Introduction to Fatigue and Cyclic Crack Growth of Metals

29 Sept 2011
Thomas Meyer, LLC
Introduction to Fatigue and Cyclic Crack Growth of Metals

• What is fatigue cracking & why is it important

• Fatigue Crack Formation
  • The basics of the process
  • Basic prediction methods
  • Complications

• Fatigue Crack Growth
  • The theoretical basis of fracture mechanics
  • Application to fatigue crack growth.
  • Complications

• Other practical considerations.
What is Fatigue?

Repeated application of stress greater than $\sim \frac{1}{2}$ of a metal’s Ultimate Strength can lead to the formation and growth of cracks.
Fatigue & Fracture techniques model the entire fatigue process.

- Crack Size
- Cycles
- Crack Formation
- Micro-structural scale
- Small Crack Growth
- Long Crack Growth
- Undisturbed Far-field stresses
- Structural Interaction with crack

**Traditional Fatigue Crack Formation**

- Traditional Fracture Mechanics
- Alabama Specialty Product, Inc
- Dirats Laboratories
- Hardman, NAVAIR, DARPA/DSO Conf.

29 Sept 2011

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Why is fatigue and fatigue analysis important?
C130A Wing Separations
June 2002, Walker CA.
& Aug 1994, Pearblossom, CA

Firefighting missions
Fatigue crack missed during inspection.

Fatigue cracks in Center Wing Box

1. Lockheed Martin Service News, Vol 30, No.2 2005
2. NTSB Press Release, 9/24/02
Fatigue Cracks in Bridges

St Aubrey Cosens Memorial Bridge, Montreal River, Jan 2003

Blanchet Bridge, I70 St Louis Mo.

Crack started from a weld.

Fatigue of Tie Rod

Missouri DOT RI05-036

Ministry of Transportation, Canada
Fatigue Fracture of High Speed Train Carriage Wheel

- Train Derailed, June 3, 1998. Eschede, Germany
- Worst rail disaster in German history. 101 deaths.
- Excessive load and wear. Scheduled inspections not performed.
- Three engineers brought to trial and fined.
Fatigue of Electrical Connections

Defibrillator Lead
5 deaths
250,000+ vulnerable

Fatigue cracking from inclusions in wire

Circuit Board Solder Joint Fatigue Crack

J. Schaffer, Fort Wayne Metals Research Products Corporation & Purdue University
Presented May 19th, 2006 at the 9th International Fatigue Congress, Atlanta

Danish National Consumer Agency
Key Fatigue Characteristics evolve through all stages of manufacturing

Key fatigue & fracture Characteristics

Phases, particles, segregation

Microstructure, texture

Bulk residual stress

Surface residual stress

Final Fatigue & Fracture Capability

Ingot
Melt practice
Cogging
Forging
Heat Treatment
Machining, grinding
Finishing
Joining
Shot Peening, media finish
Laser shock peening
Low Plasticity Burnishing
Fatigue and Fracture properties are affected by many “Material Attributes”

Attributes usually controlled by a material’s specification e.g. AMS number, company standards, part drawing.

**“Material”**
- Chemical composition
- Cleanliness (e.g. commercial quality, air melt, vacuum melt, etc)

**Form** of the material and processing
- Casting, un-HIP’d, HIP’d
  - Location in the casting
- Forging, Bar, Extrusion, Plate, Sheet
  - Texture & cold working
- Powder Metal
- Microstructure, grain size
- Overall size
- Heat treatment, overall size
- Hardness

Attributes usually controlled by part fabrication.

**Fabrication Method**
- Method of shaping:
  - milled, ground, turned, broached, EDM, Chem. Milled
- Stretching, Bending, Spinning
- Welding
- Heat treatment

**Finish**
- Surface finish
  - As-machined surface (max allowed roughness)
  - As-cast surface
  - Polished
- Special Treatments
  - Anodize with thickness specified
  - Case hardening
  - Plating
  - Cold working
Prediction methods for Fatigue Crack Formation

Crack Size

Crack Formation
Micro-structural scale
A

B

C

Small Crack Growth

D

E

Long Crack Growth
Undisturbed Far-field stresses
Structural Interaction with crack

Log Life to crack formation

Δσ

Δε
Predicting Fatigue Life Is Not An Exact Science

- There are many methods for fatigue prediction.
- Most work reasonably well under certain conditions.
- None work well for all types of loading conditions.
- None truly predict fatigue behavior from first principles:
  - fatigue prediction is highly empirical.

- Understanding the stress and strain history at the site of the crack is key to good correlation of fatigue data (and to “prediction” of fatigue life in the field.)
Choose a life prediction method to match the stress (strain) – temperature – time regime of interest.

