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CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

Effect of Irradiation-Induced Flow Localization on the Ductile Crack Resistance of a 9%Cr-Ferritic/Martensitic Steel

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Preliminary Remark / Outline

- Plastic instability / Flow localization (macroscopic)
- Dislocation channel deformation (microscopic)

Irradiation-induced Flow Localization (**IFL**)

=

flow localization

+

dislocation channel deformation

OUTLINE

Introduction → Tensile → J-R curve → SEM →Conclusions

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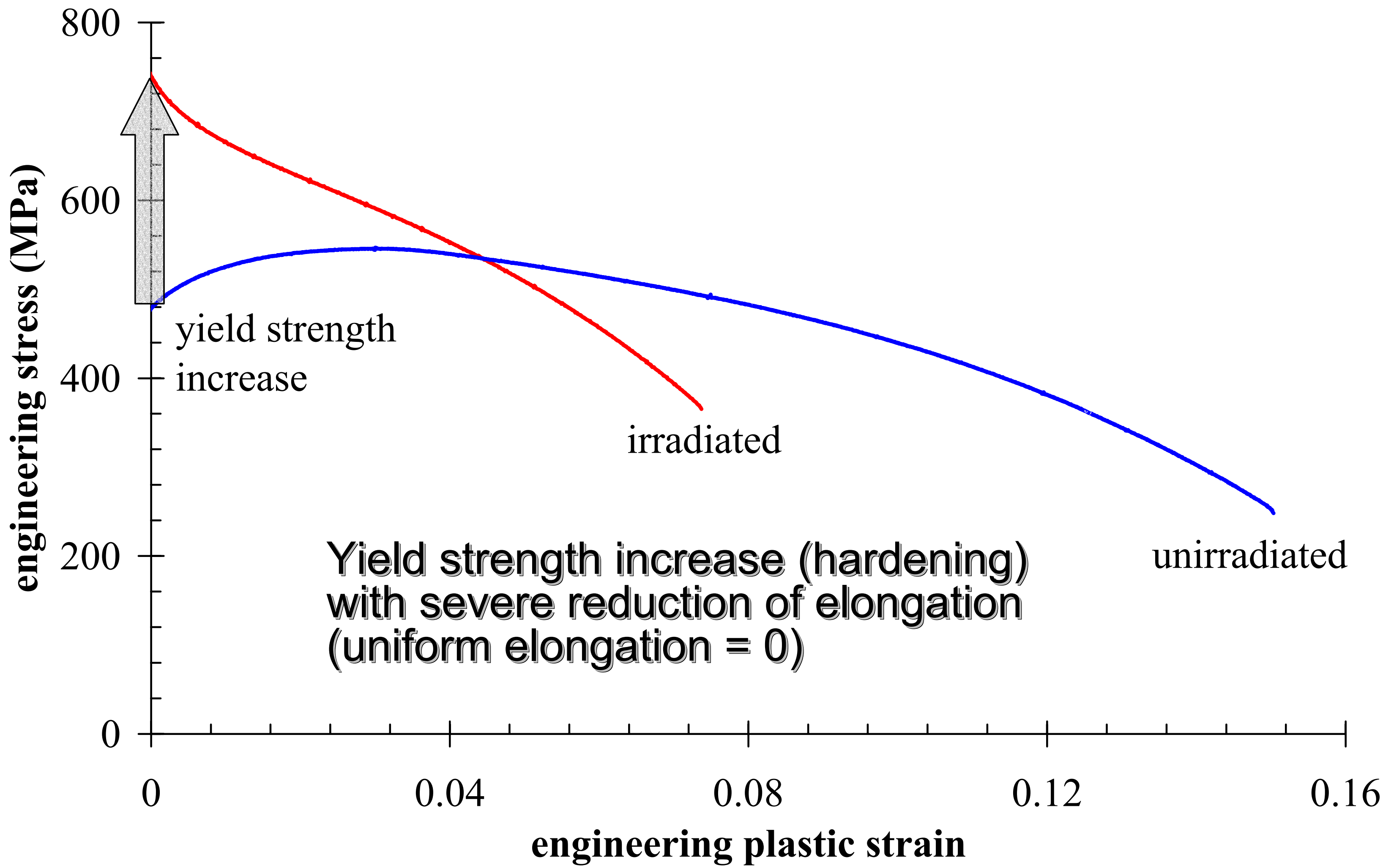
IFL Phenomenon

- **Macroscopic**
  - ⇨ usually observed at low T_{irrad}
  - ⇨ tensile test: severe reduction of uniform elongation (drastic loss of work hardening capacity) → example
- **Microscopic**
  - ⇨ TEM observation of “cleared” channels in which deformation occurs in narrow “reduced defect density” bands

☞ **deformation does not occur in a homogeneous manner but, rather, restricted to a localized region (leading to premature fracture)**

☞ **Question : what does a crack in such an environment ?**

Flow Localization Monitoring



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Experimental

- material: EUROFER-97
  - ⇨ 9-%Cr-ferritic/martensitic steel used within the Fusion Material Program
- irradiation in the BR2 reactor
  - ⇨ conditions: T_{irrad}=300°C ; Φ=0.3 – 2 dpa
- testing
  - ⇨ tensile testing (at 10^{-4} s^{-1}) at $T_{test}=T_{irrad}$
  - ⇨ 3-point bend testing using 20%-side grooved PCCv (precracked Charpy specimens) for crack resistance determination at $T_{test}=T_{irrad}$

