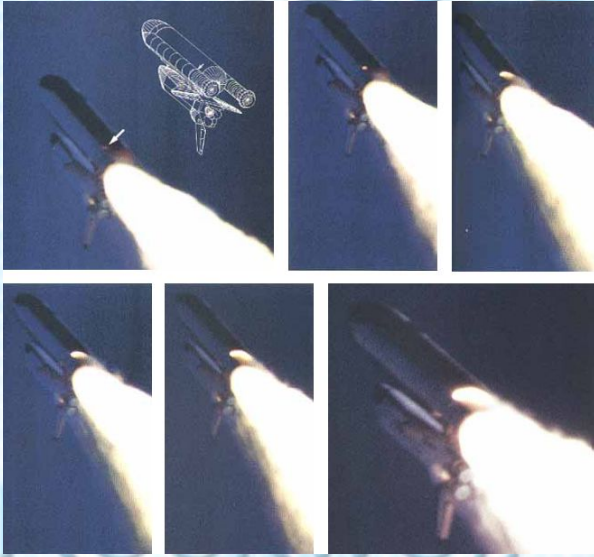


Chapter 7: Part 2

Mechanical Failure



This is just an introduction to failure analysis, a much more complex area of materials engineering.

Failure Analysis

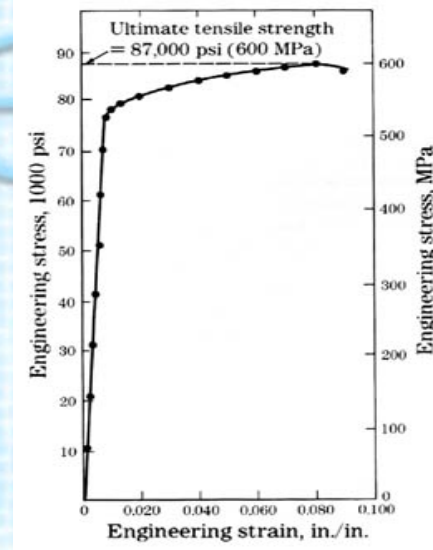
- Fractography: The study of fracture
- Analysis of fracture as a corrective tool
- Failure of parts in service
- Stress analysis of fractured parts

One More Word on Tensile Test Curve

Tensile test is also called *static testing*

Loads are applied slowly as the loading rate affects the response of the material in terms of deformation and measured strength

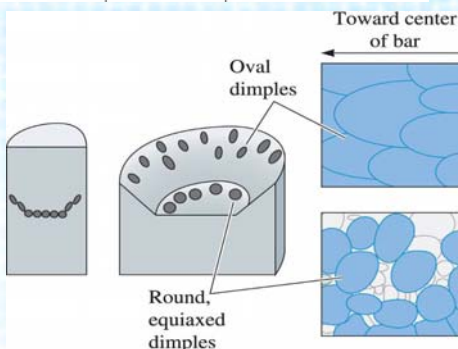
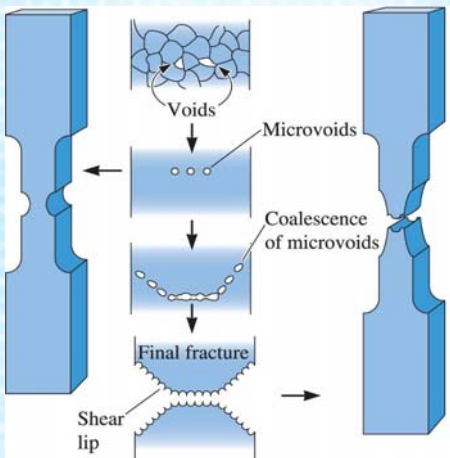
(strain-rate sensitivity)



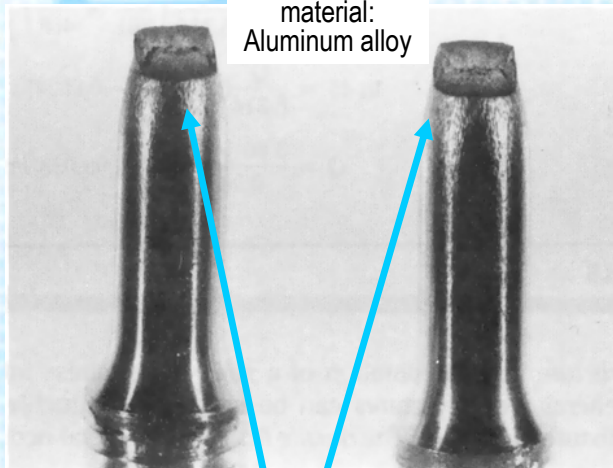
Rockwell

K_{Ic}

The Mechanism of Failure in a Tensile Test of a Ductile Metal

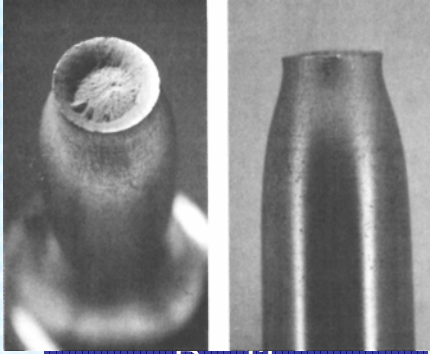


Ductile material: Aluminum alloy

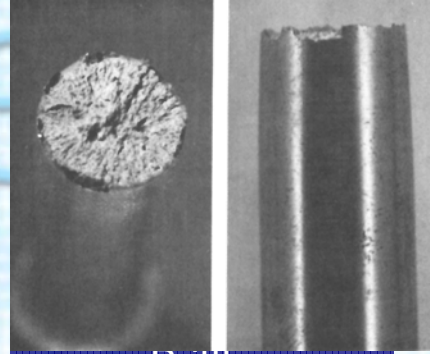


Cylindrical specimen allows observing the *cup and cone* formation in the fracture

Ductile and Brittle Fractures



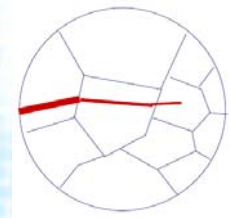
Ductile



Brittle

What is the most evident difference between these two type of fractures?

How would their stress-strain curves look?



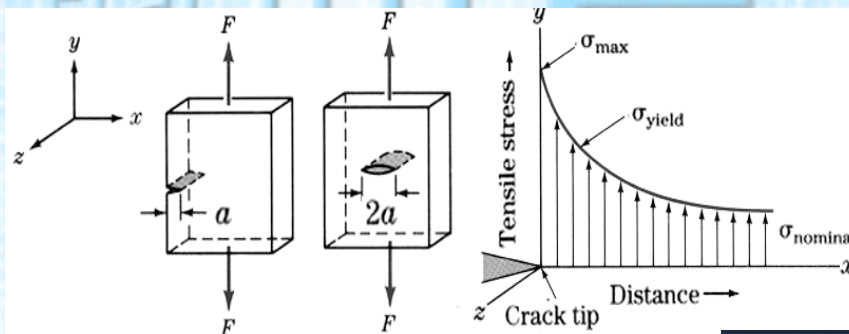
Transgranular crack mechanism explains the brightness of the brittle fracture

Rockwell

Stress Concentration

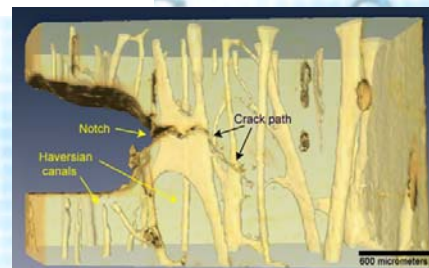
Brittle materials are seriously affected by initial flaws. How are flaws originated?
Example: glass, ceramics, hard metallic alloys

The initial flaw affects the strength of the materials as follows:



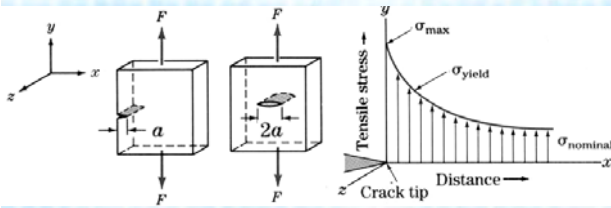
K is the stress concentration coefficient

K can be affected by the geometry of the crack (flaw) and the thickness of the sample (related to the crack)



Rockwell

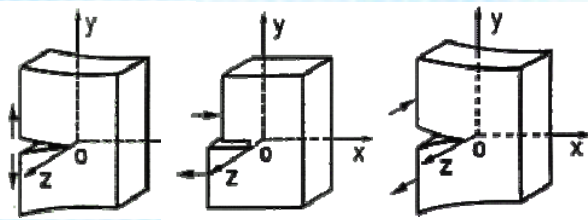
Stress Concentration (cont.)



