Chapter 6. Radiation Effects

{Portions from Smith and Olander books}

SUMMARY OF RADIATION EFFECTS

General Comment:

- Defect concentration increases with fluence
- Nuclear transmutation occurs
- Chemical reactivity changes
- Particle diffusion increases
- New phases, both equilibrium and non-equilibrium, occur
- Impurities are produced

- The changes of properties are, in general, proportional to radiation flux, particle energy, irradiation time and temperature

Structural & Mechanical

- Hardness and strength increase [radiation hardening] - due to increased defects mainly dislocations, precipitates, etc
- Ductility decreases [radiation embrittlement]
- Strain hardening decreases [or $\varepsilon_u$ decreases]
- DBTT increases [embrittlement]
- Fracture toughness decreases [upper-shelf energy, $C_v^{\text{upper-shelf}}$, decreases]
- Creep enhancement [radiation-induced and radiation-enhanced] - due to increased defects and diffusion-rates
- Low cycle fatigue life decreases and high cycle fatigue life increases - due to embrittlement and hardening respectively

Nuclear

- Burnup increases
- Reactivity decreases

Physical Properties

- Density decreases or volume increases [radiation swelling] - due to voids, cavities, depleted zones
- Electrical resistivity increases [or conductivity decreases] - due to increased defect concentration
- Magnetic susceptibility decreases
- Thermal conductivity decreases - due to increased defect concentration
Examples: (see Text) Fig. 5-2: Effects of radiation on various materials

**Reactivity:**

**Magnetic Properties**

**Thermal Properties:**
Mechanical Properties

300Cat Alloys Al-U
304 & 3416 SS (fcc)
A302B – PV Steel (bcc)

Fig. 5-4: Radiation effect on $\sigma$ - $\varepsilon$ curves (see also Fig. 18-15)

Friction ($\sigma_i$) and Source ($\sigma_s$) Hardening Terms

$$\sigma_y = \sigma_i + \sigma_s = \sigma_o + \frac{k_y}{\sqrt{d}} \Leftrightarrow \text{Hall-Petch Equation \{}\sigma_i = \sigma_{LR} + \sigma_{SR} \text{Eq.18-22\}} $$

$\sigma_i \uparrow$ with $\phi t$ & $\sigma_s^0 = 0$ and $\uparrow$ with $\phi t$  \hspace{1cm}  $\sigma_i \uparrow$ with $\phi t$ & $\sigma_s^0 \neq 0$ and $\downarrow$ with $\phi t$
Radiation Embrittlement of Ferritic Steels
(PV, reactor support steels, etc.) Figs. 5-7, 5-8 & 18.44 to 18.46:

Eq. 18.112: \[ \Delta T_{DBTT} = -\frac{\Delta \sigma_i}{\sigma_y k_y \left( \frac{d \sigma_y}{dT} + \frac{dT}{dT} \right)} \]

where \[ \Delta \sigma_i \propto \sqrt{\Delta \rho} \sim \sqrt{\phi t} \] (HW 10-2)

leads to increased DBTT (RTNDT) and decreased USE (upper shelf energy) due to radiation exposure \( \Rightarrow f(Cu, P, Ni, \phi_t, T_{irr}) \), base, weld and HAZs behave differently with weld metal being highly radiation sensitive - minimize by reducing the alloy content (particularly Cu, P and Ni).

⇒ existing structures - probable thermal annealing

- exhibit Radiation Anneal Hardening (RAH) due to C and N migrating to dislocations during annealing of irradiated steels

Vs He-Embrittlement of SSs (Breeder reactors) - section 18.10
Effect of Radiation on Creep & Fatigue

Creep
Recall \( \dot{\varepsilon}_s = A D \sigma^n \), where
\[ D \propto C_v e^{-Em/kT} \]
The vacancy concentration has now two components, thermal and neutron-induced:
\[ C_{v,irr} = C_{v,th} + C_{v,*} \]
where the superscripts th and * represent thermal and radiation respectively.
At low temperatures: thermal vacancies are negligible (\( C_{v,th} \approx 0 \)), creep would be negligible. But radiation-produced vacancies (which are not in thermal equilibrium but \( \propto \phi t \)) could be large enough to induce creep.
Whereas at high temperatures where creep already occurs in the absence of radiation, radiation enhances creep.
The radiation induced creep is shown to be proportional to stress and fluence,
\[ \dot{\varepsilon}_s^* = B \phi \sigma \quad \text{or} \quad \dot{\varepsilon}_s^* = B \phi \sigma t \]
\( \Leftrightarrow \) temperature insensitive
Thus, at low temperatures:
**radiation-induced creep**
\[ \dot{\varepsilon}_{s,irr} = \dot{\varepsilon}_s^* + \dot{\varepsilon}_{s,th} \sim \dot{\varepsilon}_s^* = B \phi \sigma \]
and, at high temperatures:
**radiation-enhanced creep**
\[ \dot{\varepsilon}_{s,irr} = \dot{\varepsilon}_s^* + \dot{\varepsilon}_{s,th} = B \phi \sigma + A D \sigma^n , n \sim 5. \]

Fatigue
Recall universal slopes method:
\[ \Delta \varepsilon = A N_f^{-0.6} + B N_f^{-0.12} \]
The first term represents the LCF which is controlled by *ductility*
\( A \propto D \) or RA
D is ductility and RA reduction in area.
The second term represents HCF controlled by *strength*:
\( B \propto \) strength \( (\sigma_{TS}) \)
Since radiation exposure results in hardening and embrittlement, fatigue strength (life) decreases in LCF and increases in HCF.