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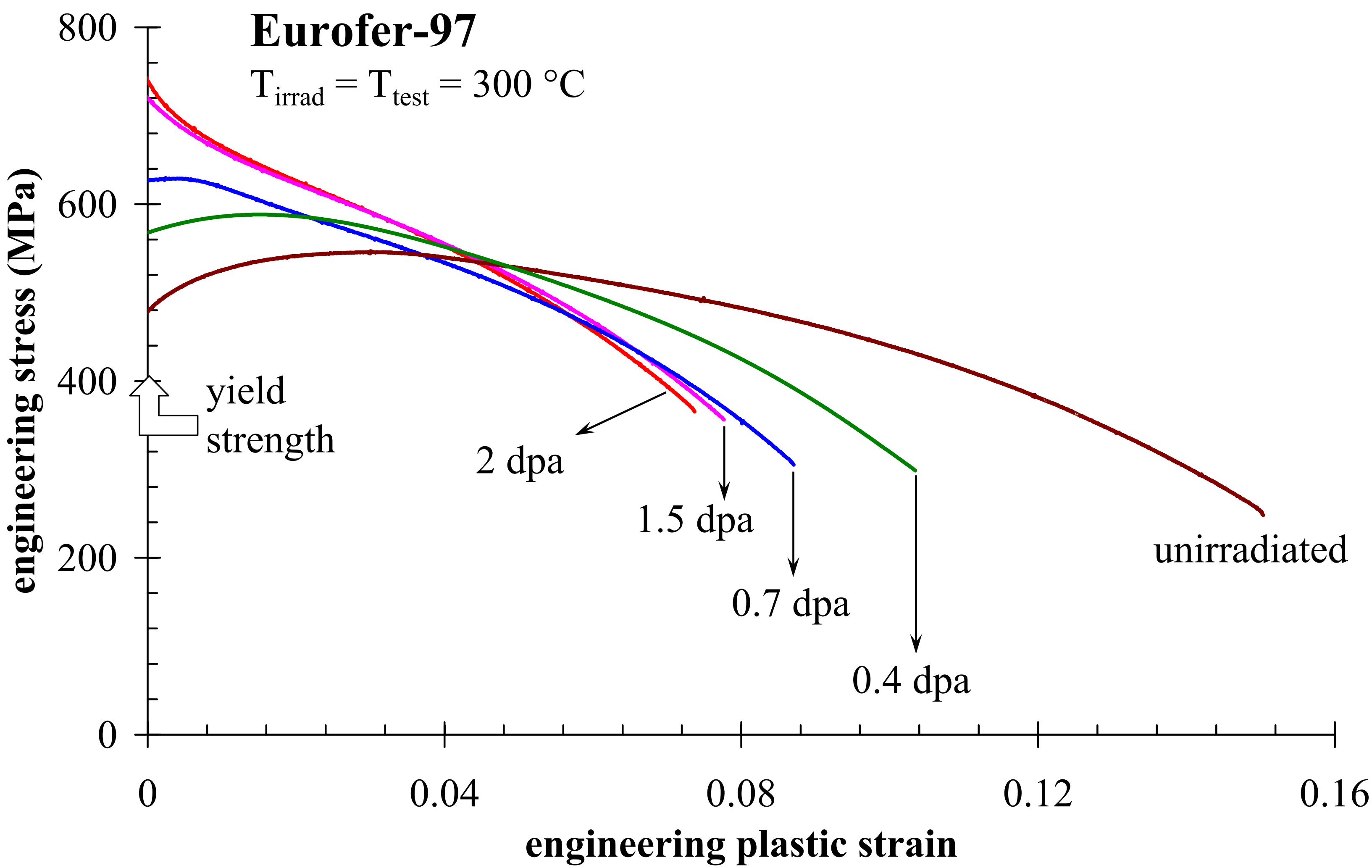
Dose Effect on the Tensile Curve



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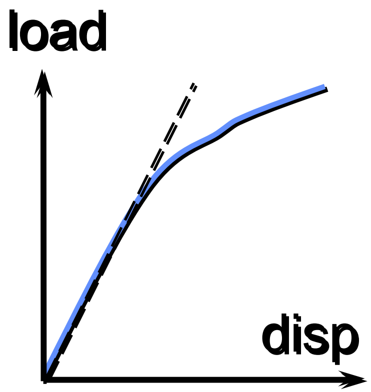
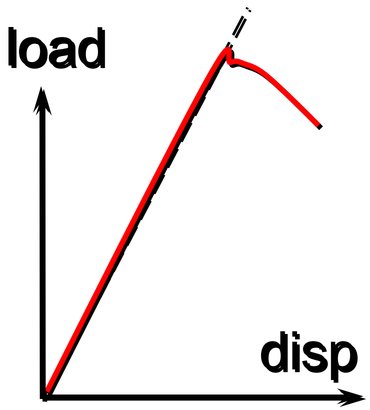
Tensile Properties

- Yield strength increase roughly as (neutron dose)$^{1/2}$
- Above ~1 dpa, no uniform elongation (work hardening drops to 0)
- Post-necking elongation is little affected by irradiation (13% to 9%)

Deformation Mode
3D versus 2D



unirradiated material: dislocations induced by plastic deformation provide additional obstacles to dislocation motion ➔ work hardening (3D)



irradiated material: induced dislocations remove irradiation defect clusters facilitating subsequent dislocation motion in a narrow cleared channel bands ➔ dislocation channel deformation (~2D)

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Flow Stress Description

$$\sigma_{flow}(\dot{\varepsilon},T,\varepsilon) = \sigma_y(\dot{\varepsilon},T) + \Delta\sigma_\varepsilon(\dot{\varepsilon},T,\varepsilon)$$

$$\Delta\sigma_\varepsilon = \alpha\,\mu\,b\,M\sqrt{\rho}$$

$$\frac{d\rho}{d\varepsilon} = \left.\frac{d\rho^+}{d\varepsilon}\right|_{stored} - \left.\frac{d\rho^-}{d\varepsilon}\right|_{annihilated}$$

Unirradiated : positive dislocation balance ➔ work hardening

Irradiated : irradiation defects cleared by moving dislocations ➔ work hardening suppressed (material softening)

$$\sigma_{flow} = \sigma_y + \Delta\sigma_\varepsilon - \Delta\sigma_{defect\ clearing}$$