The stress intensity depends on the applied stress and the width of the crack as follows:

$$\sigma = \frac{K_I}{Y\sqrt{\pi a}}$$

where s is the nominal stress, Y is a geometric constant (close to 1), K_I is a stress-concentration factor and a is the length or half-length of the crack.



Opening
Mode I

Sliding
Mode II

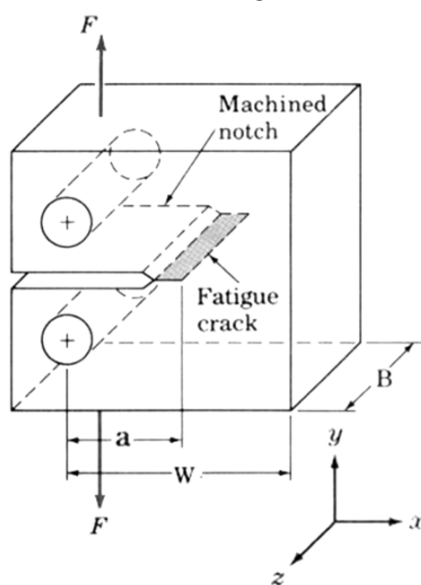
Tearing (or
anti-plane)
Mode III

Rockwell

K_{IC}

Fracture Toughness Test

When σ is the fracture stress then K_I is equal to K_{IC} , the fracture toughness of the material, i.e. a material property



$$K_{IC} = Y \sigma_f \sqrt{\pi a}$$

Strange units:

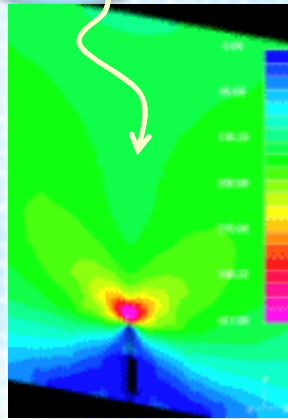
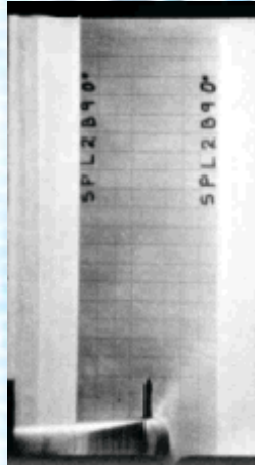
$$[K_{IC}] = [\text{MPa} \cdot \sqrt{\text{m}}]$$

$$\text{or } [\text{ksi} \cdot \sqrt{\text{in}}]$$

As a crack propagates faster in a brittle material, there is relation between ductility and K_{IC}

Simulation of Crack Propagation in a 2014 Aluminum Alloy

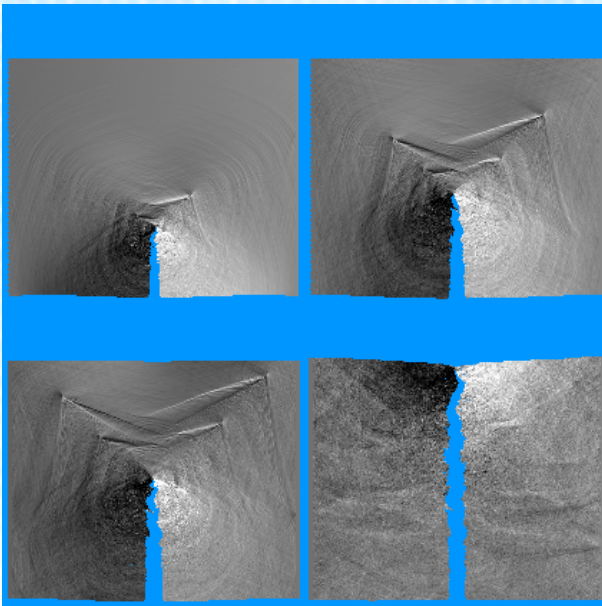
The panel is 120 mm wide by 300 mm long. Notice the plastic deformation (magenta & red) ahead of the crack tip.



The plastic deformation ahead of the crack tip in ductile materials has a kidney-shape.

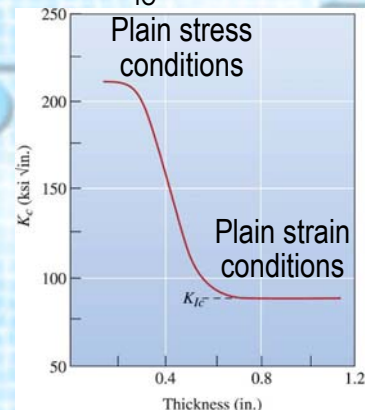
Another example in a gear. 

Simulation of a Crack Propagation in a Brittle Material



Notice the shape of the crack tip doesn't change.

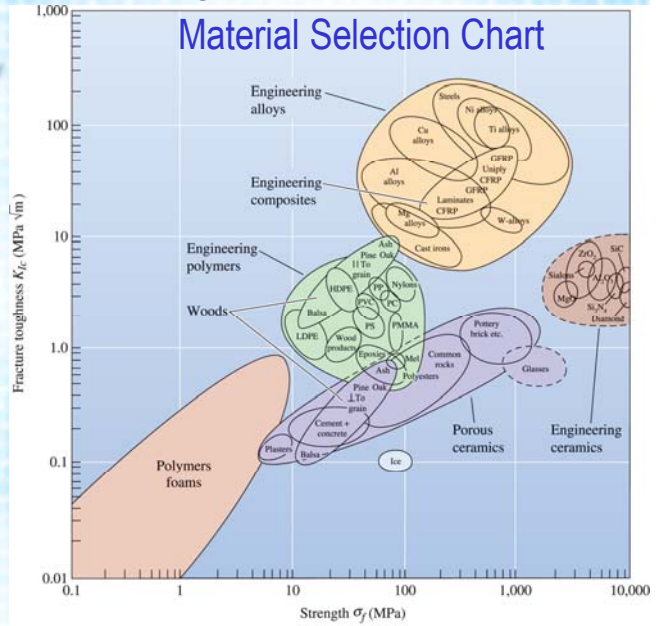
The effect of the specimen thickness also affect the value of K_{IC} :



These are some values of K_{IC} in $\text{MPa}\cdot\text{m}^{1/2}$

- Low carbon steel: 140
- Medium carbon steel: 51
- High strength Al alloys: 23
- Low strength Al alloys: 45
- Cement/concrete: 0.2
- Common glass: 0.75
- Partially Stabilized Zirconia: 9
- HDPE: 2
- LDPE: 1

Homework: Look for K_{IC} of human bone



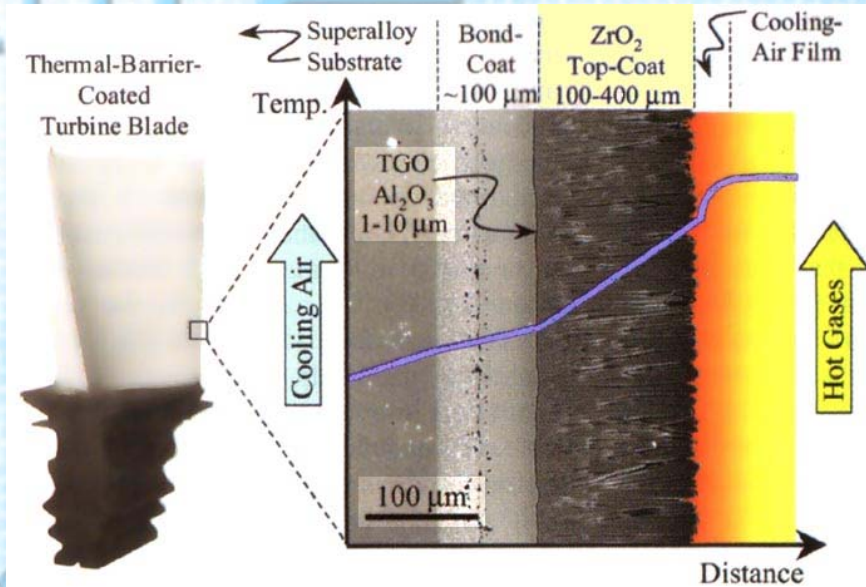
Rockwell

K_{IC}

Example

Partially stabilized zirconia (PSZ) is one the toughest ceramic materials.

If it fails at 610 MPa, calculate the maximum through-crack length it can tolerate.



