DE LA RECHERCHE À L'INDUSTRIE

Impact of fuel assembly transportation on zirconium alloys: toward a mechanistic understanding

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INDUSTRIAL BACKGROUND : END OF LIFE OF THE FUEL ASSEMBLY

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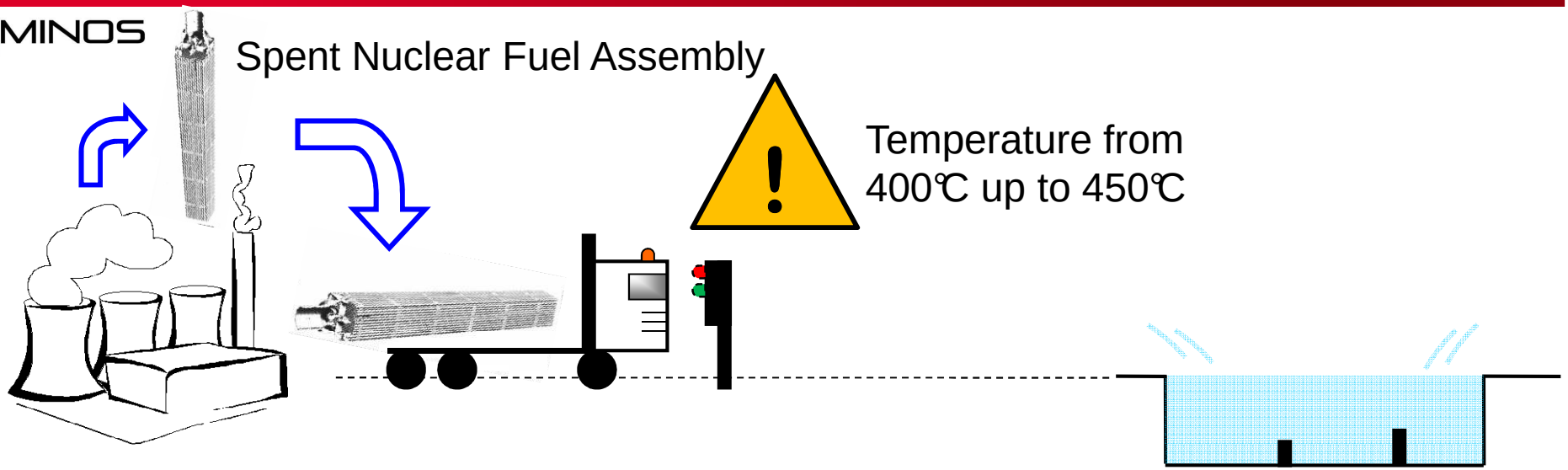
Spent Nuclear Fuel Assembly



Temperature from 400℃ up to 450℃

In-reactor use → Dry transportation → In-pool storage

Fuel assembly

Neutron irradiation of the Zr alloy cladding → Post-irradiation creep of the Zr alloy cladding and radiation damage recovery → <u>Room temperature</u> mechanical properties at retrieval ?

MATERIAL STUDIED AND RADIATION EFFECTS

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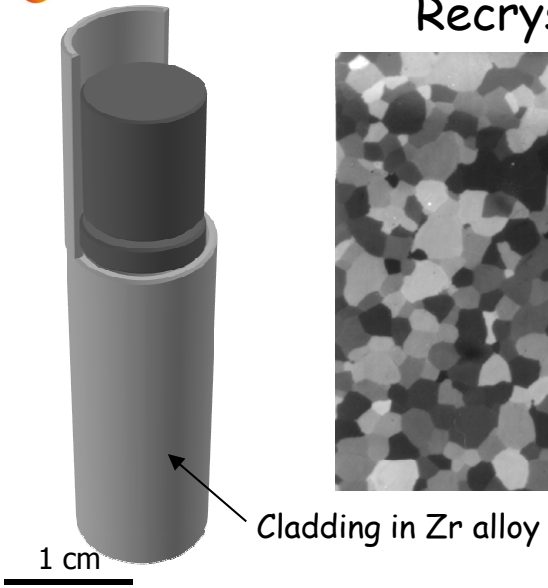
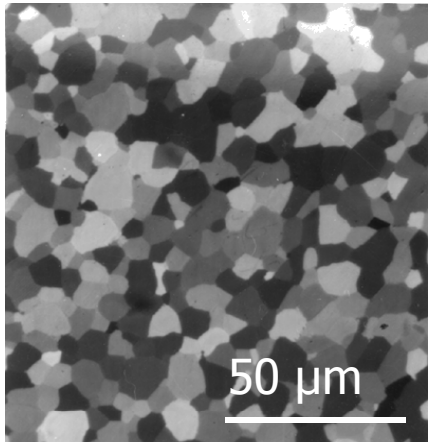
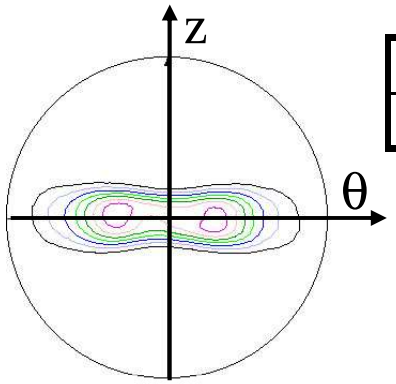


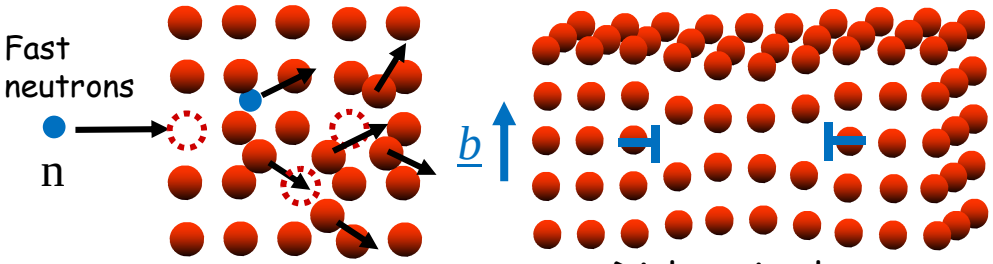
Recrystallized Zr-1%Nb alloy





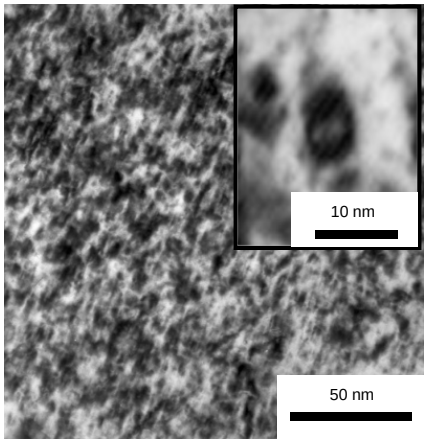
Chemical composition (% wt)

%wt	O	Sn	Fe	Cr	Nb	Zr
RXA Zr-1%Nb	0.12	0	0.02	0	1	Bal.

