Given Be w/ incident α of energy, what's the recoil?

$$^{9}Be + \alpha \longrightarrow {}^{13}C + \gamma$$

Energy conservation

$$T_\alpha + m_0 c_\alpha^2 + m_0 c_{Be}^2 = T_\gamma + m_0 c_{13}^2 + T_{c\text{-}13}$$

Momentum conservation

$$p_\alpha = p_\gamma + p_{c13}$$

Solve

$$T\alpha + [m_0 c_\alpha^2 + m_0 c_{Be}^2 - m_0 c_{c13}^2] = T_\gamma + T_{c13}$$

$$5.3\ MeV + 931.5 \frac{MeV}{amu}[9+4-13] = T_\gamma + T_{c13}$$

$$\frac{1}{c}\sqrt{(T_\alpha + 2m_0 c_\alpha^2)T_\alpha} = \frac{E_\gamma}{c} + \frac{1}{c}\sqrt{(T_c + 2m_0 c^2)T_c}$$

$$\sqrt{(T_\alpha + 2m_0 c_\alpha^2)T_\alpha} = E_\gamma + \sqrt{(T_c + 2m_0 c^2)T_c}$$

$$T_\gamma = 15.55\ MeV - T_c$$

$$\sqrt{(T_\alpha + 2m_0 c_\alpha^2)T_\alpha} = 15.55\ MeV - T_c + \sqrt{(T_c + 2m_0 c^2)T_c}$$

$$198.85\ MeV - 15.55\ MeV = \sqrt{(T_c + 2m_0 c^2)T_c} - T_c$$

$$(T_c + 183.3\ MeV)^2 = (T_c^2 + T_c 2 m_0 c_c^2)$$

$$\cancel{T_c^2} + 2\cdot 183.3 MeV T_c + (183.3 MeV)^2 = \cancel{T_c^2} + T_c 2 m_0 c^2$$

$$T_c = -\frac{(183.3\ MeV)^2}{2\cdot 183.3 MeV - 2m_0 c_c^2}$$

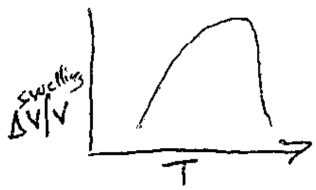
$$T_c = 1.408\ MeV$$

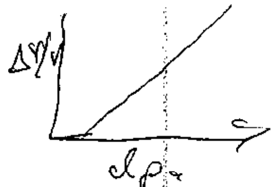
Swelling and Creep

Creep — Time-dependent deformation of a metal under constant load at high temperature

irradiation increases creep over thermal creep, or induces creep in temperatures where it wasn't before.

Swelling — volumetric expansion





Swelling is the isotropic volume expansion of a solid without an external stress. Creep is the volume conservative distortion of a solid under applied stress.

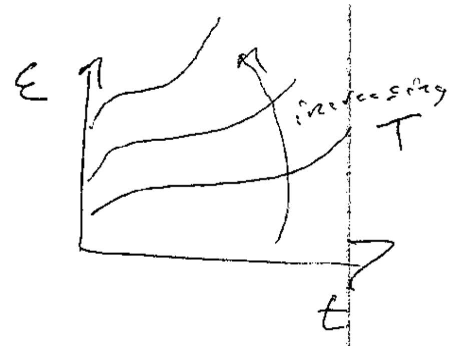
Swelling concern

- → ~~dos~~ dimensional increase
- → particle transport
- → th
- → failure path on voids
- → depends on dose, dose rate, comp, temp
- → freely migrating defects, long range migration — steel

$$C_V^0 = \frac{1}{\Omega}\exp\left(\frac{S_f}{k}\right)\exp\left(\frac{-H_f}{kT}\right)$$

