



CHAPTER 3: MACRO/MICRO ASPECTS OF FATIGUE OF METALS

- KEY PARAMETERS INVOLVED IN THE FATIGUE PROCESS
- **FATIGUE FRACTURE SURFACES AND MACROSCOPIC FEATURES**
- **FATIGUE MECHANISMS AND MICROSCOPIC FEATURES**



DEFINITION OF FATIGUE

The definition of fatigue as currently stated by ASTM:

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



DEFINITION OF FATIGUE (CONT'D)

- **“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.



DEFINITION OF FATIGUE (CONT'D)

- **“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.

FATIGUE FRACTURE SURFACES AND MACROSCOPIC FEATURES

- 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

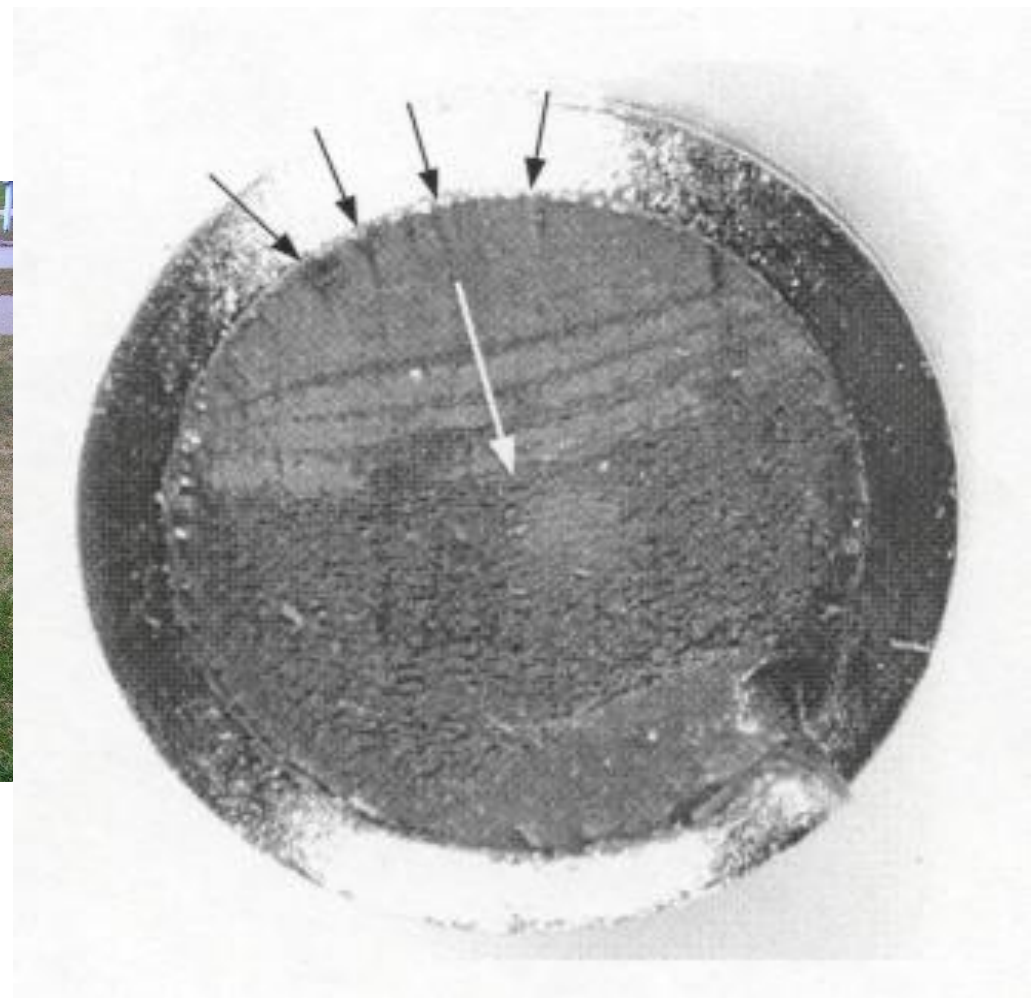
TYPICAL FATIGUE FRACTURE SURFACE



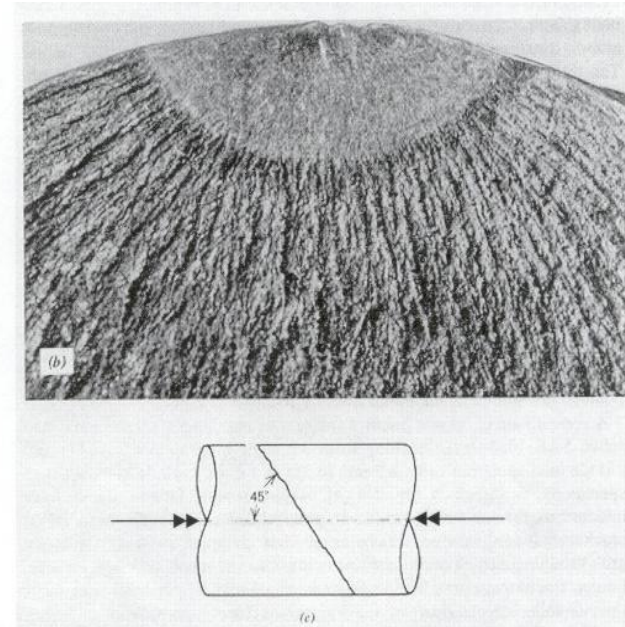
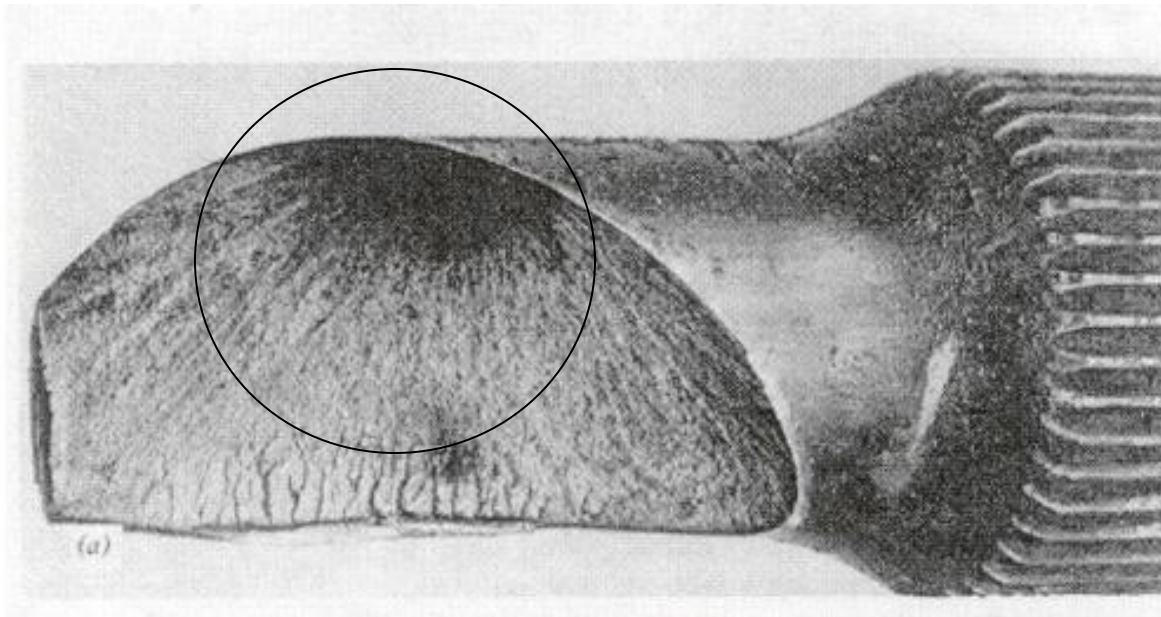
TYPICAL FATIGUE FRACTURE SURFACE (SQUARE THREAD COLUMN)



