

AE 737: Mechanics of Damage Tolerance

Lecture 17 - Crack Propagation

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schedule

- 19 Mar - Crack growth, HW6 Due
- 23-27 Mar - Spring Break
- 31 Mar - Crack growth
- 2 Apr - Crack growth, HW7 Due
- 7 Apr - Retardation

outline

- other factors affecting fatigue
- crack growth rate
- crack growth rate equations
- factors affecting crack propagation
- numerical algorithm

other factors affecting fatigue

factors affecting fatigue life

- At temperatures above one-half the melting temperature (absolute scale), creep-relaxation is significant
- This will cause the strain/stress-life curves to become rate dependent
- Occurs at room temperature for many materials (lead, tin, many polymers)
- At a sufficiently elevated temperature for any material

surface finish

- High cycle fatigue is sensitive to surface finish, samples are generally polished
- Low cycle fatigue is not sensitive to surface finish or residual stress
- The plastic deformation tends to remove residual stresses
- In high-cycle fatigue, crack initiation is important (poor surface finish allows cracks to form earlier)
- When plastic deformation is present (low-cycle fatigue), cracks form relatively quickly regardless of surface finish

surface finish

- Since low-cycle fatigue has little effect from surface finish, we could modify the strain life curve by altering only the elastic portion
- If we define the surface effect factor, m_s , we can find a new b_s to replace b in the strain-life equation

$$b_s = \frac{\log(m_s(2N_e)^b)}{\log(2N_e)}$$

surface treatments

- Treatments which decrease fatigue life:
 - Electro-plating (chrome, +corrosion resistance, -fatigue life)
 - Grinding improves surface finish, but introduces surface tension, and heat generated can temper quench
 - Stamping introduces discontinuities and irregularities
 - Forging can refine grain structure and improve physical properties, but can cause decarburization in steels, which hurts fatigue life
 - Hot rolling can also cause decarburization

surface treatments

- Some treatments improve fatigue life:
 - Cold rolling improves surface finish, introduces residual compressive stress on surface (slows crack initiation on surface)
 - Shot peening introduces many small divots on surface, which can be detrimental in corrosion, but it does cause a residual compressive stress on the surface

size

- Size can also have effects on fatigue life
- Larger parts are more susceptible to damage/imperfections at the same stress level
- This is why composites are often made from very small fibers (glass fiber, carbon fiber, ceramic-matrix composites)

size

- The exact effect of size will depend on material, one study for low carbon steels found

$$m_d = \left(\frac{d}{25.4\text{mm}} \right)^{-0.093}$$

- Which is then used to re-calculate material constants $\sigma_{fd}' = m_d \sigma_f'$, $\epsilon_{fd}' = m_d \epsilon_f'$

thermal fatigue

- Thermal loading can be introduced when two dissimilar parts are attached together, the coefficient of thermal expansion causes them to expand differently, introducing extra stresses due to the temperature change
- If the temperature is significantly different between two sides of a part thermal stresses can also be introduced

thermal fatigue

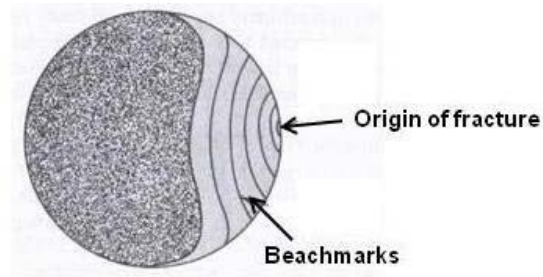
- Low temperatures generally cause a material to behave in a more brittle fashion, which alters the fatigue life
- High temperatures cause problems with creep-relaxation and can also affect the crystalline structure

