MMJ1133 – FATIGUE AND FRACTURE MECHANICS

F - FATIGUE CRACK GROWTH
Course Content:

A - INTRODUCTION
Mechanical failure modes; Review of load and stress analysis – equilibrium equations, complex stresses, stress transformation, Mohr’s circle, stress-strain relations, stress concentration; Fatigue design methods; Design strategies; Design criteria.

B – MATERIALS ASPECTS OF FATIGUE AND FRACTURE
Static fracture process; Fatigue fracture surfaces; Macroscopic features; Fracture mechanisms; Microscopic features.

C – FATIGUE: STRESS-LIFE APPROACH
Fatigue loading; Fatigue testing; S-N curve; Fatigue limit; Mean stress effects; Factors affecting S-N behavior – microstructure, size effect, surface finish, frequency.
D – FATIGUE: STRAIN-LIFE APPROACH
Stress-strain diagram; Strain-controlled test methods; Cyclic stress-strain behavior; Strain-based approach to life estimation; Strain-life fatigue properties; Mean stress effects; Effects of surface finish.

E – LINEAR ELASTIC FRACTURE MECHANICS
Fundamentals of LEFM – loading modes, stress intensity factor, $K$; Geometry correction factors; Superposition for Mode I; Crack-tip plasticity; Fracture toughness, $K_{IC}$; Plane stress versus plane strain fracture; Extension to elastic-plastic fracture.

F – FATIGUE CRACK PROPAGATION
Fatigue crack growth; Paris Law; $da/dN-\Delta K$; Crack growth test method; Threshold $\Delta K_{th}$; Mean stress effects; Crack growth life integration.
MMJ1133 – FATIGUE AND FRACTURE MECHANICS

Constant amplitude load cycles

- Fluctuating stress, $R < 1$
- Repeated stress, $R = 0$
- Completely reversed stress, $R = -1$
Fatigue crack growth life

Fatigue crack growth life
Stress intensity factor range, $\Delta K$

\[ K_I = \sigma \sqrt{\pi a Y} \]

\[ K_{I,\text{max}} = \sigma_{\text{max}} \sqrt{\pi a Y} \]

\[ K_{I,\text{min}} = \sigma_{\text{min}} \sqrt{\pi a Y} \]

\[ \Delta K_I = K_{\text{max}} - K_{\text{min}} = \Delta \sigma \sqrt{\pi a Y} \]
Fatigue crack growth behavior

For each data point:

\[
\frac{da}{dN} ; \quad \Delta K_I = \Delta \sigma \sqrt{\pi a Y}
\]
Fatigue crack growth behavior of Ti-48Al-xCr

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimensions (mm)</th>
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<tbody>
<tr>
<td>L</td>
<td>80.0</td>
</tr>
<tr>
<td>W</td>
<td>30.0</td>
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<tr>
<td>B</td>
<td>2.0</td>
</tr>
<tr>
<td>2a&lt;sub&gt;n&lt;/sub&gt;</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Fatigue crack growth rate

\[
\Delta K_I = \Delta \sigma \sqrt{\pi a Y}
\]
Fatigue crack growth rate behavior of Ti-48Al

Delta K (MPa m^{0.5}) vs da/dN (mm/cycle) for different Ti-48Al compositions.
Fractography

interlamellar fracture along $\alpha_2 - \gamma$ interface in lamellar phase and transgranular fracture across single $\gamma$ grains

Figure 5.12 FESEM fractographs of Ti-48Al fatigue crack growth specimen at x50 magnification (a) Crack initiation region (b) Crack propagation region (c) Fast fracture region.
Some fatigue crack growth rate models

Paris eqn. for Stage II
\[
\frac{da}{dN} = C(\Delta K)^n
\]

When \( R \neq 0 \), Broek & Schijve (1963)
\[
\frac{da}{dN} = C K_{\text{max}}^2 \Delta K
\]

For Stage II and Stage III, Forman et al. (1967)
\[
\frac{da}{dN} = \frac{C(\Delta K)^m K_{\text{max}}}{K_C - K_{\text{max}}}
\]

For Stage I, Stage II and Stage III,
\[
\frac{da}{dN} = C(\Delta K)^m \left[ 1 - \left( \frac{\Delta K_{th}}{\Delta K} \right)^{n_1} \right] \left[ 1 - \left( \frac{K_{\text{max}}}{K_C} \right)^{n_2} \right]
\]

