Materials: Structural performance recap

- In this *section of the course* we will
  - Consider fracture, fatigue and other failure modes
  - Design to a defined life
  - Assess how to survive complex service conditions
    - Fatigue, corrosion, wear

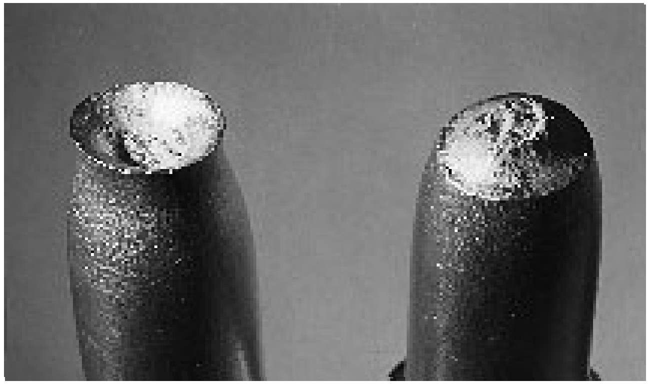
- In this *lecture block (and the next Materials lecture block)* we will
  - Re-examine fracture concepts
  - Evaluate micromechanisms of fracture
  - Consider the concepts and uses of fracture mechanics

Overview : Modes of Failure

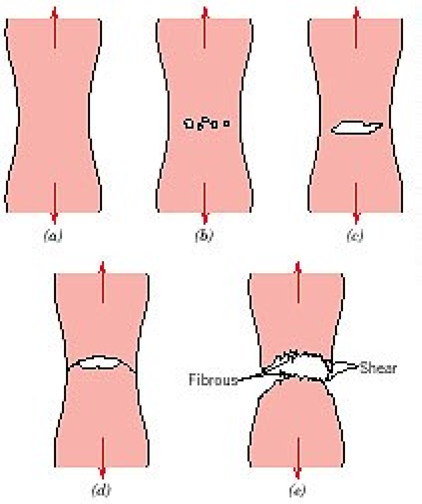
- Fracture (is it ductile or brittle?)
  - Behaviour in the presence of a stress concentration
- Fatigue (cyclic loading)
  - Initiation and growth of a defect
- Corrosion – dry or wet?
  - Essentially an oxidation process
- Wear – surface degradation

  => Local properties important (use of coatings)
- Creep – time dependent deformation (T-dependent)

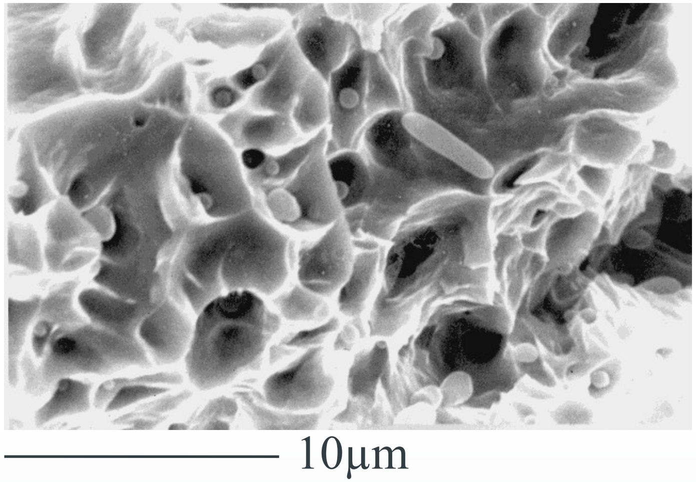
Ductile failure modes:



Typical cup-cone failure: tensile test



Al alloy ductile fracture surface

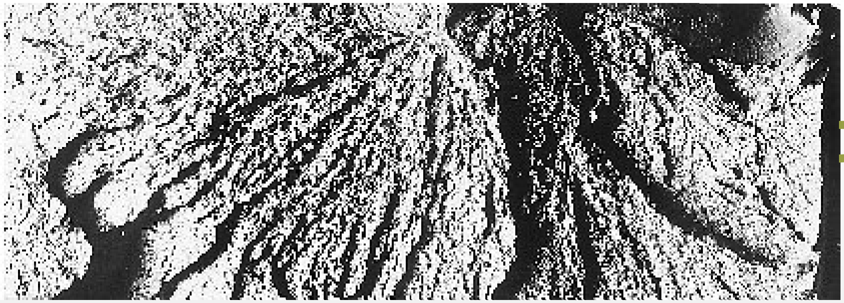


Lots of plastic flow- lots of dislocations moving around

(a) Initial necking, stress concentration in the neck region
(b) Small voids form around **hard secondary particles** (think of ball bearings in plasticine)
(c) Small voids coalesce to give an internal crack
(d) Remaining (thin) ligaments shear **and fail under maximum tensile stress**
(e) Final failure

Brittle failure modes

Intergranular – cracks along grain boundaries



Riverlines

Transgranular – cracks across grains

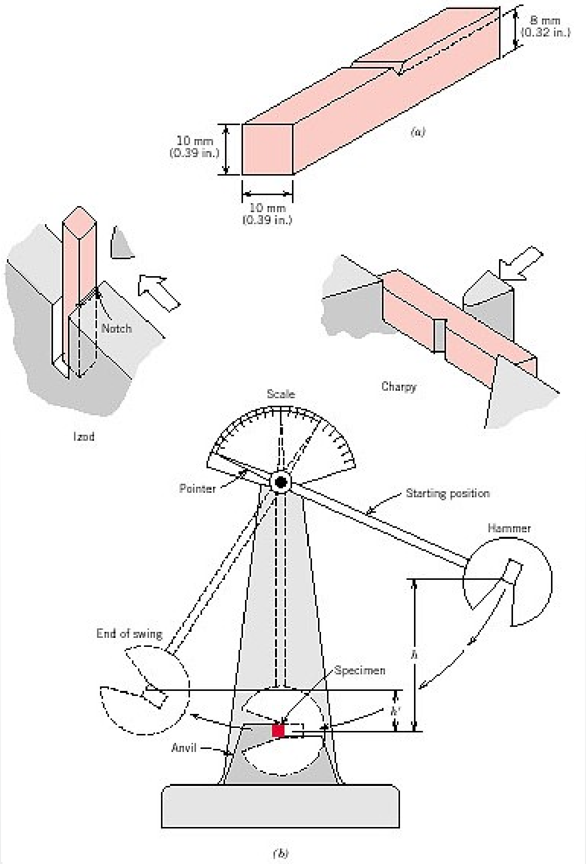
- Brittle failure is catastrophic, crack travels through the μstructure: transgranular or intergranular? Depends on which is the weakest path
- Little prior deformation, crack runs fast
  - Riverlines can be used to pinpoint the initiation site, these form because the crack front is unstable and proceeds on different planes

DUCTILE VS BRITTLE FRACTURE:

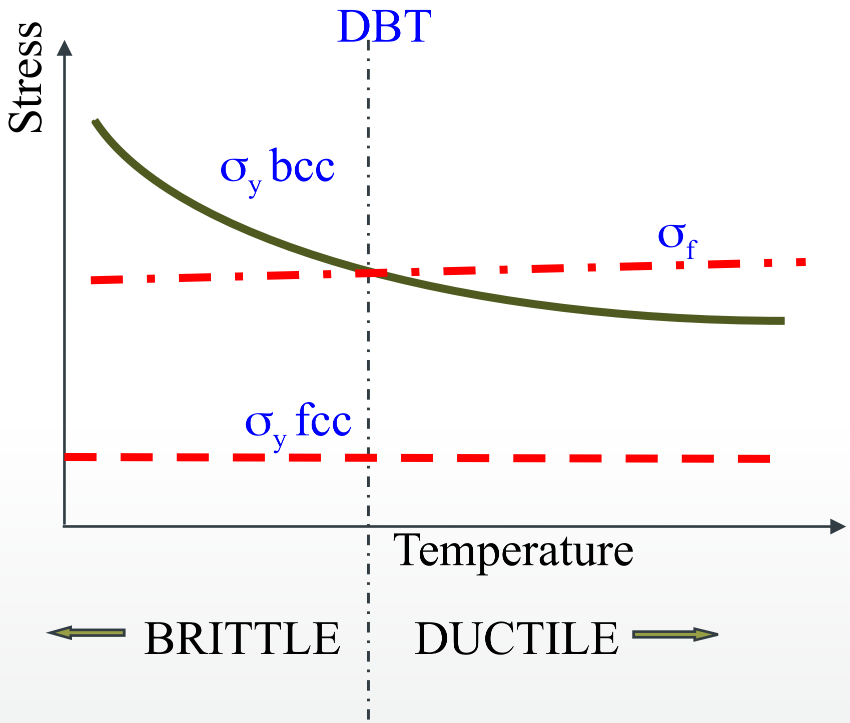
	DUCTILE	BRITTLE
Fracture surface?	Dimpled	Flat
Deformation?	Lots of plastic	Not appreciable
Crack propagation?	Slow	Rapid
Type of Failure?	Gradual	Catastrophic

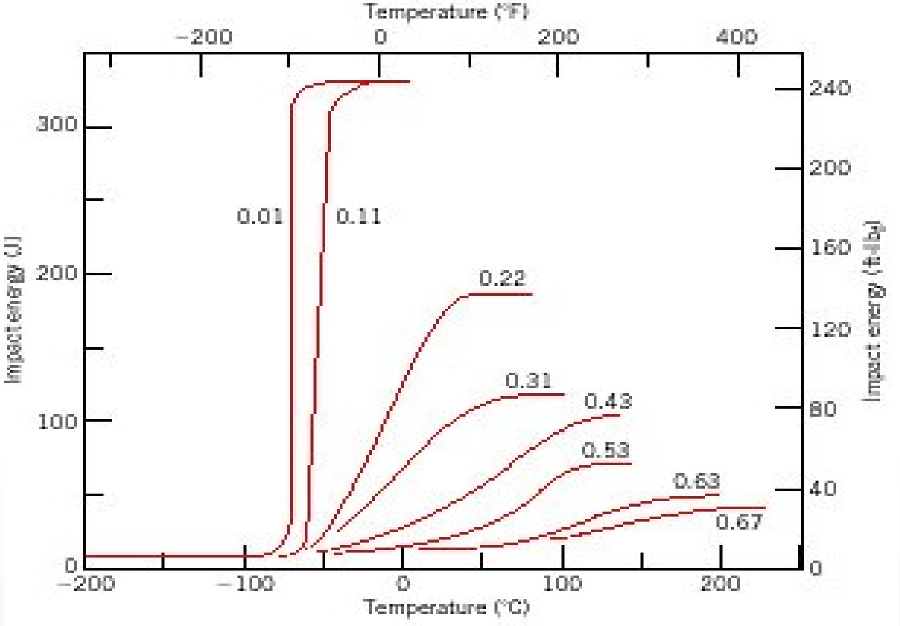
Measuring toughness

- In Part 1 you tested smooth uniaxial tensile test samples => E, σ_y, % el.(<5% termed brittle)
- Testing notched samples assesses toughness
  - Toughness is the ability of a material to resist fracture in the presence of a notch/defect
- Charpy impact: impact energy I.E.
  - Ductile failure: high I.E.
  - Brittle failure: low I.E.
  - Useful for materials ranking/QA
- BUT can we apply it to structural design?



Ductile to brittle (DBT) transition





Varying DBT with C- content In steels

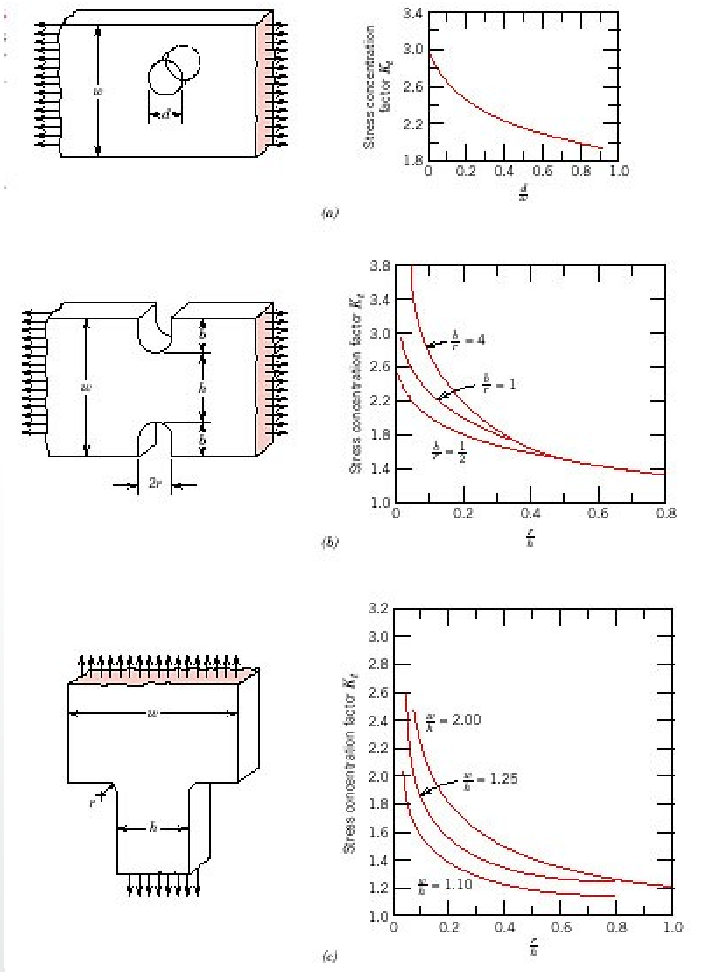
- Competition between ductile (σ_y) and brittle failure (σ_f)
- Crystal structure effects: $\sigma_y = f(T)$ for bcc and hcp case, σ_f relatively unaffected by T (revise Part 1!)
- No T-effect in fcc on σ_y or σ_f so ductile process always wins.

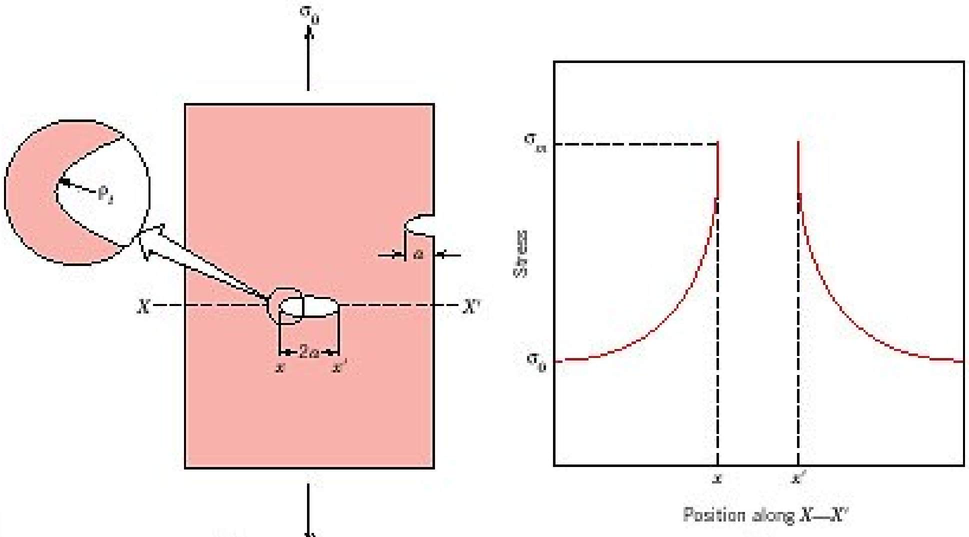
Lecture 1 : Structural performance 1

- In this *section of the course* we will
  - Consider fracture, fatigue and other failure modes
  - Design to a defined life
  - Assess how to survive complex service conditions
    - Fatigue, corrosion, wear

- In this *lecture block* we will
  - Consider the concepts and uses of fracture mechanics
  - Review torsional failure modes and factors affecting toughness
  - Evaluate fatigue fracture surfaces

Fracture mechanics concepts

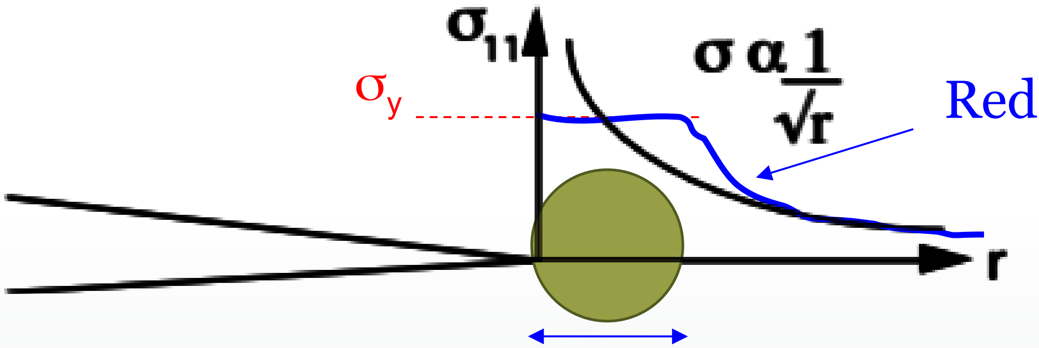




- Stress concentration factors at different notch geometries
- Stress field elevated nearer the notch root (these are ELASTIC assumptions)
- Local failure processes are controlled by the notch/crack tip stresses, failure starts here – but does it carry on?

Plastic zone at the crack tip

- What happens if the local stress is higher than σ_y?



Redistributed stresses due plasticity

Plastic zone

- We should consider the amount of material at the crack-tip in the process zone or plastic zone
- Failure events are controlled by weakest link in the microstructure in this small zone

Strain energy release rate (energy balance)

Griffith approach takes a global energy balance approach instead of considering the local crack tip stress state, if a crack grows:

- Energy is required to create (2) new surfaces (this term OPPOSES crack growth):
  - γ_e (brittle) or ($\gamma_e + \gamma_p$) if ductile, as moving the plastic zone at the crack tip requires work to be done, where γ_e = surface energy per unit area and γ_p = plastic work term, $\gamma_p >> \gamma_e$ ductile materials are tougher!

- This required energy has to be supplied by release of the stored strain energy around the crack (this is the crack driving force)

G_c, the strain energy release rate →

$$\boxed{\frac{\sigma_f^2 \pi a}{E} = 2(\gamma_e + \gamma_p)}$$

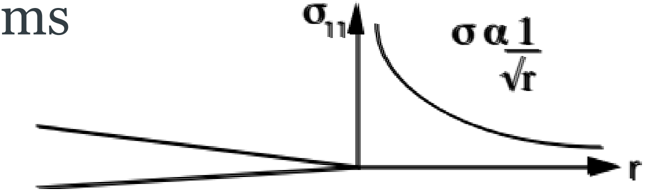
← Resistance to crack growth

- Where G_c = critical strain energy release *rate*, E = Young's modulus, a = defect length, σ_f = global fracture stress

Stress intensity factor, K

- Linear elastic theory => LOCAL stress field at the crack-tip:

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta) +$$ higher order terms

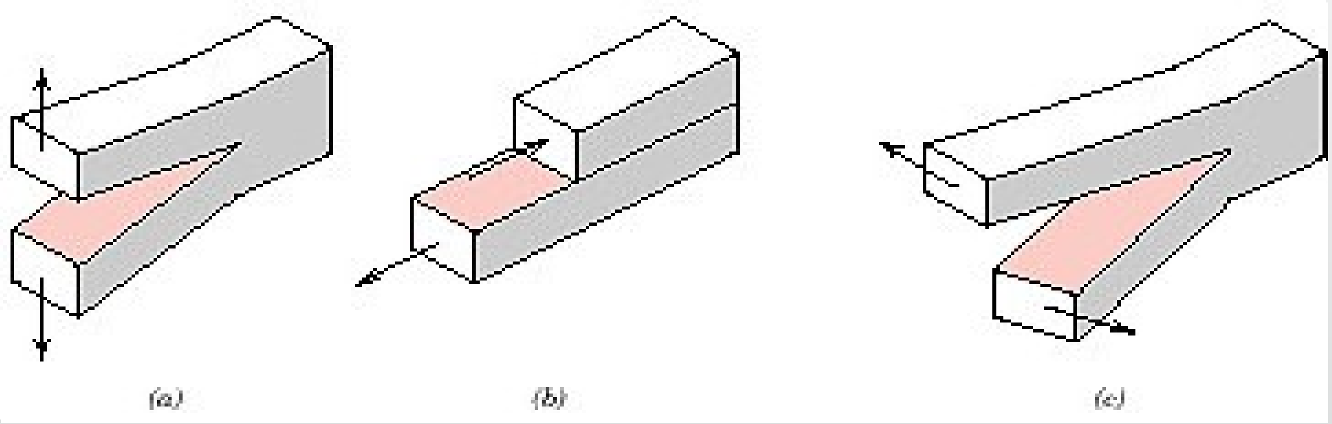


$$\sigma_f = \sqrt{\frac{2E\gamma}{\pi a}}$$

$$\Rightarrow \sigma_f\sqrt{\pi a} = \sqrt{2E\gamma} = K_c$$

$$K_C = Q\sigma_f\sqrt{\pi a}$$

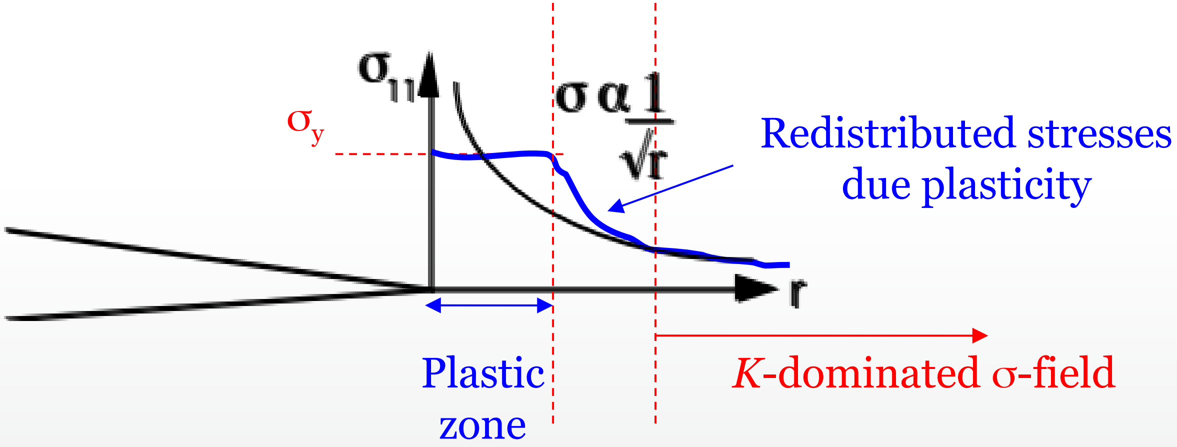
- *K* is a very useful parameter:
- It describes local crack tip stresses (and strains)
- It links to energy balance approaches
- It can be simply calculated from specimen dimensions (*W, B, a, etc.*) and external loading conditions



