Chapter 14 - Fracture and Failure Mechanisms

Fracture and failure mechanisms:

Ductile/brittle macroscopic classification:
- ductile fracture vs. brittle fracture
- ductile fracture: fracture that exhibits extensive plastic deformation
- brittle fracture: fracture that occurs without appreciable plastic deformation
- stress-strain curves are uniquely different
- "ductilness" or "brittleness" are functions of:
  - material type and condition
  - temperature
  - strain rate
  - stress state
  - environment
- fracture occurs by crack formation and crack propagation

Ductile fracture:
- extensive plastic deformation associated with failure
- crack extension proceeds slowly (stable crack growth)
- crack extension is resisted unless there is an increase in applied stress
- macroscopic failure appearance:
  - gross deformation of fracture surfaces
  - "cup/cone" surfaces
  - 45° shear lip (slant) fracture surfaces
  - Poisson contractions obvious
  - dull fracture surface
- microscopic failure appearance:
  - transgranular
  - microvoid coalescence (dimpled rupture)

Brittle fracture:
- little or no plastic deformation associated with failure
- crack propagation, once started, will continue spontaneously without an increase in applied stress
- macroscopic failure appearance:
  - no evidence of gross deformation
  - flat fracture surface
  - V-shaped "chevron" marks or lines/ridges that radiate from origin
  - smooth, shiny surface
- microscopic failure appearance:
  - transgranular
  - intergranular
  - cleavage
  - quasi-cleavage

Ductile fracture preferred failure mode vs. brittle fracture because:
- brittle fracture occurs suddenly and catastrophically without warning, whereas ductile fracture provides warning failure is imminent by virtue of observable dimensional changes
- more energy is required to induce ductile fracture

Microscopic failure mechanism nomenclature:
- transgranular failure – failure path goes through the grains
- intergranular failure – failure path goes along grain boundaries
- microvoid coalescence – failure via void formation, multiplication, and growth
- cleavage – separation along crystallographic planes
- quasi-cleavage – failure exhibiting some crystallographic features similar to cleavage but with evidence of small amounts of microscopic plastic deformation (tear ridges)
- terms described above apply to metals almost exclusively, with other terminology used for failure of other material types:
  - ceramics – mirror, mist, hackles, ….. (cleavage occurs)
  - polymers – crazes, fibrils, hackles, mirror, …..
  - composite – matrix microcracking, fiber pull-out, fiber breakage, delamination, …..
- go to handbook for documentations of failure modes for each material type

Factors contributing to brittle fracture:
1. low temperatures
2. high rates of load application
3. presence of a triaxial stress state:
   - notches, stress concentrations
   - cracks
   - thick sections
4. hostile environments (e.g., salt water)
5. microstructural factors which limit plastic flow or create likelihood of crack formation:
   - coarse grains
   - precipitation of brittle phase at grain boundaries
   - segregation of impurities to boundaries
   - increased C content in steels
   - presence of hydrogen in steel
   - improper heat treatment
   - improper welding procedures
Traditional Toughness Testing: Charpy V-notch Impact Tests

Charpy V-notch and Izod impact tests have been used for many years to characterize the “toughness” of materials, with Charpy tests being preferred for characterizing metals.

Charpy V-notch testing:
- specimen: small notched specimen
- loading: three-point bending
- loading rate: impact (velocity = \(2gh^{1/2}\) via pendulum mechanism)
- test temperature: tests conducted over a range of temperature to induce ductile-to-brittle behavior
- results: absorbed CVN energy vs. test temperature, ductile/brittle transition temperature, fracture appearance transition temperature (FATT)

Advantages of Charpy testing:
- cheap equipment
- cheap to run and to reduce data
- simple, small specimen
- fast
- historical usage
- little expertise required to run test; interpretation qualitative

Disadvantages of Charpy testing:
- results are geometry dependent (e.g., length of notch, thickness, size)
- not useful for quantitative design
- strain rates may not be meaningful to structural application
- transition temperature may not reflect material’s service response

Other toughness test methodologies are preferred for demanding structural applications of materials:
- linear elastic fracture mechanics (LEFM)
- elastic-plastic fracture mechanics (EPFM)
  - R-curve testing
  - COD testing
  - J-integral testing