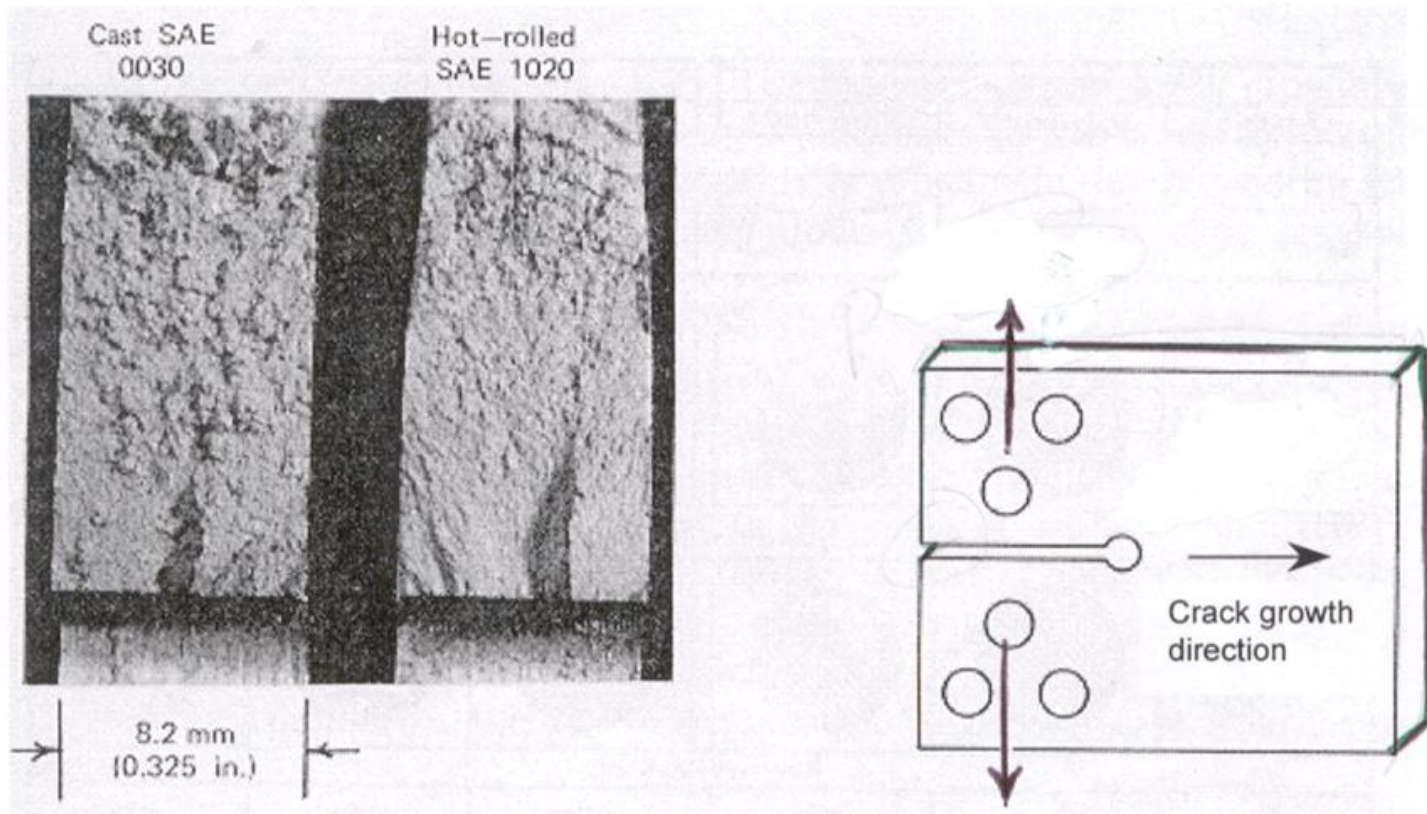
TYPICAL FATIGUE FRACTURE SURFACE (MOUNTAIN BIKE SEAT POST)



