MECH 5390 – Fatigue Analysis for Extreme Environments

Dr. Calvin M. Stewart
Department of Mechanical Engineering
The University of Texas at El Paso
Objective

• Review the macro and microstructural aspects of fatigue
Microstructural Aspects of Fatigue

• Definitions in Fatigue
• Macroscopic Features (Fracture Surfaces)
• Microscopic Features
• Progression of Fatigue in Metals
• Stages of Microscopic Fatigue Crack Growth
• Fracture Surfaces
• Fatigue Failure Examples
Definitions in Fatigue

• The definition of fatigue as stated by ASTM:

• The process of \textbf{progressive localized permanent} structural change occurring in a material subjected to conditions which produce \textbf{fluctuating} stresses and strains at some point or points and which may culminate in \textbf{cracks} or complete \textbf{fracture} after a sufficient number of fluctuations.
Definitions in Fatigue

• “Progressive” implies the fatigue process occurs over a period of time or usage. A fatigue failure is often sudden with no external warning; however, the mechanisms involved may have been operating since the beginning of the component or structure usage.

• “Localized” implies that the fatigue process operates at local areas rather than throughout the entire component or structure. These local areas can have high stresses and strains due to:
  • external load transfer,
  • abrupt changes in geometry,
  • temperature differentials, residual stresses, and
  • material imperfections.
Definitions in Fatigue

- **“Permanent”** implies that once there is a structural change due to fatigue, the process is irreversible.

- **“Fluctuating”** implies that the process of fatigue involves stresses and strains that are fluctuating or cyclic in nature and requires more than just a sustained load.

- The ultimate cause of all fatigue failures is that a “**crack**” has grown to a point at which the remaining material can no longer tolerate the stresses or strains, and sudden fracture occurs.

- **“Fracture”** implies the last stage of the fatigue process is separation of a component or structure into two or more parts.
Definitions in Fatigue

• Typical fatigue failures exhibit the following common aspects:
  • Distinct crack nucleation site or sites.
  • Beach marks indicative of crack growth.
  • Distinct final fracture region.

• Representative macroscopic fatigue fracture surfaces
Fatigue Fracture Surfaces

[Images showing fatigue fracture surfaces with annotations for origin, rotation, and final rupture]
Fatigue Fracture Surfaces

• **Stage I** – Initiation of micro-crack due to cyclic plastic deformation

• **Stage II** – Progresses to macro-crack that repeatedly opens and closes, creating bands called *beach marks*

• **Stage III** – Crack has propagated far enough that remaining material is insufficient to carry the load, and fails by simple ultimate failure
Fatigue Fracture Surfaces

- Symmetric Cycling
- Variable Amplitude Cycling
Fatigue Fracture Surfaces

Schematic drawing of a fatigue fracture surface
Fatigue Fracture Surfaces

Fatigue Striations/BeachMarks in Metal
Effect of Thickness

- For materials exhibiting ductile crack growth, the crack growth in the transitional region lags behind the plane strain region and failure in the transition region occurs on inclined planes.

- When performing lab experiments, to ensure the critical toughness is plane strain a rule of thumb has been adopted.

\[ a, B, (W - a) \geq 2.5 \left( \frac{K_{lc}}{\sigma_{ys}} \right)^2 \]

Proportional to plastic zone size.
Effect of Thickness

Figure 3.5 Transition of fatigue crack growth in sheet from tensile mode to shear mode [5] (reprinted with permission of the Noordhoff International Publishing Co.). (a) Single shear. (b) Double shear.
FCG Surfaces: Uniaxial

**High Nominal Stress**
- No stress concentration
- Mild stress concentration
- Severe stress concentration

**Low Nominal Stress**
- No stress concentration
- Mild stress concentration
- Severe stress concentration

*Tension–Tension or Tension–Compression*
FCG Surfaces: Bending

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Unidirectional Bending
FCG Surfaces: Reversed Bending

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Reversed Bending
Fatigue Fracture Surfaces

Summary of fatigue fracture surface features:

- The entire fatigue process involves the nucleation and growth of a crack or cracks to final fracture.

- The fatigue crack size at fracture can be very small or very large, occupying from less than 1 percent of the fracture surface up to almost 100 percent.

- Often the fatigue crack region can be distinguished from the final fracture region by beach marks, smoothness, and corrosion.
Fatigue Fracture Surfaces

- Fatigue cracks usually nucleate at the surface where stresses are highest and where corrosive environment and changes in geometry exist.

