Failure Analysis and Fracture

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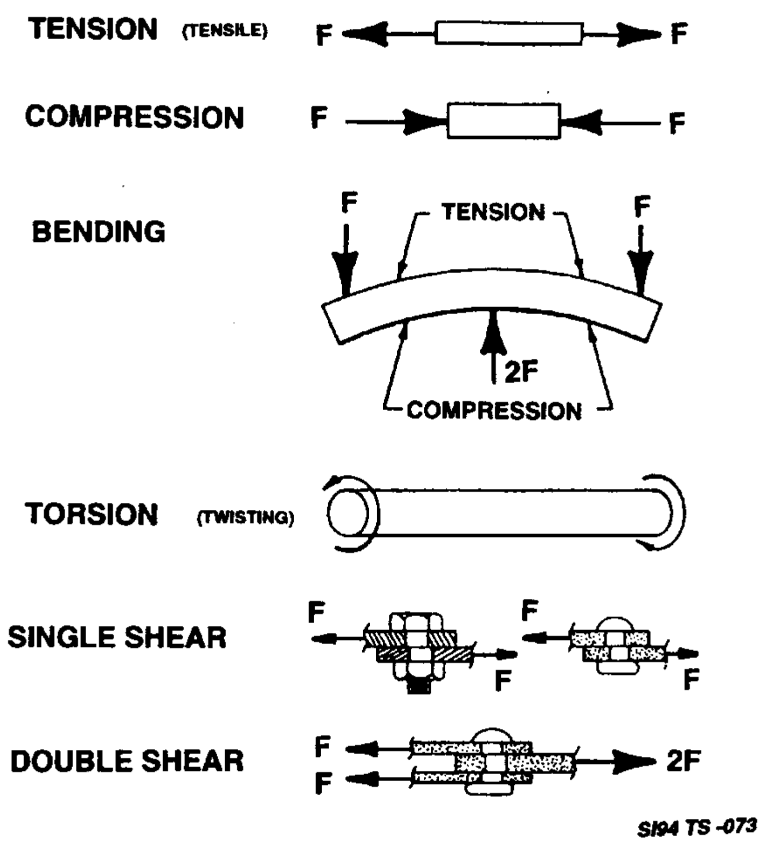
Outline

- **Failure Analysis**
  - Ductile Overstress
  - Brittle Overstress
  - Fatigue
  - Stress Corrosion
  - Embrittlement
  - High Temperature Deformation
  - Failures in Polymers and Composites

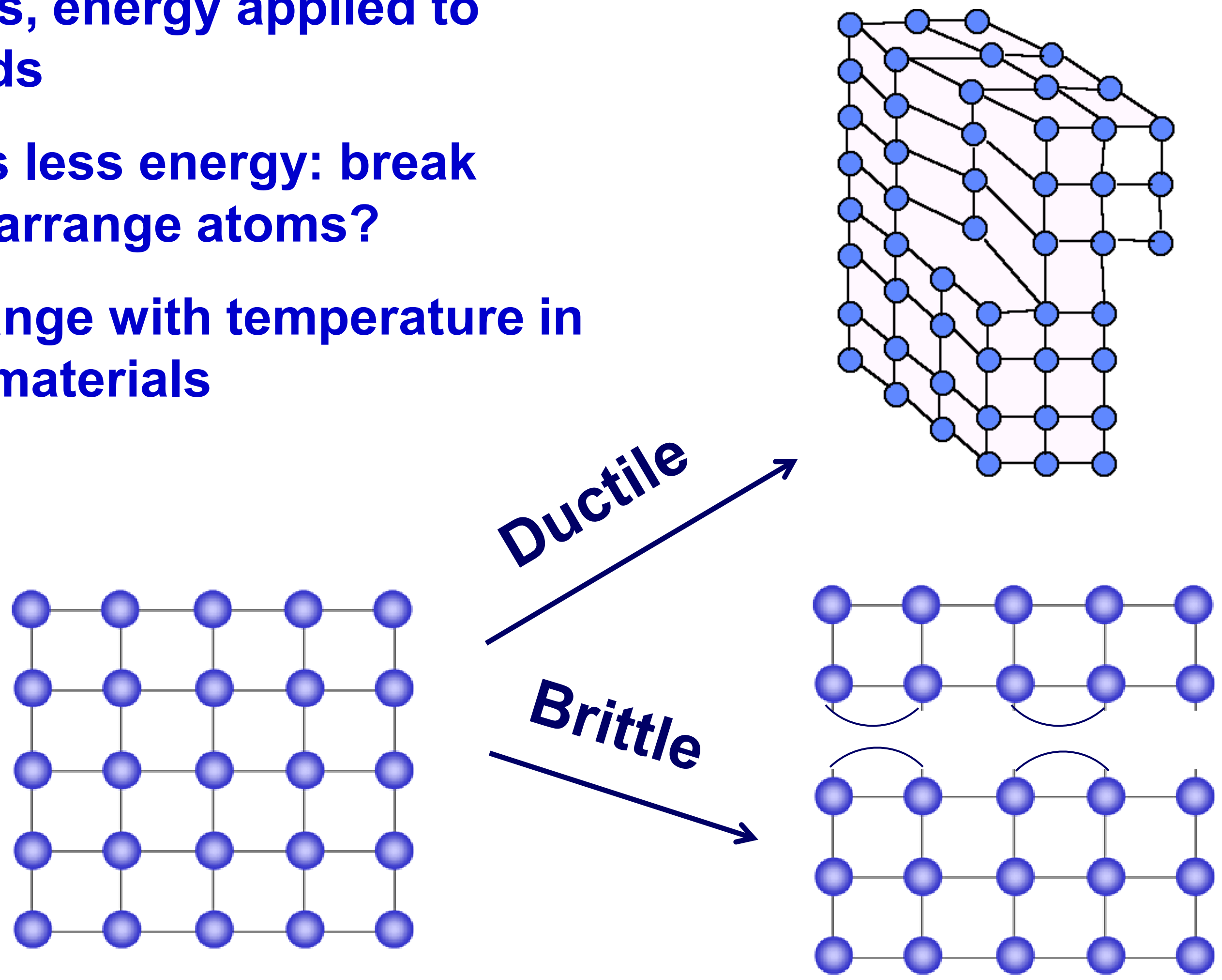
Types of Loading

- Loads impart stresses into the material
- $\sigma = \frac{F}{A}$
- The plane of max shear is 45° from direction of loading



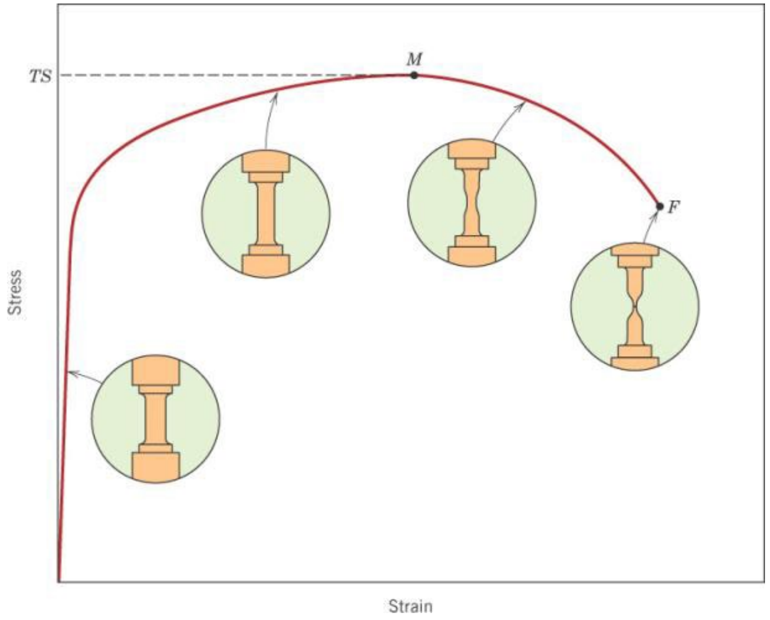
Brittle versus ductile materials

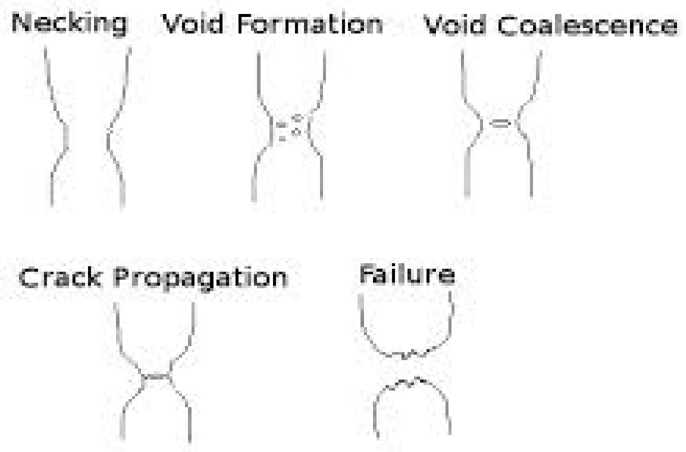
- Under stress, energy applied to atomic bonds
- Which takes less energy: break bonds or rearrange atoms?
  - Can change with temperature in certain materials



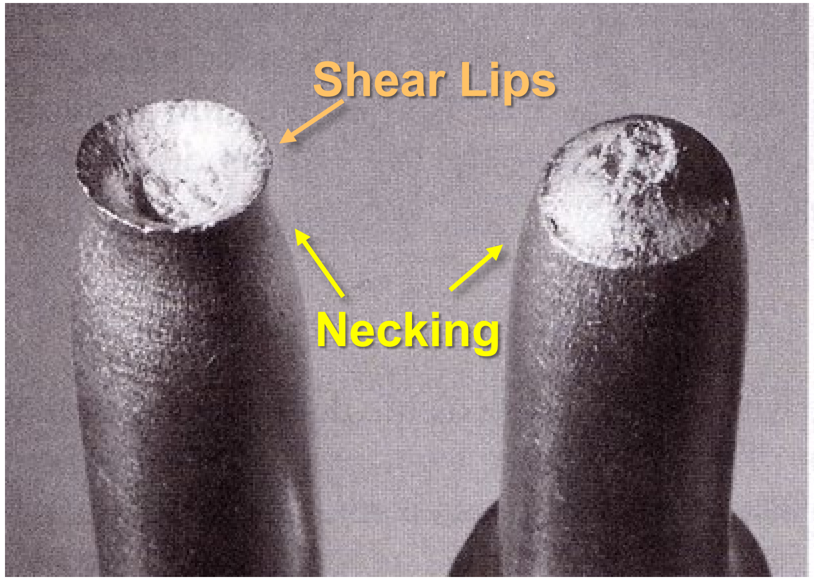
Brittle versus ductile material

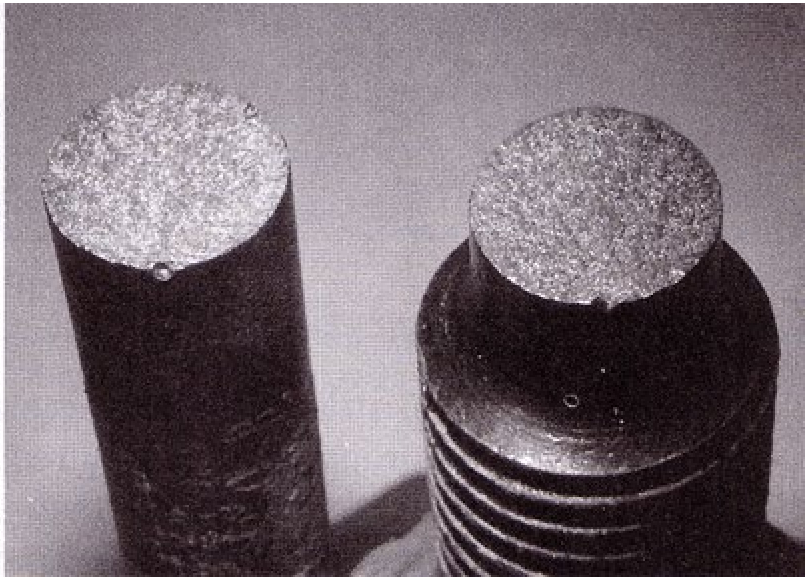
- **Ductile materials**
  - Deform plastically until local instability (necking)
  - Small voids begin to form in center of material
  - The material between these voids finally breaks
- **Brittle materials**
  - No gross deformation
  - Few indications of impending failure
  - Bonds break along weakest areas in material