Effect of Irradiation on the Load-Displacement Test Record

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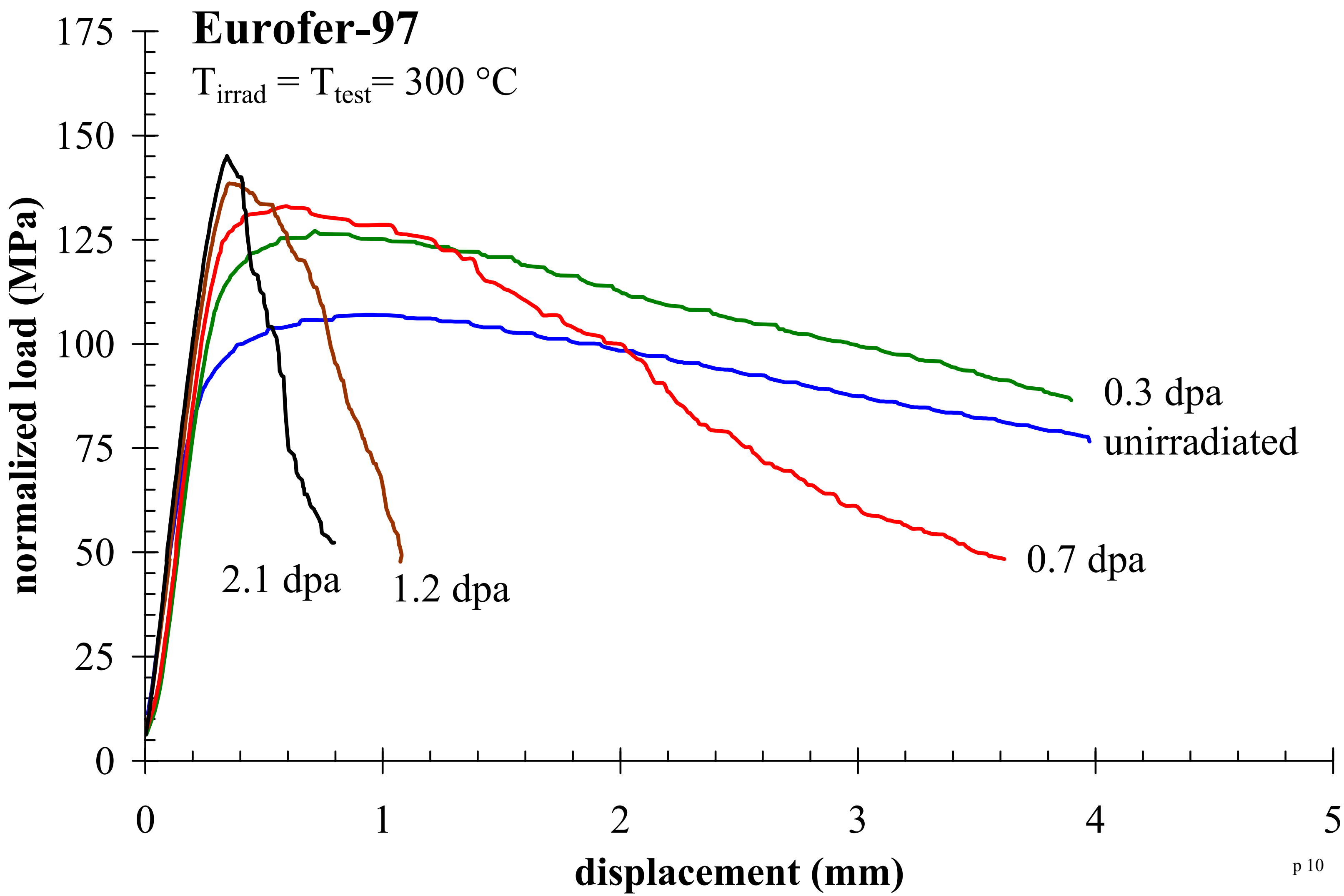
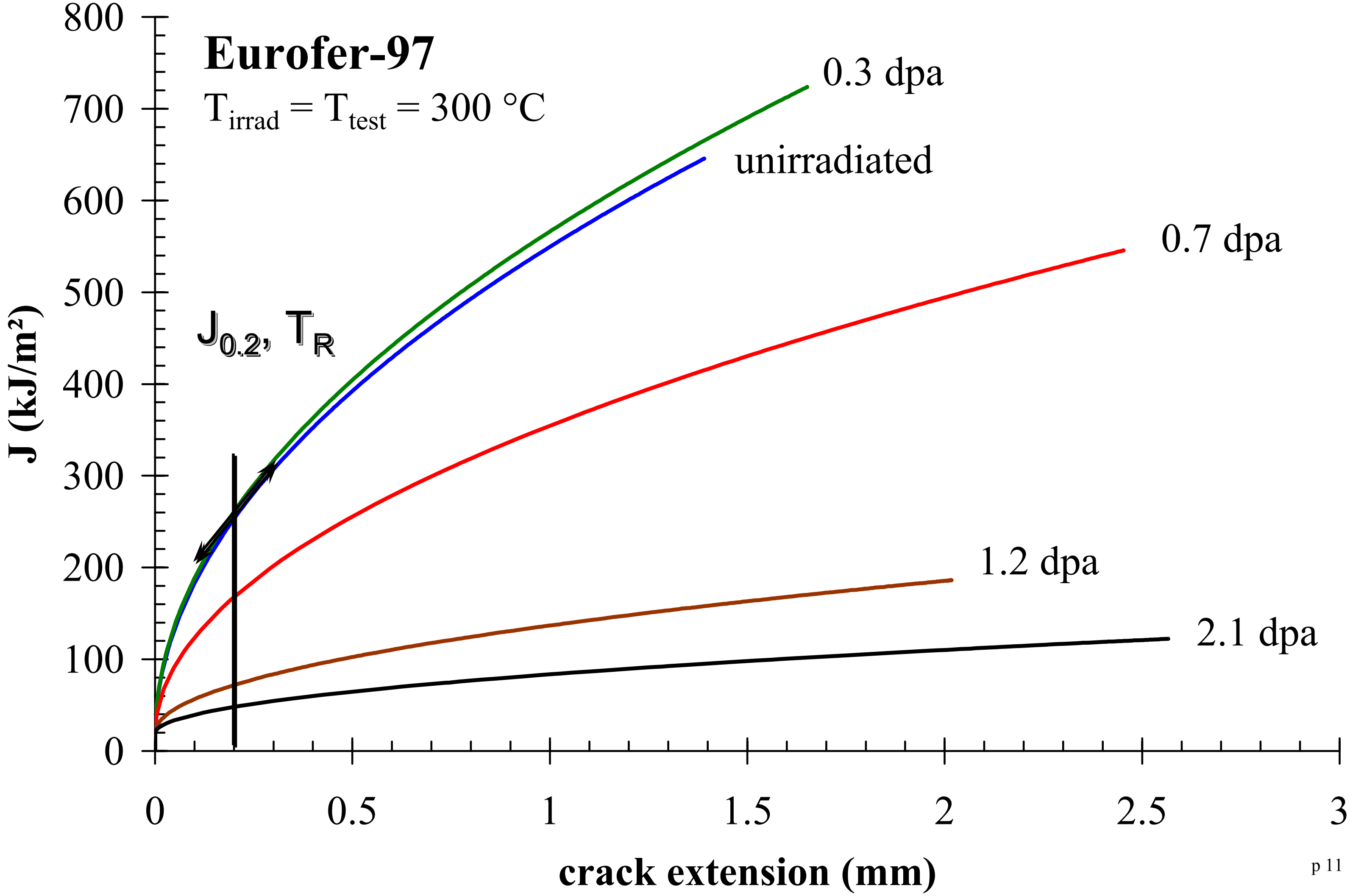
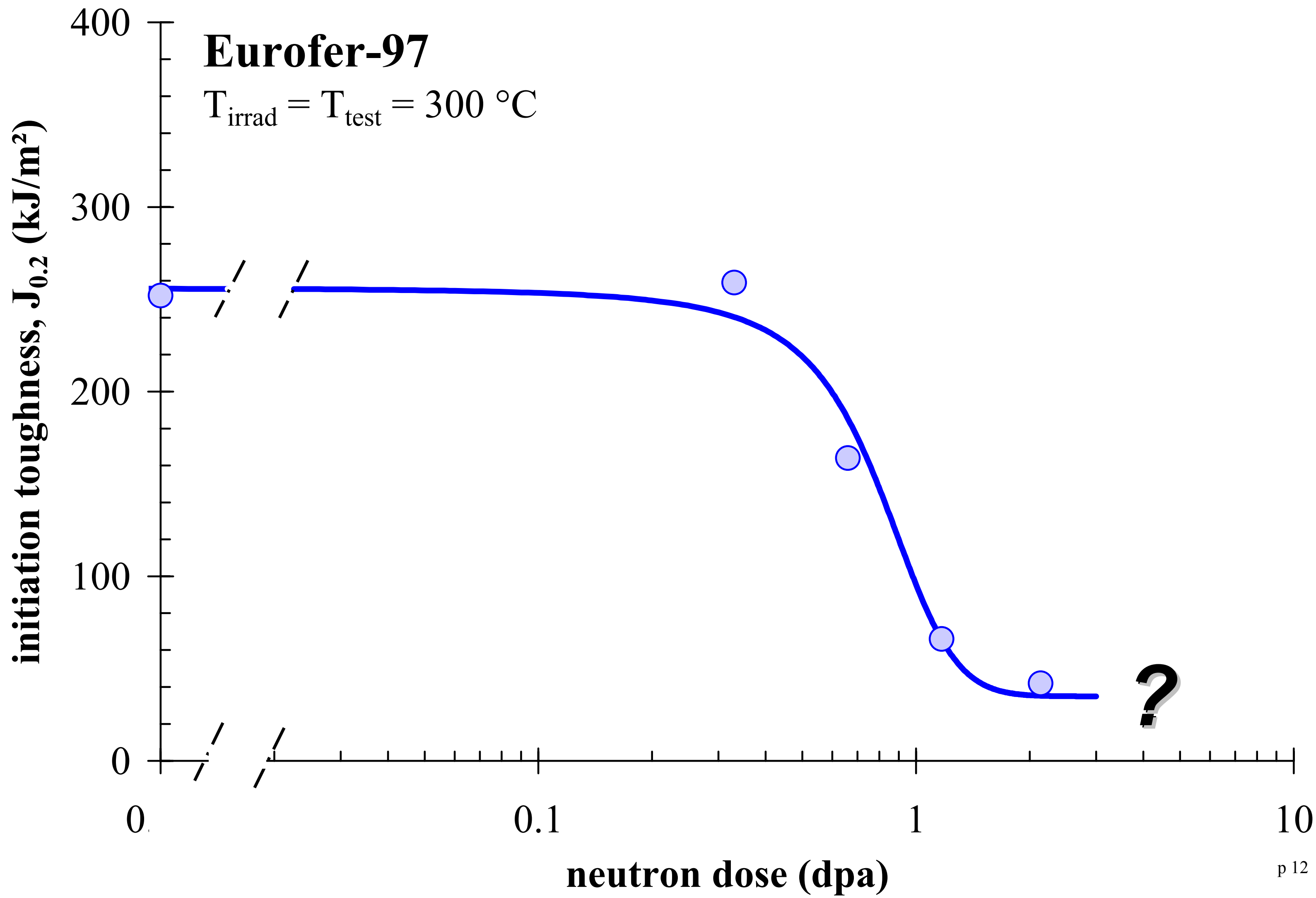