- **Microscopic fatigue cracks** usually nucleate and grow on planes of maximum shear.

- **Macroscopic fatigue cracks** often grow in the **plane of the maximum tensile stress**. However, for torsional and multiaxial loading, macroscopic fatigue cracks have also been observed to grow on planes of maximum shear.
Fatigue Fracture Surfaces

• Cyclic applications of inelastic strain to a metal can cause continuous changes until cyclic stability is reached.

• This means that the metal becomes either more or less resistant to the applied strain, i.e., the material either cyclic hardens or cyclic softens.

• Some materials may never stabilize under cyclic inelastic strain, others are cyclically stable from the onset.

• Why do metals harden or soften during cyclic deformation? The answer is related to the density and arrangement of the dislocation structure and substructure of the metal.
Microstructural Features
Microstructural Features

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Point Defects

• A, Vacancy. B, Divacancy (two missing atoms). C, Interstitial (extra atom). Different colors are used to show that the atoms have been distorted by adapting to the space available.
Line Defects **Dislocations**

- **A**, An edge dislocation in a schematic cubic crystal structure.
- **B**, The dislocation has moved one interatomic distance along the slip plane under the action of the shearing force indicated by the arrows.
- **C**, The dislocation has reached the edge of the crystal, and a unit amount of slip has been produced.
Dislocations

• An imperfection in the crystalline arrangement of atoms consisting of either an extra partial plane of atoms (edge dislocation), a spiral distortion of normally parallel atom planes (screw dislocation), or a combination of the two types.
Dislocations

- **A**, A dislocation moves without any impediment within a grain; no extra effort is needed and no strengthening effect occurs.

- **B**, The darker and slightly larger sphere represents a solute atom or coherent precipitate that presents an obstacle to the movement of the dislocation; bending of the line defect implies that the movement has been impeded and more stress is needed to pass through the obstacle.

- **C**, The dark spheres represent incoherent precipitates and the background simulates the rest of the grain. The dislocation cannot pass through the incoherent precipitate, since it does not share the same lattice with the hosting grain. The first dislocation (left) bends as it moves close to the precipitate. The second dislocation (middle) continues to bend around the precipitate while the rest of the dislocation keeps moving toward the right. Finally, the dislocation (right) completes its encircling around the precipitate; the rest of the dislocation rejoins and moves on through the non-strengthened area.

Dislocation Movement in the presence of a precipitate particle
Dislocations

This illustration shows the spatial lattice of two adjacent grains. Notice that the lattices are not aligned. There is a dislocation moving toward the grain boundary in grain A. Because of misalignment, dislocation in grain A cannot move into grain B but it is trapped at the grain boundary. In essence the grain boundary is an obstacle to dislocation movement. Therefore, the greater the number of grain boundaries the higher is the yield strength of the material.
Microstructural Features

• The relationship between dislocations and inelastic deformation is typically defined by slip, which is a shear deformation of the material.

• Slip occurs in metals within individual grains by dislocations moving along crystallographic planes.
  • For materials that are initially soft,
    • the dislocation density is low.
    • As inelastic deformation occurs as a result of stress or strain cycling, the density of dislocations increases rapidly.
    • This leads to a decrease in dislocation mobility.
  • Therefore the material cyclic hardens and the cyclic yield strength becomes greater than the monotonic yield strength.
Microstructural Features

• For materials that are initially hard or have been hardened,

• inelastic strain cycling causes the existing dislocation structure to rearrange into a configuration such that there is less resistance to deformation.

• This tends to promote greater dislocation mobility.

• Thus, the material cyclic softens, and the cyclic yield strength is less than the monotonic yield strength.
Microstructural Features

• Metals are **crystalline** in nature (i.e., atoms are arranged in an ordered manner). Most structural metals are polycrystalline and thus consist of a large number of individual ordered crystals or grains.

• The onset of slip creates an appearance of one or more planes within a grain sliding relative to each other. Slip occurs under both monotonic and cyclic loading and is the localization of plastic strain.
Common Microstructures of Metals

**FCC**
- Face-centered Cubic
- Aluminum
- 12 Slip systems

**BCC**
- Body-centered Cubic
- Iron
- 48 Slip systems

**HCP**
- Hexagonal close-packed
- Titanium
- 3 Slip systems
Microstructural Features

• The degree of slip, or cyclic deformation, is primarily related to the ductility of the metal.
  • In metals that show **brittle** behavior the extent of slip is very limited.
  • In metals that behave in a **ductile** fashion slip is abundant.
  • Thus crack **nucleation** mechanisms vary depending on the type of metal under consideration.