Creep Concern

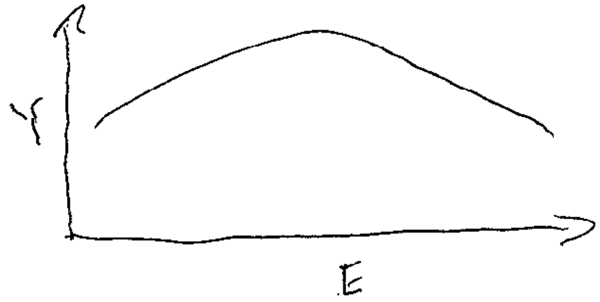
- → reduced failure time
- → deformation
- → embrittlement
- → cracking
- → lowered fracture resistance

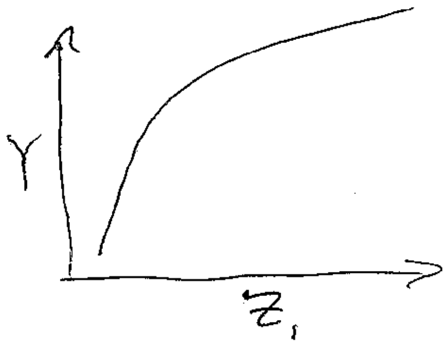


Sputtering

Y = sputtering yield = $\frac{\text{emitted atoms}}{\text{incident particle}}$

Sputtering yield depends on
- structure and comp of target
- parameters of beam
- geometry





Matsunami

$$Y_E(E) = 0.42\ \frac{\alpha_s Q_s S_n(E)}{U_0[1+0.35 U_0 S_e(\varepsilon)]}\left[1-\left(E_{th}/E\right)^{0.5}\right]^{2.8}$$

Steady State Concentration

at $t=0$

flux ratio

$0.5 < r < 2$

$$\frac{J_B}{J_A} = r\left(\frac{N_B}{N_A}\right) \Rightarrow (J_A + J_B) = Y J_i$$

at steady state

$$J_A = J_i \Rightarrow \frac{N_A}{N_B} = r\,(Y-1)^{-1}$$

Also $\rightarrow$ Preferential sputtering

at $t=0$

$$\frac{Y_A(0)}{Y_B(0)} = r\,\frac{N_A^s(0)}{N_B^s(0)} = r\,\frac{N_A^b}{N_B^b}$$

at $t=\infty$

$$\frac{N_A^s(\infty)}{N_B^s(\infty)} = \frac{1}{r}\,\frac{N_A^b}{N_B^b} \qquad \frac{Y_A(\infty)}{Y_B(\infty)} = \frac{N_A^b}{N_B^b}$$

Range Integration

$$R = \int_{E_i}^{0} \frac{dE}{dE/dx}$$

for nuclear

$$\left.\frac{dE}{dx}\right|_n = N_\pi \frac{Z_1^2 Z_2^2 e^4 M_1}{E_i M_2} \ln \frac{\Delta E_i}{E_a}$$

$$R = \int_{E_i}^{0} \frac{dE}{dE/dx} = \cancel{\int_{E_i}^{0} \frac{dE}{kE^{1/2}}}$$

for nuclear

$$\left.\frac{dE}{dx}\right|_e = kE^{1/2}$$

$$R = \int_{E_i}^{0} \frac{dE}{kE^{1/2}}$$

Maximum Energy Transfer / Weighted Average Recoil Spectrum

$$T_{max} = \Delta E = \frac{4 M_1 M_2}{(M_1 + M_2)^2}$$

Weighted Average Recoil Spectrum

$$\overline{T} = \frac{1}{2}\Delta E_i = \frac{\int_0^{\Delta E_i} T\sigma(E,T)\,dT}{\int_0^{\Delta E_i} \sigma(E,T)\,dT}$$

→ isotropic scattering w/ σ_s

for coulomb potential

$$\sigma = \frac{\pi}{4}\frac{(Z_1 Z_2 e^2)^2}{E_r^2}\left(\frac{T_m}{E_d} - 1\right)$$

$$\tilde{T} = E_d \ln\frac{\Delta E_i}{E_d} \qquad E_d \ll \Delta E_i$$

Weighted average recoil spectra

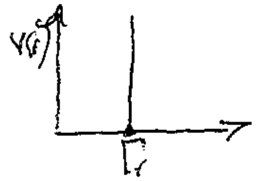
$$W(T) = \int_{E_d}^{T} T\sigma(E,T)\,dT \Big/ \int_{E_d}^{\Delta E} T\sigma(E,T)\,dT$$

harder spectrum for higher mass

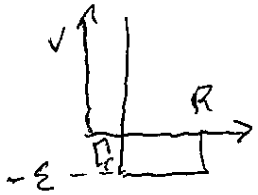
More displacements at higher recoil energy for higher primary atom energy.

