Degradation of material properties and lifetime estimation of horn under irradiation and mechanical loads

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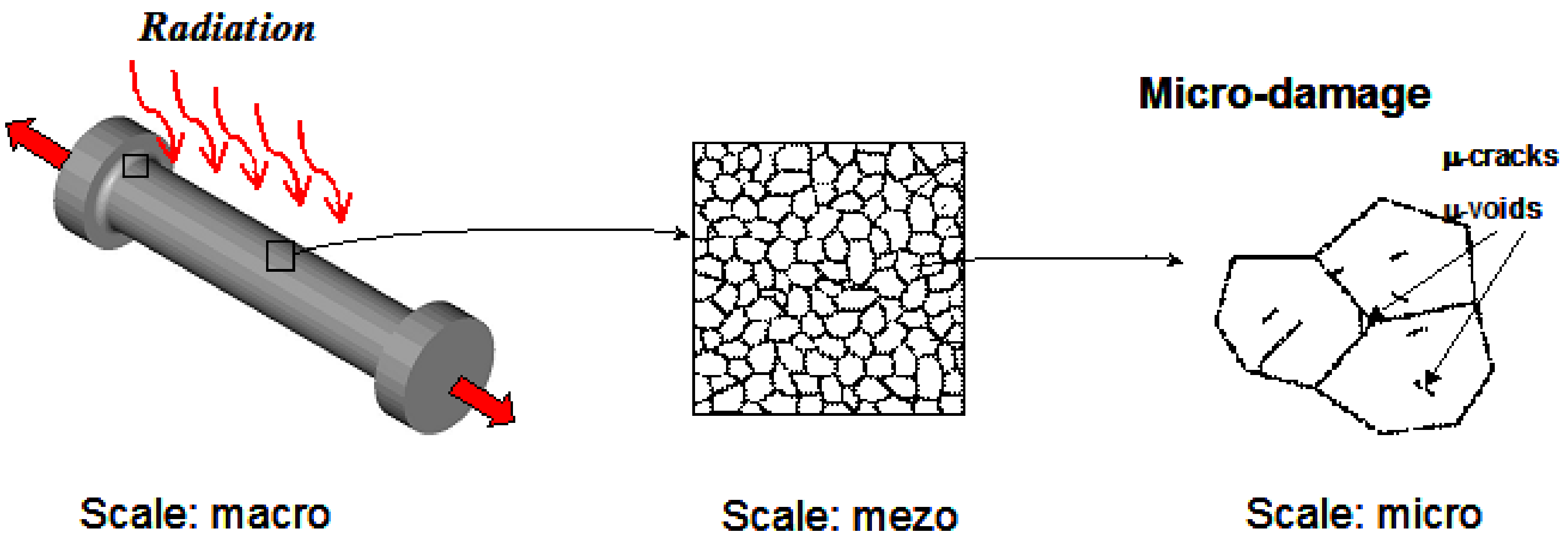
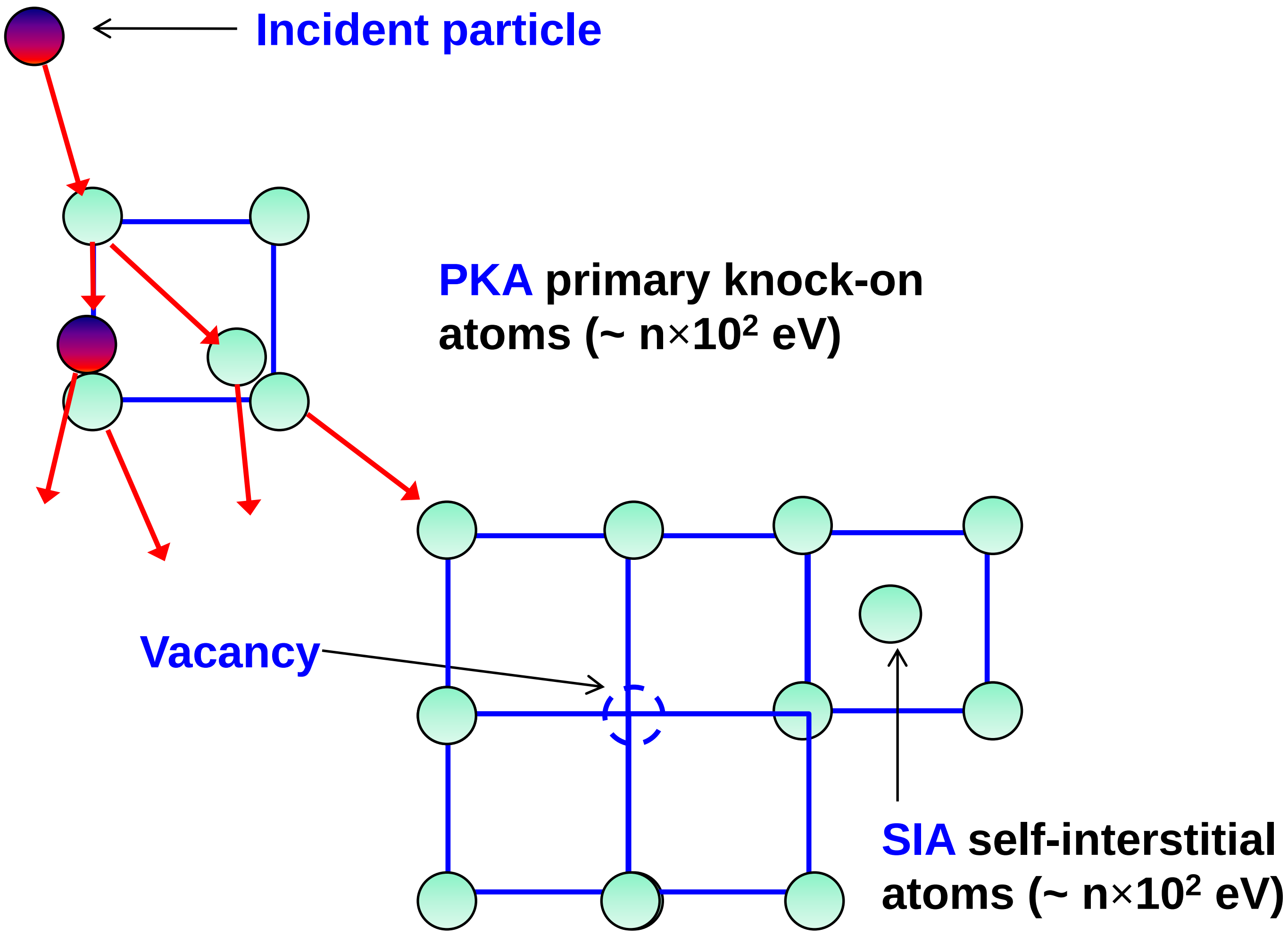
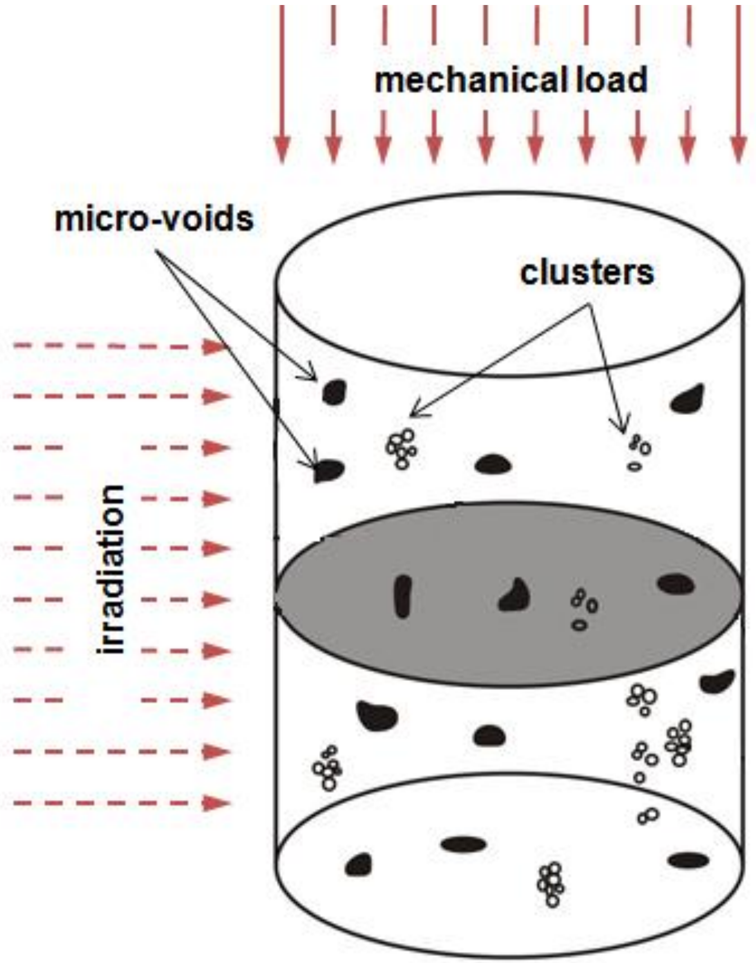
Irradiation induced micro-damage