FATIGUE FAILURE OF A TORSION SHAFT

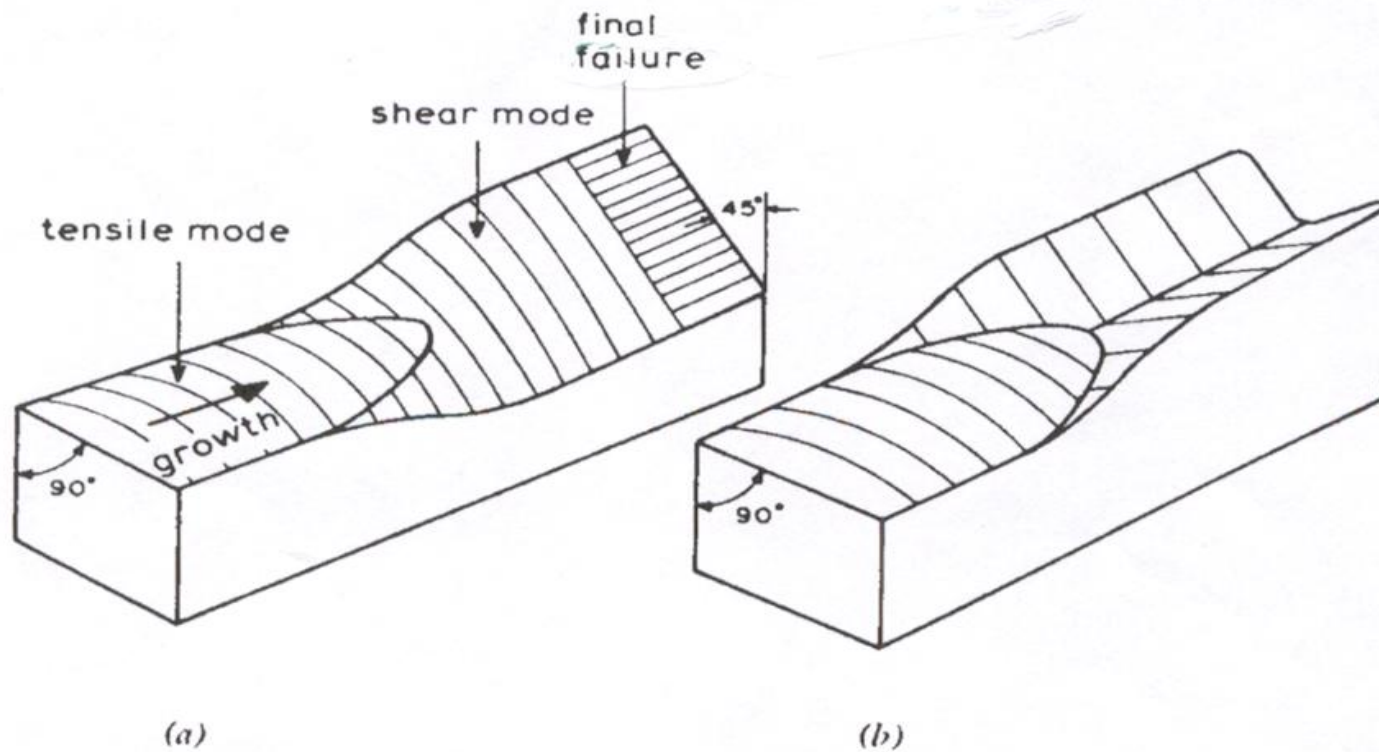


FATIGUE FAILURE OF CAST AND HR CARBON STEEL SPECIMENS

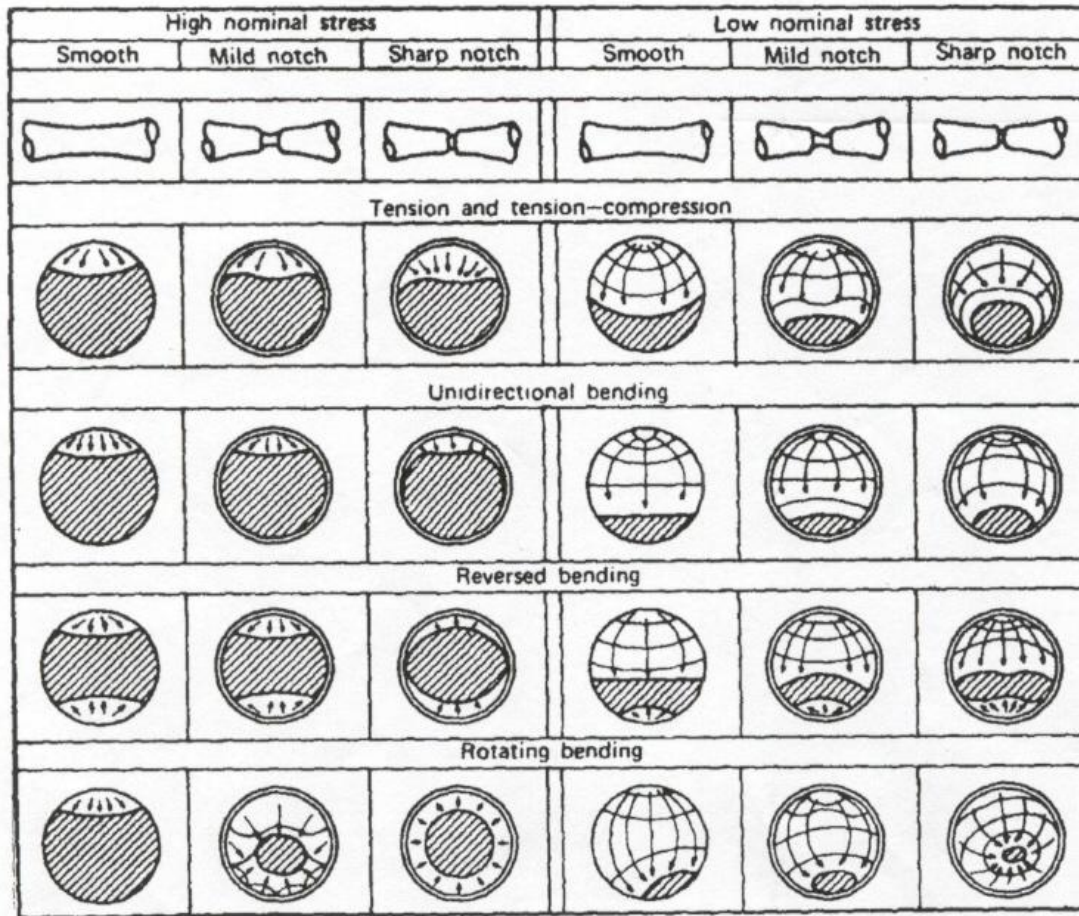


TRANSITION OF FCG IN **SHEET** FROM TENSILE MODE TO SHEAR MODE

(a) SINGLE SHEAR (b) DOUBLE SHEAR

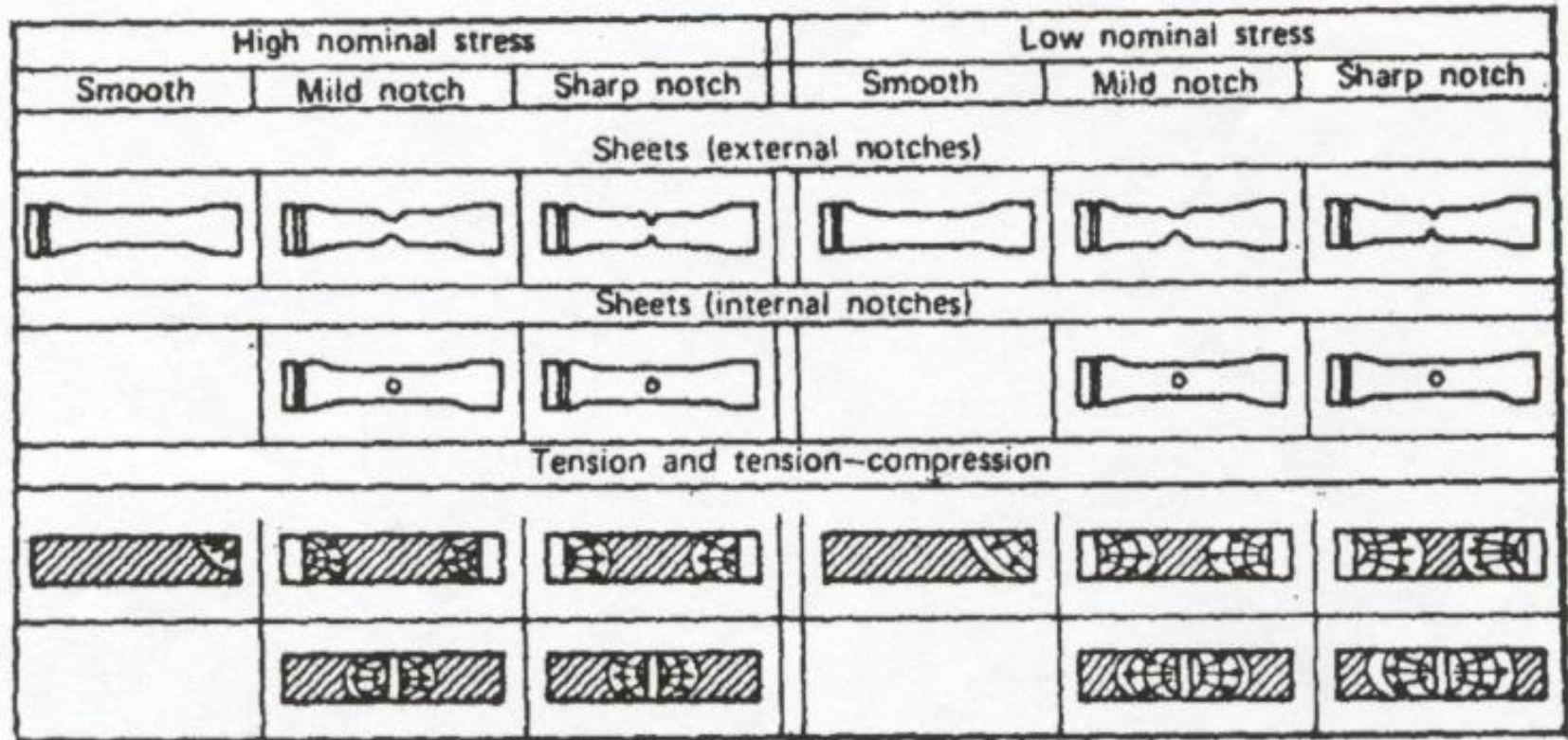


SCHEMATIC MACROSCOPIC FATIGUE FRACTURE SURFACES FOR AXIAL AND BENDING LOADS OF ROUND SPECIMENS AS A FUNCTION OF LOAD TYPE, LOAD MAGNITUDE & GEOMETRY



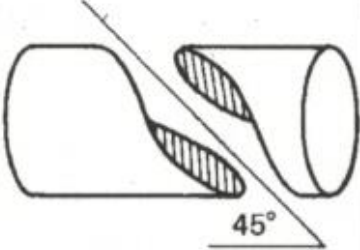
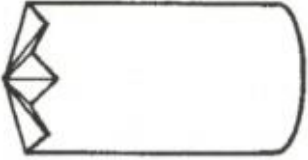

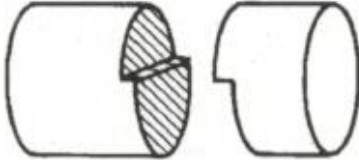
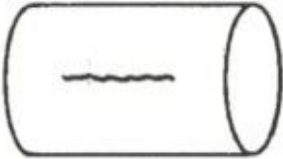
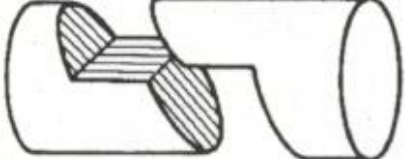
(a)

SCHEMATIC FATIGUE FRACTURES FOR AXIAL AND BENDING LOADS OF SHEET OR PLATE SPECIMENS



(b)

SCHEMATICS OF FATIGUE FRACTURES IN TORSION

Failure mode		Star pattern
Tensile		
Transverse shear		
Longitudinal shear		



FATIGUE FRACTURE SURFACES AND MACROSCOPIC FEATURES (CONT'D)

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 AND MACROSCOPIC FEATURES (CONT'D)

- 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 MECHANISMS AND MICROSCOPIC FEATURES

- 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.

FATIGUE MECHANISMS AND MICROSCOPIC FEATURES (CONT'D)

- 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.

FATIGUE MECHANISMS AND MICROSCOPIC FEATURES (CONT'D)

- **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.