Effect of Neutron Dose on the Crack Resistance



Effect of Neutron Dose on the Initiation Toughness



Neutron Dose Effect on the Tearing Resistance

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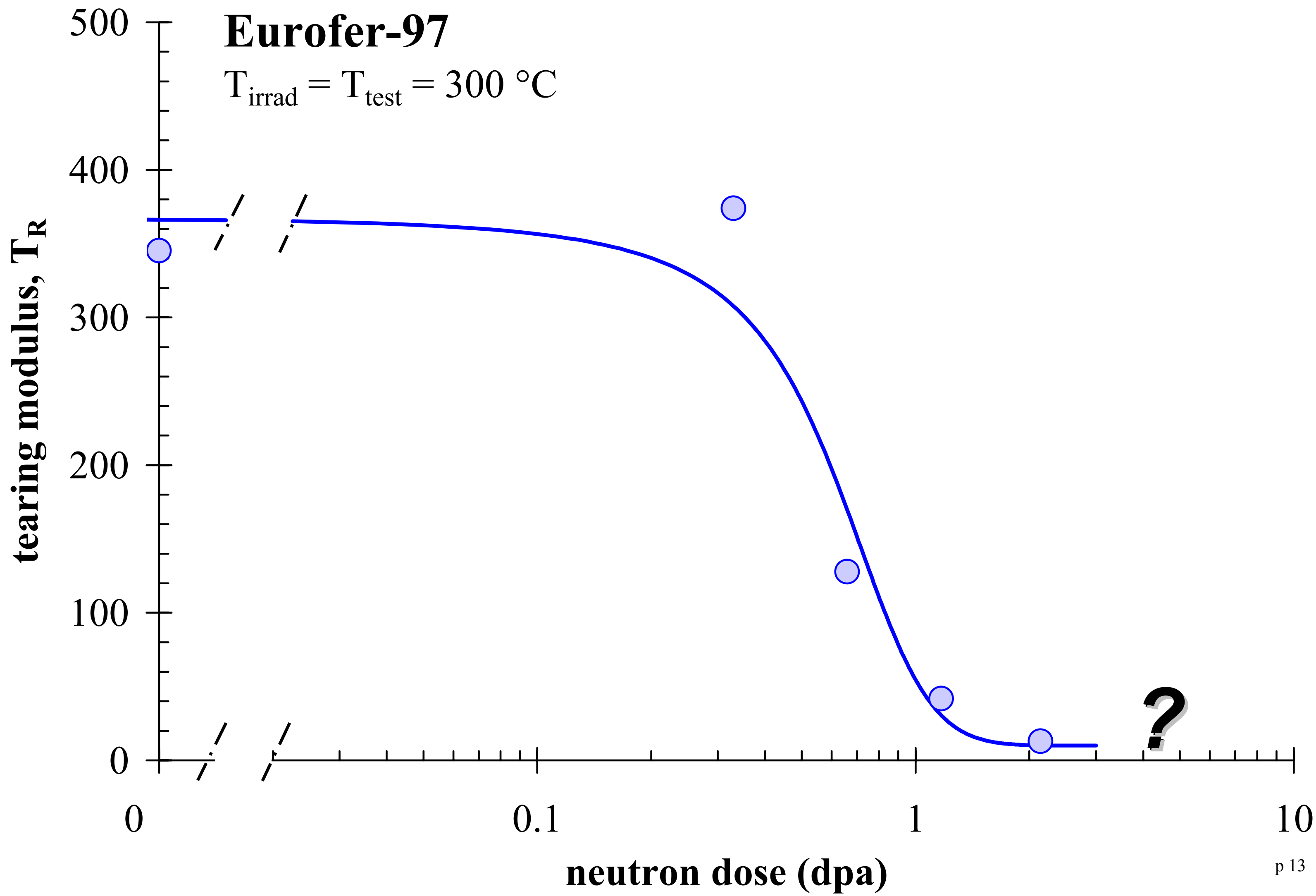

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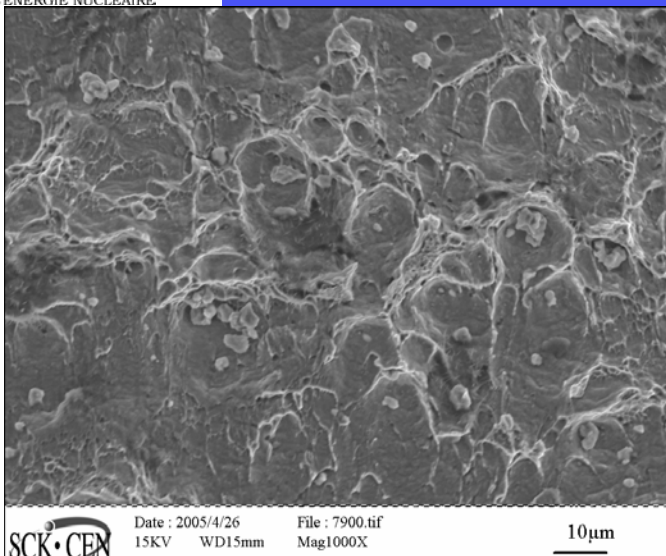
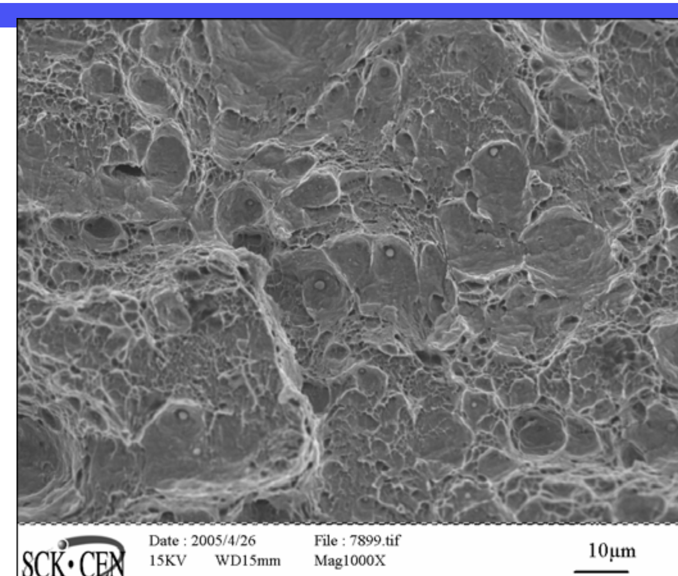
SEM Examination of the Fracture Surface