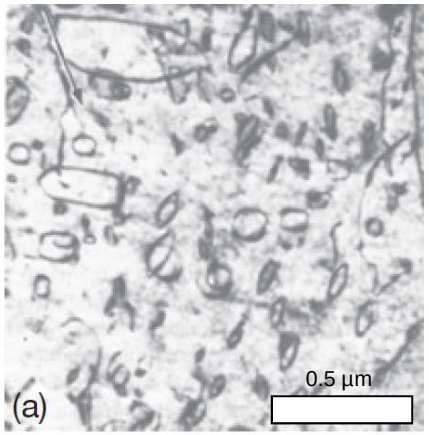


Displacement cascade

Dislocation loop



Onimus F, Siloé, 553 K, 0.6×10^{25} n m^{-2}



Griffiths M. EBR II, 700 K, 1.1×10^{25} n m^{-2}

→ creation of a high density of small loops

LOOP EVOLUTION DURING HEAT TREATMENT

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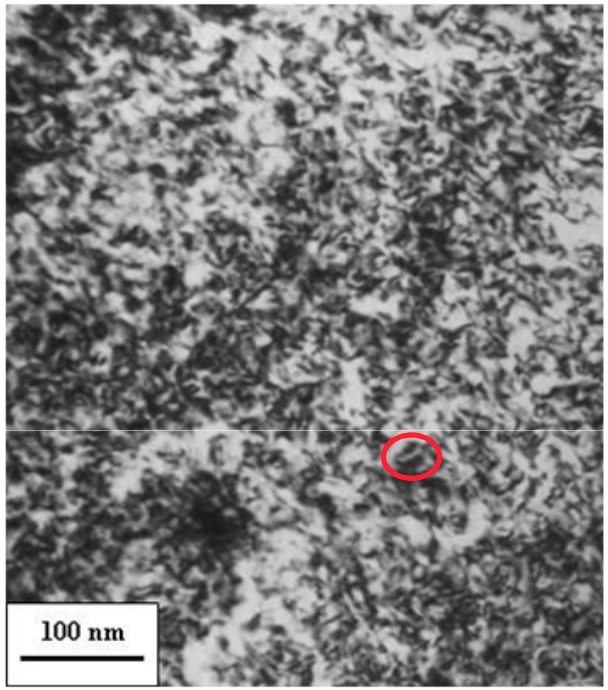
Heat treatment → to simulate transportation

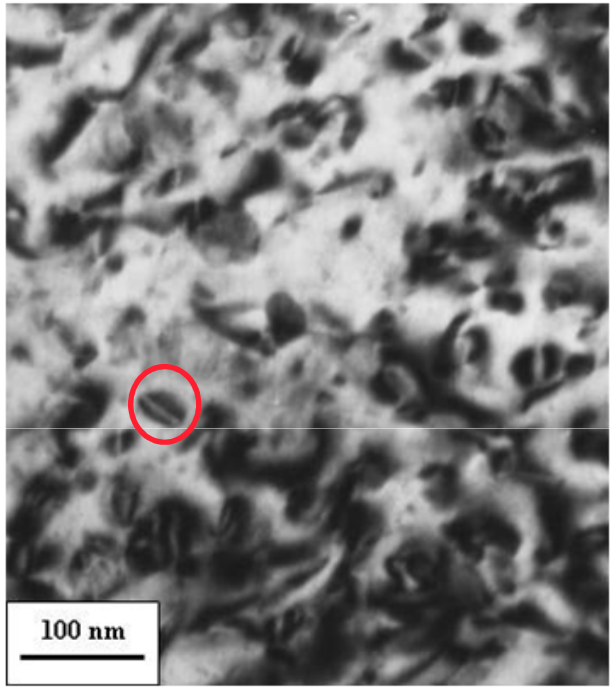


(a)

As-irradiated material

$<\rho_b> = 1{,}2.\ 10^{22}\ m^{-3}$

$<d> = 14$ nm

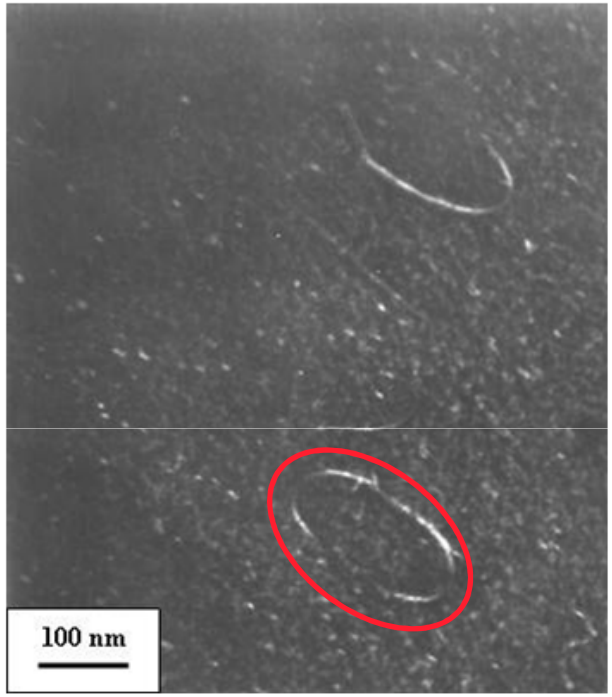


(d)

After heat treatment at 400°C during 250 h

$<\rho_b> = 2{,}5.\ 10^{21}\ m^{-3}$

$<d> = 18$ nm



(f)

After heat treatment at 450°C during 960 h

$<\rho_b> = 1{,}2.\ 10^{20}\ m^{-3}$

$<d> = 176$ nm

→ The loop size increases while the density decreases

→ Radiation damage recovery

LOOP EVOLUTION DURING HEAT TREATMENT

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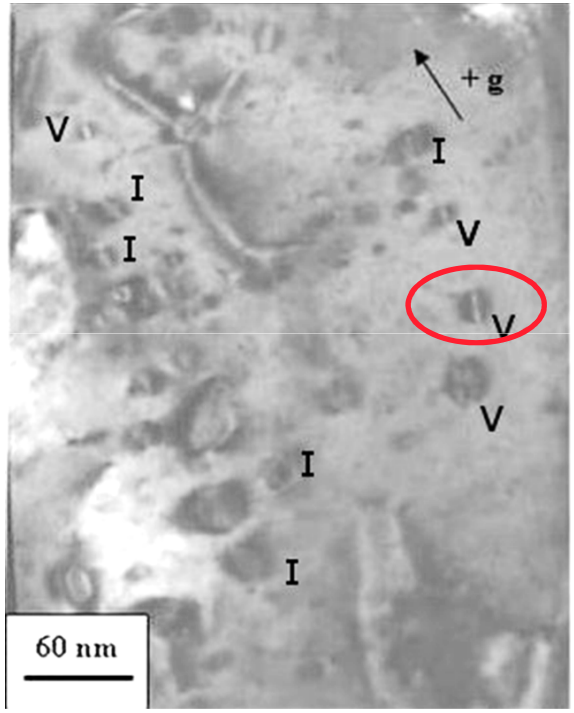
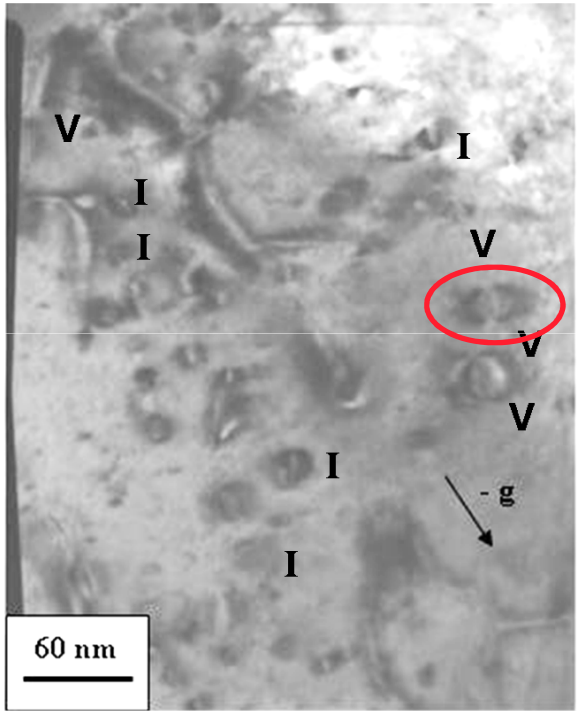
Loop nature using inside / outside contrast method