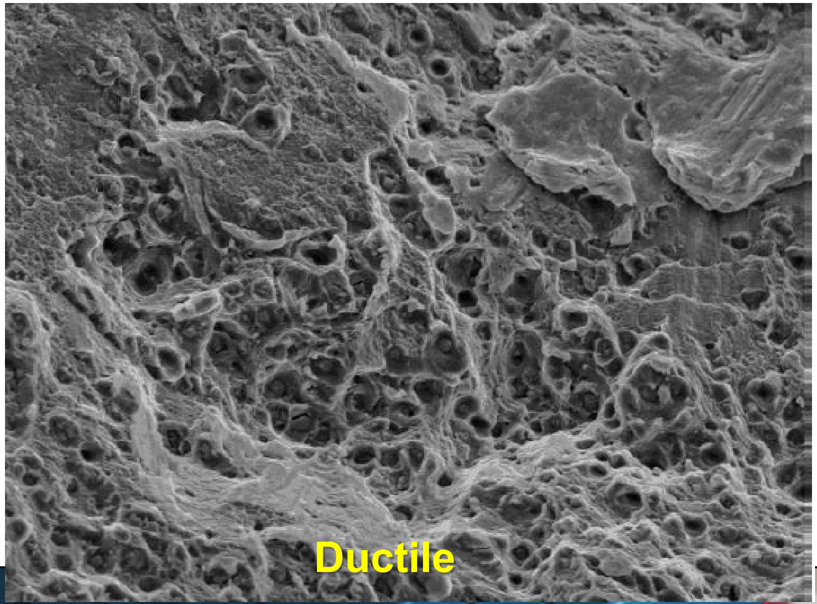


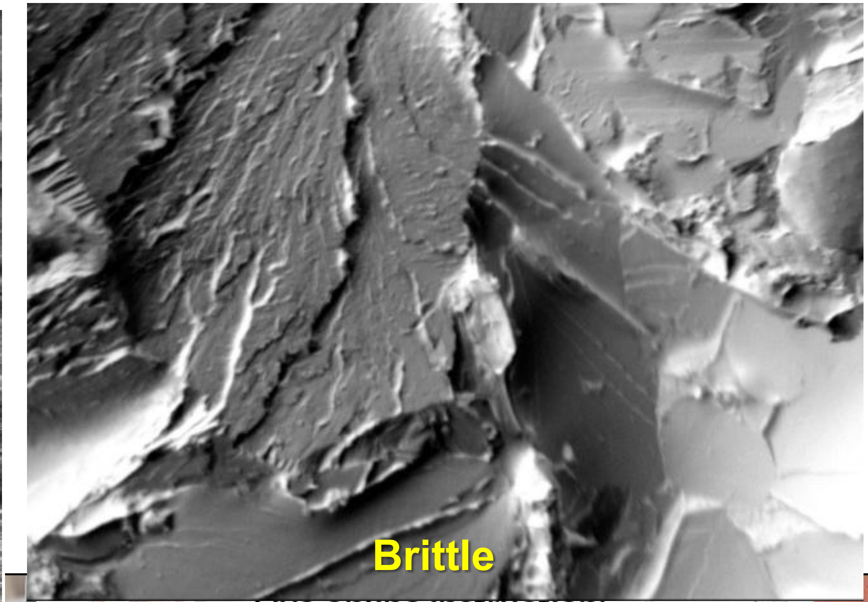


Ductile Overstress – Tension



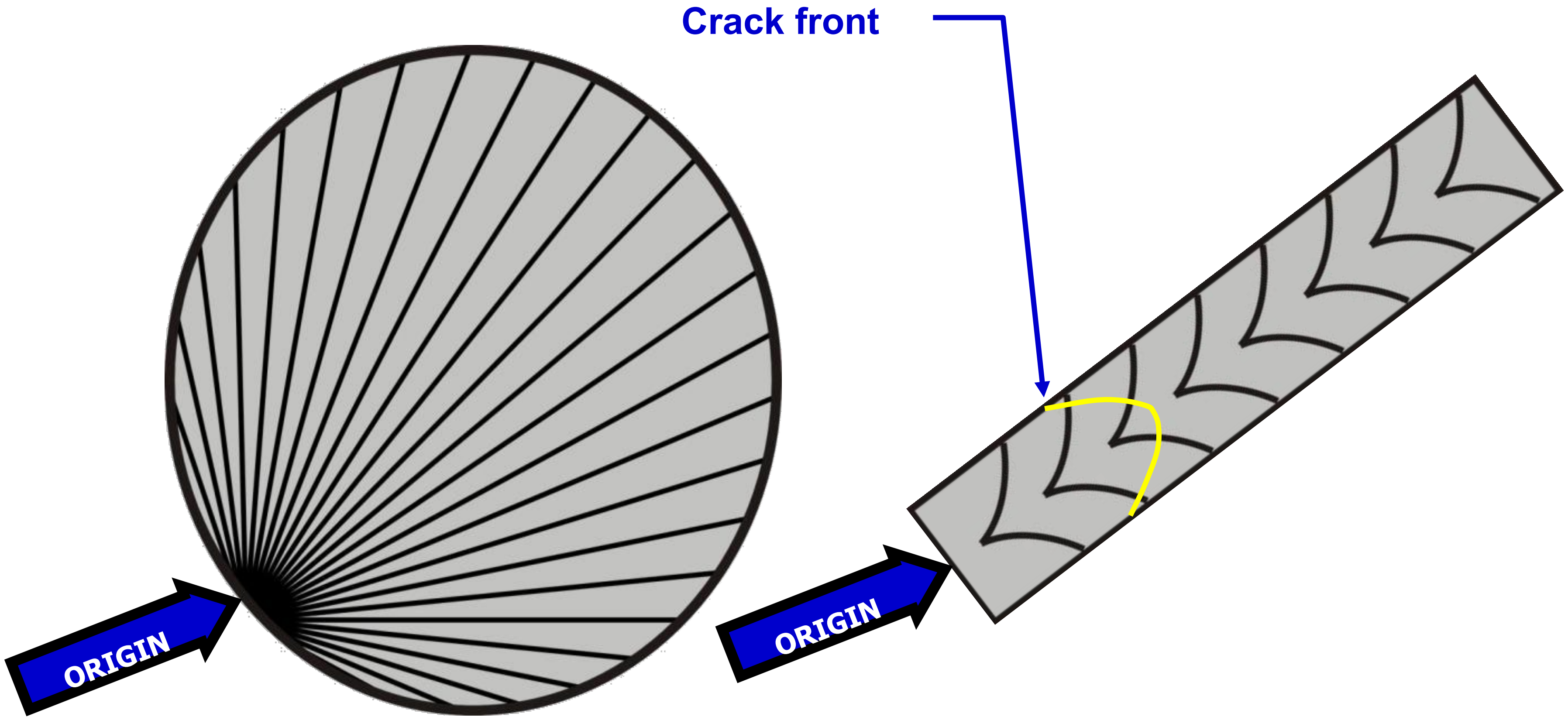






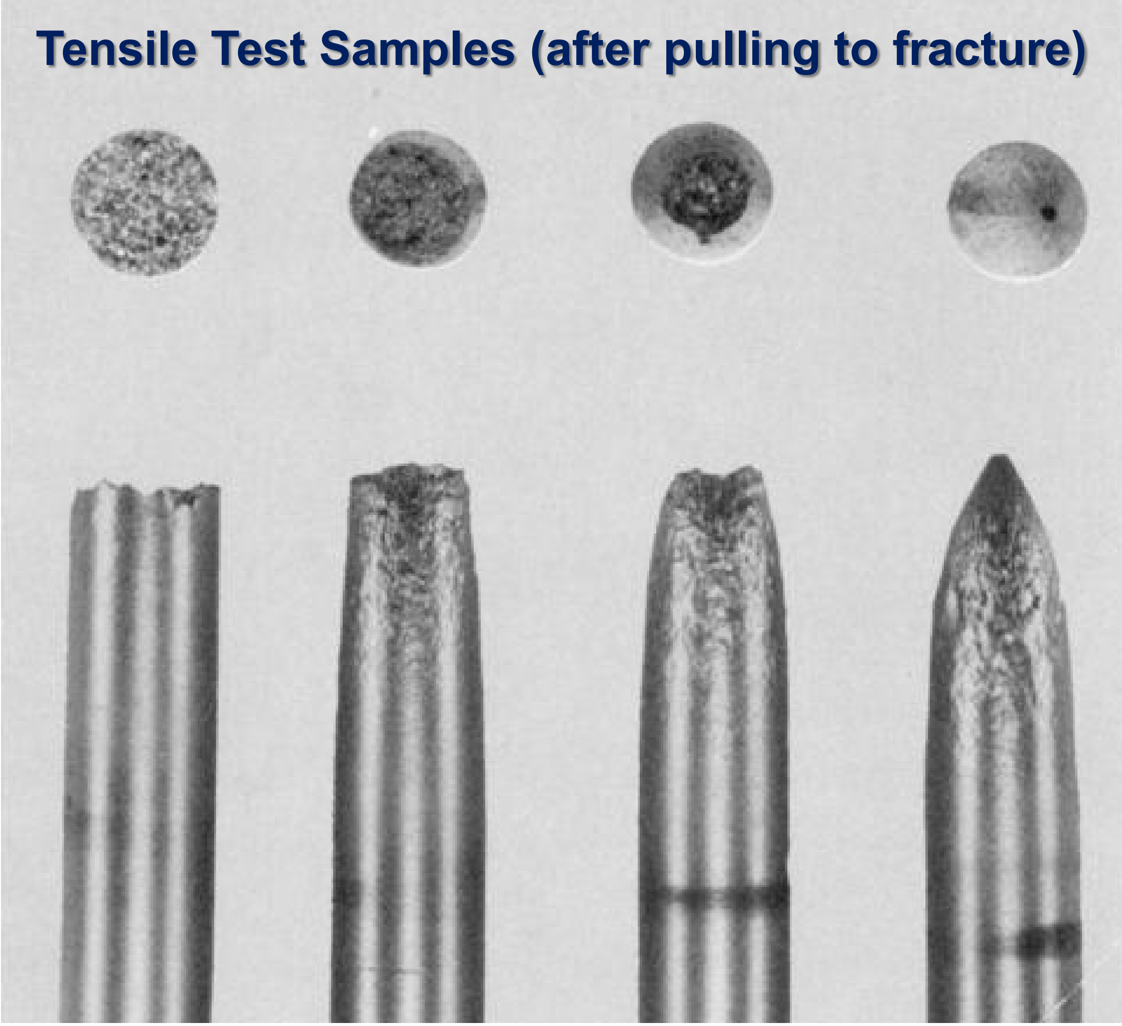
V. Kerlins and A. Phillips, Modes of Fracture, Fractography, Vol. 12, ASM Handbook, ASM International, 1987