Rockwell

K_{IC}

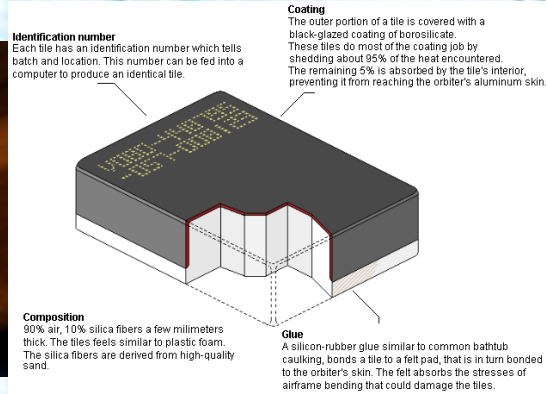
Effect of High Loading Rates (Impact Test)

Loads are not necessarily slowly applied.

Give examples of engineering applications where loads are applied suddenly.

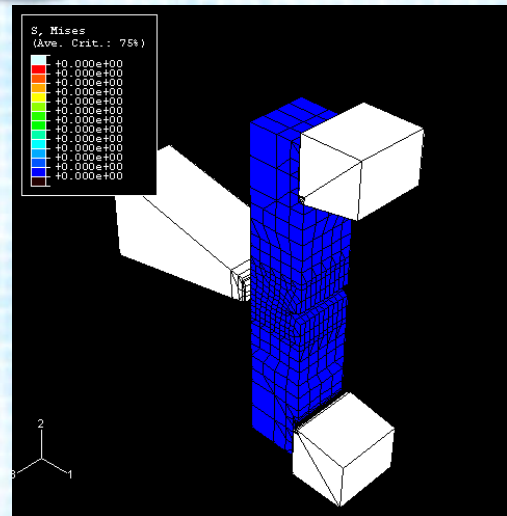
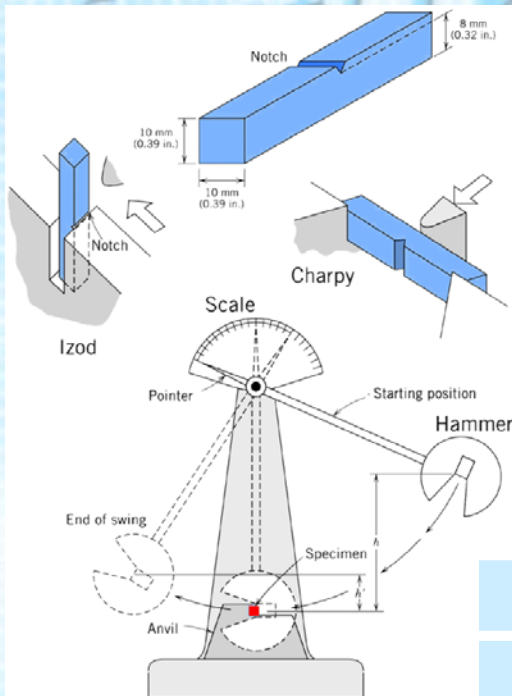


Remember the Columbia disaster?



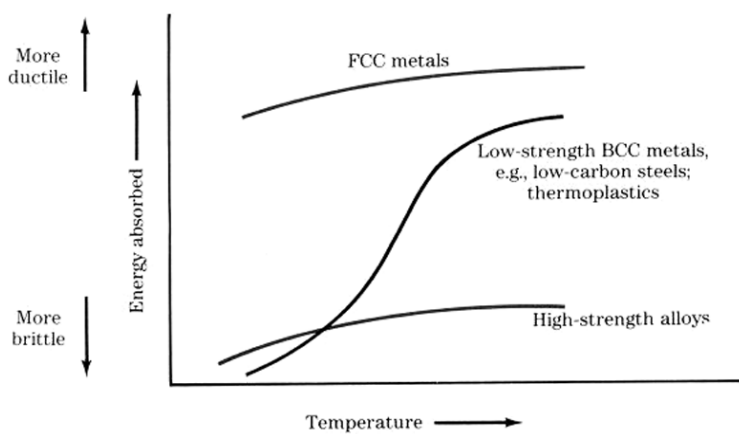
The impact test quantifies the response of materials to violent loads by measuring the absorbed energy upon fracture.

There are two different impact tests: Izod and Charpy (in the figure)

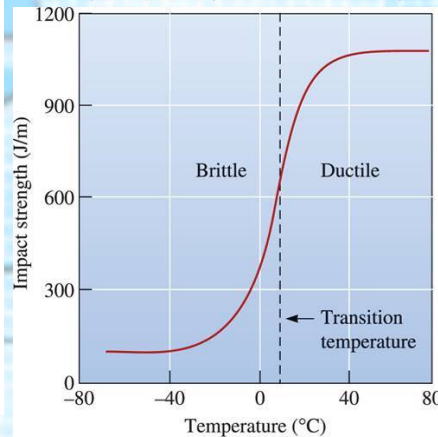


Temperature affects the absorbed energy to fracture

Effect of crystal structure in the absorbed energy



Tough nylon (thermoplastic)

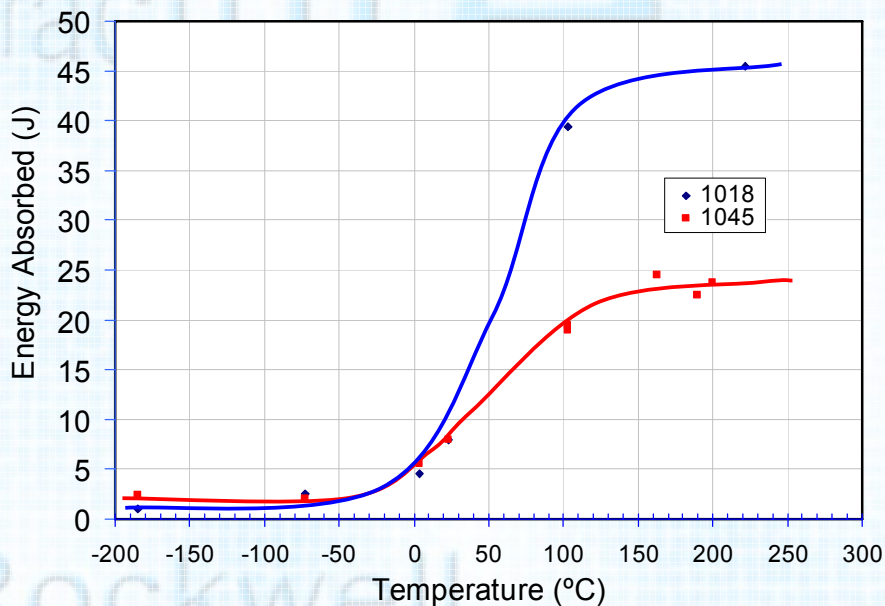


The **brittle-to-ductile transition temperature**: How do we measure it?

Homework: Investigate the effect of the glass transition temperature T_g in polymers on the brittle-to-ductile transition temperature of those materials

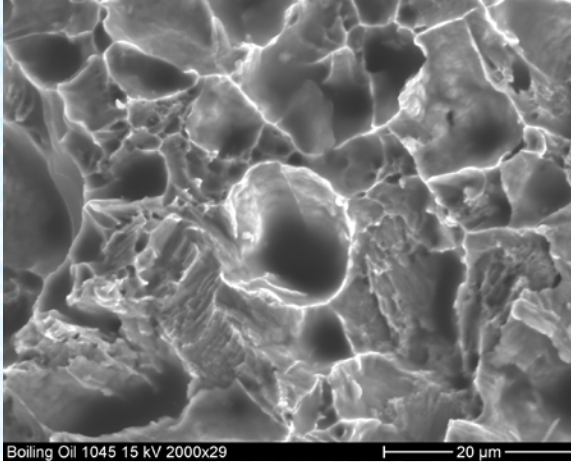
Experimental Results from Two Plain Carbon Steels: SAE 1018 and SAE 1045

Absorbed Energy vs. Temperature

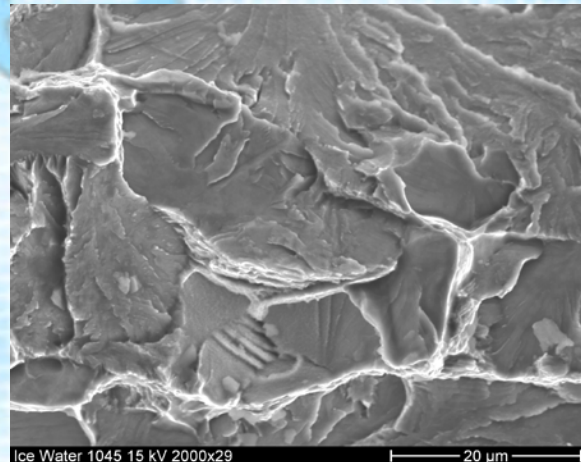


Fractures in Impact Tests

SEM Micrographs for a SAE 1045 tested at:



200°C



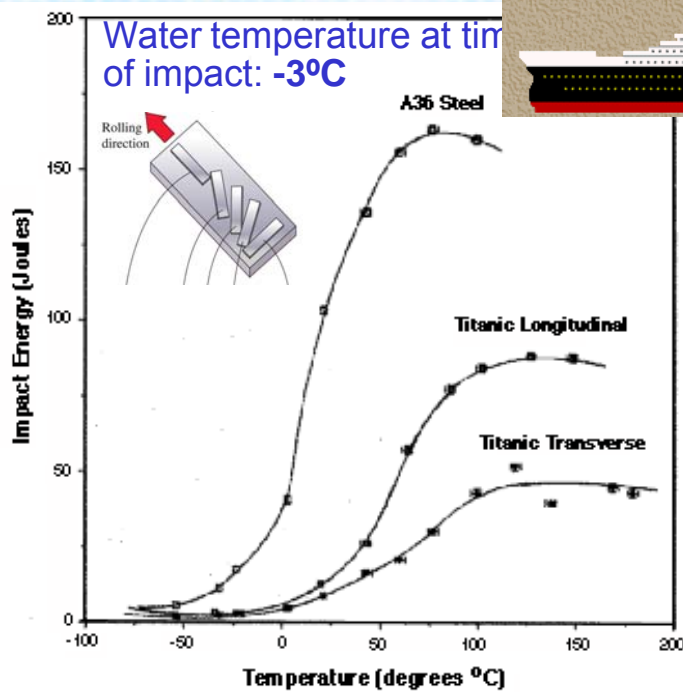
0°C

Differences?

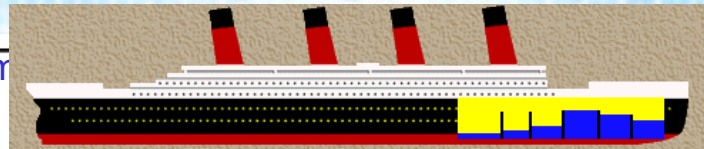
Rockwell

K_{IC}

Impact Test of the *Titanic* Steel



Water temperature at time of impact: -3°C



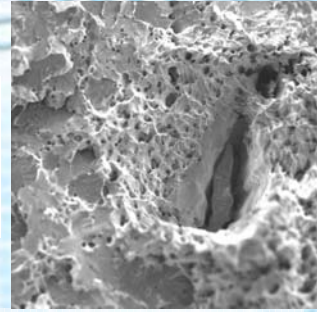
Six panels were ripped off on the starboard side of the forward hull



Artistic reconstruction of the stern port side middle section



The Fate of the Titanic...

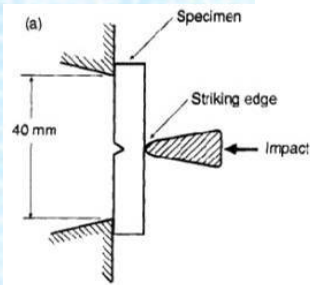


Comparison of Tensile Testing of the *Titanic* Steel and SAE 1020

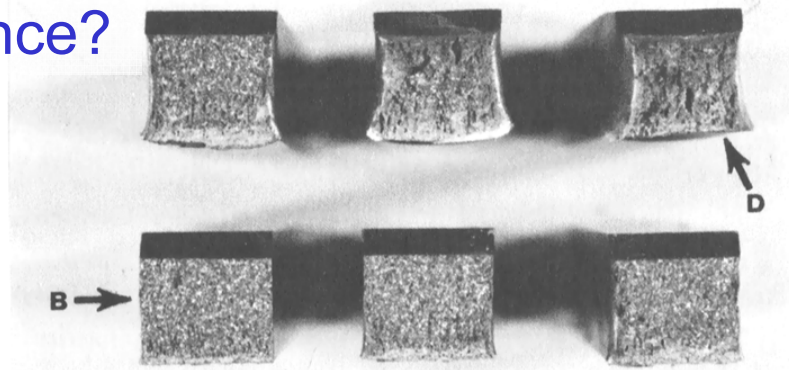
	<i>Titanic</i>	SAE 1020
Yield Strength	193.1 MPa	206.9 MPa
Tensile Strength	417.1 MPa	379.2 MPa
Elongation	29%	26%
Reduction in Area	57.1%	50%

Macroscopic Aspect of the Fractures

Main Difference?

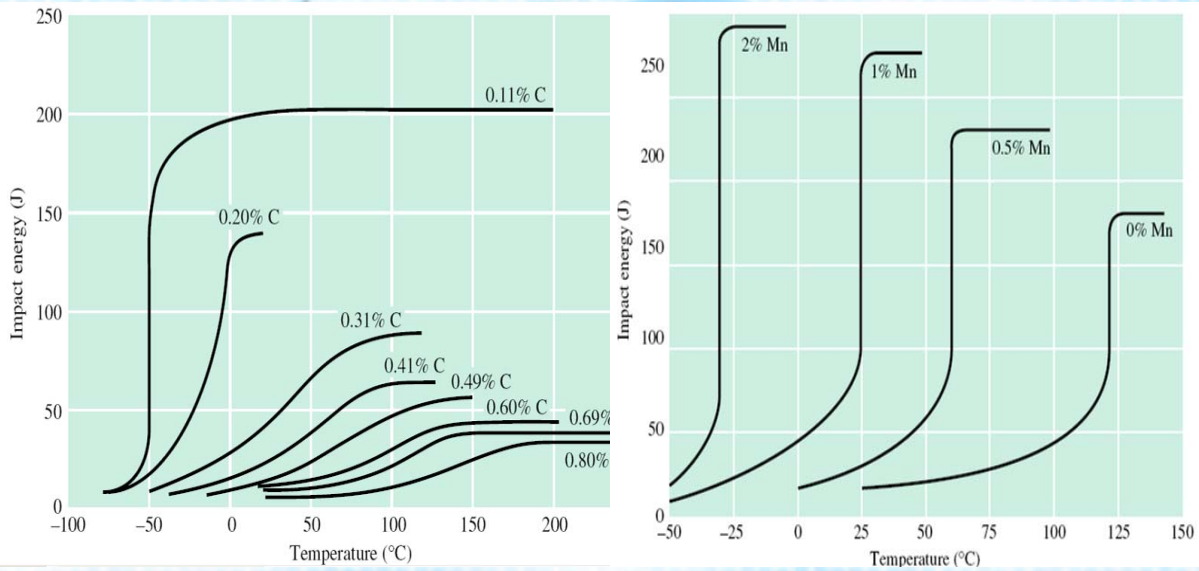


Temperature, °C (°F)	25 (75)	65 (150)	95 (200)
Energy, J (ft · lb)	34 (25)	134 (99)	152 (112)
Lateral expansion, mm (in.)	0.81 (0.032)	1.85 (0.073)	1.85 (0.073)
% fibrous	65	95	100



Temperature, °C (°F)	-18 (0)	-4 (25)	10 (50)
Energy, J (ft · lb)	5.5 (4)	13.5 (10)	23 (17)
Lateral expansion, mm (in.)	0.15 (0.006)	0.35 (0.014)	0.53 (0.021)
% fibrous	15	20	40

We can adjust the brittle-to-ductile temperature by playing with the composition of the material, p. ej. with carbon and manganese in steels.

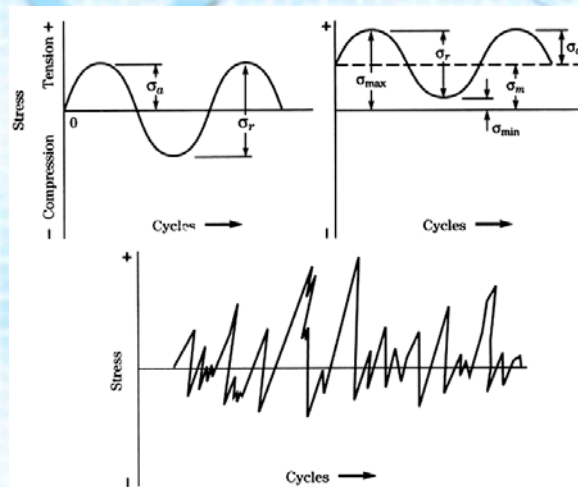


What happens to the ductile-to-brittle transition temperature?