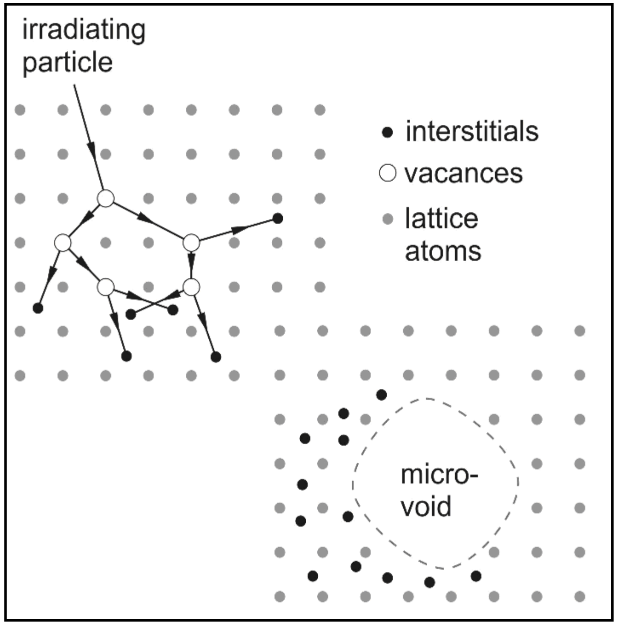


Irradiation induced defects in the lattice



Irradiation induced micro-damage – types of defects

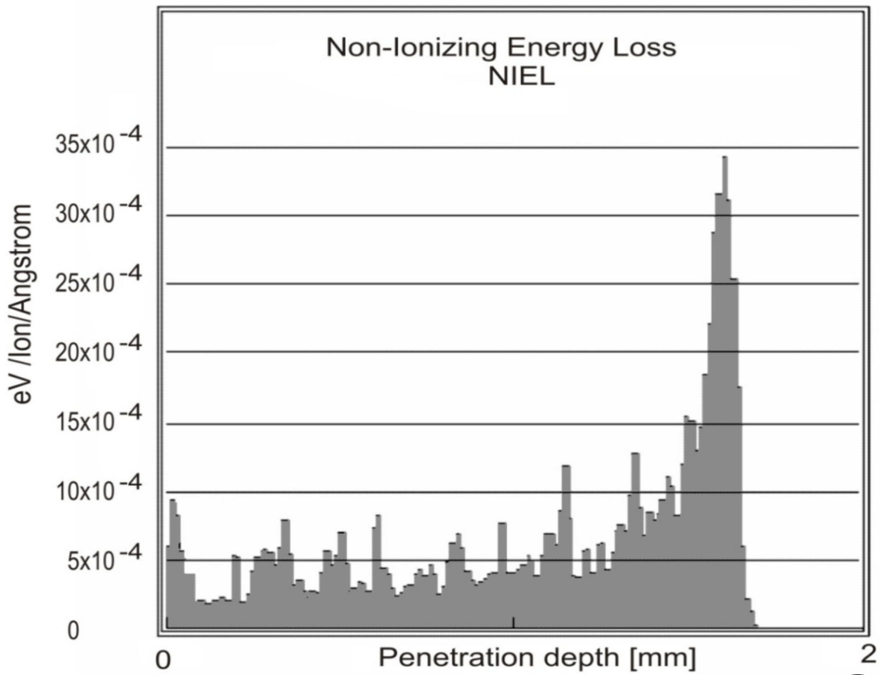




Defects due to irradiation:

1. SFT – stacking fault tetrahedron
2. Faulted or perfect dislocation loops
3. Voids – 3D vacancy clusters
4. Cavities – 3D vacancy clusters with impurities (He)

Defects induced by irradiation – voids & cavities



Displacement cascade and formation of Frenkel pairs

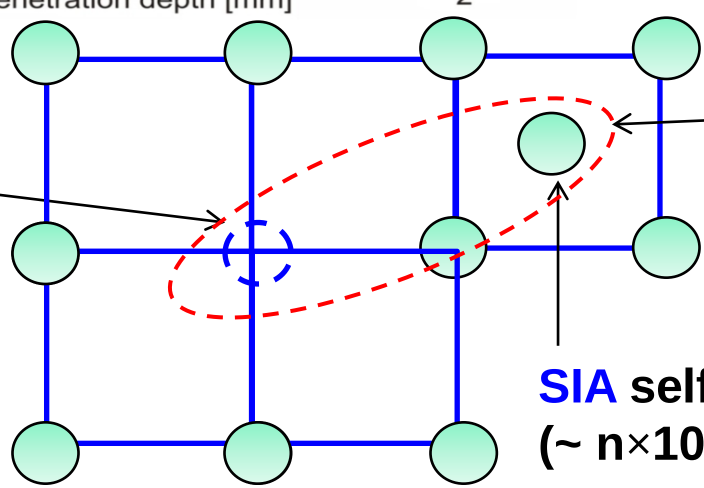
Kinchin & Pease, 1955

Norgett, Robinson, Torrens, 1975

$$\boxed{N_{NRT} = \frac{0.8E_{dam}}{2\overline{E}_d}}$$

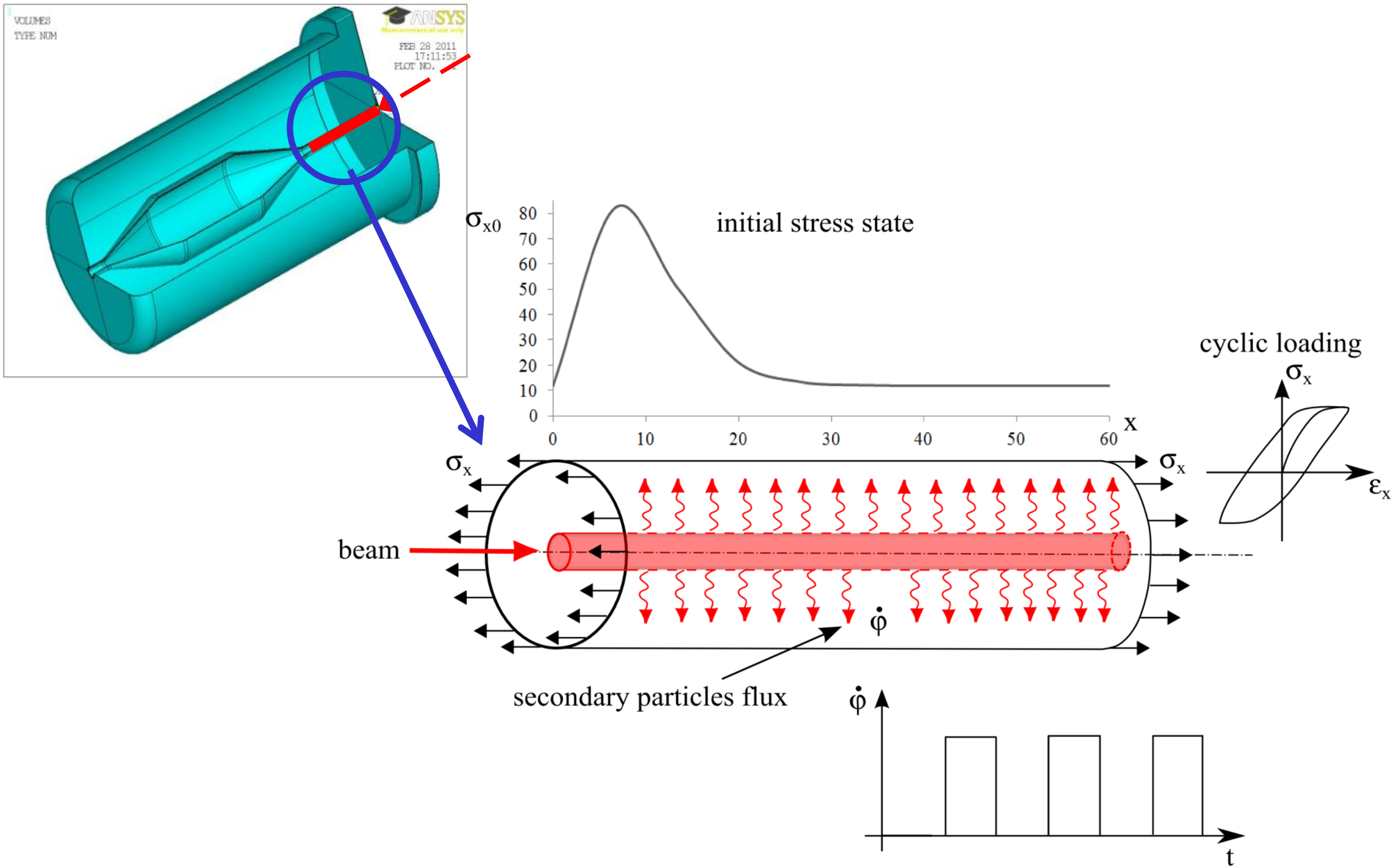
$$\boxed{E_{dam} = NIEL}$$

Vacancy

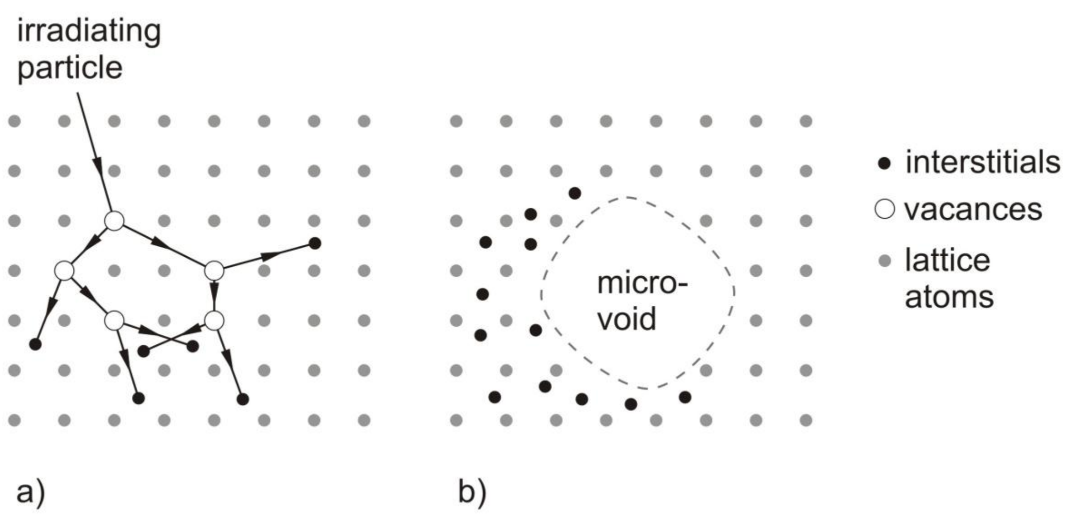


SIA self-interstitial atoms (~ n×10^2 eV)

