SOTERIA FINAL WORKSHOP

PREDICTION OF DOSE-DEPENDENT FRACTURE RESPONSE EVOLUTIONS BASED ON MATERIAL MICROSTRUCTURE OBSERVATIONS IN RPV STEELS

27TH JUNE 2018

Contribution to SOTERIA WP5

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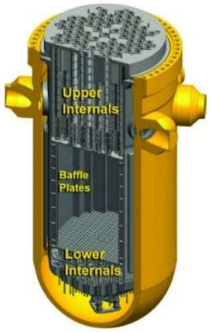
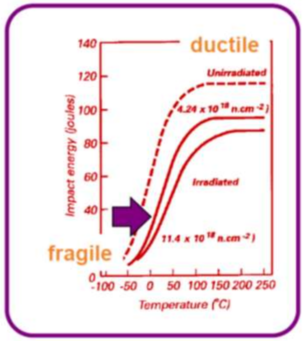
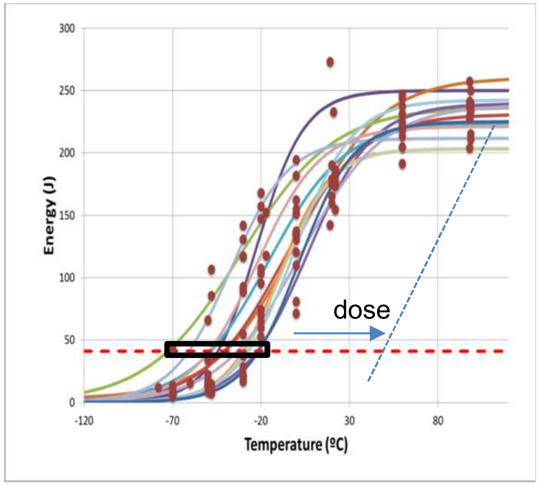
Speaker: **Christian Robertson**

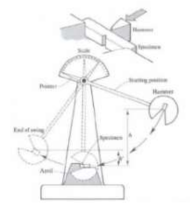
Fracture response of RPV steel forgings

Ductile to brittle transition temperature?