Locating the Origin of Fracture



- Radial marks
- Chevron marks

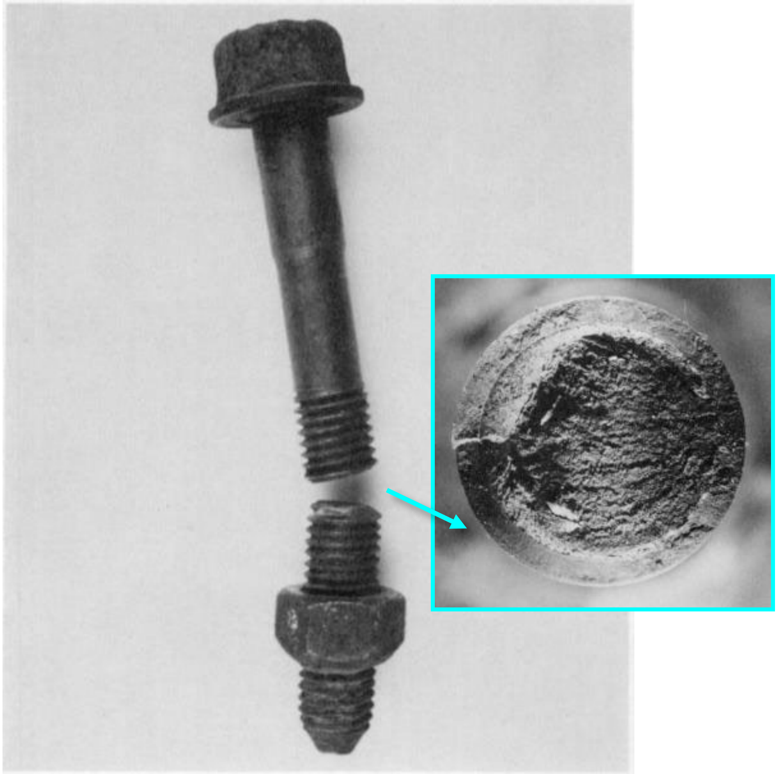
Overstress Fracture - Tension



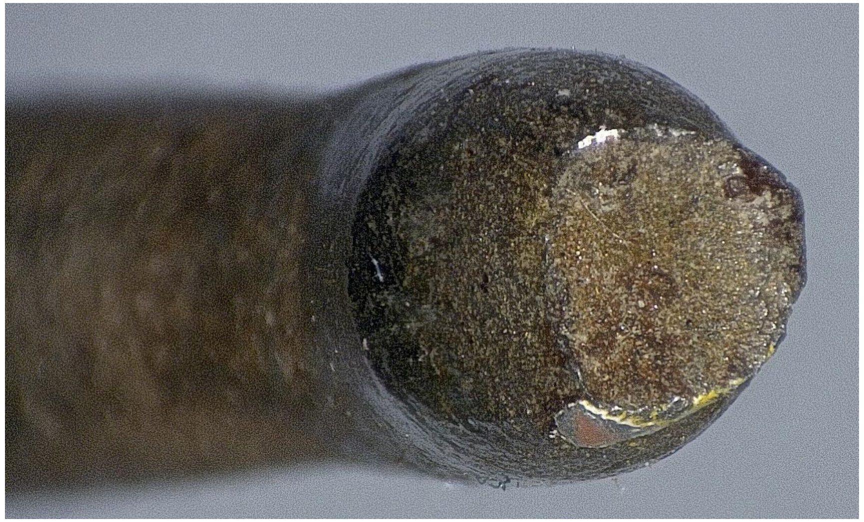
More brittle ← → More ductile

Overstress Fracture - Tension

Drill pipe end



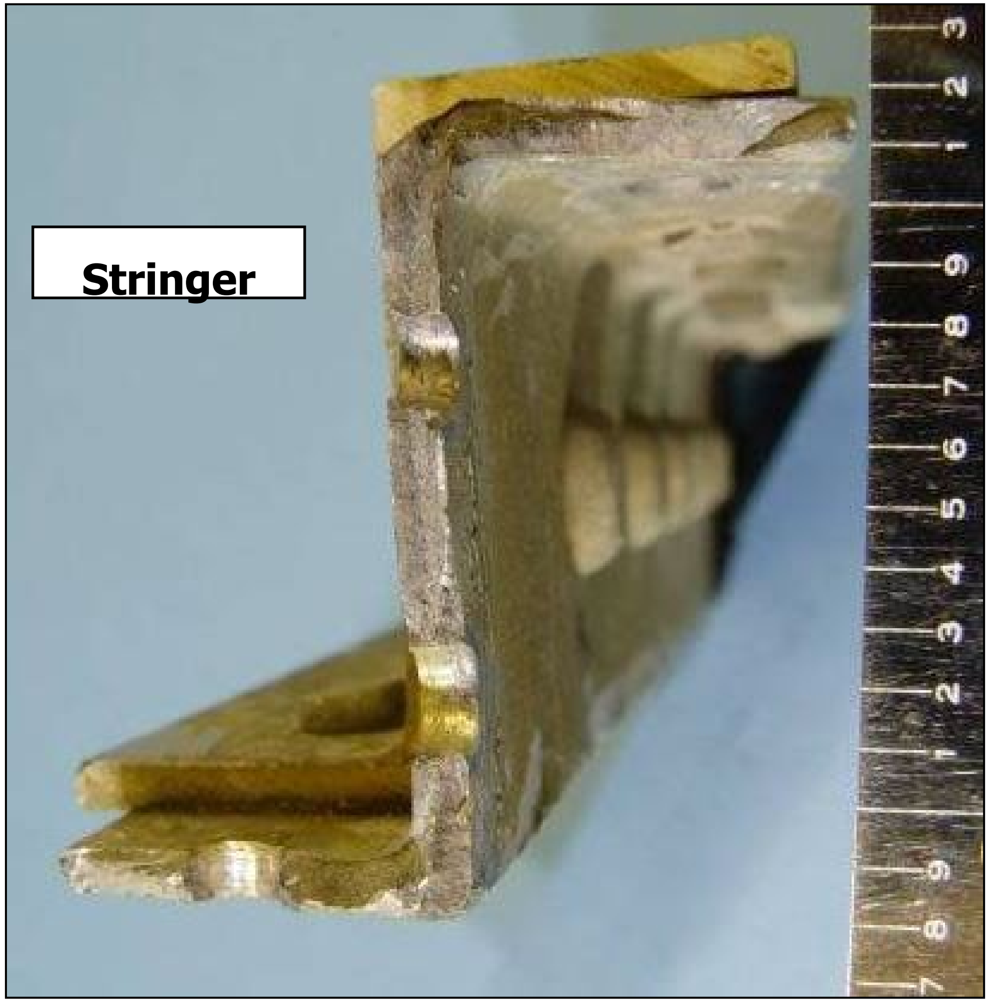
Automotive bolt



Steel bracket

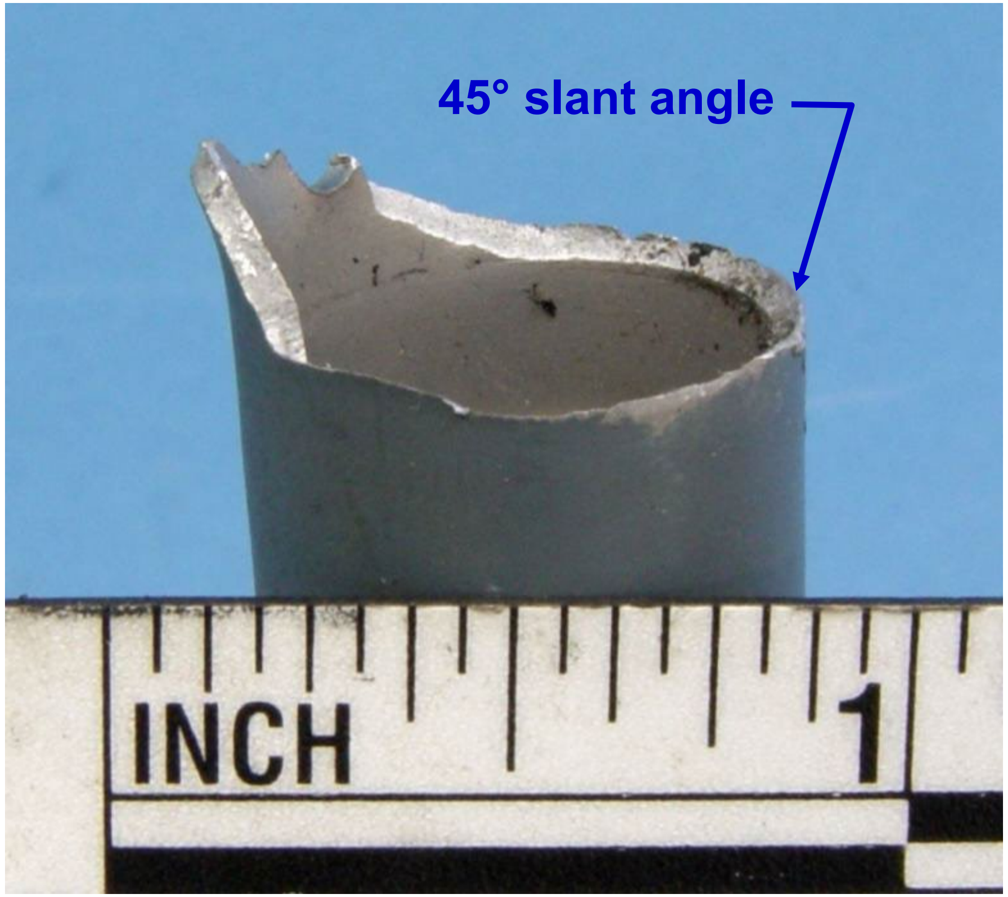
Ductile Overstress – Tension Thin Wall

- Rivet holes reduce net cross section
  - Increases local applied stress
- No out-of-plane deformation
- Fracture on <u>45° slant angles</u>
  - <u>Plane stress conditions</u>
- Dull gray fracture



