Exam 2: NE591-10: Nuclear Fuel Performance

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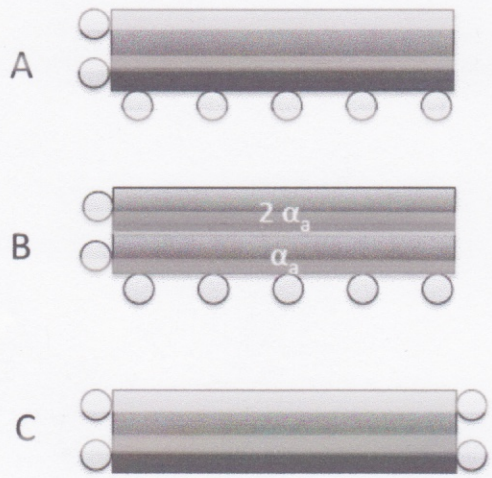
1. For each of the following scenarios, does thermal expansion lead to stress? (6 pts)
   a) No
   b) Yes
   c) Yes



2. Name three US fuel performance codes: (6 pts)

   BISON
   FALCON
   FRAPCON   etc.
   FRAPTRAN

3. What is the valence state of U in UO2? What are the possible valence states of U? (4 pts)

   +4   +3, +4, +5, +6

4. Provide an example of a 0-D defect. Provide an example of a 3-D defect. (6 pts)

0-D: vacancy, interstitial

3-D: precipitate, void, 2nd phase, etc.

5. Name three properties that vary as a function of stoichiometry in UO2. (6 pts)

thermal conductivity
lattice constant
vacancy formation energy
oxygen diffusion
Xe diffusion etc.

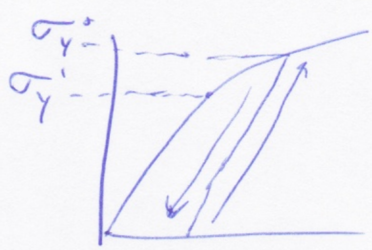
6. How does grain size affect the mechanical properties of a material? (8 pts)

- Smaller grain size inhibits dislocation motion, thus strengthening the material
  → increase in yield strength

- smaller grain size increases grain boundary length. grain boundaries are weak. thus fracture toughness decreases, more brittle material

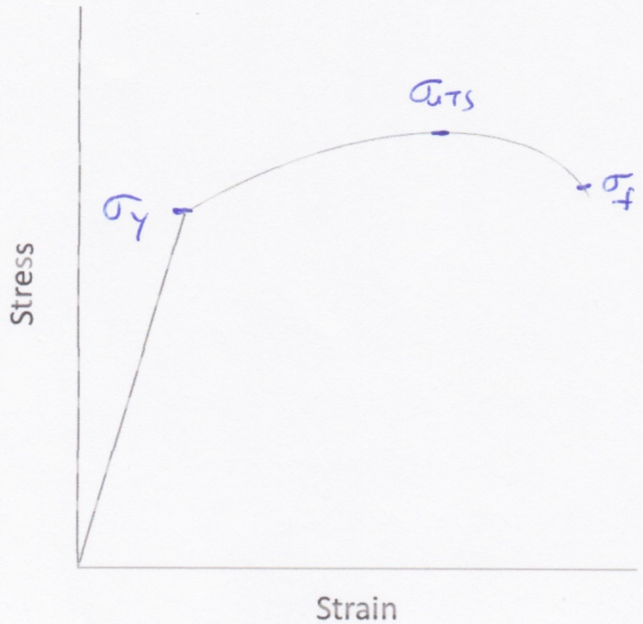
7. Define strain hardening. What causes strain hardening? (8 pts)

→ plastic deformation leading to an increase in the yield strength of a material



→ dislocations allow for plastic deformation. when dislocation density increases, can have dislocation pileup, which slows dislocation motion and increases strength

8. Given the below stress/strain curve, answer the following questions:



a. Label the yield stress, the ultimate tensile stress, and the fracture stress. (6 pts)

b. How would one determine the Young's modulus from the stress-strain curve? (4 pts)

→ slope of stress vs strain in the elastic region (before yielding)

9. Describe the differences between elastic and plastic deformation. (8 pts)

→ elastic is stretching of bonds. temporary deformation that is reversible.

→ plastic is breaking of bonds, deformation is permanent. leads to material shape change.