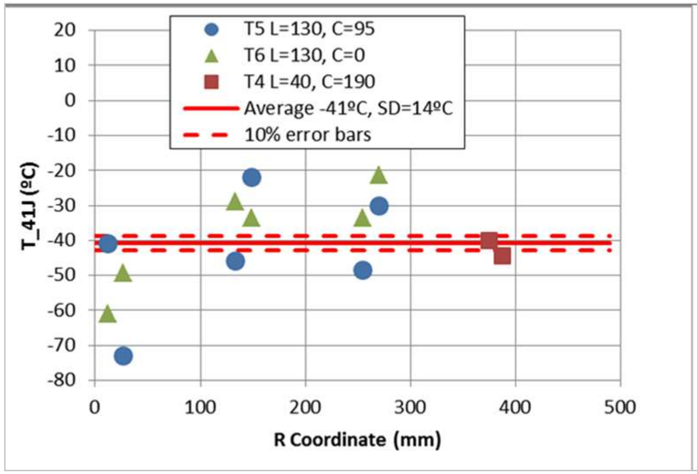


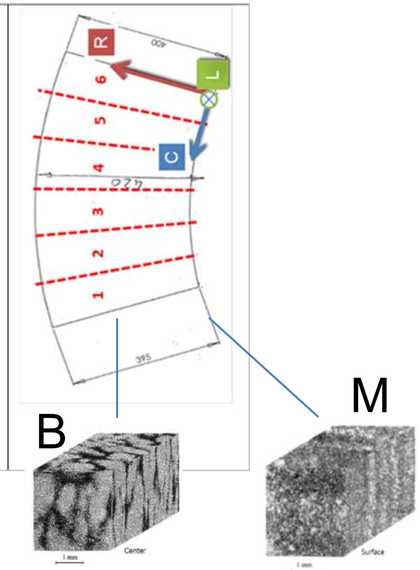






Significant data scattering in as-received condition

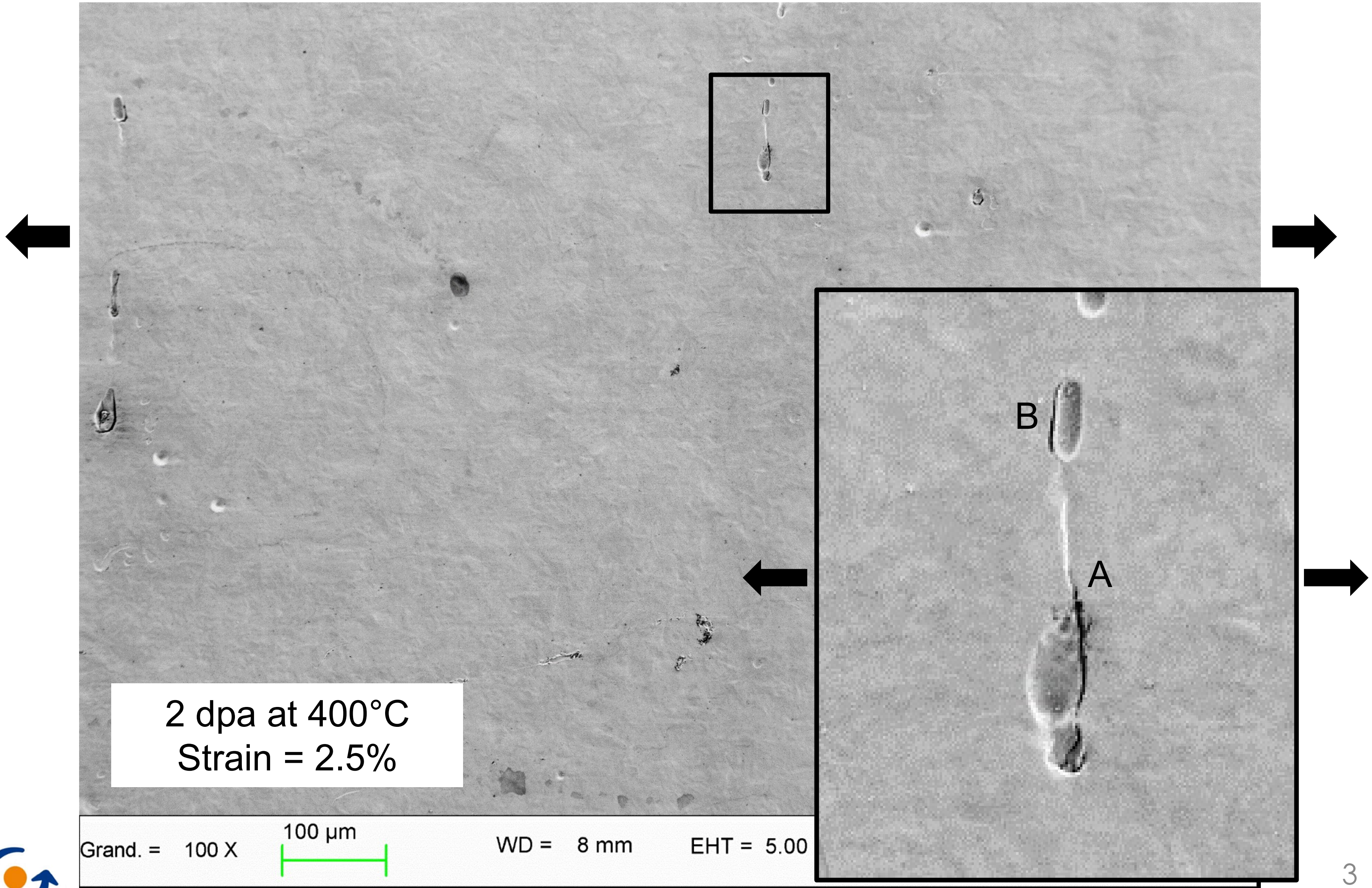




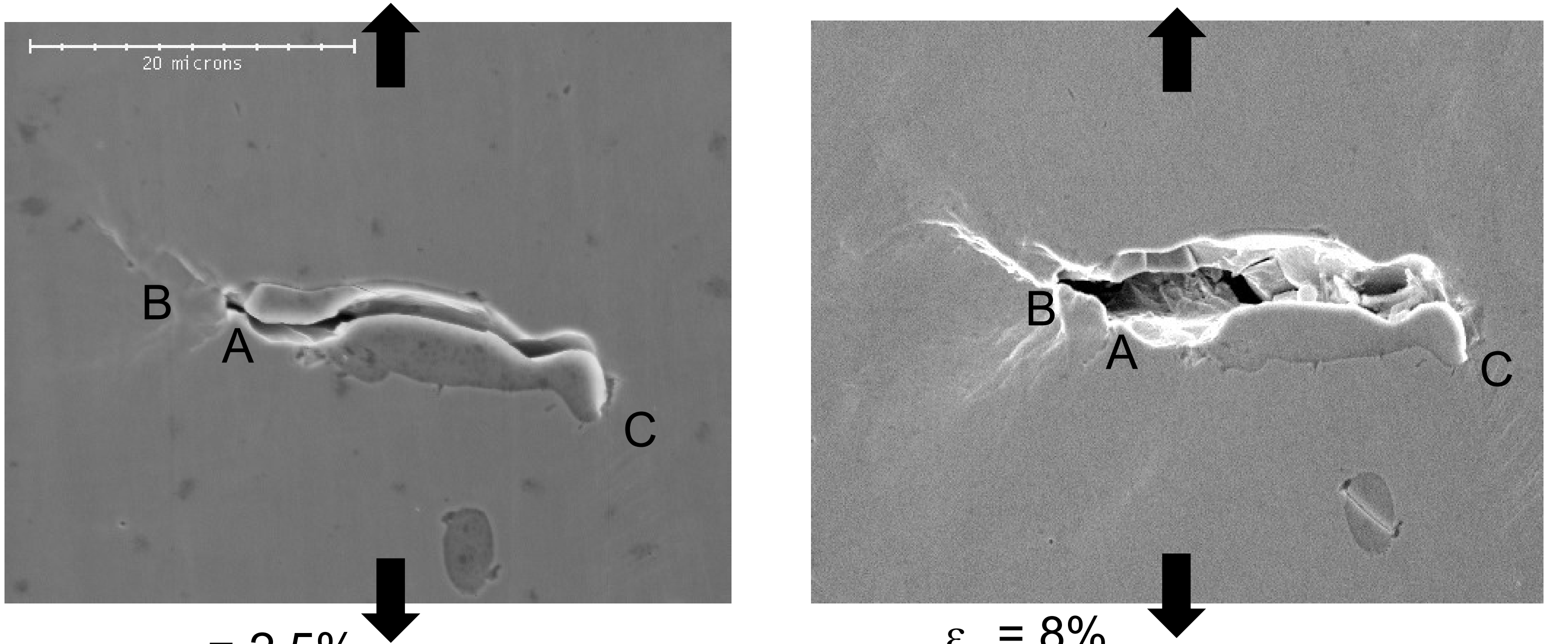
H.V. Viehrig et al. Nucl. Engi. Des. 212 (2002) 115-124

☞ Data scattering persists in post-irradiated conditions

Micro-crack initiation



Resistence to micro-crack growth



$\varepsilon_p = 2.5\%$ $\varepsilon_p = 8\%$

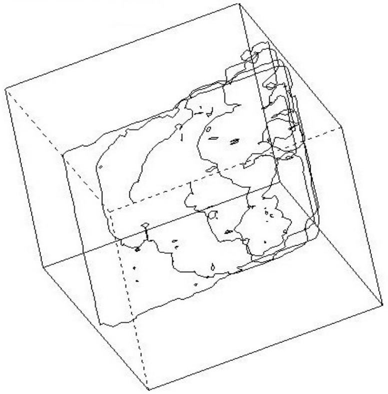
- Position A: poor resistence to crack growth (RCG) → few, thick shear bands, as crack A→B
- Position C: strong resistence to crack growth → numerous, thin shear bands

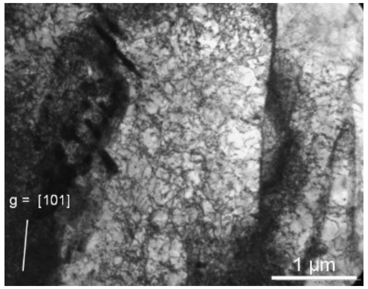
- Plastic strain spreading <u>in the matrix</u> controls the materials Resistence to Crack Growth (RCG)
- Dose-dependent evolutions in the matrix → dose-dependent RCG

Dislocation dynamics simulations?

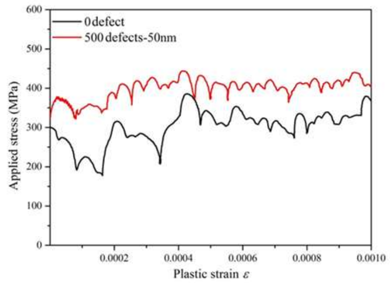
Q. Investigation of dose-dependent changes of plastic strain spreading?

Hard grain boundaries





$\varepsilon_p = 8\%$



Stress-strain response

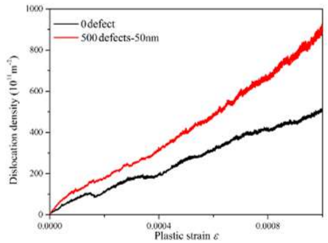
Initial FR sources

Tensile applied load

Quasi-static loading

Strain-rate controlled

DD code: dislocation mobility, multiplication, cross-slip, etc



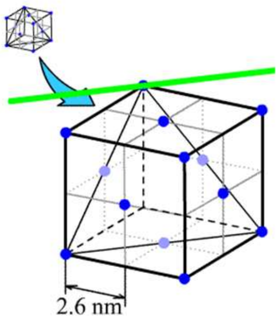
Dislocation structures

Post-Processing

Surface displacements
Local stress fields

« TRIDIS » code

Model. Simul. Mater. Sci. Eng. 6 (1998) 755-770



Discrete screw/edge lines
Discrete time step: 10^{-10} s
Discrete positions

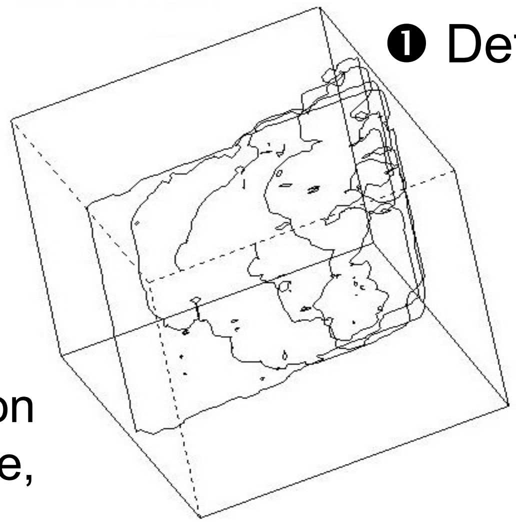
DD simulation setup

1μm³ ferritic grains (Fe-C or Fe-Cr):