V as Inside contrast



(a)

V as Outside contrast



(b)

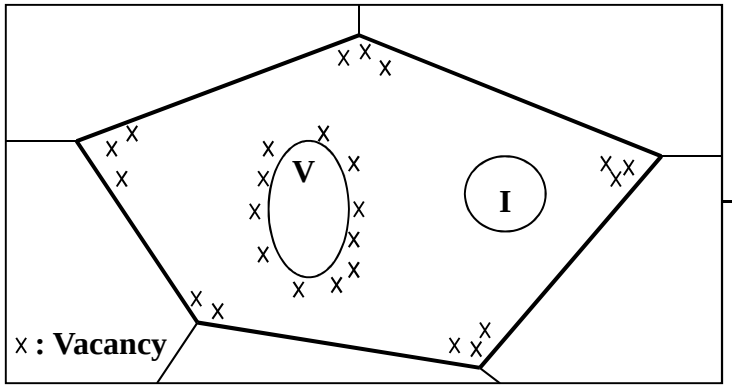
Annealing	Vacancy loops
As-irradiated	**50%**
350℃ 250 h	**50%**
350℃ 500 h	**50%**
400℃ 250 h	**65%**
400℃ 500 h	**71%**
450℃ 960 h	**100%**

→ Only vacancy loops at the end of the recovery

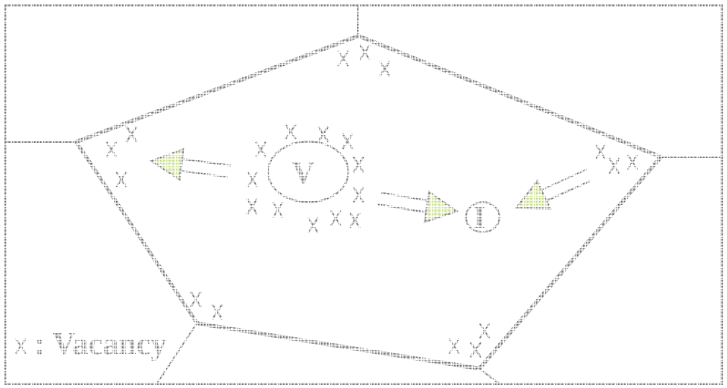
→ Interstitial loops recover faster than vacancy loops

What is the loop recovery mechanism ?

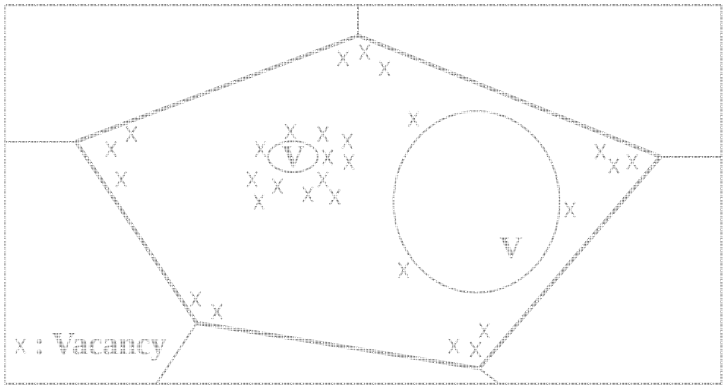
LOOP RECOVERY : MECHANISM



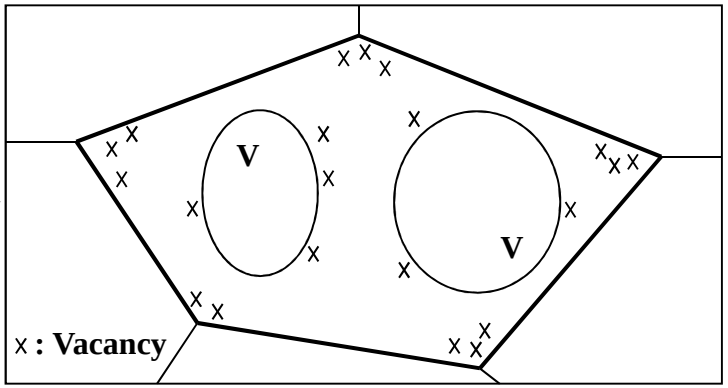
As-irradiated microstructure



Shrinking of the vacancy and interstitial loops



Shrinking of the smallest loop at the expense of the biggest loop



Annealed microstructure

Predictive modelling approach : cluster dynamic

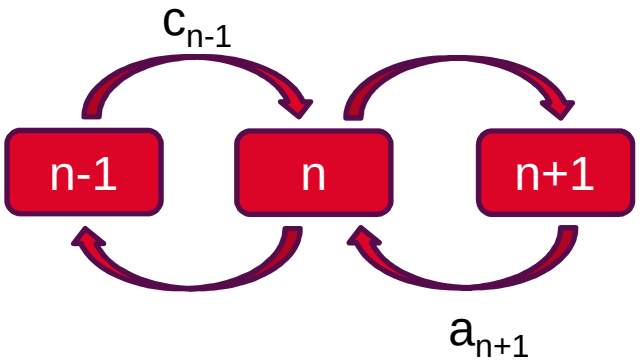
Single-vacancy evolution :

$$\frac{dC_v(1)}{dt} = \cancel{\textit{production} - \textit{annihilation}}$$

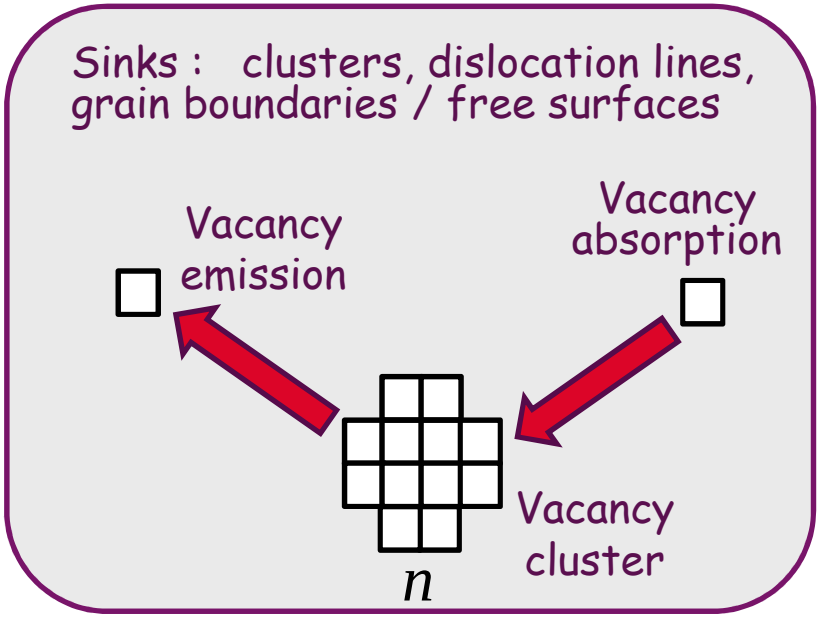
No creation of point defects during annealing