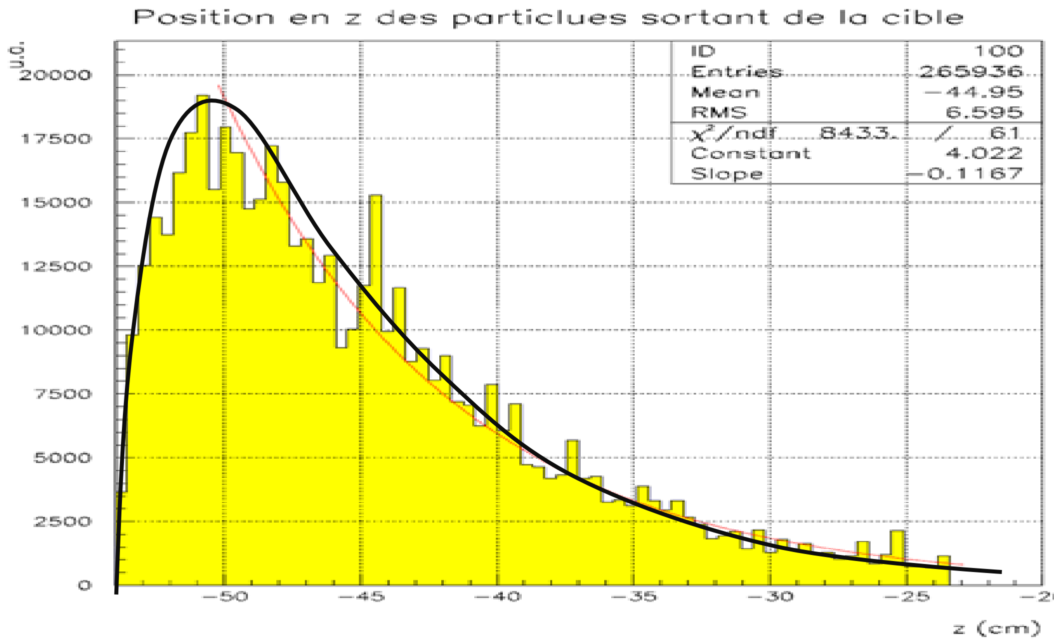
Definition of the problem



1 displacement per atom (dpa) corresponds to stable displacement from their lattice site of all atoms in the material during irradiation near absolute zero (no thermally-activated point defect diffusion).