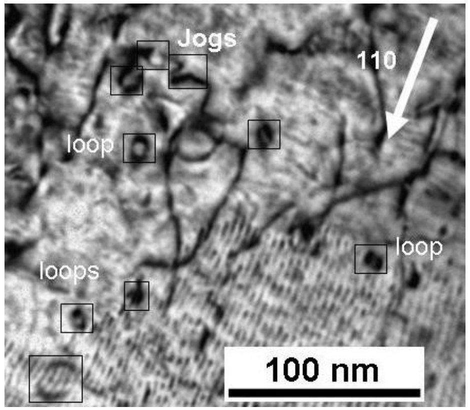
- Defect number density and defect size depend on selected dose and T_{irr} condition
- Uni-axial tension, strain-rate controlled conditions, fixed straining T°, presence of cross-slip

- **Model INPUTS**: grain size, kink-pair activation energy, phonon drag coefficient, irradiation defect size, and number density

❶ Defect-free

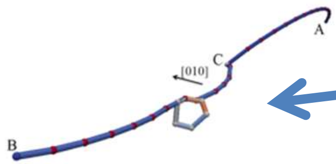


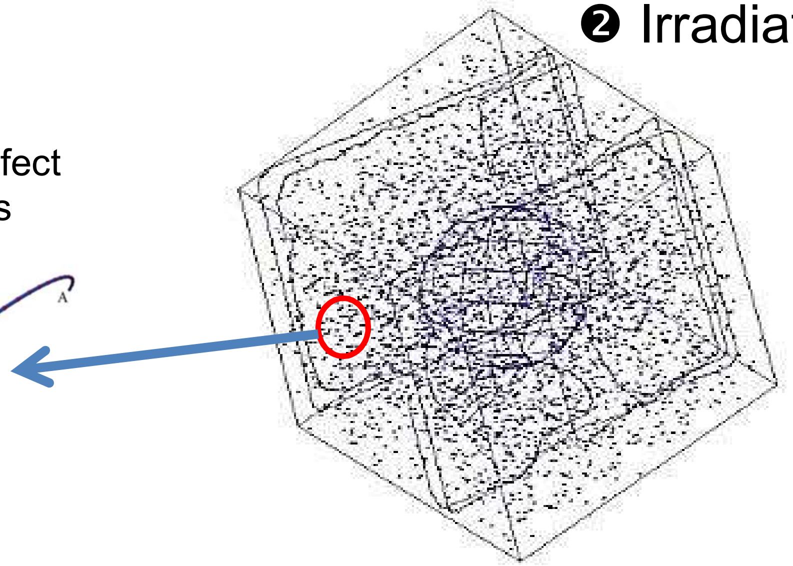
❷ Irradiated



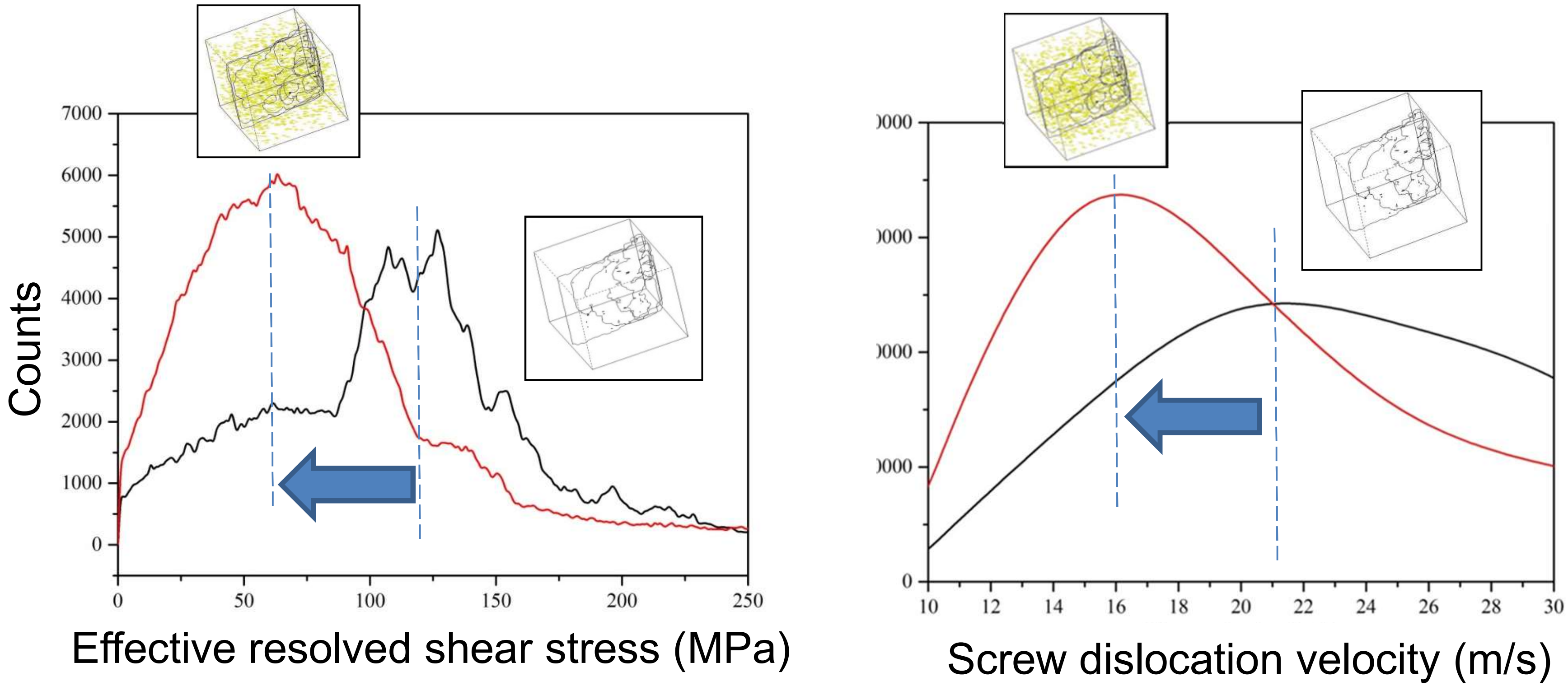
T_{irr}=400°C, dose = 1 dpa, defect size D = 50 nm