K_{IC} is fracture toughness under mode I loading.
Most brittle failures are controlled by maximum opening load

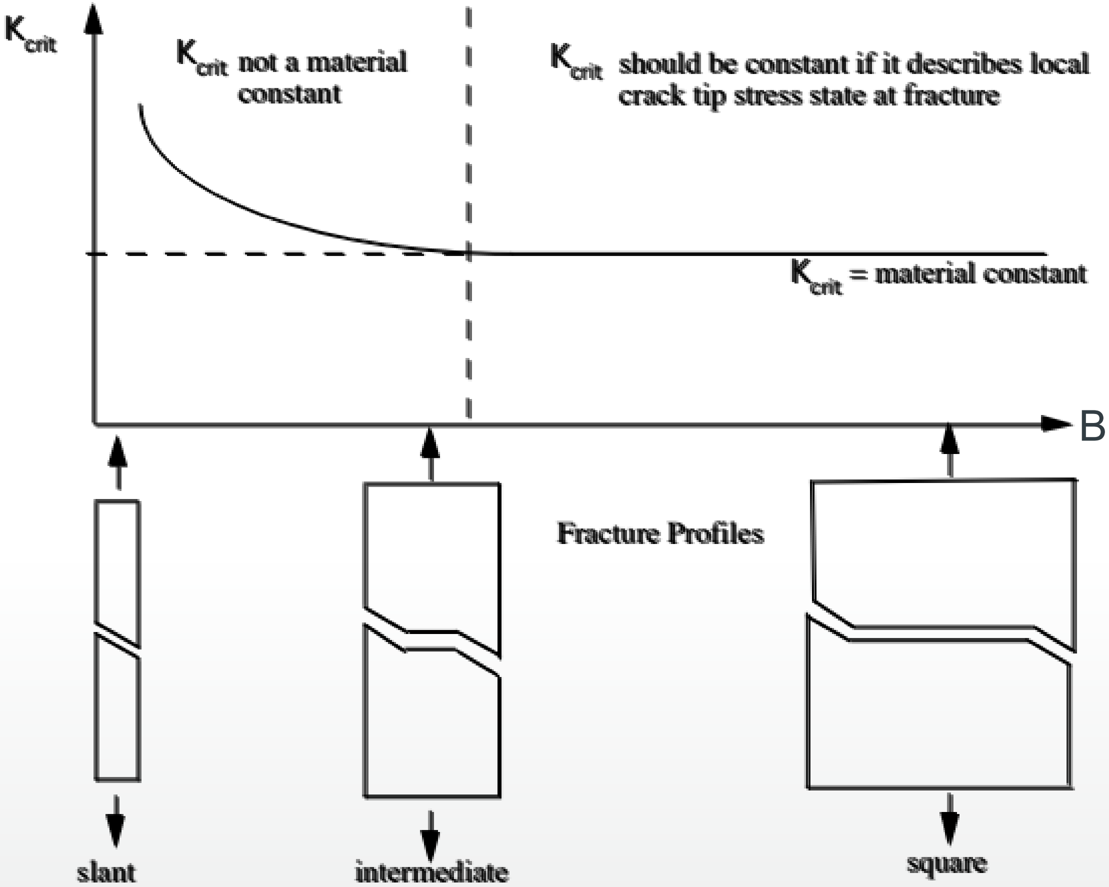
Validity of K

- K is based on linear elastic fracture mechanics
  - Assumes stress and strain directly proportional (E)



- If the K-dominated σ-field is still the main factor controlling failure events in the crack tip region, then it is still a useful descriptor
- Rule of thumb: Plastic zone ~ 1/50th of crack length, uncracked ligaments, thickness in the sample, then VALID

All in the same material



- Example: The thickness criterion in fracture toughness testing
- Plane strain condition is most critical for fracture assessment
- AND defines point at which *K* consistently defines local crack tip stresses and strains.

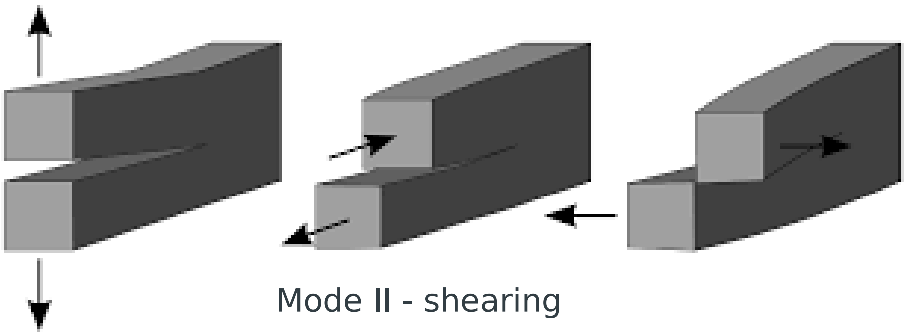
- Stress in the thickness direction ~ 0
- plane stress state
- Maximum resolved shear stress is at 45° to the tensile loading

- Centre of the specimen is under plane strain conditions (no strain allowed in the through thickness position)

⇒ high degree of constraint

⇒ **triaxial** stress state, high local stresses, most severe stress condition

Loading modes (Mode I, II or III)

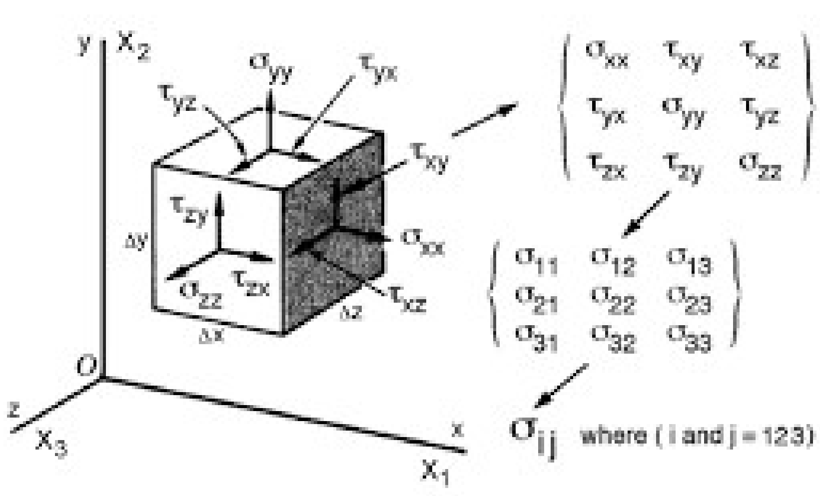


Mode I - opening

Mode II - shearing

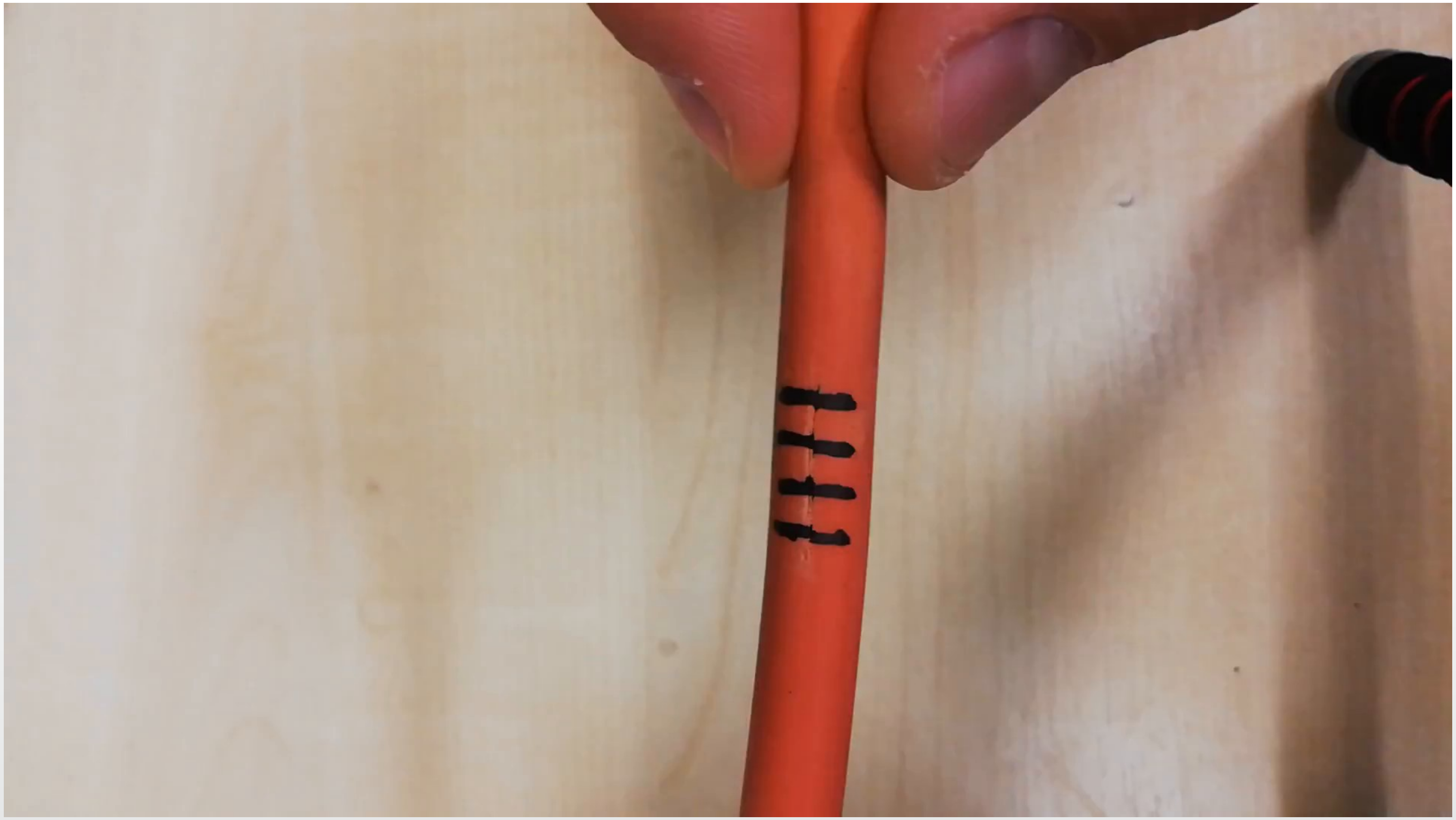
Mode III - twisting

- Brittle failure occurs along maximum opening stress
- Yield requires shear stress (for dislocations to move)
- Bending – unidirectional and reversed
- Rotating bend (off-axis rotation)

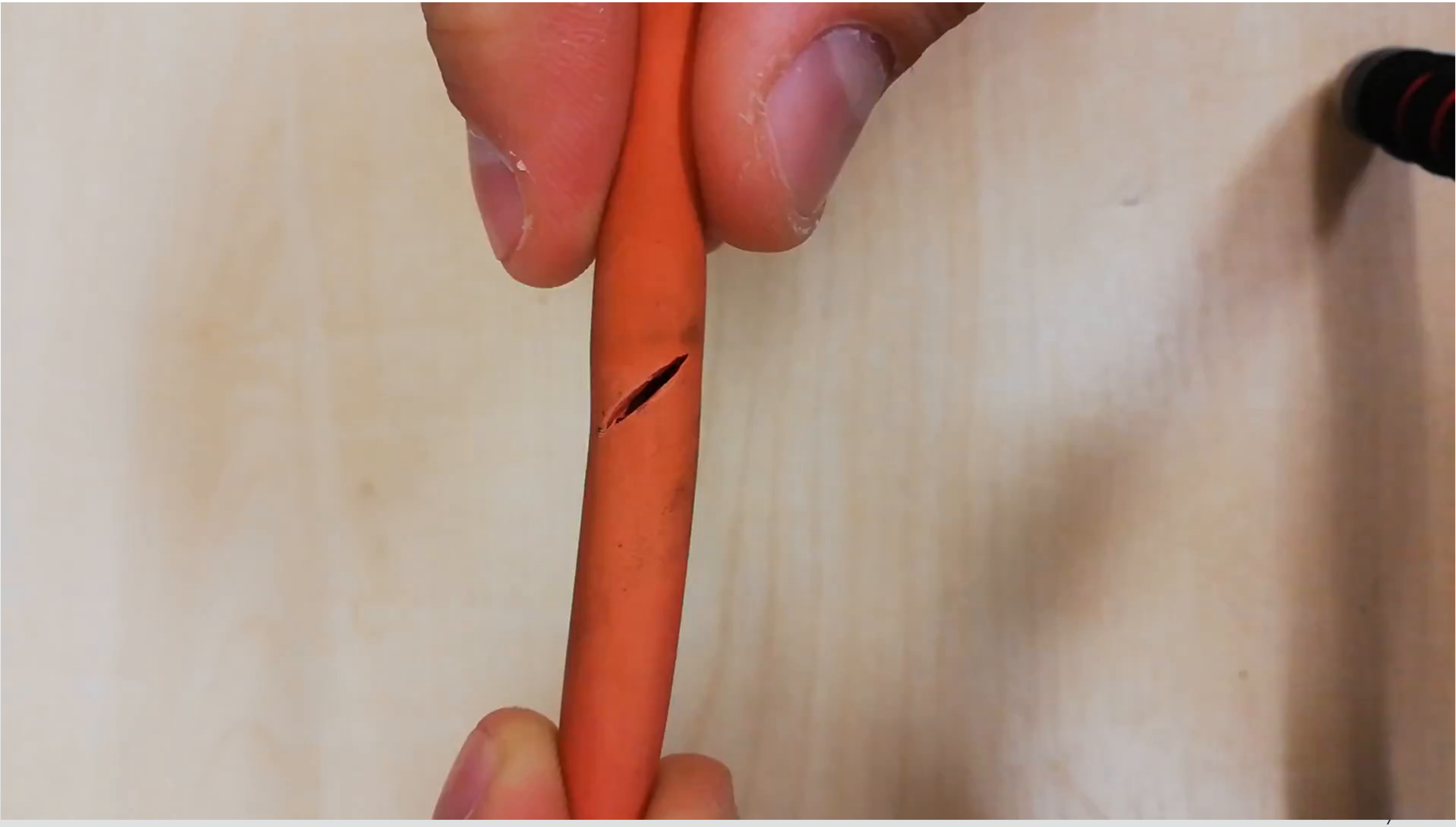


Stress tensor notation reminder

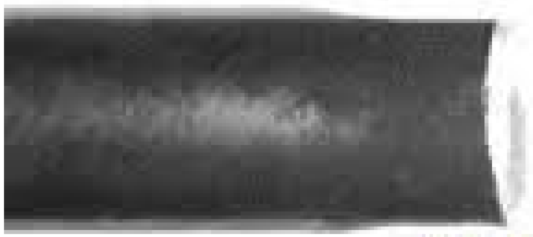
Rubber tubing under torsion (shear)



Rubber tubing under torsion (opening)



Torsion failures (Mode II or III)



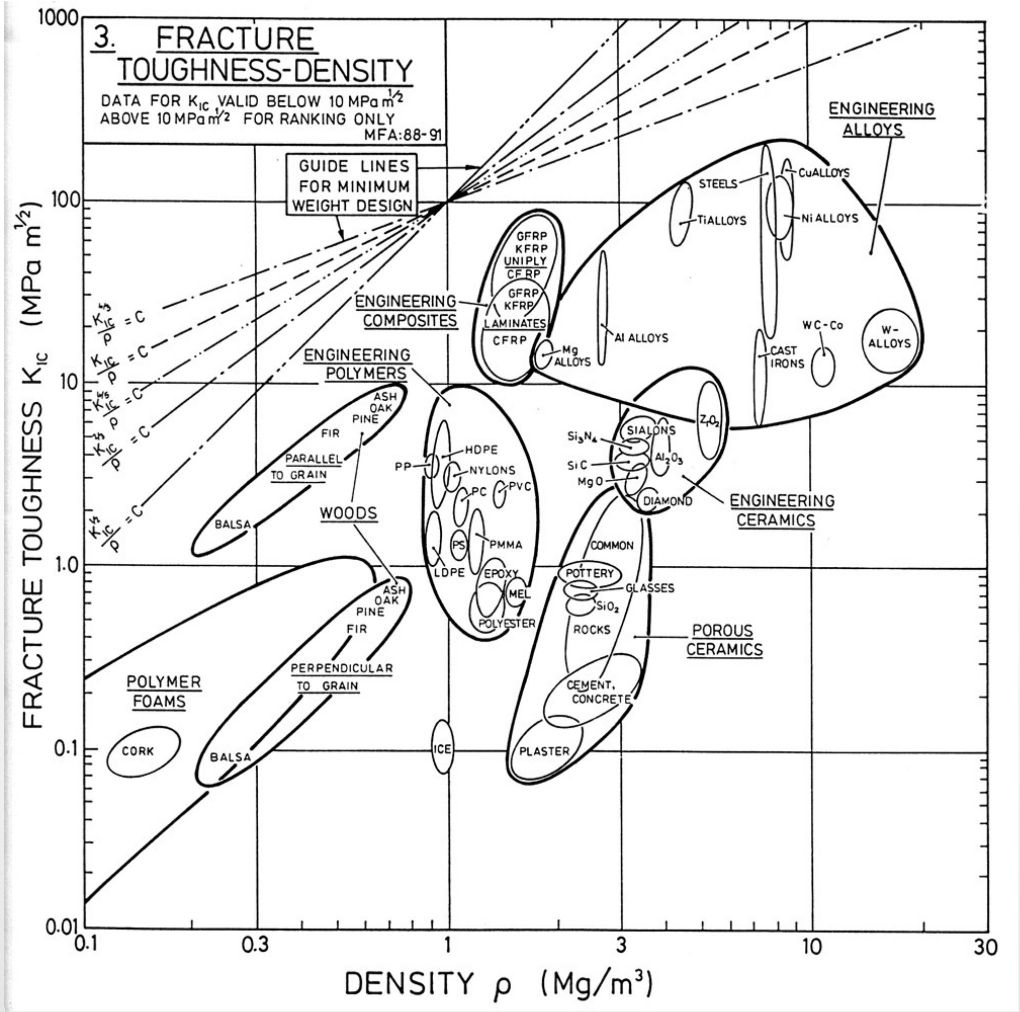
Ductile Torsion Failure

Brittle Torsion Failure

- Ductile – we see some necking. Note plane of failure is perpendicular
- Brittle – helical failure. Little deformation. Note plane of failure, maximum opening stress
- Chalk demonstration
- Rubber tube demonstration

Comparing materials

- We may need to compare materials on the basis of more than one property: Ashby maps can be very useful in materials selection and design (link to Materials selector software in design)



Factors affecting toughness

- Competition between ductile and brittle modes
  - Temperature. Toughness may decrease with decreasing temperatures (e.g. BCC and HCP metals)
  - Ductile materials are usually much tougher – stress redistributed at the crack tip, plastic work done at the crack tip
  - Generally high strength materials have low toughness
- Strain rate
  - Toughness decreases with increasing rate of deformation (no time for plastic deformation to occur at the crack tip)
- Microstructure
  - Local failure events occurring at the crack tip
  - Brittle failure: minimise brittle species on grain boundaries (intergranular), remove defects/large brittle particles in grains (initiate transgranular failure)
  - Large grains can allow big slip-band pile-ups which can initiate cleavage
  - Ductile – optimise secondary particle distribution (microvoid coalescence)

Examples of fatigue failures

Hatfield rail crash (2000)

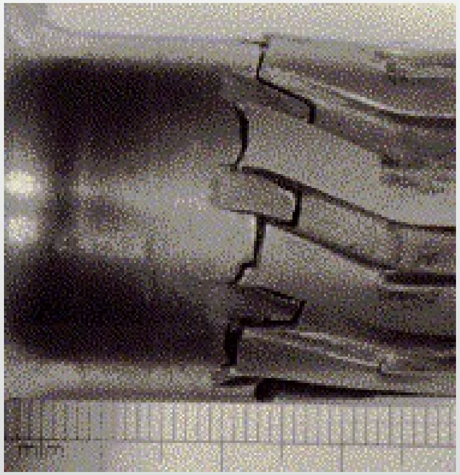
ttps://en.wikipedia.org/wiki/Hatfield_rail_crash

Bridge of glasses (polymer)