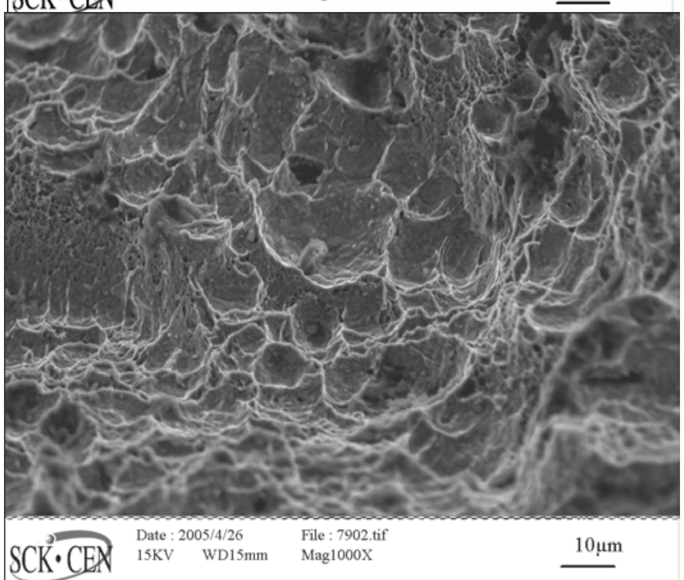
0.3 dpa



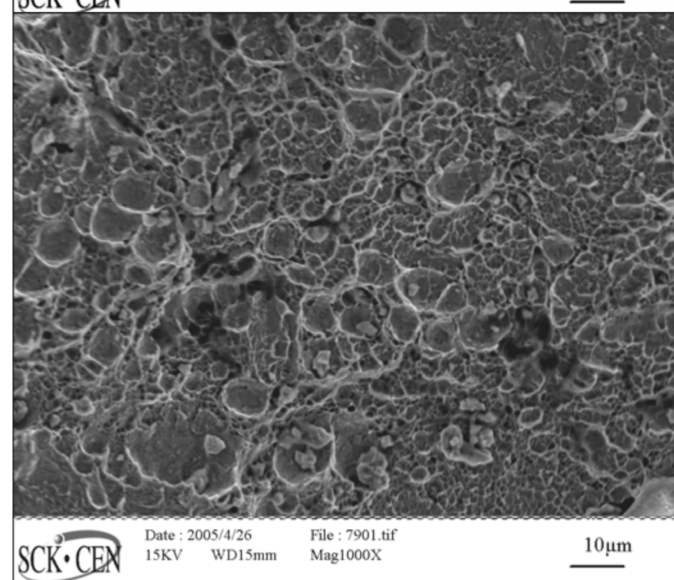
0.7 dpa



1.2 dpa



2.1 dpa



SEM Examination of the Fracture Surface