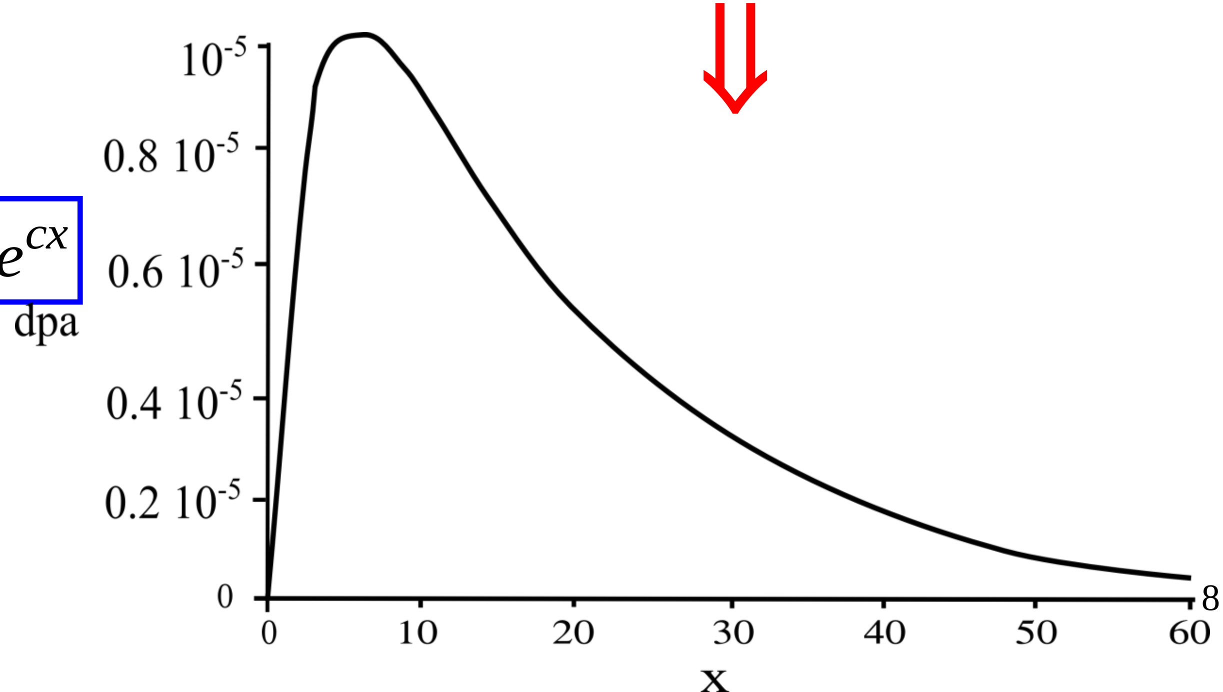


Postulated typical distribution of dpa in the horn cylindrical tangent

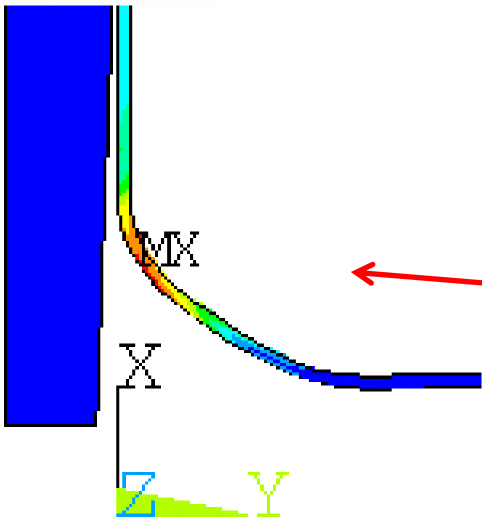


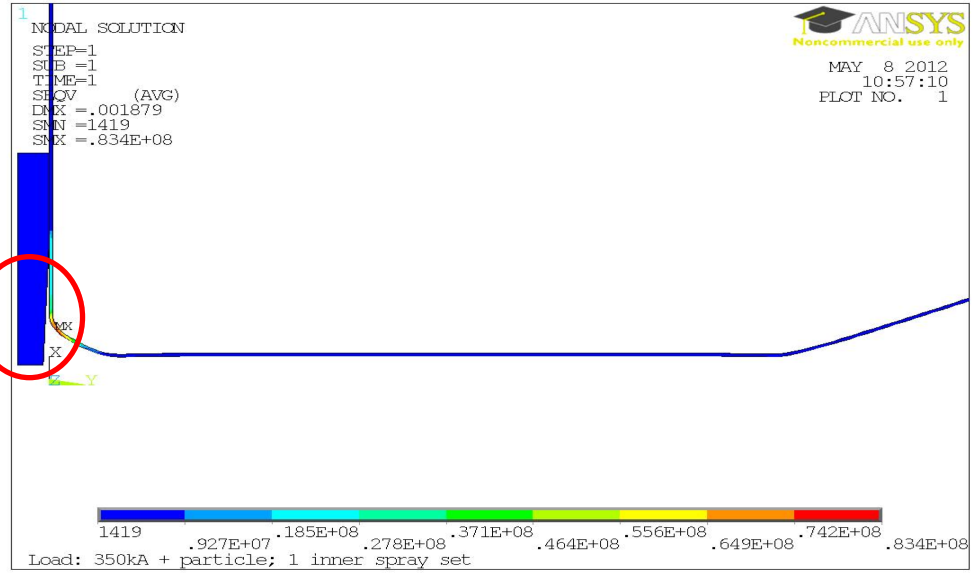
Marcos Dracos, CERN/BENE meeting 2006

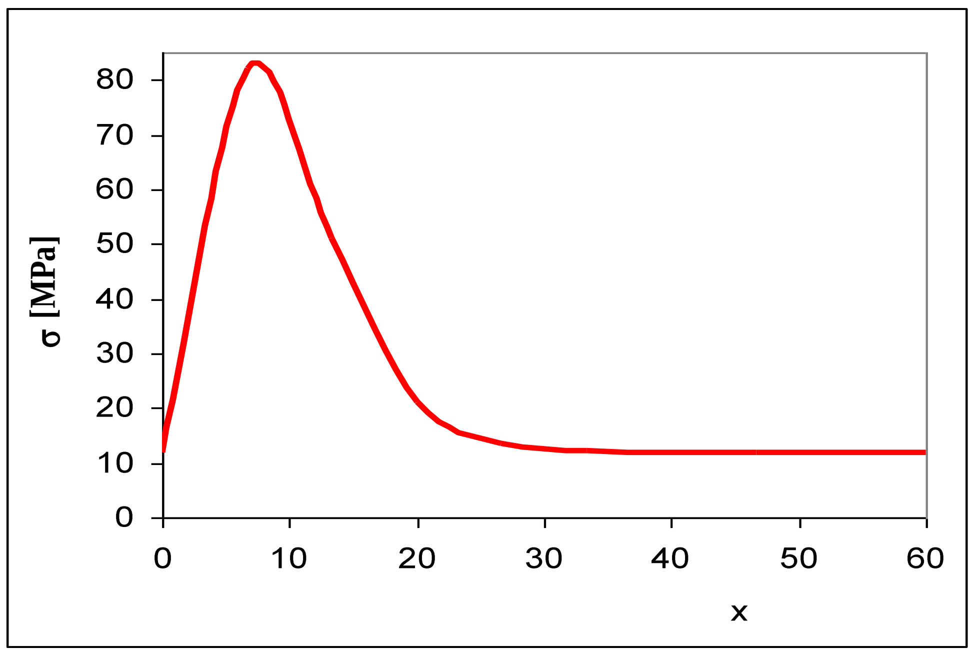
$$\boxed{dpa\,(x) = a x^{b} e^{cx}}$$



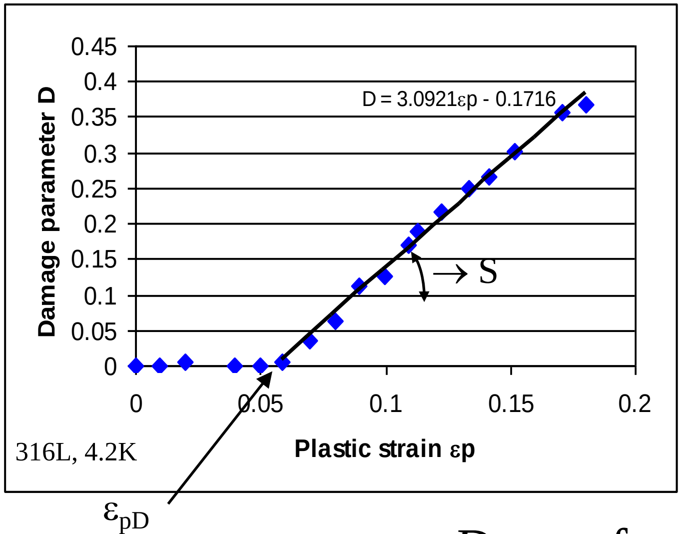
stress distribution

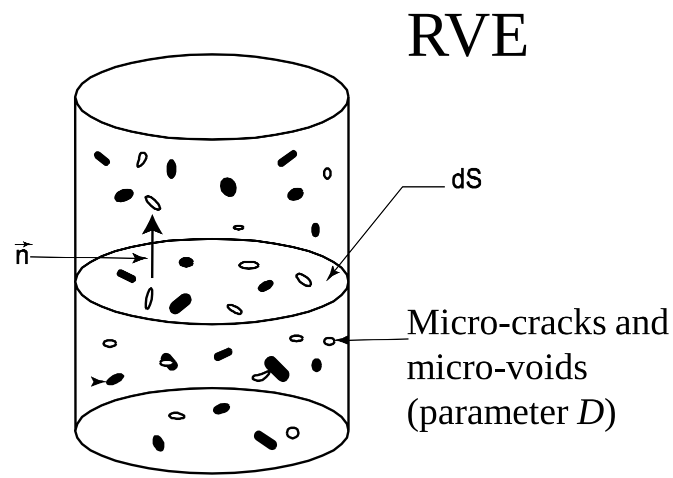




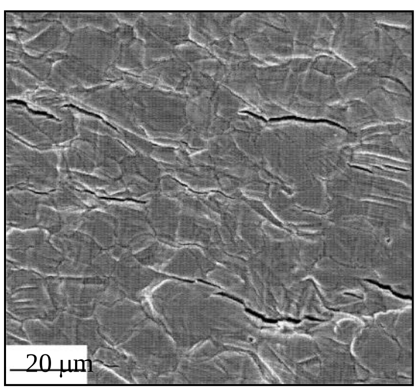


Kinetics of mechanically induced micro-damage





D – surface fraction of micro-cracks and micro-voids



$$D=\frac{dS_D}{dS}\ ;\quad 0\le D\le 1 \quad\longrightarrow\quad \underline{\underline{D}}=\sum_{i=1,3} D_i\,\underline{n}_i\otimes\underline{n}_i$$

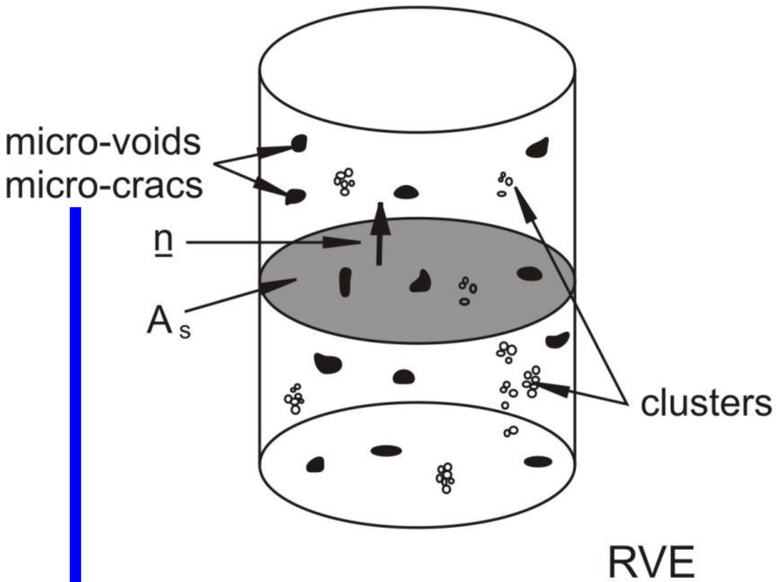
$$\boxed{\dot D=\left(\frac{Y}{S}\right)^s \dot p H\left(p-p_D\right)} \quad\longrightarrow\quad \boxed{\underline{\underline{\dot D}}=\underline{\underline{C}}\,\underline{\underline{Y}}\,\underline{\underline{C}}^T\,\dot p H\left(p-p_D\right)}$$

Chaboche, 1988; Lemaitre, 1992

Garion, Skoczeń; Int. J. Dam. Mech., 2003

Radiation and mechanical damage components additive formulation

Postulate:
both micro-damage components are treated in additive way



$$dD_{rm} = 2q_A \pi r_{c0}^{\;2} \exp\left[\alpha_r \int_0^p \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) dp\right]$$

$$D_r = D_{r0} + \int_0^{\hat{p}} dD_{rm}$$

$$\underline{\underline{D}}_r = \frac{D_r}{3} \underline{\underline{I}}$$

isotropic

$$d\underline{\underline{D}}_m = \underline{\underline{C}}\,\underline{\underline{Y}}\,\underline{\underline{C}}^T dp$$

anisotropic

$$\underline{\underline{D}} = \underline{\underline{D}}_m + \underline{\underline{D}}_r = \underline{\underline{D}}_m + \frac{1}{3} D_r \underline{\underline{I}}$$

Elastic-plastic continuum with anisotropic damage evolution

Constitutive law

$$\underline{\underline{\tilde{\sigma}}} = \underline{\underline{\underline{\underline{E}}}} : \left(\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^{p} - \underline{\underline{\varepsilon}}^{th} \right) \qquad \underline{\underline{\sigma}} = \underline{\underline{\underline{\underline{M}}}}\,\underline{\underline{\tilde{\sigma}}}$$

Yield surface

$$f_y\left(\underline{\underline{\tilde{\sigma}}}, \underline{\underline{\tilde{X}}}, \tilde{R} \right) = J_2\left(\underline{\underline{\tilde{s}}} - \underline{\underline{\tilde{X}}} \right) - \sigma_y - \tilde{R}$$

Effective hardening parameters

$$\underline{\underline{\tilde{X}}} = \underline{\underline{\underline{\underline{M}}}}^{-1} : \underline{\underline{X}} \qquad \tilde{R} = R / \left(1 - \sqrt{\underline{\underline{D}} : \underline{\underline{D}}} \right)$$