Cluster evolution :

$$\frac{dC(n)}{dt} = a_{n-1}C(n+1) - b_n C(n) + c_{n-1}C(n-1)$$



Mean-field modeling



LOOP RECOVERY : MODELLING

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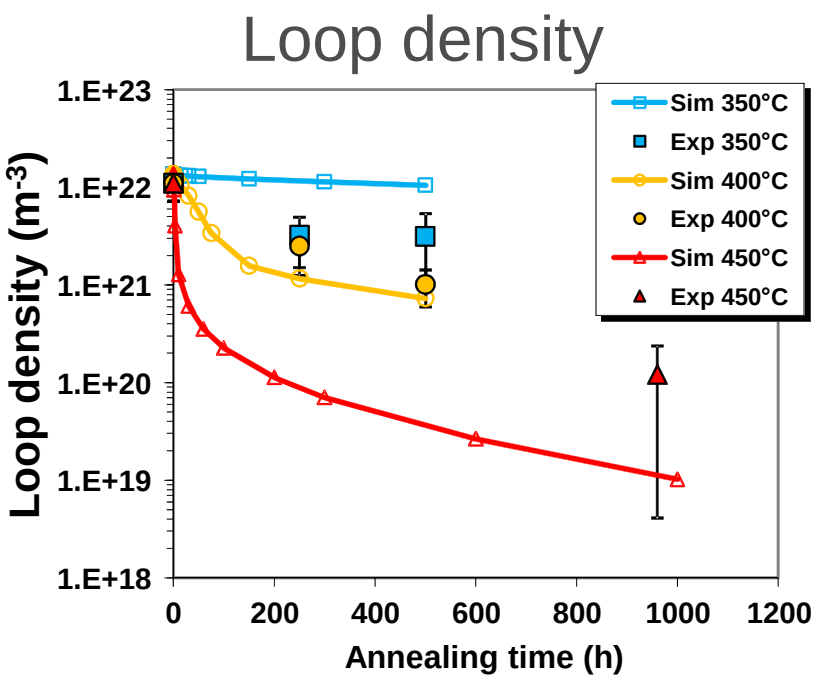
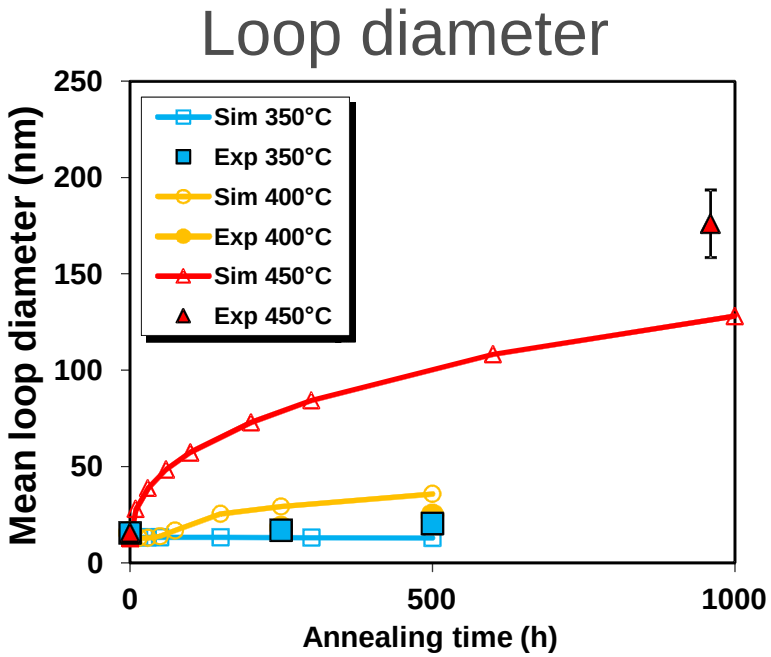
Cluster dynamic modelling → computation of loop size and density





→ Correct agreement between experiment and modeling

LOOP RECOVERY : MODELLING

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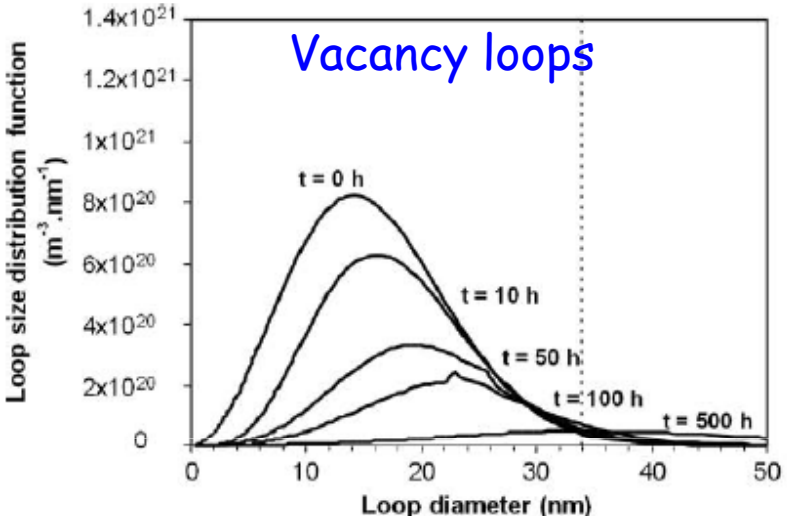
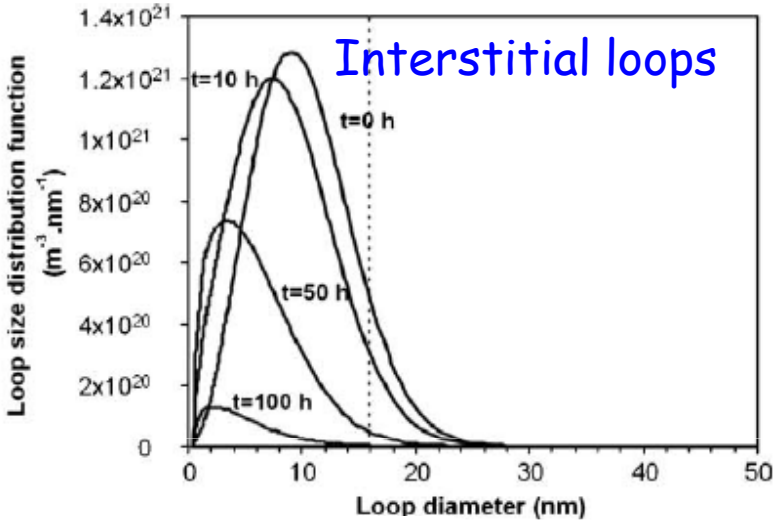
Evolution of vacancy and interstitial loop size distribution at 400°C





Evolution of the proportion of vacancy loops during heat treatment

Annealing temperature (°C)	Annealing time (h)	Experiment		Modelling
		Number of analysed loops	Percentage of vacancy loops (%)	Percentage of vacancy loops (%)
As-irradiated	As-irradiated	–	50 [23]	50
350	250	19	50	45
350	500	24	50	43
400	250	37	65	100
400	500	38	71	100
450	960	13	100	100