dislocation/defect interactions



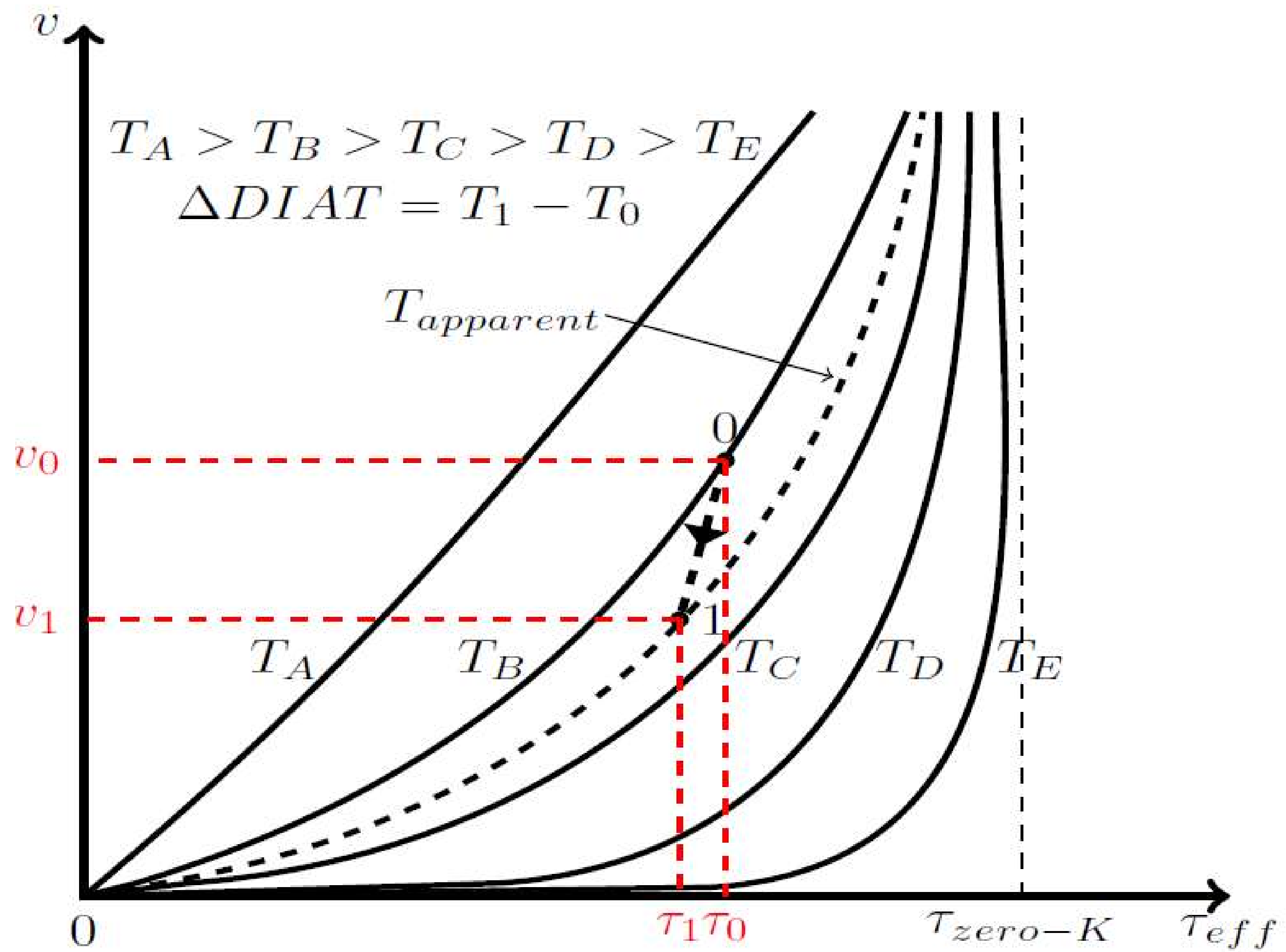


Predicted defect-induced evolutions



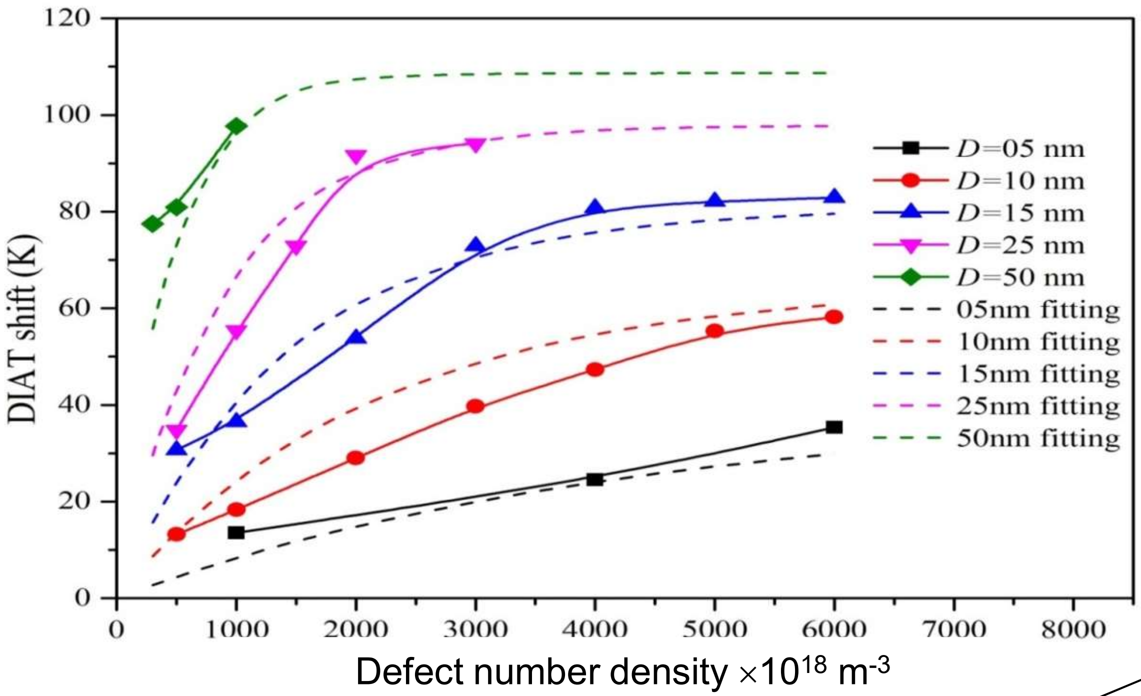
- Defect-induced effect on effective screw dislocation mobility : **statistically significant.** Why it matters?