Associated flow rule

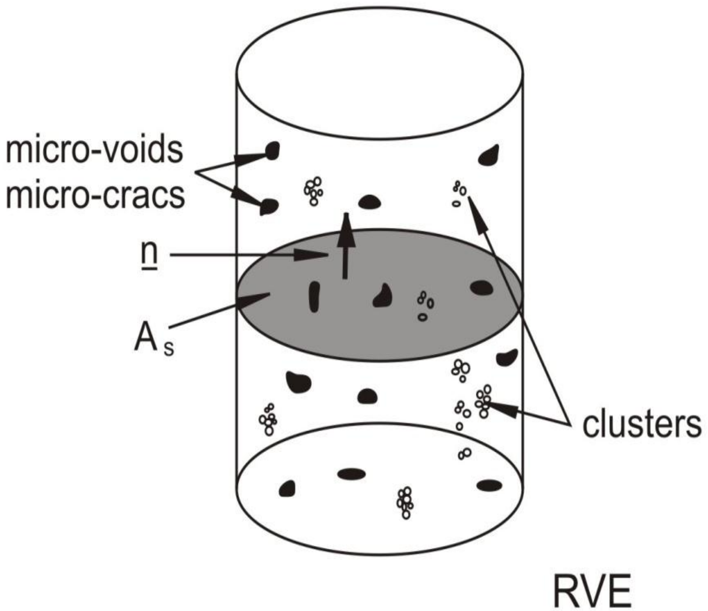
$$d\underline{\underline{\varepsilon}}^{p} = \frac{\partial f_y\left(\underline{\underline{\tilde{\sigma}}}, \underline{\underline{\tilde{X}}}, \tilde{R} \right)}{\partial \underline{\underline{\tilde{\sigma}}}} d\lambda$$

Damage evolution

$$\boxed{\underline{\underline{D}} = \underline{\underline{D}}_m + \underline{\underline{D}}_r} \qquad d\underline{\underline{D}}_m = \underline{\underline{C}}\,\underline{\underline{Y}}\,\underline{\underline{C}}^{T} dp$$

$$d\underline{\underline{D}}_{rm} = \frac{2}{3} q_A \pi r_{c0}^{\ 2} \exp\left[\alpha_r \int_0^p \exp\left(\frac{3\sigma_m}{2\sigma_{eq}} \right) dp \right] \underline{\underline{I}}$$

Clusters density and average cluster size at irradiation



$$NIEL \Rightarrow dpa$$

$$q_c = \begin{cases} C_{qI}(dpa)^{n_{qI}} & for \quad dpa < D_S \\ C_{qII}(dpa)^{n_{qII}} & for \quad dpa \geq D_S \end{cases}$$

$$r_c = \begin{cases} C_r(dpa)^{n_r} & for \quad dpa < D_S \\ r_{cr} & for \quad dpa \geq D_S \end{cases}$$

$$q_A = \left(\sqrt[3]{q_V}\right)^2 = q_c^{\ 2/3}$$

$$D_{r0} = q_A \pi r_{c0}^{\ 2}$$

Post-irradiation evolution of micro-damage

(after recombination)

$$dr_c = r_c \alpha_r \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) dp$$

Rice & Tracey 1969, Beremin 1981, Huang 1991, Pardoen et al. 1996.

Typical value of α_r for Cu is equal to 0.48

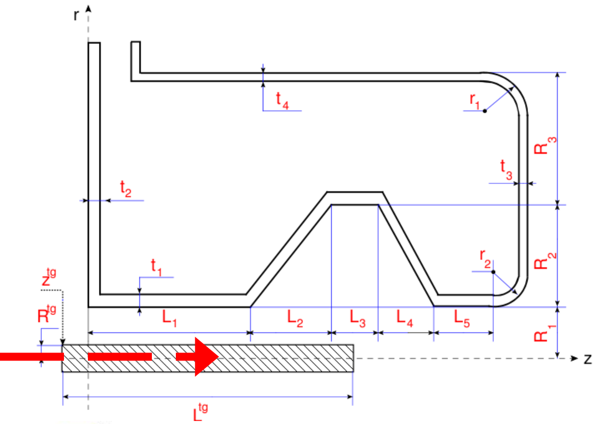
$$dA_{rm} = \pi((r_{c0} + dr_c)^2 - r_{c0}{}^2) = \pi(2r_{c0}dr_c + dr_c{}^2)$$

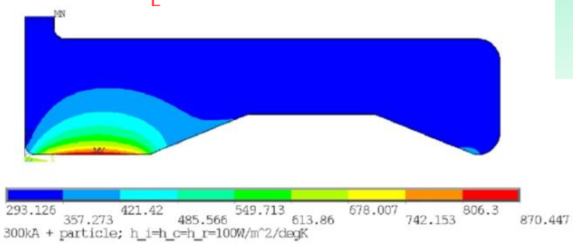
$$dD_{rm} = q_A dA_{rm} = q_A 2\pi r_{c0} dr_c$$

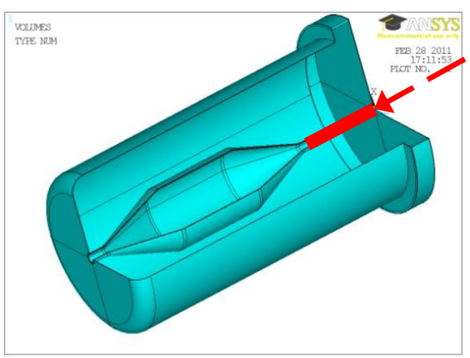
$$dD_{rm} = 2q_A \pi r_{c0}{}^2 \left\{ \exp\left[\alpha_r \int_0^p \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) dp \right] - 1 \right\}$$

Kinetic law of evolution of post-irradiation micro-damage (porosity)

Algorithm for structures subjected to pulsed irradiation







i=i+1 pulse

$$NIEL^i \Rightarrow dpa^i$$

irradiation

$$D^i_{r0} = q_A \pi r_{c0}^2$$

Quasi-static and cyclic loads

$$dr_c = r_c \alpha_r \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) dp$$