FATIGUE MECHANISMS AND MICROSCOPIC FEATURES (CONT'D)

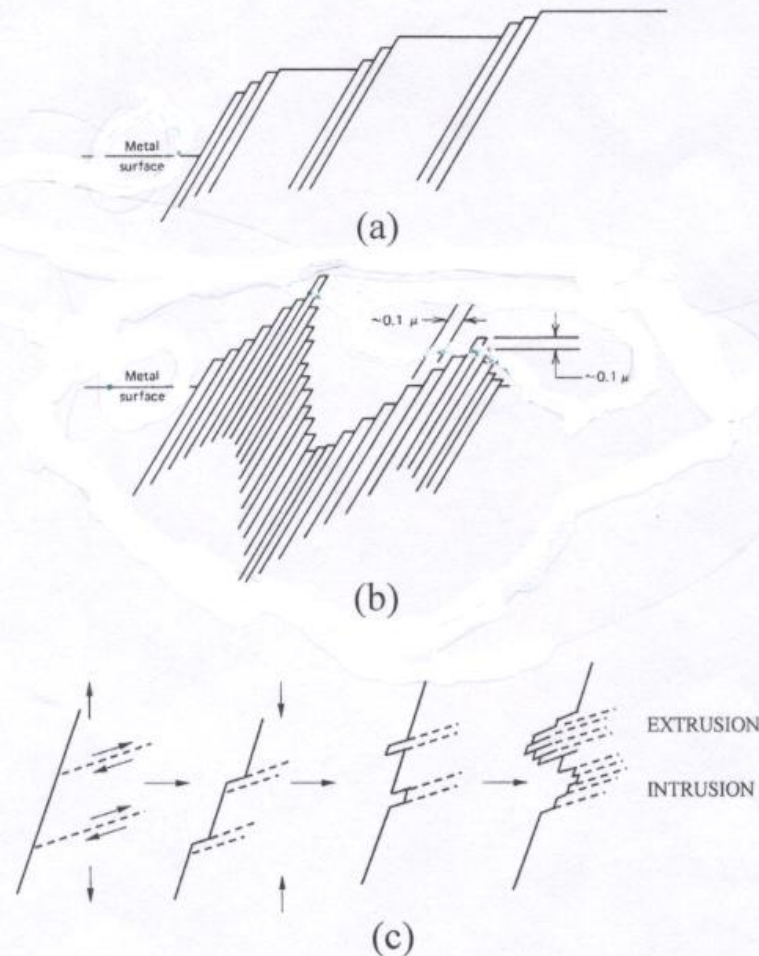
- Metals are ***crystalline*** in nature (i.e, atoms are arranged in an ordered manner). Most structural metals are ***polycrystalline*** and thus consist of a large number of individual ordered crystals or grains.
- The onset of ***slip*** creates an appearance of one or more planes within a grain sliding relative to each other. Slip occurs under both monotonic and cyclic loading and is the ***localization of plastic strain***.

FATIGUE MECHANISMS AND MICROSCOPIC FEATURES (CONT'D)

- 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.

SCHEMATIC OF SLIP DUE TO EXTERNAL LOADS

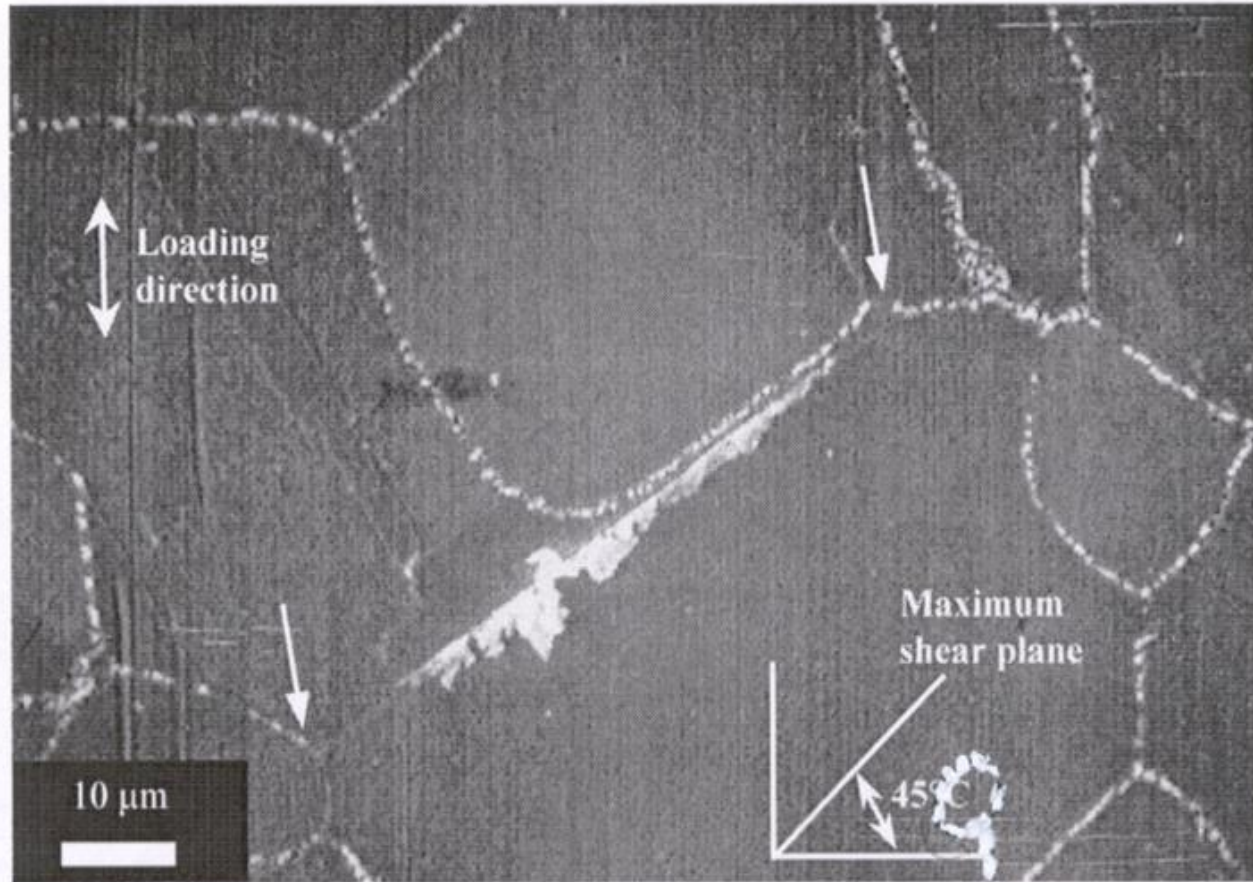
(a) coarse slip under monotonic loading, (b) fine slip under cyclic loading, (c) progressive development of an extrusion/intrusion pair under cyclic loading.



FATIGUE MECHANISMS AND MICROSCOPIC FEATURES (CONT'D)

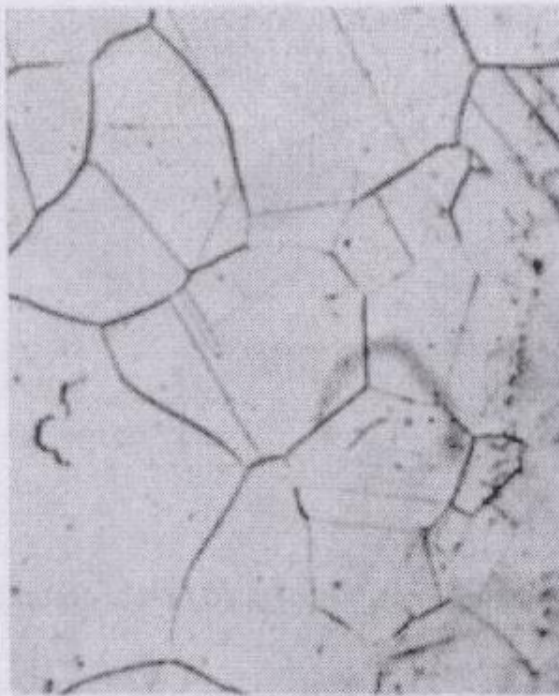
- Forsyth showed that:
 - both slip band intrusions and extrusions occurred on the ***surface*** of metals when they were subjected to cyclic loading.
 - Slip band intrusions form *concentrations*, which can be the location for cracks to develop.