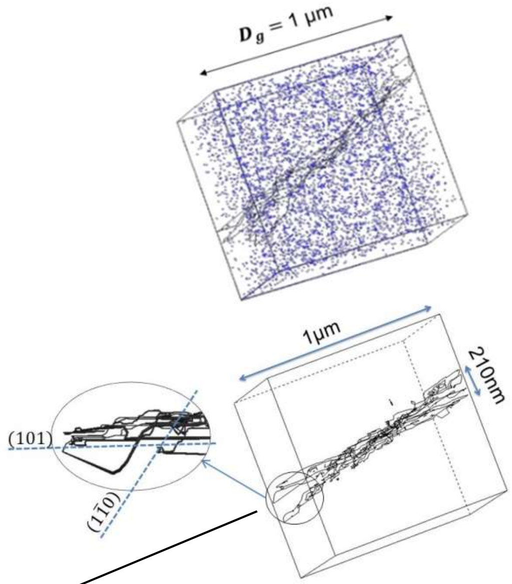
DIAT shift: interpretation



$T_{apparent} - T_0$ = Defect-Induced Apparent straining Temperature shift (ΔDIAT)

ΔDIAT: a systematical investigation





$$\Delta\text{DIAT} = \Delta T_{max}\left(1 - exp\left(-\frac{D}{\lambda}\right)\right)\left(1 - exp\left(-\boldsymbol{d}^2 DN\right)\right) \approx \Delta\text{DBTT}$$

N: defect number density (in nm^{-3}); D: defect size (in nm);
3 material-dependent scaling parameters (ΔT_{max}, d and λ)

ΔDIAT: a simple, predictive DBT shift indicator

$$\Delta \mathrm{DBTT} \approx \Delta \mathrm{DIAT} = \Delta T_{max} M$$

$\Delta T_{max} \rightarrow$ first principles elasticity theory & **dislocation statistics**

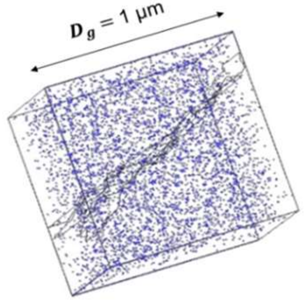
ΔH_0 (Joules)
$\tau_{Peierls}$ (MPa)
μ (MPa)
B (MPa.s)
T_0 (K)
[n] and D <u>at saturation</u>
effective τ_1(Orowan)
effective τ_0 (at T_0 = 300K)

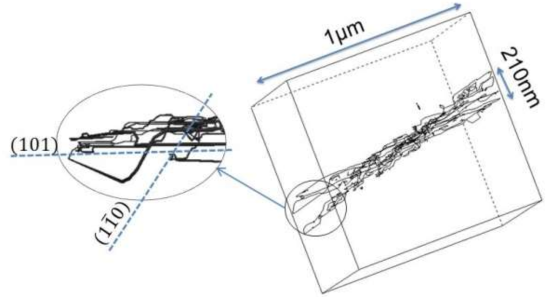
No adjustable variable/parameters

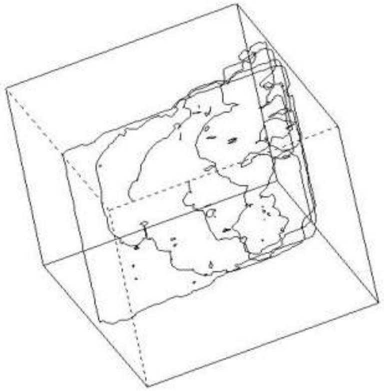
$0 < M < 1$:
dimensionless «mitigation» term

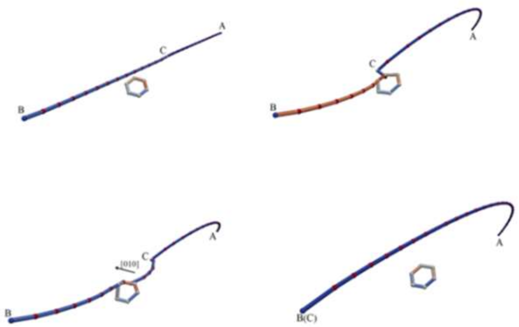
$M \propto$ «stress landscape» associated with shear band structures

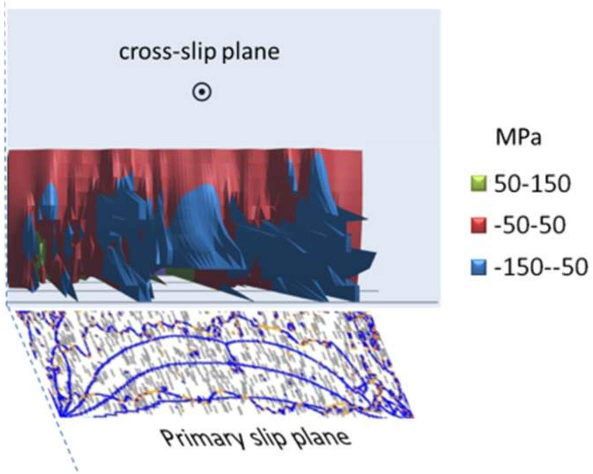
Controls cross-slip activity → *effective* defect interaction strength (τ^*) and dislocation length (X')





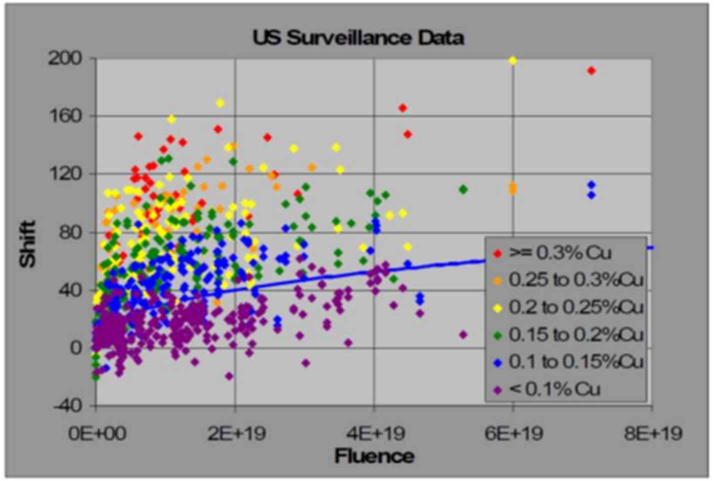






ΔDIAT/ΔDBTT comparison: data collection

Dose-dependent DBT shift



Williams, 2005 (ISQUID)

Defect number density

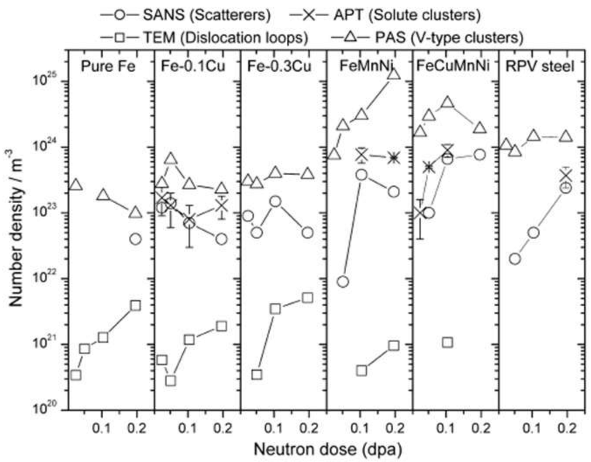
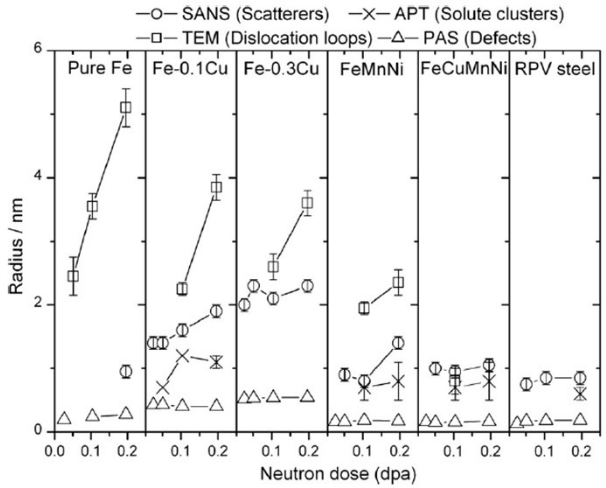


