2022/08/25

Thursday, August 25, 2022 10:13 AM

Detailed description of course topics:
http://www.rezaabedi.com/wp-content/uploads/Courses/FractureMechanics/TopicsDetails.pdf

Fracture Mechanics Topics & References

Color Code: Covered, Brief Discussion, Not Covered

1. Preliminaries: Tensors; Kinematics (displacement, strain); Stress; Balance laws; Constitutive equations
   Saouma 5.1-5.4; Anderson A2.1
2. History
   Anderson 1.2.1-1.2.5
3. Fracture modes
   3.1. Classification
        Murakami 1.1.1, 1.1.2, **1.1.3**; Saouma 4.1-4.4 (buckling, fracture, yielding, etc.); Schreurs 2.1.
   3.2. Ductile fracture
        3.2.1. Dislocation dynamics
               Hertzberg 2 (theory), 3 (slip and twinning)
        3.2.2. Void nucleation, growth, and coalescence
               Anderson **5.1**

References:

Selected Bibliography

1. T. L. Anderson, Fracture Mechanics: Fundamentals and Applications, 3rd Edition, CRC Press, USA, 2004 (**main textbook**).
2. D. Broek, Elementary Engineering Fracture Mechanics, 4th Revised Edition, Springer, 1982 (or reprint 2013).
3. B. Broek, The Practical Use of Fracture Mechanics, Springer, 1998.
4. S. Murakami, Continuum Damage Mechanics: A Continuum Mechanics Approach to the Analysis of Damage and Fracture, Springer Netherlands, Dordrecht, 2012.
5. S. Suresh, Fatigue of Materials, 2nd ed. Cambridge University Press, 1998.
6. L.B. Freund, Dynamic Fracture Mechanics, Cambridge University Press, 1998.
7. B. Lawn, Fracture of Brittle Solids, Cambridge University Press, 1993.
8. M.F. Kanninen and C.H. Popelar, Advanced Fracture Mechanics, Oxford Press, 1985.
9. R.W. Hertzberg, Deformation and Fracture Mechanics of Engineering Materials. 5th ed. John Wiley & Sons, Inc., 2012 (material focus).
10. S Al Laham, Stress Intensity Factor and Limit Load Handbook, British Energy Generation Limited, 1998.
11. H Tada, P.C. Paris, G.R. Irwin, Stress Analysis of Cracks Handbook, 3rd ed., ASME Press. 2000

From <http://rezaabedi.com/teaching/fracture-mechanics/>

Useful online courseware and links

1. Presentation on Fracture Mechanics by Dr. N. V. Phu from University of Adelaide. With special thanks to Dr. Phu, the majority of course presentations are based on Dr. Phu's presentations.
2. S. Suresh, Fracture and Fatigue, MITOpen courseware.
3. V.E. Saouma, Fracture Mechanics lecture notes, University of Colorado, Boulder.
4. P.J.G. Schreurs, Fracture Mechanics lecture notes, Eindhoven University of Technology (2012).
5. A.T. Zender, Fracture Mechanics lecture notes, Cornell University.
6. K. Ramesh, Engineering fracture mechanics lecture videos, IIT, Madras, India.
7. L. Zhigilei, MSE 2090: Introduction to the Science and Engineering of Materials, University of Virginia: Excellent lecture notes on material preliminaries such as atomic structure (ch2), crystalline solids (ch3), imperfections (ch4), mechanical properties (ch6), dislocation (ch7), and **failure (ch8)**.

From <http://rezaabedi.com/teaching/fracture-mechanics/>

Grade breakdown:

Course requirements

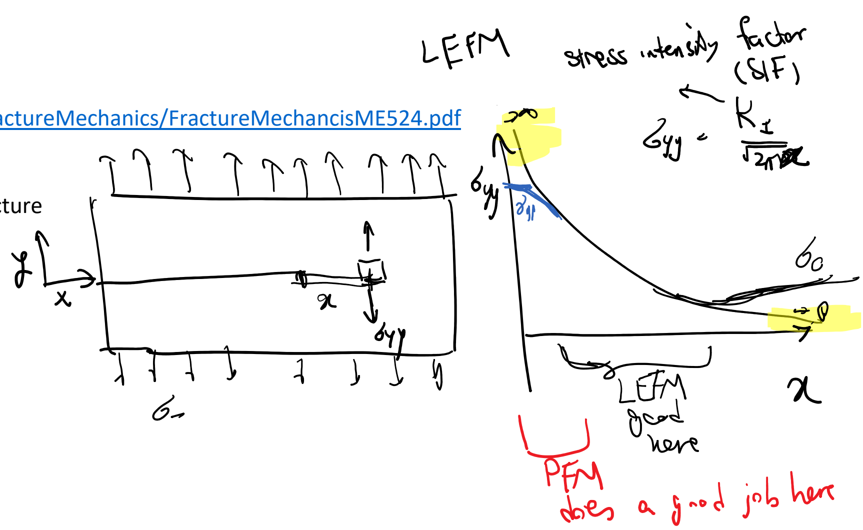
- Homework 34% + 5% (extra credit)
- Exams: Midterm + final: 34%
- Term project 16%: Use commercial software to evaluate stress intensity factor; (Ansys in class, you can use any program you like) Simple computations with cohesive and damage models.
- Report and presentation on a topic on fracture 16%: 4-page report and 10-12 minute presentation at the end of the semester. Individual topics and references will be chosen by the instructor and the student.

For the final project, you can use one of our codes or your code to perform certain fracture study and present it.