SURFACE FATIGUE MICROCRACK ALONG A SLIP BAND IN NICKEL-BASE SUPERALLOY WASPALLOY

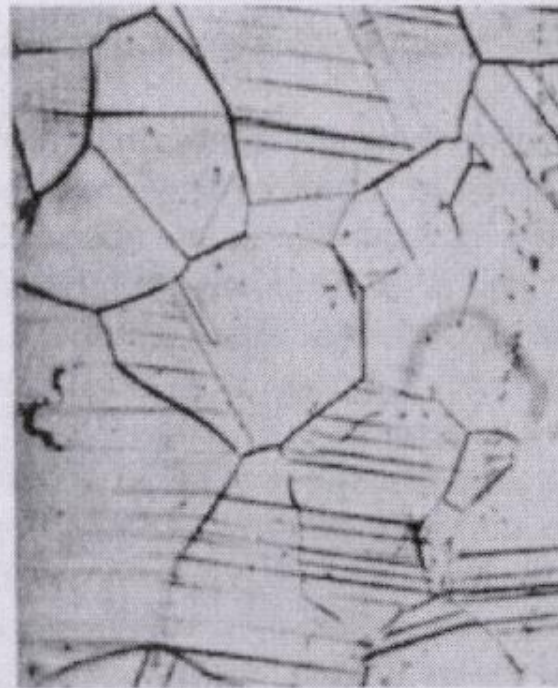


PROGRESSIVE NATURE OF SLIP IN CYCLIC LOADING

(a) After 10^4 cycles, (b) After 5×10^4 cycles, (c) After failure at 27×10^4 cycles



(a)



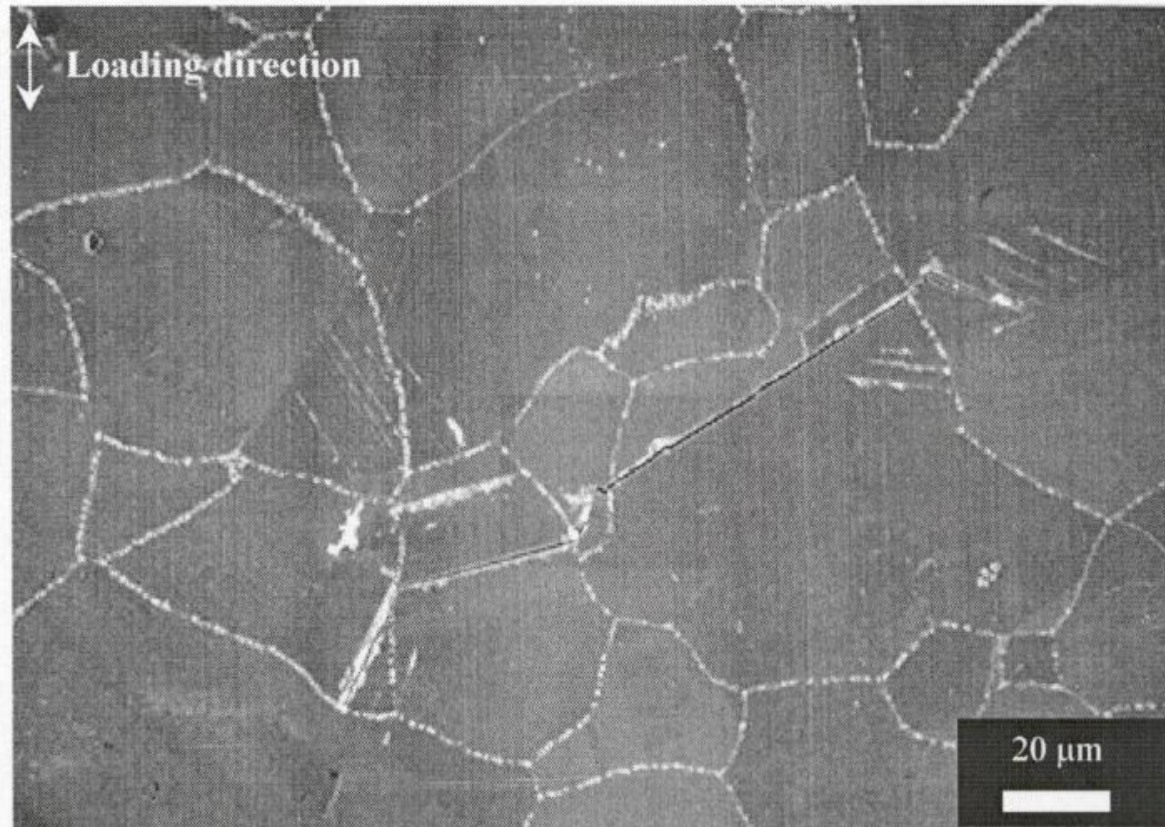
(b)



(c)

SURFACE FATIGUE MICROCRACKS

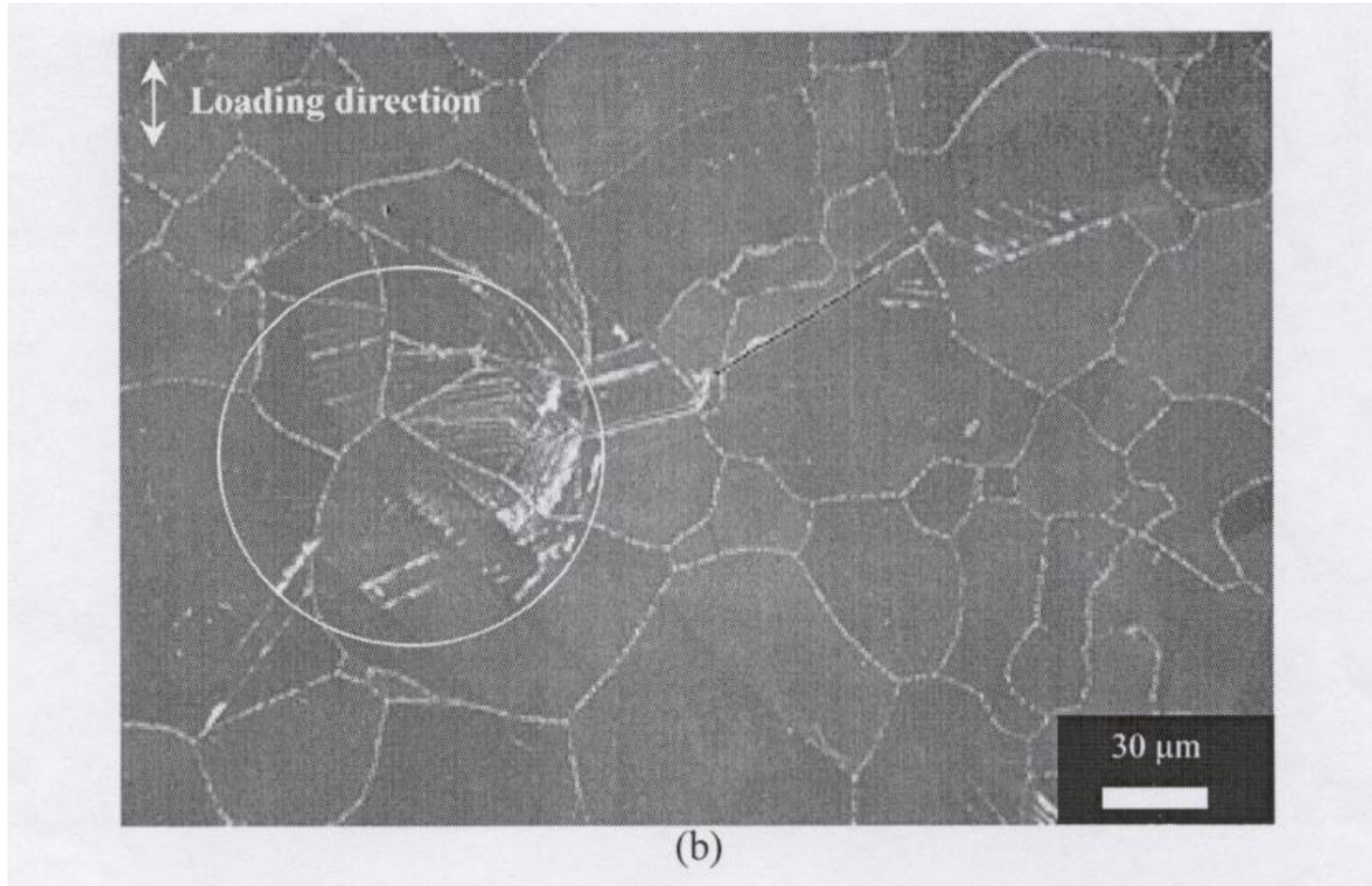
(a) Slip band **microcracks link up** between adjacent grains



(a)

SURFACE FATIGUE MICROCRACKS

(b) After further cycling the microcrack extends into adjacent grains and additional slip lines are formed





FATIGUE MECHANISMS AND MICROSCOPIC FEATURES (CONT'D)

- 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.