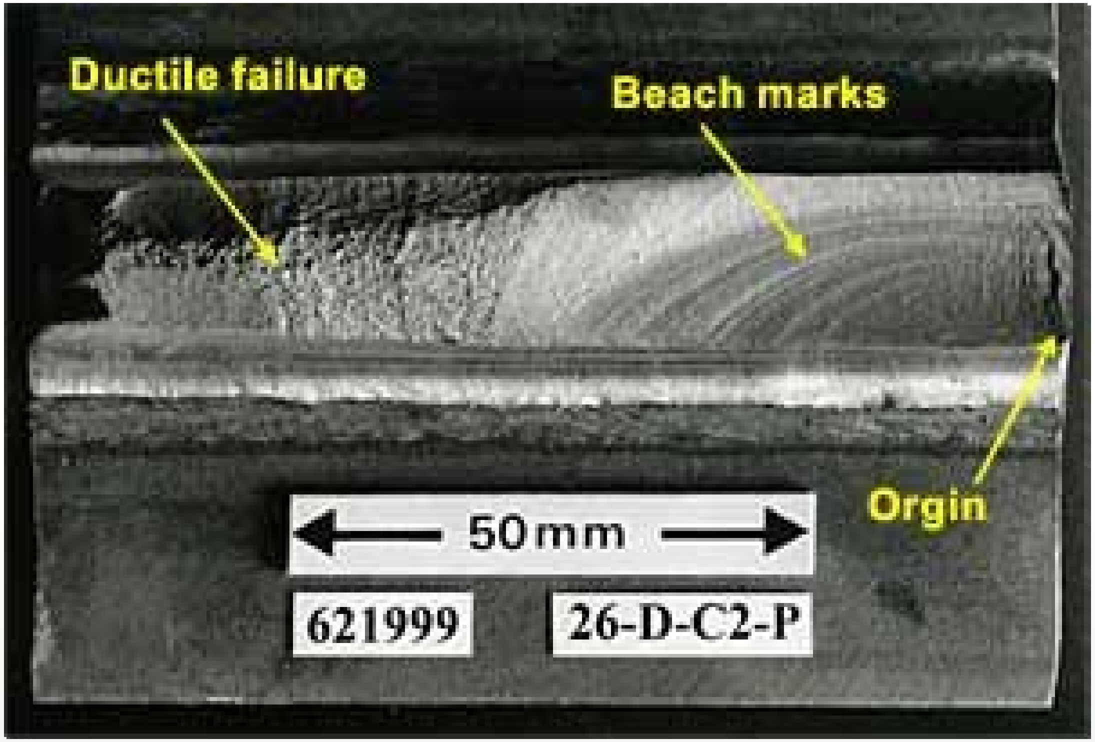
https://leancrew.com/all-this/2014/01/bridge-failure/

Vietnam A332 at Melbourne on May 6th 2014, rejectec takeoff due to uncontained engine failure

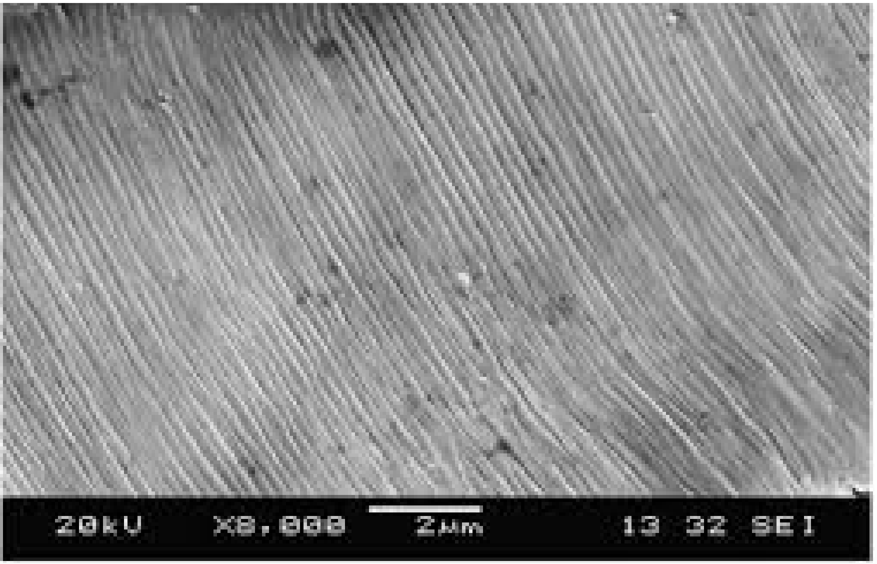
http://avherald.com/h?article=473fa0e6



Sports car drive shaft



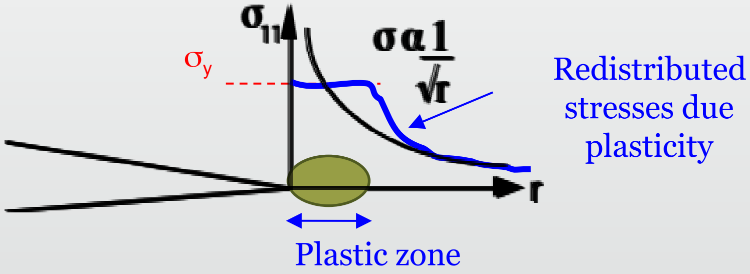
- *Shear lips* indicate the final failure region, work backwards to the fatigue crack
- *Beachmarks* are seen at low magnification: indicate the crack front, usually due to a change in cyclic loading conditions, work backwards to the fatigue origin



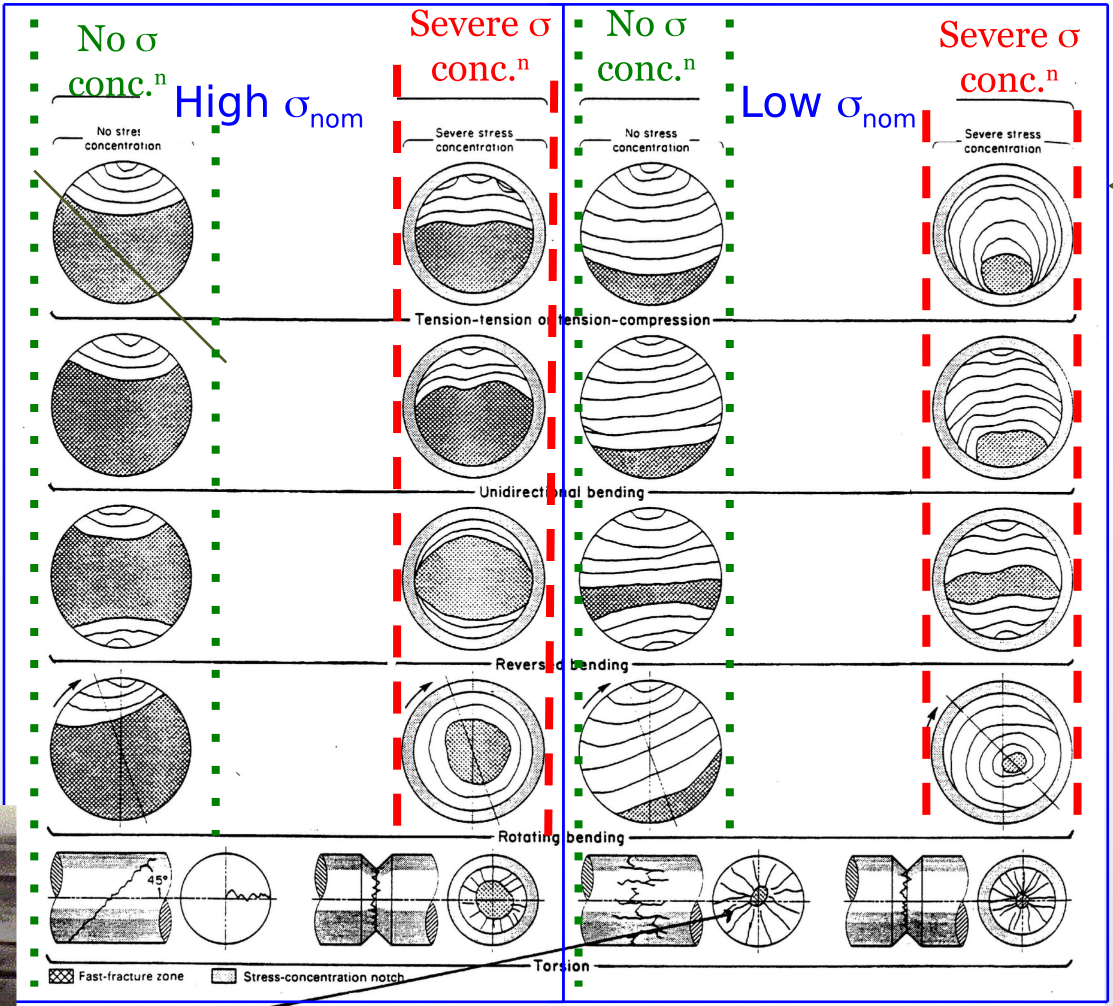
- *Striations* can sometimes be seen at higher magnification: each time the crack advances it leaves a striation – can be used to estimate crack growth rate, *da/dN*

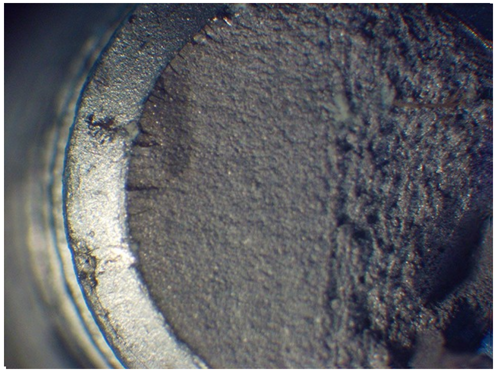
- Striations and beachmarks are NOT always observed

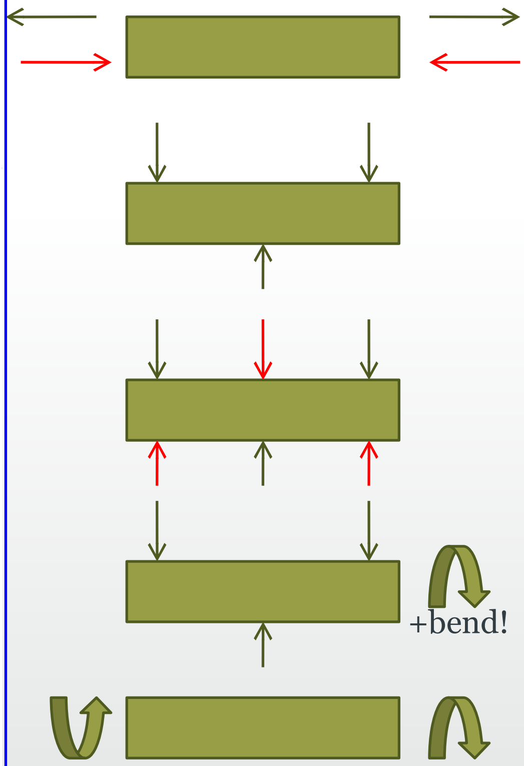
- Fatigue cracks are usually smooth and grow at 90° to the opening load, they look somewhat brittle by eye, but are the result of LOCALISED plastic deformation

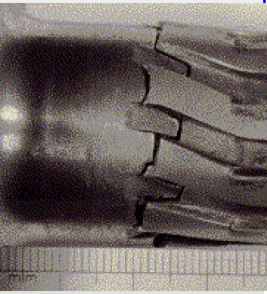


Appearance of fatigue and final fracture regions as a function of loading conditions, nominal stress, and stress concentration









Ratchet marks, like radial and chevron marks, are formed when cracks come together

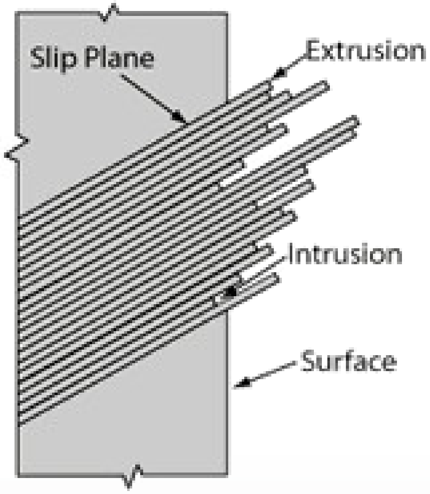
∴ indicate multiple fatigue crack origins

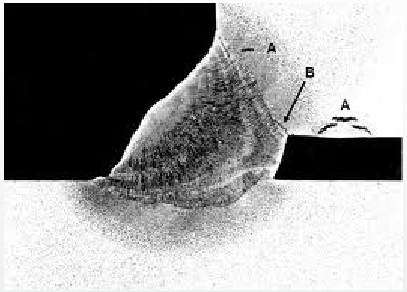
Simplified from Metals Handbook, Ninth Edition, Volume 11, “Failure Analysis and Prevention”, ASM, 1986, p 111.

Lecture 2 : Structural performance 2

- In this lecture we will
  - Evaluate micromechanisms of FATIGUE
  - Consider how to measure/predict fatigue
    - Total life approach
    - Damage tolerance approach
  - Case studies
  - Preventing fatigue

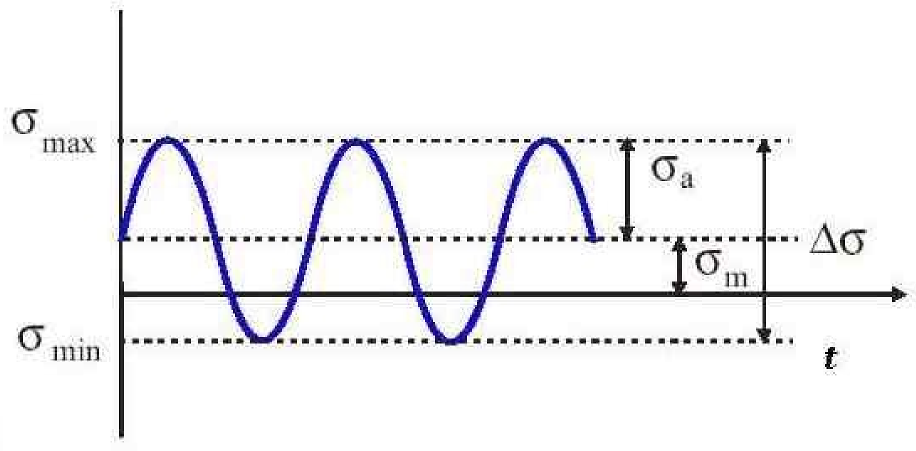
The basic process of fatigue





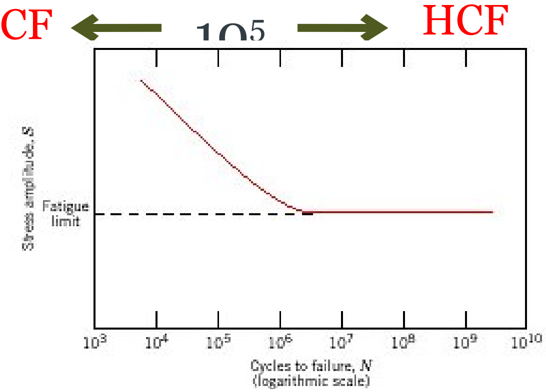
- INITIATION
  - Cracks can initiate on a perfectly smooth surface via slipband formation
  - Usually a microscopic defect already exists (cracked inclusion, pore etc)
  - Often a mesoscopic flaw exists: scratch, dent, other stress concentration
- GROWTH
  - How fast does the crack grow? What affects its journey?
- FINAL FAILURE
  - When will the crack reach a critical size to cause catastrophic failure?

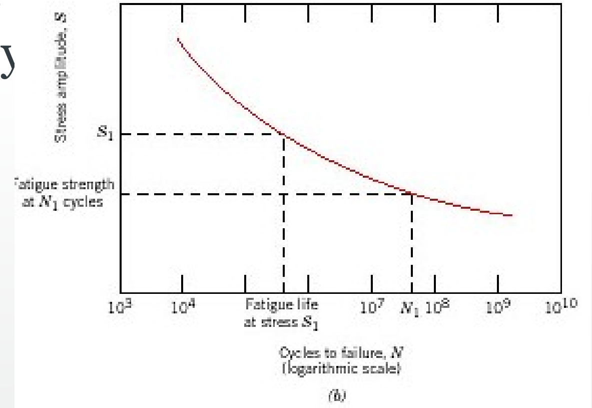
Definitions in fatigue:



Can we describ
these curves
mathematicall

LCF ← 10^5 → HCF





- Stress range $\Delta\sigma$, stress amplitude, σ_a, minimum σ_{min}, mean σ_m and maximum σ_{max} stress
- High cycle fatigue (HCF): $\boxed{\frac{\Delta\sigma}{2} = \sigma_f'(2N_f)^b}$ ← fatigue strength exponent

  Fatigue strength coefficient

  Low σ, elastic deformation
- Low cycle fatigue (LCF): $\boxed{\frac{\Delta\varepsilon_p}{2} = \varepsilon_f'(2N_f)^c}$ ← fatigue ductility exponent

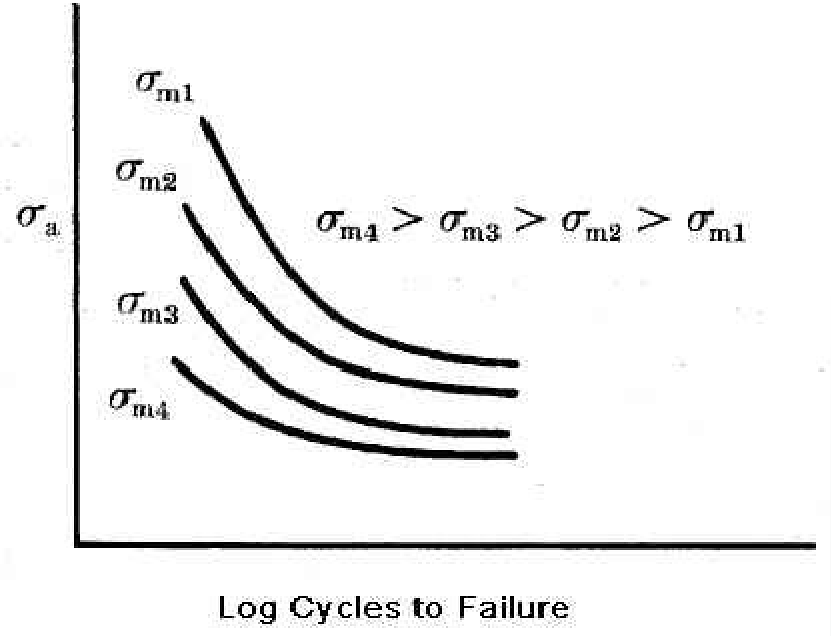
  Fatigue ductility coefficient

  High σ, plastic deformation

Mean stress effects?

As the mean applied stress increases, the stress amplitude to failure (often called the fatigue strength) for a given number of cycles decreases.

$$\sigma_a = \sigma_{a0}\left(1 - \frac{\sigma_m}{\sigma_{ts}}\right)$$



Goodman equation, assumes a linear relationship between σ_a and σ_m: where σ_{ao} = fatigue strength when $\sigma_m = 0$ and when $\sigma_a = 0$, $\sigma_m = \sigma_{ts}$ (the tensile strength)

Miner’s Rule

Miners Law of Cumulative damage

In service a component is subjected to a range of different stress or strain cycles (varying conditions). Miners Law takes this into account.

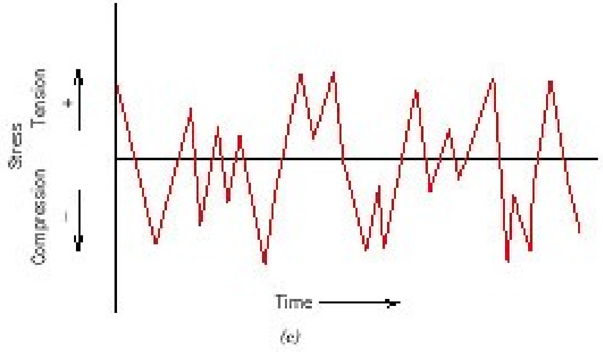
Under each set of conditions a fraction of life is expended. When the sum of the life fractions = 1 then failure occurs.

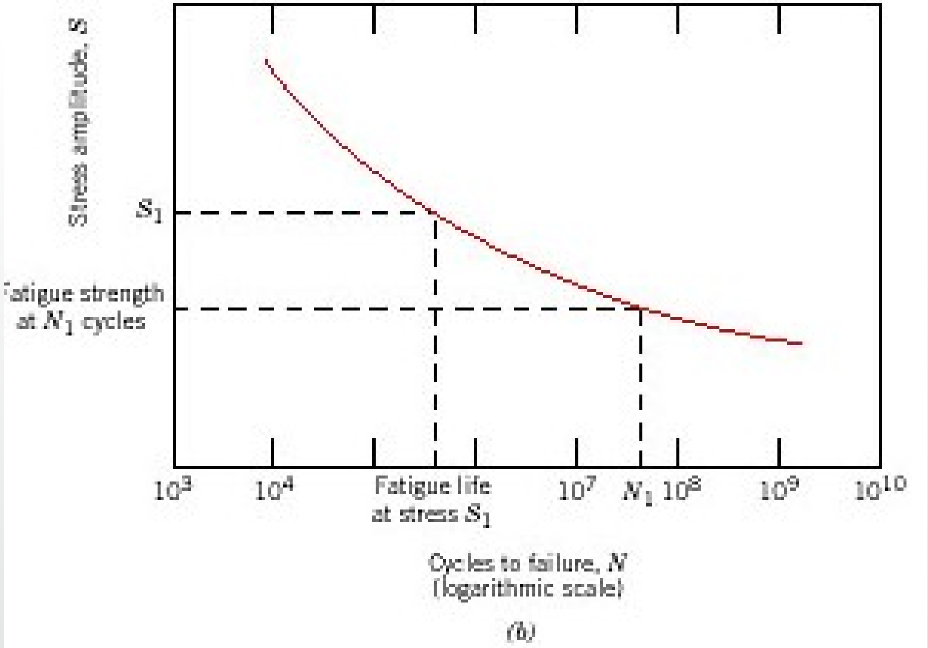
If life at condition 1 is N_1 and n_1 cycles experienced then

Life fraction experienced = n_1/N_1

For condition 2, = n_2/N_2

etc……..Failure occurs when sum of life fractions = 1





$$\Sigma\, n_i/N_i = 1$$

Total life versus damage tolerant approaches

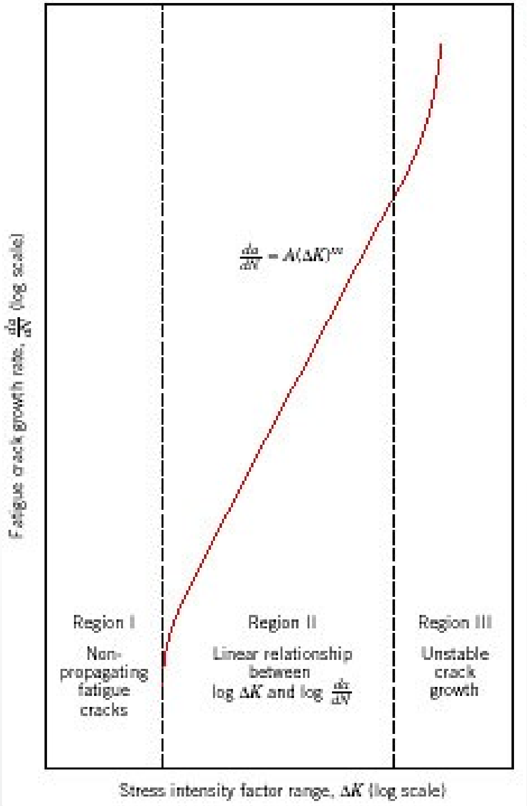
- Total life approaches, (e.g. using Miner's Rule) effectively use the equations describing S-N curves (in terms of stress, HCF, or strain, LCF)
  - This predicts total life : which is no. of cycles to initiate crack growth from pre-existing defects (N_i) AND no. of cycles to grow from initiation feature to critical crack length, N_g (when fast failure occurs)
  - Life is VERY dependent on initiation stage (e.g. S-N curves critically depend on surface finish)
  - If you use total life approach you will basically design against initiation rather than growth
- Damage tolerant approach can allow for the (almost inevitable) presence of defects

Crack growth behaviour

Paris Law: $da/dN = A(\Delta K)^m$

where A is a constant, m is the slope of log-log linear stage 2 and ΔK is the stress intensity range.