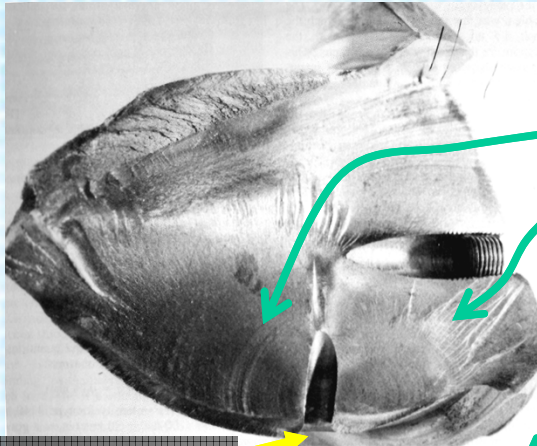
Fatigue

Failure under cyclic stresses that –in general- do not exceed the yield strength of the material.

Examples?



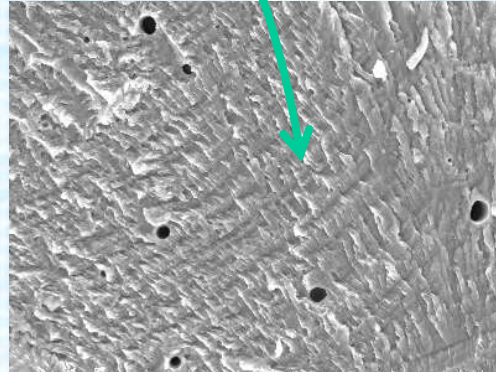
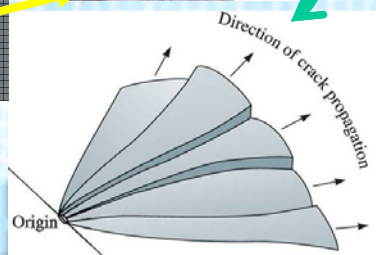
Aspect of the Fatigue Fracture



Note the main features of the fracture:

- Beachmarks
- Chevron marks
- Striations

Fracture started here. Why?

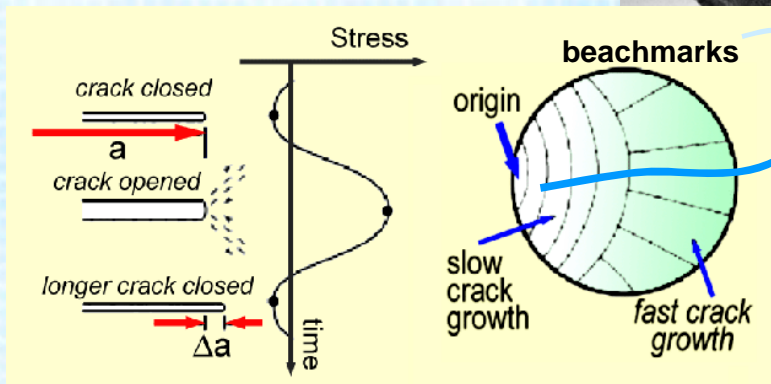
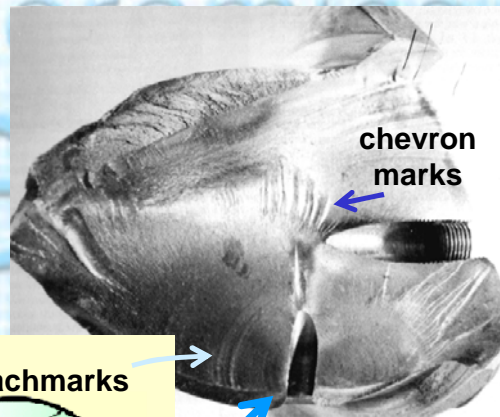


Fatigue Fracture in Stainless Steel, Mag: 2,000X

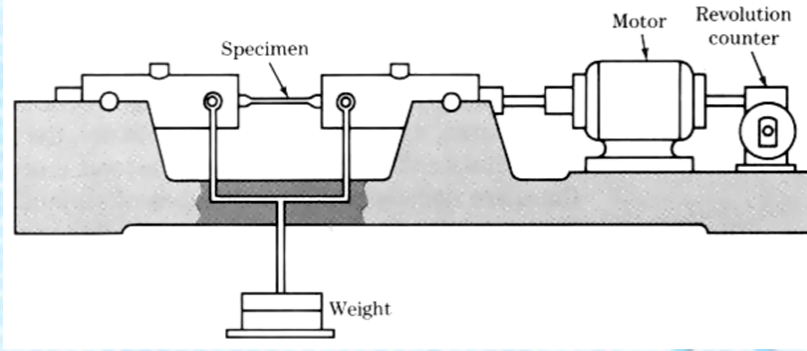
Scanning electron microscope image

Mechanism of Fatigue Crack Propagation

The cyclic stress and friction explain the morphology of the fracture

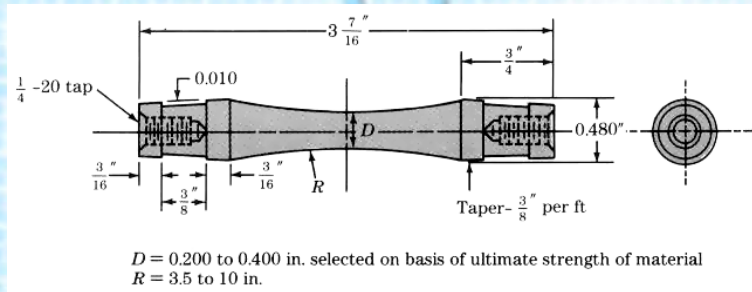


Fatigue Test

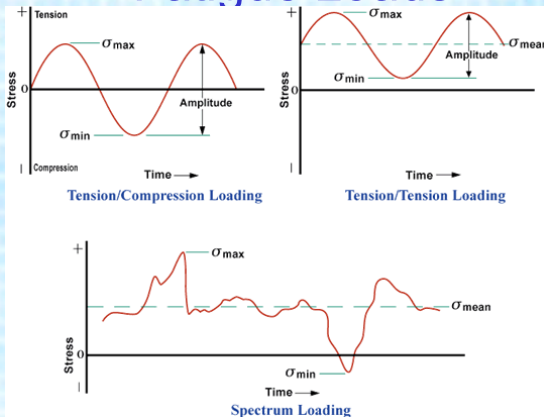


Testing Machine

Example of a standard specimen

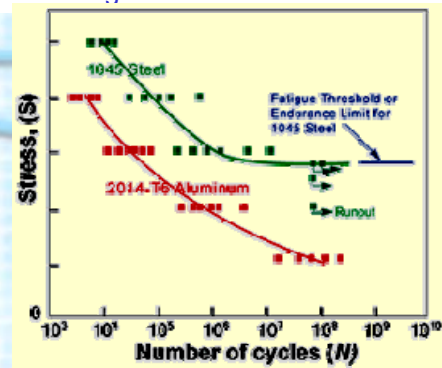


Fatigue Loads



The S-N Curve

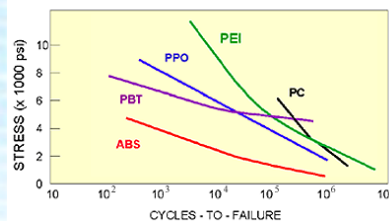
Let's understand this curve!! To the right of the curve the design is NOT safe.



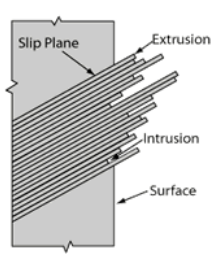
Fatigue Crack Formation and Propagation

1. Crack nucleation
2. Slipband crack growth
3. Crack growth on planes of high tensile stress
4. Ultimate ductile failure

S-N Curves for Thermoplastics



Fatigue Crack Formation and Propagation (cont.)



Dislocations accumulate near surface stress concentrations to form persistent slip bands (PSB), which are areas that rise above (extrusion) or fall below (intrusion) the surface.

These are tiny steps in the surface that serve as stress risers where tiny cracks microcracks can initiate.