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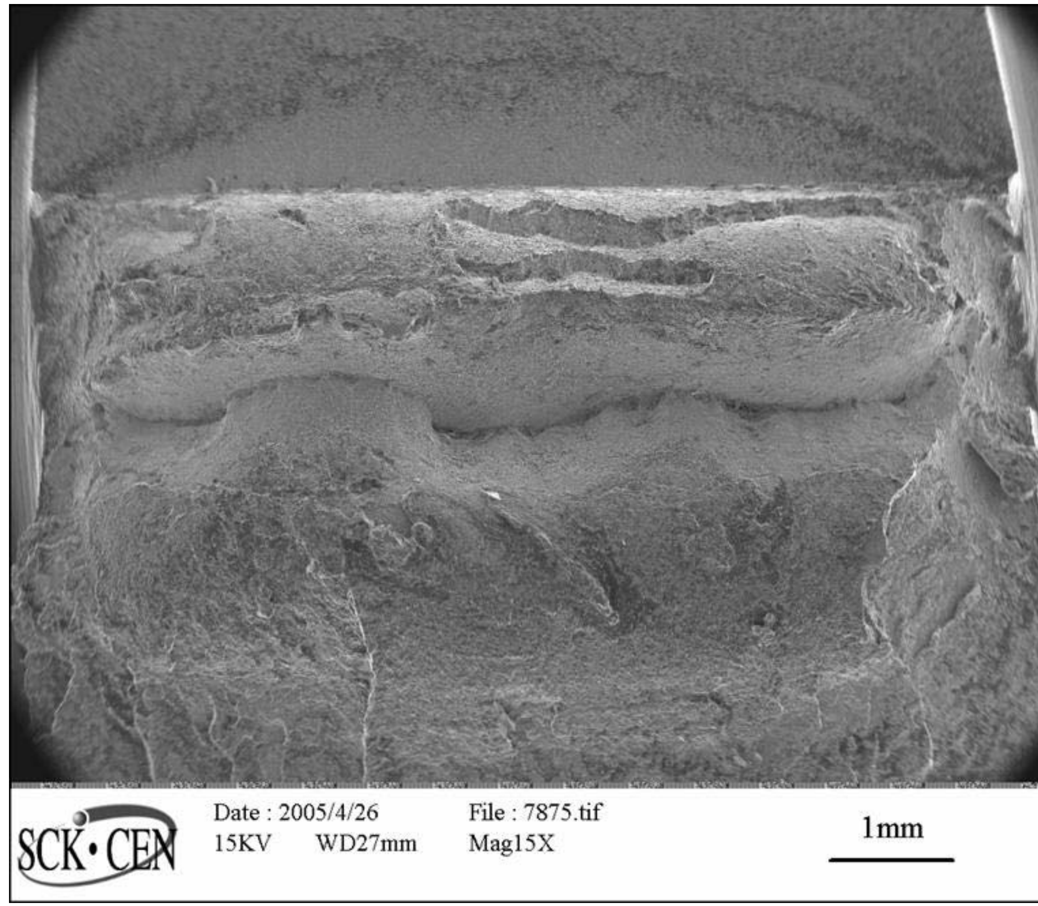
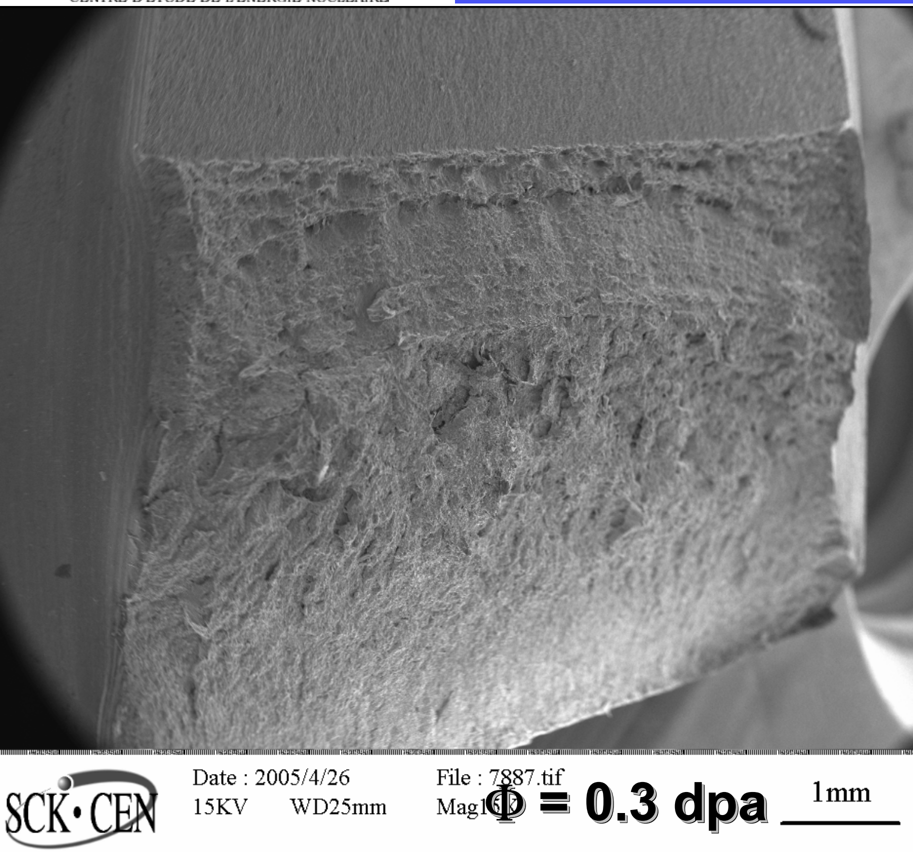
Eurofer-97