Note for ΔK, we assume only tensile portion of cycle is important



- What will we need to calculate fatigue life, N_f cycles at failure, when we have an existing defect?
  - a_i original defect length => good NDT - X-ray, ultrasound, dye penetrant, optical to determine size AND position of a_i
- a_{crit} final crack length (could be critical crack length from fracture toughness equation or a defined length, or point when uncracked ligament yields)
- Stress range ($\Delta\sigma$)
- Paris law constants A and m => known fatigue crack growth behaviour, $da/dN = \text{fn}(\sigma, a)$, as $\Delta K = Q\Delta\sigma\sqrt{\pi a}$

Predicting the lifetime (lab class)

- Lifing by integration:

$$\Delta K = Q\Delta\sigma\sqrt{\pi a}$$

Stress intensity factor range (describes local crack tip stresses)

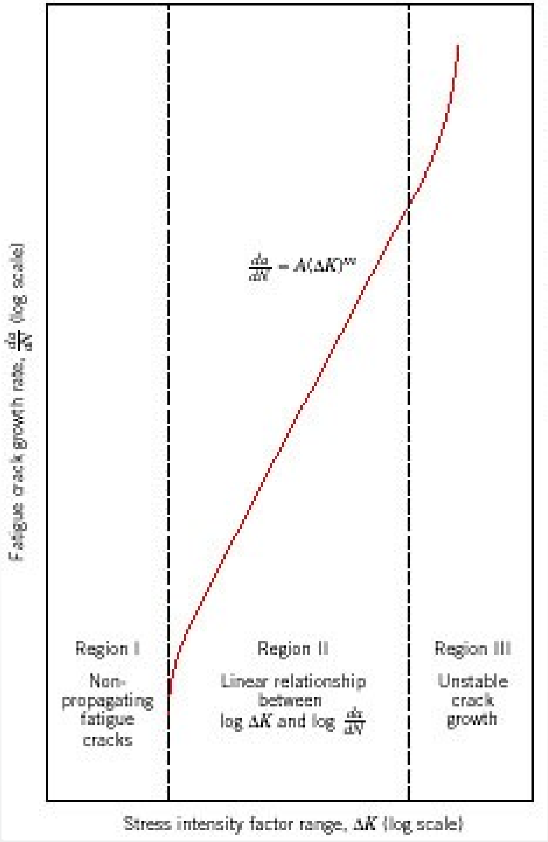
$$\frac{da}{dN} = A\left(\Delta K\right)^m$$

Paris law (describes crack growth)

$$\frac{da}{dN} = A\left(\Delta K\right)^m = A\left(Q\Delta\sigma\sqrt{\pi a}\right)^m$$

$$\int_{a_i}^{a_{crit}} \frac{1}{a^{\frac{m}{2}}} da = \int_0^{N_f} A\left(Q\Delta\sigma\sqrt{\pi}\right)^m dN$$

$$\left[\frac{a^{1-\frac{m}{2}}}{1-\frac{m}{2}}\right] = A\left(Q\Delta\sigma\sqrt{\pi}\right)^m N_f$$



where a_i = initial crack length
a_{crit} = critical crack length (for fast failure of plastic collapse to occur),
N_f = no. of cycles to failure

Predicting the lifetime (lab class)

- Lifing by integration:

$$\Delta K = Q\Delta\sigma\sqrt{\pi a}$$

Stress intensity factor range (describes local crack tip stresses)

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Paris law (describes crack growth)

$$\frac{da}{dN} = A(\Delta K)^m = A\left(Q\Delta\sigma\sqrt{\pi a}\right)^m$$

$$\int_{a_i}^{a_{crit}} \frac{1}{a^{\frac{m}{2}}} da = \int_0^{N_f} A\left(Q\Delta\sigma\sqrt{\pi}\right)^m dN$$

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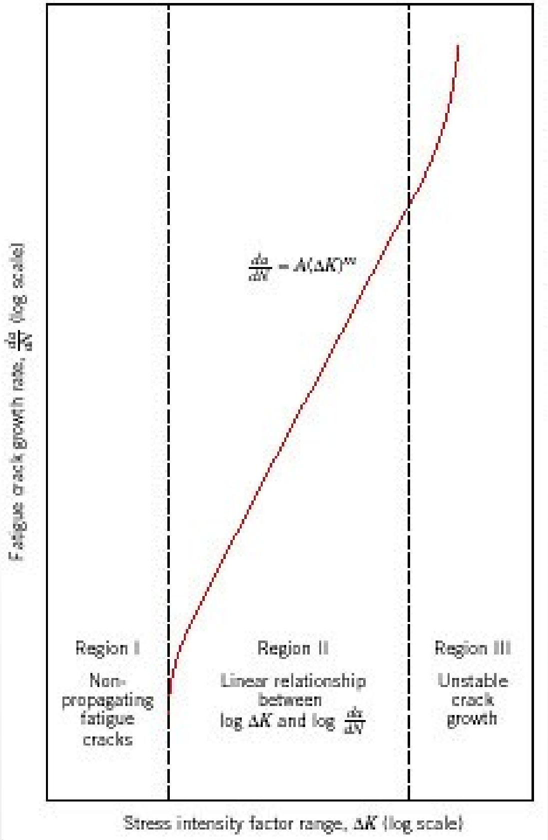

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a_{crit} = critical crack length (for fast failure of plastic collapse to occur),
N_f = no. of cycles to failure

Predicting the lifetime (lab class)

- Lifing by integration:

$$\Delta K = Q\Delta\sigma\sqrt{\pi a}$$

Stress intensity factor range (describes local crack tip stresses)

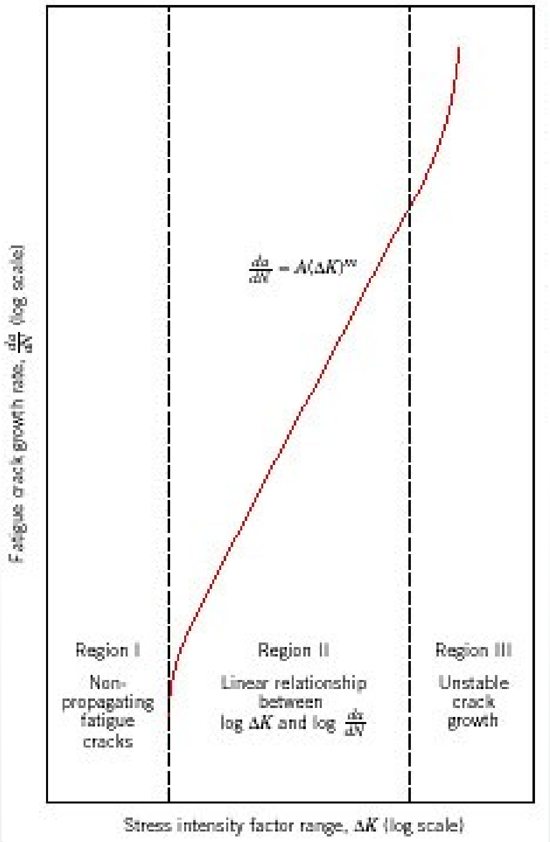
$$\frac{da}{dN} = A(\Delta K)^m$$

Paris law (describes crack growth)

$$\frac{da}{dN} = A(\Delta K)^m = A\left(Q\Delta\sigma\sqrt{\pi a}\right)^m$$

$$\int_{a_i}^{a_{crit}} \frac{1}{a^{\frac{m}{2}}}\,da = \int_0^{N_f} A\left(Q\Delta\sigma\sqrt{\pi}\right)^m dN$$

$$\left[\frac{a^{1-\frac{m}{2}}}{1-\frac{m}{2}}\right] = A\left(Q\Delta\sigma\sqrt{\pi}\right)^m N_f$$



where a_i = initial crack length

a_{crit} = critical crack length (for fast failure of plastic collapse to occur),

N_f = no. of cycles to failure

Predicting the lifetime (lab class)

- Lifing by integration:

$$\Delta K = Q\Delta\sigma\sqrt{\pi a}$$

Stress intensity factor range (describes local crack tip stresses)

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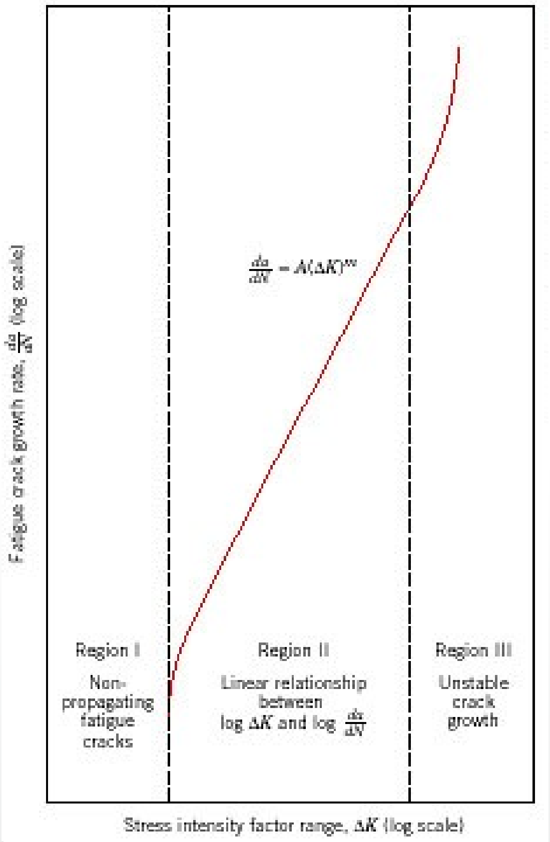
Paris law (describes crack growth)



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$$\int_{a_i}^{a_{crit}} \frac{1}{a^{\frac{m}{2}}}\,da = \int_0^{N_f} A\left(Q\Delta\sigma\sqrt{\pi}\right)^m dN$$

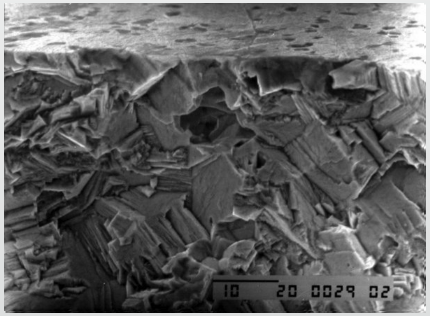
$$\left[\frac{a^{1-\frac{m}{2}}}{1-\frac{m}{2}}\right]_{a_i}^{a_{crit}} = A\left(Q\Delta\sigma\sqrt{\pi}\right)^m N_f$$

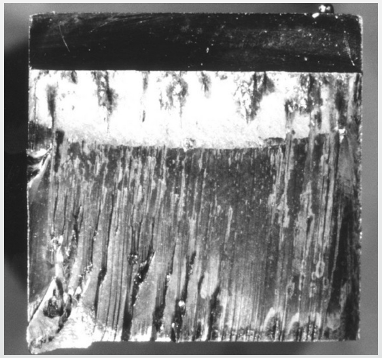
where a_i = initial crack length
a_{crit} = critical crack length (for fast failure of plastic collapse to occur),
N_f = no. of cycles to failure

Anomalous crack growth….

- But does the fatigue crack always grow at 90° to the maximum opening stress?
- If the crack is propagating in Stage II mode (Paris regime) then usually yes
- When does it grow under shear ? Stage I crack growth behaviour, usually very early stages of crack growth

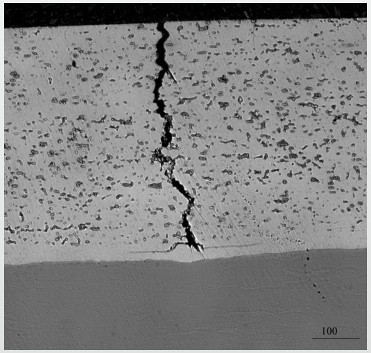
Crack initiation/early growth
in turbine disc alloy.
Pore initiation
Faceted Stage I crack growth





Fracture surface of a
single crystal turbine alloy

Crack growing across
very different materials.
Soft:hard. Crack deflects

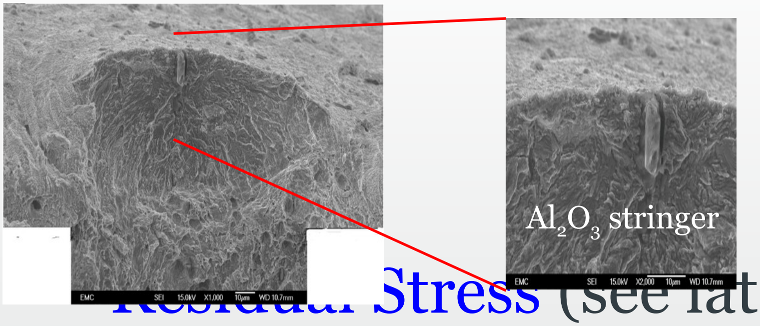


Plain journal bearing

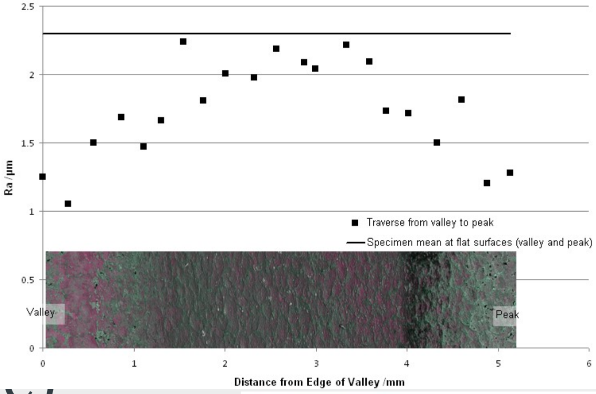
Crack deflection at moderate
T in turbine disc alloy. Why?

Reducing fatigue

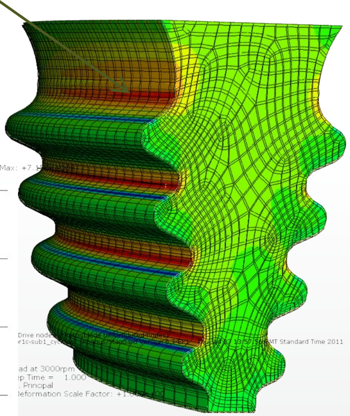
- Fatigue strength is affected by 5 main factors
- Macroscopic stress concentrations ("hot spot" stresses)
- Microscopic stress concentrations
  - Surface roughness
  - Defects



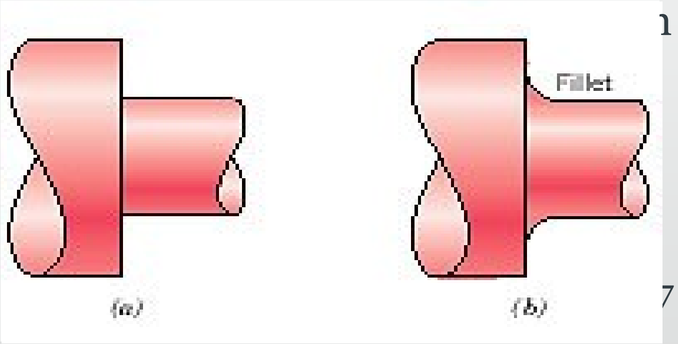
- Residual Stress (see later slide)



Steam turbine blade root



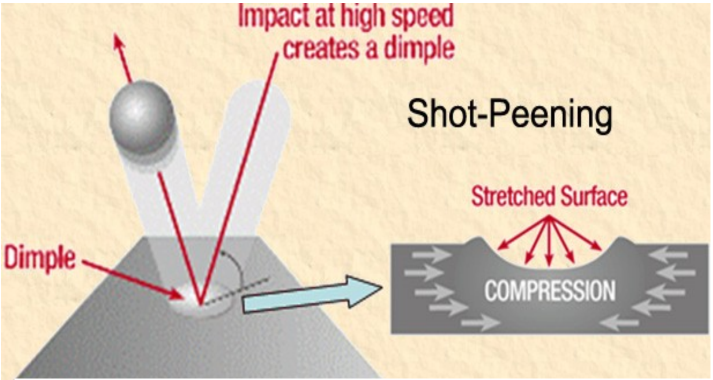
Use fillets to minimise stress

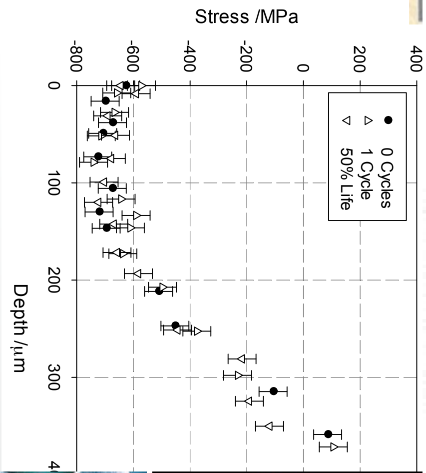


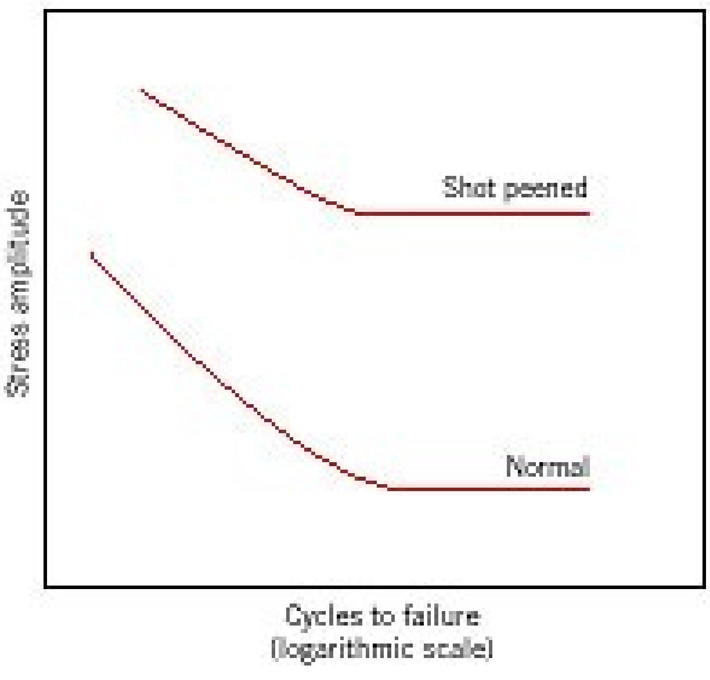
- Environment (see later slide)

Shot peening

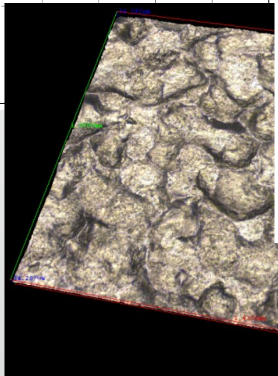
- Compressive (surface) residual stress
- Increased surface roughness
- Work hardened surface layer
- Residual stress
  - Affects σ_{mean}
  - HCF benefit
- Harder surface





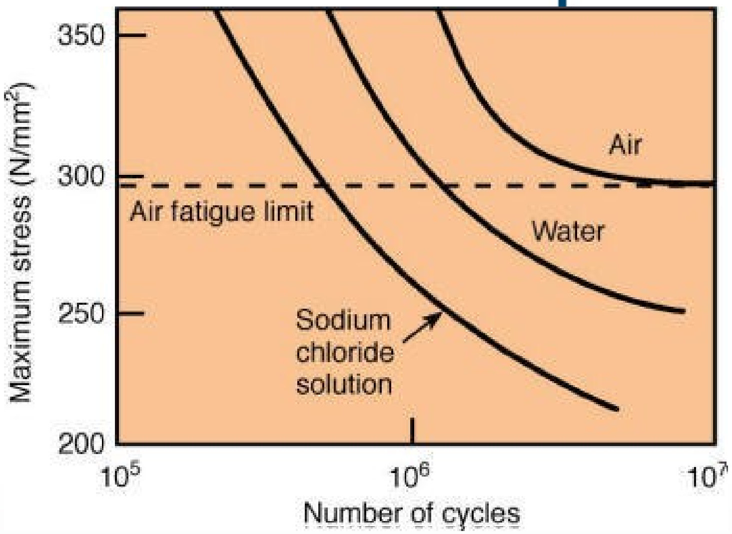


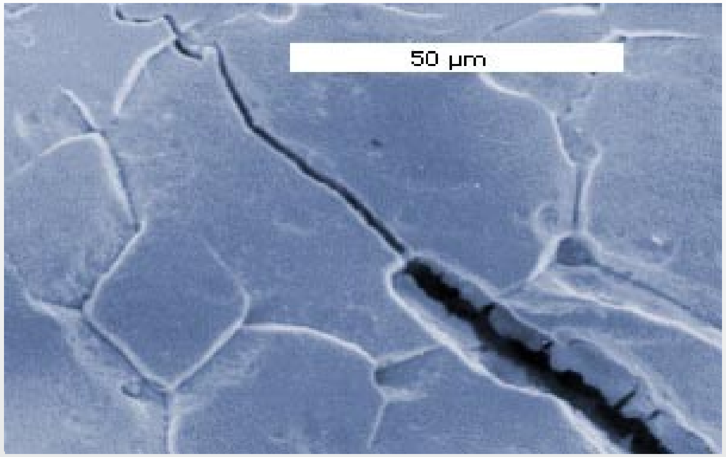
Applied to stress concentration features