Course presentation:
http://www.rezaabedi.com/wp-content/uploads/Courses/FractureMechanics/FractureMechancisME524.pdf

Outline:
1. Overview of fracture mechanics, ductile versus brittle fracture
2. Linear Elastic Fracture Mechanics (LEFM)

   - Energy approach (Griffith, 1921, Orowan and Irwin 1948)
   - Stress intensity factors (Irwin, 1960s)



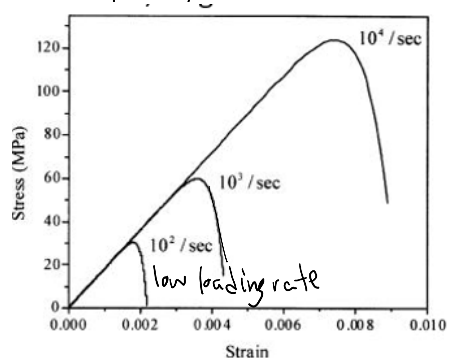
3.Nonlinear / Plastic Fracture Mechanics
- Crack tip opening displacement (CTOD), Wells 1963
- J-integral (Rice, 1958)

- Crack tip opening displacement (CTOD), Wells 1963
- J-integral (Rice, 1958)

FEM does a good job here

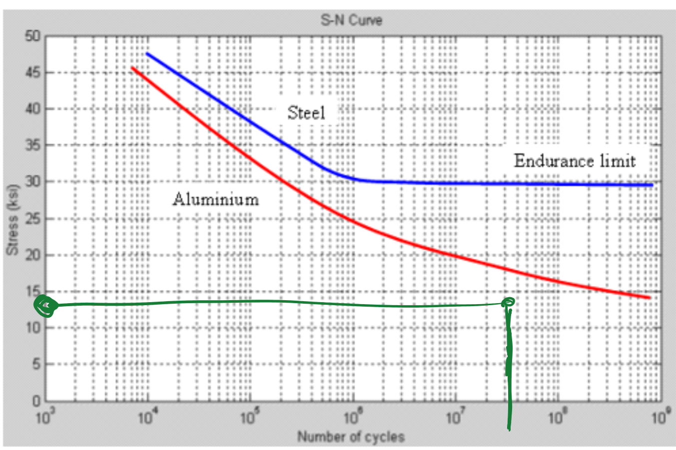
4. Dynamic Fracture Mechanics

One example of dynamic fracture

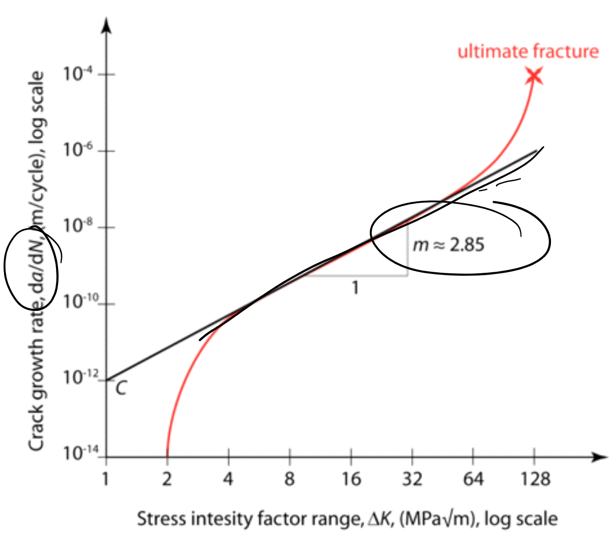


Source: Y.Q. Zhang, H. Hao, J. Appl Mech (2003)

5. Fatigue
   a. Older approach S-N (stress number of cycle), S-N-P (probability)

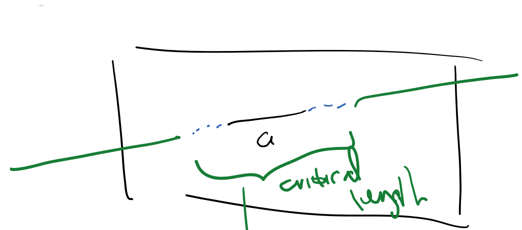


no direct mention of crack length



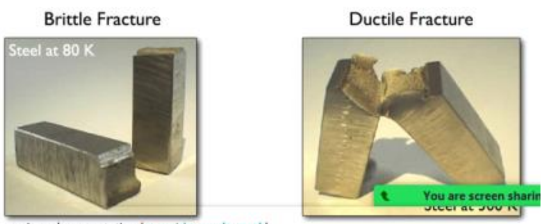
$$\frac{da}{dN} = C(\Delta K)^m$$

crack length; # cycles; const; change of SIF; const power



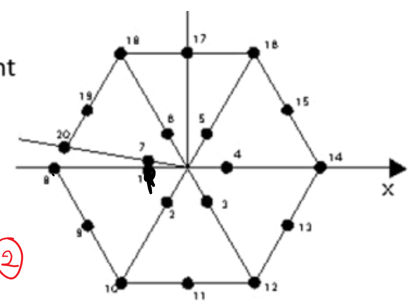
want to avoid the crack to get to its critical size

Ductile versus Brittle Fracture
- Stochastic fracture mechanics
- Microcracking and crack branching in brit fracture

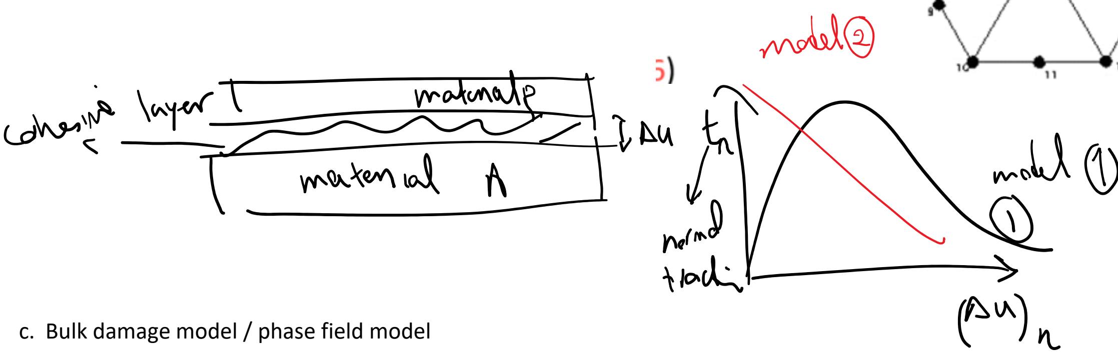


quippy documentation (www.jrkermode.co.uk)

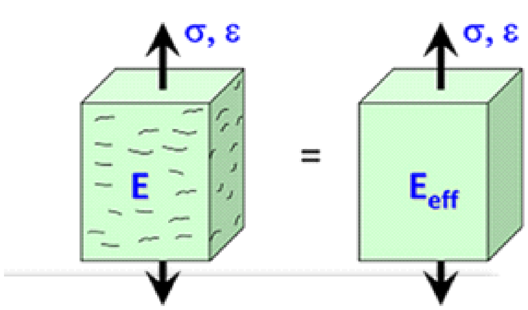
Singular Element



6. Computational Fracture Mechanics
   a. Finite Element: How to calculate SIF, J integral, ... from finite element solution
   b. Cohesive models



   c. Bulk damage model / phase field model



underwood.faculty.asu.edu

Design philosophies:

- Safe life

  The component is considered to be free of defects after fabrication and is designed to remain defect-free during service and withstand the maximum static or dynamic working stresses for a certain period of time. If flaws, cracks, or similar damages are visited during service, the component should be discarded immediately.

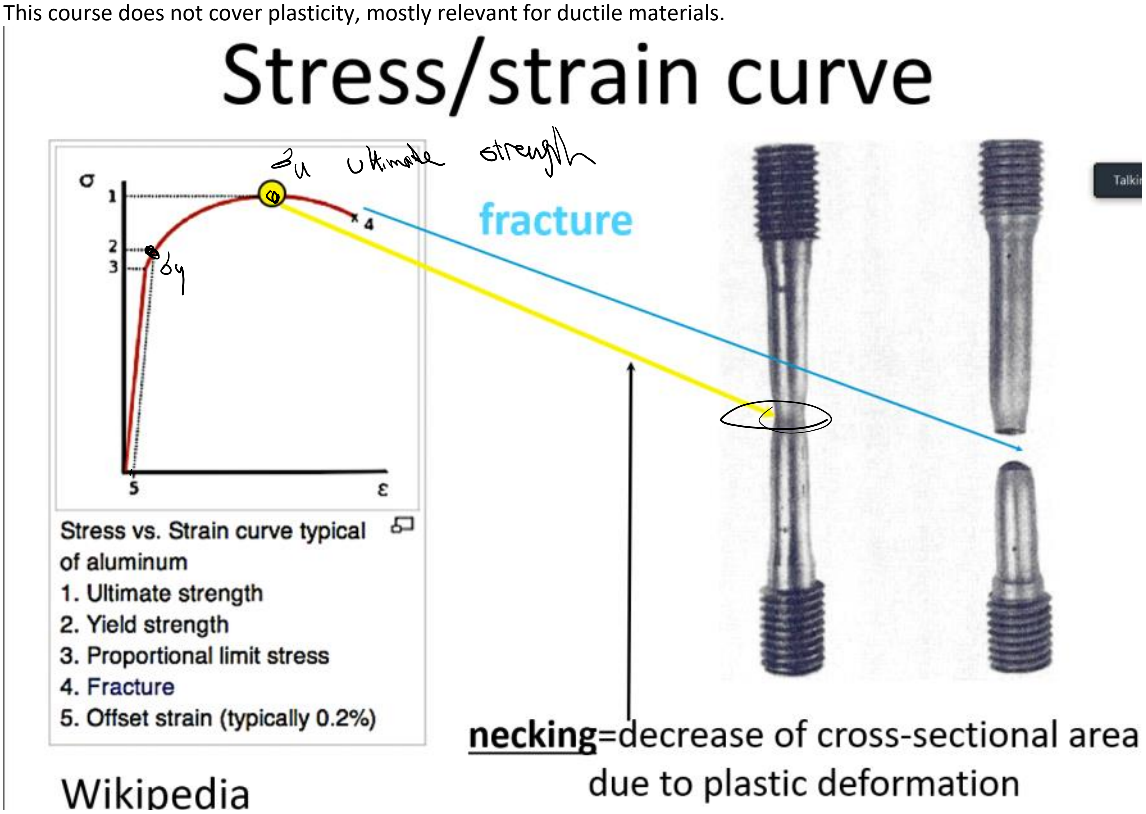
  like fatigue S/N

- Damage tolerance

  The component is designed to withstand the maximum static or dynamic working stresses for a certain period of time even in presence of flaws, cracks, or similar damages of certain geometry and size.

  like Paris law for fatigue

Fracture Mechanics:
In this this course we mainly deal with cracks or models that approximate a population of cracks (damage and phase field model).
This course does not cover plasticity, mostly relevant for ductile materials.



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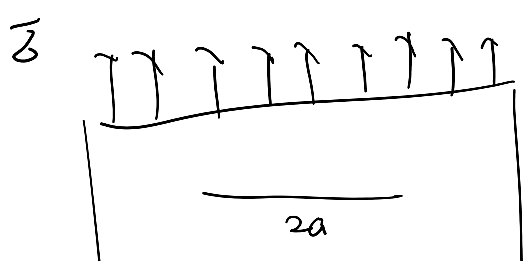
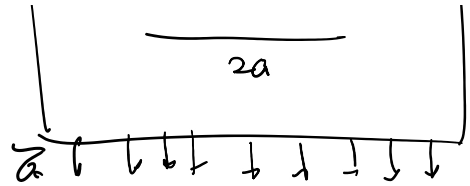
3 typical problems in fracture mechanics:

-- 3 sets of parameters:
1. Applied loads σ
2. Material properties:
   a. Elastic modulus E
   b. Fracture toughness K_Ic
   c. …



2. Material properties:
    a. Elastic modulus E
    b. Fracture toughness K_Ic
    c. ...
3. Defect characteristics, e.g. crack size: a

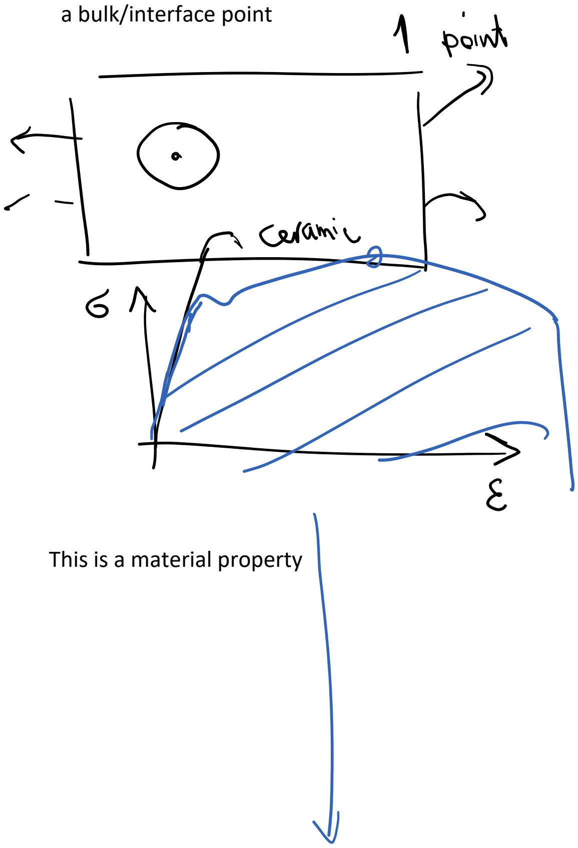


3 types of problem:

A. 1 & 2 are given (applied load and material are known) and we want to obtain maximum allowable defect size. We'll monitor for that crack size.
B. 1 & 3 are given: load and defect size (a defect size that can be detected by nondestructive evaluation) and the goal is to determine target material. This is rate and can have no realistic solution (KIc may become too high)
C. 2 & 3 given we want to obtain safe load for the structure

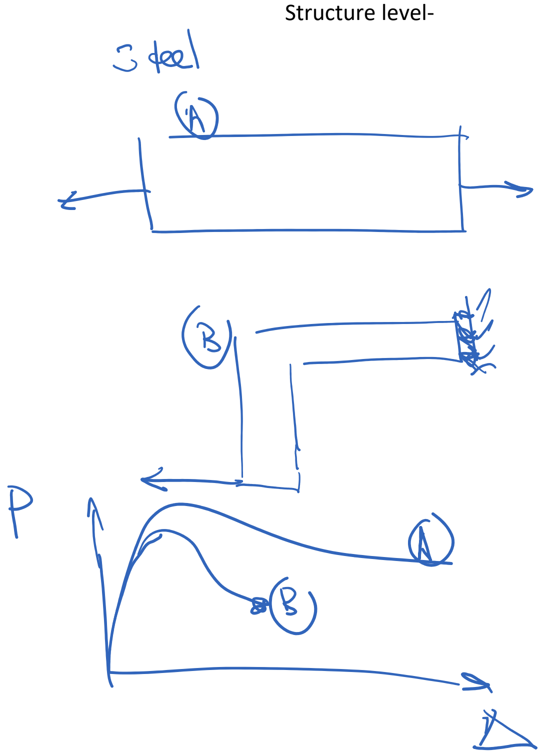
Ductile vs. Brittle fracture

- Ductile vs Brittle fracture can be for the whole structure or a bulk/interface point

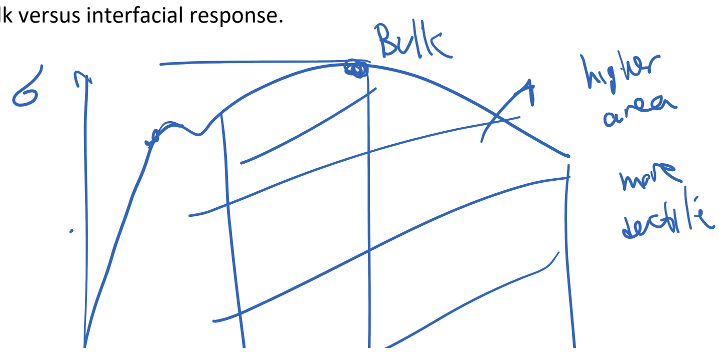


This is a material property

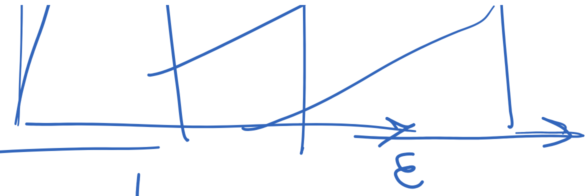
Structure level-



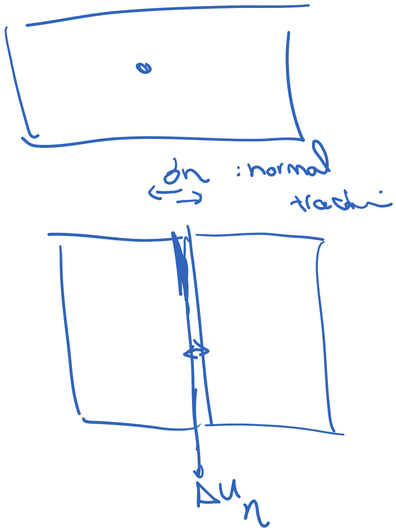
- Ductile vs Brittle for a point can be discussed in the context of bulk versus interfacial response.

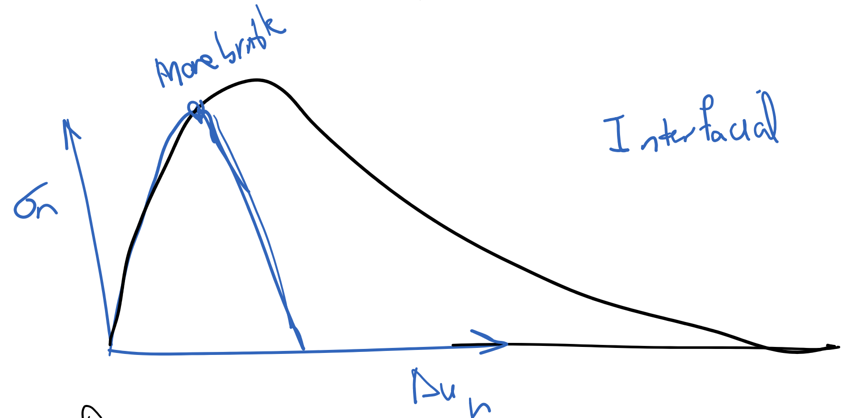


Bulk

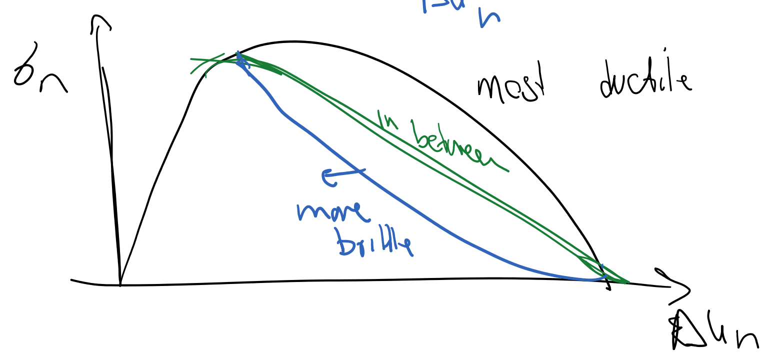


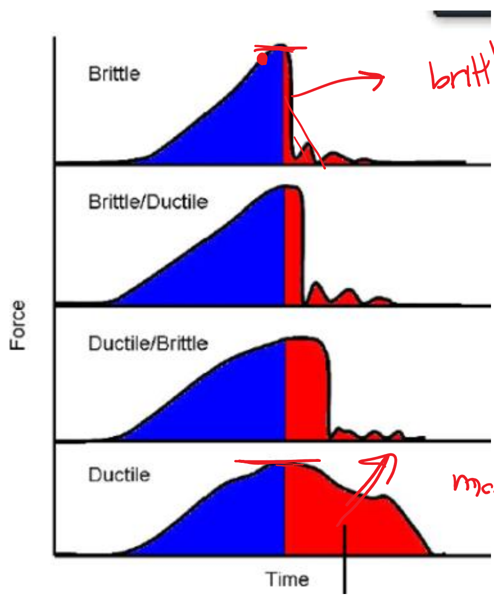
Traction separation, relation





Interfacial



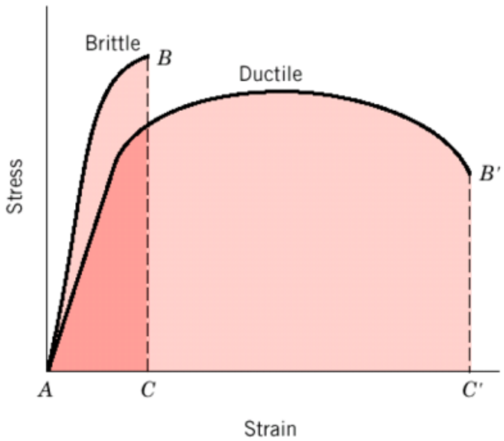


brittle "response" beyond peak or softening point is negligible

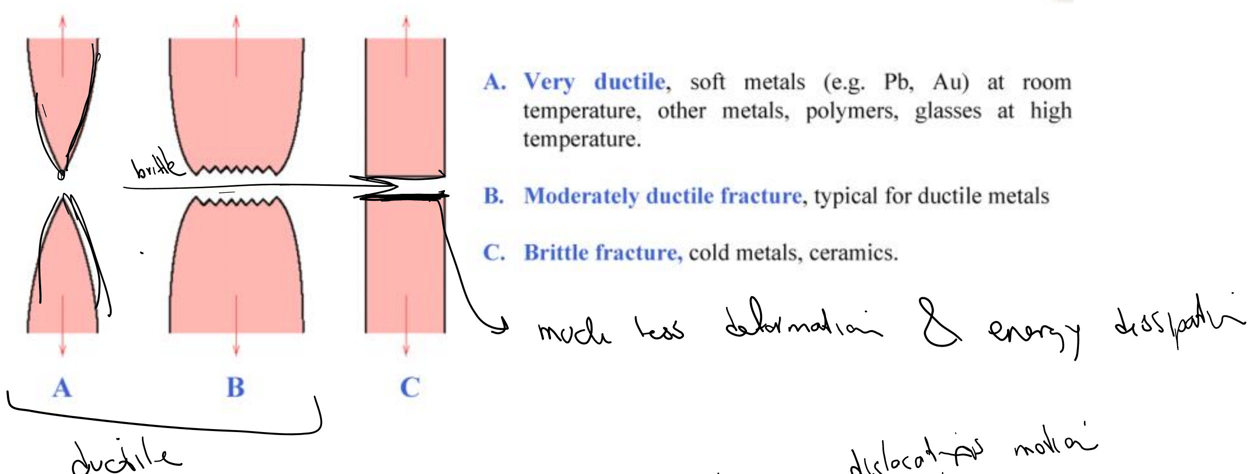
most ductile

In many instances, we prefer ductile fracture because A) it can absorb more energy and B) It provides wanting before catastrophic fracture.

- **Ductile materials** - extensive plastic deformation and energy absorption ("toughness") before fracture
- **Brittle materials** - little plastic deformation and low energy absorption before fracture



Brittle vs. Ductile Fracture



A. Very ductile, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature.

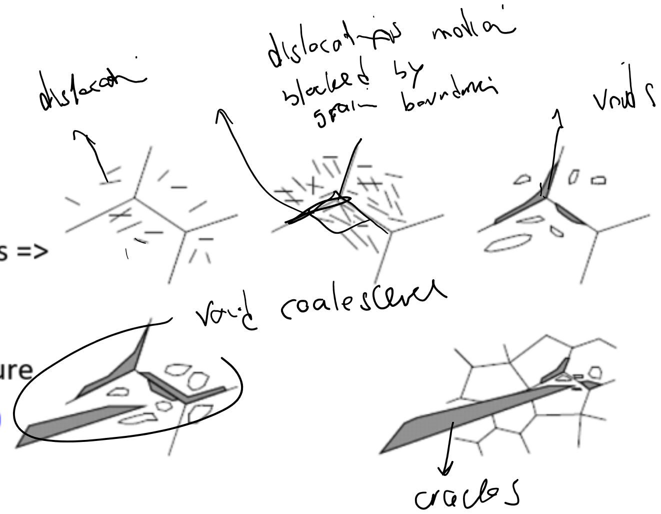
B. Moderately ductile fracture, typical for ductile metals

C. Brittle fracture, cold metals, ceramics.

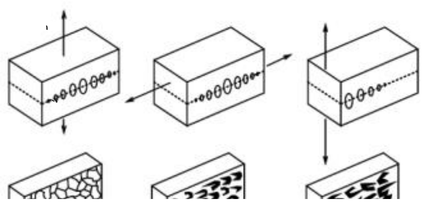
Shearing

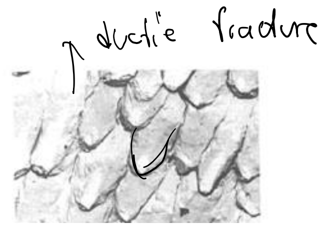
- Applied stress =>
- Dislocation generation and motion =>
- Dislocations coalesce at grain boundaries =>
- Forming voids =>
- Voids grow to form macroscopic cracks
- Macroscropic crack growth lead to fracture

Plastic deformation (ductile material)

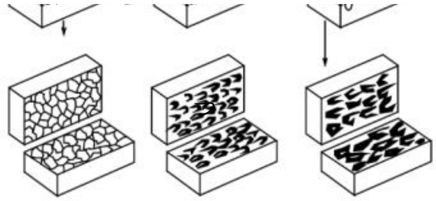


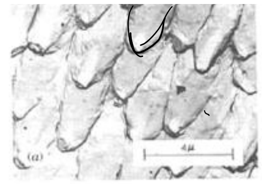
Dough-like or conical features



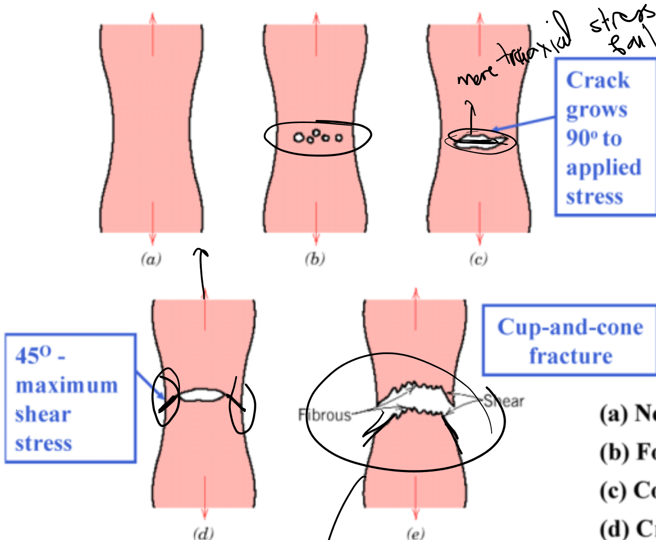


Dough-like or conical features



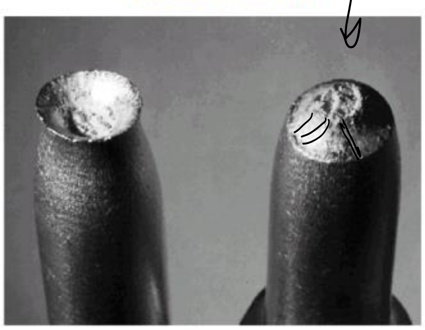


Ductile Fracture (Dislocation Mediated)

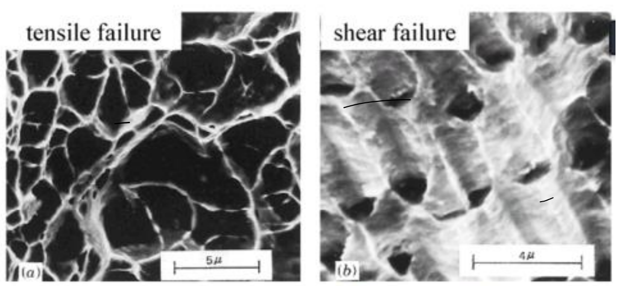


(a) Necking
(b) Formation of microvoids
(c) Coalescence of microvoids to form a crack
(d) Crack propagation by shear deformation
(e) Fracture

Ductile Fracture



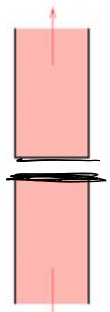
(Cup-and-cone fracture in Al)



Scanning Electron Microscopy: *Fractographic* studies at high resolution. Spherical "dimples" correspond to microvoids that initiate crack formation.

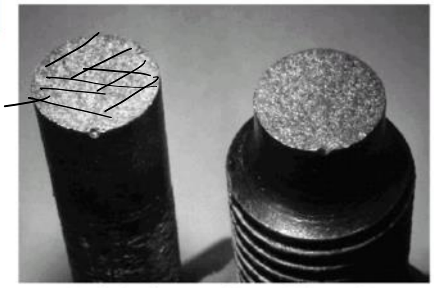
Brittle Fracture (Limited Dislocation Mobility)

- No appreciable plastic deformation
- Crack propagation is very fast
- Crack propagates nearly perpendicular to the direction of the applied stress
- Crack often propagates by cleavage - breaking of atomic bonds along specific crystallographic planes (cleavage planes).



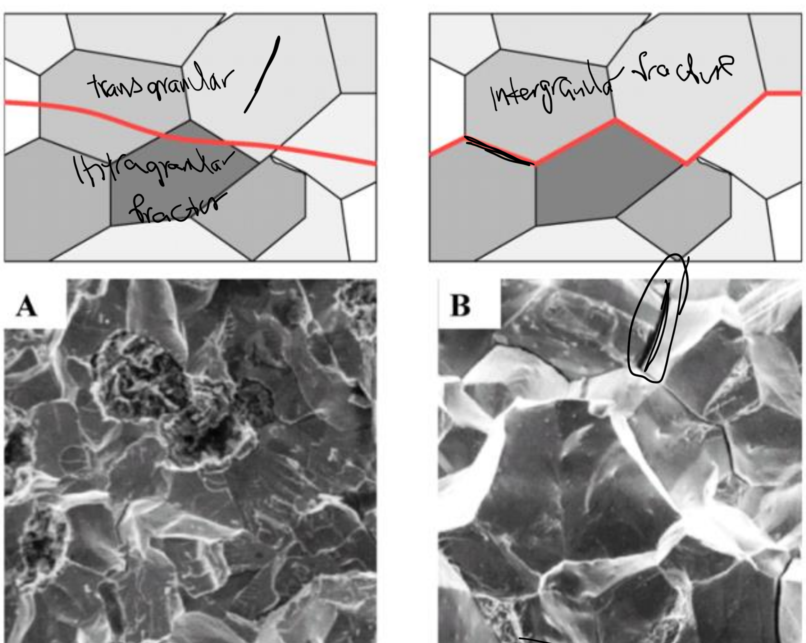
all maximum tensile stress

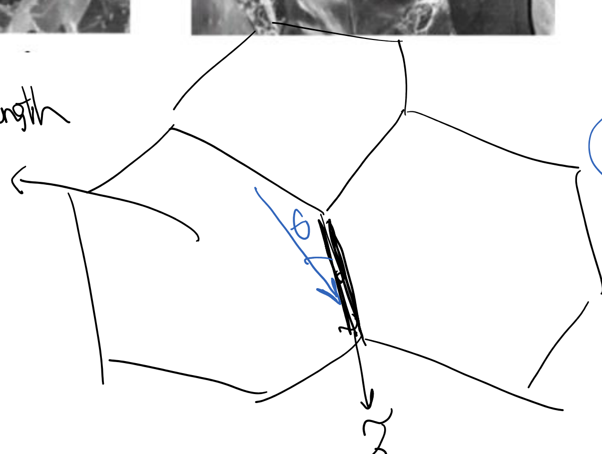
very flat



Brittle fracture in a mild steel

Granular fracture





(1) $\theta \to 0$ → favors intergranular
$\theta \to 90$ → " intragranular

(2) $\tilde{\sigma} / \sigma_0$ ↘ more intragranular fracture

bond strength

more intragranular fracture

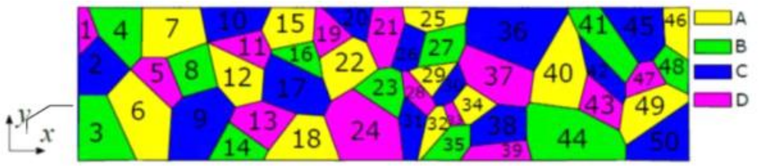
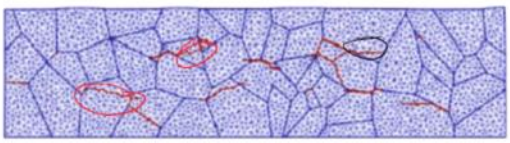
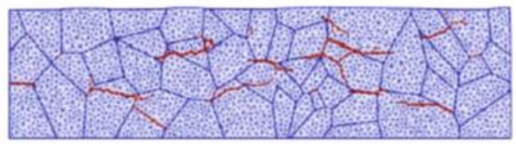


FIGURE 13. The location of 50 grains of materials A, B, C, D in a square domain.

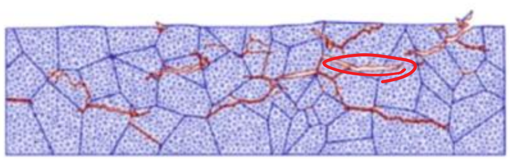
Strong interface



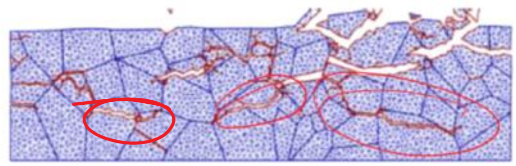
(e) $t = 5.10$



(f) $t = 5.40$

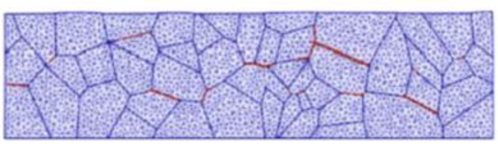


(g) $t = 5.85$

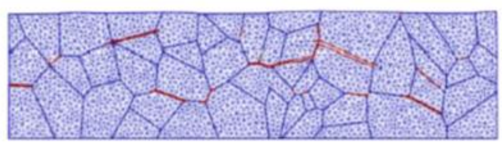


(h) $t = 6.45$

Weaker interface

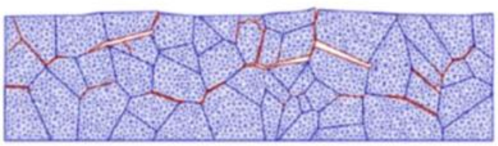


(e) $t = 5.10$

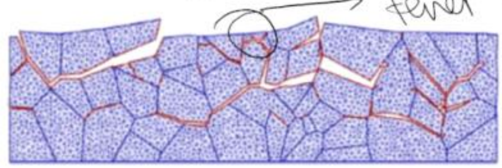


(f) $t = 5.40$

fewer transgranular fracture



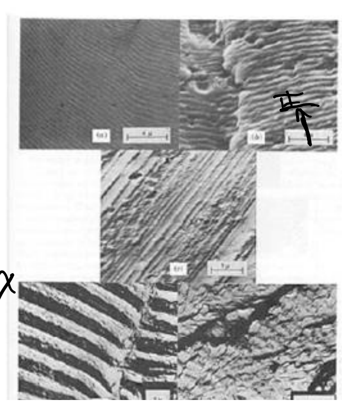
(g) $t = 5.85$

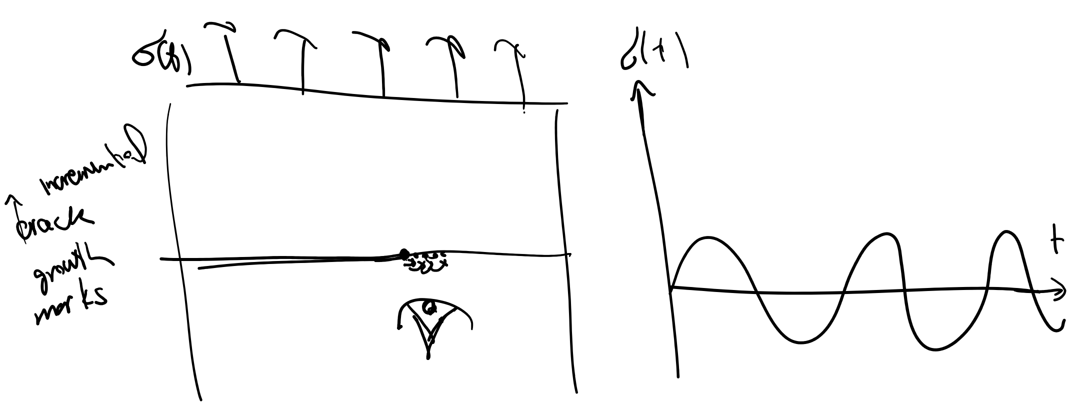


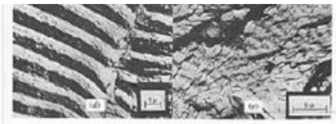
(h) $t = 6.45$

Fracture features for fatigue

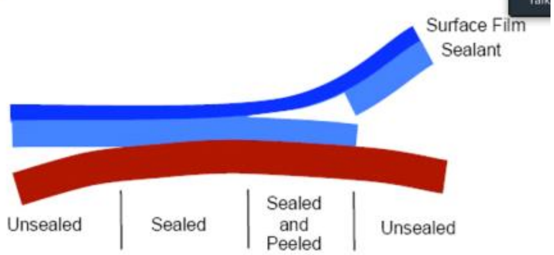
Fatigue







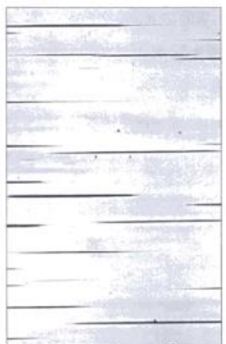
Delamination (De-adhesion)

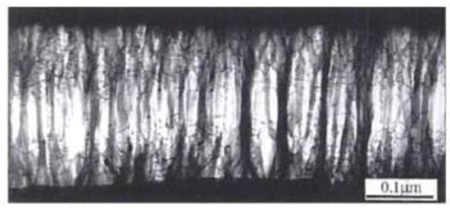


Crazing

- Common for polymers
- sub-micormeter voids initiate

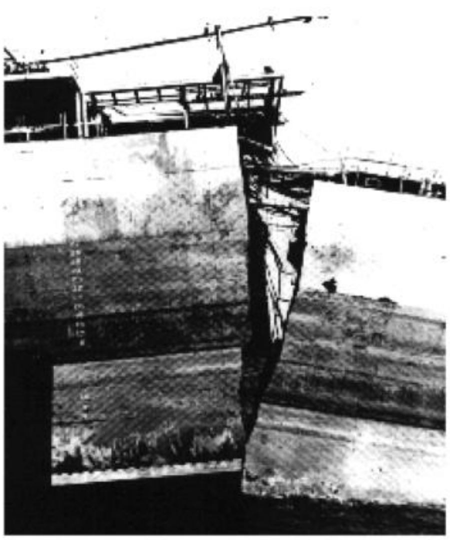
stress whitening because of light reflection from crazes





3.3 Ductile to brittle transition

Ductile-to-brittle transition

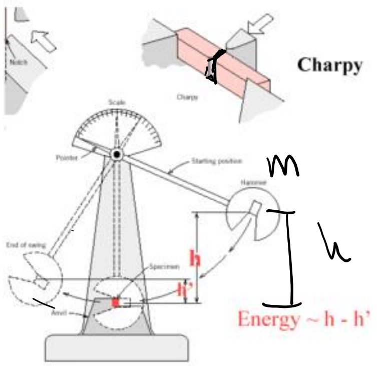


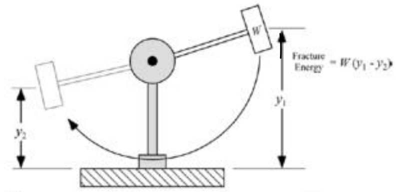
Low temperatures can severely embrittle steels. The Liberty ships, produced in great numbers during the WWII were the first all-welded ships. A significant number of ships failed by catastrophic fracture. Fatigue cracks nucleated at the corners of square hatches and propagated rapidly by brittle fracture.

Temperature influence

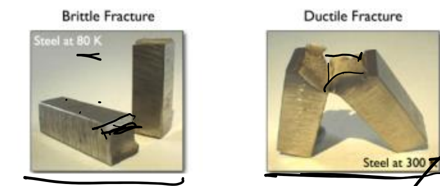
Testing ductility

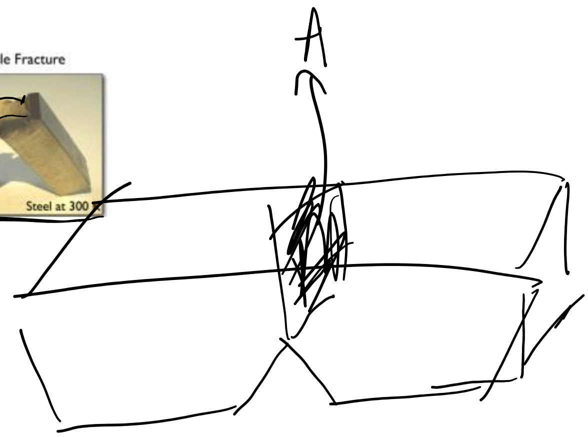
Charpy v-notch test





Influence of temperature on Cv





Energy lost = $mg(h-h')$

= fracture energy = $A(2\gamma)$

↓ fracture toughness

$$\gamma = \frac{mg(h-h')}{A}$$