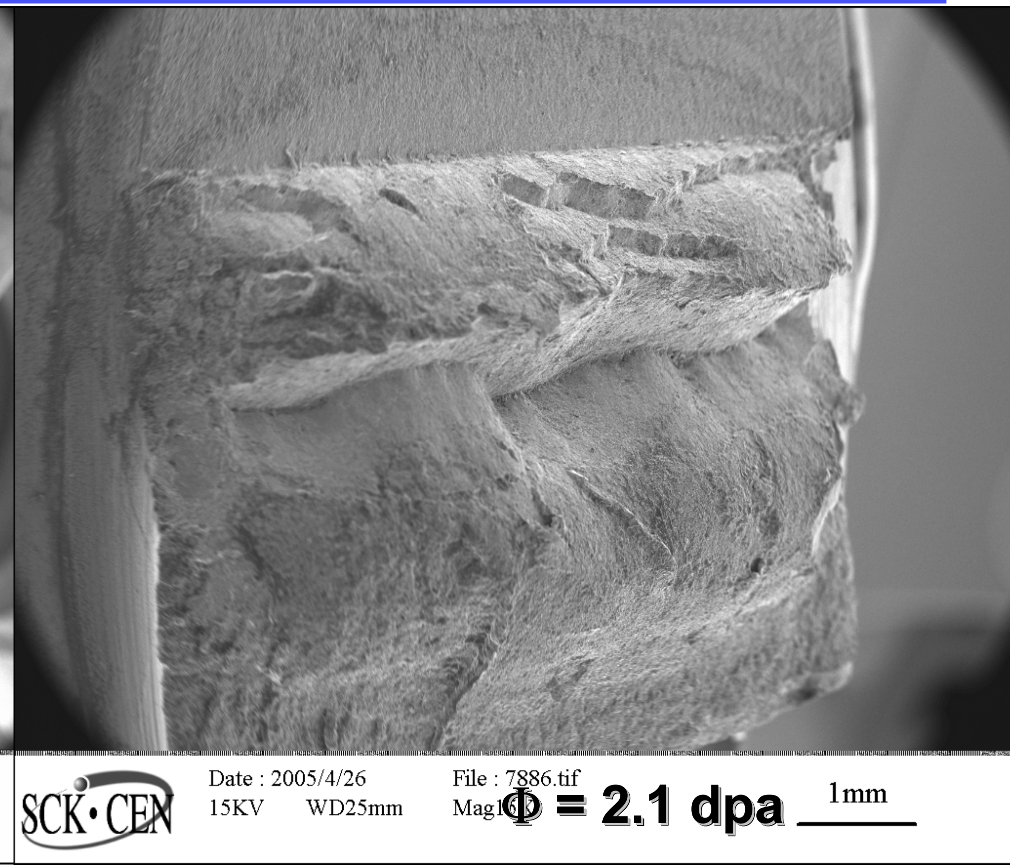
T_{irrad}=T_{test}=300°C

Φ=2.1 dpa



SEM Examination of the Fracture Surface





classical ductile fracture

jerky crack propagation along preferential planes

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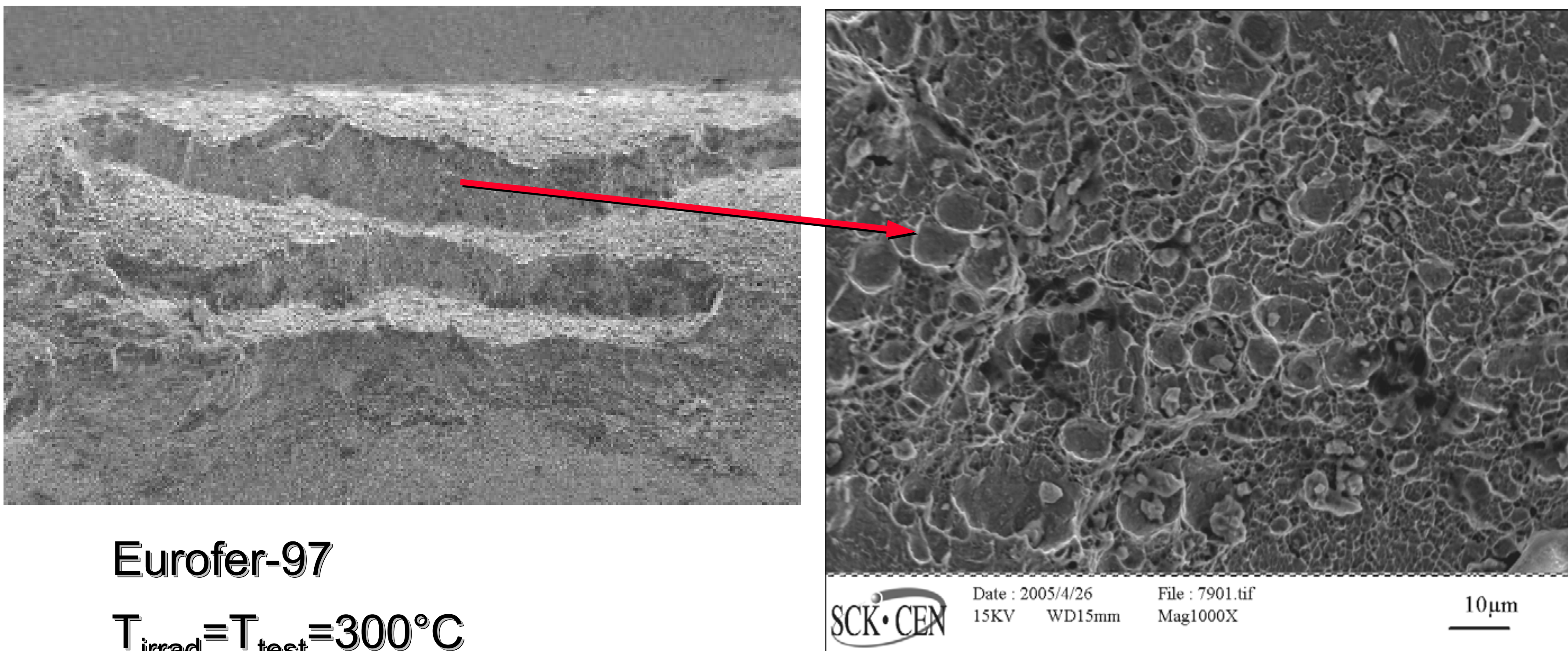
SEM Examination of the Fracture Surface



Eurofer-97

$T_{irrad}=T_{test}=300°C$

$\Phi=2.1$ dpa

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Fracture Zone Process

- **unirradiated condition**
  - homogeneous fracture process zone
  - classical ductile fracture

- **irradiated condition**
  - restricted fracture process zone where the material is highly degraded facilitating crack extension
  - fracture controlled by the **plastic strain incompatibility** in the heterogeneous process zone

  - the known microvoid coalescence process occurs in a region where plastic strain incompatibility promotes early void nucleation and accelerated coalescence

Ductile Fracture Description

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Ductile fracture mechanism

nucleation, growth and coalescence of voids around second phase particles

Unirradiated condition

Microvoid processes occur in a homogeneous process zone

$$\varepsilon_{nucleation} = f\left(\sigma_{ij}, \varepsilon_{ij}, \kappa\right)$$

κ =f(interface strength, strain incompatibility)

$$\frac{dR}{R} = \alpha \; exp\left(1.5\xi\right) d\varepsilon_p$$

ξ: stress triaxiality ratio

$$\left(\frac{R}{R_0}\right)_c \; or \; \lambda_{int\,ervoid\;ligament}$$

Irradiated : microvoid process can easily be completed because of the heterogeneity introduced by the irradiation-induced localized deformation at the boundary between the two regions

Conclusions

- **Irradiation-induced flow localization is an important issue that should be further investigated**
  - its monitoring using only a tensile test is not appropriate. Fracture toughness test is more appropriate.
  - change of deformation mode from 3D to 2D.
- **Occurrence of flow localization drastically reduces the tearing resistance**
- **Further work**
  - effect of loading rate
  - microstructure (desirable)

  - indications of reduction of IFL at dynamic rates. If confirmed, caution with Charpy impact data

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