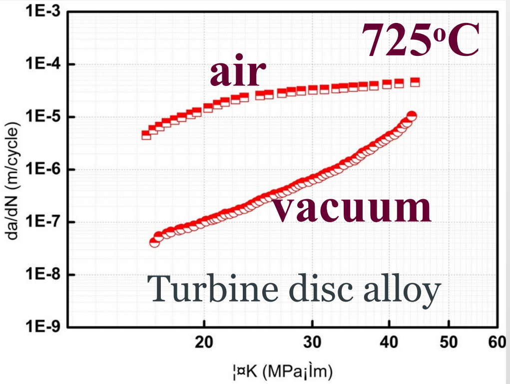


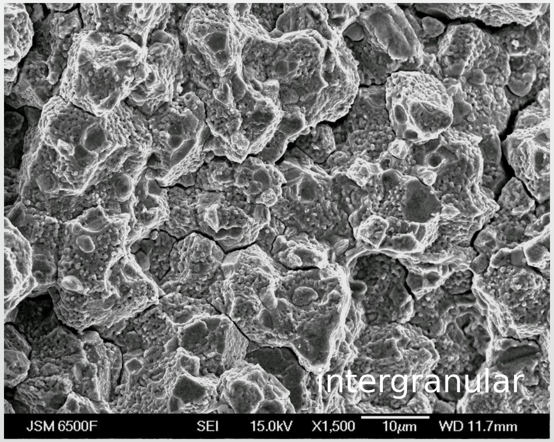
Synergistic effects (environment)

- Environment can severely affect fatigue limit
- Implies *initiation* is affected
    - Pit formation
    - Preferential attack of certain parts of the microstructure
- *Crack growth rate* can also be greatly increased
    - Oxidation at high temperatures (g.b. attack)





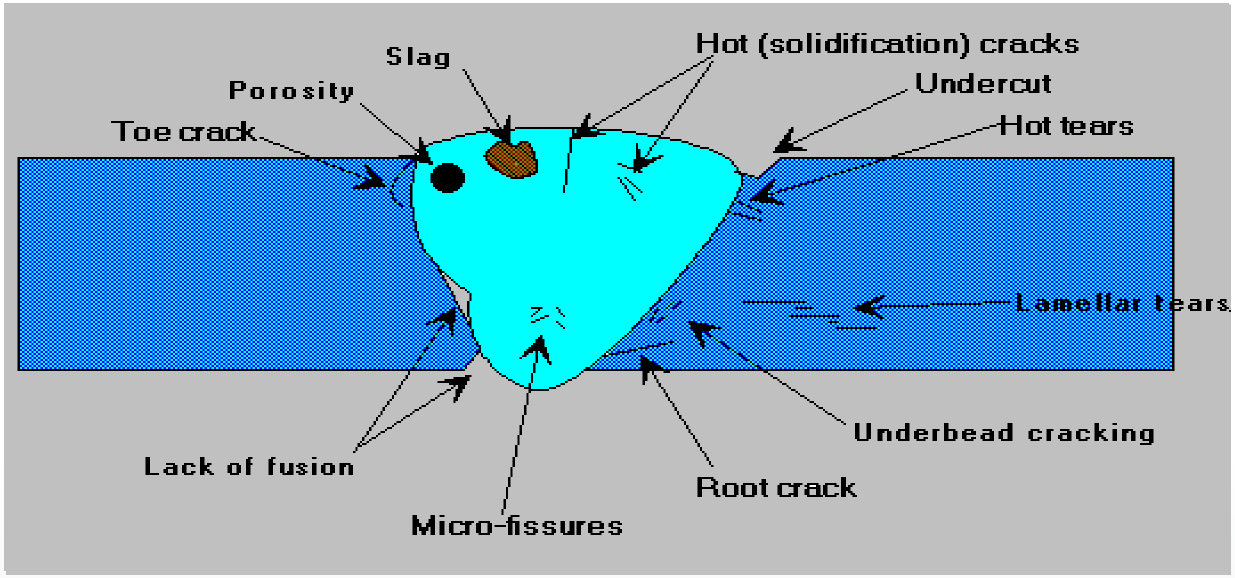




Check out what we do at Southampton: http://www.southampton.ac.uk/engineering/research/themes/materials_and_surface_engineering/structural_materials.page

Consider a weld

- Do we expect a weld to be good at resisting fatigue?



- Are there macro/mesoscopic stress raisers?
- How about microscopic defects?
- The rapid heating and cooling has 2 main effects
    - Alters microstructure in and around the weld, so mechanical properties vary across the weld
    - Results in detrimental TENSILE residual stresses

Lecture 3 : Structural performance 3

- In this lecture we will consider
    - Some electrochemistry (to understand corrosion)
    - Electrode potentials and the galvanic series
    - Polarisation and passivation
    - Types of corrosion (general and localised)

Corrosion - introduction

Materials deteriorate in service as a result of dry oxidation and wet corrosion.

Corrosion results in a change in surface properties and loss of mechanical properties.

Billions of £/annum are spent in the UK on corrosion issues.

We need to revisit some electrochemistry

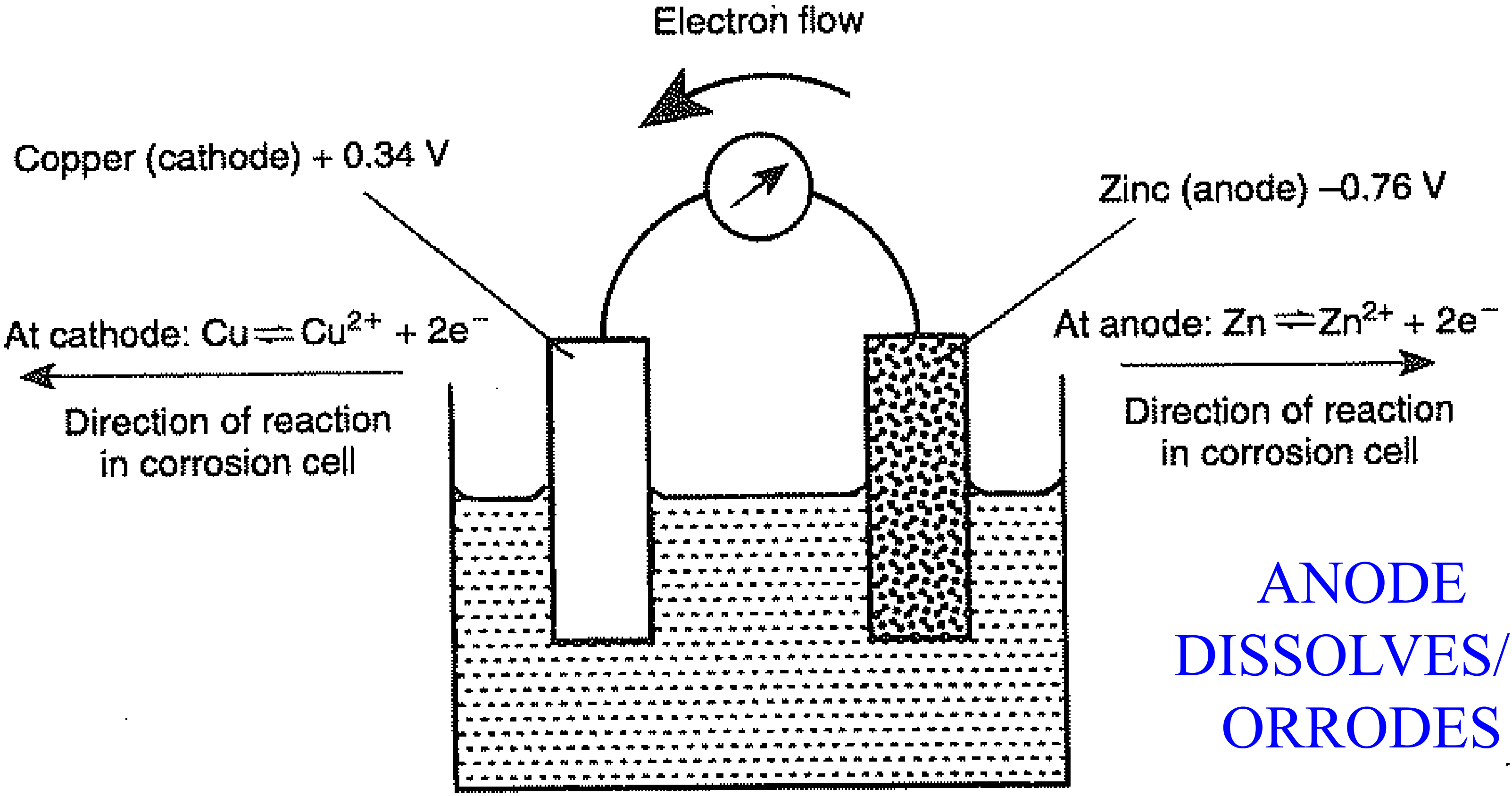


Figure 5.9 *Galvanic cell between copper and zinc*

ANODE DISSOLVES/CORRODES

Corrosion or Galvanic cell

Wet corrosion: electrochemical cells

- Electrochemical considerations: two half reactions

Anode: $M \rightarrow M^{n+} + ne^-$

metal lost

e.g. $Fe \rightarrow Fe^{2+} + 2e^-$

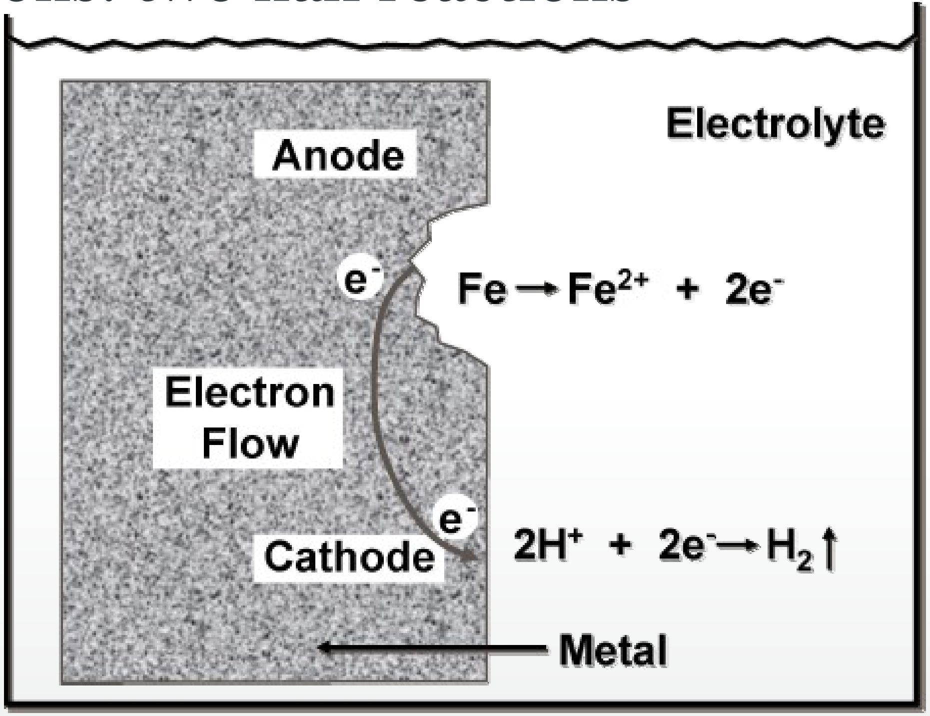
Cathode: (depends upon the environment):

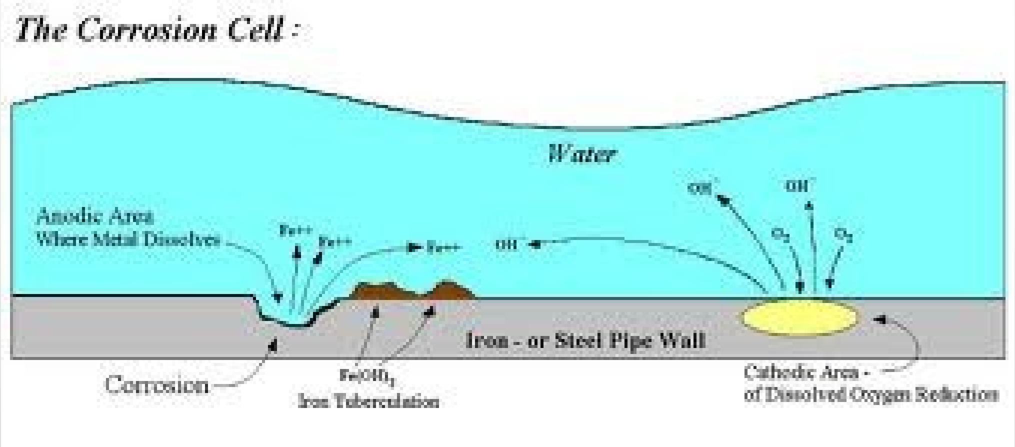
Acid

$H^+ + e^- \rightarrow H$

Neutral/basic

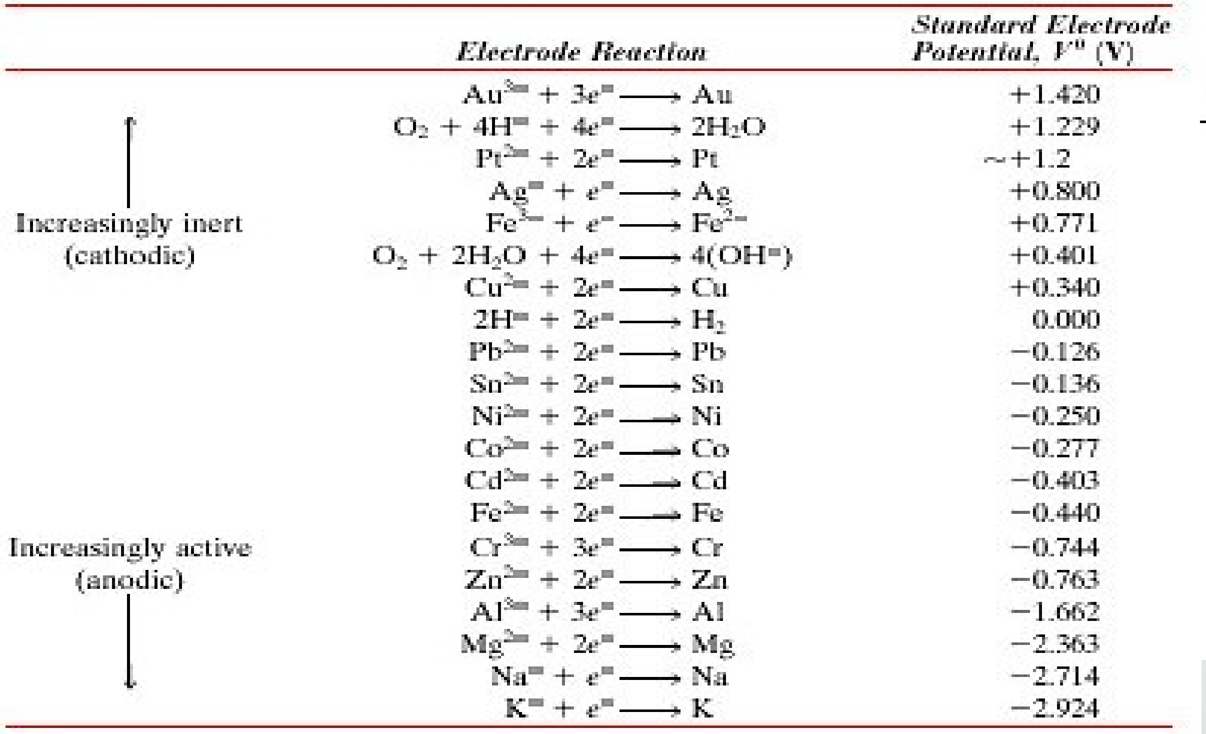
$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$



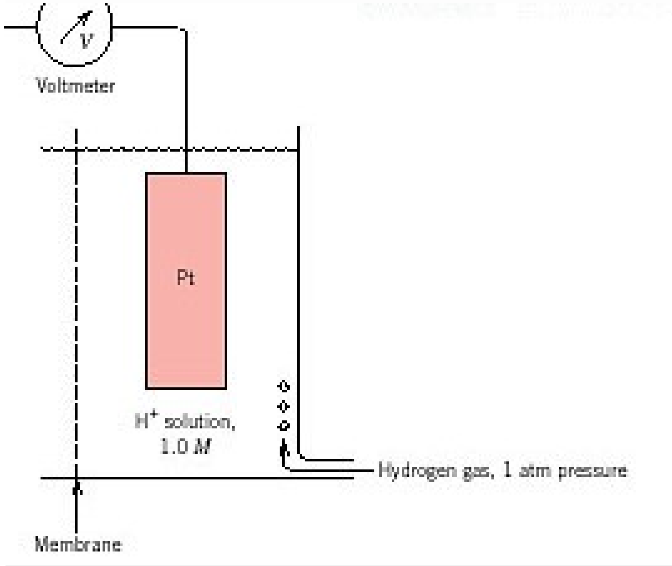


Electrode potentials: driving force

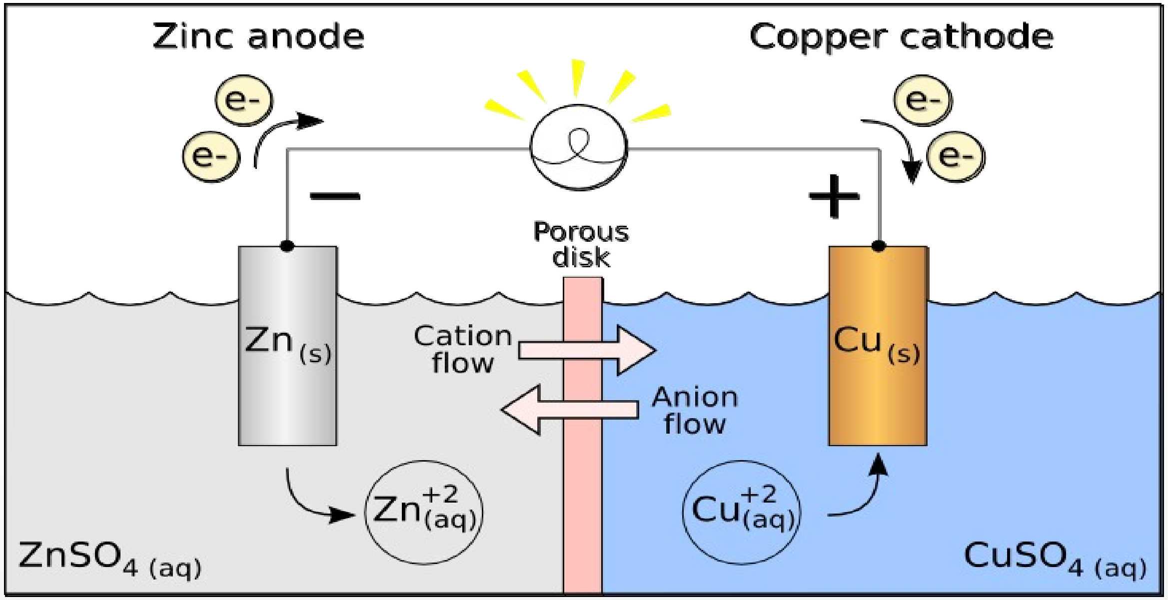
- In the same environment different elements oxidise at different rates. The standard electrode half cell potential gives us a measure of reactivity.