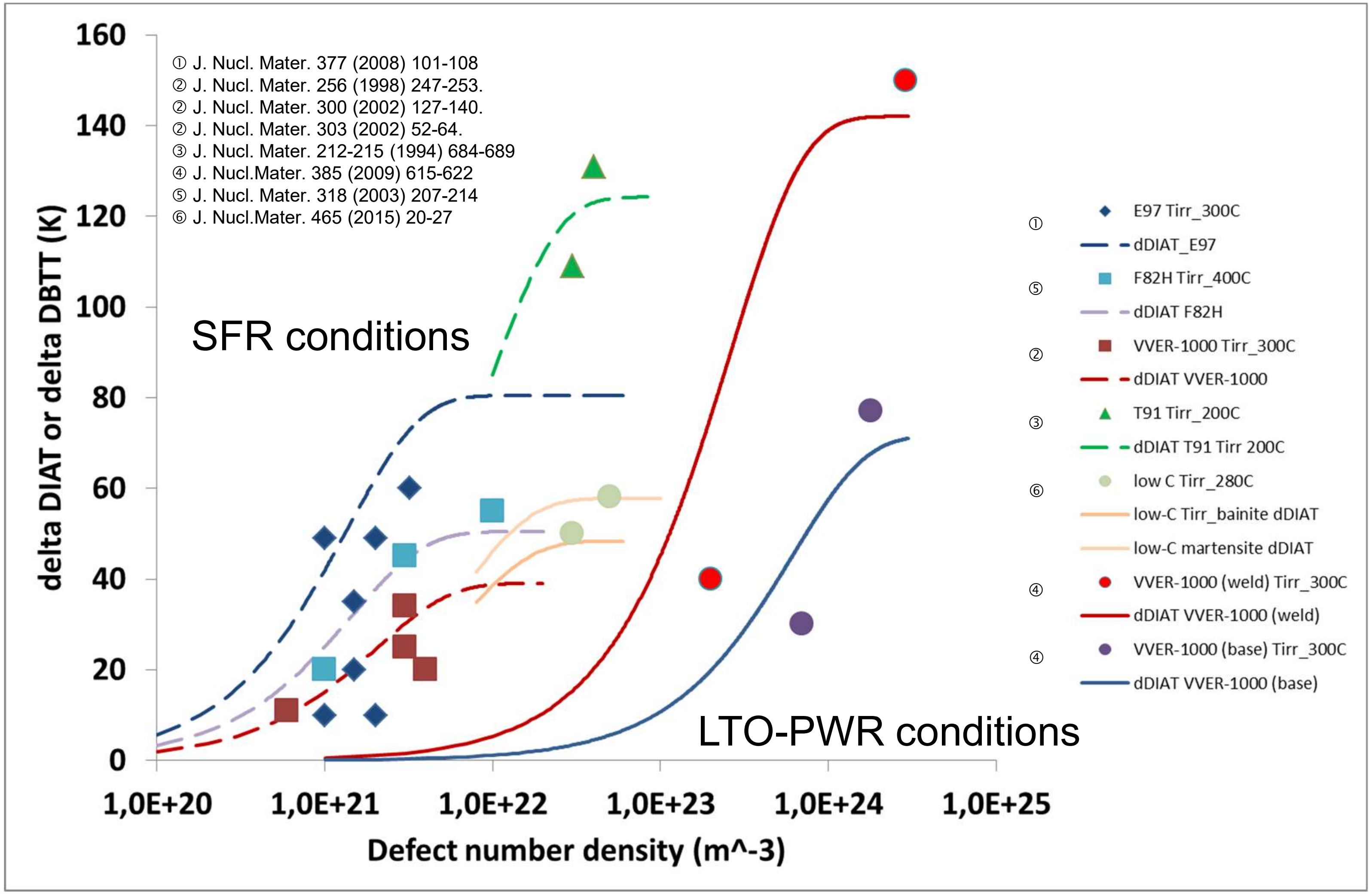
Fig. 3. Number density of radiation-induced damage as functions of dose from APT, SANS, TEM and PAS measurements.

Defect size



Journal of Nuclear Materials 406 (2010) 84-89

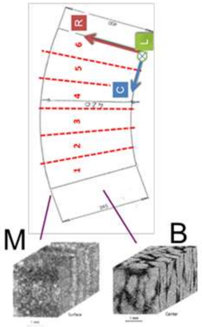
ΔDIAT/ΔDBTT comparison

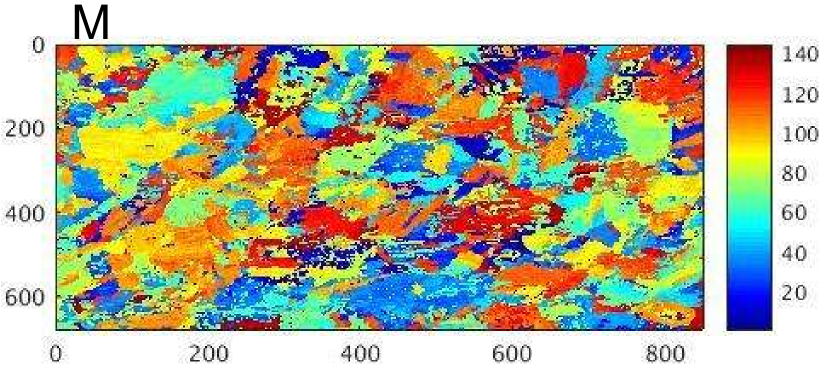


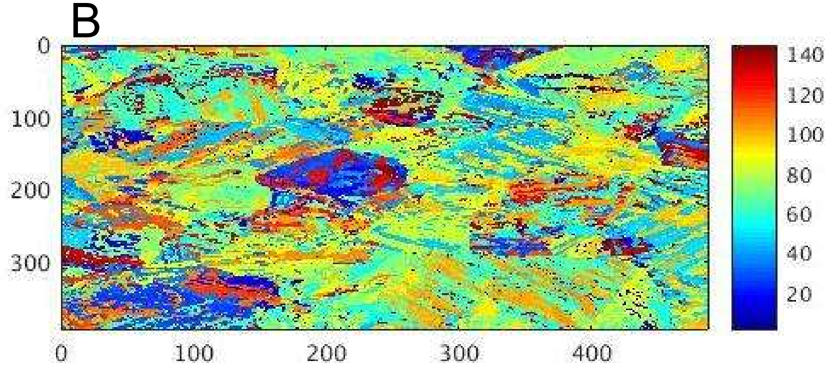
- ΔDIAT ≈ ΔDBTT [irradiation conditions: little or no segregation at fracture initiators (particles or GB)]
- Absolute toughness levels: link with local approach of fracture/MIBF approach/models
- Support/link dose-dependent crystal plasticity…