$$dD^i_{rm} = q_A dA_{rm} = q_A 2\pi r_{c0} dr_c$$

$$D^i_r = D^i_{r0} + \int_0^{\hat{p}} dD^i_{rm}$$

Quasi-static and cyclic loads

$$\dot{D}^i_m = \left(\frac{Y}{S}\right)^s \dot{p} H\left(p - p_D\right)$$

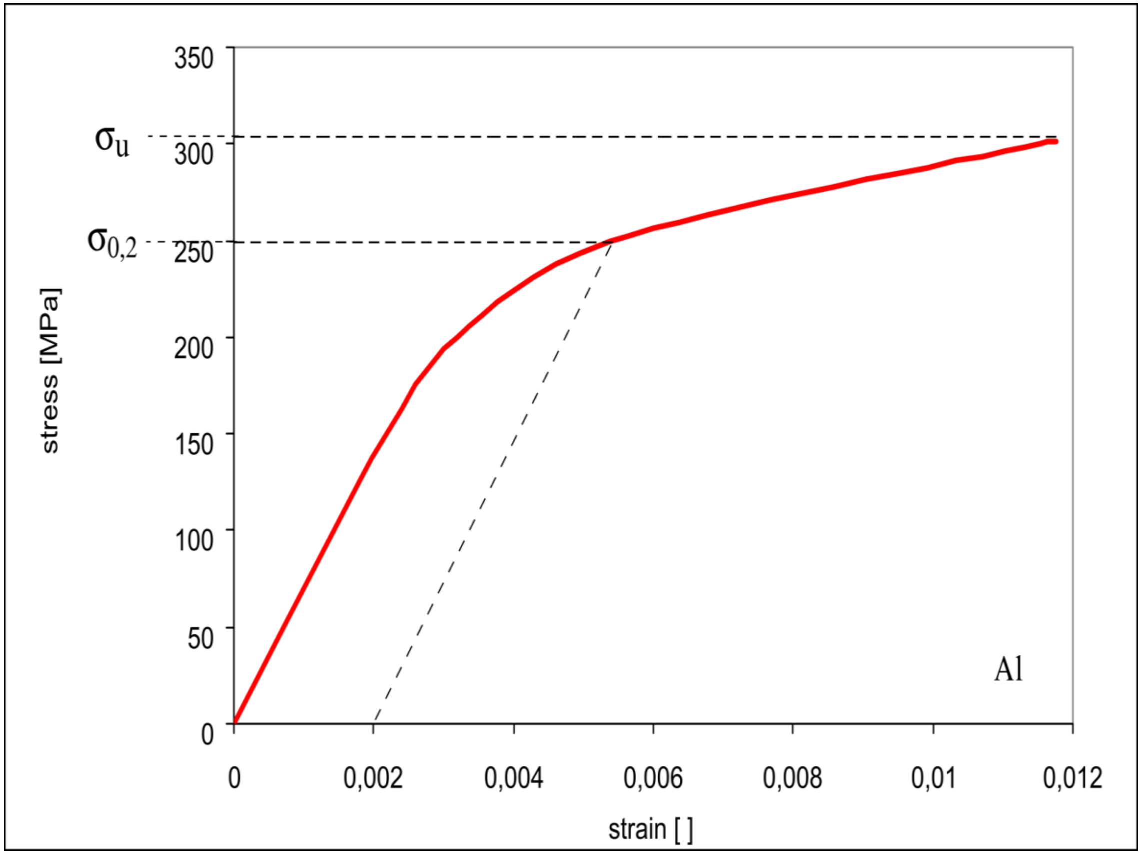
$$D^i = D^i_m + D^i_r$$

$$D = \sum_{i=1}^{N} D^i$$

stress-strain curve

Ramberg–Osgood equation

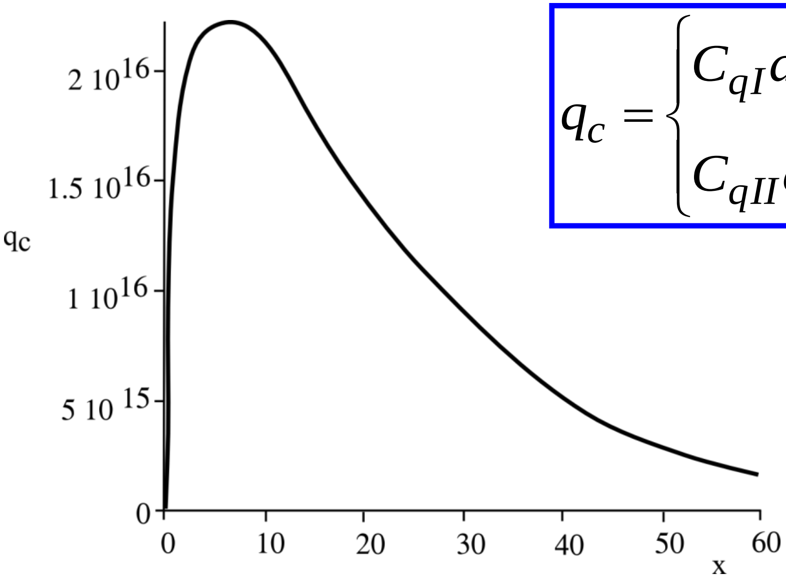
$$\boxed{\varepsilon = \frac{\sigma}{E} + K\left(\frac{\sigma}{E}\right)^n}$$



$\sigma_{0,2}$=250 MPa

σ_u=310 MPa

Clusters density at irradiation

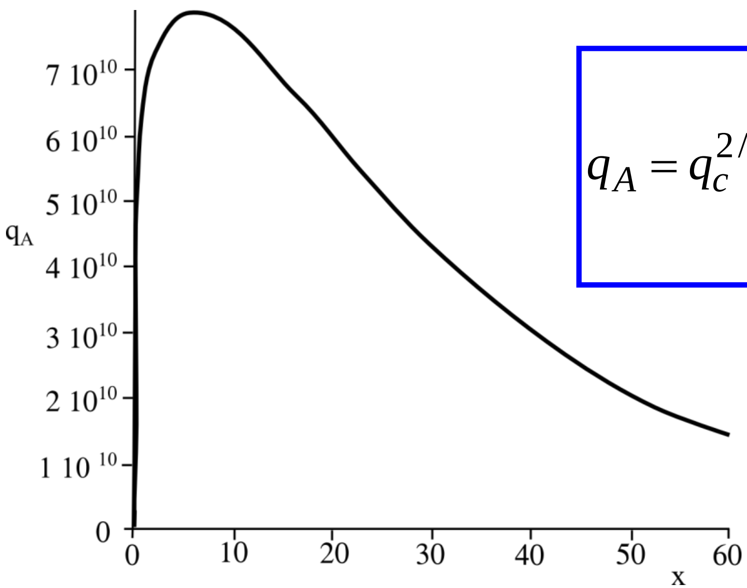


$$q_c = \begin{cases} C_{qI} a x^{b n_{qI}} e^{c n_{qI} x} & \text{for} \quad dpa < D_S \\ C_{qII} a x^{b n_{qII}} e^{c n_{qII} x} & \text{for} \quad dpa \geq D_S \end{cases}$$

where:

$C_{qI} = 0.3 \cdot 10^{20}$ $\qquad n_{qI} = 0.83$

$C_{qII} = 0.2 \cdot 10^{20}$ $\qquad n_{qII} = 0.145$



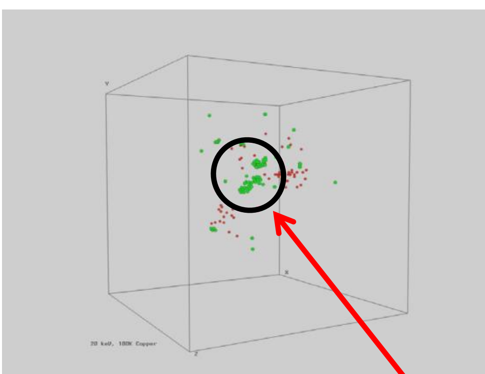
$$q_A = q_c^{2/3} = \begin{cases} \left(C_{qI} a x^{b n_{qI}} e^{c n_{qI} x}\right)^{2/3} & \text{for} \quad dpa < D_S \\ \left(C_{qII} a x^{b n_{qII}} e^{c n_{qII} x}\right)^{2/3} & \text{for} \quad dpa \geq D_S \end{cases}$$

Cluster size at irradiation

$$r_{c0} = \begin{cases} C_r\, a\, x^{b\, n_r} e^{c\, n_r x} & for \quad dpa < D_S \\ r_{cr} & for \quad dpa \geq D_S \end{cases}$$

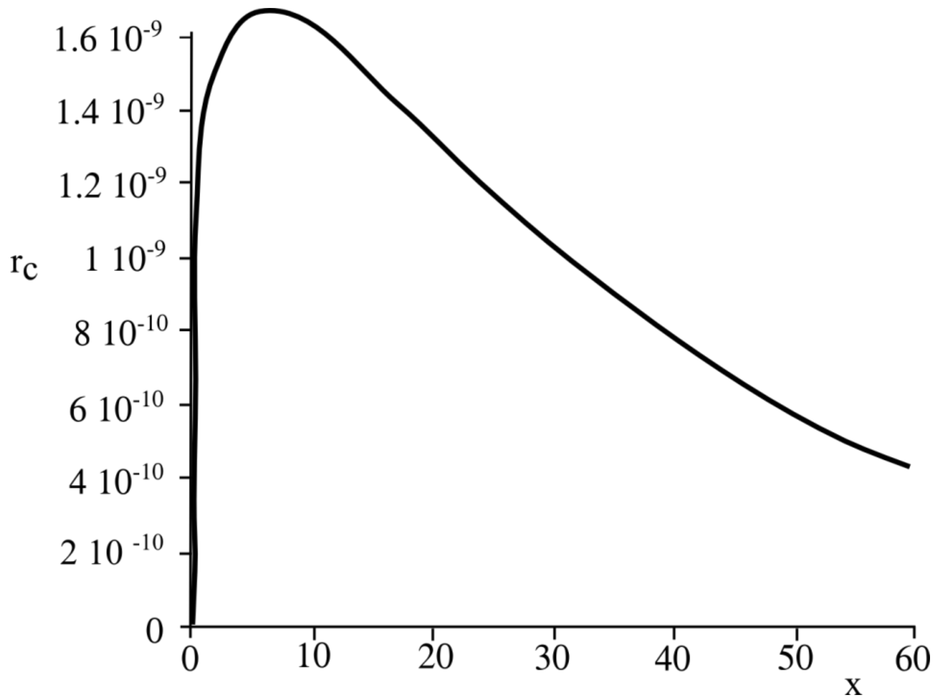
$C_r = 0.1 \cdot 10^{-6}$ $\quad n_r = 0.15$