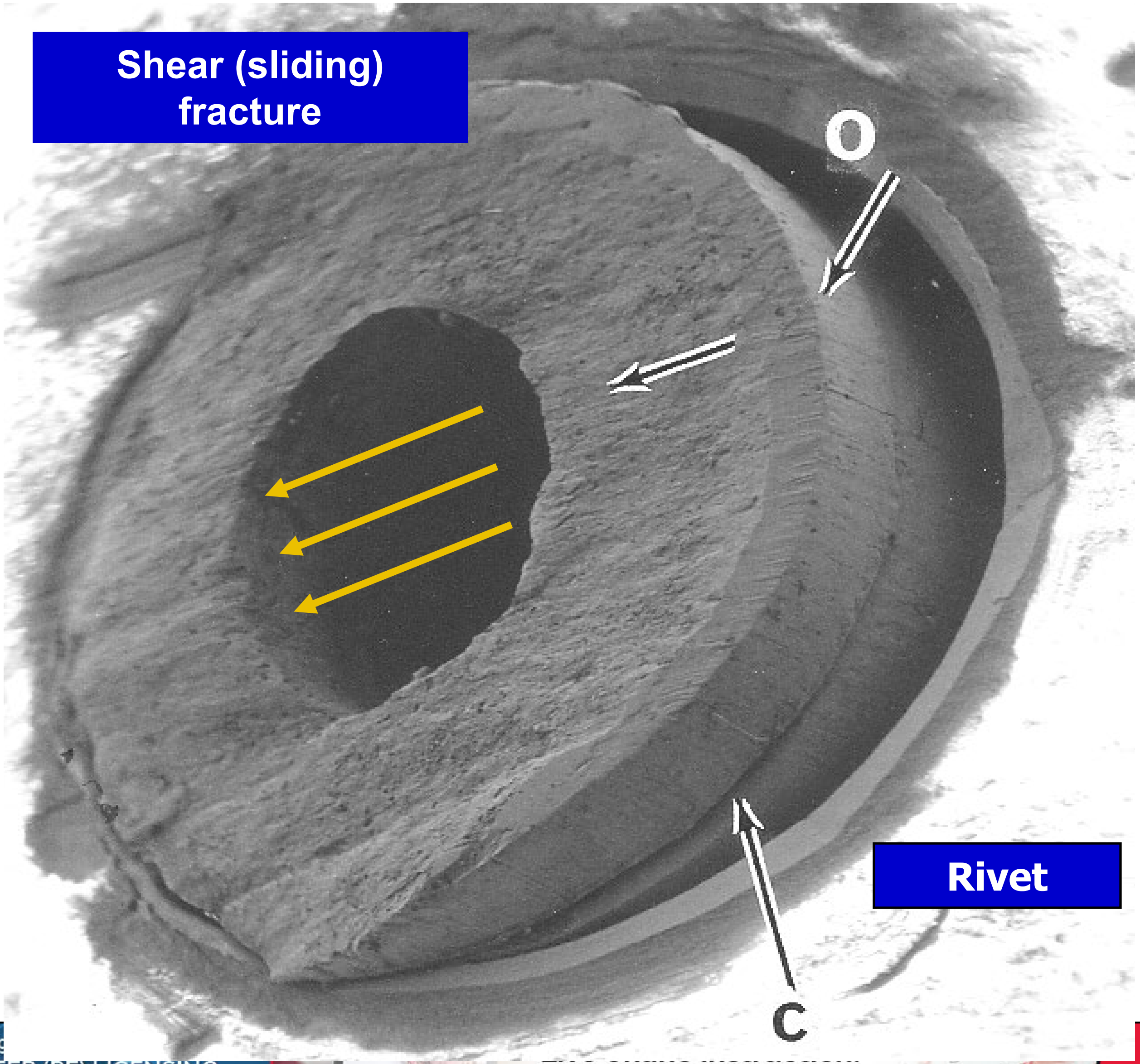
Ductile Overstress – Tension Medium Ductility

- No substantial necking or elongation
- Out of plane bend at final tear
- Fracture on 45° slant angles

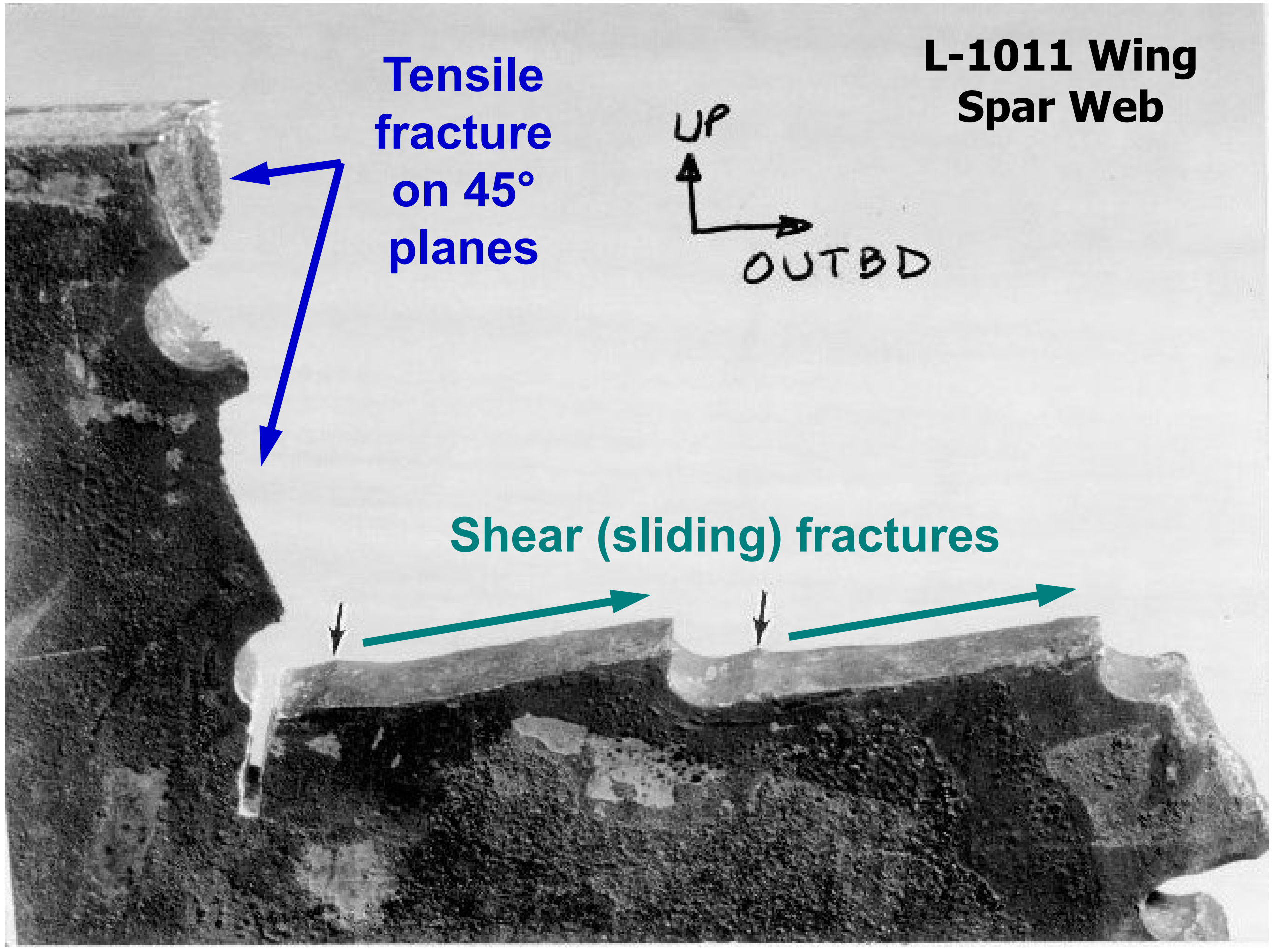


Ductile Overstress – Shear

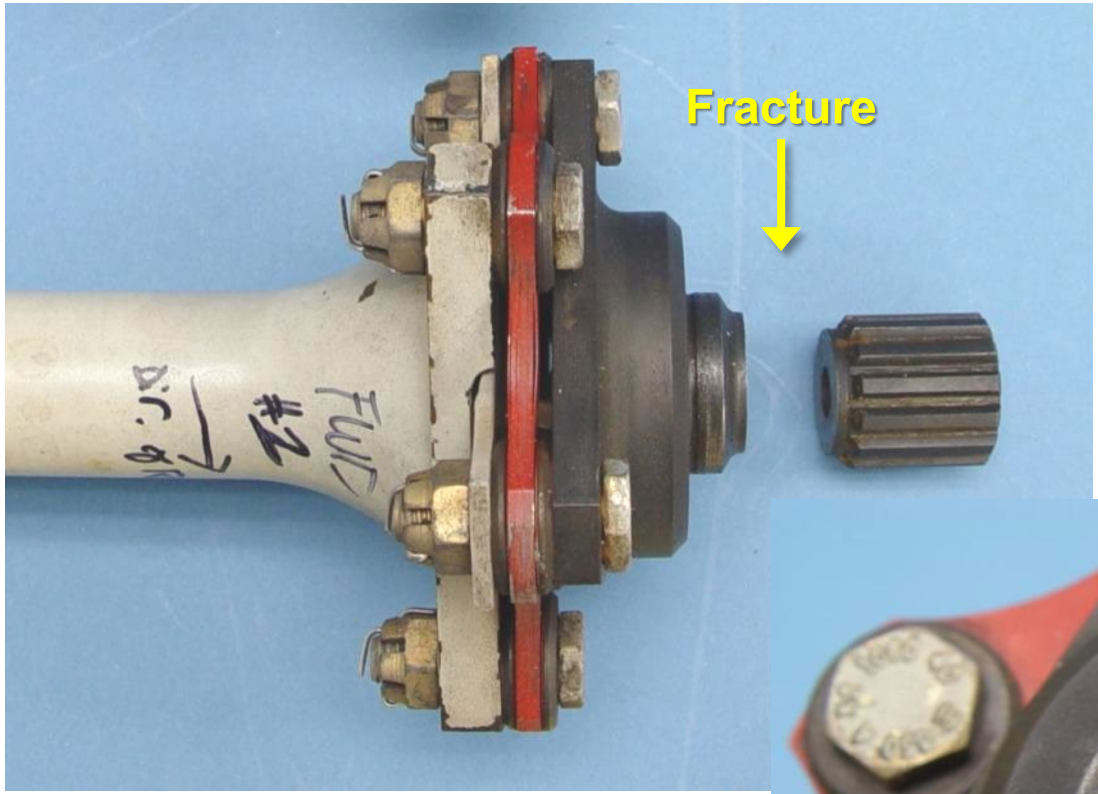
- Fracture along shear plane
- Permanent deformation
- Texture in direction of shear



