Design Criteria—Fracture Toughness

• Even though one knows $\sigma_{ys}$, $\sigma_u$, and $E$, how does one deal with materials of varying thicknesses which contain notches (cracks)?

Stress Intensity Factors

• Defined by G. R. Irwin as:

$$K = \sigma_{ave} \sqrt{\pi c}$$

where $\sigma_{ave} =$ average stress
$c =$ half length of the crack

• Mode of Deformation (figure 13-8)

$K_I$, $K_{II}$, $K_{III}$,.....

• Fracture toughness, $K_c$

$K_c$ represents a critical event similar to yielding in a simple tensile test. The notch, or flaw, suddenly begins to grow, and complete fracture occurs.

• $K_c$ depends on thickness of specimen

(Figure 13-10)

$K_{lc}$ is the plane strain fracture toughness and the "safe" value
• Crack arrest toughness, $K_{la}$

*Ability of material to arrest a dynamically propagating crack under plain strain conditions*

**Problem**

The steel 4340 is chosen for a certain structural member. It has the following properties:

\[
\sigma_{ys} = 1.5 \text{ kN/mm}^2
\]

\[
\sigma_u = 1.85 \text{ kN/mm}^2
\]

\[
K_{lc} = 1.5 \text{ kN/mm}^{3/2}
\]

What is the largest crack that can be tolerated in this steel if the maximum average operating stress is 60% of the ultimate strength?

**Answer**

The critical stress is:

\[
\sigma_c = \frac{K_{lc}}{\sqrt{\pi C}} = 0.6\sigma_u
\]

and the largest allowable crack is:

\[
2c = \frac{2K_{lc}^2}{(0.6\sigma_u)^2\pi} = 1.1\text{mm}
\]
• Relationship between allowable fracture toughness, operating temperature, and DBTT (see figure 3-4).

  Note: Data obtained in reactors at $10^{13}$ n/cm²-s may give slightly different results than a $10^{10}$ n/cm²-s flux at RPV walls.

• What is the final DBTT that should be used?

  Final DBTT = Initial DBTT + $\Delta$DBTT + Margin

• Below 4 x $10^{19}$ n/cm²:

  $\Delta$DBTT = \([470\text{Cu} + 350(\text{Cu x Ni}) - 10] f^{0.27}\) \[3-2\]

  where Cu, Ni = wt%
  DBTT in °F
  $f =$fluence in units of $10^{19}$

• Above 4 x $10^{19}$ n/cm²:

  $\Delta$DBTT = 283 $f^{0.194}$

• Margin Term (use 2 standard deviations)

  $2\sigma = 2\sqrt{\sigma_0^2 + \sigma_d^2}$

  where $\sigma_0 = 0$ if DBTT is measured
  $= 17$ if DBTT not measured

  $\sigma_d = 24$ if $\Phi t < 4 \times 10^{19}$
= 0 if $\Phi t > 4 \times 10^{19}$

all values in °F

Recent Guidelines

• USNRC Reg. Guide 1.99 Rev. 2

$$\Delta DBTT = [CF] f(0.28-0.1 \log f) \quad [3-5]$$

where $CF$ is a function of Cu & Ni and a table is given in Reg. Guide 1.99, Rev. 2

• For the new margin,
  $$\sigma_d = 28 \text{ for welds}$$
  $$\sigma_d = 17 \text{ for base metals}$$

• Note correlation with observed and calculated $\Delta DBTT$,
  (Figure 3-5), (Table 3-3)

USNRC Upper Shelf Toughness Requirements

• 10 CFR 50, Appendix G specifies a minimum upper shelf Charpy impact energy requirement of 68 J (50 ft-lb)

• 10 CFR 50 also requires that the NRC be notified 3 years in advance of the date when it is estimated that the 68 J limit will be violated

• At least 10 US reactors are expected to approach or violate the 68-J limit
before the expiration of their current operating licenses.

**Fatigue**

- Second leading cause of failure in PWR vessels

(However, in some US plants with low-radiation-sensitive materials [i.e., Cu< 0.1 wt. % and Ni< 0.6 wt. %] and fluences < 5 x 10^{18} n/cm^2, fatigue could become the leading cause of failure)

- Fatigue failure consists of 2 major stages:
  a.) Crack initiation
  b.) Crack growth

- PWR's have advantage over BWR's in crack initiation because of the low O_2 concentration in PWR's.

- Crack growth rates:
  Sub-surface cracks: \( \frac{da}{dn} = (0.0267 \times 10^{-3}) \Delta K^{3.726} \text{ in cycle} \)

  Surface cracks: large \( \Delta K \)'s
  \( \frac{da}{dn} = (1.01 \times 10^{-1})(3.75R + 0.06)\Delta K^{1.95} \text{ in cycle} \)

  small \( \Delta K \)'s
  \( \frac{da}{dn} = (1.02 \times 10^{-6})(26.9R - 5.725)\Delta K^{5.95} \text{ in cycle} \)
where \( R = \frac{K_{\text{min}}}{K_{\text{max}}} \)

**Effect of Environment**

- See figure 3-6 for the combined effects of mechanical (cycle dependent) and corrosion (time dependent) crack growth.

**Mitigation of Embrittlement Damage**

- **Reduction of Thermal Stresses**
  
  1) Change operating procedures to eliminate off-normal events  
  2) Physically change the plant design

- **Flux Reductions**
  
  1) Use low-leakage core loading pattern (25-50% effect)  
  2) Shielding by placing steel rods or dummy fuel elements at outer edge (up to 90% effect)

- **Thermal Annealing**
  
  - Wet annealing (with water) at 345 °C has been accomplished in 2 reactors
Dry annealing (in air) @ 430 to 475 °C has been accomplished in Russian, Finnish, and US reactors.

-See figure 3-8 for extent of annealing

• Surveillance Programs

-See figure 3-9 for location of retrievable specimens

-See figure 3-10, 3-11 for flux profiles

-Anisotropy of materials properties is addressed by taking specimens from different rolling directions (figure 3-12)