• Words such as crack “initiation,” “formation,” and “nucleation,” have been used interchangeably throughout the engineering community to describe the early stages of the fatigue damage process. In this book, the words “nucleate” or “nucleation” will primarily be used.
Nucleation

• In polycrystalline materials
  – Always a few crystals oriented to slip easily
  – Weak crystals yield first
  – Does not affect overall stress-strain behavior
  – Grain is unloaded and loaded with local hardening
  – Stress increases until local failure occurs

• Factor affecting Nucleation
  • Alloying composition
  • Phase composition
  • Presence of inclusions
  • Grain Size
  • Environment
  • Cyclic rate
  • Temperature
Intrusions and Extrusions

• Forsyth showed that:

• both slip band **intrusions and extrusions** occurred on the **surface** of metals when they were subjected to cyclic loading.

• Slip band intrusions form concentrations, which can be the location for cracks to develop.
Intrusions and Extrusions

Static Mechanical Test
Intrusions and Extrusions

Fatigue Mechanical Test
Intrusions and Extrusions

Fatigue Mechanical Test
Persistent Slip Bands (PSBs)

• **Def:** Persistent slip bands (PSBs) are the precursors to the fatigue crack. Typically observed 45 degrees from axis of nominal load.

• Most of the slip bands can be eliminated by removing several microns from the surface by electropolishing.

• However, a few slip bands may become more distinct and have therefore been labeled “persistent slip bands.”

• It has been found that fatigue cracks grow from these persistent slip bands.
Persistent Slip Bands (PSBs)

Fig. 2  Approximate profile of surface at a persistent slip band in copper determined from an interferogram. The copper single crystal was cycled over the plastic strain range 0.0025 for 30,000 cycles. Source: Ref 7
Slip Bands

Figure 3.9  Surface fatigue microcrack along a slip band in nickel-base superalloy Waspaloy (courtesy of R. R. Stephens).
Figure 3.11  Surface fatigue microcracks. (a) Slip band microcracks linked up between adjacent grains. (b) After further cycling, continued development and additional formation of slip lines as the microcrack extended into adjacent grains (courtesy of R. R. Stephens).
Progression of Slip

Figure 3.10 The progressive nature of slip in nickel subjected to cyclic loading [13] (reprinted with permission of John Wiley and Sons, Inc.). (a) After $10^4$ cycles, general fine slip has developed. (b) After $5 \times 10^4$ cycles, some of the original slip lines have intensified and broadened. (c) After failure at $27 \times 10^4$ cycles, continued development of the intense slip lines has occurred, with some grains and some regions still showing very little evidence of slip.
Microstructural Features

- The introduction of the **scanning electron microscope** in the 1950’s allowed significant advances to be made in understanding **fatigue mechanisms**.

- Optical microscopes have magnification limitations of approximately 1000X and have a very shallow depth of field. Therefore, using optical microscopes at high magnification with surfaces that are not extremely flat usually result in poor quality micrographs.

- Scanning electron and transmission electron microscopes provide excellent depth of field at magnifications in excess of 10,000X, thus providing excellent images of fatigue artifacts.
Microstructural Features

- Fatigue cracks often nucleate at or near surface, because:
  - Inelastic deformation is easier at the surface
  - Intrusion/extrusion develops on the surface
  - Stresses/strains from external loads are usually greatest on the surface (i.e. bending, torsion)
  - Stress concentrations from manufacturing processes often exist on the surface (such as machining marks)
  - Environmental attach such as corrosion occurs on the surface
Microstructural Features

• **Not all fatigue cracks nucleate along slip bands** although in many cases slip bands are at least indirectly responsible for microcracks initiating in metals.

• Under fatigue loading conditions, fatigue cracks may nucleate at or near material discontinuities. **Discontinuities** include inclusions, second-phase particles, corrosion pits, grain boundaries, twin boundaries, pores, voids, and also slip bands.