→ Correct agreement between experiment and modeling

RADIATION HARDENING RECOVERY : MODELING

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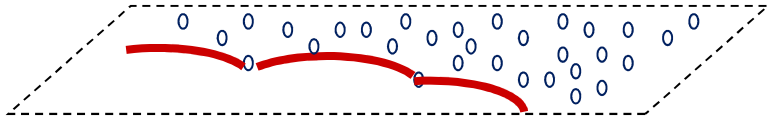
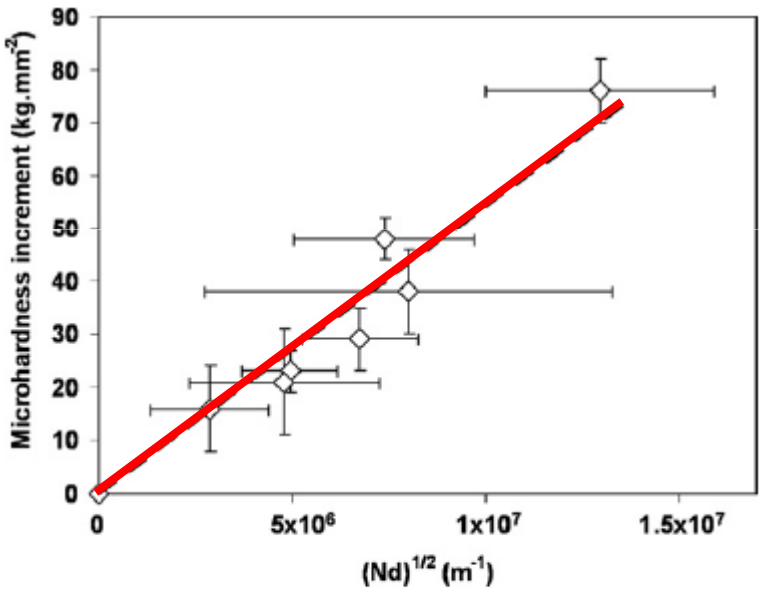
High density of small loops
-> pinning of dislocations
-> radiation hardening



$$\Delta\tau_c = \alpha\mu b\sqrt{Nd}$$



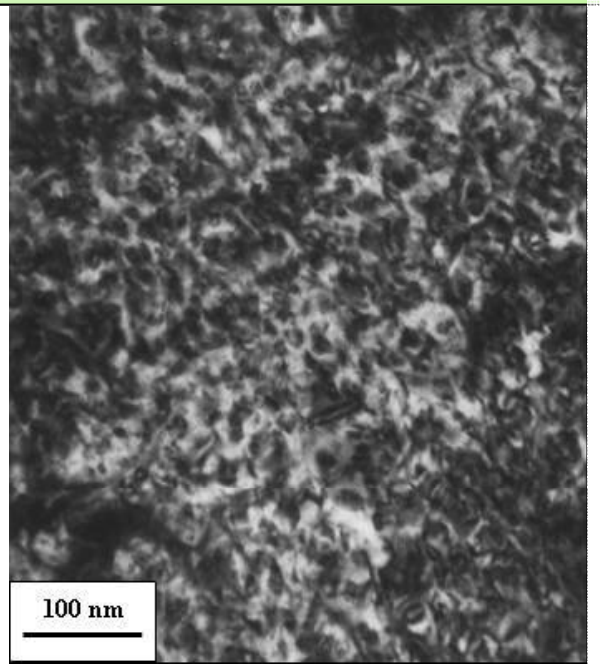
Hardness as a function of the loop density & size

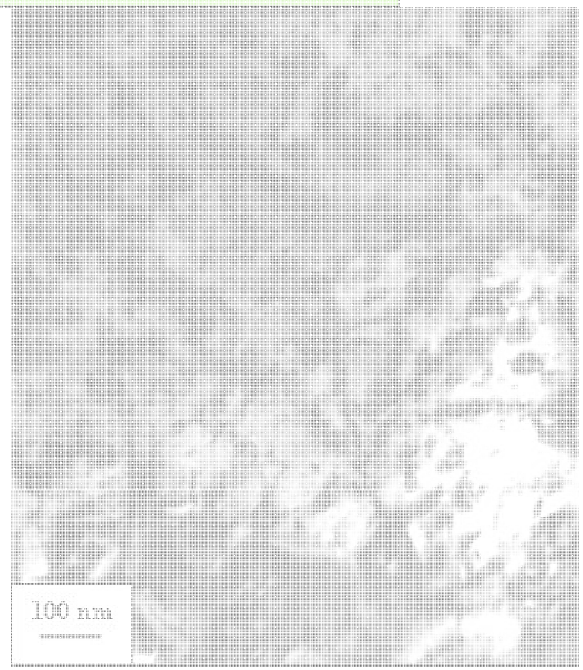
→ Radiation hardening recovery during heat treatment

→ Correct prediction of radiation hardening recovery

LOOP RECOVERY DURING POST-IRRADIATION CREEP

Post-irradiation creep → to simulate transportation





As-irradiated

Creep test at 400°C during 240 h under 130 MPa

After post-irradiation creep :