Stephens et al., 1980
Effects of load ratio on fatigue crack growth rate behavior

For $R > 0$, (Walker)

$$\frac{da}{dN} = \frac{C(\Delta K)^n}{(1 - R)^n(1 - \lambda)}$$

$C$ and $n$ are Paris coefficient and exponent for $R = 0$
Fatigue crack growth rate data

\[ \frac{da}{dn} = 5.01 \times 10^{-9} (\Delta K)^{3.1} \]

(PARIS EQUATION)

\[ \Delta K \] (MPa V m)

\[ \frac{da}{dn} \] (m/cycle)

TITANIUM ALLOY
Ti-6Al-4V [2]

SCATTERBAND FOR HIGH STRENGTH STEELS WITH
\( \sigma \approx 730-2100 \) MPa [5]

ALUMINIUM ALLOY
2024-T3 [4]

STAINLESS STEEL
AISI 304 [6]

STEEL
Fe 510 [3]
Sample test question:
The fatigue crack growth rate behavior of an aluminum alloy is shown in Figure Q4. (i) Determine the coefficient and exponent of the Paris equation for stage II fatigue crack growth rate region, as shown by the curve. (ii) Calculate the critical length of a through-thickness edge crack for fast fracture of the plate under fatigue loading with stress amplitude of 110 MPa. Assume the geometry factor, $Y = 1.12$. (iii) Another plate of width 50 mm has a through-thickness center-crack of length 18 mm. The plate is subjected to fatigue loading with load ratio, $R = 0$. Determine the fatigue crack growth rate when the operating stress amplitude is 10 MPa.
Effect of thickness on fatigue crack propagation

When the crack grows, size of plastic zone increases, plane stress condition develops
Effect of temperature on fatigue crack propagation

At moderately low temperature, reaction kinetics are slower, which diminishes environmental effect.

At very low temperature, increased yield stress counterbalance the temperature effects.
Effect of microstructure on fatigue crack propagation

welded A516 steel

Base metal
HAZ
HAZ (800 hr)

Microstructures (10x)

Base metal
HAZ
Weld metal

M.N. Tamin, CSMLab, UTM
Fatigue crack growth rates

\[ \frac{da}{dN} \text{ (mm/cycle)} \]

\[ \Delta K_\alpha \text{ (MPa}\sqrt{m}) \]

- Base metal
- HAZ
- HAZ (800 hr)
Fatigue crack growth mechanisms

HAZ

HAZ (420 °C, 800 hours)

- Faceted planes
- Secondary cracks
- Fatigue striations
Corrosion fatigue crack growth rate

- reduce $\Delta K_{th}$
- increase $da/dN$ for a given crack-tip driving force

Figure 11.7 Corrosion fatigue crack growth rates for 4340 steel in 3 percent salt water solution [12] (reprinted by permission of the American Society for Testing and Materials).
Influence of temperature on fatigue crack growth rate behavior

Figure 11.12 Fatigue crack growth rate, \( \frac{da}{dN} \), versus stress intensity factor range, \( \Delta K \). (a) Low carbon steel at room temperature and \(-160^\circ\text{C} (113 \text{ K})\) showing a crossover [38]. (b) Fe-2.4 Si steel for region II at room temperature and at low temperatures [40] (copyright ASTM; reprinted with permission). (Note: \(^\circ\text{C} = \text{K} - 273\).)
Fatigue Crack Growth Mechanisms

The physical understanding of the fracture process in materials.

\[ \Delta K_I = \Delta \sigma \sqrt{\pi a Y} \]
Fatigue Crack Growth Mechanisms

Fatigue crack growth rate data for TiAl intermetallic alloy

Figure 1: Fatigue crack growth behavior of cast Ti-48Al alloy with as-cast, duplex and nearly-lamellar microstructures, in vacuum environment at 10^{-7} torr.
Fatigue Crack Growth Mechanisms

Fatigue crack growth rate data for TiAl intermetallic alloy

Figure 2: Fatigue crack growth behavior in the duplex microstructure illustrating extensive crack bridging effect. Each type of symbols represents data from different specimen.

Figure 6: Fatigue crack growth in duplex microstructure of cast Ti-48Al alloy. Loading direction is vertical. $\Delta K = 16.5$ MPa\(\sqrt{m}\)