• Microcracks in high strength or brittle behaving metals are often formed directly at inclusions or voids, and then grow along planes of maximum tensile stresses.
Stages of Fatigue Crack Growth (FCG)
Elevated temperature (700°C) grain boundary crack in Waspaloy

Surface inclusion/slip band crack in Waspaloy

Elevated temperature (500°C) surface pore/slip band in Waspaloy

Cracking within phases in lamellar structure in a Ti alloy
Stages of Fatigue Crack Growth (FCG)

- The two stages of fatigue crack growth are stage I (shear mode) and stage II (tensile mode).
  - A fatigue crack is shown to nucleate at the surface and grow across several grains controlled primarily by shear stresses and shear strains, and then grow in a zigzag manner essentially perpendicular to, and controlled primarily by, the maximum tensile stress range.
  - Slip line progression precedes the fatigue crack tip vicinity.
Stages of Fatigue

4. Stage I
(shear) fatigue crack

3. Intrusions, extrusions

2. Persistent slip bands

5. Stage II fatigue crack

1. Cyclic slip
Stages of Fatigue Crack Growth (FCG)

Shear mode
Stage I

Tensile mode
Stage II

loading direction

free surface
Figure 3.14 Surface crack profile of transcrystalline fatigue crack growth in aluminum–lithium alloy ML377. The direction of crack growth is from left to right (courtesy of R. R. Stephens).
Stages of FCG

• Most fatigue cracks grow:
  • across grain boundaries
    (transcrystalline/transgranular)
  • Or
  • along grain boundaries
    (intercrystalline/intergranular)

• depending on the material, load, and environmental conditions.
Microstructural Features

- A wide range of fatigue crack growth mechanisms can exist

- Three of the more common modes are:
  - striation formation,
  - microvoid coalescence, and
  - microcleavage
Striation Formation

- The ripples are called fatigue striations.
- These **striations are not the beach marks.** Actually, one beach mark can contain thousands of striations.
- Electron microscopic magnification between 1,000x and 50,000x must be used to view striations.
- They may not be seen clearly because of substantial surface rubbing and pounding during repeated loading. They are also difficult to find in high strength materials.
Striation Formation

• In many studies, each striation has been shown to represent one load cycle.

• However, several other studies have shown there is not a one-to-one correspondence between a single striation and each cycle.

• Thus a combination of other fracture mechanisms along with striation formation might be responsible for advancing the crack front.
Microvoid Coalescence

- Microvoid coalescence (MVC) takes place by the nucleation of microvoids, their growth, and coalescence during plastic deformation.

- The formation of these voids evolve into "dimples". The size and density of "dimples" is generally related to the distribution spacing of the inclusions or precipitates inherent to the metal.

- The process of MVC is generally considered a high energy process and in fatigue usually occurs at high crack growth rates.

- The fracture surface due to MVC usually has a dull & fibrous appearance.
Microcleavage

- Microcleavage crack growth is considered a **lower energy process** and therefore an undesirable fatigue crack growth mechanism.

- Cleavage or microcleavage involves fracture along specific crystallographic planes and is **transcrystalline** in nature.

- Cleavage facets are usually **flat**, and often contain several parallel ridges or cleavage planes.
Microcleavage

• The fracture surface appearance from cleavage is usually bright and appears shiny due to the high reflectivity of the flat cleavage facets.

• Cleavage is regarded as the most “brittle” form of fracture in crystalline materials.

• The likelihood for cleavage is increased whenever plastic flow is restricted, such as
  • at low temperature,
  • high strain rate, or in
  • notched components.
Microstructural Features

• Materials that exhibit **ductile** behavior often display appreciable **striations** and **microvoid** coalescence.

• Microvoid coalescence and cleavage are fracture mechanisms that can occur under either monotonic or cyclic loading conditions.

• **Striations** do not occur under monotonic loading conditions as their formation relies on the **cyclic** nature of fatigue.
Microstructural Feat.

- In general, slip occurs first, followed by fine cracks that can be seen only at high magnification.
- These cracks continue to grow under cyclic loading and eventually become visible to the unaided eye.
- The cracks tend to combine such that just a few major cracks grow.
- These cracks (or crack) reach a critical size, and sudden fracture occurs.
- The higher the stress magnitude, the sooner all processes occur.
- Cracks may also stop without further growth as a result of compressive residual stress fields or as a crack grows out of a high-stress region such as a notch.
Microstructural Features

• From the perspective of alloy design, conditions that favor good crack nucleation resistance and microcrack growth under fatigue loading may not favor good macrocrack propagation resistance and vice versa.

• For example, fine grain sizes tend to offer the best resistance to crack nucleation and microcrack growth. Grain boundaries tend to act as crack stoppers or deflectors thus reducing fatigue crack growth rates.