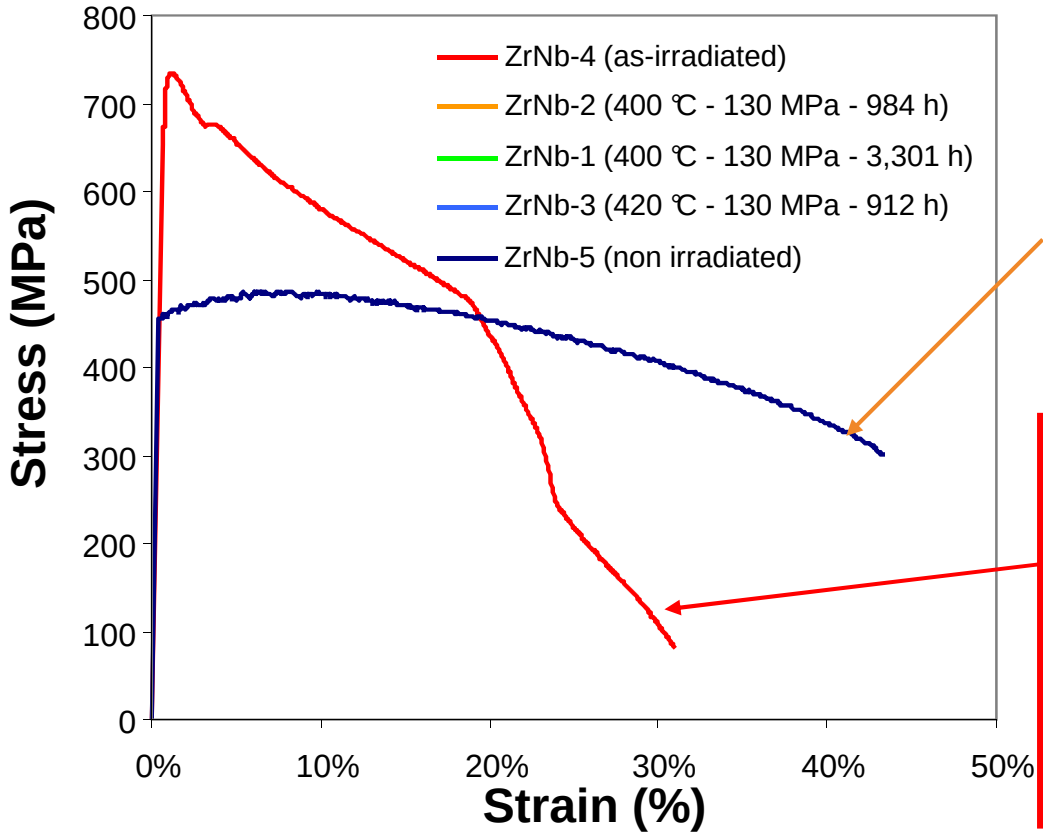
→ decrease of the loop density

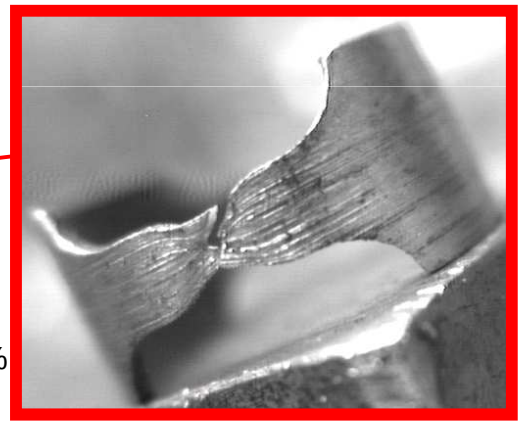
(+ increase of the loop size)

→ Radiation damage recovery during creep

→ Effect on the tensile mechanical behavior ?

IMPACT ON ROOM TEMPERATURE BEHAVIOR





- Irradiation induced hardening (increase of the yield stress and ultimate tensile strength)

- Loss of macroscopic ductility (decrease of the uniform elongation), but the failure remains ductile (strong necking)

→ What are the deformation mechanisms ?

DEFORMATION MECHANISM OF AS-IRRADIATED MATERIAL

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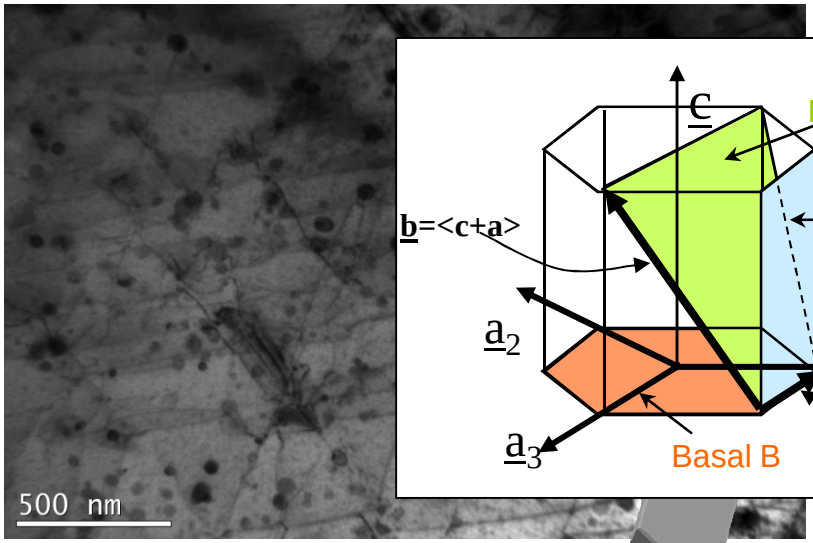
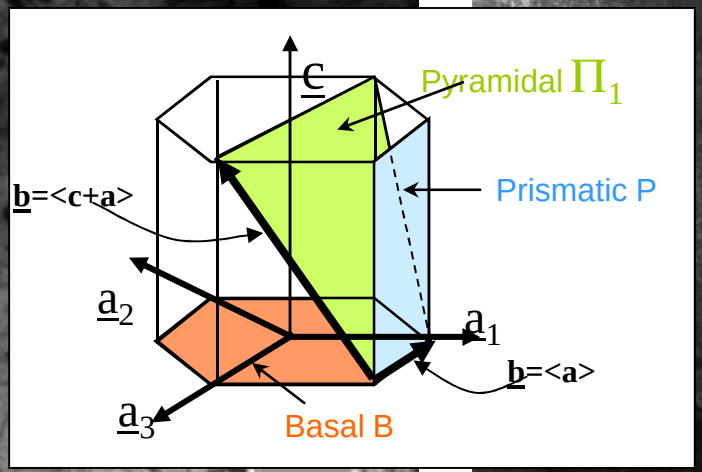
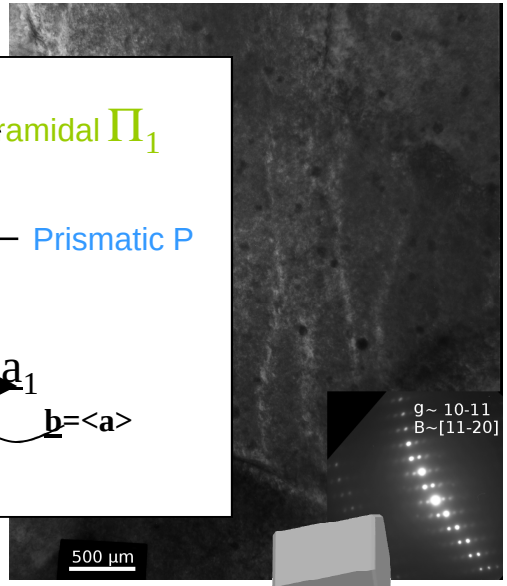
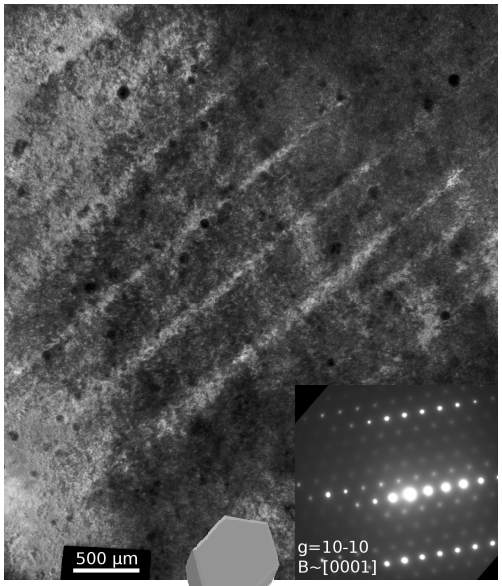
RT tensile test on non irradiated material

Ring tensile test at room temperature after irradiation









→ homogeneous glide of dislocations in the prismatic planes mainly

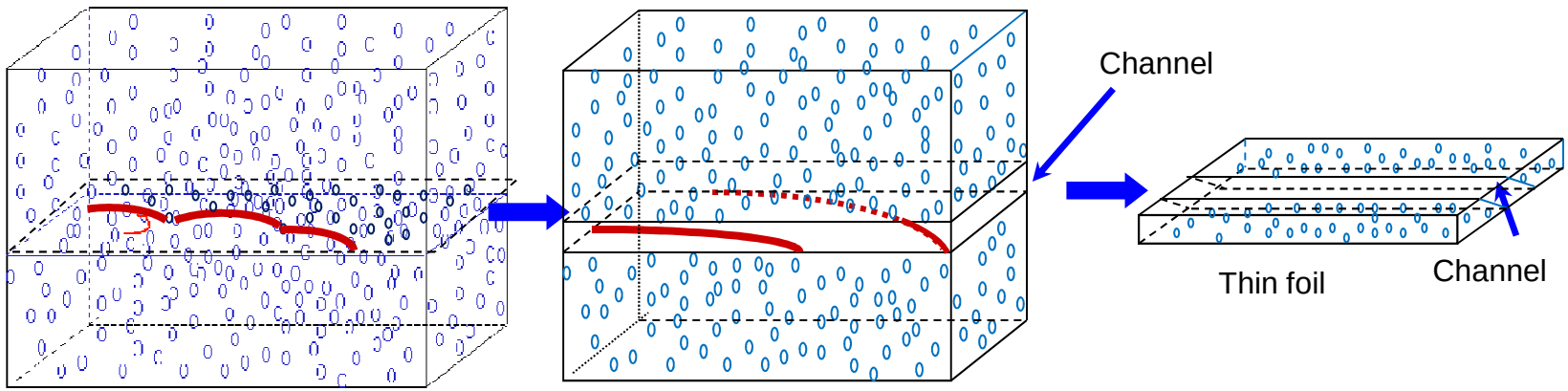
Channels in the basal plane

Channels in the prismatic planes

- Heterogeneous deformation inside the grains (dislocation channeling)
- both basal and prismatic slip can be activated (depending on the grain orientation)