crack growth rate

fracture surface



fracture surface



Fatigue Fracture with Beachmarks

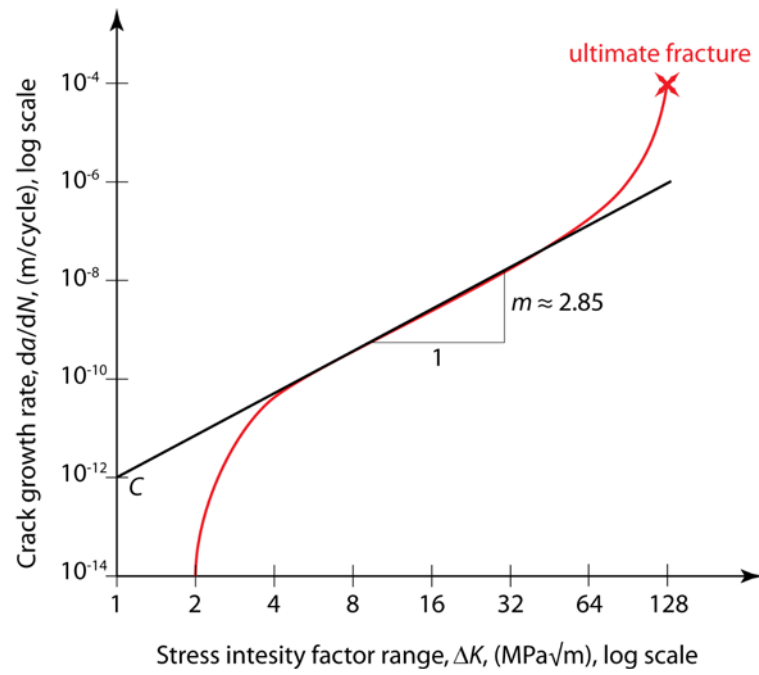
crack growth rate

- We can observe that fatigue damage occurs through crack propagation
- “cracks” and fracture mechanics have been omitted from all our fatigue discussion thus far
- It would be beneficial to predict at what rate a crack will extend

crack growth rate

- Crack growth rate can be measured experimentally
- Using a center-crack specimen, a fatigue load is applied
- The crack length is measured and plotted vs. the number of cycles
- The slope of this curve ($\frac{da}{dN}$) is then plotted vs. either $K_{I\max}$ or ΔK_I on a log-log scale
- This chart is then commonly divided into three regions

da-dN vs K



region I

- In Region I crack growth is very slow and/or difficult to measure
- In many cases, da/dN corresponds to the spacing between atoms!
- The point at which the da/dN curve intersects the x-axis (usually with a relatively vertical slope) is called the fatigue threshold
- Typically 3-15 $\text{ksi}\sqrt{\text{in}}$ for steel
- 3-6 $\text{ksi}\sqrt{\text{in}}$ for aluminum

region II

- Most important region for general engineering analysis
- Once a crack is present, most of the growth and life occurs in Region II
- Generally linear in the log-log scale

region III

- Unstable crack growth
- Usually neglected (we expect failure before Region III fully develops in actual parts)
- Can be significant for parts where we expect high stress and relatively short life

crack growth rate curve

- The crack growth rate curve is considered a material property
- The same considerations for thickness apply as with fracture toughness (K_c vs. K_{Ic})
- Is also a function of the load ratio, $R = \sigma_{min}/\sigma_{max}$

R effects

- While the x-axis can be either ΔK or K_{max} , the shape of the data is the same
- When we look at the effects of load ratio, R , the axis causes some differences on the plot
- With ΔK on the x-axis, increasing R will shift the curve up and to the left, shifting the fatigue threshold and fracture toughness on the graph as well

R effects

- With K_{max} on the x-axis, increasing R shifts the curve down and to the right, but fatigue threshold and fracture toughness keep same values
- In general, R dependence vanishes for $R > 0.8$ or $R < -0.3$. This effect is known as the band width

crack growth rate equations

crack growth rate equations

- There are many crack growth rate equations of varying complexity
- The “best” form to use will depend on design needs

growth equations

- The important features in curve-fit equations are
 1. Region II curve fit (linear on log-log scale)
 2. Region I curve fit (fatigue threshold)
 3. Region III curve fit (critical stress intensity)
 4. Stress ratio effects
 5. Band width of R-curves

paris law

- The original
- Fits the linear portion (Region II)
- Does not fit Region I, Region III, or have R-dependence

$$\frac{da}{dN} = C(\Delta K)^n$$

- Note: this assumes the x-axis is ΔK , but $\Delta K = (1 - R)K_{max}$, so we can easily convert

walker

- Region II is usually all that is needed for engineering, but R-dependence is often an important effect to capture
- Walker modified the Paris law to account for R-dependence

$$\frac{da}{dN} = C[(1 - R)^m K_{max}]^n$$

- Gives a good fit for Region II with R-dependence and band width

forman

- The Forman equation was developed to capture the effects of Region II and Region III
- Also includes the effects of R , but does not control the band width of R effects

$$\frac{da}{dN} = \frac{C[(1 - R)K_{max}]^n}{(1 - R)K_c - (1 - R)K_{max}}$$

modified forman

- The Forman equation can be modified to include the effect of band width

$$\frac{da}{dN} = \frac{C[(1 - R)^m K_{max}]^n}{[(1 - R)^m K_c - (1 - R)^m K_{max}]^L}$$

collipriest

- The Collipriest equation fits Regions I, II and III, but has no R-dependence

$$\frac{da}{dN} = C_1 + C_2 \tanh^{-1} \left[\frac{\log \left(\frac{K_{max}^2}{K_o K_c} \right)}{\log(K_c / K_o)} \right]$$

modified collipriest

- Following the same methods as before, we can modify the Collipriest equation for R-dependence and band width control

$$\frac{da}{dN} = C_1 + C_2 \tanh^{-1} \left[\frac{\log \left(\frac{(1-R)^m K_{max}^2}{K_o K_c} \right)}{\log(K_c / K_o)} \right]$$

