Design Criteria-Fracture Toughness

- ***Even though one knows σ_{ys}, σ_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 σ_{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.

- **Kc depends on thickness of specimen**

(Figure 13-10)

K_{Ic} is the plane strain fracture toughness and the "safe" value

- **Crack arrest toughness, K_{Ia}**

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:

$$\sigma_{ys} = 1.5 \frac{kN}{mm^2}$$

$$\sigma_u = 1.85 \frac{kN}{mm^2}$$

$$K_{Ic} = 1.5 \frac{kN}{mm^{3/2}}$$

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:

$$\sigma_c = \frac{K_{Ic}}{\sqrt{\pi c}} = 0.6\sigma_u$$

and the largest allowable crack is:

$$2c = \frac{2K_{Ic}^2}{(o.6\sigma_u)^2 \pi} = 1.1mm$$

- **Relationship between allowable fracture toughness, operating temperature, and DBTT (see figure 3-4).**

Note: Data obtained in reactors at 10^{13} n/cm^2-s may give slightly different results than a 10^{10} n/cm^2-s flux at RPV walls

- **What is the final DBTT that should be used?**

Final DBTT = Initial DBTT + ΔDBTT + Margin

- **Below 4×10^{19} n/cm^2:**

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

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

- **Above 4×10^{19} n/cm^2:**

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

- **Margin Term (use 2 standard deviations)**

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

where σ_o = 0 if DBTT is measured
= 17 if DBTT not measured

σ_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**

$$\Delta DBTT = [CF]\, f^{(0.28-0.1 \log f)} \qquad [3\text{-}5]$$

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

- **For the new margin,**

  σ_d **= 28 for welds**

  σ_d **= 17 for base metals**

- **Note correlation with observed and calculated ΔDBTT,**

  (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: $\frac{da}{dn} = \left(0.0267 x 10^{-3}\right)\Delta K^{3.726} \ \frac{in}{cycle}$

Surface cracks: large ΔK's

$$\frac{da}{dn} = \left(1.01 x 10^{-1}\right)(3.75R + 0.06)\Delta K^{1.95} \ \frac{in}{cycle}$$

small ΔK's

$$\frac{da}{dn} = \left(1.02 x 10^{-6}\right)(26.9R - 5.725)\Delta K^{5.95} \ \frac{in}{cycle}$$

where $R = \frac{K_{min}}{K_{max}}$

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)