- **Stress** or **Strain**
- **Temperature** \( \sim \frac{1}{2} T_{\text{melt}} \) (absolute scale)
- **Large Cyclic Plastic Strains**
- **Small / Confined Plastic Strains**
- **Elastic Strains**
- **Strain-Life Methods**
- **Stress-Life Methods**
- **Creep-Fatigue Methods**
- **Dominated by Creep**
During a fatigue cycle, irreversible work is done on the material which forms cracks.

\[ \sigma_{\text{mean}} = \text{Mean Stress} = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2} \]

\[ \sigma_{\text{cyclic}} \quad \text{Cyclic Stress} \]

\[ \text{R ratio} = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \]

\[ \sigma_{\text{cyclic}} = 2\varepsilon_{\text{cyclic}} \]

At least two variables are needed to describe the hysteresis loop:

- cyclic stress & R ratio
- max stress & R ratio
- cyclic stress & steady stress
- strain range & mean stress
- area & ”location” of hysteresis loop
- ...

Dimensions: work per cubic inch

\[ \frac{\text{Lbs}}{\text{in}^2} \times \frac{\text{in}}{\text{in}} = \frac{\text{in} - \text{Lbs}}{\text{in}^3} \]
Common Stress-Life methods

- The S-N curve (Stress-Life)

- Constant Life Diagrams

Cyclic Stress

Low Cycle Fatigue (LCF)

High Cycle Fatigue (HCF)

R or mean stress = constant

1000 100,000 Millions

Cycles

Stress

Constant Amplitude, Uni-Axial Stress

Steady Stress

Constant Life

Lower Life

Higher Life

Cyclic Stress

Steady Stress
R ratio influences fatigue strength

AISI 4340 Air Melt, 200 Ksi UTS, RT Smooth, Axial Loading MMPDS03
There are several forms of Constant Life Diagrams

Combinations of $S_c$ & $S_m$ that give the same fatigue life

$R=-1$ Fatigue Strength at a certain life

- Goodman
- Modified Goodman
- Soderberg
- Gerber
Strain- Life Methods

Useful when
- the part will experience large cyclic plastic strains
- the expected fatigue life is very low (less than a few thousand cycles)
- the part is controlled by deflections or strains
  (e.g. thermally induced strains, strain at notches)

\[ \varepsilon_{\text{total}} = \varepsilon_{\text{elastic}} + \varepsilon_{\text{plastic}} \]

\[ \Delta \varepsilon_{\text{tot}} = \Delta \varepsilon_{\text{elastic}} + \Delta \varepsilon_{\text{plastic}} \]

- Requires inelastic analysis
- Is difficult to apply if
  - Residual stress is significant.
  - Surface finish effects are important.
Strain-Life Approach

- Based on smooth specimen, strain controlled tests.

\[
\frac{\Delta \varepsilon_p}{2} = \varepsilon_f (N)^c
\]

\[
\frac{\Delta \varepsilon_{el}}{2} = \frac{\sigma_f}{E} (N)^b
\]

\[
\frac{\Delta \varepsilon_{total}}{2} = \frac{\sigma_f}{E} (N)^b + \varepsilon_f (N)^c
\]

Plastic portion of Strain range

Elastic portion of Strain range ("reversible" portion of the loop)

Merges with S-N data at longer lives.

IN718
NASA TN D-7532
Some complications in real world situations

- Spectrum of loads; not constant amplitude
- Multi-axial stresses
- Non-proportional cycling
- High temperature
- Unique surface finishes & Processes
Spectrum Loading

Random stress amplitudes

Complicated, but repeatable duty cycles

Block Loading (Change in the mission)

How does damage accumulate when stress amplitude is not constant?
How do you count the number of cycles?
Rainflow Method to Identify Fatigue Cycles
Multi-axial stresses & Non-proportional cycling

Critical plane methods correlate life with Shear and Normal stress on two planes inclined 45° and 90° to the surface

• Different planes are more highly loaded during non-proportional loading.
• Orientation of the planes relative to global coordinate system may also change

There are many models proposed.

Wang
Brown
Bannantine
Miller

Dang Van
Socie
Fatemi
Kurath

Morrow
Garud
Papadopoulos
Sines
Crossland

& others
Cyclic Crack Growth

Crack Size

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Micro-structural scale

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Structural Interaction with crack

\( \frac{da}{dN} \)

\( \Delta K \)

Hardman, NAVAIR, DARPA/DSO Conf.
Stress near a crack

- Assuming no yielding, the theoretical stress is infinite at the crack tip.
- The local stress ahead of the crack is

\[ \sigma_y = \frac{K_I}{\sqrt{2\pi x}} = \frac{\phi S_{\text{nominal}}}{\sqrt{2\pi x}} \]

The “steepness” of the stress gradient near a crack is quantified by the Stress Intensity Factor, \( K_I \)

- its units are Ksi-√in
- the value of \( K_I \) depends upon
  - the applied stress \( \sigma_{\text{nominal}} \)
  - the crack length \( a \)
  - geometry of cracked body \( \phi \)
Under Cyclic Loading, the rate of crack growth is controlled by $\Delta K$, the Stress Intensity Range.

\[ \Delta K = \phi(\Delta \sigma) \sqrt{\pi a} \]

Crack growth rate increases with stress and crack length.