$r_{cr} = 0.11 \cdot 10^{-6}$



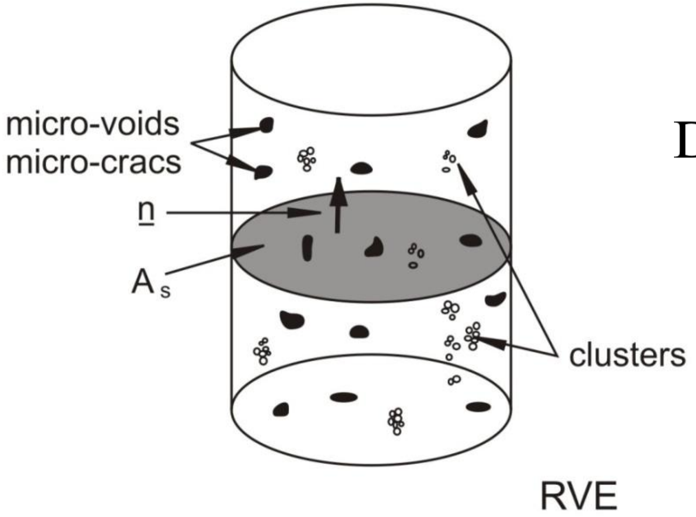
Cluster

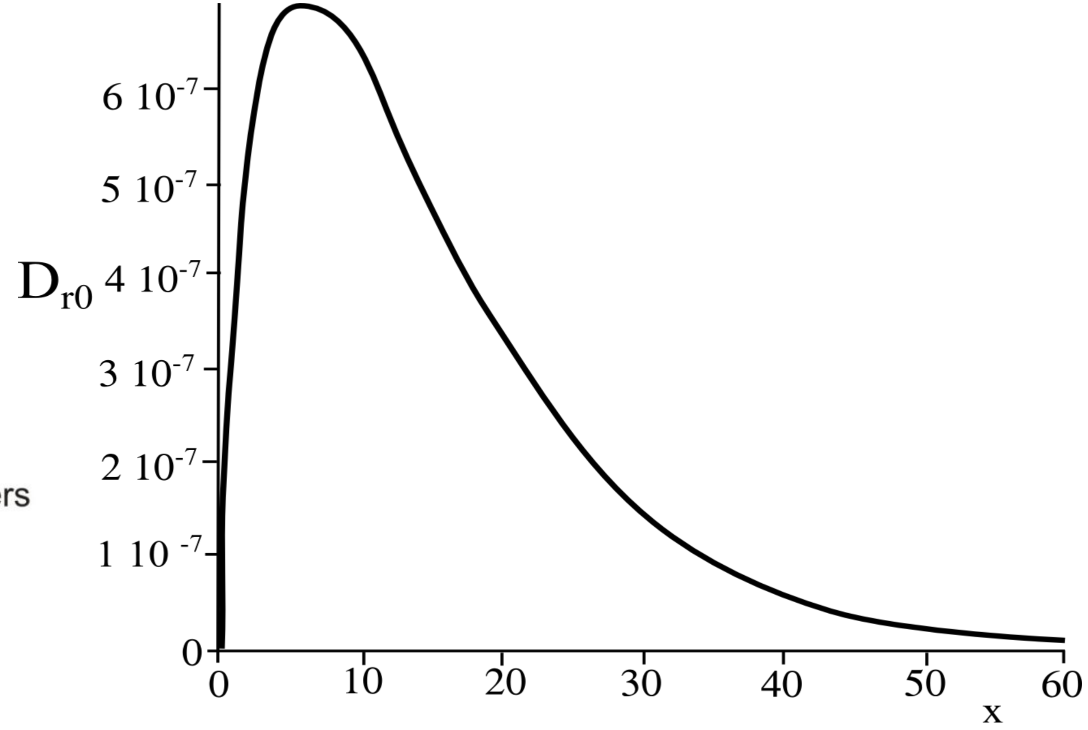
of micro-voids



Irradiation damage

$$D_{r0} = \begin{cases} \left(C_{qI} a x^{b n_{qI}} e^{c n_{qI} x}\right)^{2/3} \pi r_{c0}^2 & for \quad dpa < D_S \\ \left(C_{qII} a x^{b n_{qII}} e^{c n_{qII} x}\right)^{2/3} \pi r_{c0}^2 & for \quad dpa \geq D_S \end{cases}$$

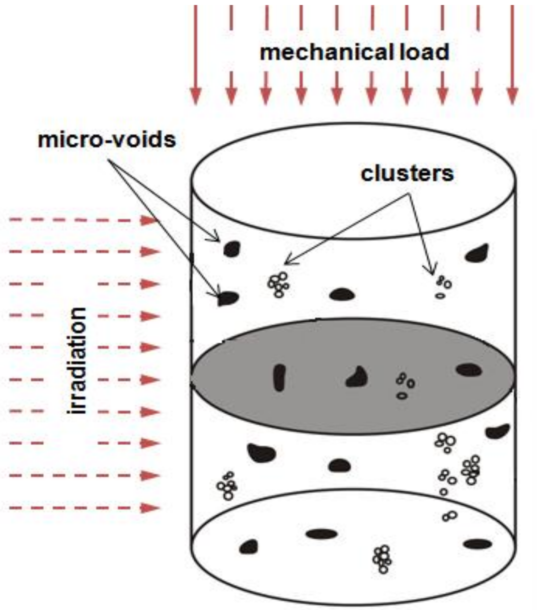


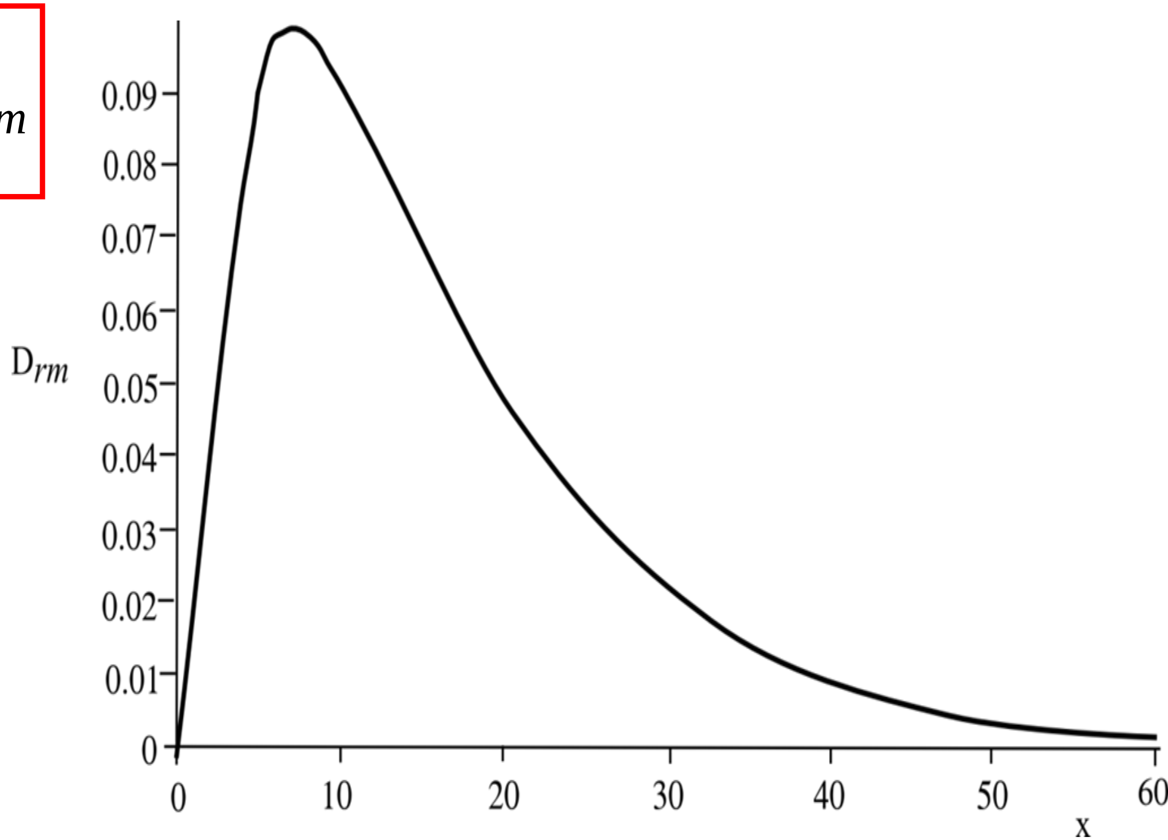


Evolution of radiation induced micro-damage along the horn cylindrical tangent

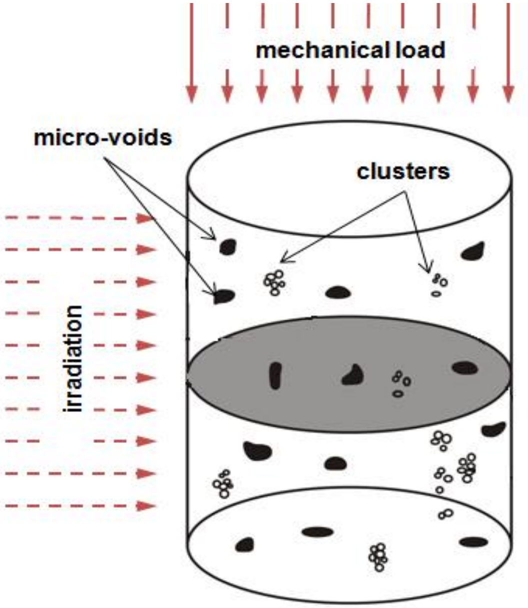
$$dD_{rm} = 2q_A \pi r_{c0}^{\ 2} \left\{ \exp\left[\alpha_r \int_0^p \exp\left(\frac{3\sigma_m}{2\sigma_{eq}} \right) dp \right] - 1 \right\}$$

