_0 h_0$
- Primary & secondary creep

$$\sigma_{eq}(t) \approx \sigma_z(t) \approx \frac{F(t)}{S(t)} \approx \frac{F(t)h(t)}{h_0 S_0}$$

macroscopic hardening \Leftrightarrow primary creep & increase in section

Uniaxial temptation is strong

Identification of UO_2 viscoplastic behaviour : Comparison 1D and 2D modelling



■ Various models of the device have been set-up :

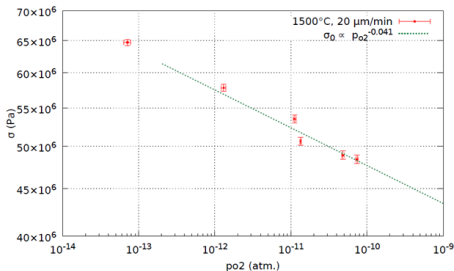
- 1D models based on MTest

- 2D and 3D models based on Licos/Cast3M

■ Very close results of simple 1D and 2D models on the force/displacement curve

- If $X \ll \sigma$, analysis is straightforward
- Plotting $\text{Log}(\sigma) = f(\text{Log}(p_{O_2})) \Rightarrow -\alpha/n$

$$\dot{\epsilon} \propto K p_{O_2}^{\alpha} \sigma^n$$



- Data points lie in ~ **straight line**
- Flow stress Decreasing $f(p_{O_2}) \Rightarrow$ consistent with $\alpha > 0$ and $[Vu]$ **increasing function of p_{O_2}**
- $-\alpha/n \sim -0.041 \Rightarrow$ if $n \sim 4$, $\alpha \sim 1/6$

Conclusions

- This talk shows recent improvements to the description of UO_2 viscoplasticity :
 - The control of oxygen partial pressure is crucial :
 - to derive more physical constitutive equations.
 - to reduce experimental dispersion.
 - Consistent models of the device based on proper finite strain constitutive equations have been set-up
- Those results are preliminary and the experimental data used covers only a limited range of loadings (stress, temperature, grain size, etc..)
- In particular, the constitutive equations shown here will evolve.
- More compressive tests required :
 - non monotonic loadings
- Four points bendings tests.

- This research is part of the INSPYRE project, which has received funding from the Euratom research and training programme 2014-2018 under Grant Agreement No 754329.



INSPYRE

Investigations Supporting MOX Fuel Licensing
in ESNII Prototype Reactors