FATIGUE MECHANISMS AND MICROSCOPIC FEATURES (CONT'D)

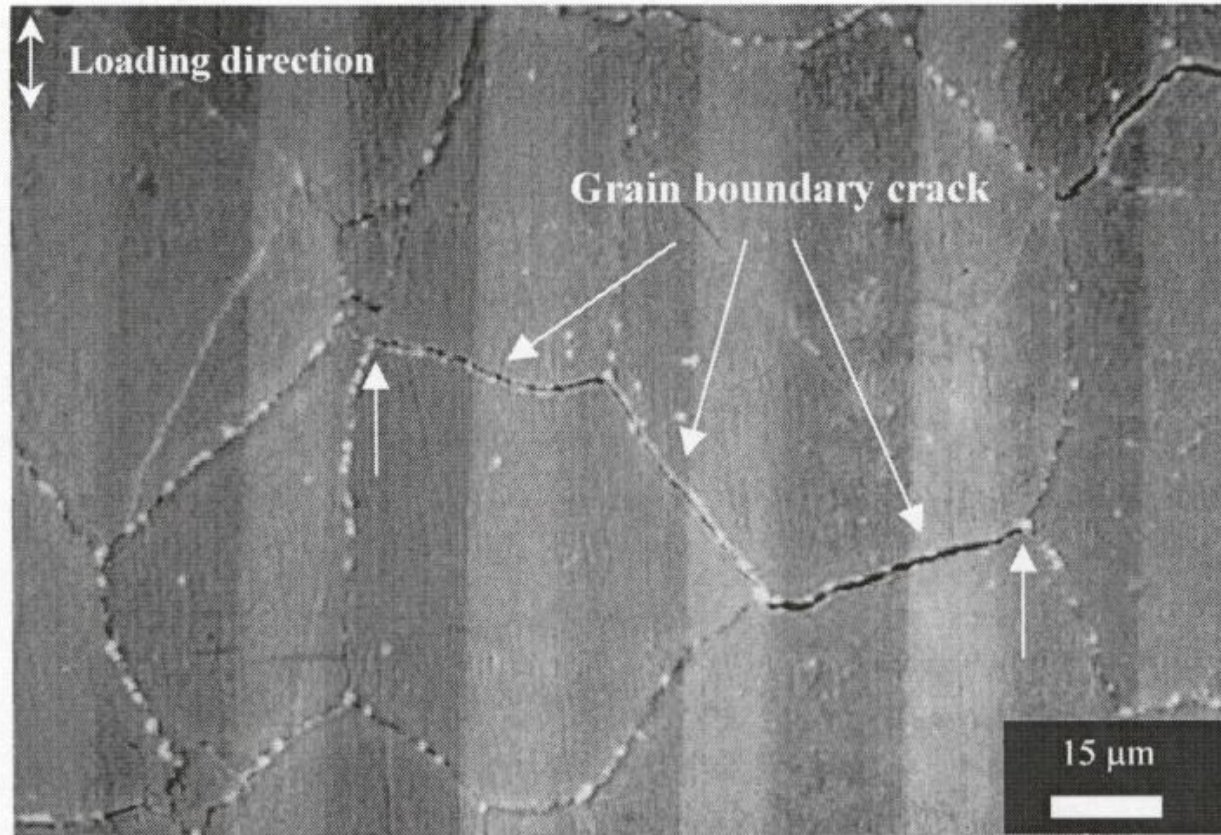
- Fatigue cracks often nucleate at or near surface, because:
 - Inelastic deformation is easier at the surface
 - Intrusion/extrusion develops on the surface
 - Stresses/strains from external loads are usually greatest on the surface (i.e. bending, torsion)
 - Stress concentrations from manufacturing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

FATIGUE MECHANISMS AND MICROSCOPIC FEATURES (CONT'D)

- 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.

FATIGUE MICROCRACKS NUCLEATED DUE TO VARIOUS MECHANISMS

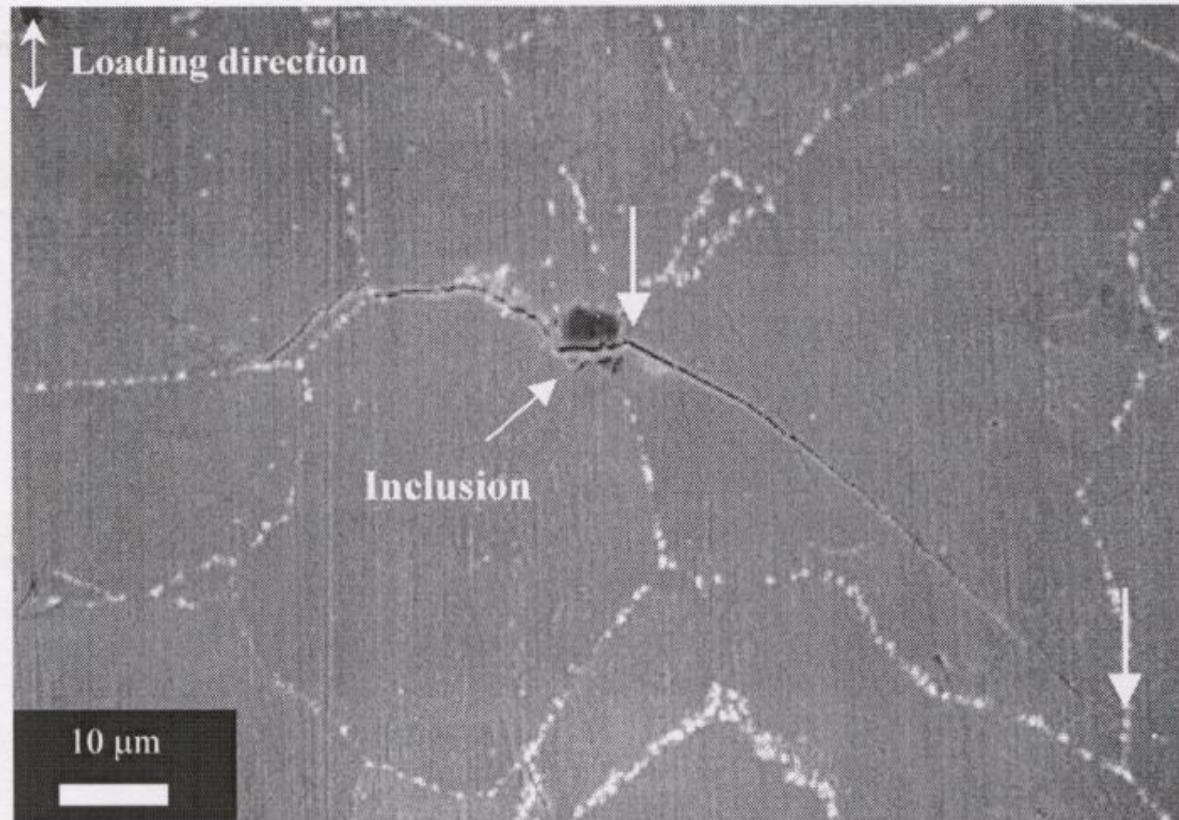
(a) **Elevated temperature (700 C) grain boundary crack** in Waspaloy



(a)