- For a cleaner graph, experimental data at different R-values is sometimes plotted vs. K_{eff}
- $K_{eff}^* = (1 - R)^m K_{max}$

nasgrow growth rate equation

- A very complicated curve fit is provided in the NASGROW growth rate equation

$$\frac{da}{dN} = C \left[\frac{1-f}{1-R} \Delta K \right]^n \frac{\left[1 - \frac{\Delta K_{th}}{\Delta K} \right]}{\left[1 - \frac{K_{max}}{K_{crit}} \right]}$$

- The curve fit parameters can be found in p. 307 of your text (or the NASGROWLW/AFGROW documentation)

boeing-walker growth rate equation

- The Boeing-Walker growth equation is given as (for $R \geq 0$)

$$\frac{da}{dN} = 10^{-4} \left(\frac{1}{mT} \right)^p [K_{max}(1 - R)^q]^p$$

conversion of constants

- Much of the data available to us is from Boeing, and given in terms of the Boeing-Walker equation
- We can re-write some other equations to more easily convert parameters between the various equations
- Walker-Boeing:

$$\frac{da}{dN} = 10^{-4} \left(\frac{1}{mT} \right)^p [\Delta K (1 - R)^{q-1}]^p$$

- Walker-AFGROW:

$$\frac{da}{dN} = C_w [\Delta K (1 - R)^{m-1}]^{n_w}$$

- Forman:

$$\frac{da}{dN} = \frac{C_F}{(1 - R)K_c - \Delta K} (\Delta K)^{n_f}$$

conversion of constants

Walker-Boeing	Walker-AFGROW	Forman
$10^{-4}\left(\frac{1}{mT}\right)^p$	$C_w = 10^{-4}\left(\frac{1}{mT}\right)^p$	$C_F = (K_c - 1)10^{-4}\left(\frac{1}{mT}\right)^p$
q	$m = q$	
p	$n_w = p$	$n_f = p$

paris example

- A wide center-cracked panel with $C = 6.75 \times 10^{-10}$ and $n = 3.89$ (with units in ksi and inches)
- If the crack is initially 1 inch long, find the crack length after 5,000 cycles of 15 ksi loading
- What if the load cycles varied from 5 ksi to 15 ksi? ($m = 0.6$)

factors affecting crack propagation

factors affecting crack propagation

- thickness
- stress ratio
- temperature
- environment
- frequency
- crack orientation
- manufacturer
- heat treatment

thickness

- We already discussed the effects of thickness on fracture toughness
- The same effects are important in crack propagation
- In thin (plane stress) plates, cracks can be treated as through cracks
- In thick plates (plain strain), we generally need to consider the crack shape

thickness

- Cyclic life is primarily a function of K_i/K_c where K_i is the stress intensity factor in the first cycle
- Other experiments indicate a relationship between $\frac{d(a/Q)}{dN}$ and K_{max}
- Q is a shape parameter for elliptical flaws

temperature

- In general (for most aluminum alloys) cracks propagate more slowly with a decrease in temperature
- This trend is exactly opposite the trend for K_{IC}
- The effect varies in different materials
- Most materials benefit from slightly lower temperatures, but as temperatures are further decreased the crack growth rate increases again

temperature

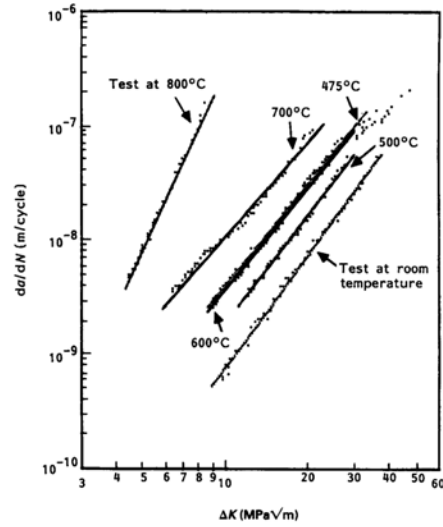


Fig. 2 Mid-range fatigue crack-growth rates with alternating stress intensity factor for 18%Cr-Nb ferritic stainless steel at room temperature, 475, 500, 600, 700 and 800°C; $R = 0.1$, $f = 15$ Hz