Ductile Overstress - Shear



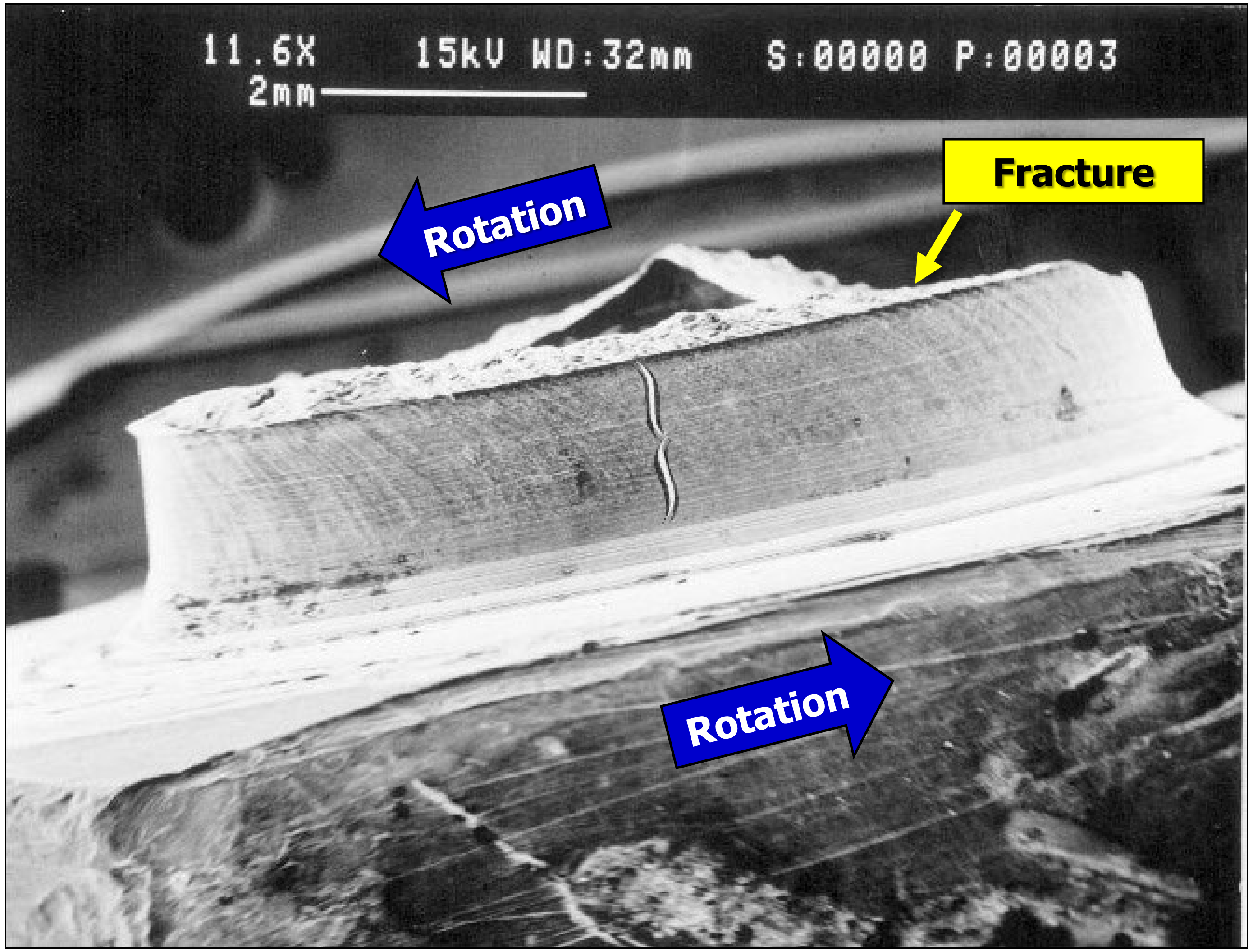
Ductile Overstress - Torsion



Fracture on one plane with faint patterns on surface

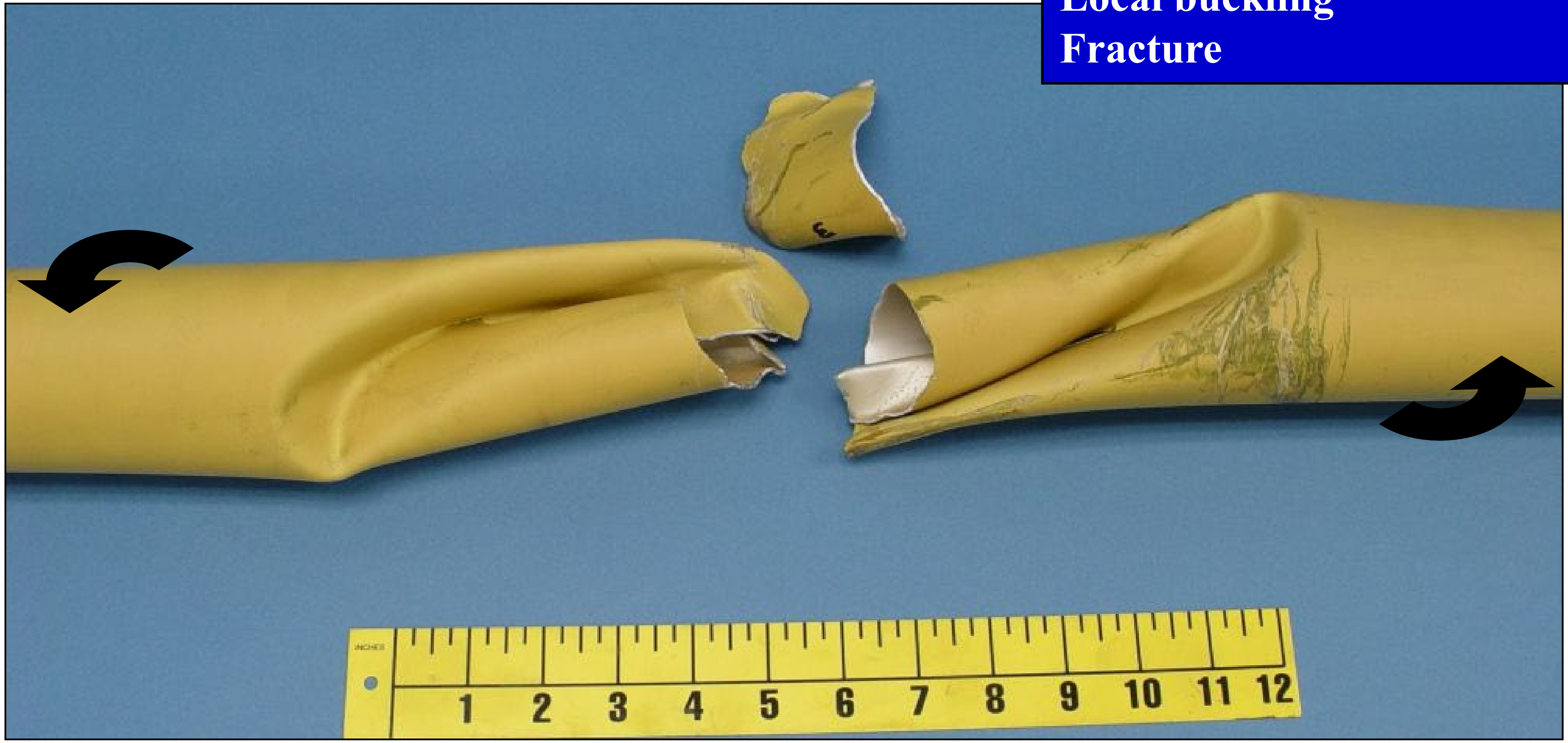
Ductile Overstress - Torsion

Marks on side of shaft show permanent deformation



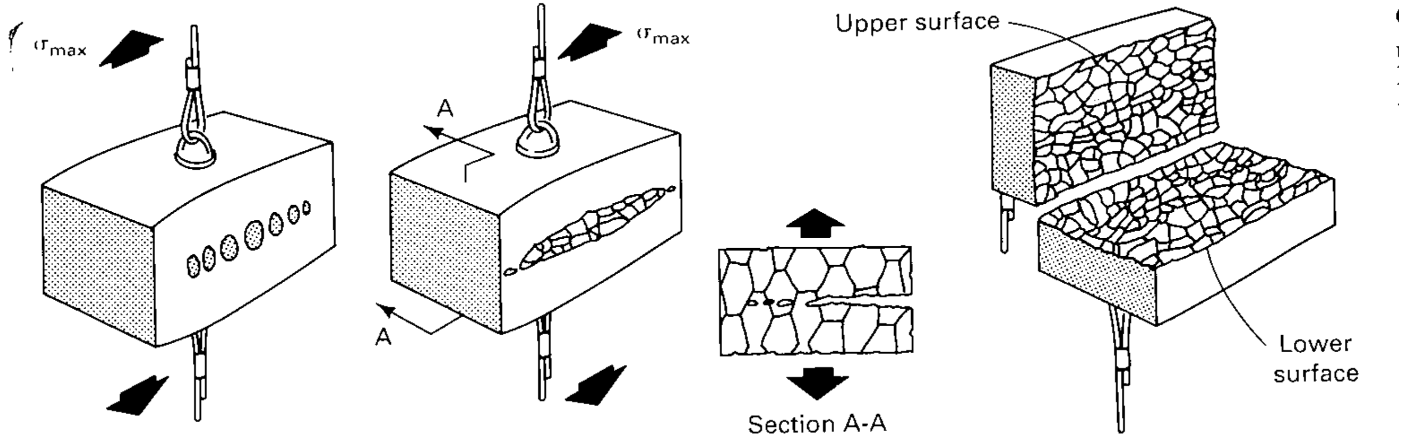
Ductile Overstress - Torsion

Tail rotor drive shaft
Thin-walled tube
Local buckling
Fracture



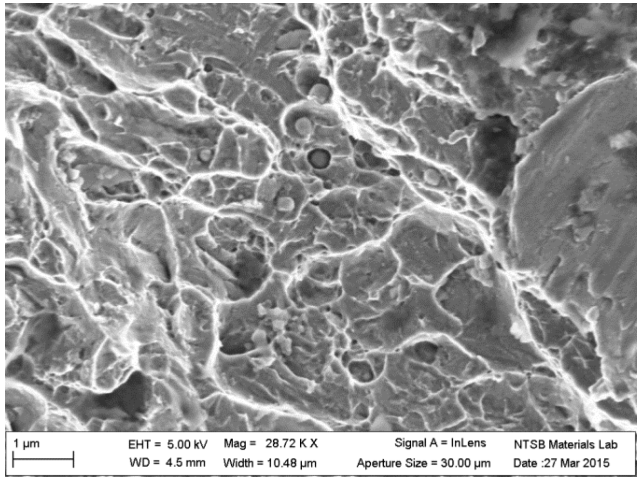
Dimple morphology from Mode I

Mode I – Tension



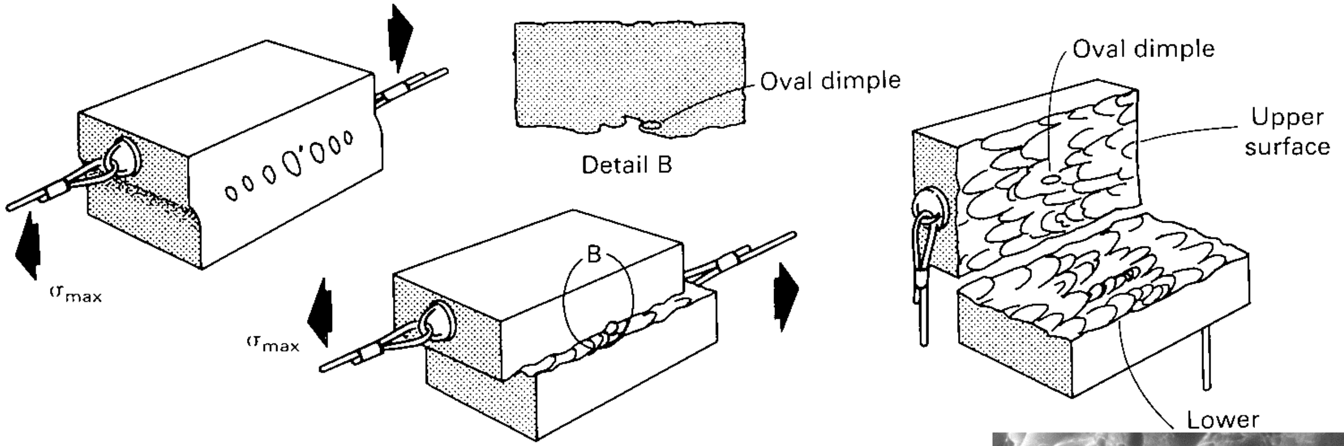
V. Kerlins and A. Phillips, Modes of Fracture, *Fractography*, Vol. 12, *ASM Handbook*, ASM International, 1987