IV-Application: post-irradiation fracture response analysis of 2 model materials

EBSD: grain orientation maps ☞ 2 model materials (Martensite&Bainite), same chemical composition

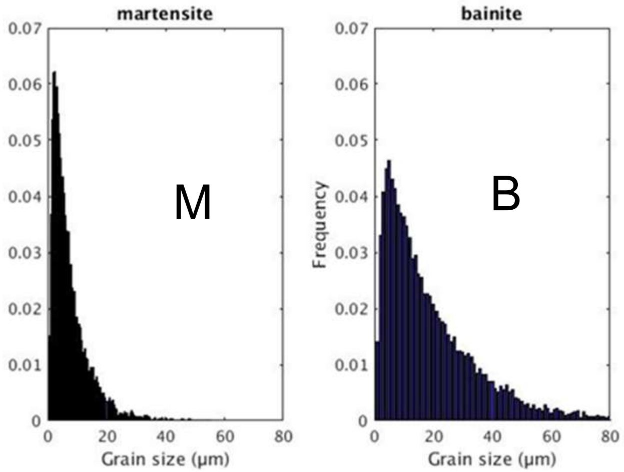






B. Marini etal. JNM 465 (2015) 20-27

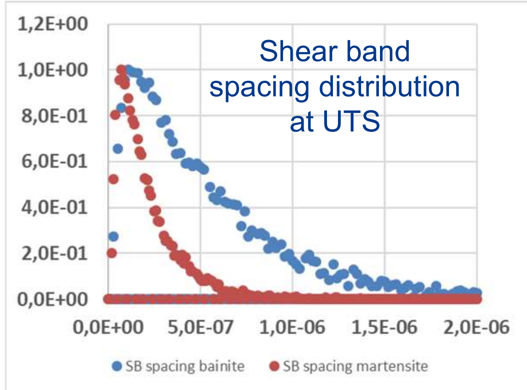
Grain size/orientation distributions

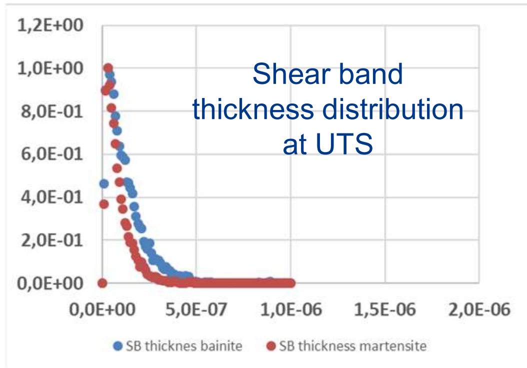


Neutron irradiation

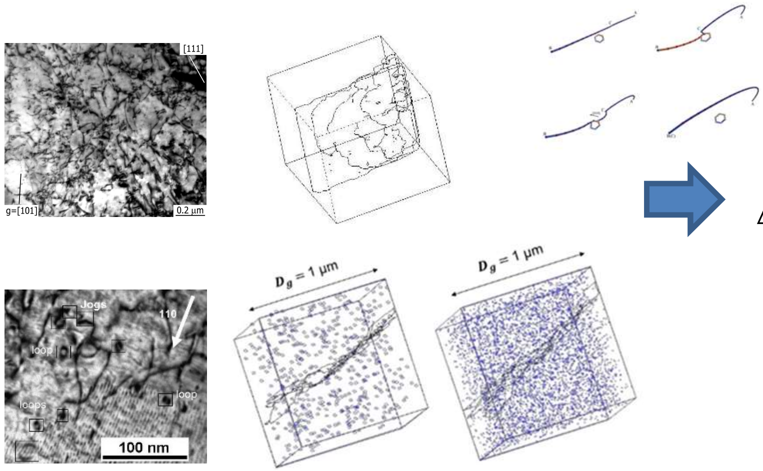
0.1 dpa, 290°C

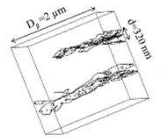
Defect size & number density





IV-Validation: DIAT/DBTT comparison

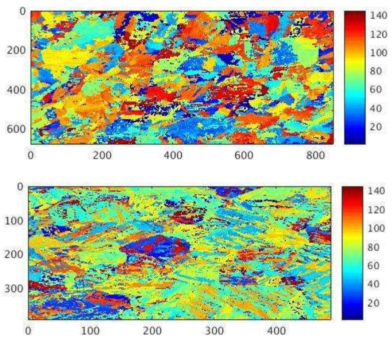


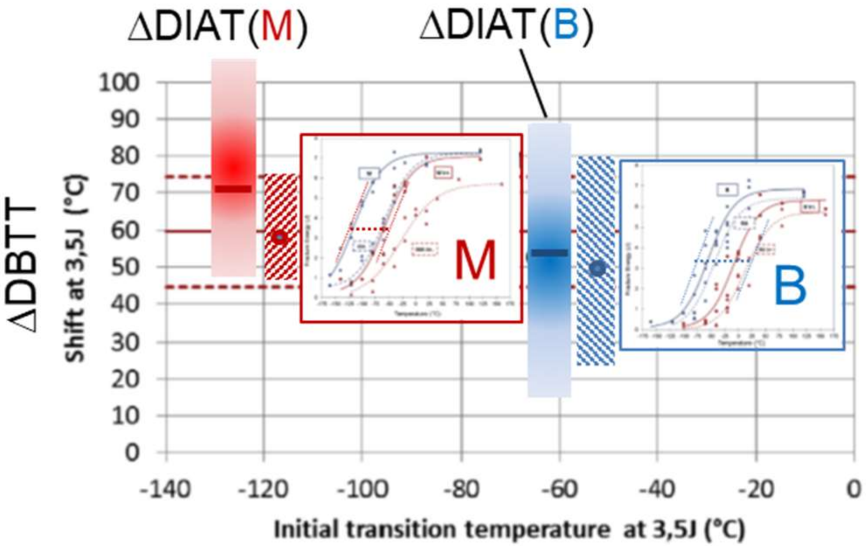


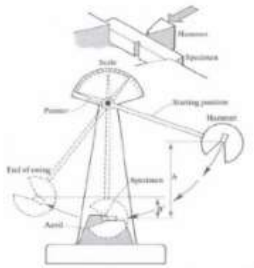
$$\Delta \mathrm{DIAT} = \Delta T_{max}\left(1 - exp\left(-\frac{D}{\lambda}\right)\right)\left(1 - exp\left(-d^2 DN\right)\right)$$

M

B



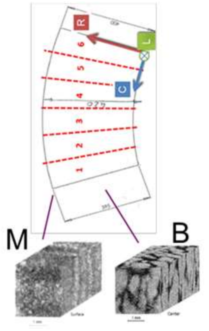




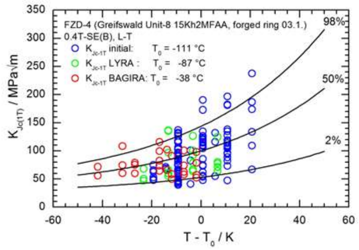
☞ DIAT: estimation de la fragilisation induite par l'irradiation / mesures non-destructives