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

DOT/FAA/AR-05/15
R-ratio changes the crack growth rate curves

- \( R = 0.7 \)
- \( R = 0 \)
- \( R = -1 \)

Fatigue Crack Propagation Rate, \( \frac{da}{dN} \), in. / cycle

<table>
<thead>
<tr>
<th>Stress Ratio, ( R )</th>
<th>Frequency, ( f, \text{Hz} )</th>
<th>No. of Specimens</th>
<th>No. of Data Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.00</td>
<td>0.5 - 30</td>
<td>6</td>
<td>55</td>
</tr>
<tr>
<td>-0.70</td>
<td>13.7 - 30</td>
<td>6</td>
<td>52</td>
</tr>
<tr>
<td>0.00</td>
<td>0.5 - 33</td>
<td>17</td>
<td>90</td>
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<tr>
<td>0.30</td>
<td>0.5 - 33</td>
<td>9</td>
<td>102</td>
</tr>
<tr>
<td>0.70</td>
<td>0.5 - 33</td>
<td>7</td>
<td>80</td>
</tr>
</tbody>
</table>

Aluminum 7075-T6 sheet
MMPDS
Complications in fatigue crack growth:

There is significant uncertainty in the threshold region
  • Cracks on the same size scale as the material microstructure
  • Difficult to devise a test in the threshold region.

Critical crack size / fracture toughness.

Crack growth in spectrum loading depends upon loading history.
  • Retardation due to Overload
  • Crack Closure

Crack path in complicated structures is not easily known.

Stress Intensity Factors in complicated structures require high degree of idealization or FEA
The value of $K_I$ depends upon the crack length, applied stress and geometry

$$K_I = \phi S \sqrt{\pi a}$$

- $K_I$ & $\phi$ are known for many simple situations

However, .... Idealizing your complex part with one of the known solutions can be a difficult task.
When standard “K” solutions don’t work

When cracks are long compared to the structure, standard K solutions
• do not match the geometry
• do not account for load redistribution

Finite Element Analyses are needed to obtain the correct stress intensity factors.
Practical Consideration for preventing fatigue fractures
You must consider scatter in the fatigue process!

Scatter in life can be very large:
The lowest life in 1000 samples is often as low as 1/10\textsuperscript{th} of the typical life.
Working Stress Levels should account for **All** variables

A common approach is to apply “Knock-down” factors to simple specimen tests

- Stress concentration & Kf
- Temperature
- Scatter (75% of typical, A-basis)
- Surface finish & misc. effects
- Size factor (to account for volume effects. e.g. bending, torsion, section type)

- Factor of Safety
Two Complementary Elements in Designing for Fatigue

Safe Life
- Predicts how a crack develops, where none existed before.
- There is no universally accepted model from first principles.
  - All models are empirical – much data is needed.
  - None apply over all regimes of operation.
  - Each material “family” has subtle – but significant differences.

Damage Tolerance
- Sets inspection intervals in case a part is defective.
- A part is assumed to be cracked from “day one”.
- Fracture mechanics methods are used to calculate remaining life to fracture.
  - Methods are empirical – less data is needed than for Safe Life.
  - There is closer tie to theoretical mechanics than in Safe Life.
- Must inspect for cracks upon entering service & at inspection intervals.
Major Points Summary

• Fatigue & fracture is important in many industries
  • The Form Fabrication & finish of the part is important

• There are many methods to predict fatigue crack formation
  • No single method works over all regimes of loading & temperature
  • All methods are empirical. A data-base is needed
  • The key to accurate life prediction is accurate stress-strain evaluation

• Fatigue cracks have a theoretical basis for crack tip stress singularity, $K$
  • Cyclic growth rates are related empirically to $\Delta K$.
  • There are three regions of growth rate.
    • Plasticity at the crack tip affects the rate curve and how a crack grows in
      spectrum loading
    • There is uncertainty in the threshold region
  • The key to growth predictions is accurate determination of the stress intensity factor.

• Some Practical Considerations for Fatigue Fracture Prevention
  • Include factors for surface conditions, material scatter,
  • Consider accuracy & consistency of stress / strain prediction. Calibrate!
  • Consider adding a Damage Tolerance approach
Accurate Finite Element Analysis is a key ingredient of fatigue and fracture life prediction

Stress-strain history for crack initiation
• Regardless of the life regime
• Needed for all types of life models.

Stress intensity factor versus crack size for crack propagation
• Regardless of the type of crack rate model that is used
• Becomes even more critical for cracks large enough to interact with structural boundary conditions.