	Electrode Reaction	*Standard Electrode Potential, V^0 (V)*
	$Au^{3+} + 3e^- \longrightarrow Au$	+1.420
	$O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O$	+1.229
	$Pt^{2+} + 2e^- \longrightarrow Pt$	~+1.2
	$Ag^+ + e^- \longrightarrow Ag$	+0.800
↑ Increasingly inert (cathodic)	$Fe^{3+} + e^- \longrightarrow Fe^{2+}$	+0.771
	$O_2 + 2H_2O + 4e^- \longrightarrow 4(OH^-)$	+0.401
	$Cu^{2+} + 2e^- \longrightarrow Cu$	+0.340
	$2H^+ + 2e^- \longrightarrow H_2$	0.000
	$Pb^{2+} + 2e^- \longrightarrow Pb$	−0.126
	$Sn^{2+} + 2e^- \longrightarrow Sn$	−0.136
	$Ni^{2+} + 2e^- \longrightarrow Ni$	−0.250
	$Co^{2+} + 2e^- \longrightarrow Co$	−0.277
	$Cd^{2+} + 2e^- \longrightarrow Cd$	−0.403
	$Fe^{2+} + 2e^- \longrightarrow Fe$	−0.440
Increasingly active (anodic) ↓	$Cr^{3+} + 3e^- \longrightarrow Cr$	−0.744
	$Zn^{2+} + 2e^- \longrightarrow Zn$	−0.763
	$Al^{3+} + 3e^- \longrightarrow Al$	−1.662
	$Mg^{2+} + 2e^- \longrightarrow Mg$	−2.363
	$Na^+ + e^- \longrightarrow Na$	−2.714
	$K^+ + e^- \longrightarrow K$	−2.924



Example of standard electrode potential



Consider the Zn-Cu cell

Cell potential is most negative minus the least negative

$Zn^{2+} + 2e^- \rightarrow Zn$ -0.76V

$Cu^{2+} + 2e^- \rightarrow Cu$ +0.34V

Cell potential is -0.76 -(+0.34) = -1.1 V

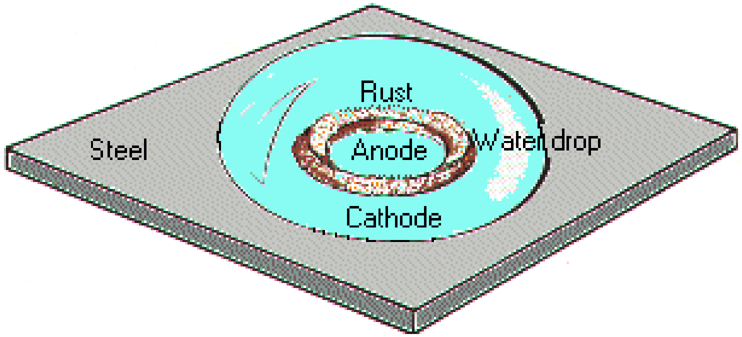
Effect of electrolyte concentration

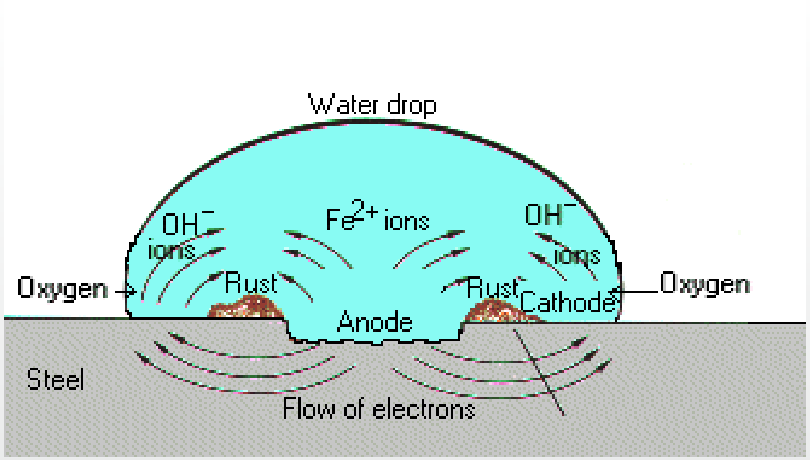
- This is given by the Nernst equation:

- $E = E_o - (0.592/n)\log C_{ion}$

  (n is the number of electrons transferred and C_{ion} is molar concentration)

- Gives rise to concentration cells





Corrosion rates

- Faradays Law
  - Weight dissolving = $k\,I\,t$

(where I = current, t = time, k=constant)

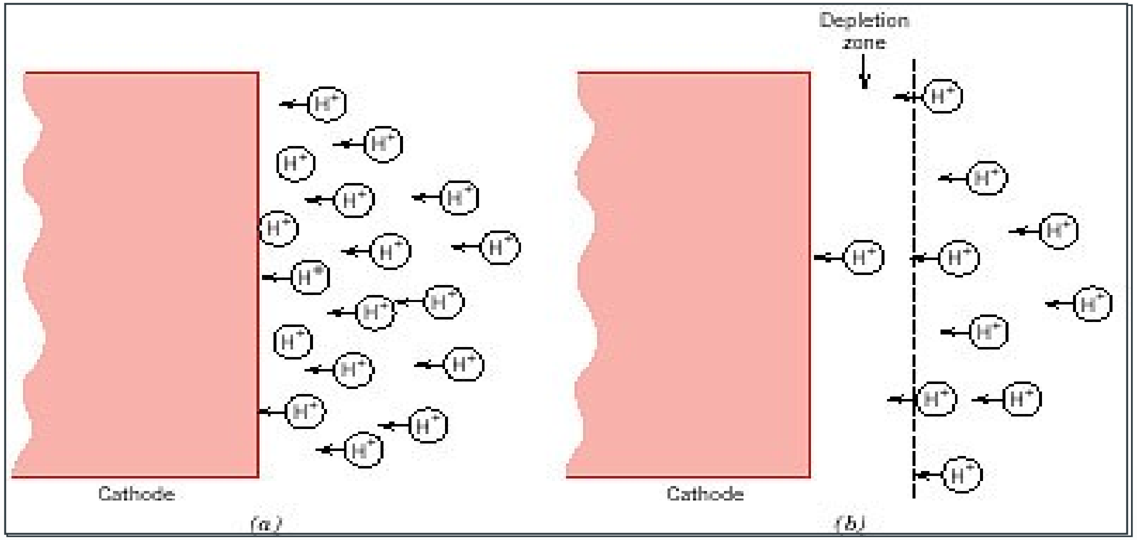
Rate (mass dissolved per unit area per second) = $k\,I/A$

Where A = area

=> Rate proportional to current density

- This is a general corrosion rate
  - BUT we need to consider polarisation and passivation effects

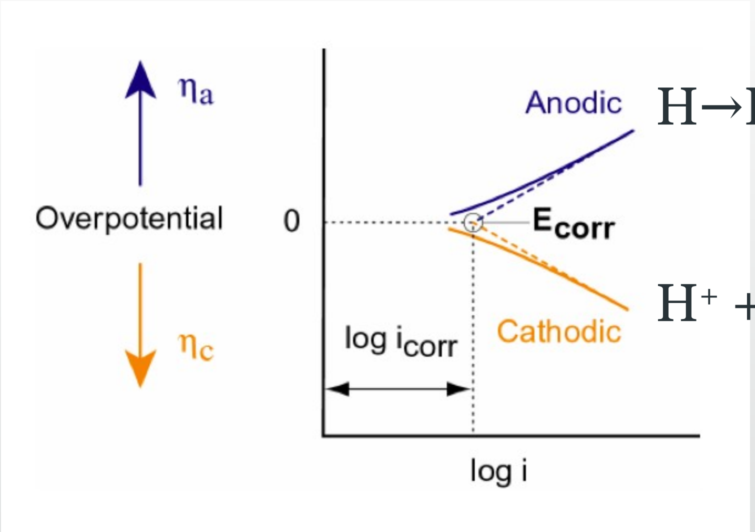
Polarisation 1



Ions move and electrons flow in the electrochemical cell

Depletion zone forms, this affects the electrode potential (i.e. cathode becomes more negative)

- Each half reaction can be anodic or cathodic
- Polarisation makes anodic reaction more positive and cathodic reaction more negative

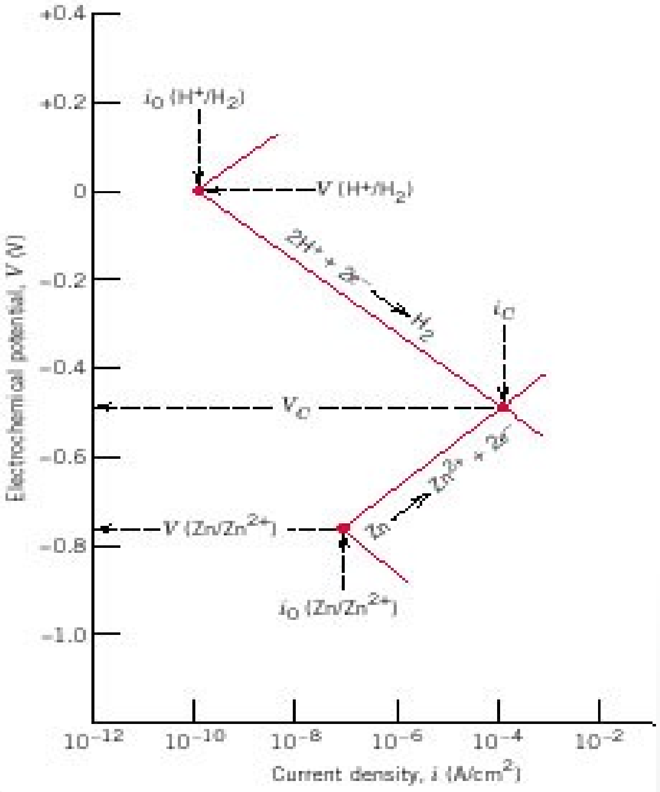


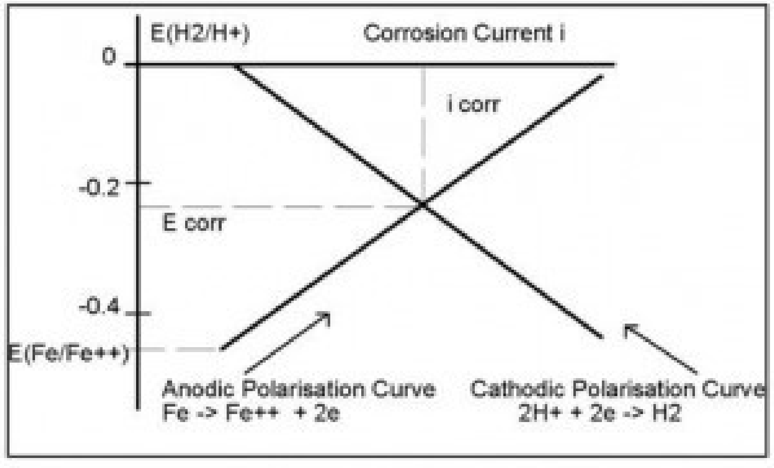
$H \rightarrow H^+ + e^-$

$H^+ + e^- \rightarrow H$

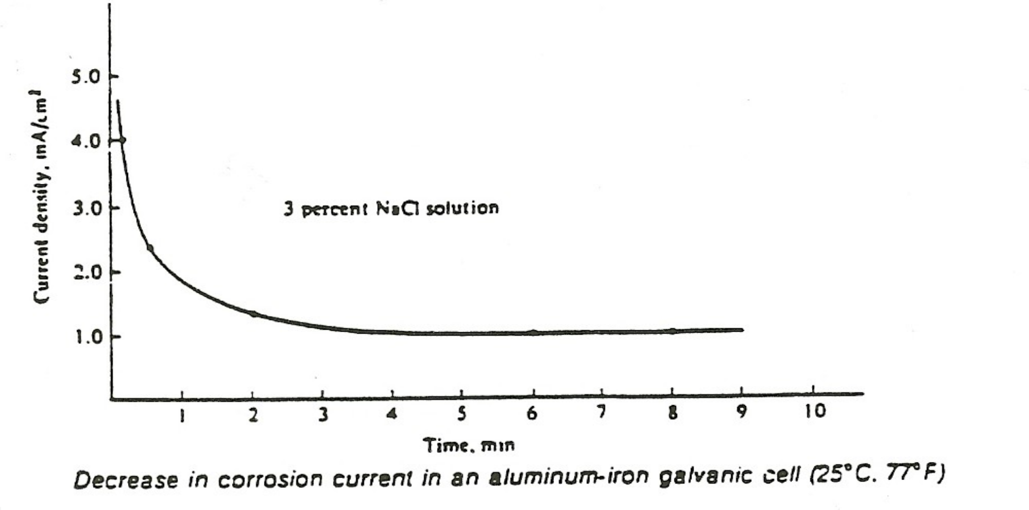
Polarisation 2

- Initial electrode potential defines the starting point of the two possible half reactions
- Polarisation results in E changing for anodic and cathodic curves
- Point where anodic and cathodic curves cross (for 2 different half-reactions) defines the corrosion current and potential
- High i_c = FAST corrosion





Polarisation 3



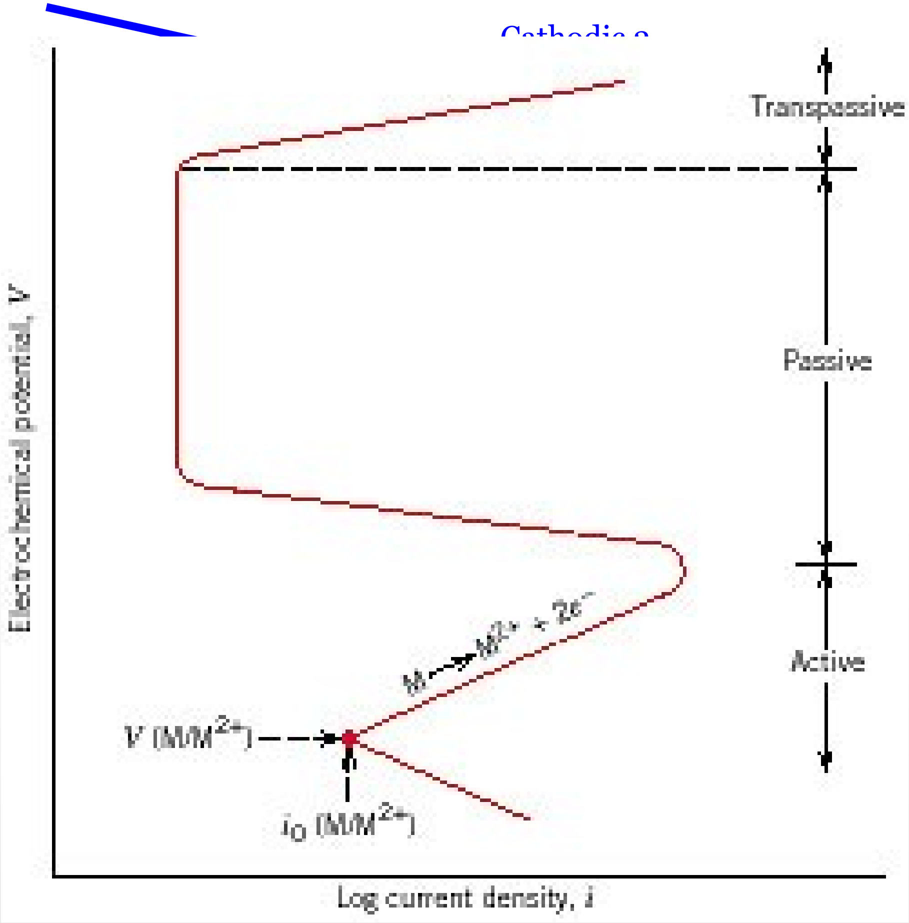
Decrease in corrosion current in an aluminum-iron galvanic cell (25°C, 77°F)

- Polarisation effectively slows down corrosion
- Polarisation is good
- Higher potential (energy) required to keep cell going

Corrosion rate is often determined by availability of species for cathodic reaction

Passivation (stainless steels)

- Under certain circumstances, some metals form a protective (passive) layer on the surface and this inhibits further reaction
- This is normally an oxide
- Whether or not it forms depends on the cathodic reaction and where it intersects the anodic line (consider 3 possible cathodic curves)
- This may be a stable situation, or not!



- In safe conditions, layer is repaired immediately if broken
- In unsafe (reducing) conditions, oxide is not repaired and becomes active

Corrosion types

- Uniform (we've just done)
- But now we need to consider:
  - Galvanic
  - Pitting
  - Crevice
  - Intergranular
  - Cavitation
  - Erosion

- This is an example of uniform/general corrosion
  - Reaction occurs all over the surface
  - Measurable
    - Predict life
    - Preventable

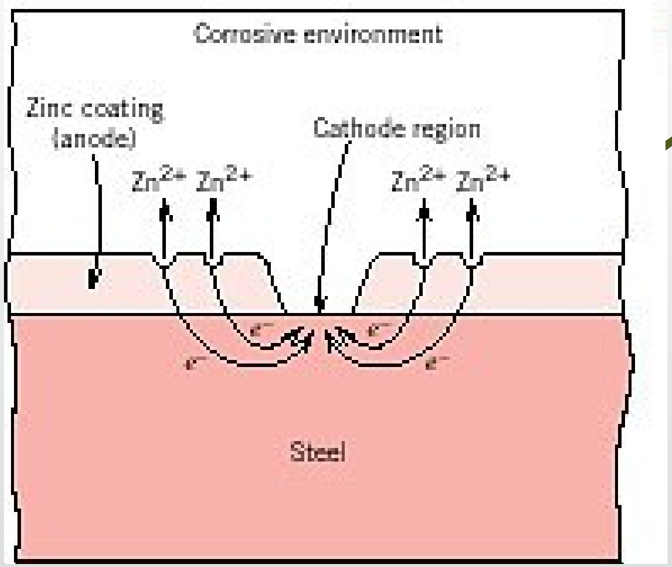
Localised corrosion

- All the other mechanisms are localised. Their corrosion rates can be **100000 x greater** than those of uniform corrosion.

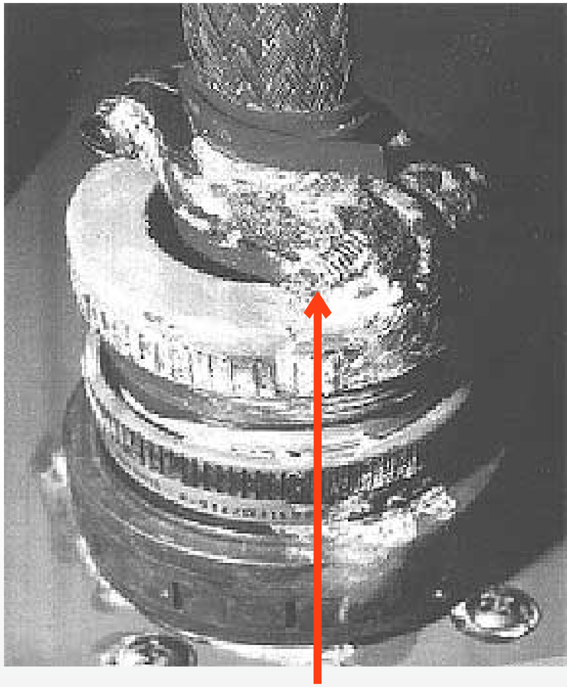
- Key points are;
  - Electrochemical driving force
    - Difference in electrode potentials
  - Sizes of anode and cathode
    - Cathode controls reaction rate
    - Big cathode – big surface area – big reaction rate
    - Large anode - corrosion spread over big area
    - Small anode – concentrated corrosion

Galvanic corrosion (good/bad?)

- Dissimilar metals and electrolyte, generally avoid dissimilar metals in contact, you will promote a corrosion cell!
- Zinc anodic - with respect to steel – corrodes preferentially
- BUT can be used for corrosion protection (sacrificial anode)



We do want this

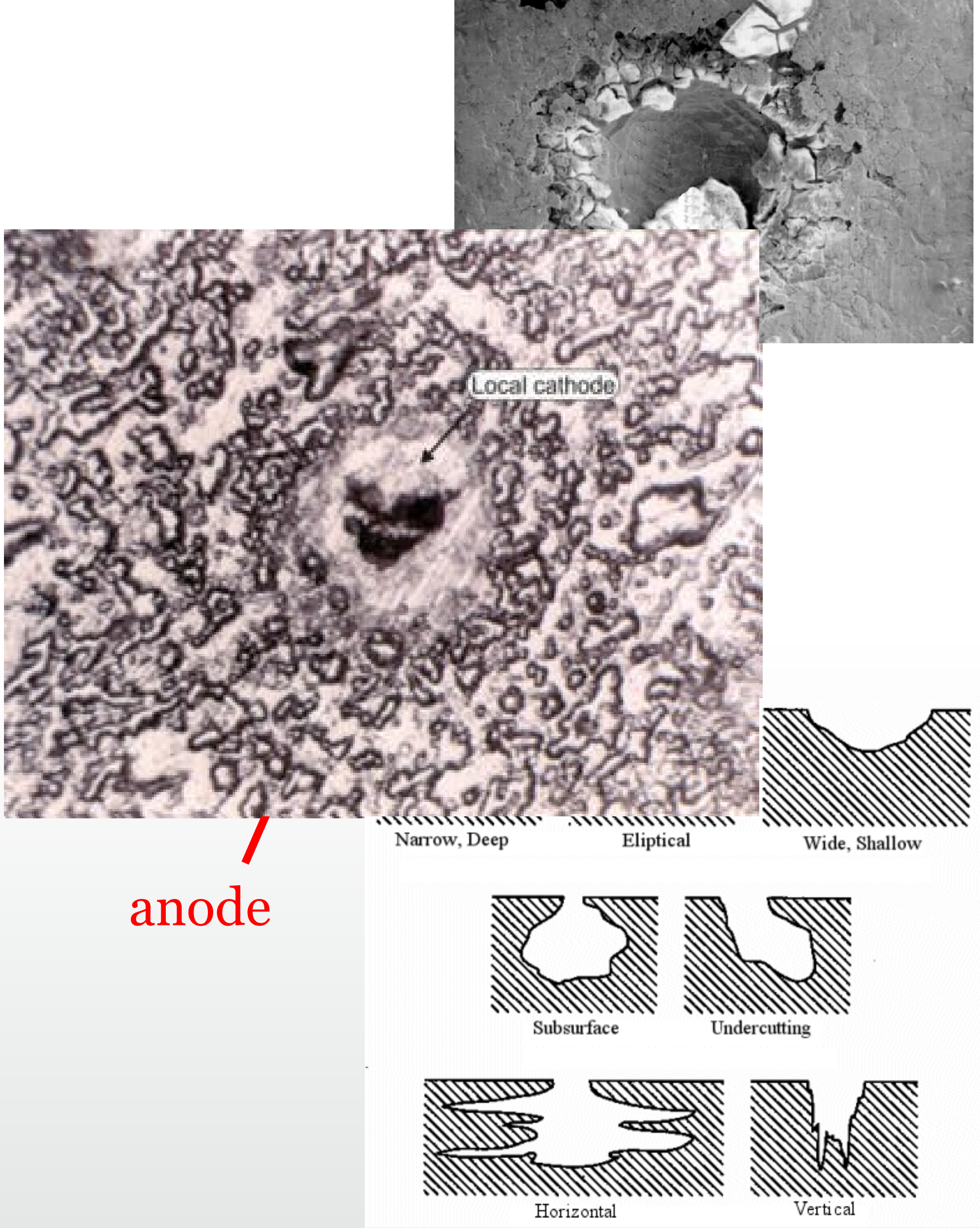


We don’t want this

Even when the coating is removed the steel substrate is still protected as the Zn is the anode and continues to corrode