Potential Forms

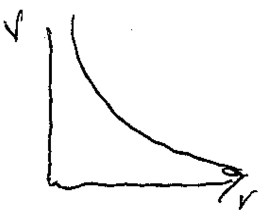
Hard sphere –
$$V(r) = \begin{cases} \infty, & r < \Gamma_r \\ 0, & r > \Gamma_r \end{cases}$$



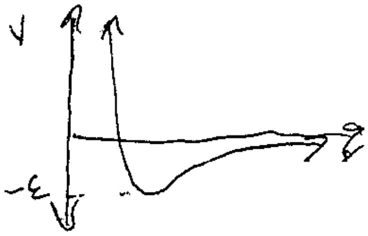
Square well –
$$V(r) = \begin{cases} \infty & r < \Gamma_r \\ -\varepsilon & \Gamma_r < r < R \\ 0 & r > R \end{cases}$$



Inverse Power –
$$V(r) = \varepsilon\left(\frac{\Gamma_r}{r}\right)^n$$



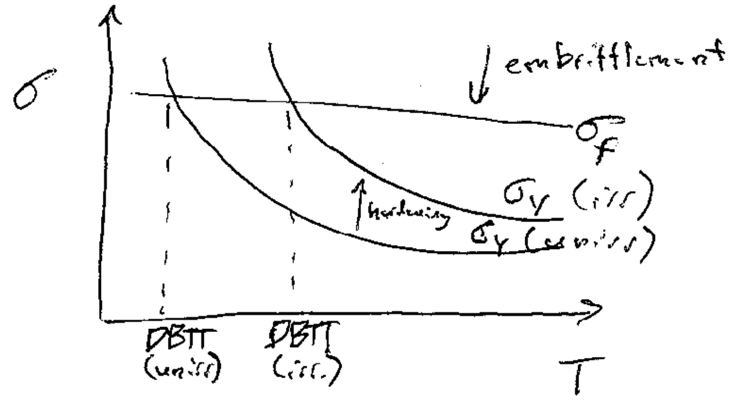
Lennard-Jones
$$V(r) = \varepsilon\left[\left(\frac{\Gamma_r}{r}\right)^m - \left(\frac{\Gamma_r}{r}\right)^n\right]$$



Ductile to Brittle Transition Temperature

DBTT defined as the point in temperature where the yield and fracture stresses are equal! Means it fractures immediately after the elastic deformation section.

Increased by irradiation as shown below



→ neutron environment effect on DBTT is approx

$$\Delta T_{41} = A\Phi^{(0.28 - \log \Phi)}$$

so increases change in DBTT w/ increasing fluence

Reversal

→ Thermal annealing - depends on irradiation

almost full recovery after 70-150 hr at 450°C

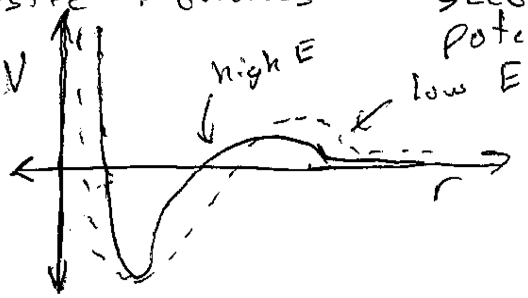
[1] Was - p.