FATIGUE MICROCRACKS NUCLEATED DUE TO VARIOUS MECHANISMS

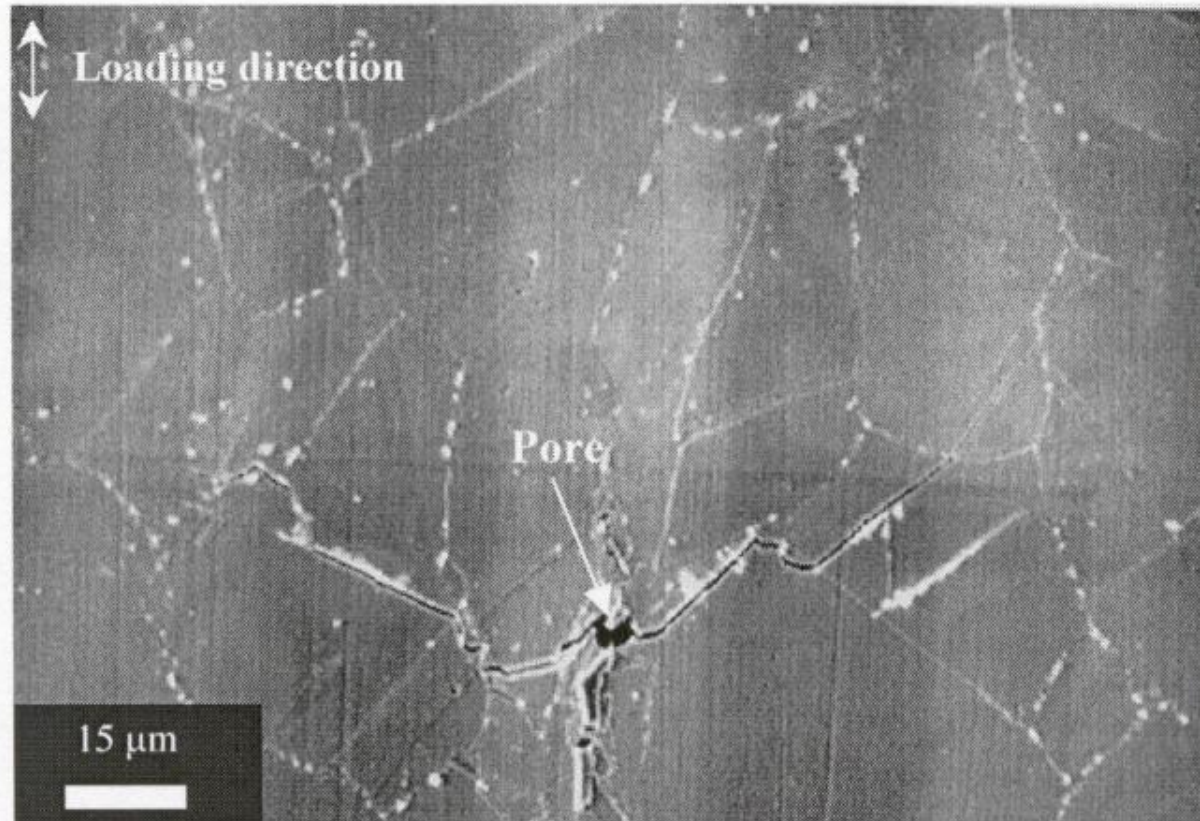
(b) **Surface inclusion**/slip band crack in Waspaloy



(b)

FATIGUE MICROCRACKS NUCLEATED DUE TO VARIOUS MECHANISMS

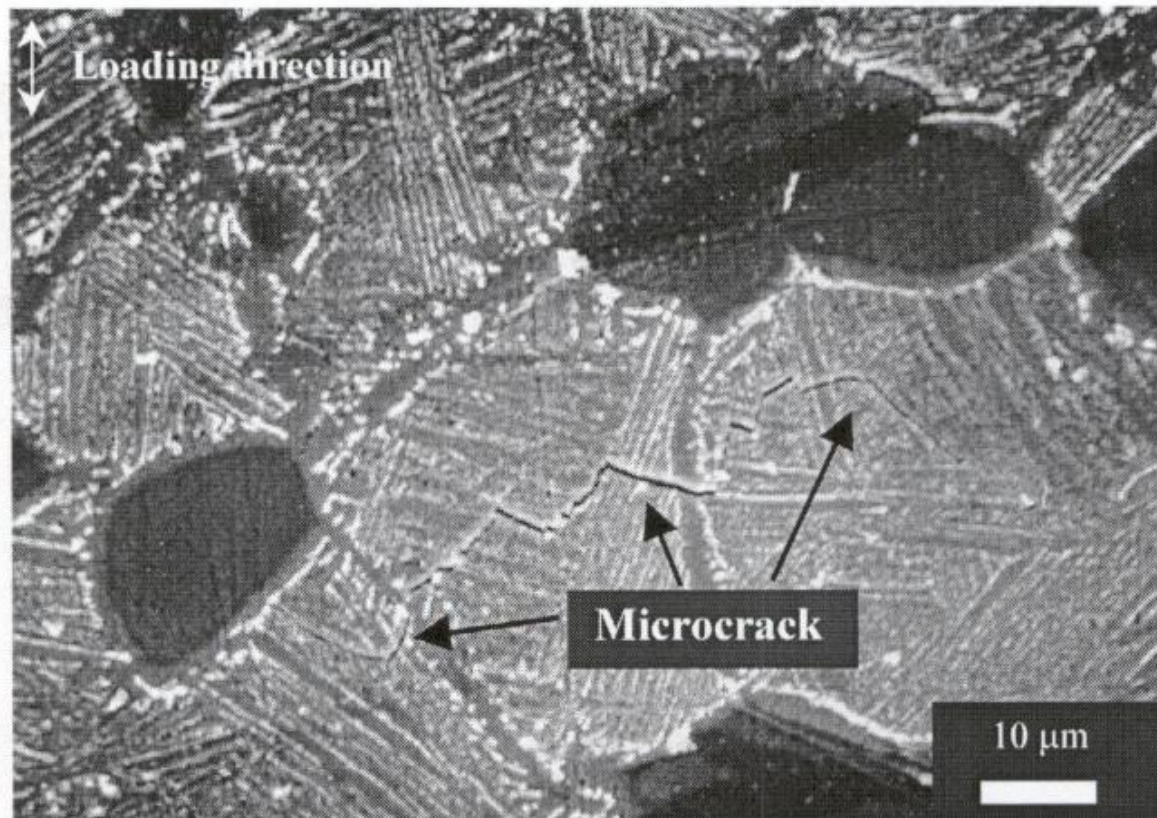
(c) **Elevated temperature (500 C) surface pore/slip band** in Waspaloy



(c)

FATIGUE MICROCRACKS NUCLEATED DUE TO VARIOUS MECHANISMS

(d) **Cracking within phases** in lamellar structure in a Ti alloy

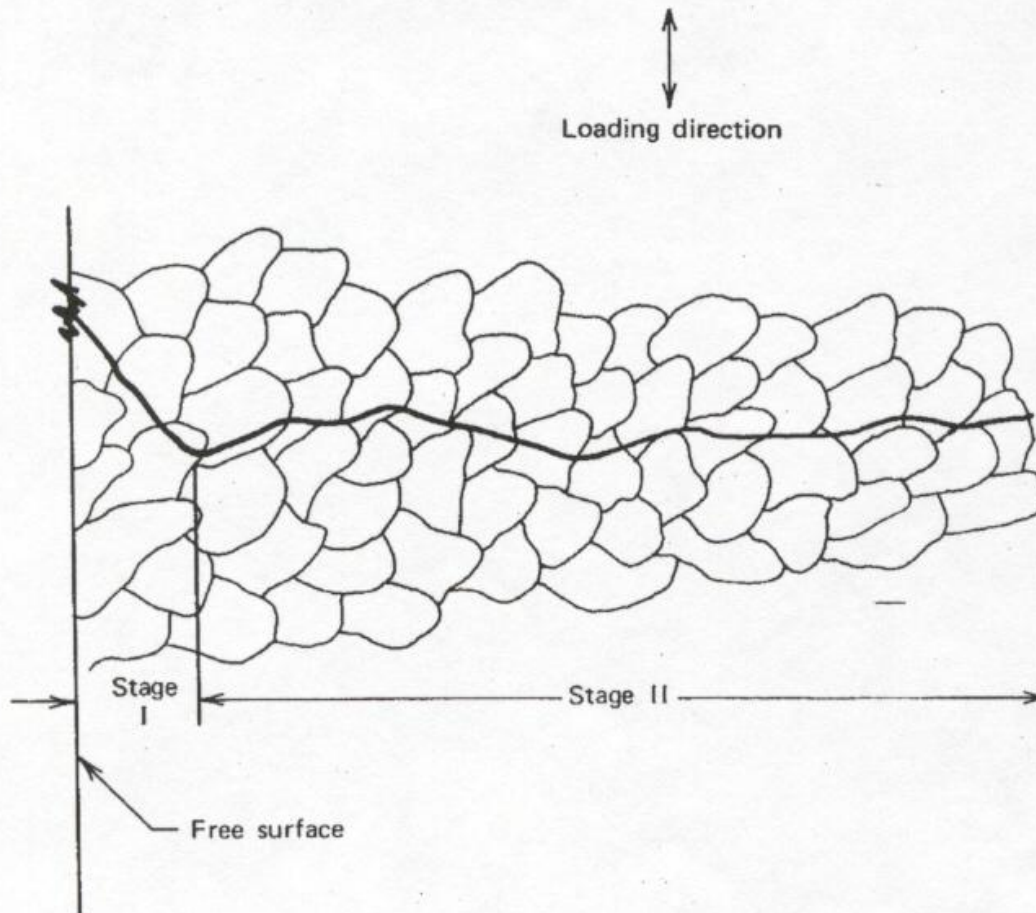


(d)

FATIGUE MECHANISMS AND MICROSCOPIC FEATURES (CONT'D)

- The two stages of fatigue crack growth are **stage I** (shear mode) and **stage II** (tensile mode).
 - Fatigue crack growth is shown schematically in Fig. 3.13.
 - 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.