SUMMARY

RPV steel forgings include different position-dependent microstructures



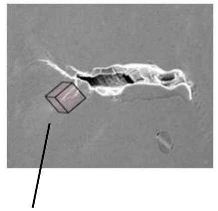
Initial RPV steel heterogeneities ↔ fracture data scattering, in both as-received and post-irradiated conditions



Dose-dependent fracture response evolutions: DIAT concept

☞ ΔDIAT level characterizes plastic strain spreading around micro-crack initiators (inclusions or GB)

☞ΔDIAT ~ ΔDBTT in a broad range of irradiation conditions (defect size and number density)



$$\Delta\text{DIAT} = \Delta T_{max}\left(1 - exp\left(-\frac{D}{\lambda}\right)\right)\left(1 - exp(-d^2 DN)\right)$$

Evaluation of dose-dependent fracture response using non-destructive testing

☞ Time and cost effective procedure; support to conventionnal surveillance programs

☞ Adapted to actual, heterogeneous structural materials, including weld joints

Thanks for your attention

Questions?

Dislocation stress-velocity response

FCC models (Cu, FCC Fe)

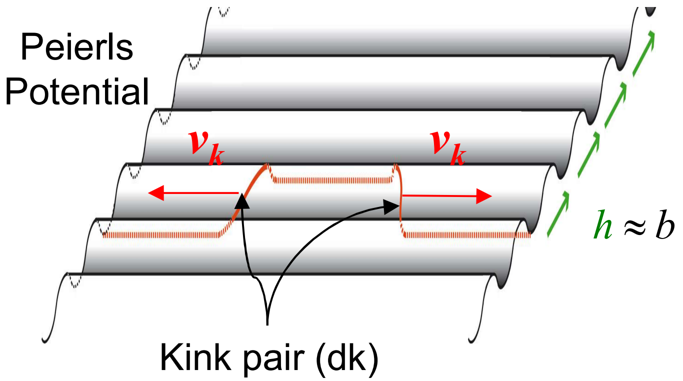
Screw ~ Edge

Negligible Peierls barrier (τ_p~10 MPa)

Phonon-drag mechanism

$$v_{screw}(\tau) = v_{edge}(\tau) = \frac{\tau b}{B}$$

- τ : applied stress >> τ_p
- ***B*** : Viscous drag coefficient
- ***b*** : Burgers vector module
- τ_p : Peierls Stress



BCC Fe and Fe alloys

Screw ≠ Edge

Velocity anisotropy depends on T°

Low temperature	High temperature
Significant Peierls barrier (τ_p~1GPa)	**Athermal** regime

Low temperature: Significant Peierls barrier (τ_p~1GPa)

Thermally activated mobility

$$v_{screw}(\tau, T) \ll v_{edge}(\tau) = \frac{\tau b}{B}$$

High temperature: **Athermal** regime

$$v_{screw} \approx v_{edge}$$

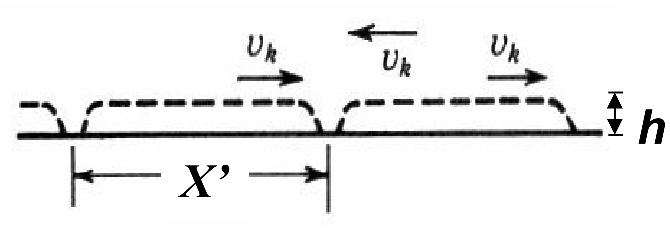
Low-T screw dislocation mobility mechanism

- **Nucleation** of a kink pairs (thermally activated)
- Kink pair **propagation** $v_k \propto \tau$ « effective » $B_k < B_{edge}$

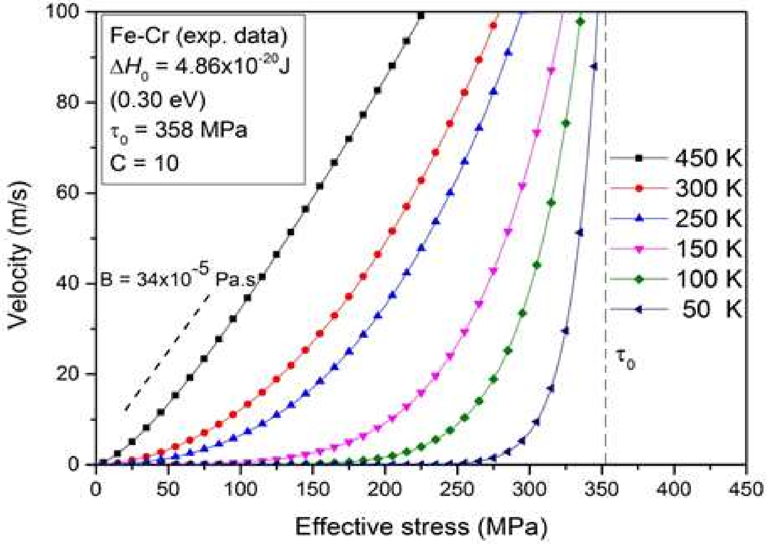
Dislocation mobility rules for RPV steels

Journal of Nuclear Materials 504 (2018) 84-93

$$v_{screw} = hJX'$$



- h : distance between Peierls valleys
- J **[m^{-1}s^{-1}]** : kink pair **nucleation rate** per unit length
- X' **[m]** : kp **mean free path** before annihilation with another dk [increases with kink velocity (v_k) and decreases with J]



$$v_{screw}(\tau^*, T) = \underbrace{\frac{8\pi b(\tau^*)^2}{\mu B h}}_{} X' \exp\left(-\frac{\Delta G(\tau^*,T)}{k_B T}\right)$$

Stress-dependent pre-factor

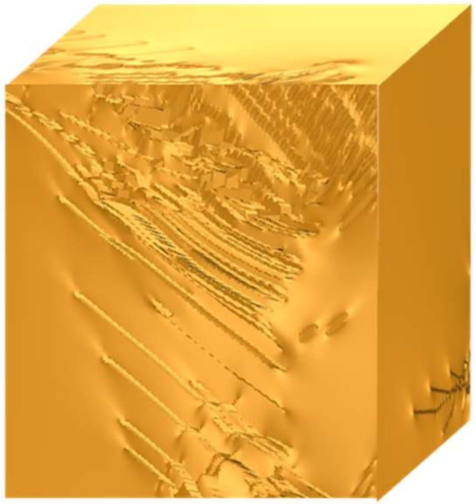
☞ **Progressive transition from Low-T to Room-T**

ΔDIAT: a simple, predictive DBT indicator

Stress landscape ↔ shear band spreading

Grain size and grain orientation
Dose-dependent τ_{YS} (MPa)
Strain per shear band
[n] and D <u>at considered dose, irradiation-T°</u>
Defect strength (MPa)
Dislocation accumulation rate with ε_p

Shear band spacing and thickness: micro-model based on **DD simulation results**



Micro-model validation based on comparison with experimental observation of strained specimens