Equiaxed Dimples



Dimple morphology from Mode II

Mode II - Shear



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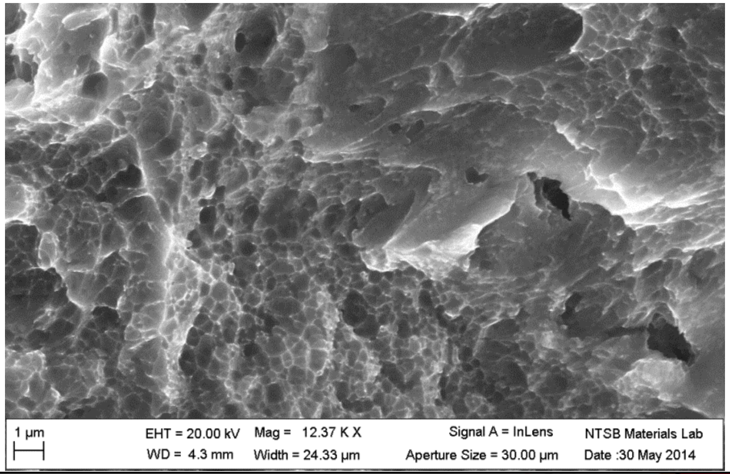
Shear Dimples



BRITTLE BEHAVIOR

Overstress – Brittle

Fracture on plane 90° to tensile stress

Possibly a small shear lip at edges of materials with limited ductility

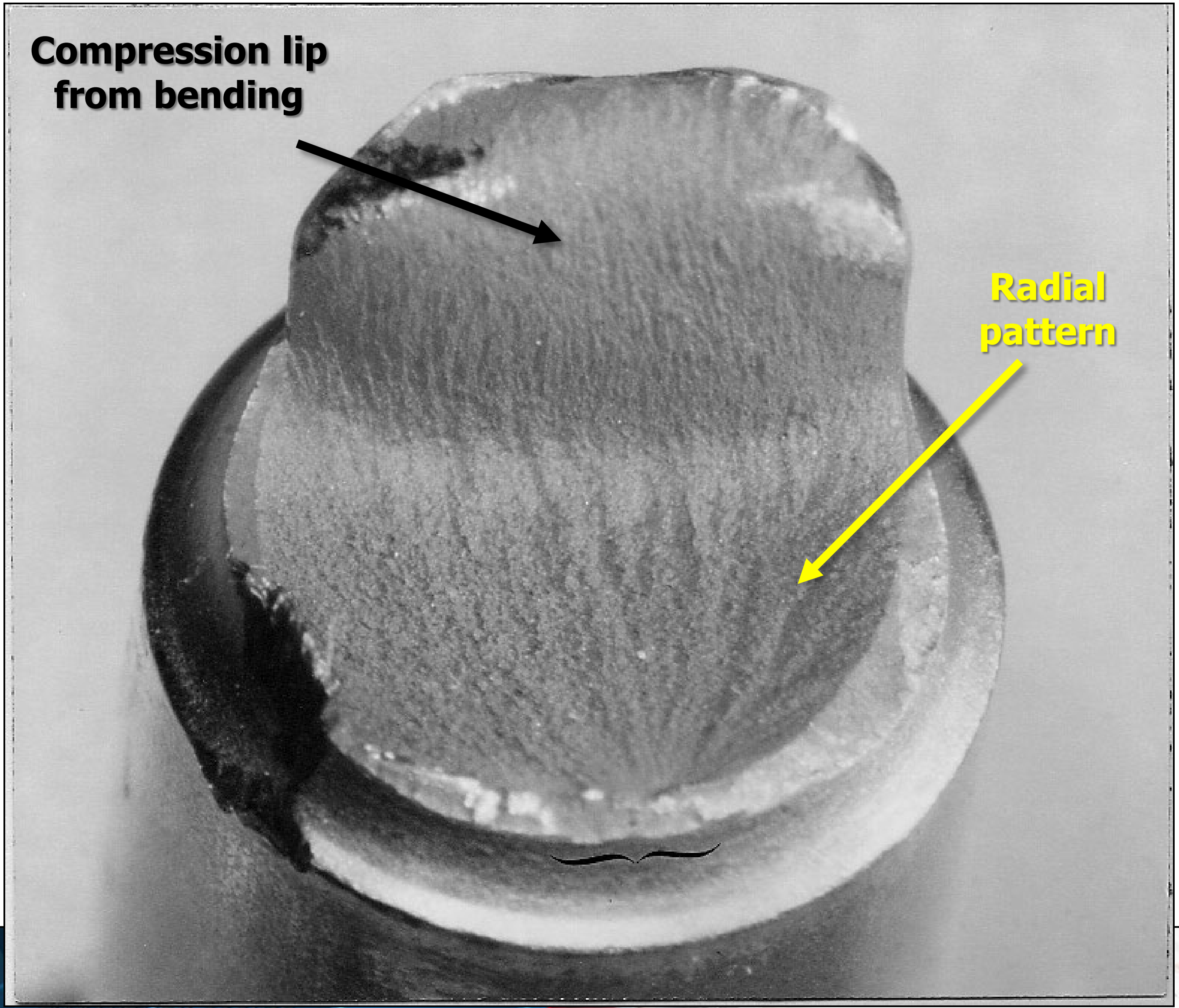
Rough fracture surface

No macroscopic deformation

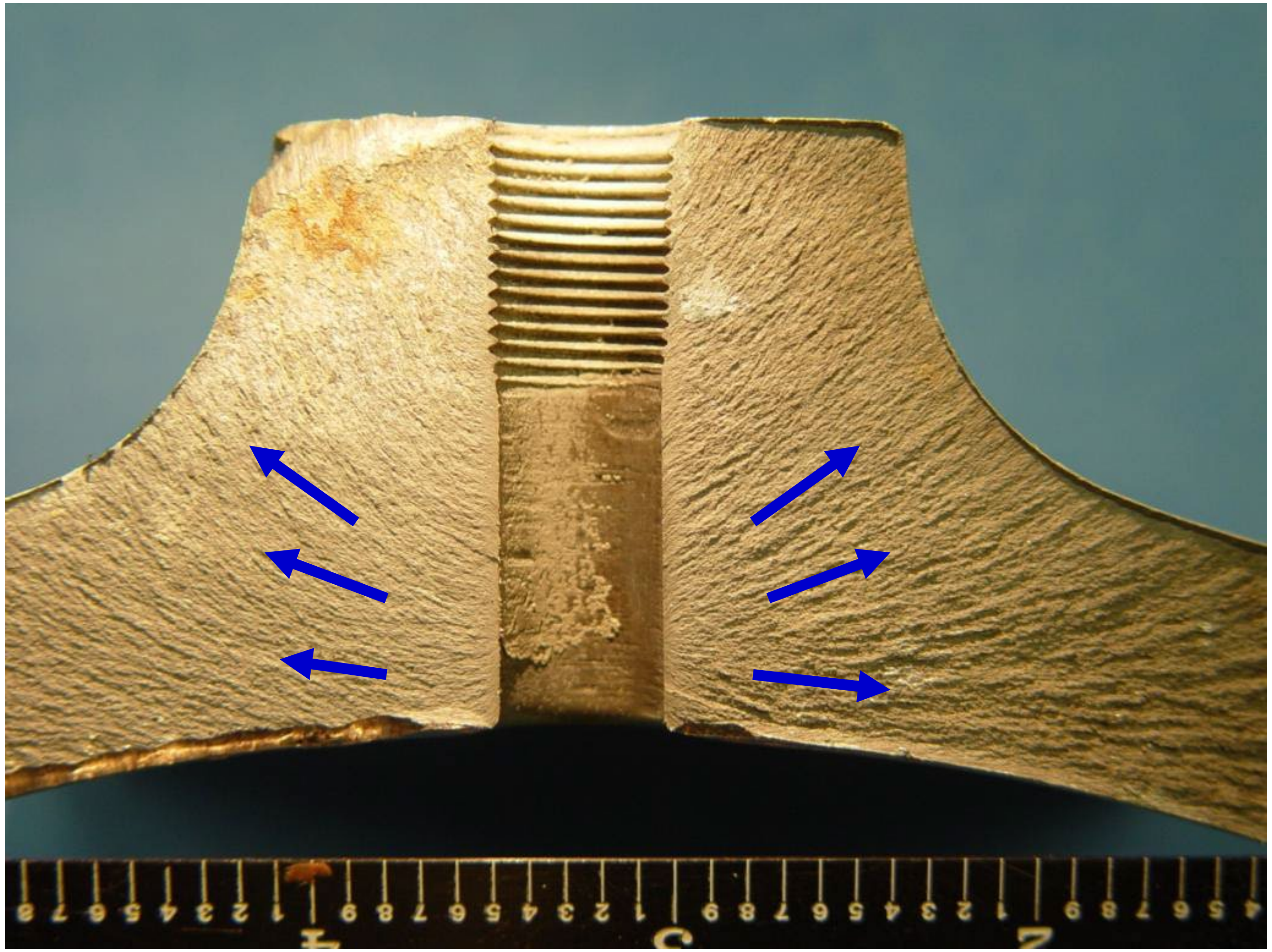
Possible crack front propagation marks (Chevron marks, radial lines)

