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Sub-boundary characterization of crept uranium dioxide fuel pellets, by EBSD and ECCI

Mariem Ben Saada¹,²
H. Mansour², N. Maloufi², N. Gey², B. Beausir², X. Iltis¹

Email: Mariem.BENSAADA@cea.fr

EBSD: Electron BackScattered Diffraction
ECCI: Electron Channeling Contrast Imaging

Creep 2015, June 01– June 04, 2015, Toulouse, France
The fuel rods consist of:

(1) UO₂ pellets pilled up in
(2) a zirconium alloy cladding tube cooled by pressurized water
In service the UO$_2$ pellets undergo significant plastic deformation by creep

**Nominal conditions**

- **Irradiation cycle (1 cycle ~ 1 year)**
  - Start of irradiation
  - 1 cycle
  - 2 cycles

- **9.5 mm**

- **Temperature increase (pellet center)**

**Under irradiation:**

- thermal gradient + fission products
  - Fuel swelling
  - Large stresses and cracks in the pellet

**Power transient**

- **Brittle region**
- **Viscoplastic region**
- **Viscoplastic-deformation**

Cracking in a UO$_2$ pellet subjected to 2 annual PWR cycles, followed by 12 hours at a linear power of 430 W/cm.

**Increasing power causes:**

- An increase of pellet temperature up to about 1500-2000°C in its central part
  - Viscoplastic-deformation: Creep of the pellet

- To avoid cladding failure

- Increase the creep of the fuel (viscoplastic deformation)
Sintering conditions [1,2]

Uniaxial pressing of the powder under 400 MPa

+ Sintering heat treatment at 1900°C for 4h, under an atmosphere of Ar + 5% H₂

Compression creep tests at 1500°C [1,2]

Our reference sample

- 50 MPa
- test duration: 2.7h
- mean deformation: ~ 8%

SEM micrograph (BSE mode) of an UO₂ sample

Grain size : 25µm

Strain rates measured in the creep test at 1500°C under various stresses [2]
Creep damage

- Intergranular cavities
- Sub-grains formation
- Dislocations density increase

TEM studies

SEM studies

1978
A. Alamo et al.
CEA
Fontenay aux Roses

2002
F. Dherbey et al.
CEA
Grenoble

2014
J. Fouet et al.
CEA
Cadarache

Primary slip
\{001\}<110>

\(\varepsilon\)

Primary slip
\{110\}<110>

+ Cross slip
\{111\}<110>

Dislocation network*

Density of dislocations
OUR AIM is to characterize the sub-boundaries created by dislocational creep in UO₂.

**EBSD**
Electron BackScattered Diffraction

**BULK MATERIAL SEM**

**ECCI**
Electron Channeling Contrast Imaging [3]

**Microscope**

**Pole piece**

**BSE Detector**

Acquisition of Orientation map to:
- Identify the low angle boundaries (sub-grains),
- Quantify the Geometrically Necessary Dislocations (GND)

To identify crystallographic defects like dislocations and their arrangement in sub-grains boundaries [4]

BSE image at high magnification in specific diffraction condition

1 µm
RESULTS: EBSD ANALYSIS ON THE REFERENCE SAMPLE ε=8%

The deformation induced a network of low angle boundaries

EBSD resolves low angle boundaries revealed by misorientations down to 0.1°!
The lattice curvature measured by EBSD can be used to evaluate the local density of GNDs.

From the disorientation between two neighboring points: $\Delta \theta$

Separated spatially by $\Delta x$,

the lattice curvature: $k = \frac{\Delta \theta}{\Delta x}$

and the GND’s density: $\rho = \frac{k}{b}$

Per EBSD step unit

$b = a/2<110>$

Nye dislocation density tensor

$$\alpha = \begin{bmatrix} ? & a_{12} & a_{13} \\ a_{21} & ? & a_{23} \\ ? & ? & a_{33} \end{bmatrix}$$

LEM3 Software
Sub-grain n°1

EBSD: GND evaluation from lattice curvature

\[ \Delta \theta \in [0.1^\circ \text{ to } 0.3^\circ] \]

\[ \rho_{\text{EBSD}} = \frac{k}{b} = 3 \times 10^{13} \text{ to } 9 \times 10^{13} \text{ m}^{-2} \]

GNDs density

ECCI: Dislocations arrangement in low angle boundaries

\[ \rho_{\text{ECCI}} = 8 \times 10^{13} \text{ m}^{-2} \]
RESULTS: SUB-BOUNDARIES ANALYSIS BY EBSD AND FURTHER BY ECCI

Sub-grain n°2:

Misorientation angle $\Theta$

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<tr>
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</tr>
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<td>0.25</td>
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Previous TEM result

Dislocation Network shown by ECCI

F. Dherbey et al. 2002
CONCLUSION: EBSD and ECCI are powerful tools to analyse creep damage in UO₂

• EBSD: Quantification of low angle boundaries down to 0.1°,
  Their evolution with the creep deformation,
  Evaluation of the dislocation density

• ECCI: Imaging of the dislocations in the low angle boundaries
  with a TEM quality image but in bulk material,
  Analyse their arrangement in hexagonal network,
  Deduce the dislocation density

In coming work, we plan to use these techniques to understand the deformation mechanisms in bulk UO₂ material
Thank you for your attention

REFERENCES:


