Departments of Materials Science & Engineering
University of California, Berkeley

Mechanical Behavior of Engineering Materials

Robert O. Ritchie

MSE 113

Fall 2018

MSE 113
Mechanical Behavior of Engineering Materials

Lecturer: Prof. R. O. Ritchie, Rm. 324 HMMB (or 62-239, MSD, LBNL)

TA: Amy Wat*: email: amy.wat@berkeley.edu*

BRIEF COURSE DESCRIPTION:

A presentation is given of deformation and fracture in engineering materials, including elastic and plastic deformation from simple continuum mechanics and microscopic viewpoints, dislocation theory, alloy hardening and creep deformation, fracture mechanisms, linear elastic and nonlinear elastic fracture mechanics, toughening of metals, ceramics and composites, environmentally-assisted cracking, fatigue failure, subcritical crack growth, stress/life and damage-tolerant design approaches.

GRADING:

Homeworks:	15%
Mid-Term I:	20%
Mid-Term II:	20%
Final:	45%

MSE 113
Required and Reference Texts

R.W. Hertzberg *et al*.: Deformation & Fracture Mechanics of Engineering Materials (Wiley, 2012, 5th ed.)

Mechanical Behavior of Materials:

F.A. McClintock, A.S. Argon: *Mechanical Behavior of Materials* (Addison-Wesley, 1966)*
M.A. Meyers, K K. Chawla: *Mechanical Behavior of Materials* (Cambridge, 2009, 2nd ed.)
M. A. Meyers, K.K. Chawla: *Mechanical Metallurgy: Principles and Applications* (Prentice-Hall, 1984)

Fracture Mechanics:

T.L. Anderson: *Fracture Mechanics: Fundamentals and Applications* (CRC Press, 1999, 3rd ed.)*
D. Broek: *Elementary Engineering Fracture Mechanics* (Sijthoff and Noordhoff, 1982, 3rd ed.)
J.F. Knott: *Fundamentals of Fracture Mechanics* (Halstead Press, 1973)*
S.T. Rolfe, J.M. Barsom: *Fracture and Fatigue Control in Structures* (Prentice-Hall, 1987, 2nd ed.)
H. L. Ewalds, R. J. Wanhill: *Fracture Mechanics* (Arnold, 1984)*
B.R. Lawn: *Fracture of Brittle Solids* (Cambridge Univ. Press, 1993, 2nd ed.)

Fatigue:

S. Suresh: *Fatigue of Materials* (Cambridge Univ. Press, 1998, 2nd ed.)*

Environmentally-Influenced Failure:

J.C. Scully: *Fundamentals of Corrosion* (Pergamon, 1975, 2nd ed.)

Mechanical Testing:

Metals Handbook, 9th ed., vol. 8 (American Society for Metals)

Failure Analysis/Fractography:

Metals Handbook, 9th ed., vol. 12 (American Society for Metals)

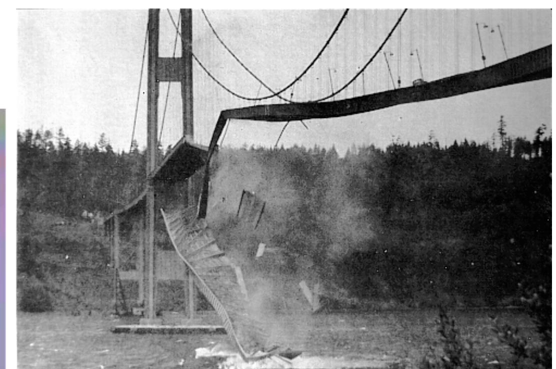
Continuum Mechanics/Elasticity:

E.P. Popov: *Introduction to Mechanics of Solids* (Prentice-Hall, 1968)
S.H.Crandall, N.C.Dahl, T.J.Lardner: *Introduction to the Mechanics of Solids* (McGraw, 1978, 2nd ed.)

Why Mechanical Properties are Important

- Why does stuff fail?
- How does it fail?
- What type of stuff fails?
  - ships, bridges and planes
  - micromachines
  - medical devices
  - **you!** (bones, teeth)
- Can we prevent it?

Sknyliv Airshow, Lviv, Ukraine (2002)

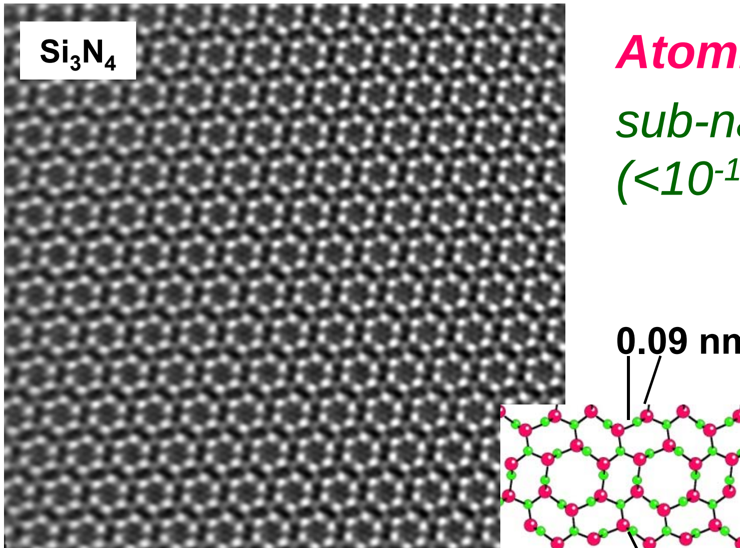


Tacoma Narrows suspension bridge (1940)

(1001crash.com)

B-52 bomber, Fairchild Air Force Base, WA (1994)

Length Scales in Material Behavior

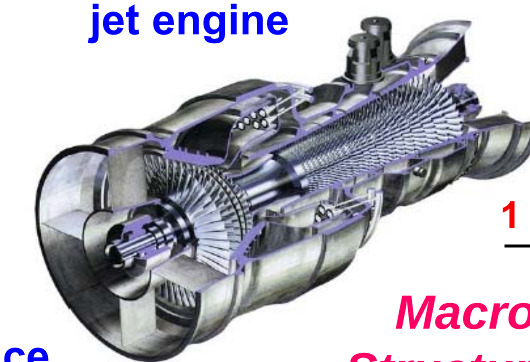


ceramic crystal 0.1 nm

Atomic structure

sub-nanometer
($<10^{-10}$ m)

jet engine



1 m

Macro Structures

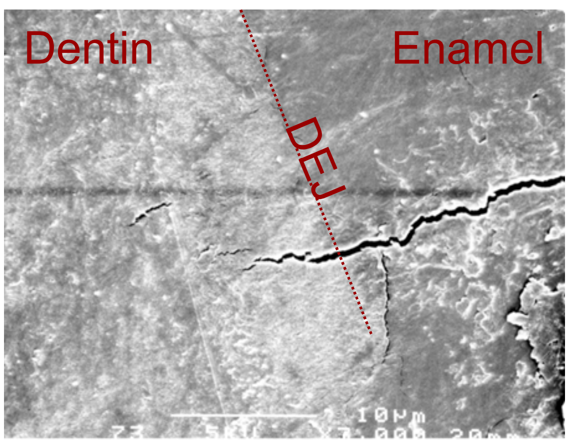
cm to m
(10^{-2} to 1 m)

prosthetic device

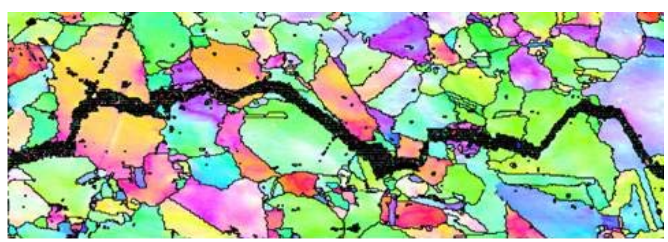
10 mm

Microstructures

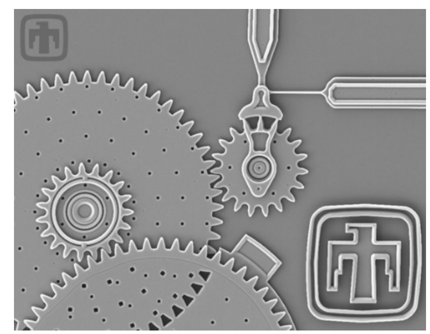
micrometers
($\sim 10^{-3}$ m)



crack in a human tooth 1 µm



fatigue crack in Ni alloy blade 10 µm



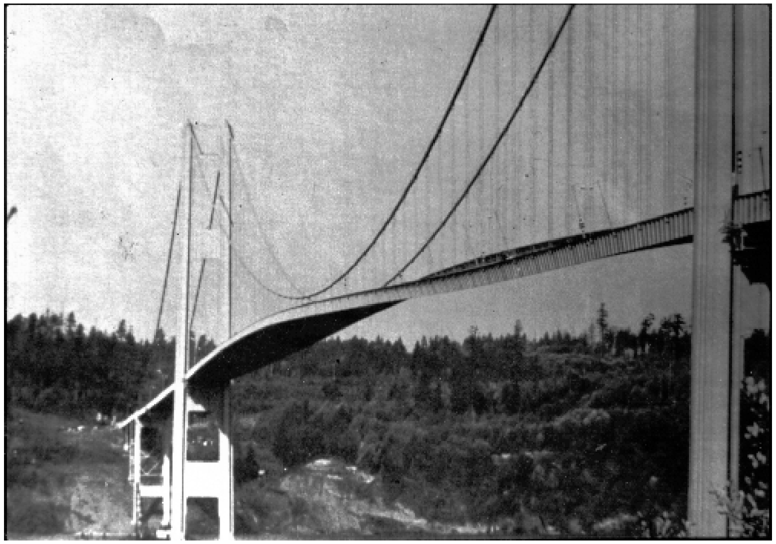
micromachines 10 µm

MEMS/NEMS – Micro/ Nano-electromechanical systems

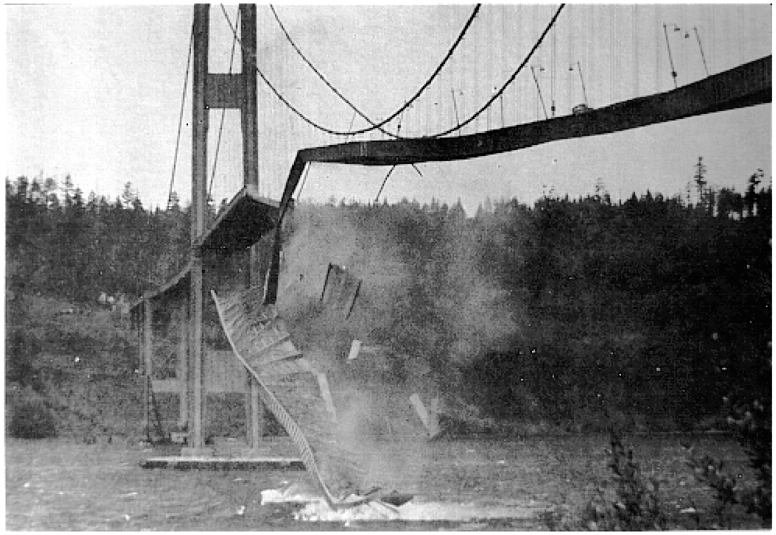
How do things break?

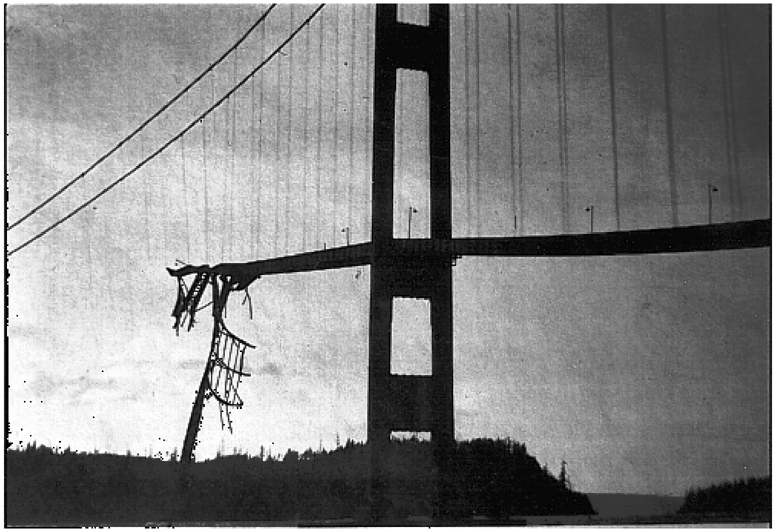
- by plastic deformation - yielding
  - *e.g.*, by bending a paper clip
- by (instantaneous) fracture
  - *e.g.*, by breaking a pencil or a tooth or by impact fracture
- by fatigue (delayed fracture)
  - *e.g.*, by bending that paper clip back and forth several times
- by environmentally-assisted cracking (delayed fracture)
  - *e.g.*, by bending that paper clip back and forth under (salt) water
- by corrosion and/or wear (surface damage)
  - *e.g.*, by corroding away or simply wearing something out

Failure by Plastic Deformation



- plastic (permanent) deformation of a bridge
- deformation led to eventual collapse
- Tacoma Narrows suspension bridge, near Puget Sound, failed on at 11 am Nov. 7, 1940, after only having been open for traffic a few months





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- by corrosion and/or wear (surface damage)

  - e.g., by simply corroding away or wearing something out

Instantaneous Impact Fracture

Brittle fracture of SS Schenectady, Jan. 1943

- 500 T2 tankers and 2700 Liberty ships were built during WWII
- prefabricated all-welded construction, with brittle steel
- one vessel was built in 5 days!

- initially, some 30% of Liberty ships suffered catastrophic failure
- cracks started at stress concentrations (*e.g.*, hatchways) and propagated rapidly through the steel hull as the metal became too brittle at low temperatures

SS John P. Gaines split in two in 1943

Instantaneous Impact Fracture

- Air France charter flight from Paris to New York - July 25, 2000
- the Concorde crashed into a hotel shortly after take-off, 5 miles from airport, with 109 fatalities
- attributed to a piece of metal on the runway causing the bursting of a tire
- the impact of the tire debris on the fuel tank punctured it, leading to loss of engine power, and the subsequent crack
- an example of *foreign-object damage (FOD)*

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Fatigue & Delayed Fracture

- De Havilland Comet, first commercial jet aircraft, had five major crashes in 1952 - 54 period
- caused by fatigue cracks initiated at square windows, driven by cabin pressurization and depressurization

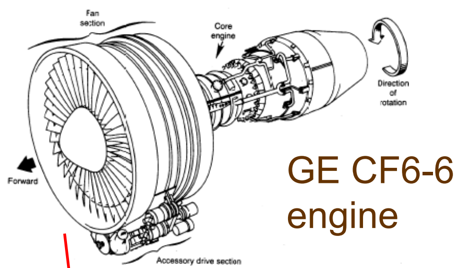
- Aloha Airlines Boeing 737, in route from Hilo to Honolulu (April 1998) undergoes explosive decompression – 1 fatality
- caused by a weakening of the fuselage due to corrosion and small cracks – led to Aging Aircraft Initiative

McDonnell Douglas DC-10 Crashes

- McDonnell–Douglas DC-10 is a three-engine medium-range wide-body aircraft
- the aircraft suffered many notable crashes
  - March 3, 1974 (Paris) - Turkish Airlines flight 981, rear cargo door blew out – all 333 passengers & 12 crew lost
  - May 25, 1979 (Chicago) - American Airlines 191 lost left engine on take-off – all 258 passengers & 13 crew lost
  - July 19, 1989 (Souix City) – United Airlines 232 crashed killing 110 of 258 passengers

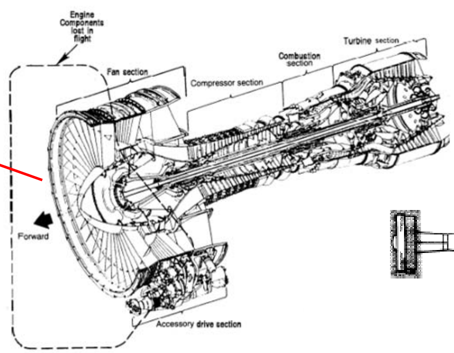
    a fatigue crack in the fan disk in the tailed-mounted engine fractured the disk; the resulting debris severed all three hydraulic control systems. The only way to steer the plane was by adjusting the thrust of the two remaining wing-mounted engines. However, on landing the tip of the right wing contacted and the aircraft skidded, somersaulted and caught fire.

United 232 Souix City Iowa Crash

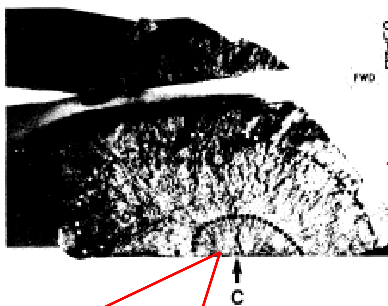


GE CF6-6 engine

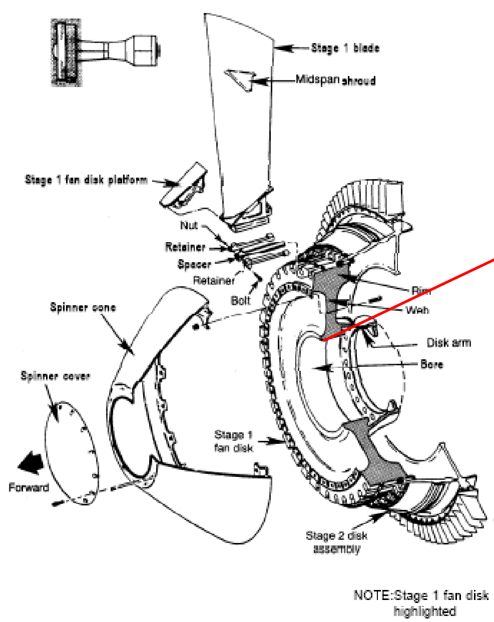
fan disk

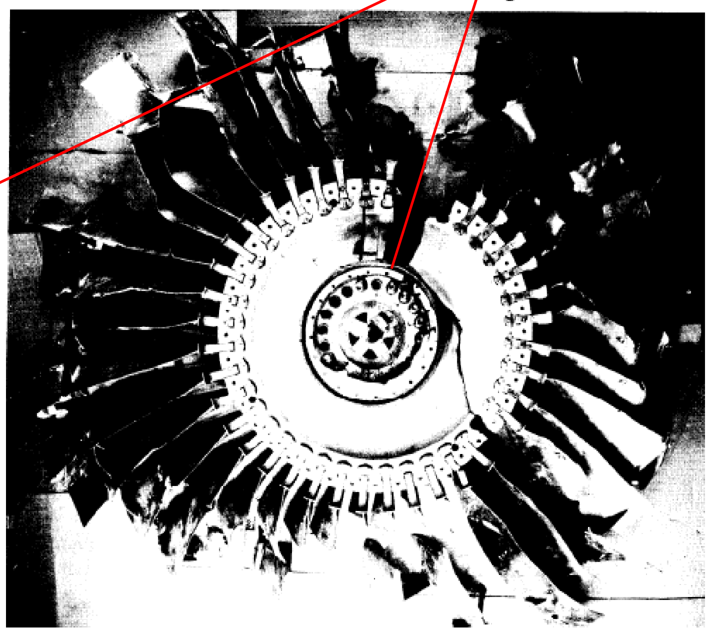


- Ti alloy (Ti-6Al-4V) fan disk fractured due to 0.6-inch fatigue crack, that initiated from a 0.015-0.055 inch α-inclusion in the cast metal
    - the crack from the bore grew for many years and was missed by some 6 inspections



1 inch





- debris from failure severed all hydraulic control lines
- parts of the fractured fan disks were not found for several months

July 19, 1989, Souix City, Iowa

reconstructed fan disk

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- **by wear (surface damage)**
  - *e.g.*, by simply wearing something out

Failure due to Wear

- A major wear problem is with railroad tracks, where surface wear from metal-to-metal rolling contact can damage the rails leading to derailment

Rail collapse leads to derailment of a locomotive in UK, in 1981

Derailment of 100 ton tank wagon and the rest of the train in Lincolnshire, UK in 1982

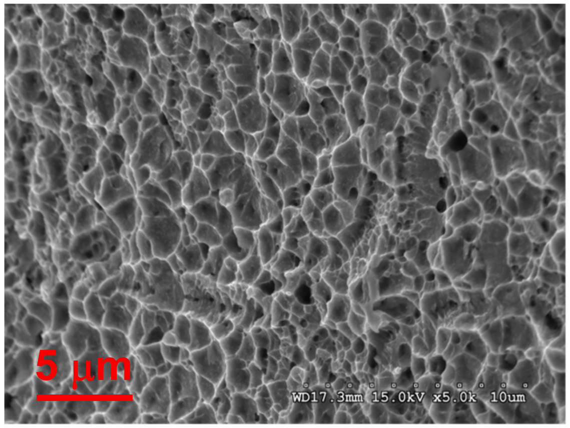
crack initiation

surface wear (delamination) can lead to catastrophic fatigue fracture of the rail

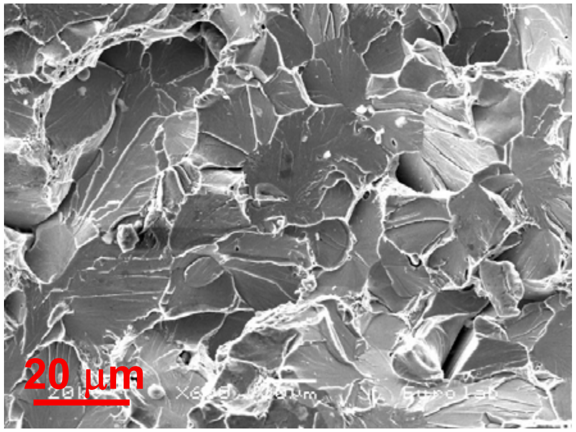
(from http://danager-ahead.railf.net)

Fractography

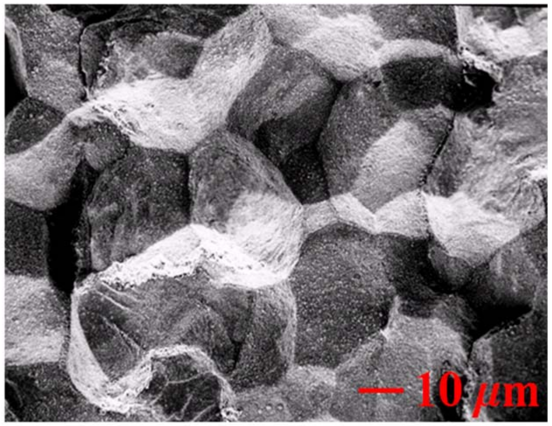
Ductile fracture



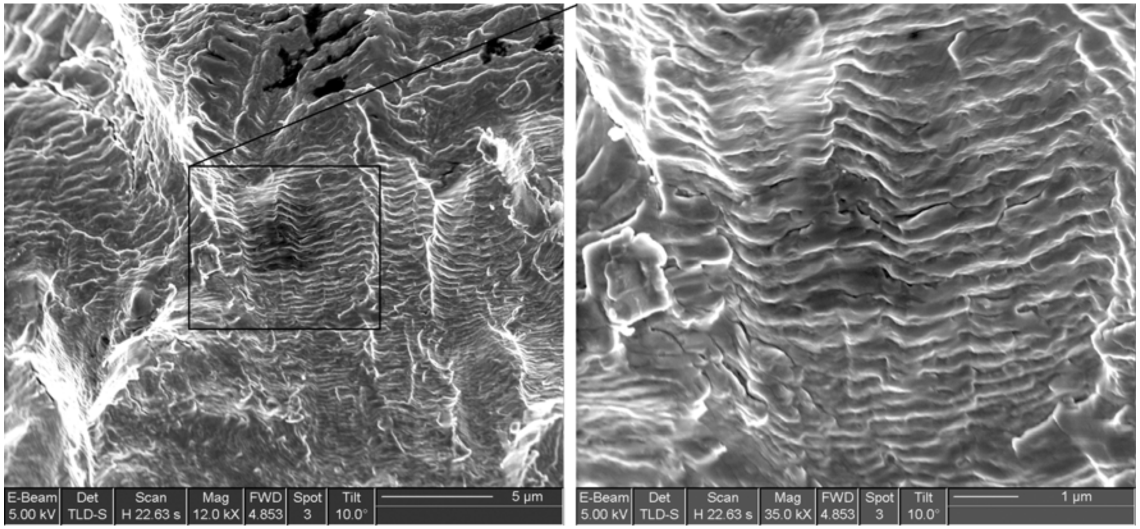
Brittle fracture



Creep fracture

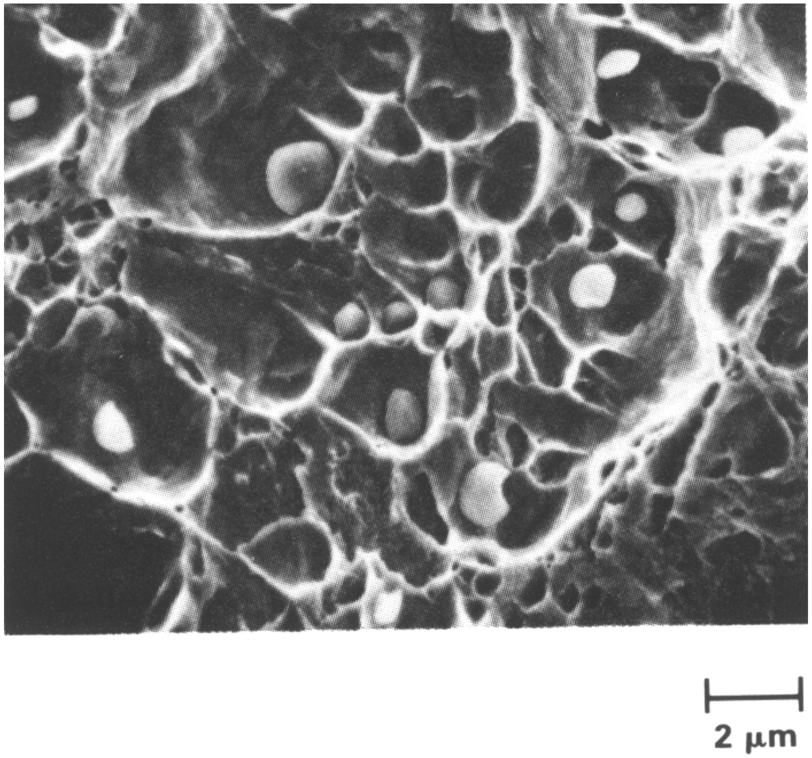


Fatigue fracture

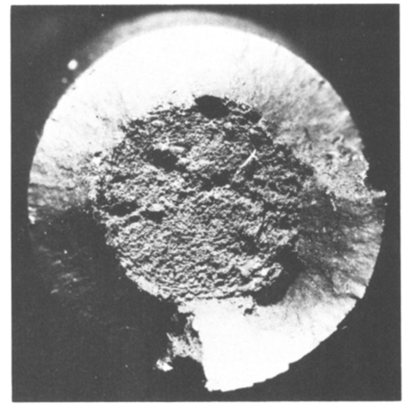


Ductile Fracture

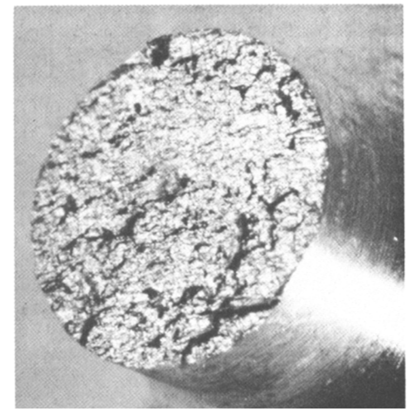
microvoid coalescence



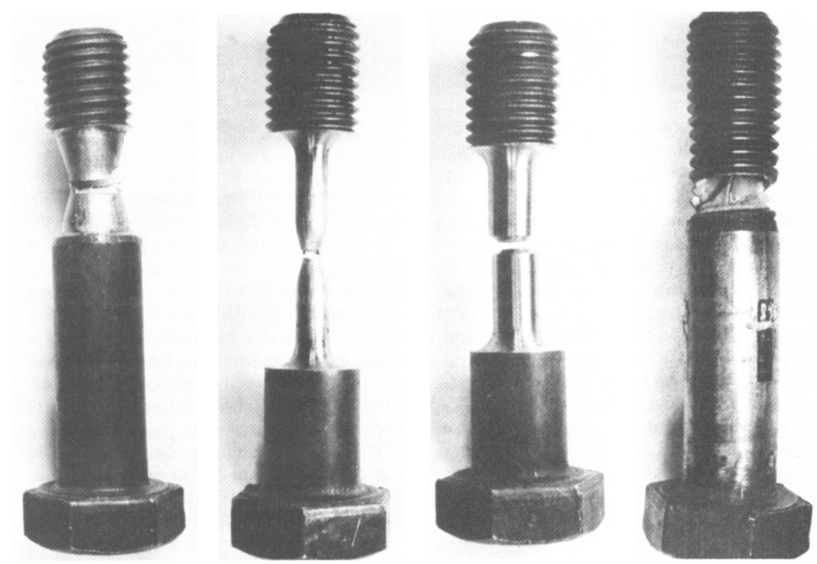
- *ductile fracture* is the "desirable" form of fracture as it requires high energy
- it results from the coalescence of small voids formed around particles, e.g., inclusions, precipitates, in the metal



"cup-and-cone" ductile fracture

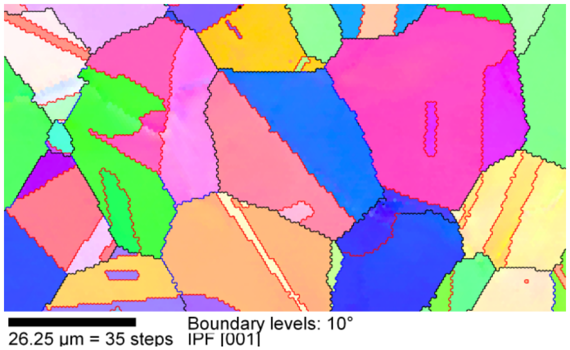


"flat" brittle fracture

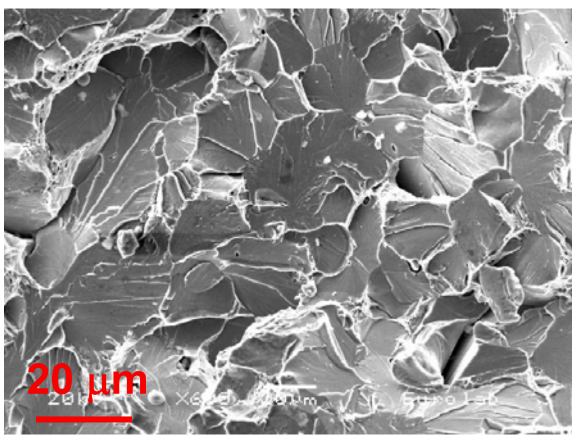


(*ASM Metals Handbook*, vol. 12, 1987)

Brittle Fractures

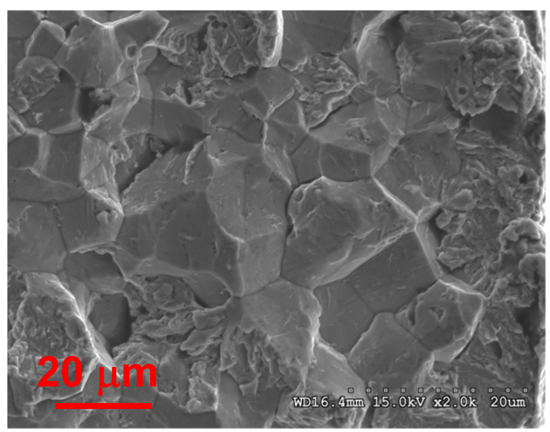


- most materials are polycrystalline consisting of many crystals (grains)
- brittle fracture is generally *transgranular* (cleavage) with the crack propagating through the grains
- when the grain boundaries are "embrittled", fracture can be *intergranular*

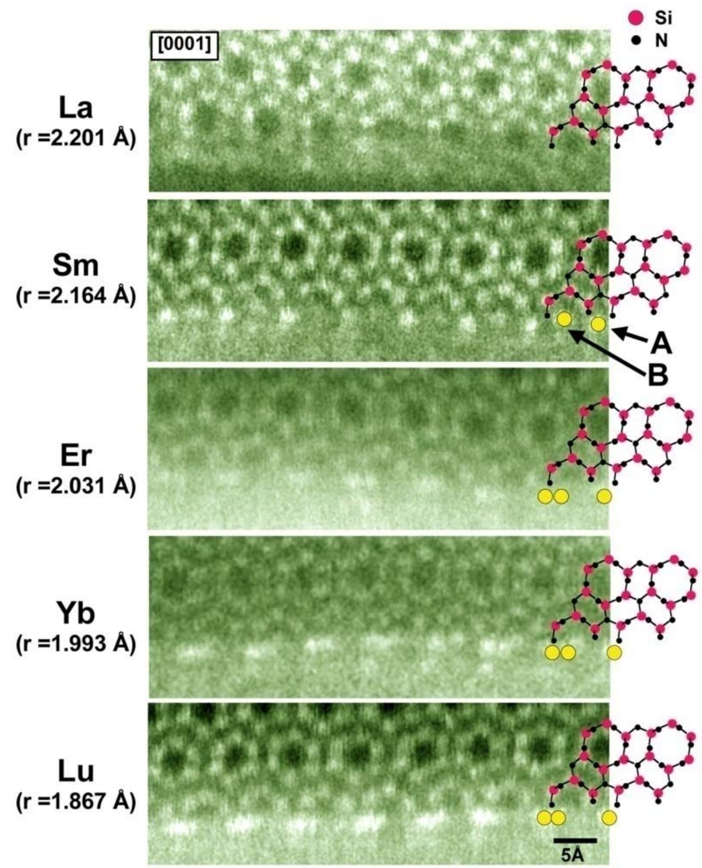


transgranular cleavage

- segregation of impurity element atoms, *e.g.*, S, P, O, H, to grain boundaries can cause such embrittlement



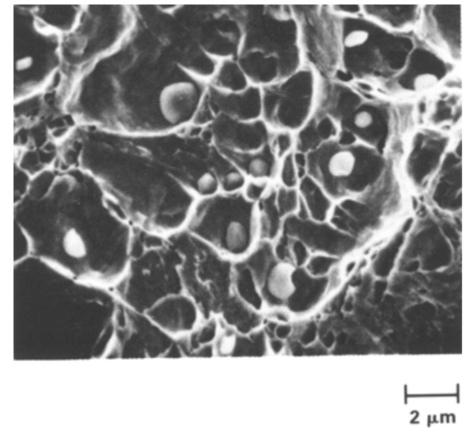
intergranular fracture

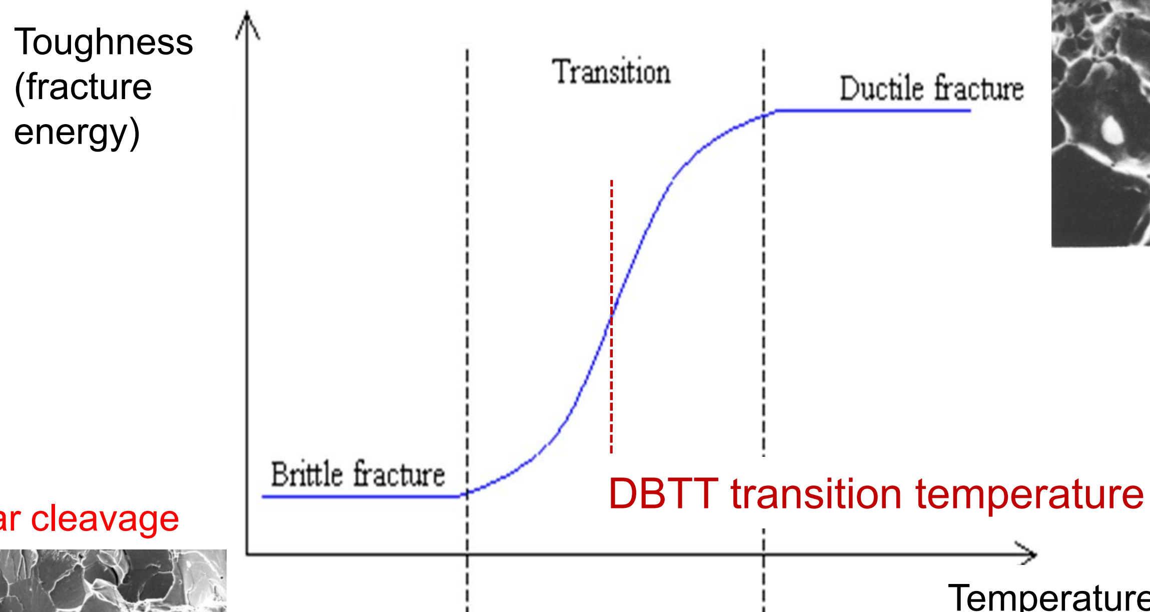


Ductile-to-Brittle Transition

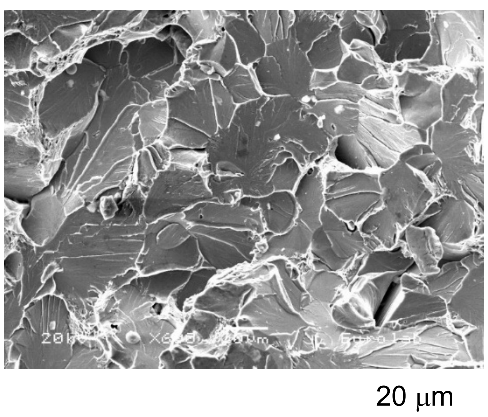
Many materials, like steels (and rubber), show a ductile-to-brittle transition (glass transition)

microvoid coalescence





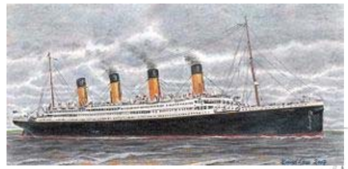
transgranular cleavage

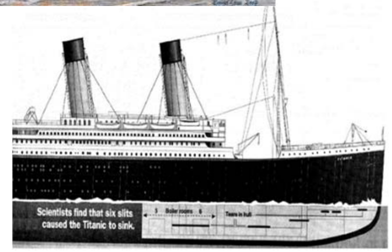


- Rubber shows a glass transition temperature, below which it is brittle, like glass, and above which it behaves like rubber
- Similarly, many metals like steel display a ductile-to-brittle transition temperature. Above this temperature, they are ductile, whereas below they are brittle with typically an order of magnitude lower toughness (energy required for fracture)

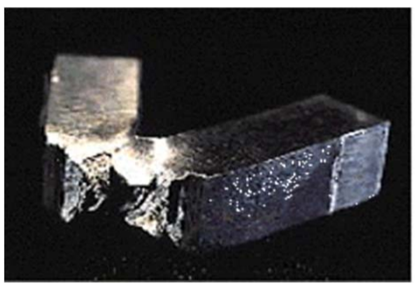
Sinking of the RMS Titanic

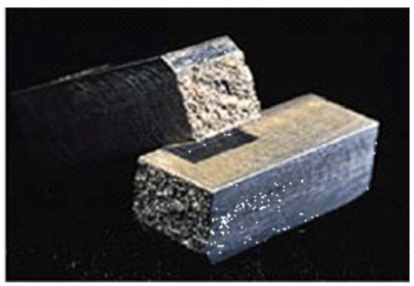
- On April 14, 1912, RMS Titanic hit an iceberg in the north Atlantic and sank in just over 2 hrs
- 1500 of Titanic's 2223 passengers lost





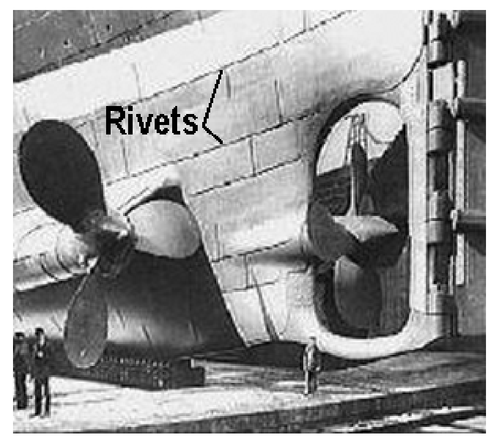
Why did the ship sink so fast?





1. **poor steel:** steel was very brittle with high O & S content

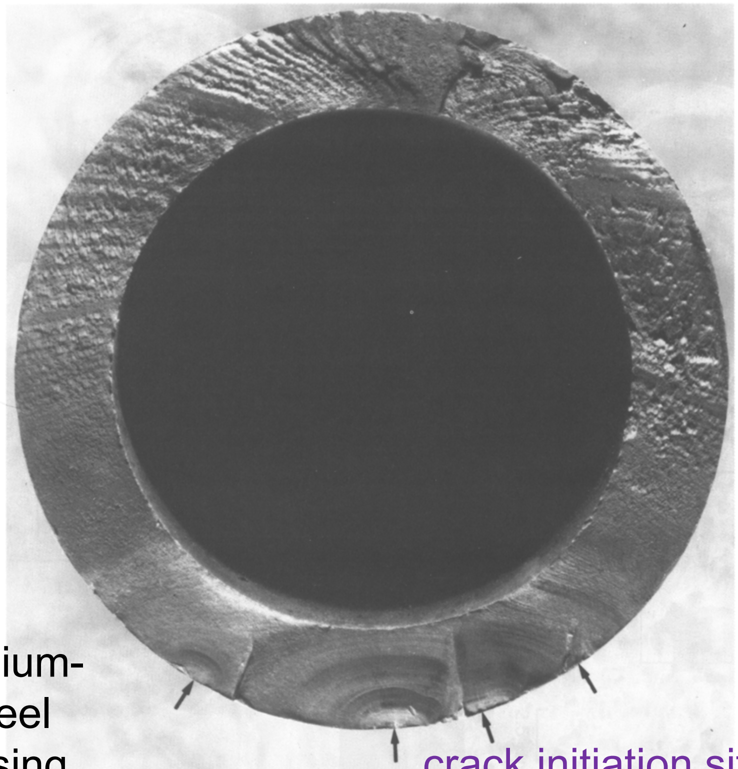
2. **poor rivets:** hull held together by 3 million very brittle wrought iron rivets containing excessive slag



(*Encyclopedia Britannica*, www.britannica.com/titanic; *The Gazette Online*, vol. 28 (32) 1999; www.jhu.edu~gazette/1999)

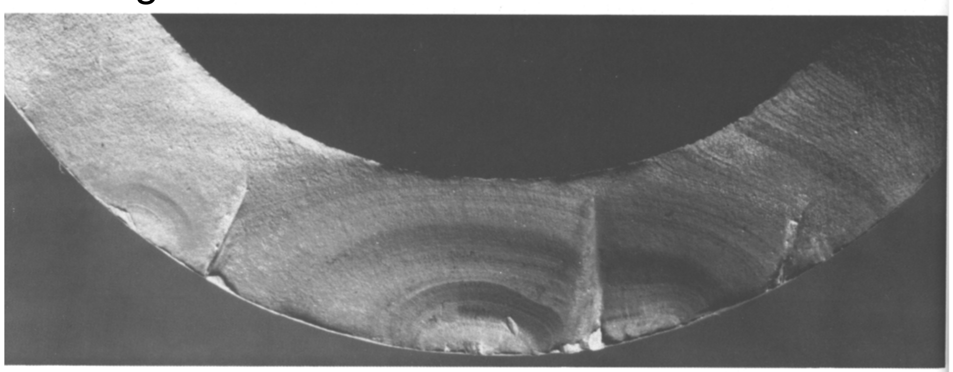
Fatigue Fractures

- more than 80% of all failures are caused by fatigue, *i.e.*, prolonged failure *under cyclic (alternating) loads*
- to the naked eye, fatigue fractures are characterized by smooth, “half-moon”, regions with radiating bands
- microscopically, smaller bands, called *striations*, can often be seen – these are the location of the crack each cycle

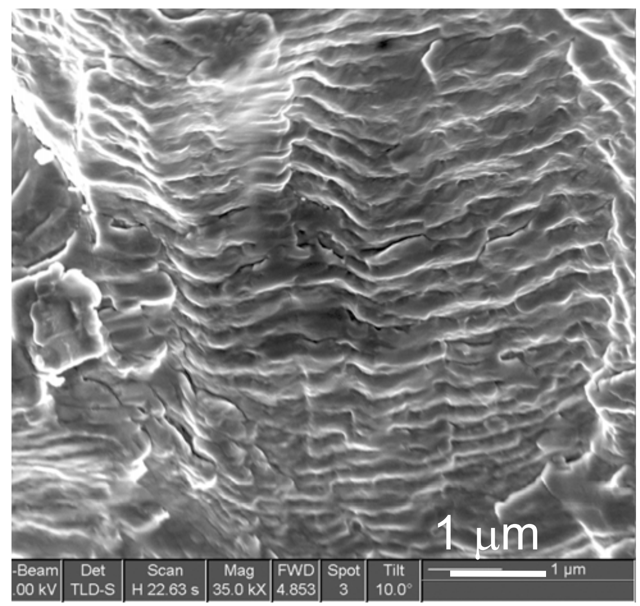


medium-C steel housing

crack initiation sites

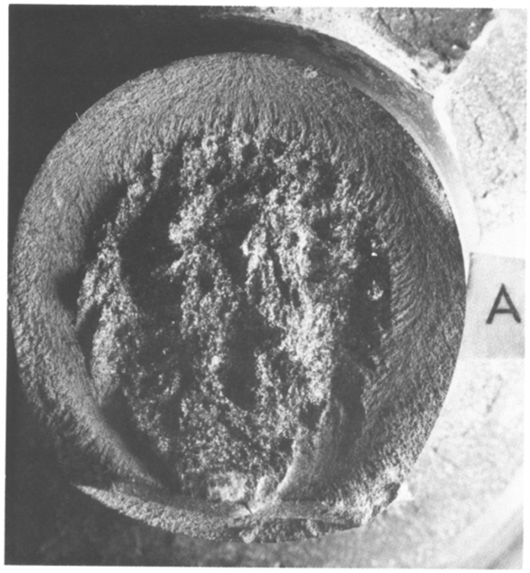


(after D. J. Wulpi, *ASM Metals Handbook*, vol. 12, 1987)



Fatigue vs. Instantaneous Failure

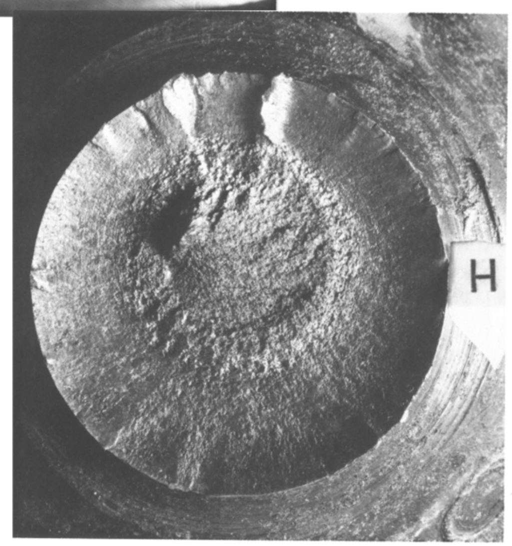
Failure of an axial shaft (*e.g.*, a car's steering column or axle)

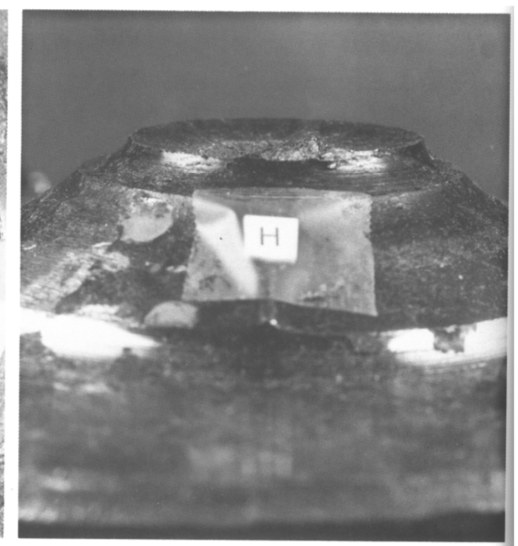


Bending (overload) fracture

medium carbon steel (AISI 1050) automobile axle

Fatigue (rotary) failure

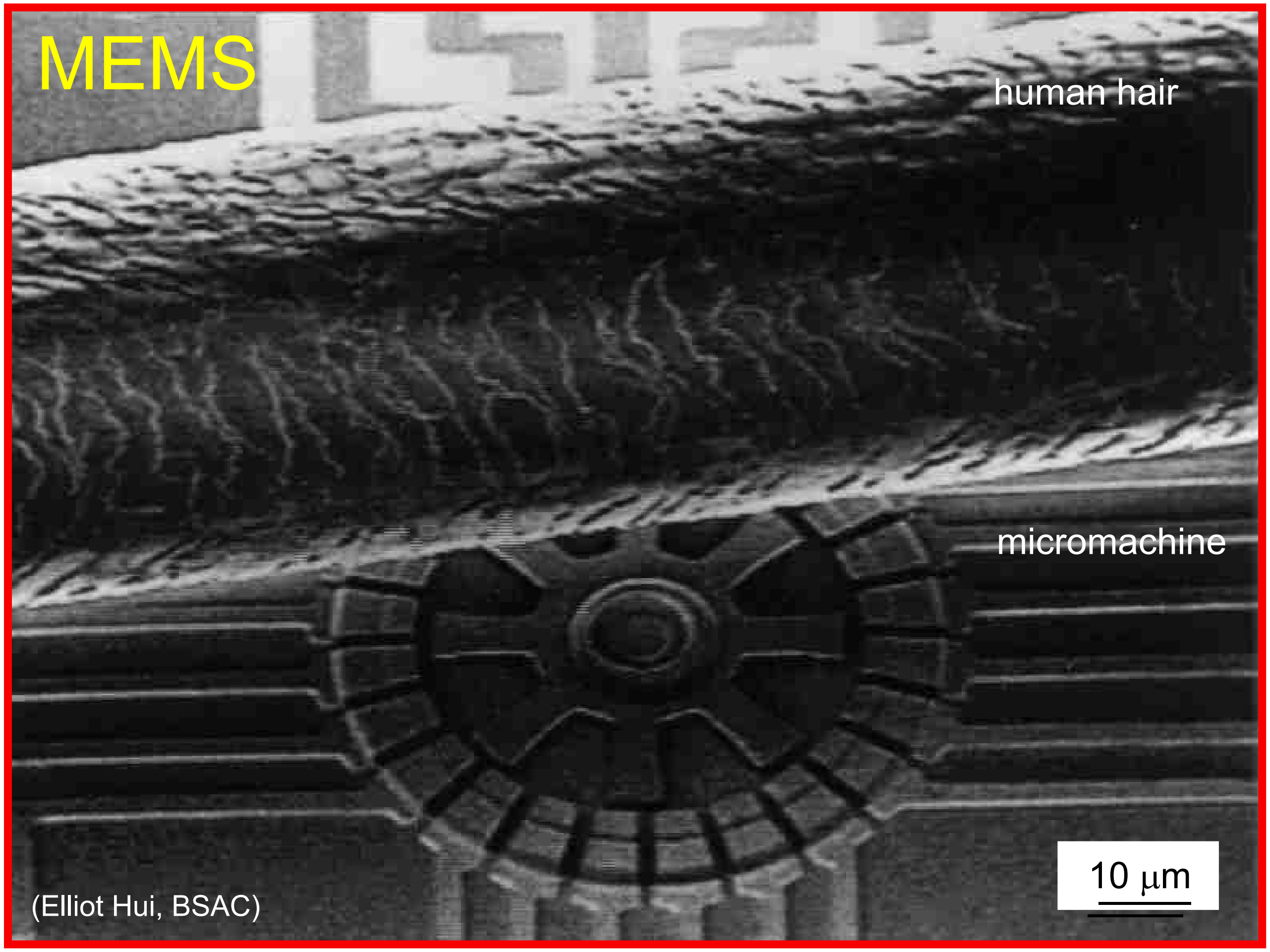




- a fatigue failure would imply a process that has occurred over some period of time, and would have likely <u>caused the accident</u>
- an overload fracture would be an instantaneous event likely <u>caused by the accident</u>

(after Z. Flanders, *ASM Metals Handbook*, vol. 12, 1987)

What about small structures?

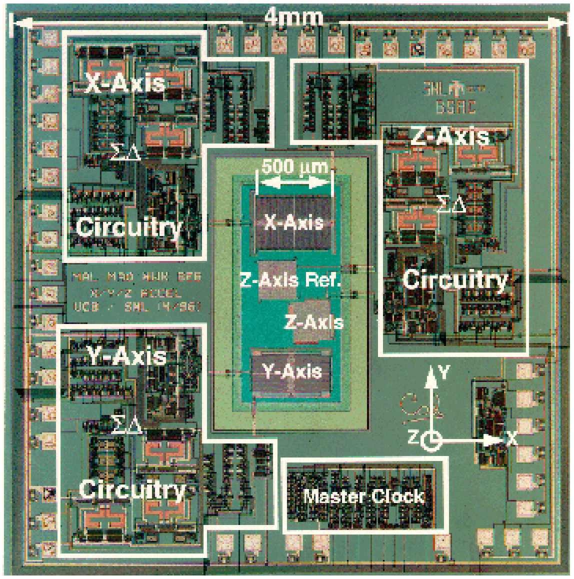


- The dimensions of current micro-machines (MEMS) are on the order of micrometers (microns – μm), *i.e.*, millionths of a meter
- next generation machines (NEMS) may be on the order of tens to hundreds of nanometers (nm), *i.e.*, nearly a trillionth of a meter!

- a silicon MEMS micromotor next to a strand of human hair
- the diameter of the hair is about 50 μm (50,000 nm!)

What are Micromachines?

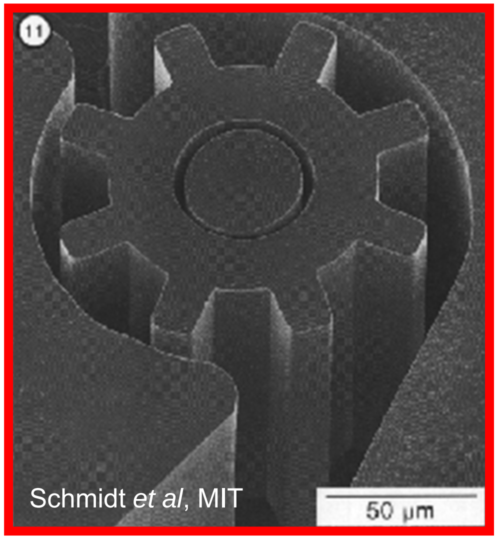
- **Micromachines are known as MEMS**
  - **m**icro-**e**lectro-**m**echanical-**s**ystems
  - many applications are used today
    - inertial sensors (*e.g.*, in air bags)
    - medical devices
    - memory and mass storage
    - micro-mirrors for digital projection
  - not to mention future applications
    - "pocket turbines" (to power the soldier of the future!)



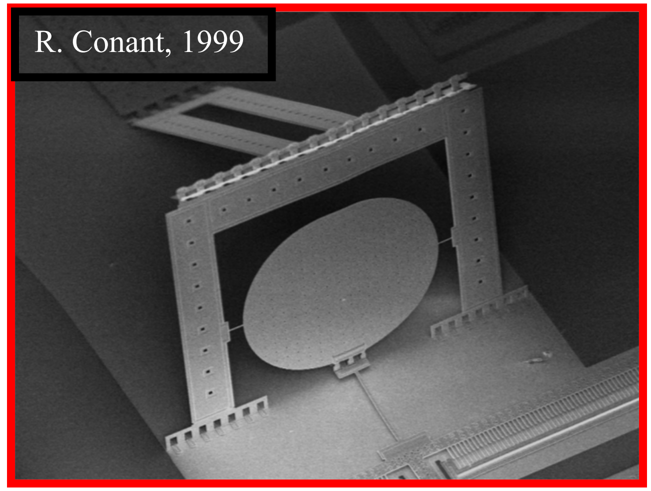
Analog Devices air bag sensor

- **Next generation of machines may even be smaller - NEMS**
  - **n**ano-**e**lectro-**m**echanical-**s**ystems

Micromachines or MEMS

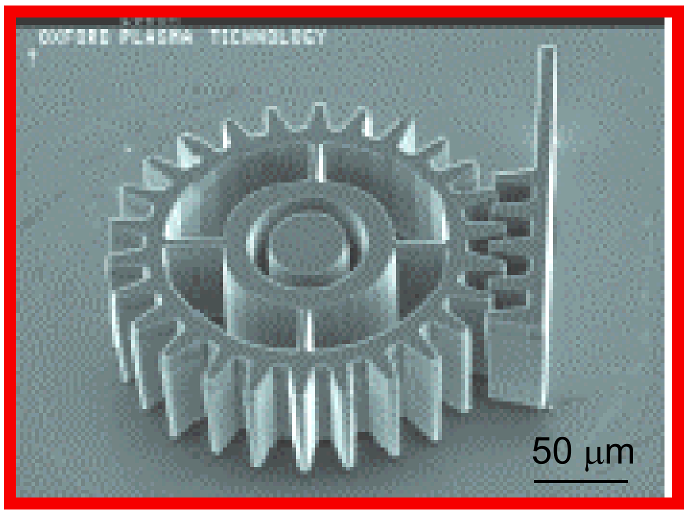


microturbine

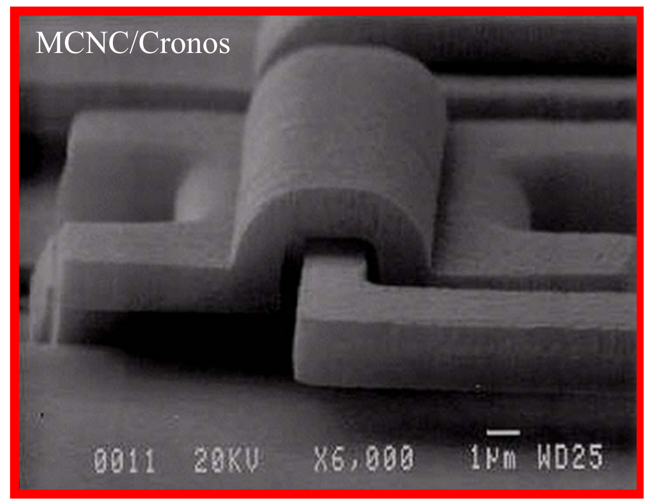


micron-scale moveable mirrors

gears

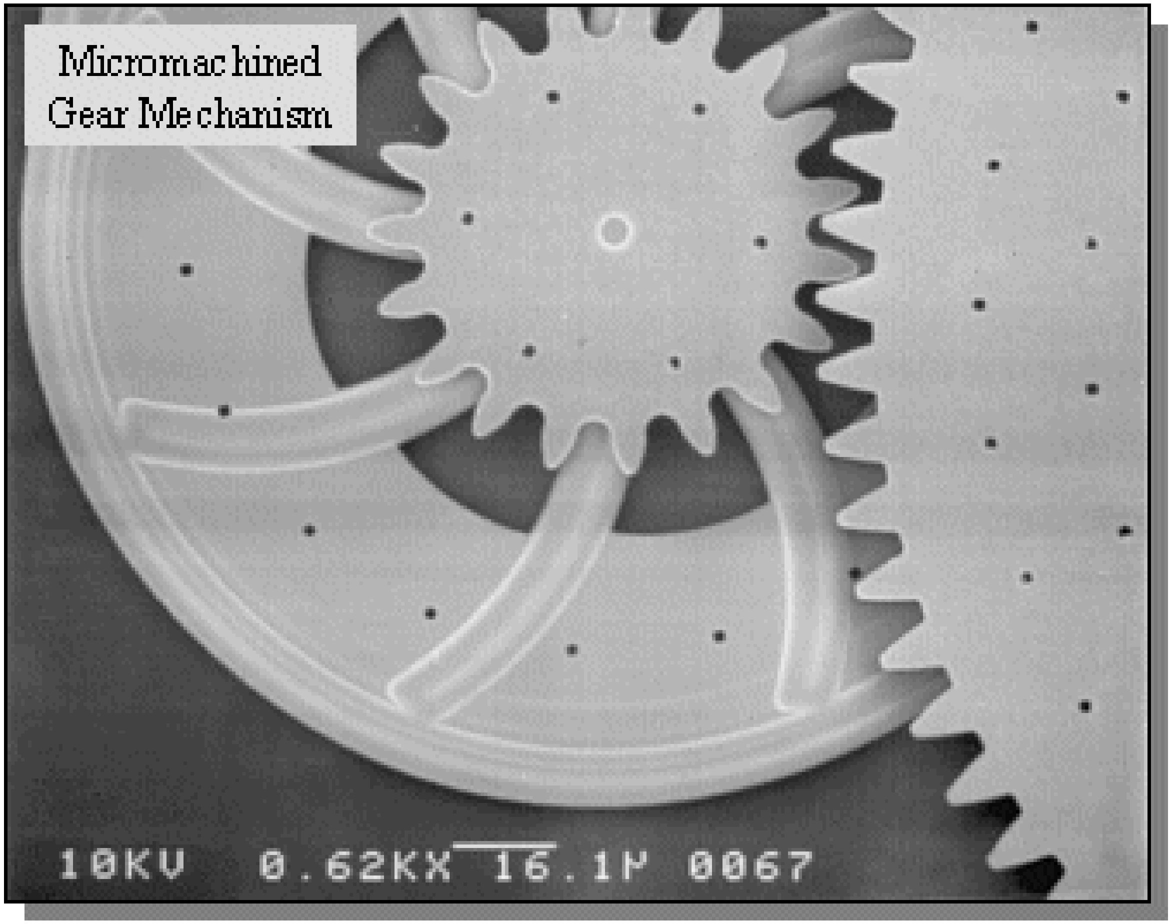


microhinge

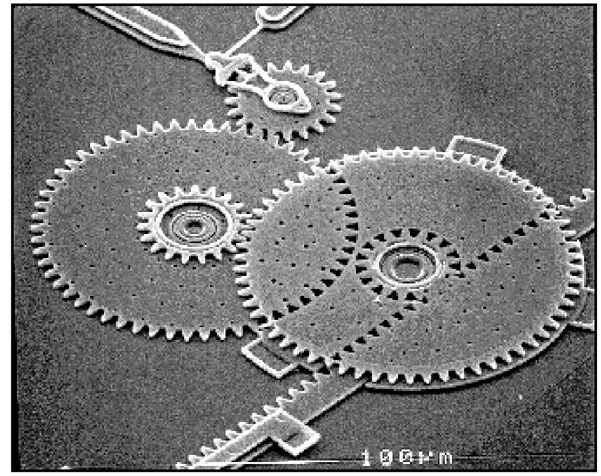


Applications: cogs and gears

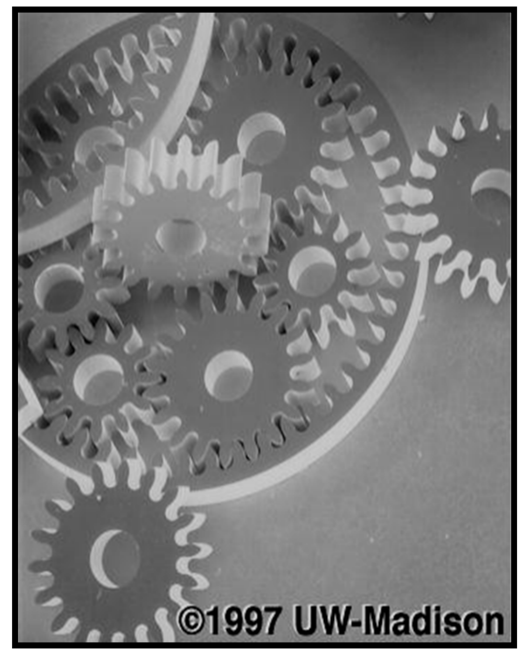
J. H. Comtois, Air Force Research Laboratory, 1998.



Sandia Nat.Labs

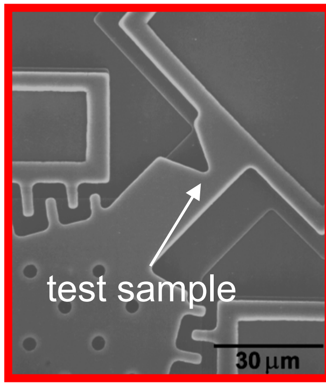


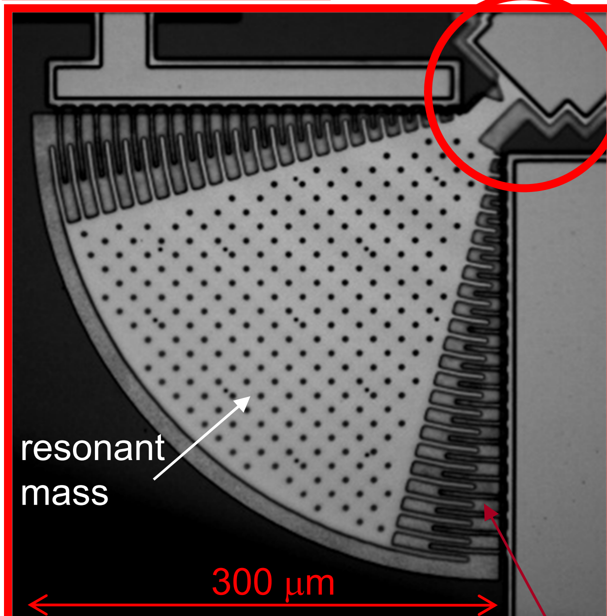
10 µm



- Micron-scale cogs and gears are used extensively in mechanical micromachines

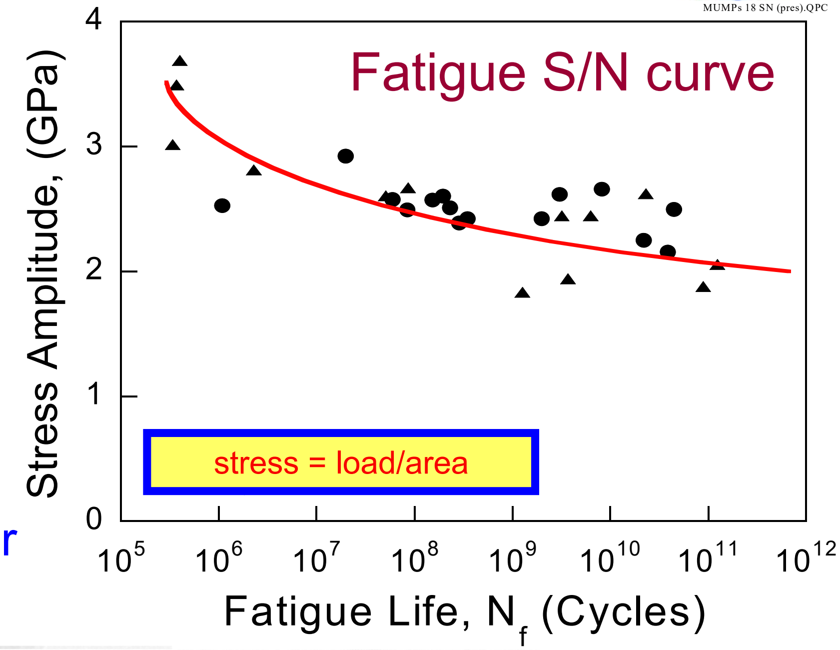
Mechanical Testing at the Microscale





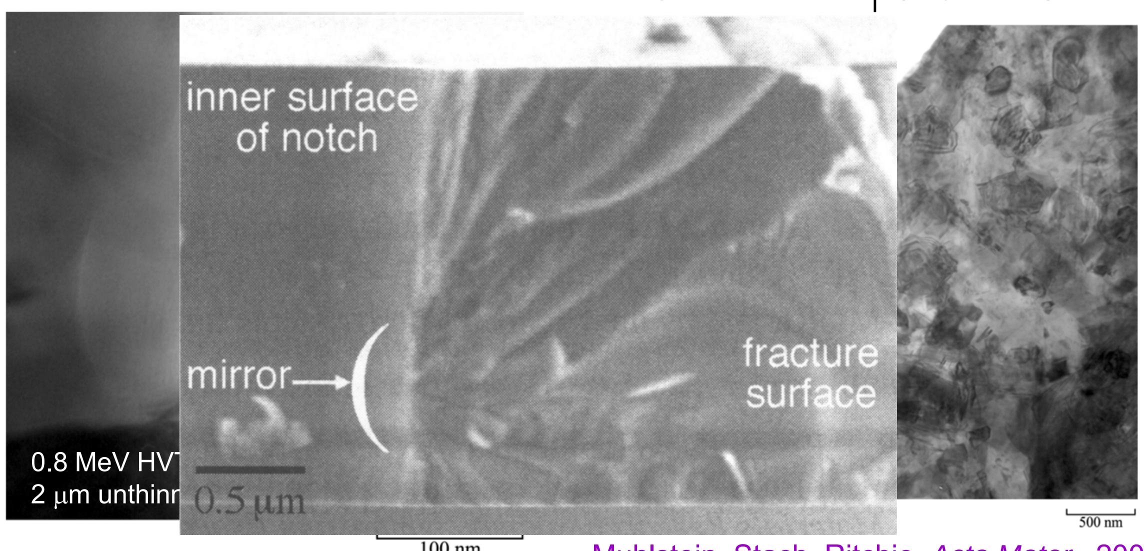
comb drives

- 2 μm thick n-type polysilicon thin films fail at $>10^9$ cycles at half their strength
- bulk silicon is not susceptible to fatigue
- fatigue due to moisture-induced nanoscale cracks in SiO_2 oxide layer



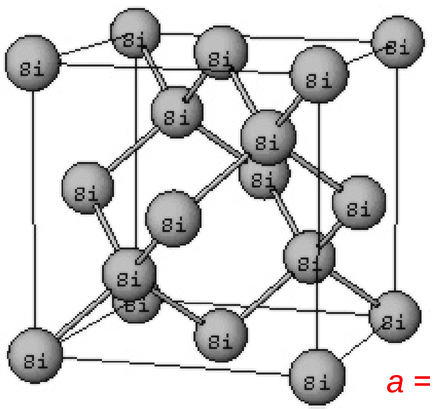
Brown, Van Arsdell, Muhlstein *et al.*

testing to $>10^{11}$ cycles



Muhlstein, Stach, Ritchie, *Acta Mater.*, 2002

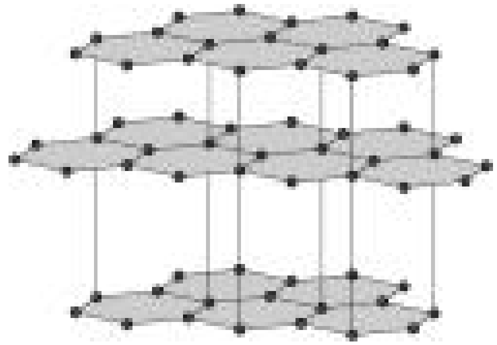
Alloptropic Forms of Carbon



a = 0.534 nm

diamond

- all strong (covalent) bonds

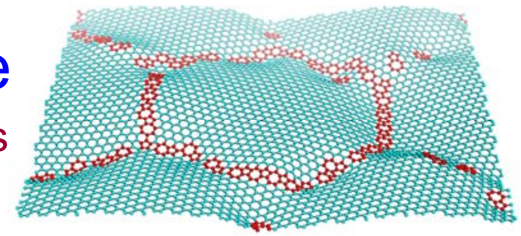


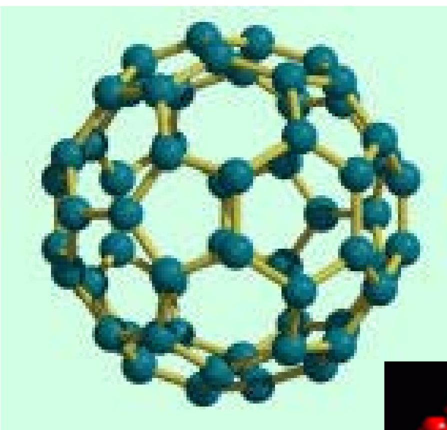
graphite

- strong bonds in layers
- weak (Van der Waals) bonds between layers

graphene

- strong bonds in sheets

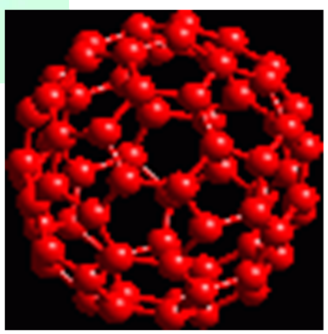




carbon C_{60}

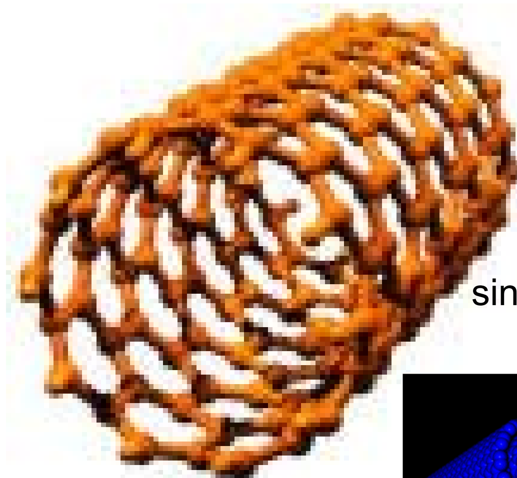
- all strong (covalent) bonds

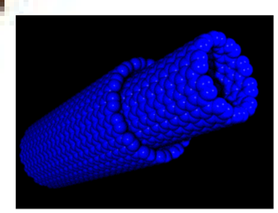
carbon C_{70}



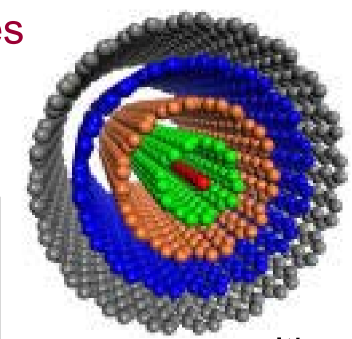
carbon nanotubes

- strong bonds in tubes
- weak bonds between tubes



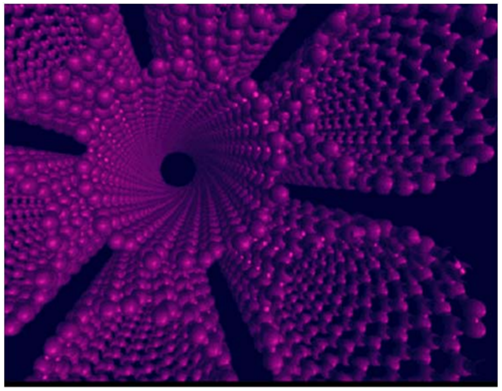


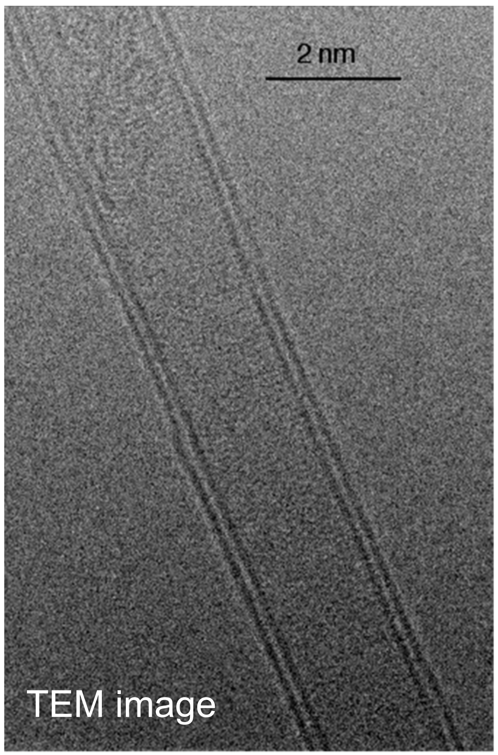
single wall



multi wall

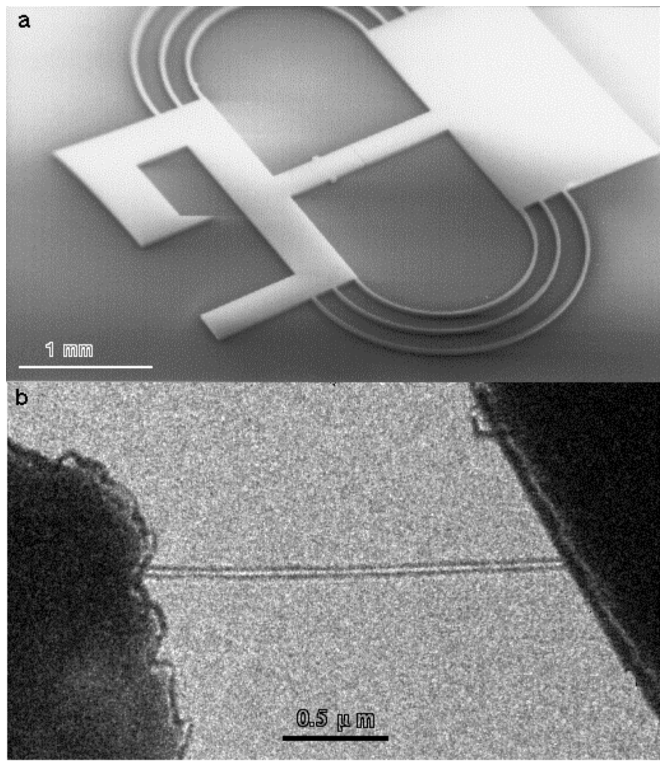
Mechanical Testing of Carbon Nanotubes



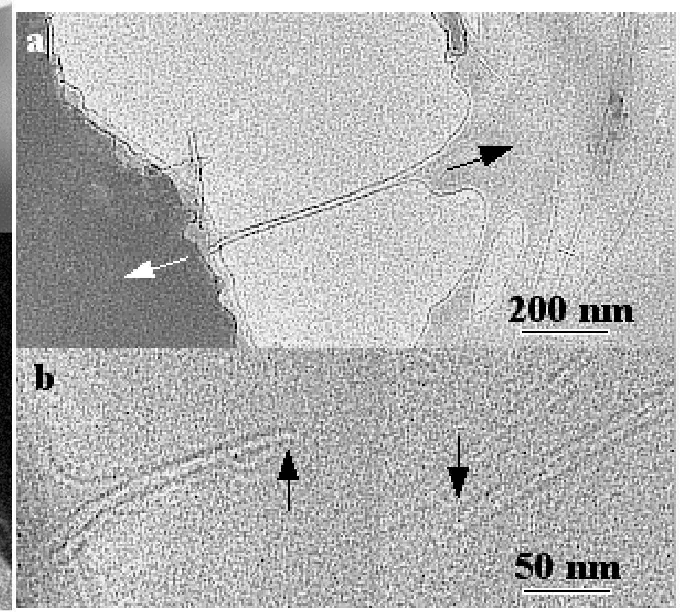


Denchzk, Ritchie, Zettl, *et al*.

- Carbon nanotubes, few nm in diameter, claimed to be the world's strongest material!



in situ mechanical test in TEM to measure the strength of a 12-nm thick carbon nanotube

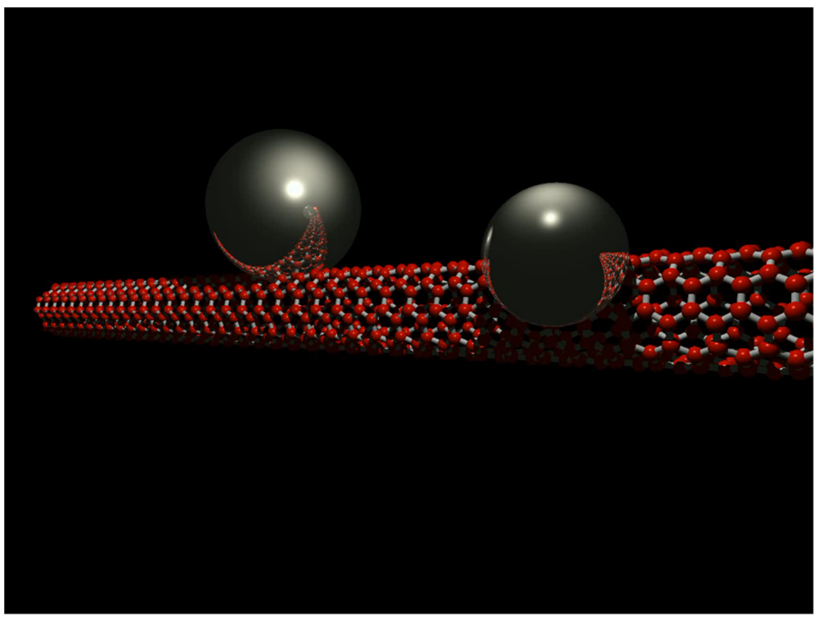


- Strength of the nanotube was measured as 150 GPa, i.e., roughly 5 times stronger than Kevlar or carbon fibers and more than 50 times stronger than hardened steel

NEMS Machines

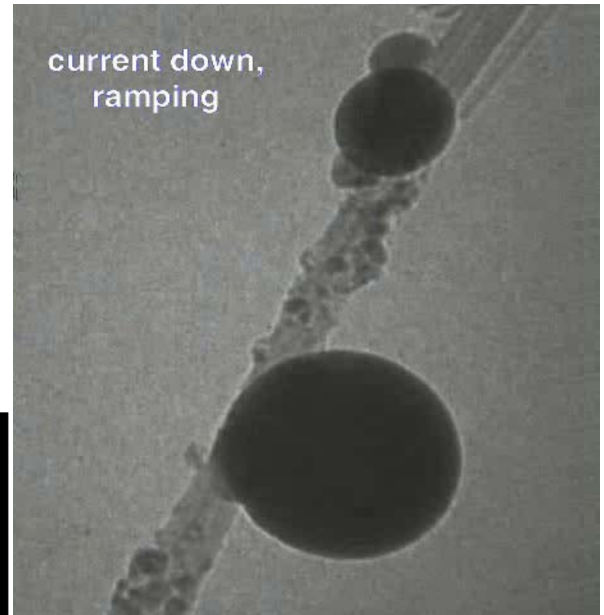
- by reversing the electrical current along a CNT, can metal can be transported along the tube
- by putting the metal globs between two nanotubes, we can move then apart and do work (linear nano-motor)

animation



2 nm

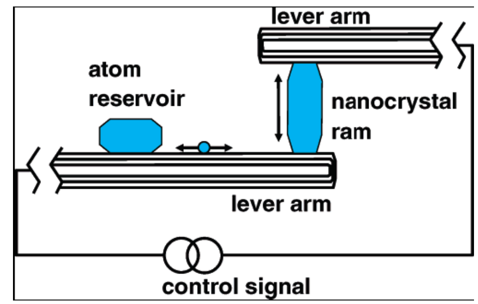
thermally-activated electrically-directed In surface diffusion



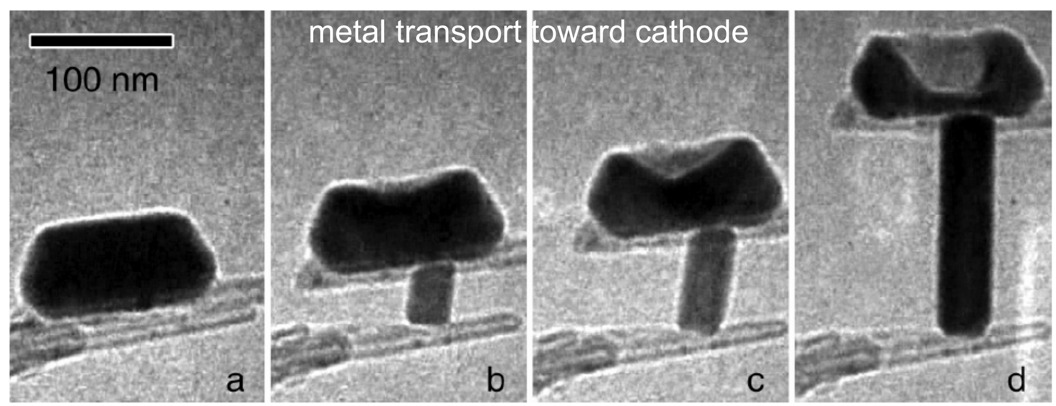
5 nm

TEM image

linear nano-motor



- motor force ~1 nN
- power densities ~ 20 MW/m^3 - 8 GW/m^3



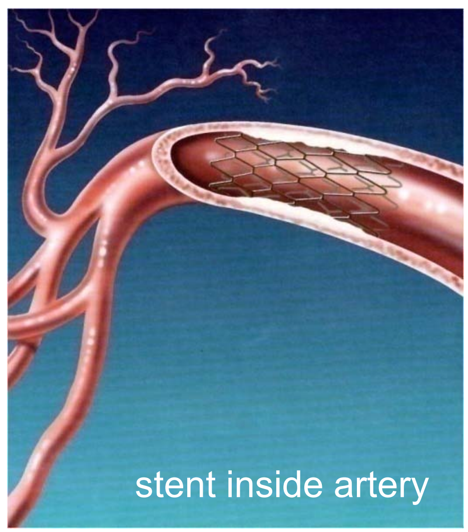
Regan, Aloni, Ritchie, Dahmen, Zettl, *Nature*, 2004

Regan, Aloni, Ritchie, Zettl, *Nano Lett.*, 2005

Failure by Plastic Deformation

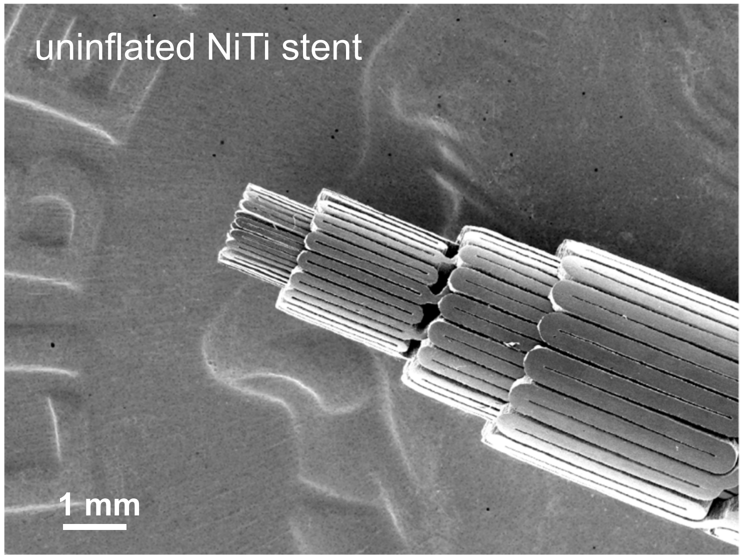
Nitinol is a 50:50 nickel-titanium alloy

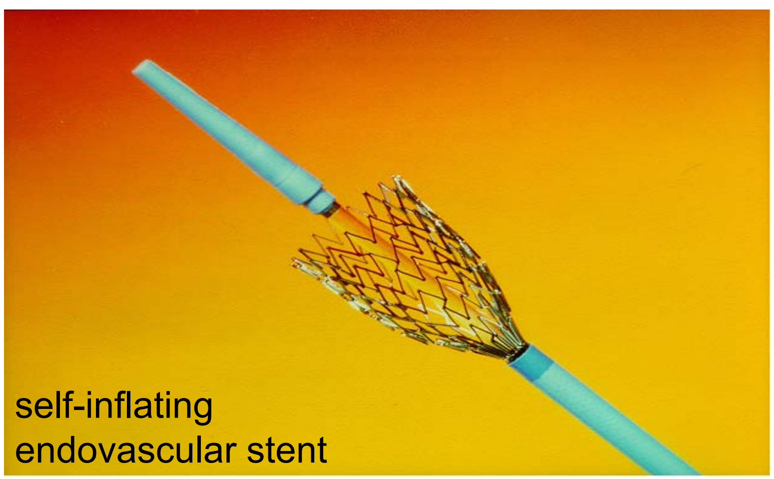
- most materials only deform reversibly (i.e., elastically) when deformed a small amount (e.g., when stretched for less than 1% change in length)
- after that the deformation is permanent (plastic deformation)
- however, a very few metals, so-called shape-memory/superelastic metals, e.g., Nitinol, are much more flexible



Nitinol is used for eye-glass frames, dental drills and endovascular stents

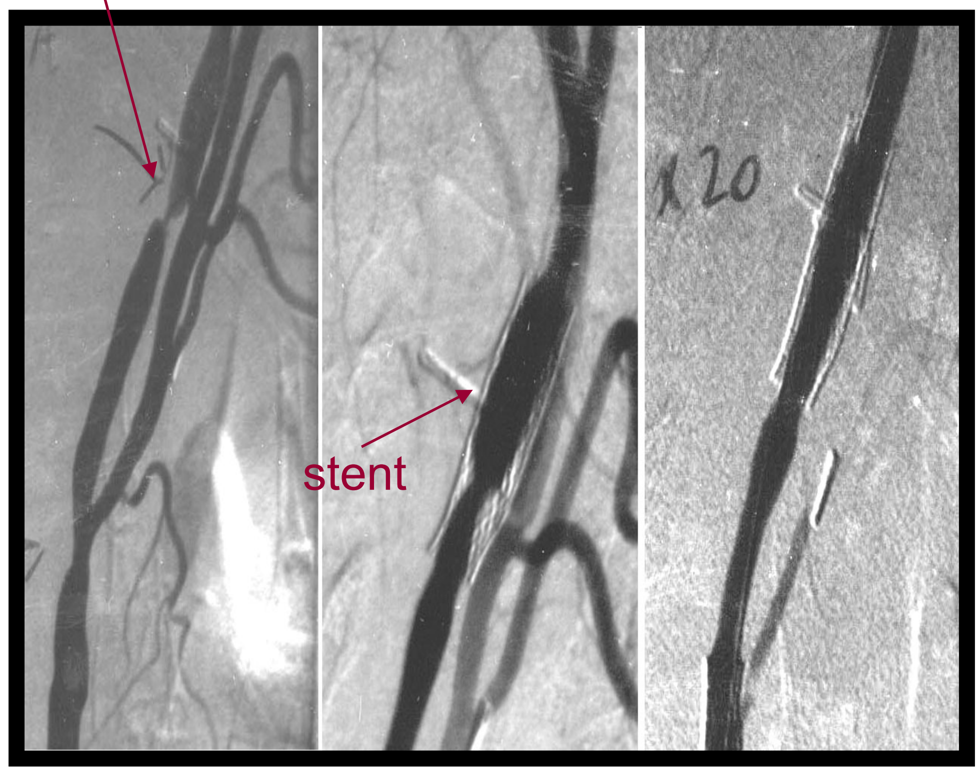
Stenting of Arteries





- Stents manufactured with:
  - stainless steel
  - cobalt-chronium alloy
  - Nitinol (Ni-Ti alloy)

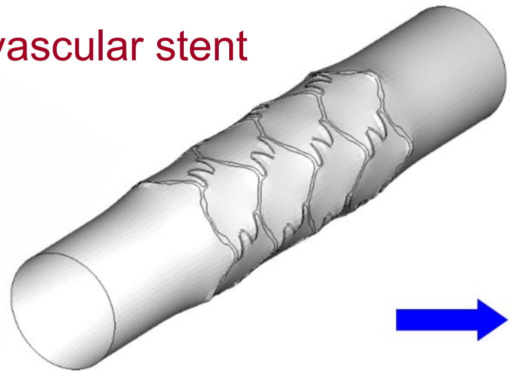
occlusion



made by NDC, a J&J Company, Fremont, CA

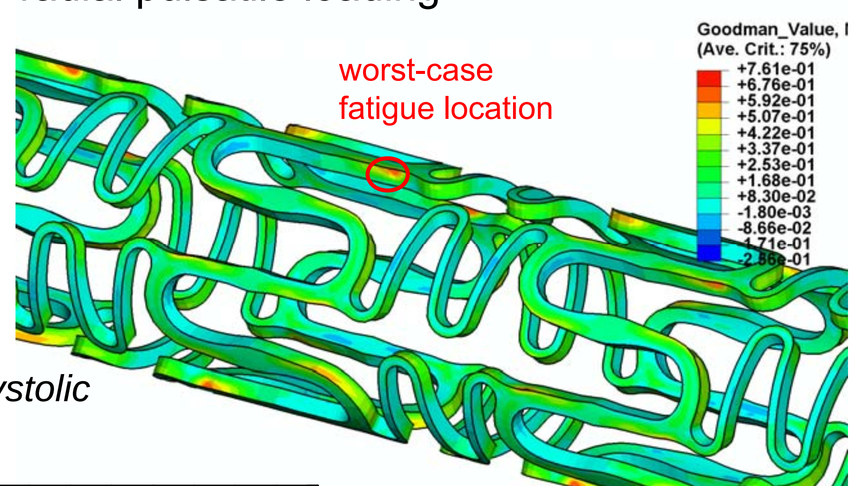
Stress-Life Predictions for Stents

Cordis
cardiovascular stent

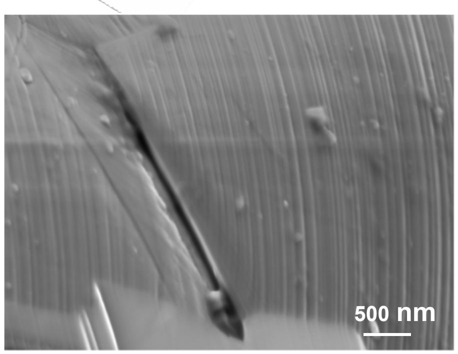


Co-Cr alloy

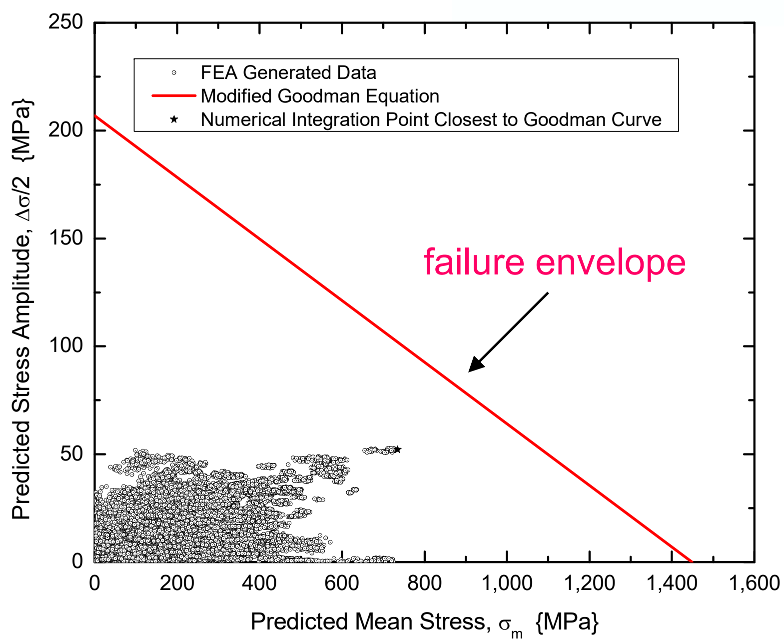
radial pulsatile loading

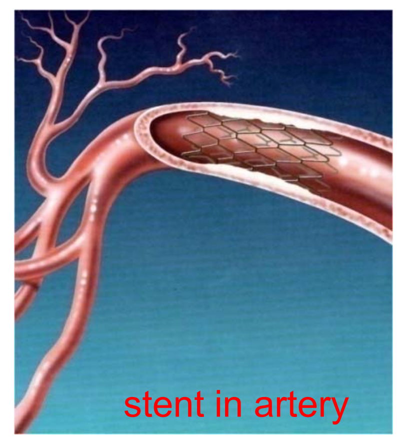


Internal pressures representing systolic & diastolic loads



small cracks formed during
ultrasonic cleaning

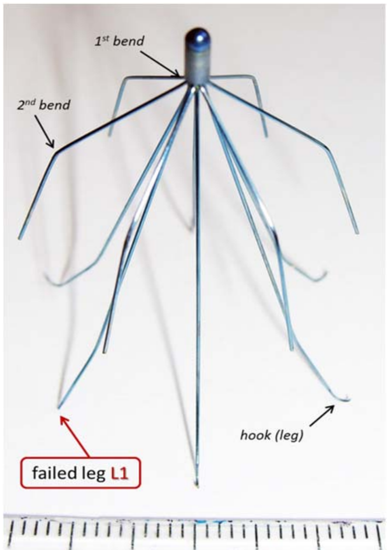


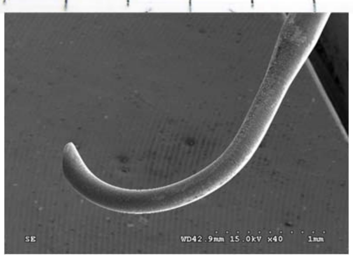


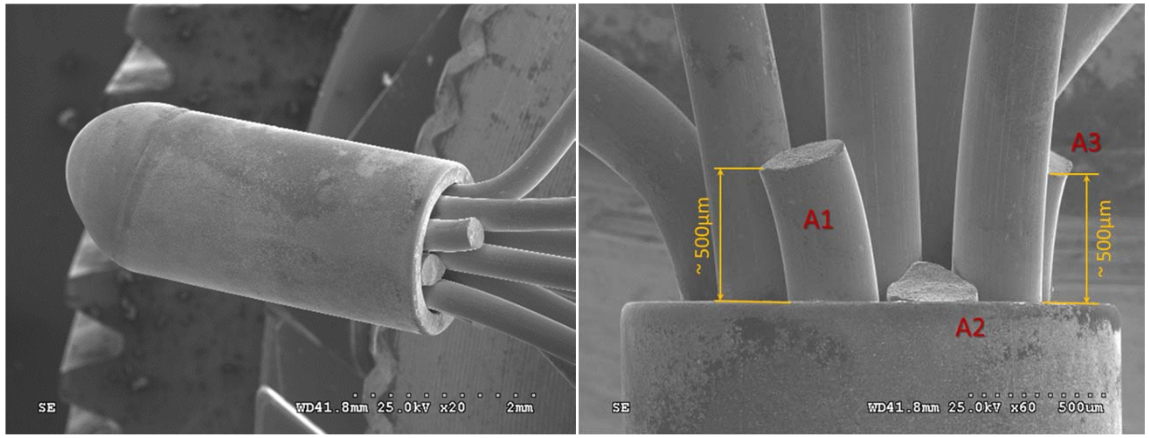
Ramesh, Bergermeister, Grishaber, Ritchie, *Biomaterials* 2006

Failure of Vena Cava Filters

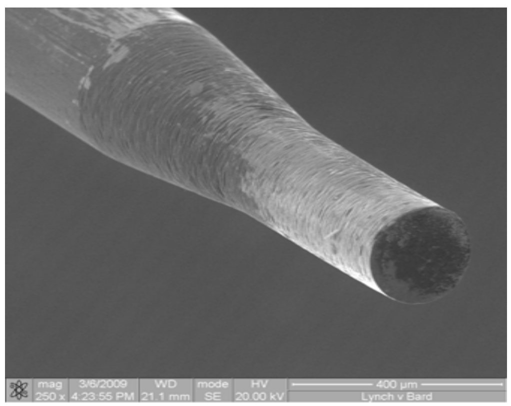
Bard vena cava filter

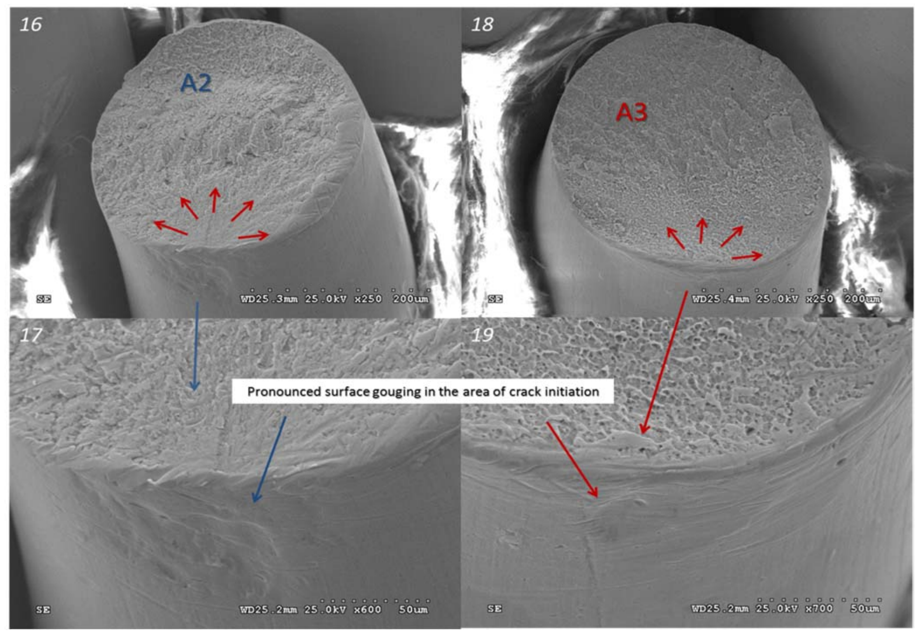




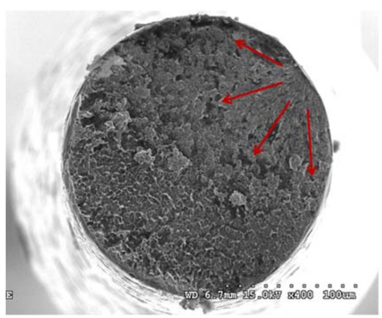


Filters made with 6 arms (shorter wires to arrest blood clots) & 6 legs (longer wires with anchor hooks), made from super-elastic Nitinol





Hooks on legs prematurely fail due fatigue cracks initiated in the grinding marks; this causes the filter to migrate & promotes perforations & further fractures

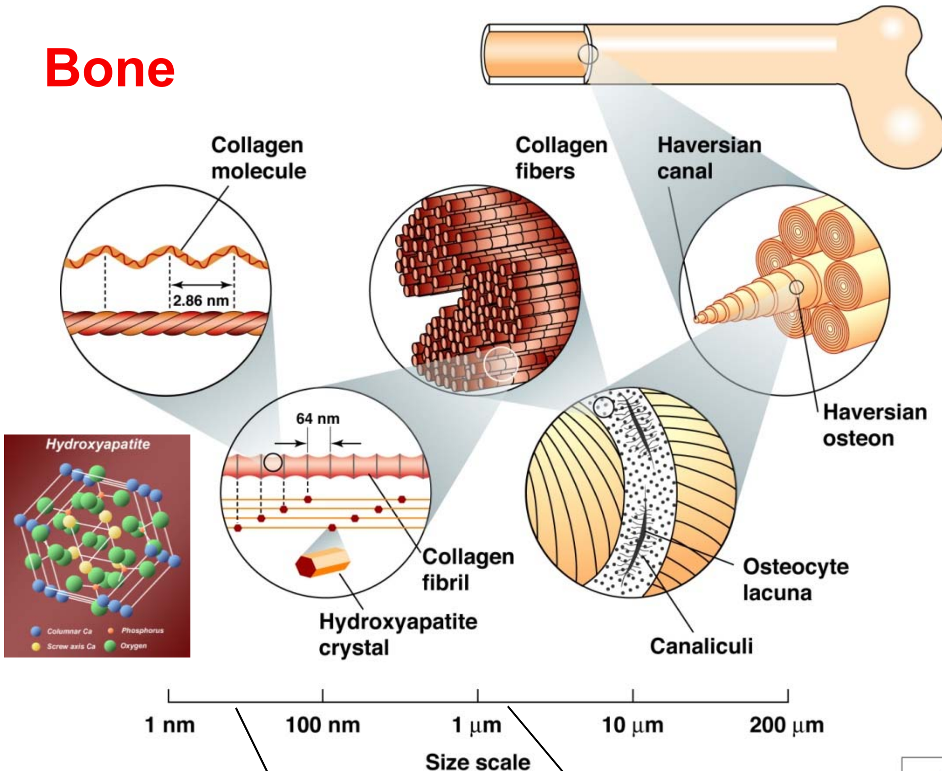


Fatigue cracks, often initiated in bending from surface markings, prematurely fracture the arms

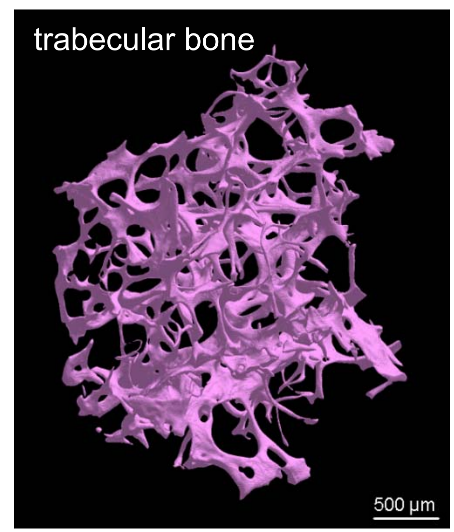
Structure of Teeth & Bone

Complex, hierarchical structures

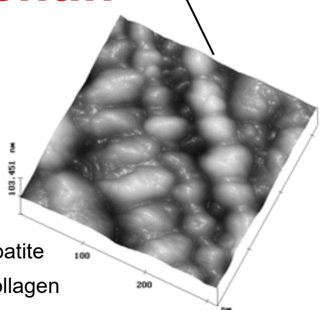
Bone



- **building blocks:** collagen & nano-crystalline hydroxyapatite mineral
- **at nano-scale:** mineralized collagen fibrils
- **at micron scale:** lamellar structure of collagen fibers
- **at micron scale:** in dentin - tubules
- **at hundreds of microns:** in bone - osteons/ Haversian canals
- **at macro scale:** size and type of the tooth or bone



Dentin

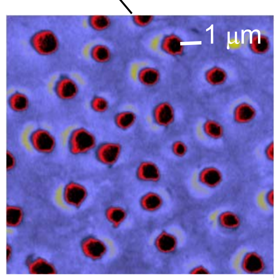


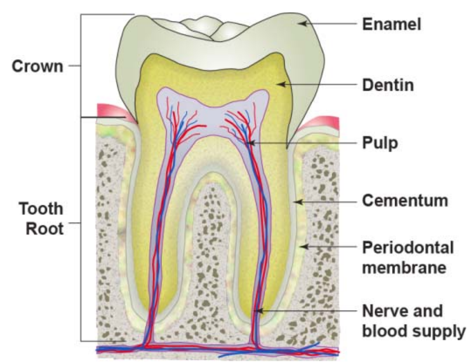
Dentin is:

45 vol% apatite

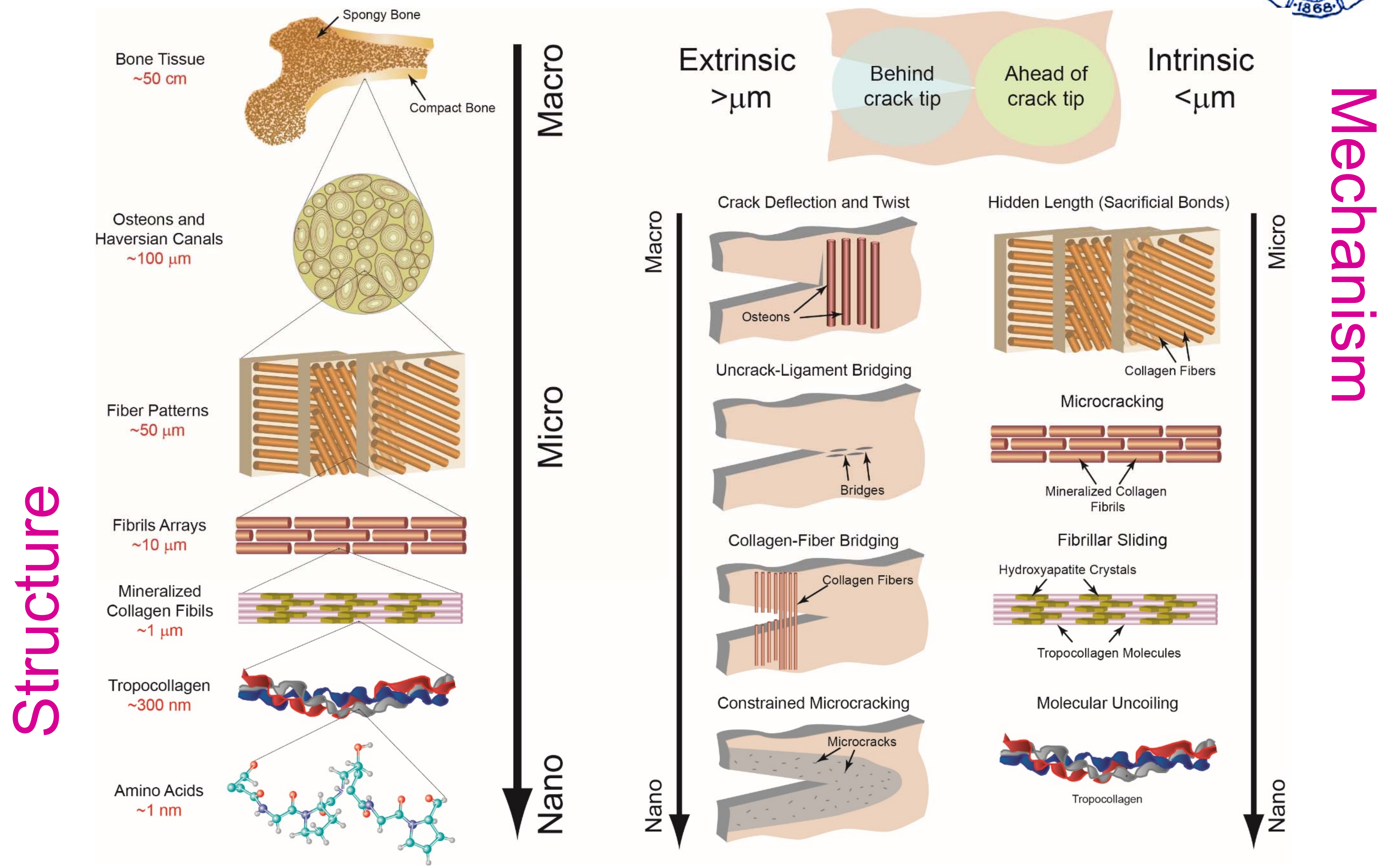
30 vol% collagen

25 vol% fluid





Seven Hierarchies of Structure of Bone



Weiner & Wagner, *Rev. Mat. Sci.*, 1998

Launey, Buehler, Ritchie, *Ann. Rev. Mater. Res.*, 2010

Origins of Toughening in Bone

Extrinsic Toughening Mechanisms

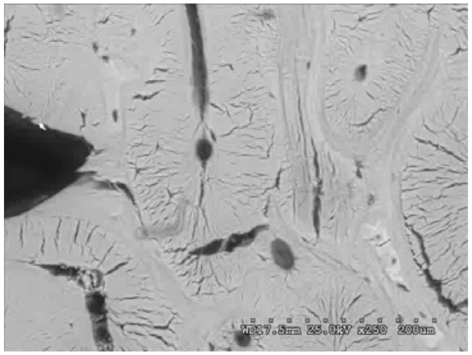
2-D *in situ* SEM imaging

- monitoring *in situ of* how cracks interact with the microstructure, while simultaneously taking quantitative R-curve toughness measurements

transverse

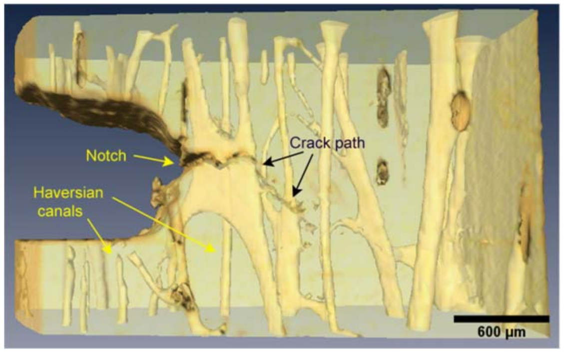
crack deflection/twist

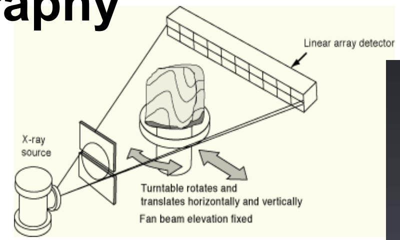
longitudinal

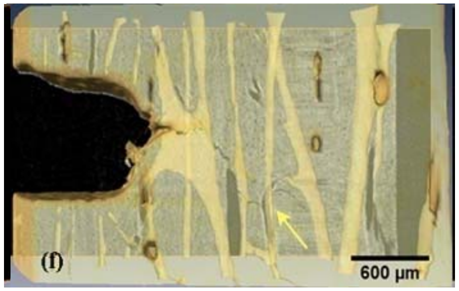


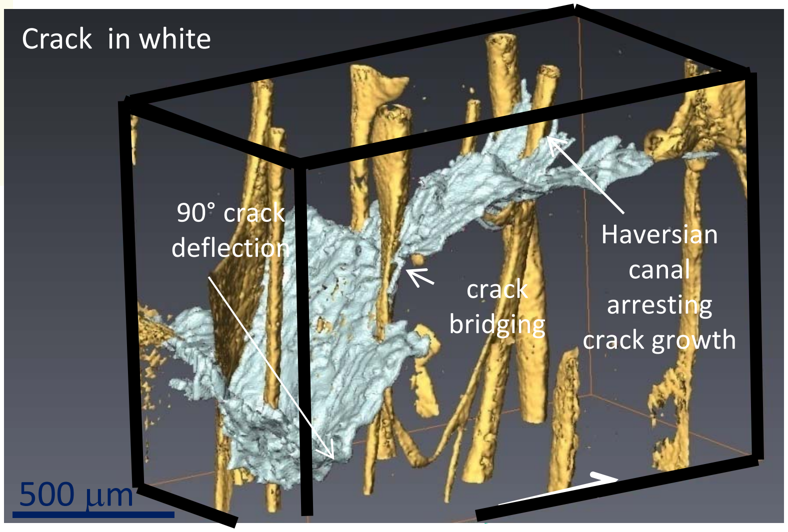
crack bridging

3-D computed X-ray tomography







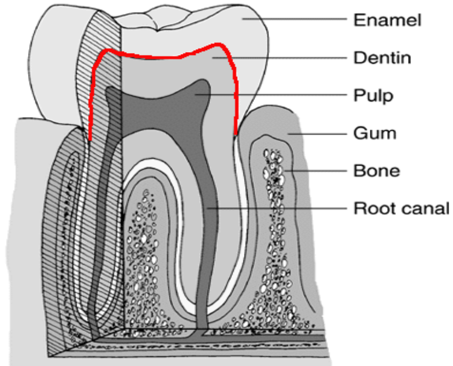


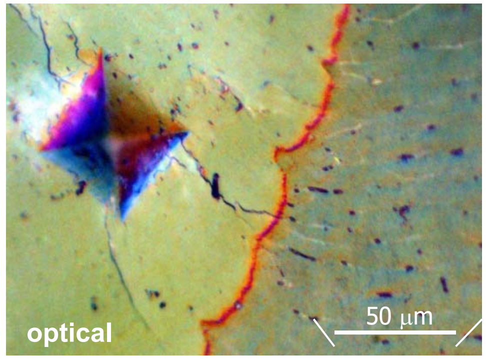
direction of crack propagation

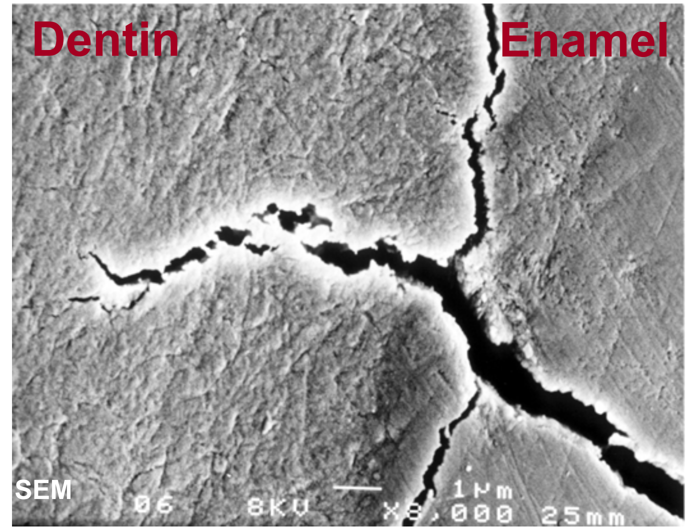
- 3-D imaging of crack paths and resulting toughening mechanisms

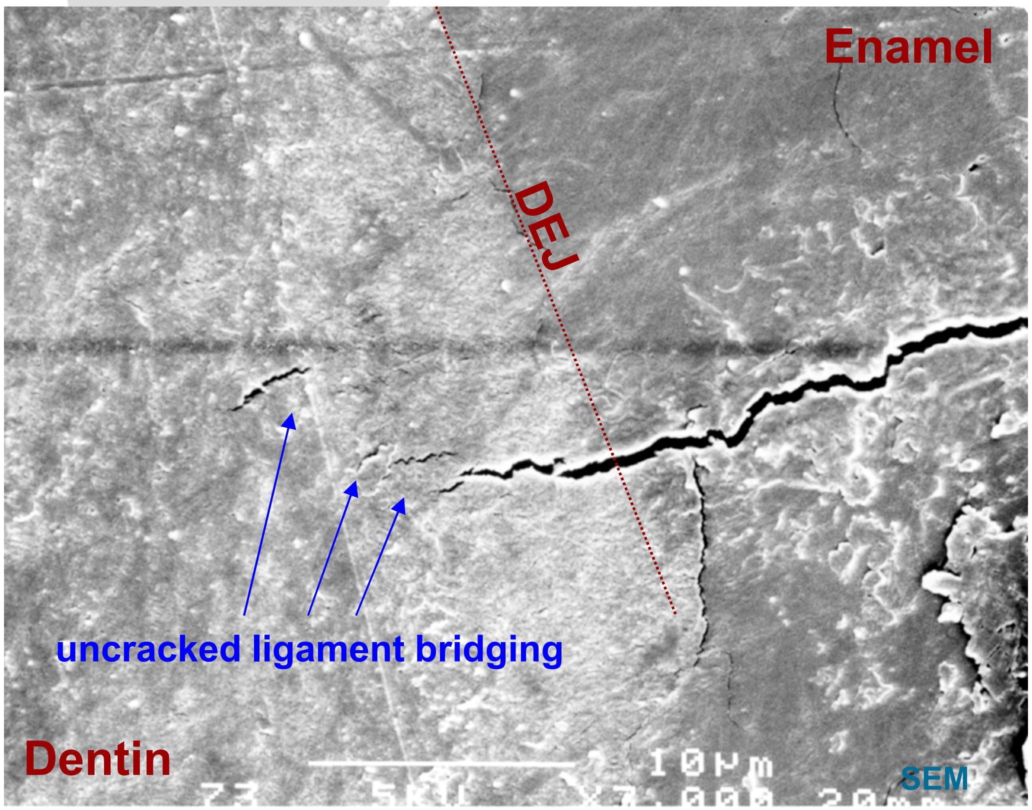
Koester, Ager, Ritchie, *Nature Mater*., 2008

Crack Arrest in the DEJ Region in Teeth







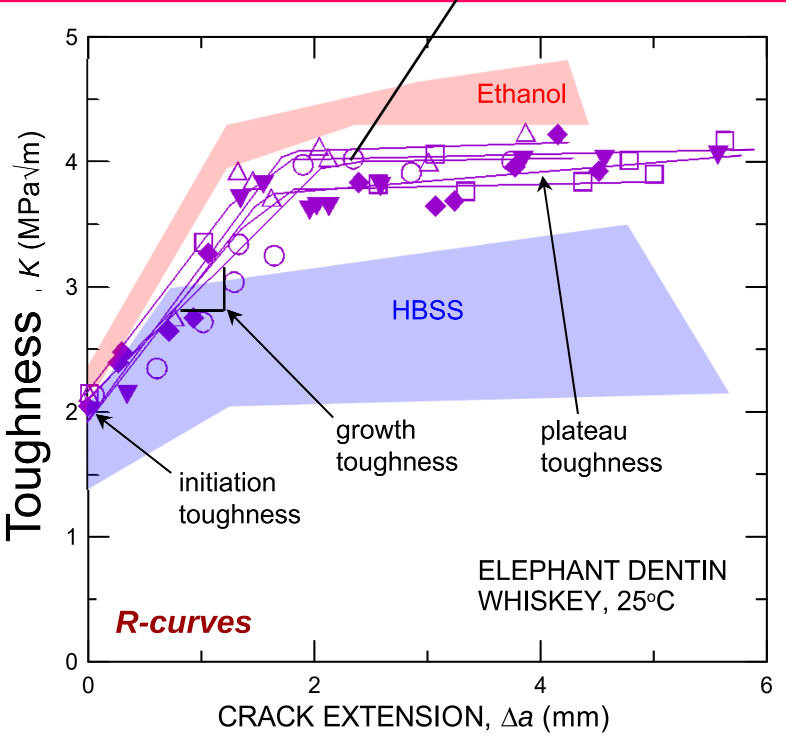


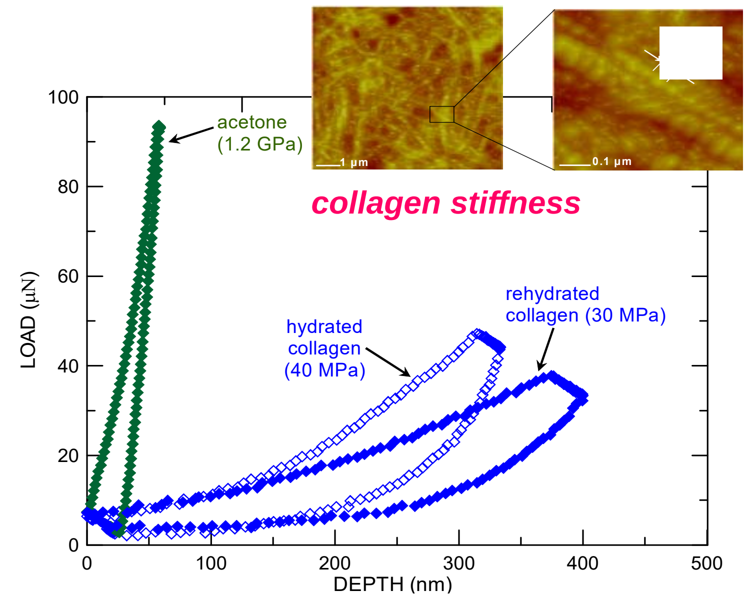
- cracks in harder enamel do not necessarily break the tooth as they arrest “at” the dentin-enamel junction (DEJ)
- cracks arrest when they form elastic bridges in the (mantle) dentin due to the formation of uncracked ligaments in the crack wake

Imbeni, Kruzic, Marshall, Marshall & Ritchie, *Nature Mat.*, 2005

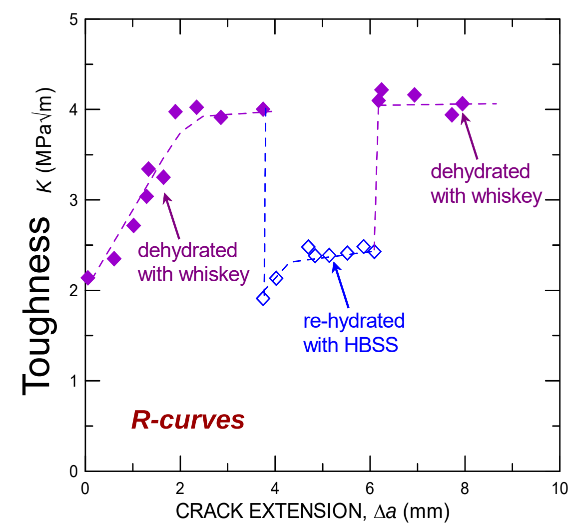
Alcohol Toughens Teeth – for a while!

86-proof Black & White scotch whiskey





AFM-based pico-indentation



- compared to water, alcohol increases the toughnesss of dentin
- but you do need to keep the alcohol in your mouth, as the effect is reversible!
- effect associated with direct collagen-collagen H-bonding in polar solvants

Nalla, Kinney, Tomsia & Ritchie, *Journal of Dental Research*, 2006

Nalla, Balooch, Ager, Kruzic, Kinney & Ritchie, *Acta Biomaterialia*, 2005