-> easier basal slip than before irradiation

DEFORMATION MECHANISM OF AS-IRRADIATED MATERIAL



High density of small loops
-> pinning of dislocations
-> radiation hardening

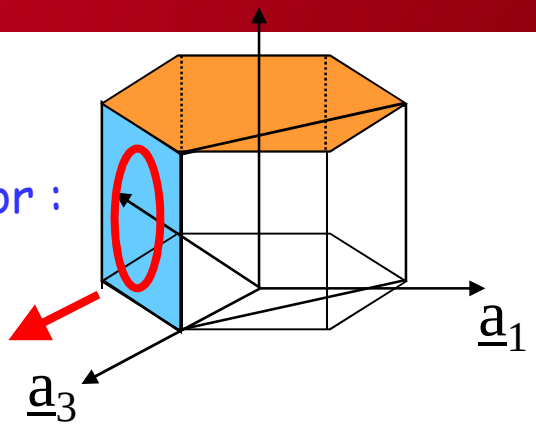
Clearing of loops by gliding dislocations
-> microscopic strain softening
-> early localization of the deformation at the specimen scale
-> decrease of the Uniform Elongation observed during ring tensile tests

-> Why is the basal slip more easily activated after irradiation than before irradiation ?

DEFORMATION MECHANISM OF AS-IRRADIATED MATERIAL

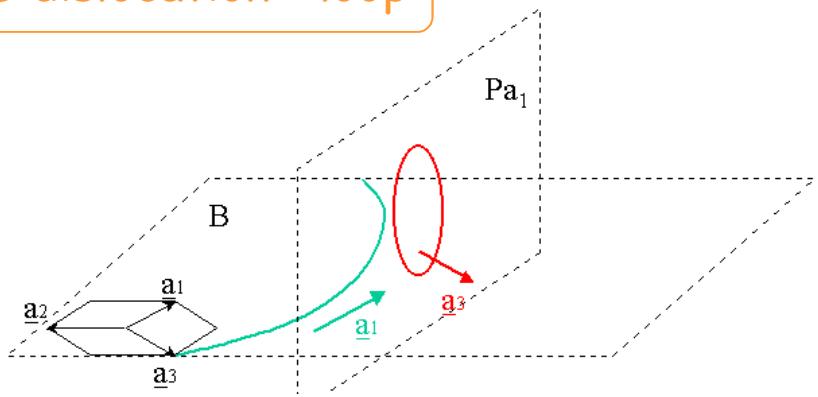
Loop Burgers vector :