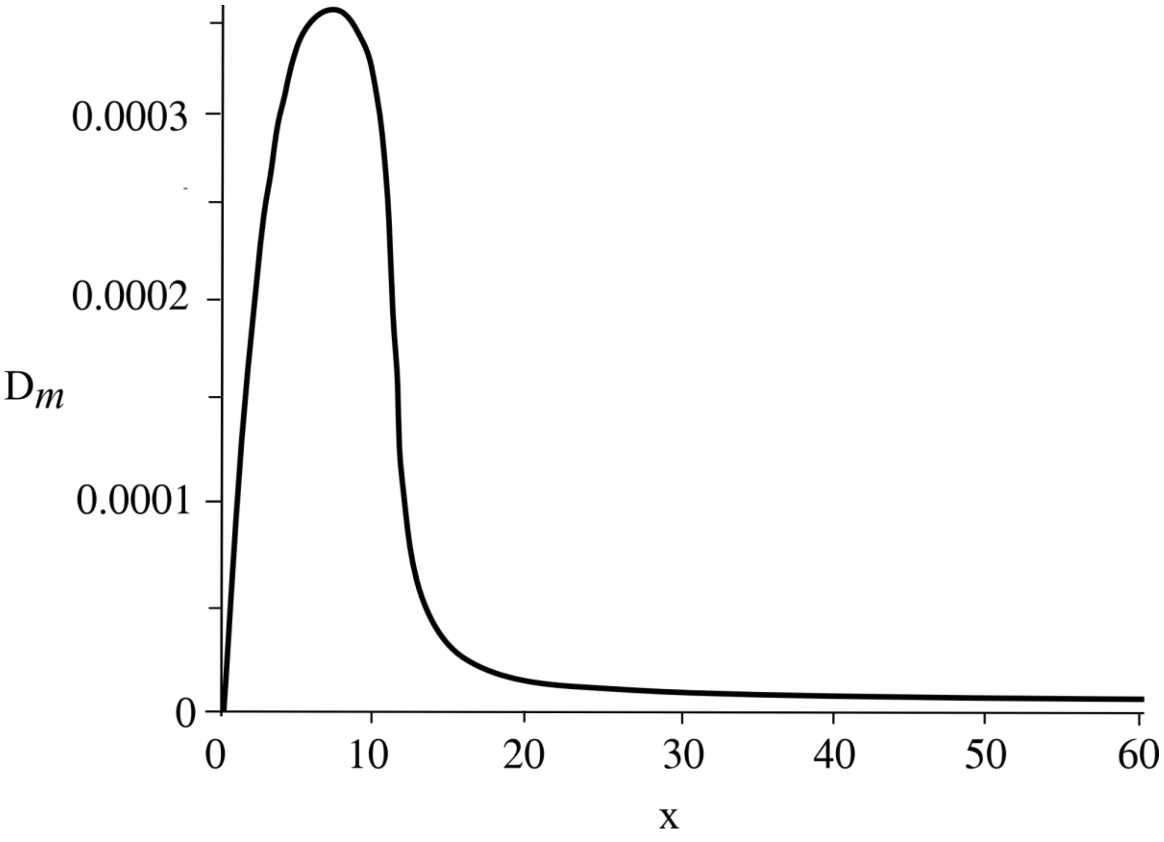
$$D_{rm} = D_{r0} + \int_0^{\hat{p}} dD_{rm}^i$$



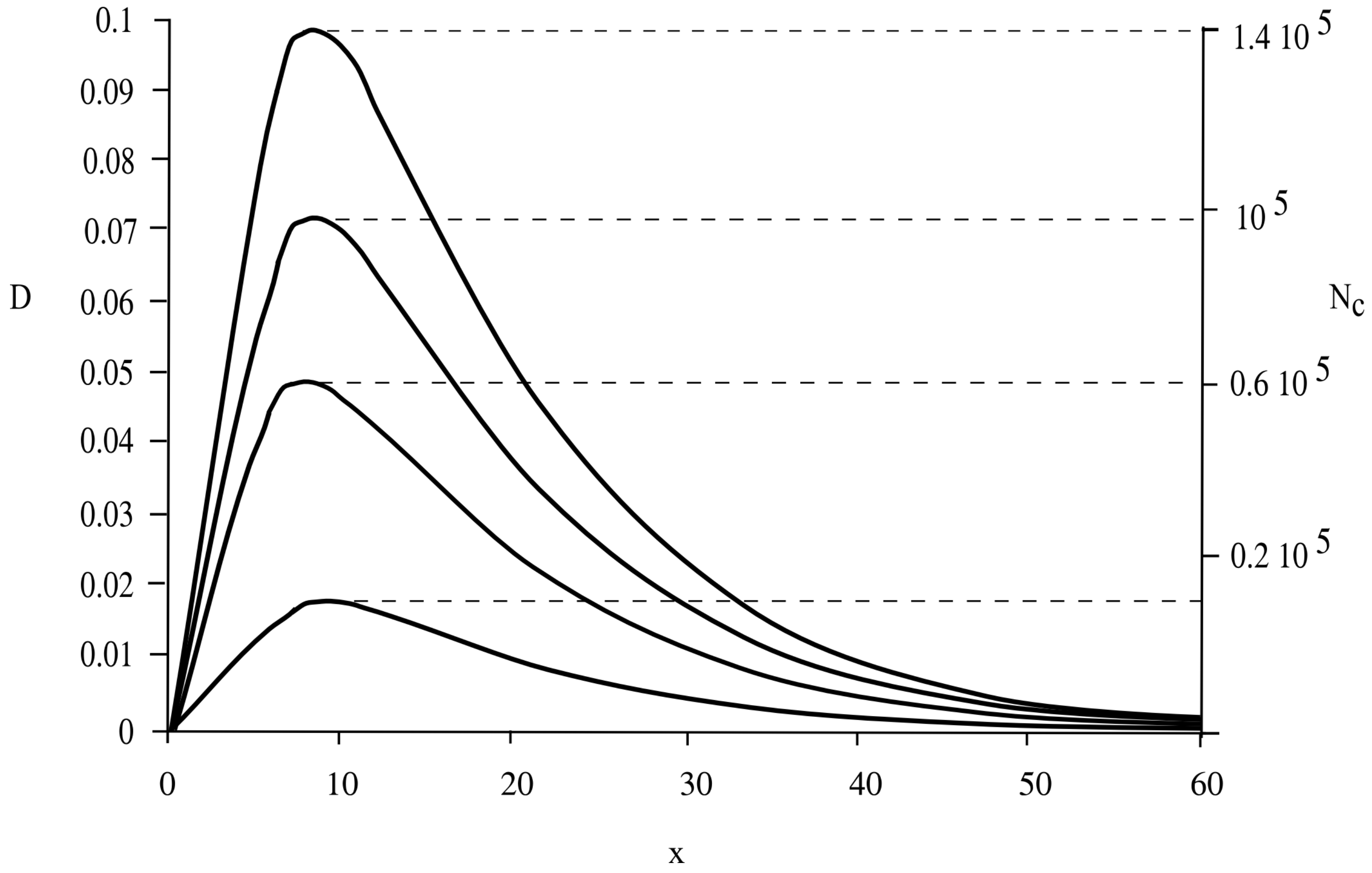


Evolution of mechanically induced micro-damage along the horn cylindrical tangent.

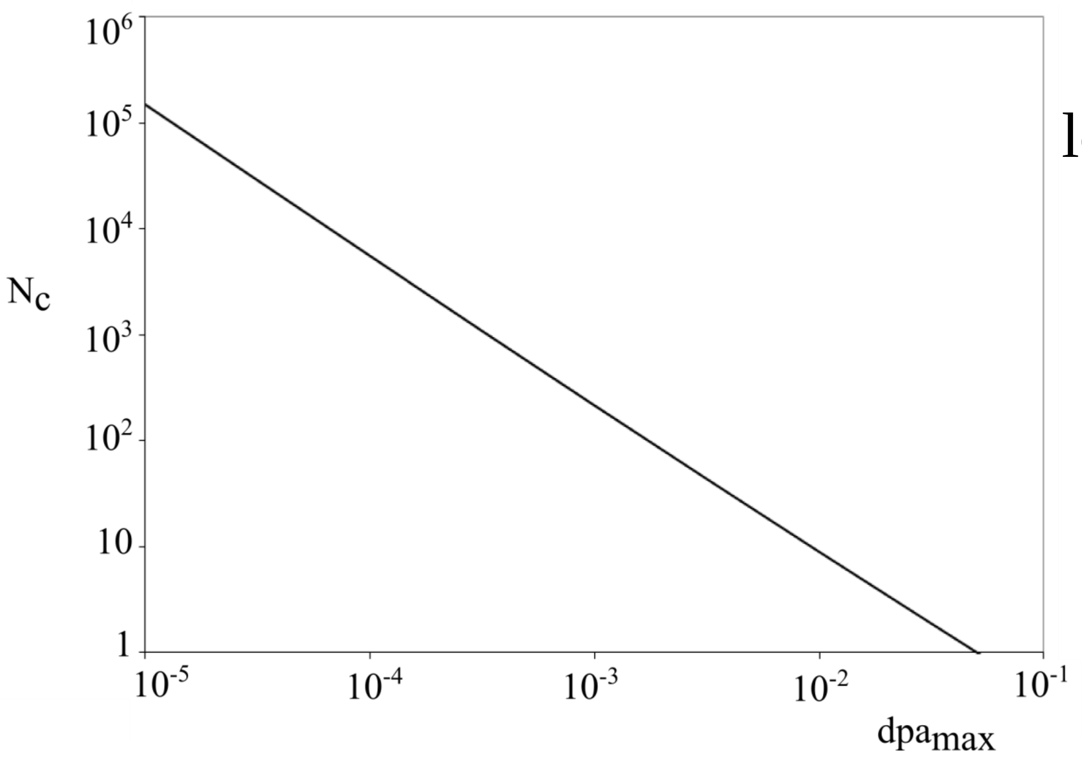




Evolution of total damage parameter as a function of distance and number of cycles



Evolution of mechanically induced micro-damage along the horn cylindrical tangent.



$$\log(N_c) = a + b \log(dpa_{max});$$

$$\boxed{N_c = C(dpa_{max})^b;}$$

where:

$a = 1.9;$ $b = 1.4$

Conclusions

1. **Irradiation induced damage measured in „dpa" has to be converted to classical micro-damage parameter D. Evolution of D is governed by type Rice-Tracey kinetic law of damage evolution and is expressed in terms of stress state and strains.**

2. **Evolution of micro-damage can be simulated as a function of static, cyclic or dynamic loads imposed on the analysed structure.**

3. **In particular, lifetime of horn can be determined by means of the above presented approach.**