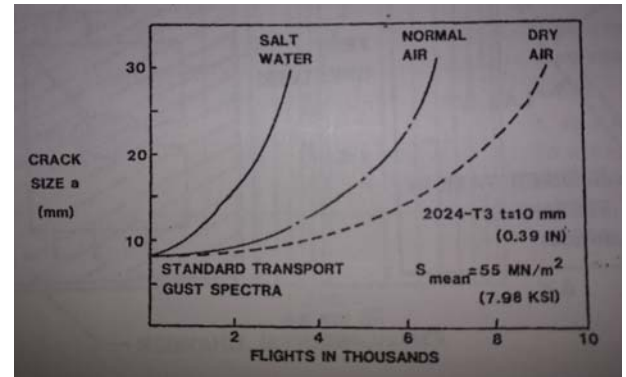
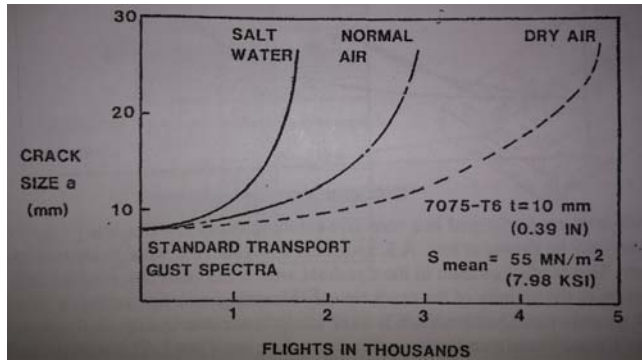
temperature

- In general, temperature effects can not be predicted well
- Instead, materials should be tested at a range of temperatures to establish a range of operating temperatures with corresponding crack growth data

environment

- There are many conditions in the environment that can affect crack growth
- Moisture greatly increases the crack growth rate
- Salt water increases crack growth rate even further
- These effects have varying strength depending on the material used

environment



environment

- Further, the shape of the applied load curve has a significant effect when combined with adverse environments
- Crack growth is faster when the load increases slowly and decreases rapidly
- Crack growth is slower when the load increases rapidly and decreases slowly

environment

- When the environment is corrosive, the test frequency is of particular importance
- At low frequencies, a corrosive environment increases the threshold, K^{th}
- However in Region II, crack growth is faster
- This effect can be explained by the corrosive environment blunting the crack tip

frequency

- There is conflicting information about the effect of frequency in the absence of a corrosive environment
- Some experiments have found a frequency dependence, while others have not
- Many claim that the frequency dependence is due to small amounts of water in air during frequency dependence experiment

crack orientation

- For rolled plates, a crack will generally propagate faster parallel to the rolling direction
- In many materials, however, the difference between orientations is not significant when compared to scatter, and it is often neglected
- Some materials behave very differently with different crack orientations (i.e. the slope of the paris law curve is different), so care should be taken based on the material used

manufacturer

- Different manufacturers of the same material can produce different crack growth rates
- Some reasons for this may be
 - Slight variation in composition
 - Site cleanliness (inclusions)
 - Heat treatment/cold rolling variations

heat and surface treatments

- Different heat and surface treatments are often applied
- They provide various benefits (corrosion resistance, residual stress, residual stress relief)
- But they will also affect the crack growth rate

numerical algorithm

numerical algorithm

- While the Paris Law can be integrated directly (for simple load cases), many of the other formulas cannot
- A simple numerical algorithm for determining incremental crack growth is

$$a_{i+1} = a_i + \left(\frac{da}{dN} \right)_i (\Delta N)_i$$

- This method is quite tedious by hand (need many a_i values for this to be accurate)
- But is simple to do in Excel, MATLAB, Python, or many other codes
- For most accurate results, use $\Delta N = 1$, but this is often unnecessary
- When trying to use large ΔN , check convergence by using larger and smaller ΔN values

boeing-walker example

- Use the Boeing-Walker equation to find the crack length after 20000 cycles of 15 ksi load on a large, center-cracked sheet of bare 2024-T3 in dry air, with an initial crack of 0.5”
- Use the numerical algorithm with $\Delta N = 1000$

convergence example

- compare the results from the previous example with $\Delta N = 10, 100, 10000$ and direct integration

variable load cases

- In practice variable loads are often seen
- The most basic way to handle these is to simply calculate the crack length after each block of loading
- We will discuss an alternate method, which is more convenient for flight “blocks” next class
- We will also discuss “retardation” models next class

variable load example

- For the same material as above (2024-T3, center-cracked, dry air), consider 20000 cycles with 15 ksi load followed by 10000 cycles of 5 - 20 ksi.