b=<a>=1/3 <11$\bar{2}$0>

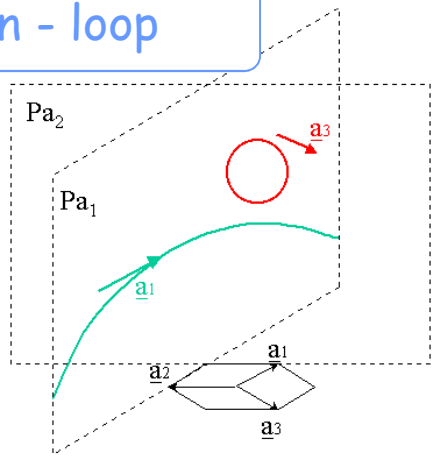


Dislocation Burgers vector : b=<a>=1/3 <11$\bar{2}$0>

B dislocation - loop



P dislocation - loop

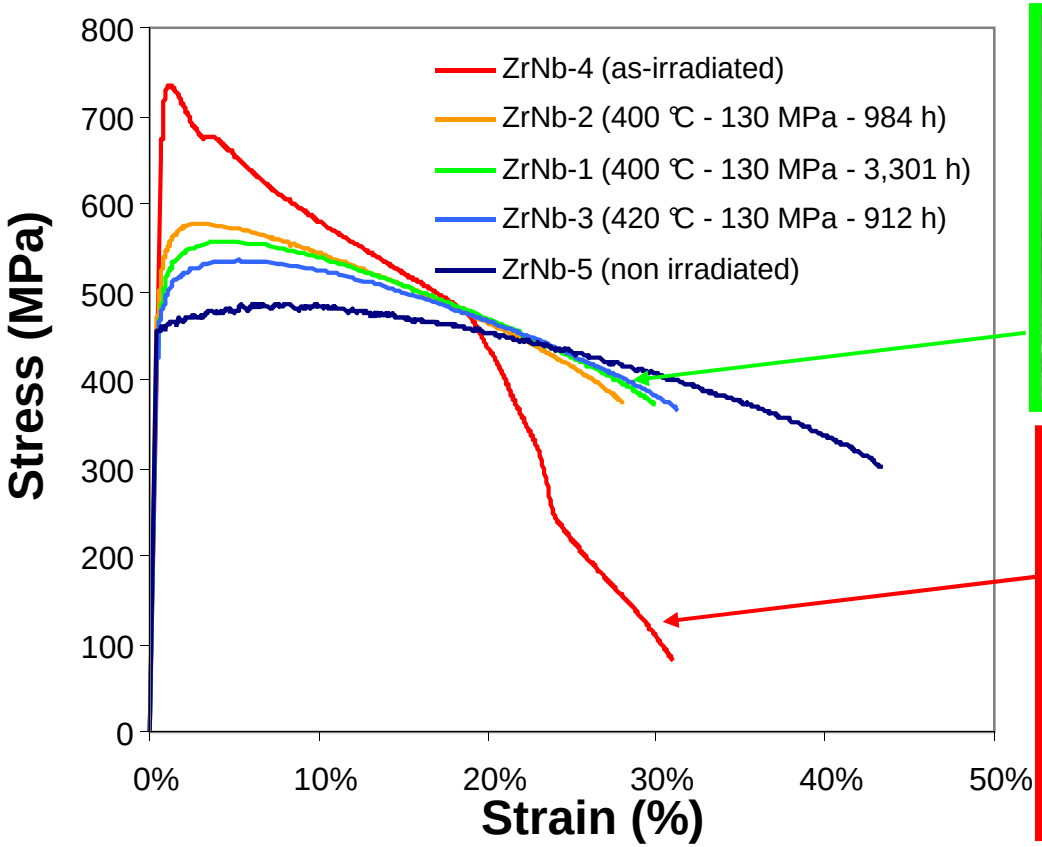


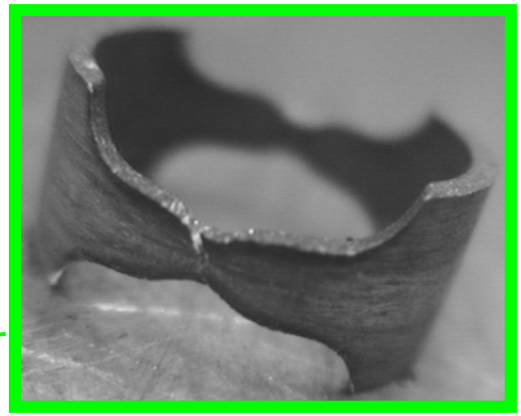
⇨ Glissile junction

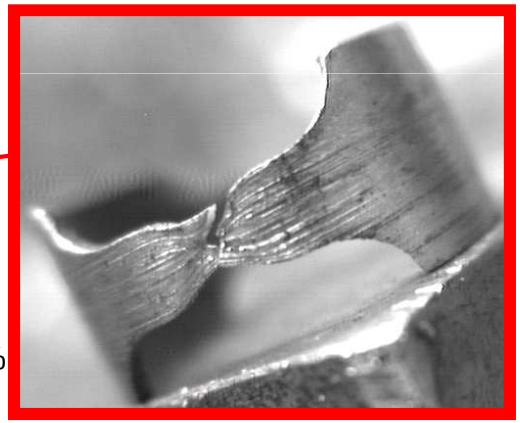
⇨ Sessile junction

→ Easy Basal channeling / difficult Prismatic channeling

IMPACT ON ROOM TEMPERATURE BEHAVIOR



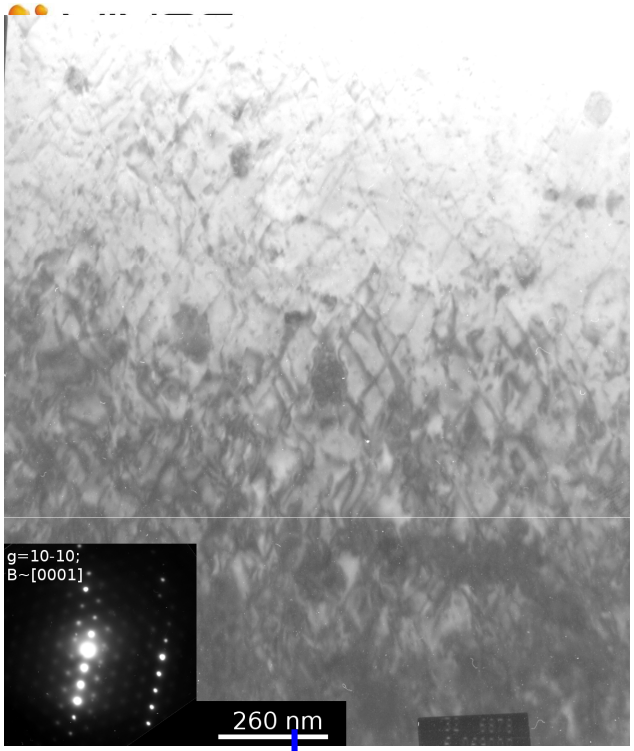


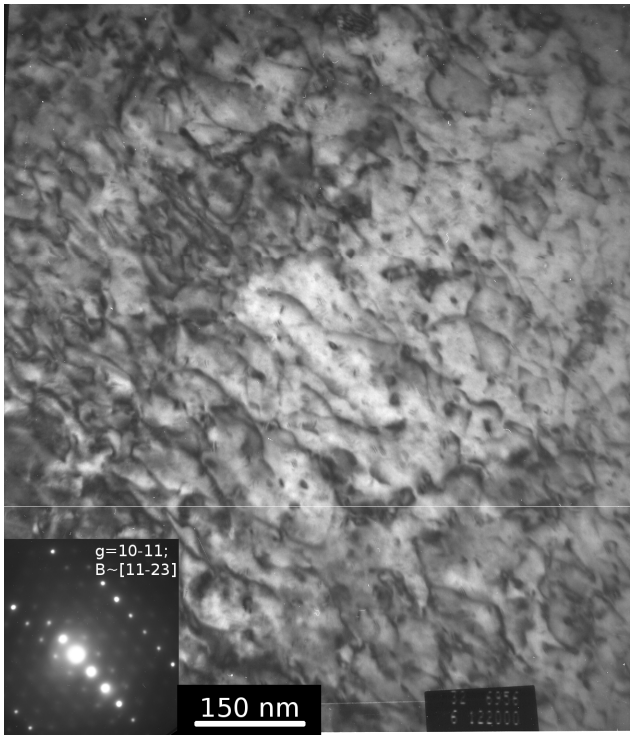


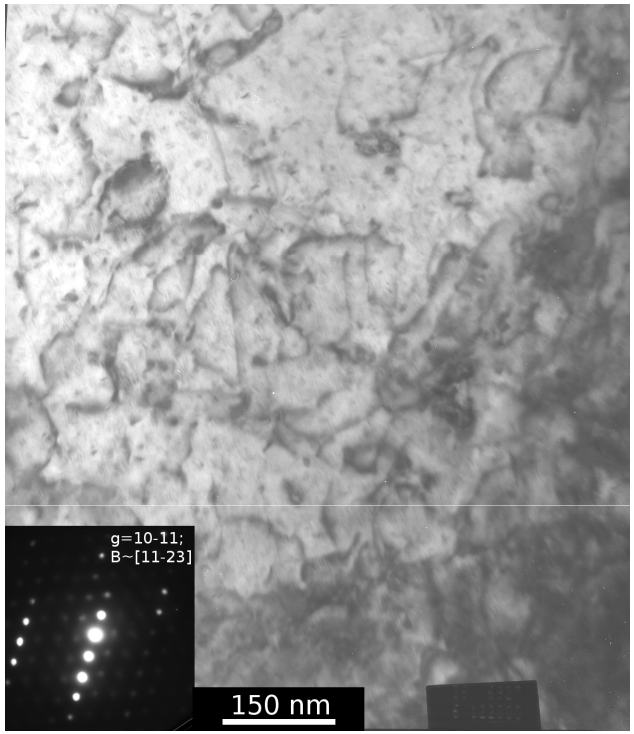
- Recovery of the radiation induced hardening after creep test
- Recovery of the macroscopic ductility (uniform elongation)

→ What are the deformation mechanisms ?

IMPACT ON ROOM TEMPERATURE BEHAVIOR







Testing after creep at 400°C

Testing after creep at 420°C

Prismatic glide mainly

After ring tensile test following post-irradiation creep :
-> very few remaining loops → lower radiation hardening
-> homogeneous prismatic glide mainly, no channel
→ recovery of the uniform elongation

CONCLUSIONS

- Radiation damage recovery :
  - Occurs by exchange of vacancies between loops
  → Shrinking of Int loops and of small Vac loops at the expense to bigger Vac loops

  Cluster dynamic modeling :
  → Correct prediction radiation damage recovery & radiation hardening recovery

  Mechanical behavior after neutron irradiation :
  - decrease of the uniform elongation due to the dislocation channeling
  - failure occurs after a strong necking -> ductile failure
  - evolution of activated slip systems explained by junction between dislocations and loops

  Impact of transportation (post-irradiation creep) :
  - radiation hardening recovery due to the loop annealing during creep
  - recovery of the uniform elongation due to homogeneous glide of dislocations

  -> better knowledge and understanding of the effects of transportation on the mechanical properties of the fuel assembly at retrieval

Thank you !