- Not the same as crack arrest marks

Locating the Origin Radial Pattern

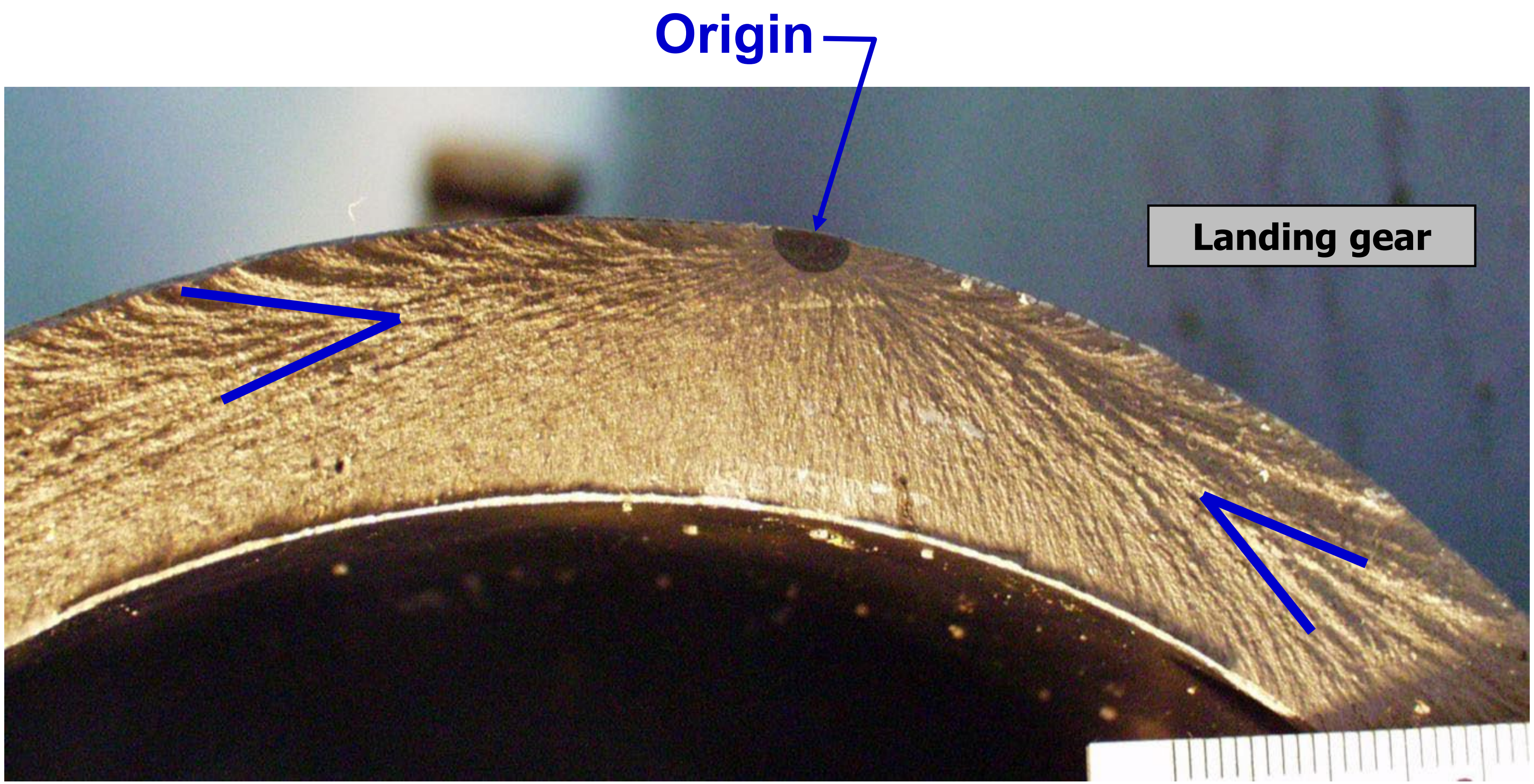


Radial Pattern Limited Ductility



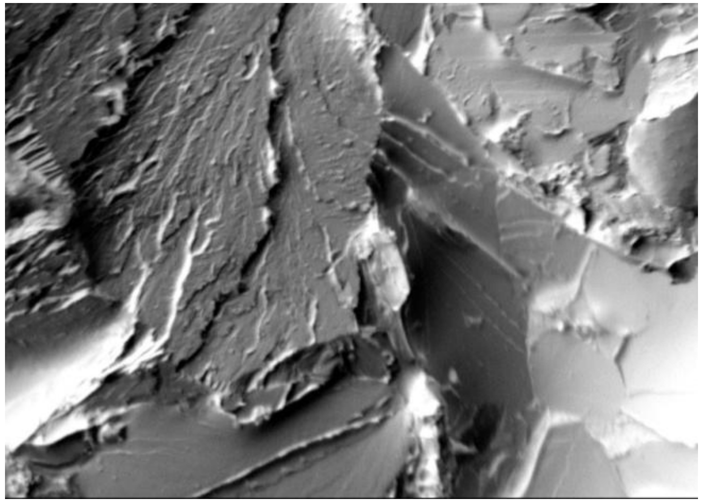
Small shear lips at edges of fracture

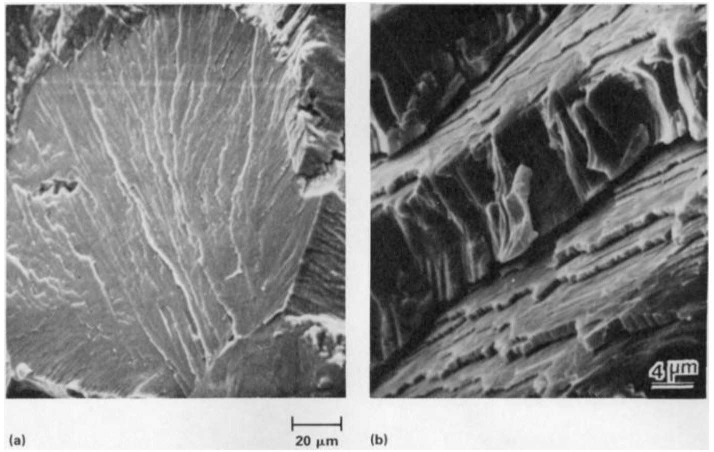
Chevron Pattern



Cleavage Fracture

- Low energy fracture that propagates on low index crystallographic planes
- Cleavage features
  - Feathers, Tongues
  - Steps
  - River patterns
  - Chevrons

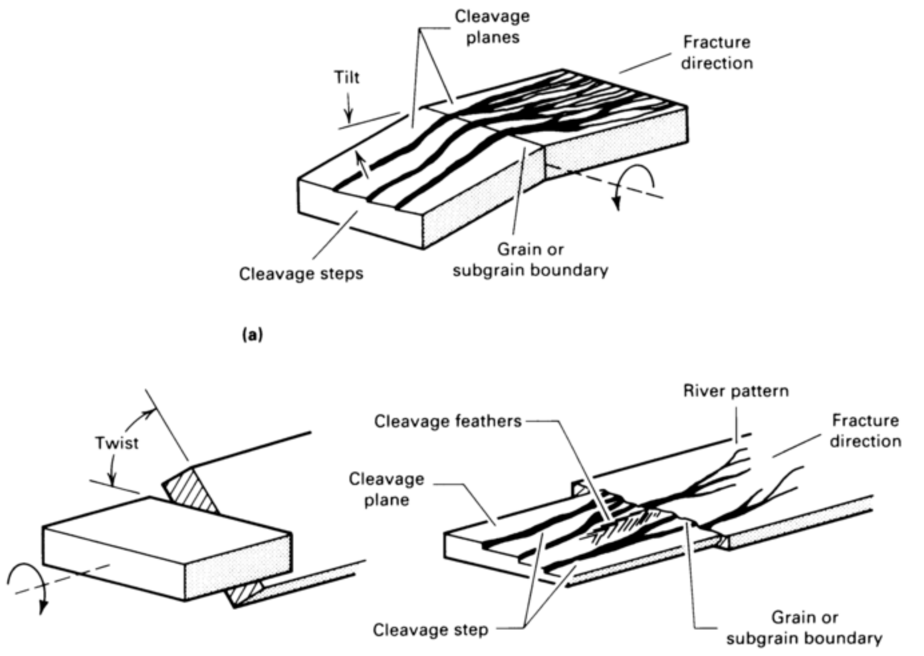




V. Kerlins and A. Phillips, Modes of Fracture, *Fractography*, Vol. 12, *ASM Handbook*, ASM International, 1987

Cleavage Fracture

- **Crystals/grains split along low index planes**
- **Occurs at "sufficiently low" T**
- **Still a certain amount of plastic deformation**



V. Kerlins and A. Phillips, Modes of Fracture, *Fractography*, Vol. 12, *ASM Handbook*, ASM International, 1987

Griffith Fracture in Brittle Materials

- $\sigma_f = \sqrt{\frac{\gamma E}{4a}\left(\frac{\rho}{d}\right)}$
  - $\sigma_f =$ average applied stress where crack will grow
  - $\gamma =$ specific surface energy
  - E = Young's modulus
  - 2a = crack length
  - $\rho =$ radius of curvature at end of crack
  - d = mean interatomic distance
- As the crack grows, there is less stress needed to advance cracks
  - Crack velocity will accelerate

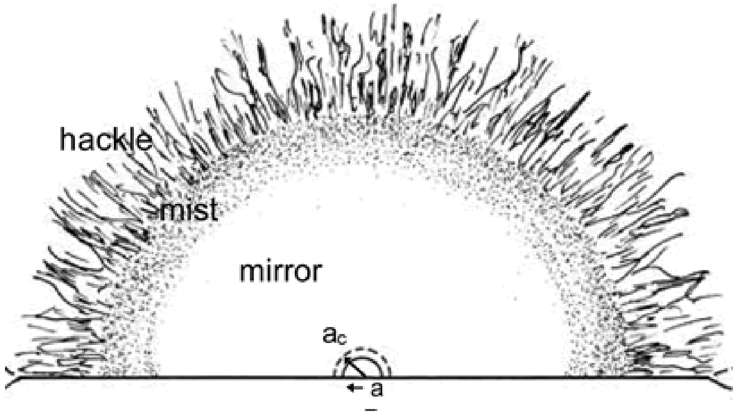
If crack is internal, its length is 2a!