Pitting

- Locally active (anodic or cathodic) spot on a surface
- $M \rightarrow M^{n+} + ne$
- Cathode surrounds the anode
- $O_2 + 2H_2O + 4e \rightarrow 4OH$
- Big cathode and small anode
  - Very fast dissolution at pit



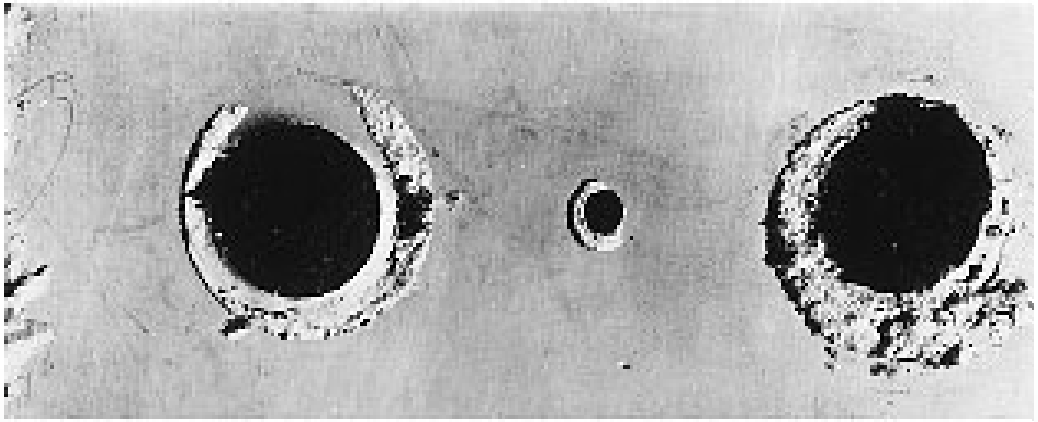
- Why is it an anode?
- This produces a stress concentration feature => fatigue

Lecture 4 : Structural performance 4

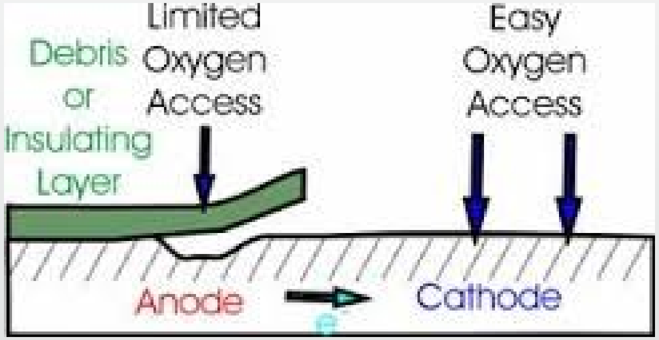
- In this lecture we will
  - Evaluate micromechanisms of local corrosion in more detail
  - Further consider surface properties
  - Wear processes and coating strategies
  - Example exam questions

Crevice corrosion

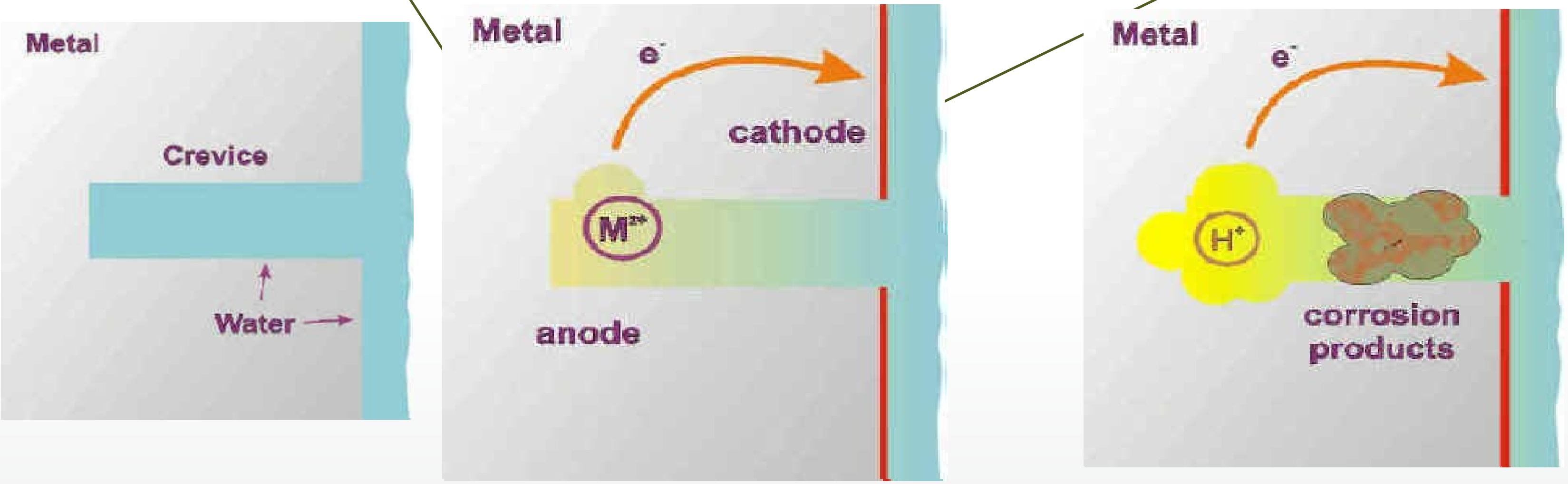
- Localised, rapid, dangerous
- May occur under head of bolt, beneath dirt
- Geometrical feature
- Linked to assembly



Cell driven by difference in oxygen concentration – high at edge, low away from free surface



Crevice corrosion mechanism



Low oxygen

High oxygen, cathode reaction!

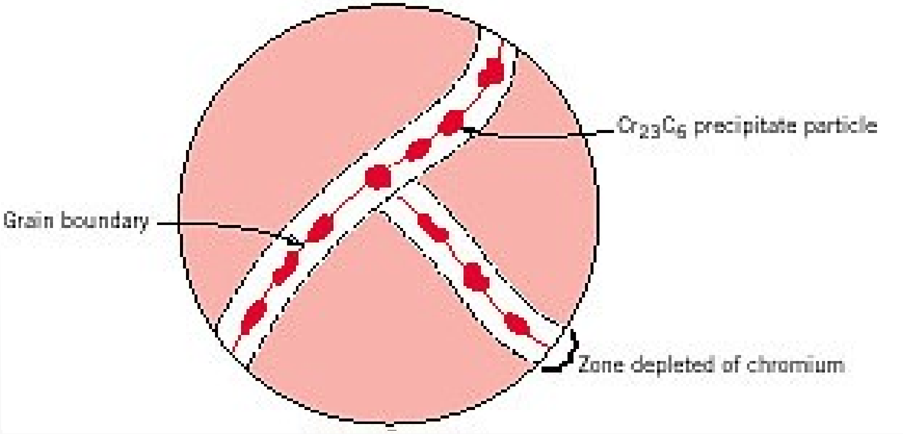
- Initially oxygen distributed uniformly over surface and in gap
- General corrosion uses oxygen in gap - stagnant
- Anode in gap, free surface becomes large cathode
- Rapid corrosion: corrosion products may worsen the situation

Intergranular corrosion

- Preferential attack at grain boundaries
- Eg weld decay in stainless steel
- Cool slowly from high temp, chrome carbides precipitate at grain boundaries - uses up chromium
- Grain boundaries active, centre of grains passive
- Tiny cell, rapid corrosion of anode

3 grains magnified

anode

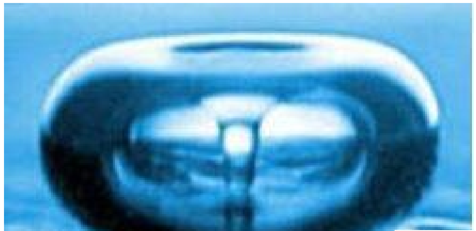


- Stainless steel has >12% Cr – forms chrome rich oxide which protects
- If chromium is removed (forms precipitates) oxide near precipitates is not

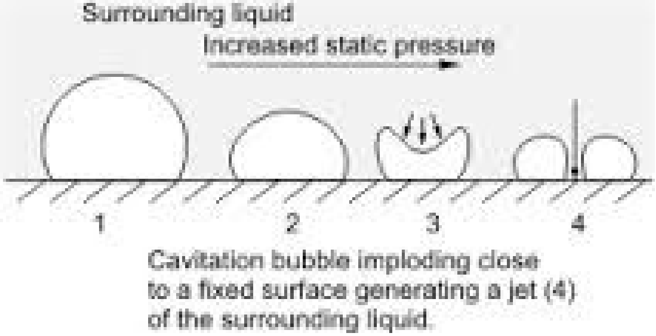
Preventing weld decay

- Cool quickly from high temperature
  - Prevents carbide precipitation and hence chromium depletion
- Reduce carbon content of stainless steel (minimise carbide formation)
- Alloy with an element that is a better carbide former than chromium (leave Cr in solution)

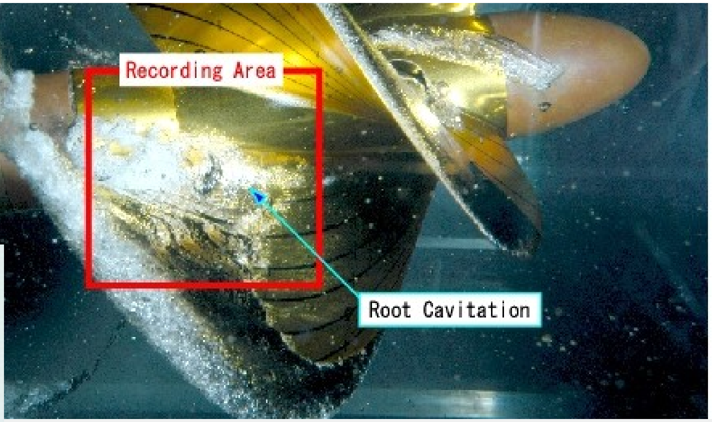
Cavitation



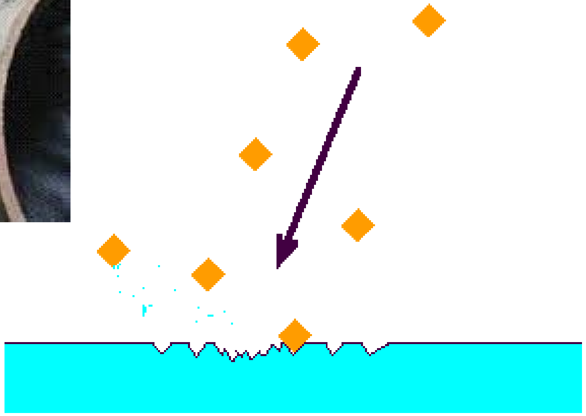
- Collapse of bubbles
- Varying pressure
- Bubbles destroy protective films
- Combined corrosion and fatigue/erosion



Cavitation bubble imploding close to a fixed surface generating a jet (4) of the surrounding liquid.



Erosion

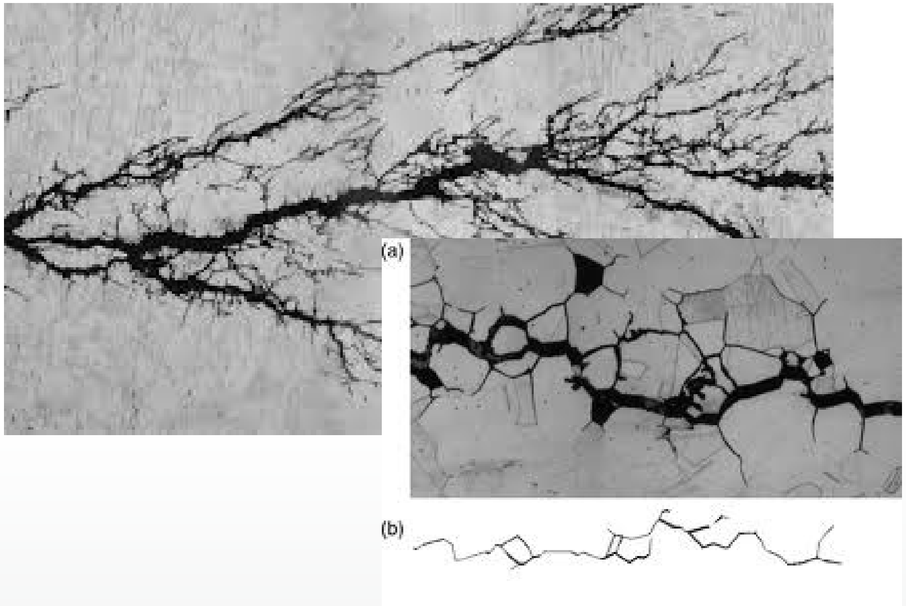


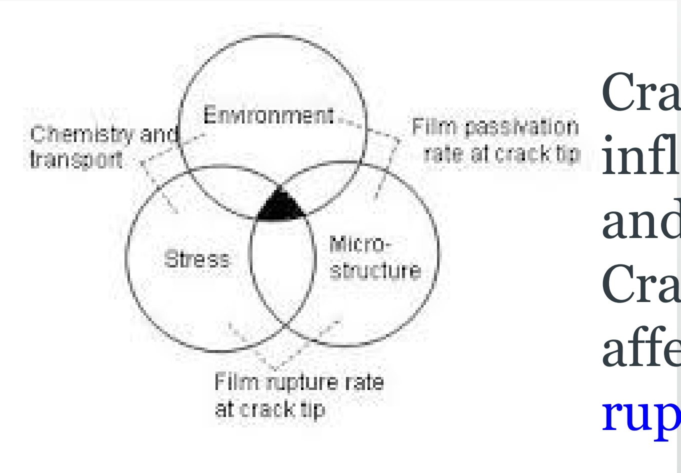
- Flow of particles in liquid or air
- Depends on flow media
- Depends on flow velocity and angle
  - 90o – plastic deformation or brittle failure process
  - Lower angle: abrasion
- Depends on design (piping)
- Combines with corrosion

corrosion-doctors.org

Stress corrosion cracking

- Catastrophic, grain boundary attack
- Little warning, crack grows at stress levels well below (as low as 1%) those predicted from K_{IC} values
- Need combination of specific material and corrosive environment combination and tensile stress
- Can define K_{ISCC} a threshold value (below which SCC doesn't occur)



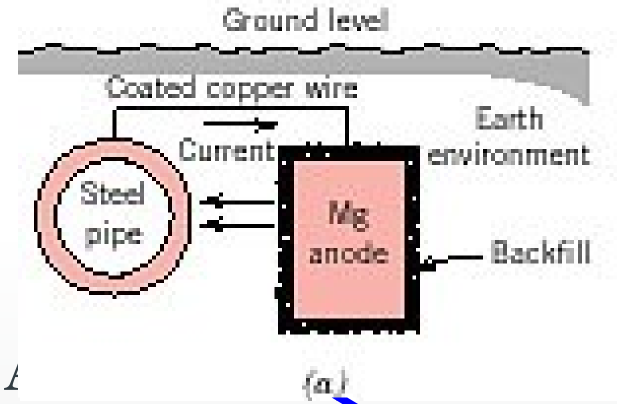


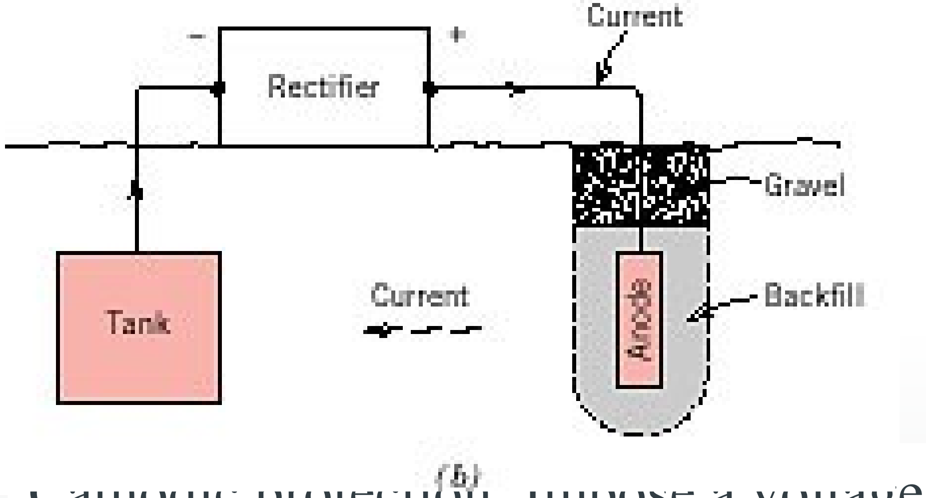
Crack is growing under influence of *local* stress state and chemical conditions

Crack tip chemical state affected by stress state (oxide rupture and reformation)

Corrosion protection

Anode we can afford to lose

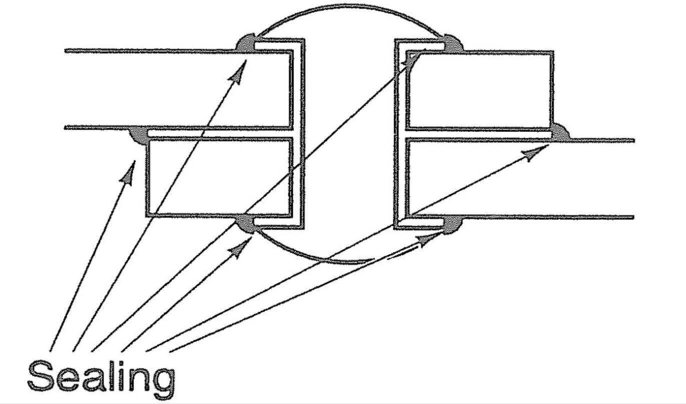




A
protection: Mg is
a sacrificial anode

Cathode – so
won't dissolve

Cathodic protection: impose a voltage to
force the cell



Sealing the system to prevent
corrosion: Oxygen all used up, so only a
little preliminary corrosion

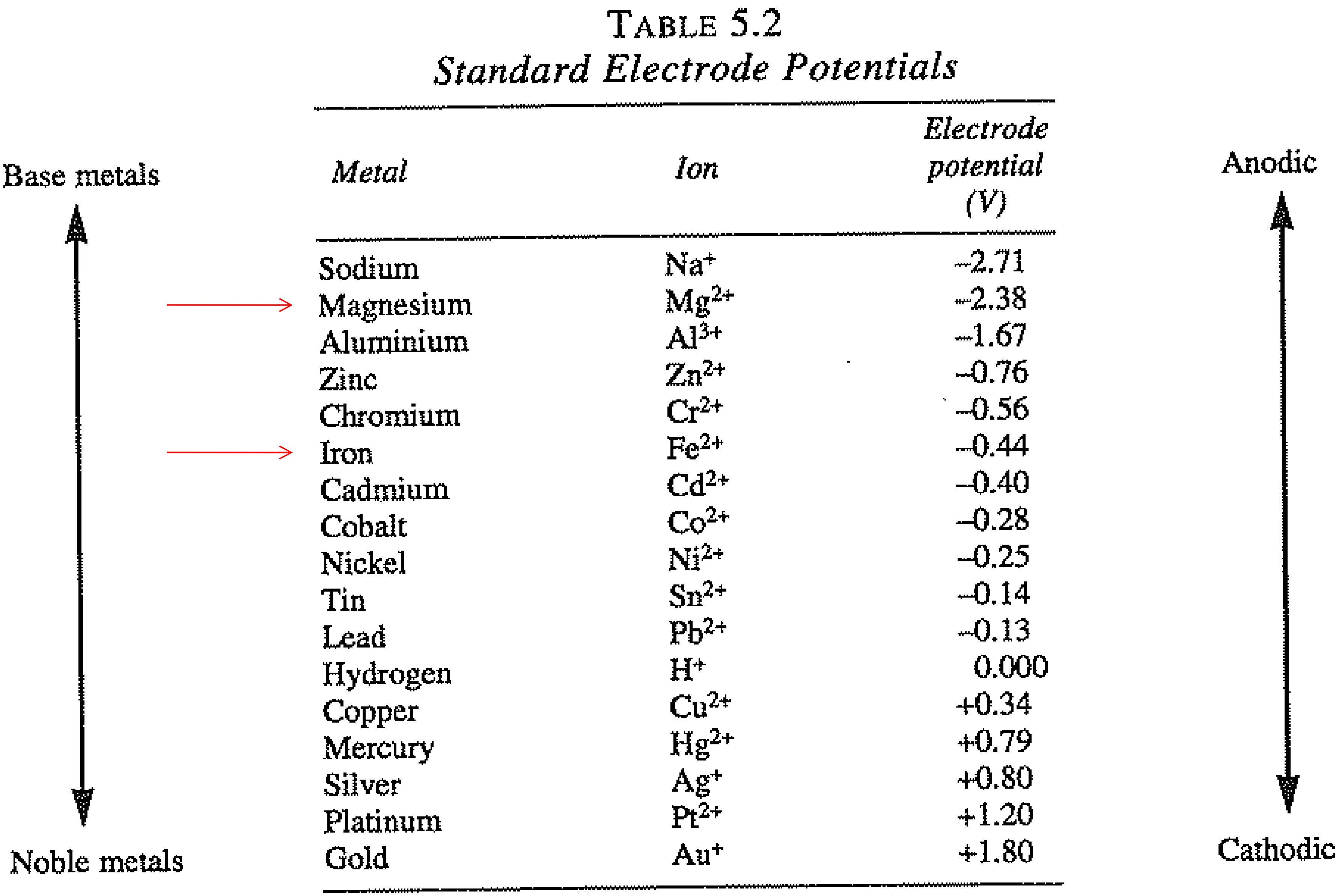


Table 5.2

Standard Electrode Potentials

Metal	*Ion*	*Electrode potential (V)*
Sodium	Na^+	–2.71
Magnesium	Mg^{2+}	–2.38
Aluminium	Al^{3+}	–1.67
Zinc	Zn^{2+}	–0.76
Chromium	Cr^{2+}	–0.56
Iron	Fe^{2+}	–0.44
Cadmium	Cd^{2+}	–0.40
Cobalt	Co^{2+}	–0.28
Nickel	Ni^{2+}	–0.25
Tin	Sn^{2+}	–0.14
Lead	Pb^{2+}	–0.13
Hydrogen	H^+	0.000
Copper	Cu^{2+}	+0.34
Mercury	Hg^{2+}	+0.79
Silver	Ag^+	+0.80
Platinum	Pt^{2+}	+1.20
Gold	Au^+	+1.80