Once a crack forms, its length a will increase with every cycle N as follows:

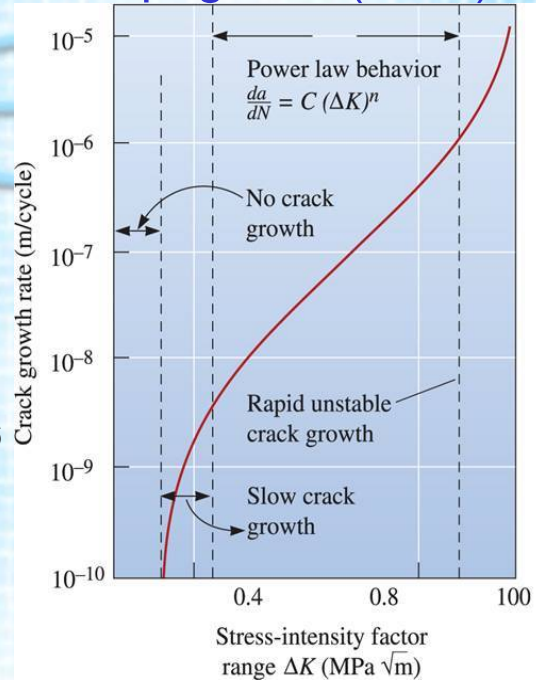
$$\frac{da}{dN} = C \cdot (\Delta K)^n \sim (\Delta\sigma)\sqrt{a}$$

typically 1 to 6

--crack grows even though $K_{max} < K_c$

--crack grows faster if

- $\Delta\sigma$ increases
- crack gets longer
- loading frequency increases.



These are some of the factors affecting fatigue resistance

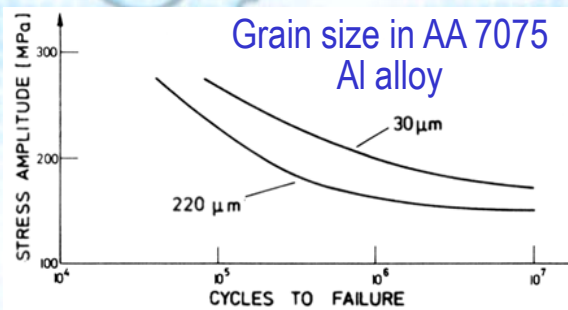
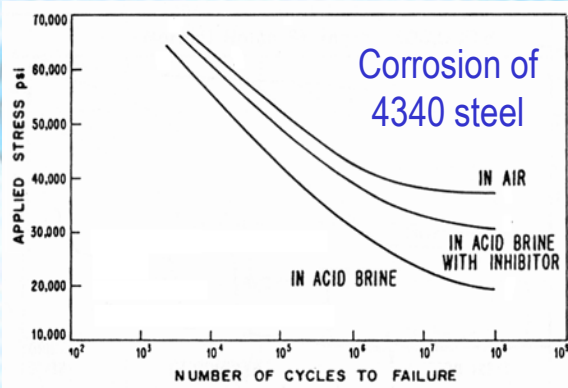
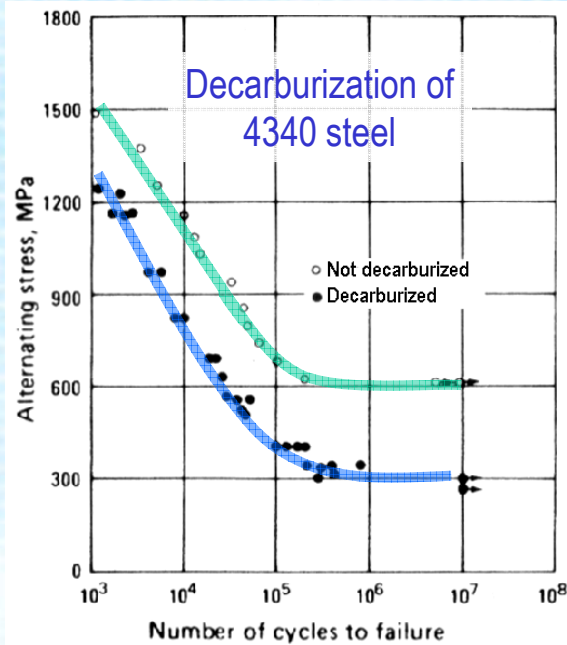
- Stress concentration: a design problem
- Surface roughness: surface finishing
- Environment: corrosion effects
- Surface condition: surface treatments, superficial defects

Case Study: Crankshaft

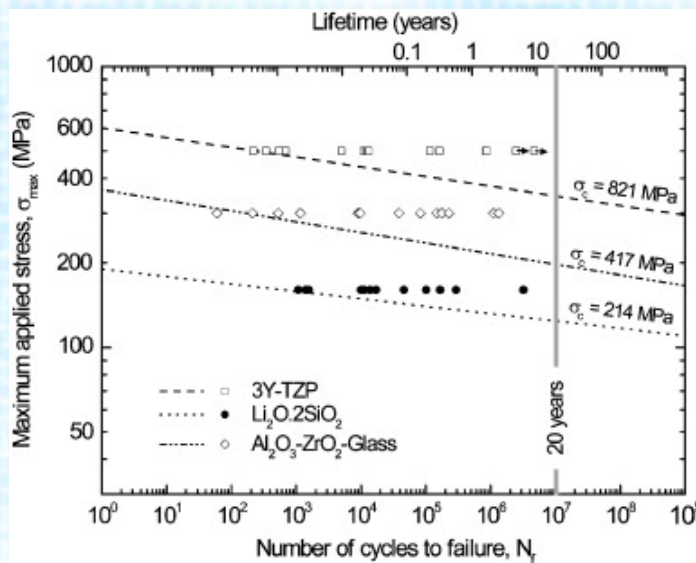


All these factors are considered during failure analysis

Examples of different factors affecting fatigue strength



Fatigue lifetime in water of three dental materials



Number of cycles to failure for 3Y-TZP, Al₂O₃-ZrO₂-Glass and Li₂O·2SiO₂ framework components (dashed lines) submitted to different maximum applied stresses (σ_{max}).

Experimental data obtained from the cyclic lifetime tests at a constant maximum applied stress. The lifetime scale in years was calculated assuming a conservative mastication frequency of 1400 cycles/day

Creep

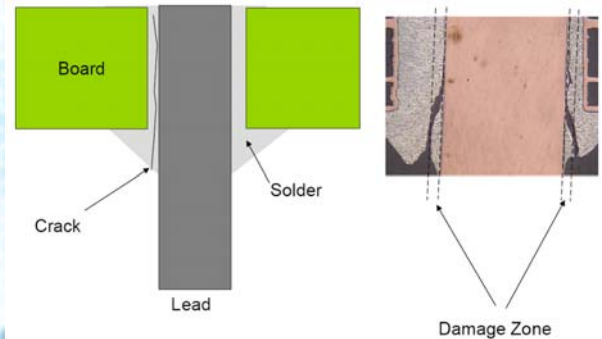
It can be defined as a **time-dependent strain**. It is particularly important in materials that are designed to work at “high temperature.”

Let’s define “high temperature” first!

“High” in terms of what? Or compared to what? $T > 0.4T_m$

Example: microchips and connectors
(electronic packaging materials)

Soldering alloys are subject to creep.



Blades in turbine engines are typical examples of a material subject to creep.

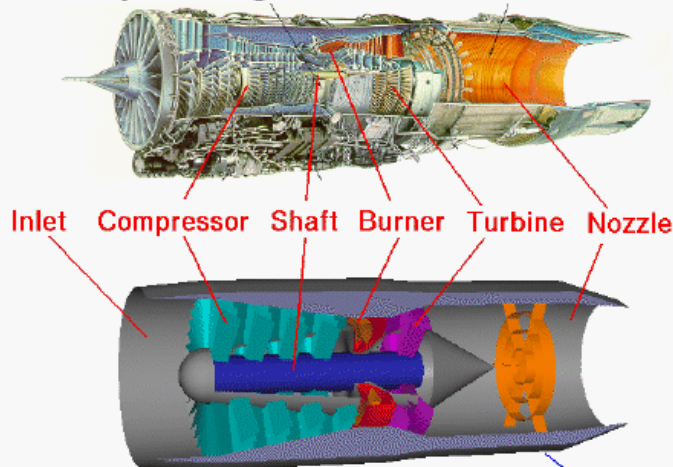


Gas Turbine Parts

Glenn
Research
Center

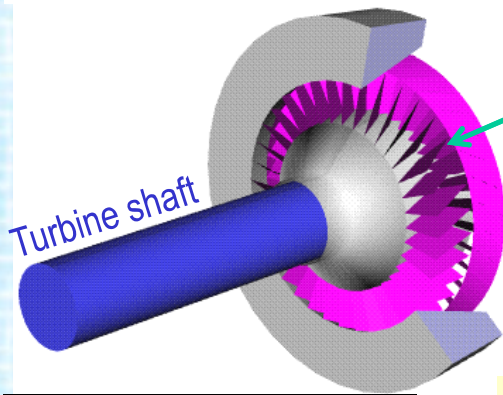
Pratt & Whitney F100 Engine

Photo

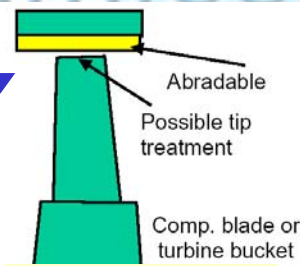


Simplified Computer Drawing

Turbine blades are subject to very high centrifugal forces

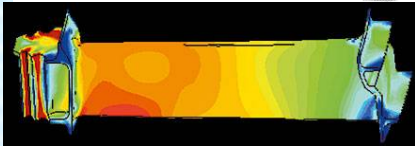
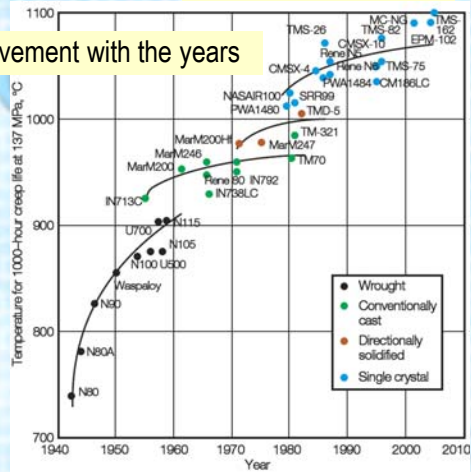