• However, as the crack grows,
  • fine grain materials promote a flatter crack path that tends to promote higher crack growth rates, while
  • coarse grain materials tend to promote a rougher crack path which usually offers greater resistance to macrocrack growth through crack closure and crack tip deflection mechanisms.
Material Characterization Tools

- **Optical Microscopy (approx. 1000x to 1500x)**
  - Grains and Grain boundaries, Beach Marks, Voids, Large precipitate particles
  - Res: 500 nm

- **Scanning Electron Microscopy (approx. 10,000x to 500,000x)**
  - Striations, small precipitate particles
  - Res: 10 nm

- **Transmission Electron Microscopy (approx. 5,000,000x)**
  - Dislocations, Nano-particles, topological closed packed precipitate particles
  - Res: 2 nm

- **Addons (EDS, EBSD, XRD)**

TEM image showing the presence of dislocations and dislocation loops in AISi4CNT-GD samples
Dos and Don’ts in Design

• Do recognize that fatigue is a localized progressive permanent behavior.

• In general, the entire fatigue process involves the nucleation and growth of a crack or cracks to final usually sudden fracture.

• Cracks tend to nucleate along slip lines oriented in the planes of maximum shear. Cracks can also nucleate at grain boundaries, inclusions, pores, and other microstructural features or discontinuities.
Dos and Don’ts in Design

• Crack growth usually consists of microcrack growth along maximum shear planes followed by macrocrack growth along the maximum tensile stress plane. However, conditions exist where macrocrack growth may occur on planes of maximum shear.

• Depending on the material and stage of the fatigue process, crack growth can proceed by a number of mechanisms such as striation formation, microvoid coalescence, and cleavage.
Dos and Don’ts in Design

• Surface features such as ratchet marks, beach marks, and river patterns help to identify a failure as a fatigue failure.

• Certain material characteristics may favor good crack nucleation resistance, good microcrack growth resistance, or good macrocrack propagation resistance, but not necessarily all three. Thus, the selection of a material for a given application may be dictated by the importance of the various fatigue processes.
Dos and Don’ts in Design

• Do examine fracture surfaces as part of a post failure analysis, since substantial information concerning the cause of the fracture can be ascertained. The examination can involve a small magnifying glass or greater magnification up to that of the electron microscope.

• Don’t put fracture surfaces back together again to see if they fit, or allow corrosive environments to reach the fracture surface. These can obliterate key fractographic details.

• Do recognize that most fatigue cracks nucleate at the surface and therefore surface and manufacturing effects are extremely important.
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Assignments

• Problem 3.1 from the text.
• Problem 3.2 from the text.
Contact Information

Calvin M. Stewart  
Associate Professor  
Department of Mechanical Engineering  
The University of Texas at El Paso  
500 W. University Blvd.  
Suite A126  
El Paso, Texas 79968-0717

Email: cmstewart@utep.edu  
URL: http://me.utep.edu/cmstewart/  
Phone: 915-747-6179  
Fax: 915-747-5019
References

• Shigley’s Mechanical Design.
• https://pocketdentistry.com/17-wrought-metals/#f0020
• http://geofaculty.uwyo.edu/neil/glaciology/photos.html
Additional Fractography
Fatigue Fracture Examples

- AISI 4320 drive shaft
- B– crack initiation at stress concentration in keyway
- C– Final brittle failure

Fig. 6–3

Fatigue Fracture Examples

- Fatigue Fracture of an AISI 8640 pin.
- Fatigue failure initiating at mismatched grease holes
- Sharp corners (at arrows) provided stress concentrations

Fig. 6-4

Fatigue Fracture Examples

- Fatigue failure of forged connecting rod
- Crack initiated at flash line of the forging at the left edge of picture
- Beach marks show crack propagation halfway around the hole before ultimate fracture

Fig. 6–5

Fatigue Fracture Examples

- Fatigue failure of a 200-mm diameter piston rod of an alloy steel steam hammer
- Loaded axially
- Crack initiated at a forging flake internal to the part
- Internal crack grew outward symmetrically

Fig. 6–6

Fatigue Fracture Examples

- Double-flange trailer wheel
- Cracks initiated at stamp marks

Fig. 6–7

Fatigue Fracture Examples

- Aluminum alloy landing-gear torque-arm assembly redesign to eliminate fatigue fracture at lubrication hole

Fig. 6–8