Corrosion prevention

- Think where the anode is, avoid small anodes and large cathodes (corrosion = current)
- Anodes produced by oxygen depletion, galvanic series
- Good detailing
- Avoid sharp edge
- Welded joints preferable to bolted joints (avoid crevices)
- Provide drainage holes and avoid water traps
- Avoid bimetallic corrosion
- Protective coatings – oxides, paints (affect conductivity of electrons)

Corrosion prevention

- Corrosion control
  - Materials selection:
    - Metallic
    - Nonmetallic
  - Coatings:
    - Metallic
    - Inorganic
    - Organic
  - Design:
    - Avoid:
    - Excessive stresses
    - Dissimilar metal contact
    - Crevices
    - Exclude air
  - Cathodic and anodic protection:
  - Environmental control:
    - Temperature
    - Velocity
    - Oxygen
    - Concentration
    - Inhibitors
    - Cleaning

Wear (tribology)

- Failure mechanisms based on surface properties
- Complex loading occurs
- Leads to
  - Loss of fit
  - Fatigue
  - Seizure

Abrasion - hardness

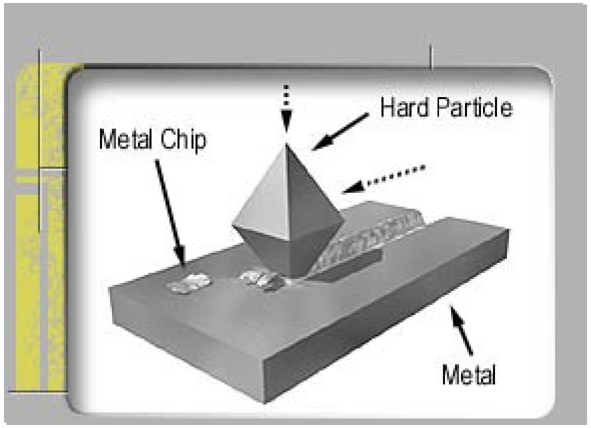
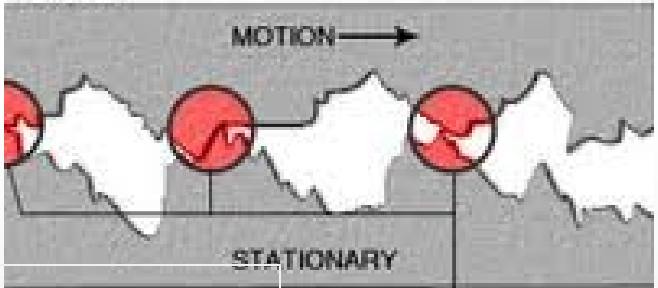
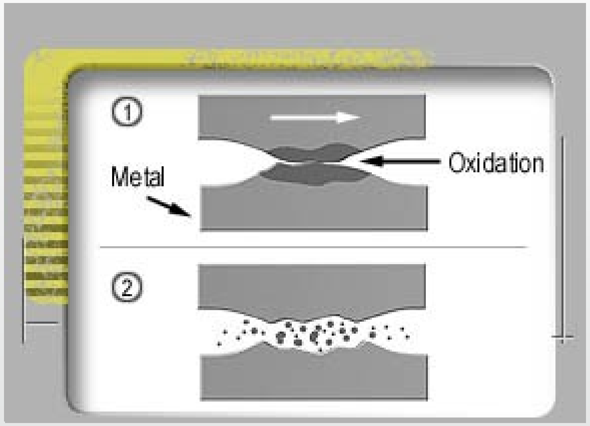


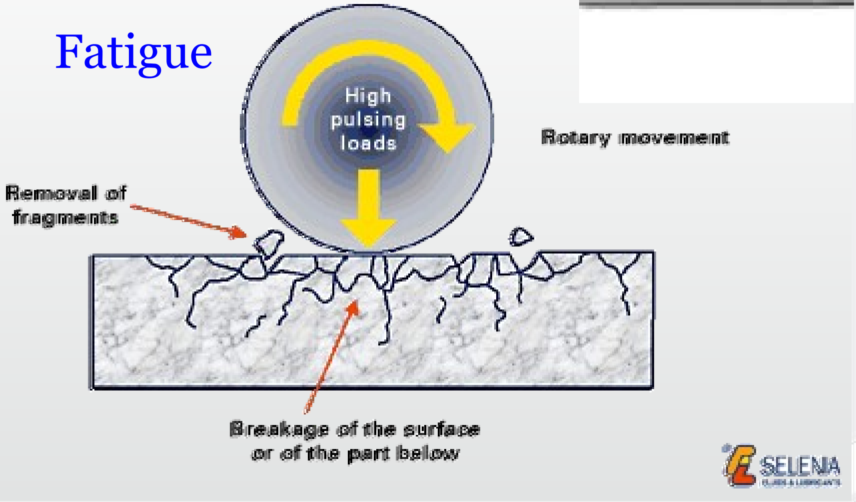
FIGURE 1



Adhesion
Low chemical affinity

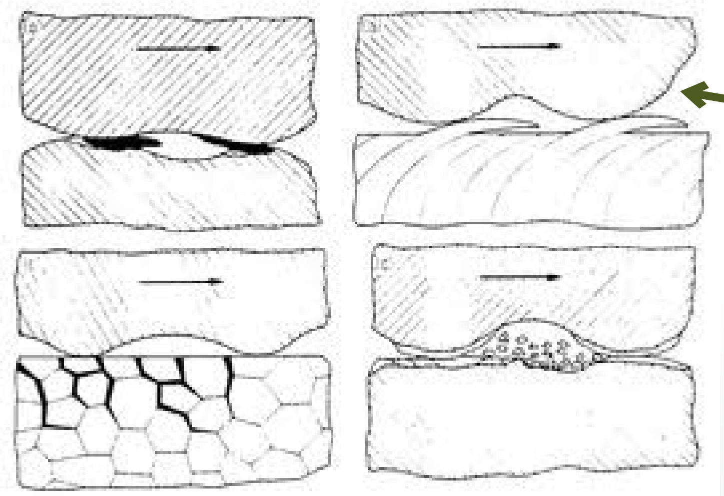


Fatigue

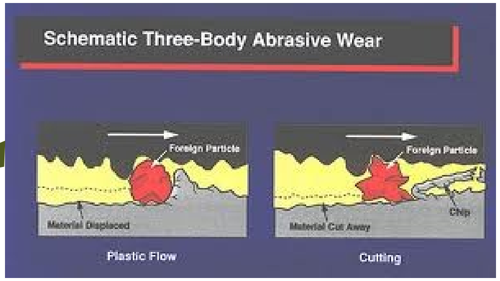


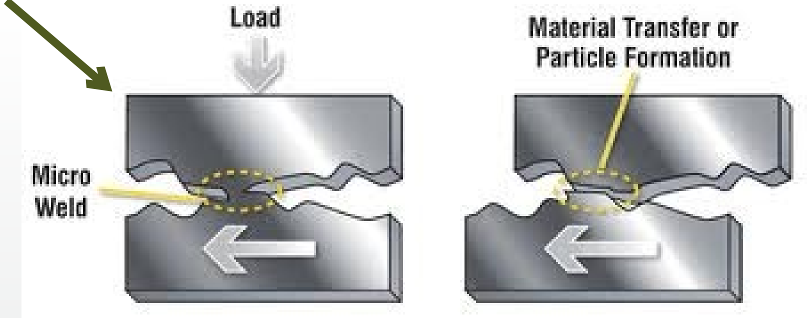
Wear mechanisms

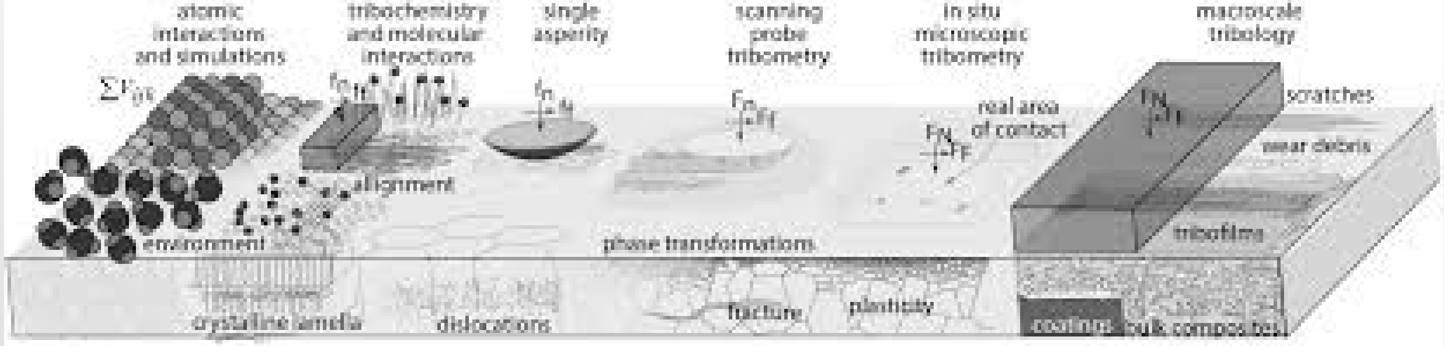
- Consider mechanisms in more detail



Sliding wear
Abrasive wear (2 body and 3 body)
Adhesive wear







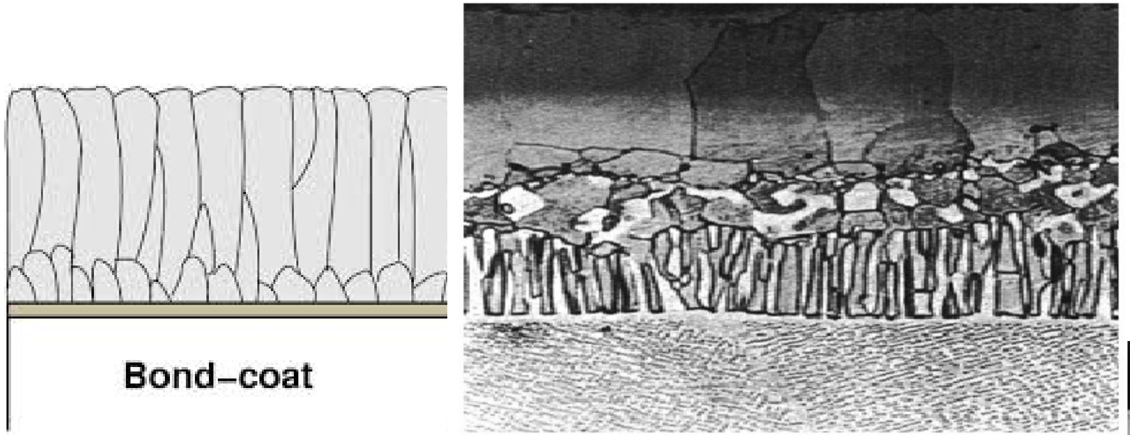
Tribology occurs at various length scales!

Check out what we do at Southampton: http://www.southampton.ac.uk/ncats/overview/

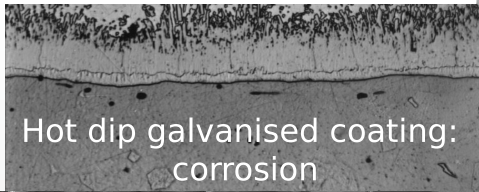
Controlling surface properties

- Surface treatments (reaction produces the coating)
  - Anodising (oxide)
  - Carburising
  - Nitriding

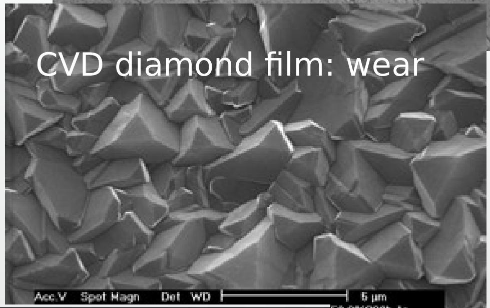
- Coatings
  - Many methods
  - Hot dip
  - Weld deposits
  - Chemical/ electrochemical
  - Chemical and physical vapour deposition



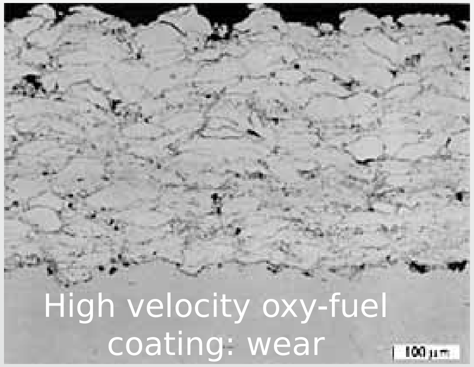
Thermal barrier coating (TBC): Aluminide bond coat (CVD) then thermally grown oxide (TGO) then PVD TBC ceramic coating (turbine blade)



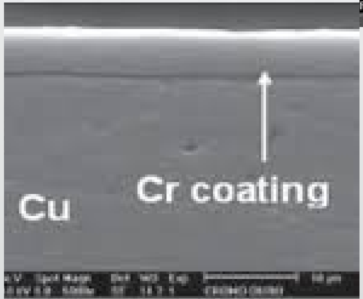
Hot dip galvanised coating: corrosion



CVD diamond film: wear



High velocity oxy-fuel coating: wear



Fatigue

(i) A large flat plate of a metal alloy is subjected to cyclic tensile and compressive stresses of 120 and 30 MPa respectively. NDT examination revealed the presence of surface cracks 1.00 mm in length. If the plane strain fracture toughness is 45 MPa√m and the values of the Paris law constants *A* and *m* are 2 x 10^{-12} and 3 respectively for Δσ in MPa and *a* in metres, calculate the life of the plate. You may assume that the parameter Y (Q) = 1 and is independent of crack length [10 marks]

$$\Delta K = \Delta\sigma\sqrt{\pi a}$$

where Δσ = 120 MPa (compressive stresses don't affect fatigue)

a_i = initial (surface) crack length = 1 x10^{-3} m

a_{crit} = critical crack length (for fast fracture to occur) = $\frac{1}{\pi}\left(\frac{K_{IC}}{\sigma_{max}}\right)^2 = 0.0448m$

N_f = no. of cycles to failure

Fatigue

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

$$\frac{da}{dN} = A(\Delta K)^m = A\left(Q\Delta\sigma\sqrt{\pi a}\right)^m$$

$$\int_{a_i}^{a_{crit}} \frac{1}{a^{\frac{m}{2}}}\,da = \int_0^{N_f} A\left(Q\Delta\sigma\sqrt{\pi}\right)^m dN$$

$$\left[\frac{a^{1-\frac{m}{2}}}{1-\frac{m}{2}}\right]_{a_i}^{a_{crit}} = A\left(Q\Delta\sigma\sqrt{\pi}\right)^m N_f$$

$$\left[\frac{a^{-\frac{1}{2}}}{-\frac{1}{2}}\right]_{1x10^{-3}}^{0.0448} = 2\times10^{-12}\left(120\times10^{6}\sqrt{\pi}\right)^3 N_f$$

$$N_f = \frac{\left[\frac{0.0448^{-\frac{1}{2}}}{-\frac{1}{2}}\right] - \left[\frac{0.001^{-\frac{1}{2}}}{-\frac{1}{2}}\right]}{2x10^{-12}\left(120\sqrt{\pi}\right)^3} = \left[\frac{53.796}{1.92x10^{-5}}\right]$$

$N_f = 2{,}801{,}904$ cycles

Fatigue

(ii) Sketch the fracture surface of a shaft containing a keyway which has failed under asymmetrical reverse bending. Identify the following features on your sketch:

(a) fatigue origins (b) region of fatigue crack growth (c) region of final fracture

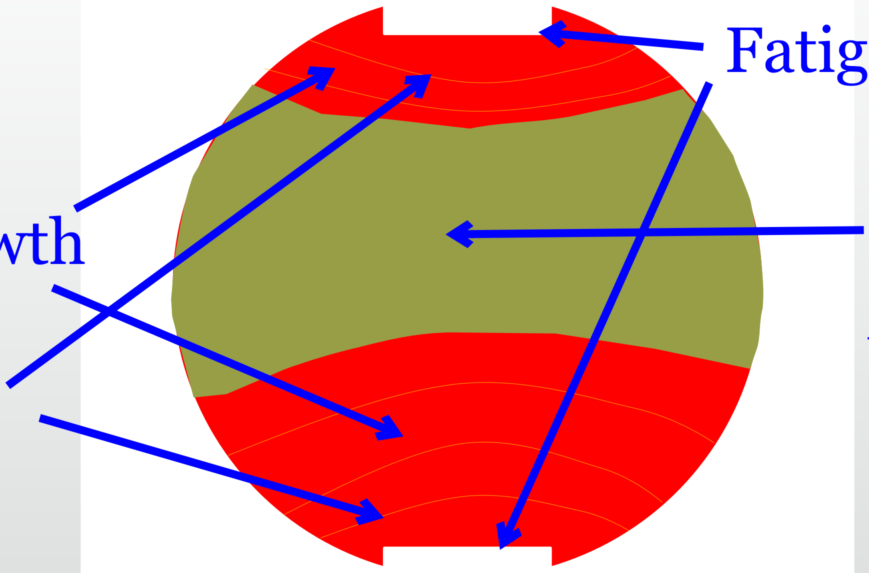
(d) beach marks With regard to understanding of the cause of failure, comment on the significance of each of these features. [12 marks]

Fatigue

(ii) Sketch the fracture surface of a shaft containing a keyway which has failed under asymmetrical reverse bending. Identify the following features on your sketch:

(a) fatigue origins (b) region of fatigue crack growth (c) region of final fracture

(d) beach marks With regard to understanding of the cause of failure, comment on the significance of each of these features. [12 marks]



Fatigue origins

Fatigue crack growth

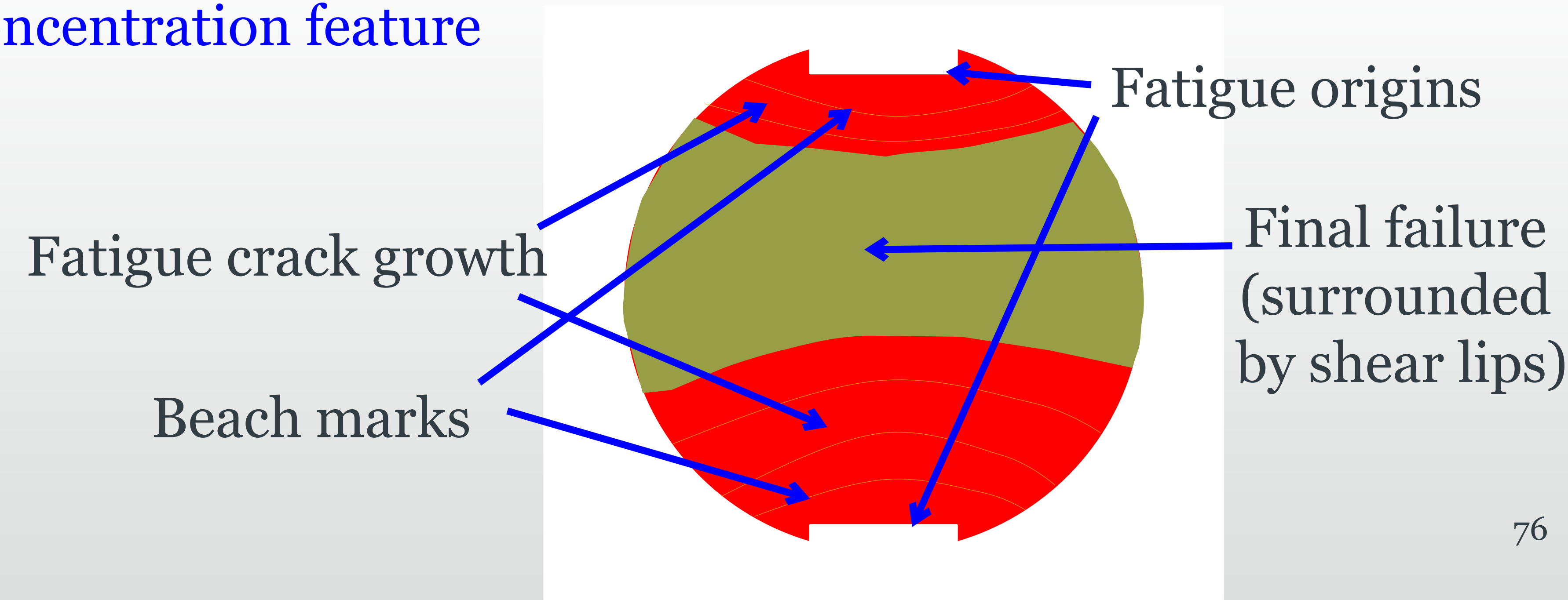
Final failure (surrounded by shear lips)

Beach marks

Fatigue

(ii) With regard to understanding of the cause of failure, comment on the significance of each of these features. [12 marks]

Shear lips indicate final fracture region, smoother regions indicate fatigue, beachmarks are concentric features, pointing back to fatigue initiation, often see ratchet marks indicating where several cracks may have initiated. Keyway – stress concentration feature



Fatigue

(iii) What are fatigue striations and why would you not see them with a visual inspection? [3 marks]

Fatigue

(iii) What are fatigue striations and why would you not see them with a visual inspection? [3 marks]

These are concentric microscopic markings, indicating the progression of the crack front with each cycle (aside: form due to repeated blunting and sharpening at the crack tip) they will not be visible without a high magnification microscope