Macroscopic parameters to Potential Well shapes

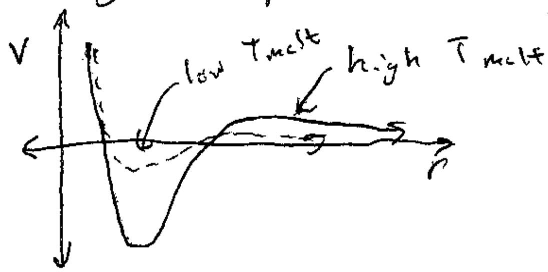
Binding Energy – Depth of well

$$E_b \cong \Delta H_s \cong \frac{1}{2} n_c N_A \epsilon_b$$

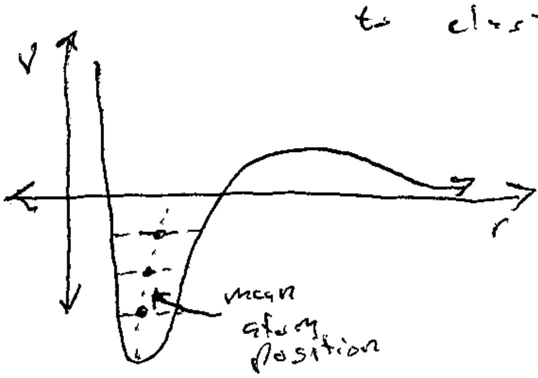
Elastic Modulus – second derivative of potential at it's minimum



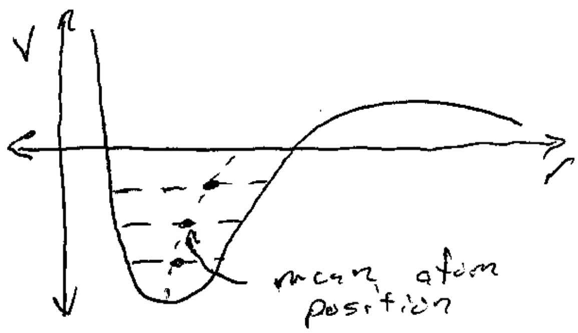
Melting Temperature – proportional to Binding Energy



Coefficient of Thermal Expansion – inversely proportional to elastic modulus



High E, low thermal expansion

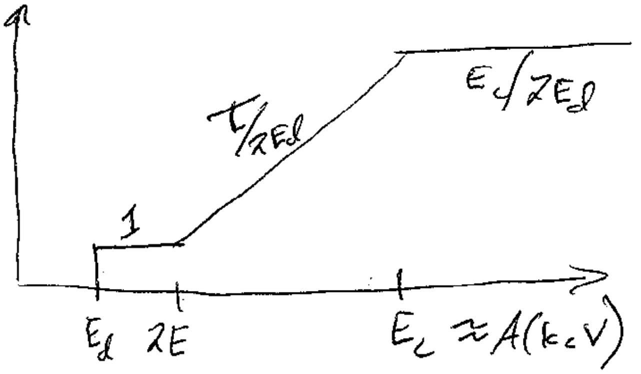


Low E, high thermal expansion

[1] Nastasi p. 19–24

DPA Calculations

we have $\nu(T)$ = # of displacements



$$\Delta = \frac{4M_1 M_2}{M_1 + M_2}$$

Hard sphere

$$\sigma(E,T) = \frac{\sigma_p}{\Delta E} = \frac{C}{E}$$

displacement rate

$$R_d = \int_{E_d}^{\Delta} \phi(E)\, \sigma_d(E,T)\, E$$

$$\sigma_d = \int_{E_d}^{\Delta E = T_{max}} \nu(T)\, \sigma(E,T)\, dT$$

$$\sigma_d = \int_{0}^{E_d} \left[(0)\frac{\sigma_p}{\Delta E} + (1)\frac{\sigma_p}{\Delta E} + \frac{T}{2E_d}\frac{\sigma_p}{\Delta E} \right] dT$$

$$= \left(\frac{\sigma_p}{\Delta E}\right)(2E_d - E_d) + \left(\frac{\sigma_p}{2\Delta E_d}\right)\left(\frac{(\Delta E)^2}{2} - \frac{E_d^{\,2}}{2}\right)$$

R_d is dpa/sec

Stopping Power / Cross Section

$$S \equiv \frac{dE/dx}{N} = \cancel{\frac{1}{N} \int dE/dx \, dE}$$