10. Consider a fuel rod with a pellet radius of 4.5 mm that is experiencing a linear heat rate of 250 W/cm. What is the maximum stress experienced by the pellet, assuming that the fuel has k = 0.1 W/cm-K, E = 290 GPa, ν = 0.3, and α = 8.2e-6 1/K? (12 pts)

$$\sigma_{max} = \sigma_\theta (r = R_F)$$

$$\sigma_\theta = -\sigma^* (1 - 3\eta^2)$$

$$\sigma^* = \frac{\alpha E (T_0 - T_s)}{4(1-\nu)} \qquad \eta = \frac{r}{R_F} \rightarrow \frac{R_F}{R_F} = 1$$

$$\Delta T = T_0 - T_s = \frac{LHR}{4\pi k_F} = \frac{250}{4\pi(0.1)} = 199 \text{ K}$$

$$\sigma^* = \frac{(8.2\times10^{-6})(290\times10^3 \text{ MPa})}{4(1-0.3)}(199) = \boxed{169 \text{ GPa}}$$

$$\sigma_\theta = -\sigma^* (1 - 3\eta^2)$$

$$\sigma_\theta = -169(1 - 3(1^2)) = \boxed{338 \text{ GPa}}$$

11. Consider the stress state in a zircaloy fuel rod pressurized to 20 MPa with an average radius of 5.6 mm and a cladding thickness of 0.6 mm.

a) Calculate all three components of the stress using the thin walled cylinder approximation. (6 pts)

$\sigma_\theta = \frac{pR}{\delta}$ $\sigma_z = \frac{pR}{2\delta}$ $\sigma_r = -\frac{1}{2}p$

$p = 20$
$\delta = 0.6$
$R = 5.6$

$$\boxed{\begin{aligned} \sigma_\theta &= 187 \text{ MPa} \\ \sigma_z &= 93 \text{ MPa} \\ \sigma_r &= -10 \text{ MPa} \end{aligned}}$$

b) Calculate all three components of the stress at the midpoint assuming a thick-walled cylinder. (8 pts)

$$\sigma_r = -p \frac{(R_o/r)^2 - 1}{(R_o/R_i)^2 - 1} \qquad \sigma_\theta = p \frac{(R_o/r)^2 + 1}{(R_o/R_i)^2 - 1} \qquad \sigma_z = \frac{p}{(R_o/R_i)^2 - 1}$$

$R_i = 5.3$
$R_o = 5.9$

$r = 5.6$ $\frac{R_o}{r} = \frac{5.9}{5.6} = 1.05$ $\frac{R_o}{R_i} = 1.11$

$$\sigma_r = -20 \frac{1.05^2 - 1}{1.11^2 - 1} = \boxed{-8.8 \text{ MPa}} \qquad \sigma_\theta = 20 \frac{1.05^2 + 1}{1.11^2 - 1} = \boxed{181 \text{ MPa}}$$

$$\sigma_z = \frac{20}{1.11^2 - 1} = \boxed{86 \text{ MPa}}$$

c) Calculate the maximum strain, with the stress components from (b) and with E=180 GPa and ν=0.28. (4 pts)

max strain from max stress $\rightarrow$ ϵ_θ

$$\epsilon_\theta = \frac{1}{E}\left(\sigma_\theta - \nu(\sigma_r + \sigma_z)\right) = \frac{1}{180 \times 10^3}\left(181 - 0.28(-8.8 + 86)\right)$$

$\epsilon_\theta = 8.85 \times 10^{-4}$

12. Calculate the centerline temperature of the fuel before and after thermal expansion. R_f = 0.5 cm. t_{gap} = 0.02 cm, $T_{C\mathbb{Q}}$ = 450 K, k_{fuel} = 0.05 W/cm-K, k_{gap} = 0.04 W/cm-K, k_{clad} = 0.15 W/cm-K, LHR = 325 W/cm, $\alpha_c = 4.5\text{x}10^{-6}$ 1/K, $\alpha_f = 15\text{x}10^{-6}$ 1/K, T_{ref}(fuel=clad) = 300 K. (18 pts).

Remember: $\Delta T_{gap} = \frac{LHR}{2\pi R_f k_{gap}/\delta_{gap}}$

$$T_s - T_{cl} = \Delta T_{gap} = \frac{LHR\ \delta_{gap}}{2\pi R_f\ k_{gap}} = \frac{325}{2\pi(0.5)}\frac{0.02}{0.04} = 51.7\text{ K}$$

$$T_s = 450\text{ K} + 51.7\text{ K} = 501.7\text{ K}$$

$$\Delta T_f = T_0 - T_s = \frac{LHR}{4\pi k_f} = \frac{325}{4\pi(0.05)} = 517\text{ K}$$

$$T_0 = \Delta T_f + T_0 = 501.7 + 517 = \boxed{1018\text{ K}}$$

$$\Delta t_{gap} = \bar{R}_c\alpha_c(\bar{T}_c - T_{ref}) - \bar{R}_f\alpha_f(\bar{T}_f - T_{ref})$$

$$\bar{T}_c = 450\text{ K} \qquad \bar{T}_f = \frac{1018 + 501.7}{2} = 760\text{ K}$$

$$\Delta t_{gap} = 0.52\,(4.5\times10^{-6})(450-300) - 0.5\,(15\times10^{-6})(760-300)$$

$$\Delta t_{gap} = -0.0031$$

$$t_{new} = 0.02 - 0.0031 = 0.017\text{ cm}$$

$$\Delta T_{gap} = \frac{325}{2\pi(0.5)}\frac{0.017}{0.04} = 44\text{ K}$$

ΔT_f is unchanged

$$T_0 = \Delta T_f + \Delta T_{gap} + T_{cl} = 517 + 44 + 450 = \boxed{1011\text{ K}}$$