SCHEMATIC OF STAGE I (SHEAR MODE) AND STAGE II (TENSILE MODE) TRANSCRYSTALLINE MICROSCOPIC FCG



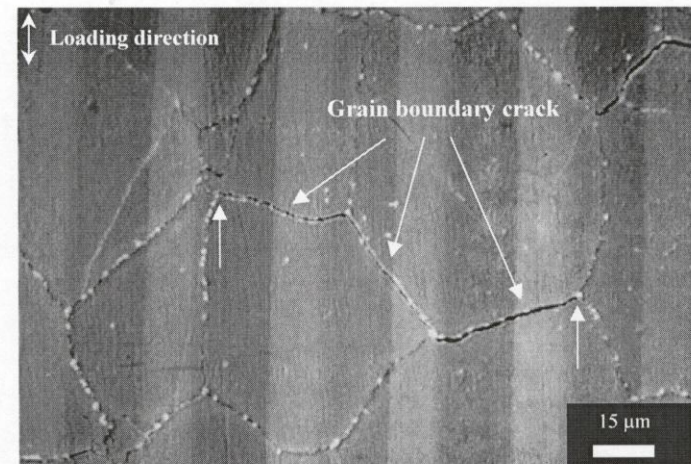
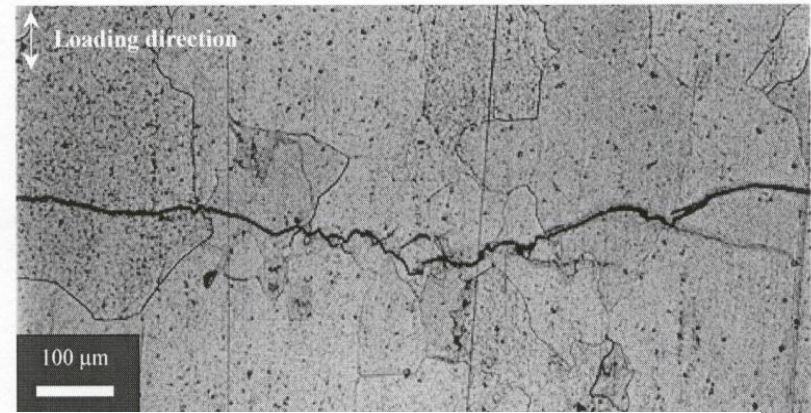
FATIGUE MECHANISMS AND MICROSCOPIC FEATURES (CONT'D)

- Most fatigue cracks grow:
 - across grain boundaries (**transcrystalline**)

Or

- along grain boundaries (**intercrystalline**)

depending on the material,
load, and environmental
conditions.



(a)

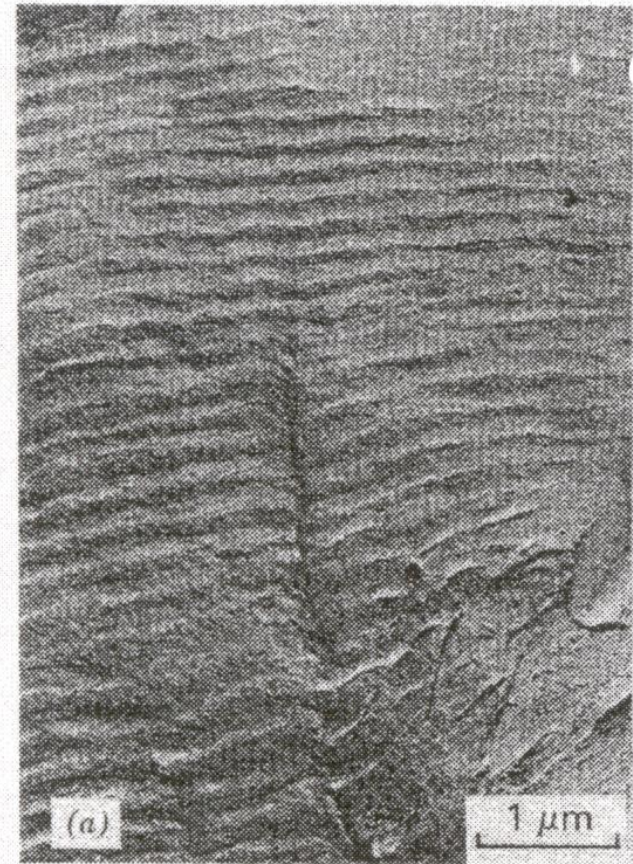


FATIGUE MECHANISMS AND MICROSCOPIC FEATURES (CONTINUED)

- 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.



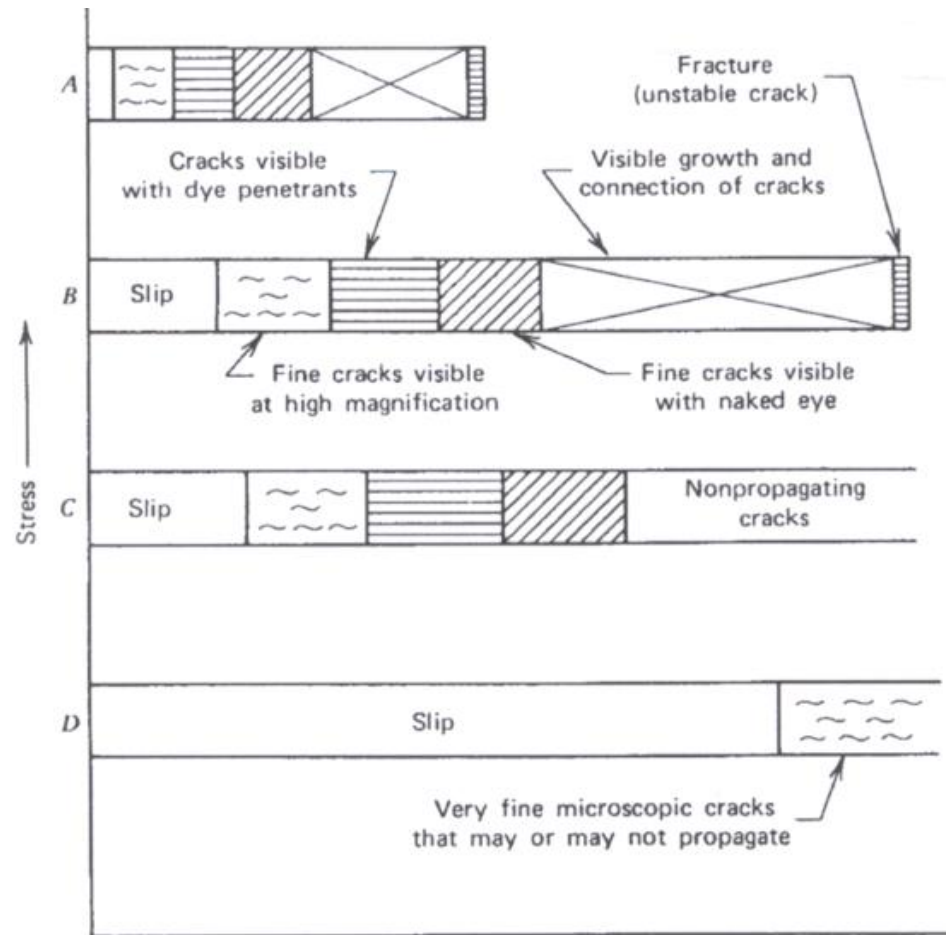
MICROCLEAVAGE

- 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.

FATIGUE MECHANISMS AND MICROSCOPIC FEATURES (CONT'D)

- 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.

SCHEMATIC REPRESENTATION OF THE TYPICAL STAGES OF THE FATIGUE DAMAGE PROCESS



FATIGUE MECHANISMS AND MICROSCOPIC FEATURES (CONT'D)

- 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.

SUMMARY AND 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.

SUMMARY AND DOS AND DON'TS IN DESIGN (CONTINUED)

- 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.

SUMMARY AND DOS AND DON'TS IN DESIGN (CONTINUED)

- 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.

SUMMARY AND DOS AND DON'TS IN DESIGN (CONTINUED)

- 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.