Engine performance increases with smaller blade tip clearances

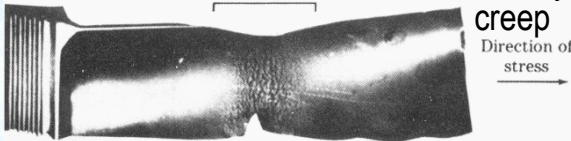


Force acting on each blade: $F = m \cdot R \cdot \omega^2$

Material improvement with the years

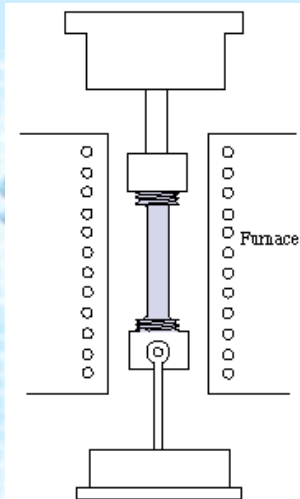
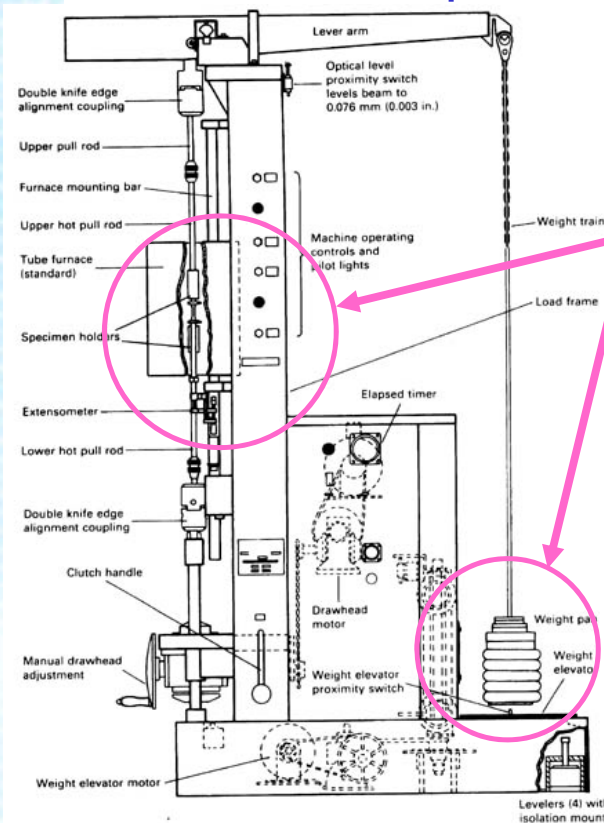


Turbine blade failed by creep



Creep Test Machine

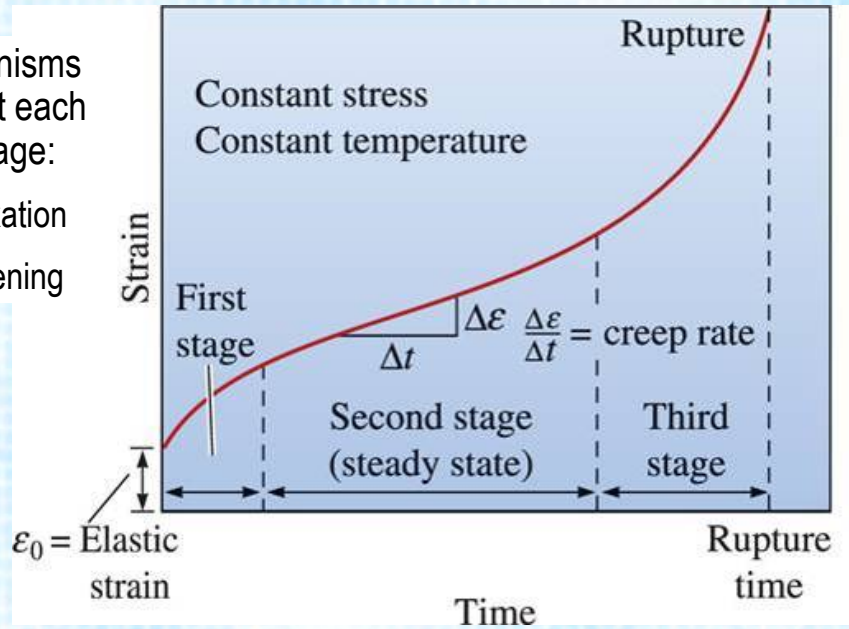
Note the **constant load** which makes this test different from a regular tensile test with a furnace. There is **no** moving crosshead!



Creep Test Curve (Strain-Time Curve)

Different mechanisms compete against each other at each stage:

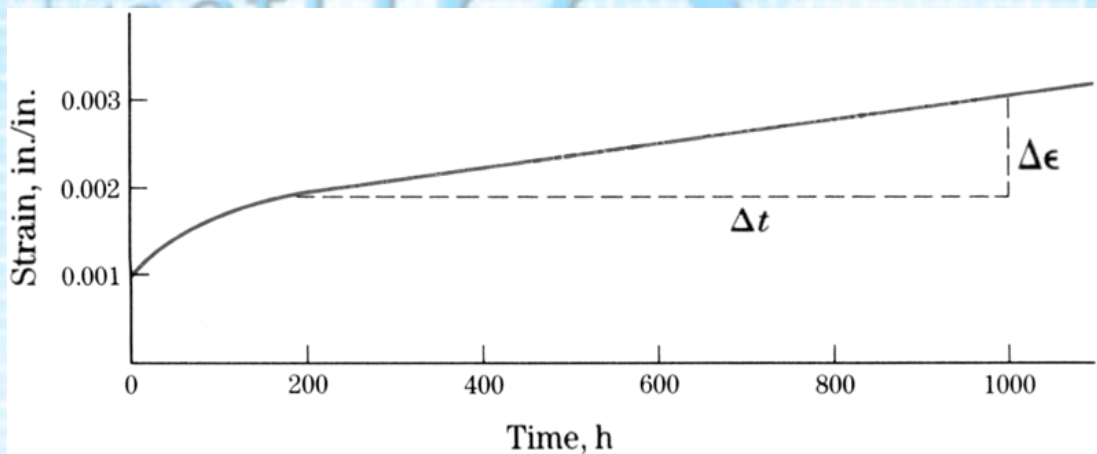
- Stress relaxation
- Strain hardening



Rockwell

K_{IC}

Steady State Creep Rate



$$\dot{\epsilon} = \frac{d\epsilon}{dt} = \frac{\Delta \epsilon}{\Delta t}$$

For the secondary creep stage it is easy to predict the strain after a given time

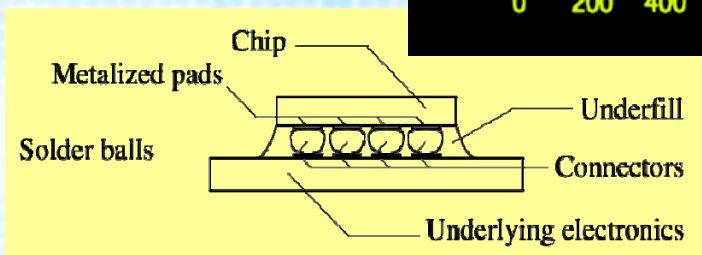
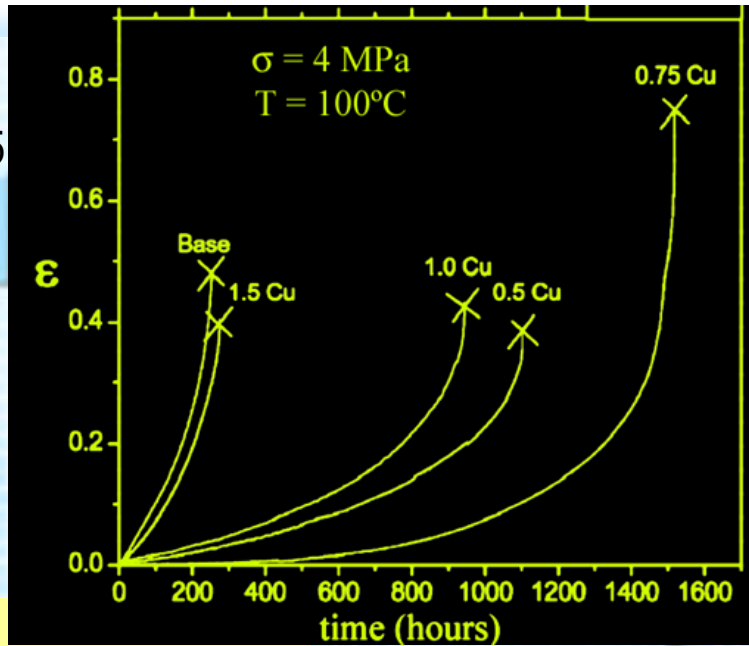
Rockwell

K_{IC}

Another Example

Creep curves for Sn 3.5 wt.%Ag + Cu (Pb-free) solder alloys

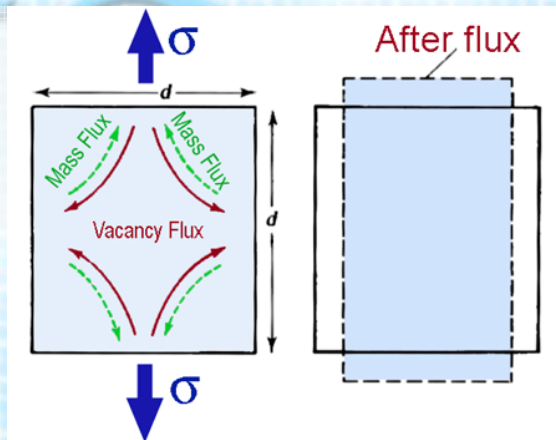
In some materials the secondary creep is not well defined



Flip-chip packaging technology for IC fabrication

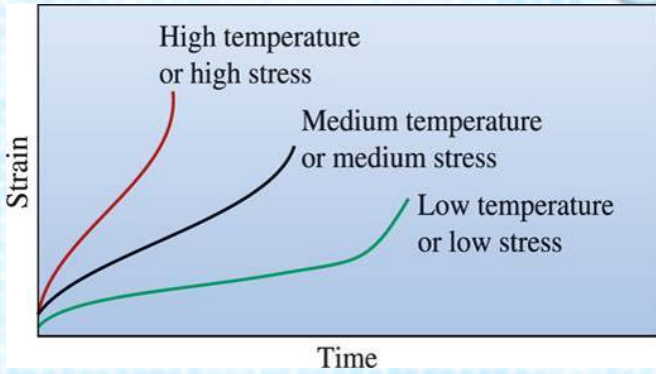
One model to describe the phenomenon is diffusional (Nabarro-Herring) creep

The Nabarro-Herring model applies to high temperatures. Can you explain how to reduce creep in turbine blades based on this diffusional creep model?

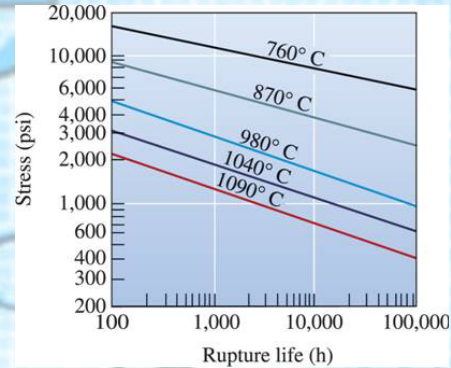


Notice that this is *bulk* or *lattice* diffusion (compared to grain boundary diffusion)

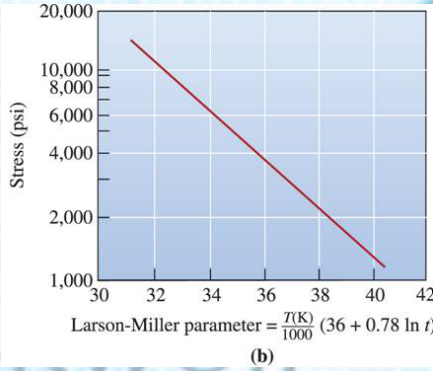
Effect of Temperature and Stress on the Strain-Time Curve



The problem is the number of factors affecting the creep phenomenon: ϵ , σ , t_R , ϵ

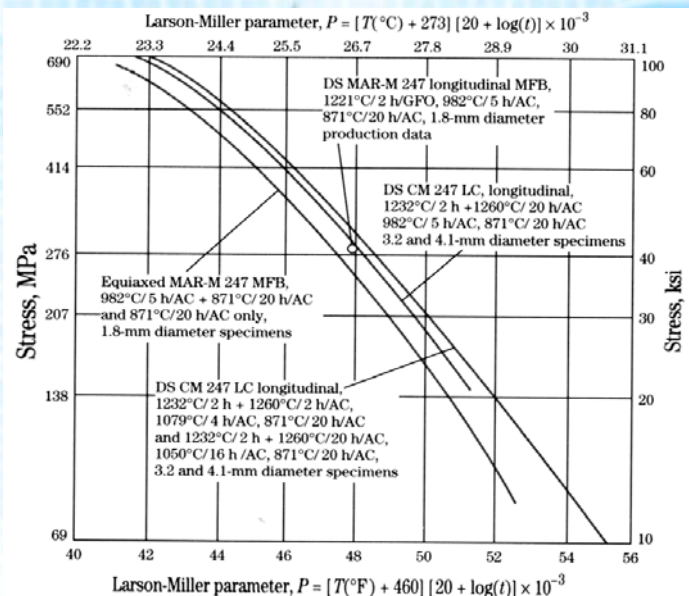


The solution: the Larson-Miller parameter



This is a purely empirical number needed for design

Larson-Miller Parameter

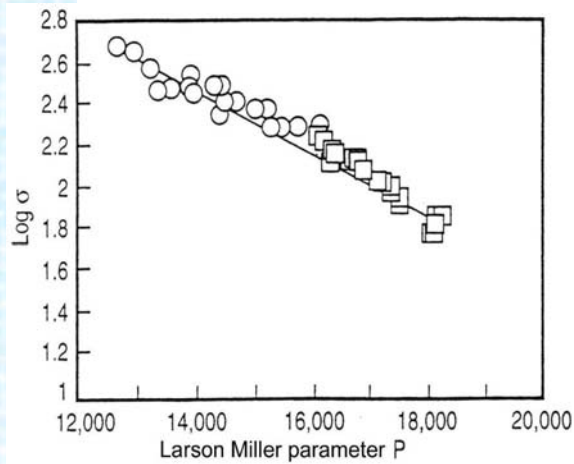


This parameter synthesizes the combined effect of applied stress and temperature on the time-to-rupture

In this case the parameter P takes the form:

$$P = T [\log t_r + C]$$

Larson-Miller Parameter (cont.)

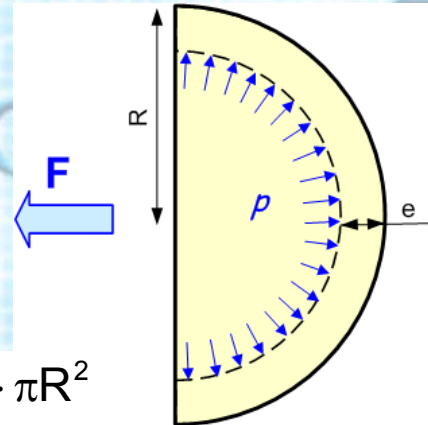


Example: Zircaloy-4

Assume a spherical container of radioactive waste with a half-life of 40,000 years and at 300°C. The container is working at an internal pressure of 42 atm. Radius of the container is 1 m, and its thickness, 2.5 cm. Question: Is the design safe?

$$P = T \cdot [20 + \log t_r]$$

where σ is in MPa, T is in K, and t_r in hours
 1 atm = 0.1013 MPa



$$F = \sigma \cdot A_o = \sigma \cdot (2\pi \cdot R \cdot e) = p \cdot A = p \cdot \pi R^2$$

Rockwell