Griffith Fracture in Ductile Polycrystalline Materials

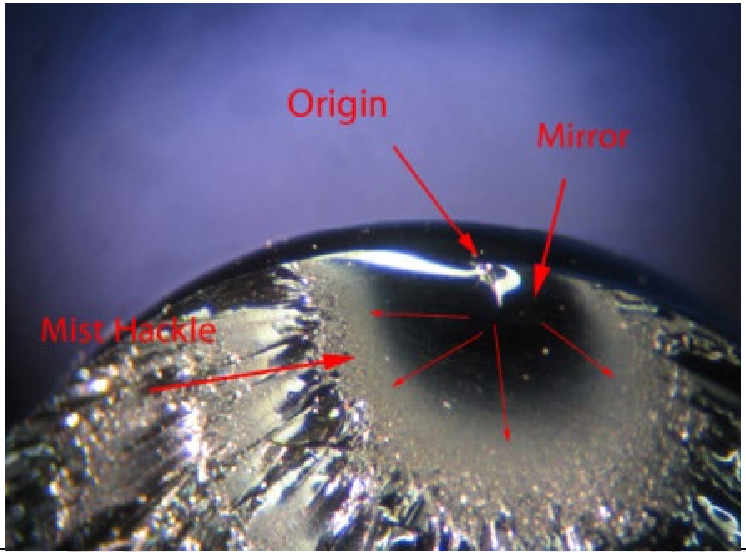
- $\sigma_f = \sqrt{\frac{4\gamma E}{\pi \bar{d}}}$
  - $\sigma_f =$ applied stress for cleavage
  - $\gamma =$ effective surface energy
  - E = Young's modulus
  - $\bar{d} =$ average grain diameter
- As the grain size decreases, more applied stress needed for cleavage fracture

Fracture In Polymers and Amorphous Materials

- **Exhibit a three-zone morphology**
  - Mirror
  - Mist
  - Hackle
- **Other features**
  - Rib markings
  - Wallner lines
  - Conic markings



ASTM C1678-09, *Standard Practice for Fractographic Analysis of Fracture Mirror Sizes in Ceramics and Glasses*



Polymer Features

- Mirror
  - Featureless, smooth
  - Larger and more common in more brittle materials
  - The remnant of a ruptured craze ahead of crack tip
- Mist
  - Not as smooth as mirror region
  - Crack acceleration prior to rapid crack growth
- Hackles
  - Divergent radiating lines
  - High energy dissipation due to localized plastic deformation on the fracture surface
  - Rapid local changes in stress field, crack velocity, and fracture path

Polymer Features

- River Lines
  - Intensity based on material and mixed loading modes
  - Trace back to origin of fracture
- Wallner Lines
  - Formed when stress waves reflecting back from surfaces interfere with crack front
  - Typically curved
- Conic marks
  - Wake lines formed from interaction of main crack front with a new secondary crack in front of crack front

Recap

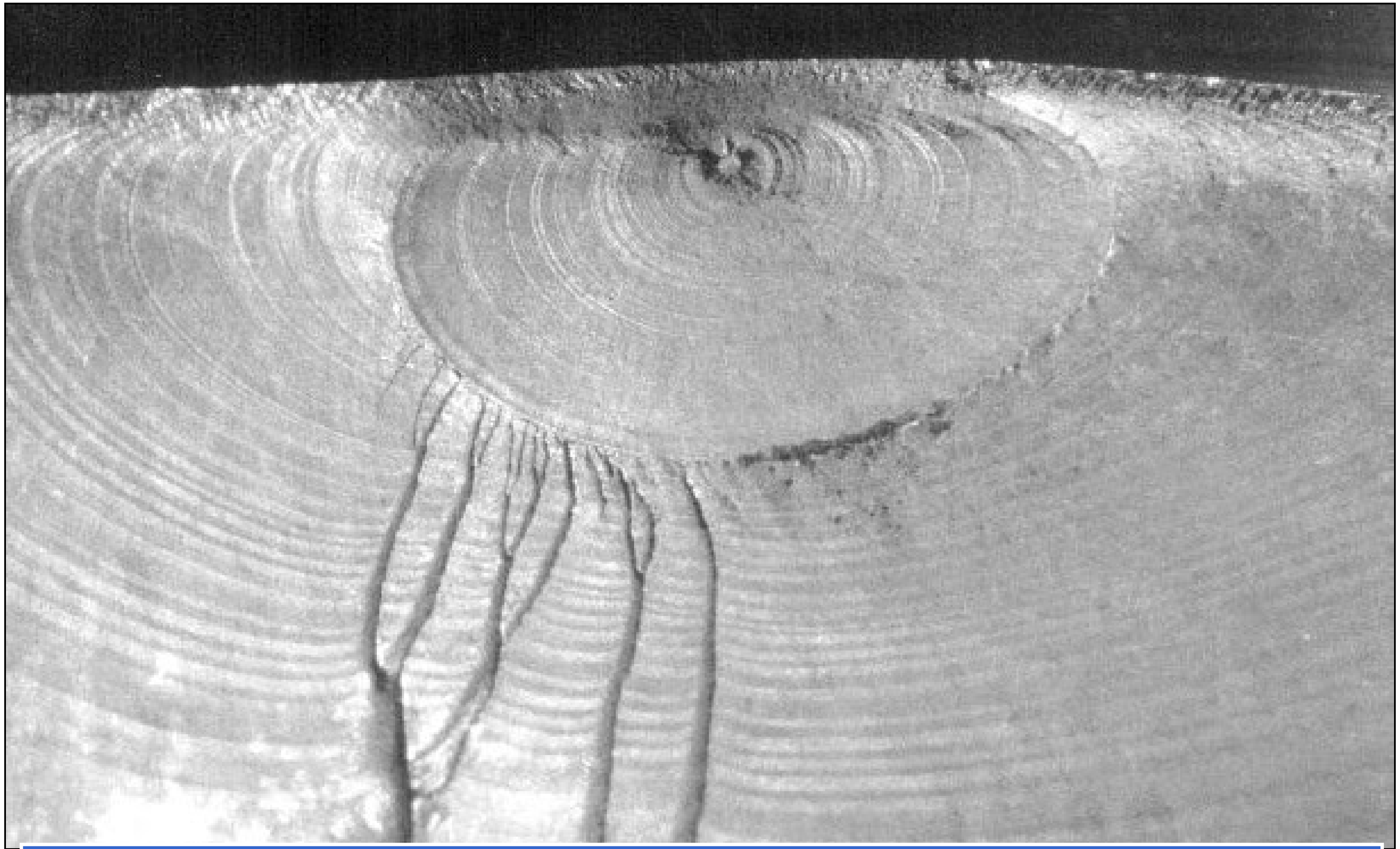
Ductility	Mode	Local Deformation	Fracture Surface Orientation	Plane Stress
Ductile	Tension	Necking	Cup/Cone (45° on edges, 90° in middle)	45
	Compression	S-Buckling, bulging	(45°)	
	Torsion	Twisted grain flow, crush buckling	90°	
	Shear	Bending in shear direction	Direction of shear	
Brittle	Tension	No local def.	90°	
	Compression	No local def.	90°	
	Torsion	No local def.	45°	
	Shear	No local def.	90°	

PROGRESSIVE CRACKING

Pre-existing damage

- Structure was weaker than intended, as a result of some degradation:
  - Fatigue cracking
  - Corrosion
  - Wear
  - Excessive temperature
  - Mechanical damage
  - Residual tensile stresses
  - Improper processing
  - Combinations
- Could be caught by inspection or by life limits

Fatigue Cracking

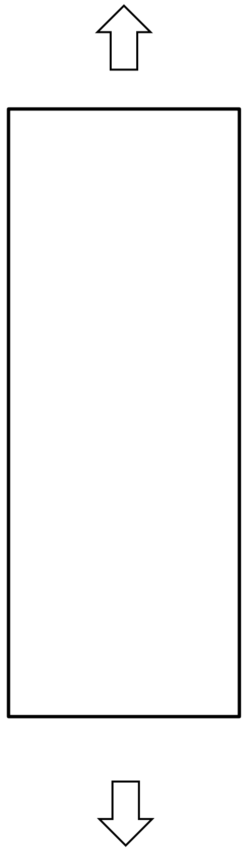


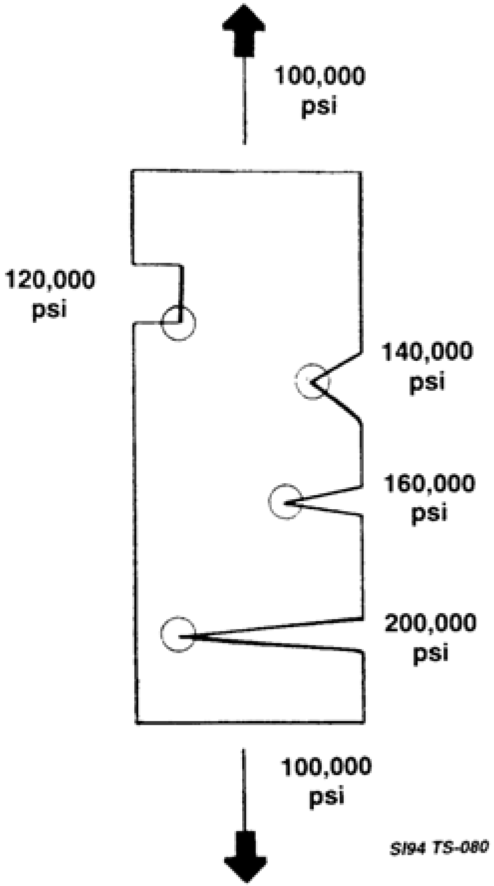
Fatigue:
A mechanism by which a crack initiates and grows under the application of cyclic stresses below the tensile strength.

Fatigue Features

- A lack of gross deformation adjacent to the fatigue region
- Propagation on a plane that is 90° to tensile stresses (like brittle cracks)
- Lack of a shear lip in the fatigue region
- A fracture surface that is smoother and possibly discolored
- Ratchet marks when multiple origins are present
- Possibly a fatigue banding pattern with smoothly curving crack arrest positions

Fatigue Crack – Stress Concentration

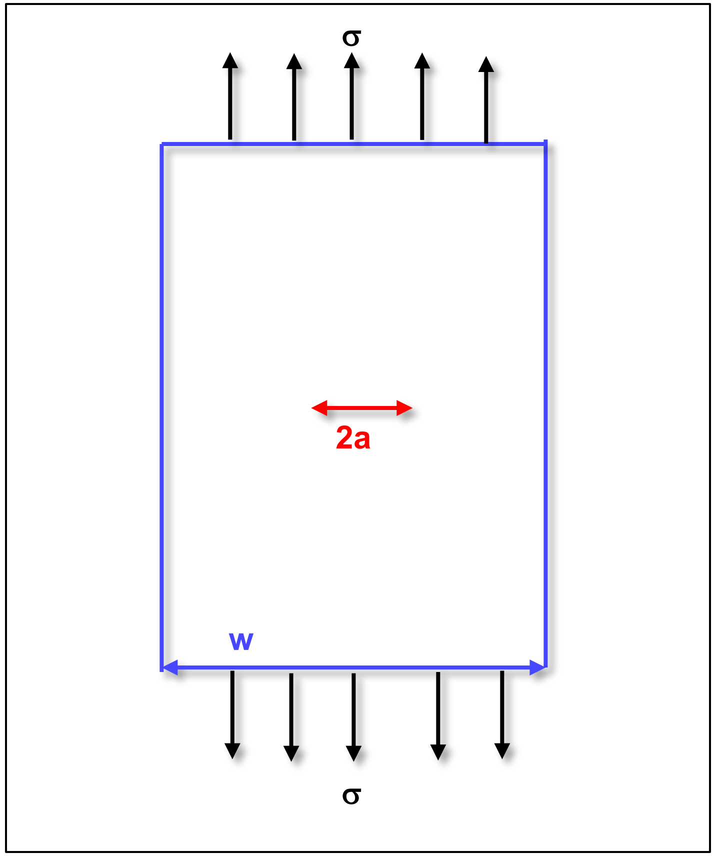




Stress is uniform across part absent stress concentrations

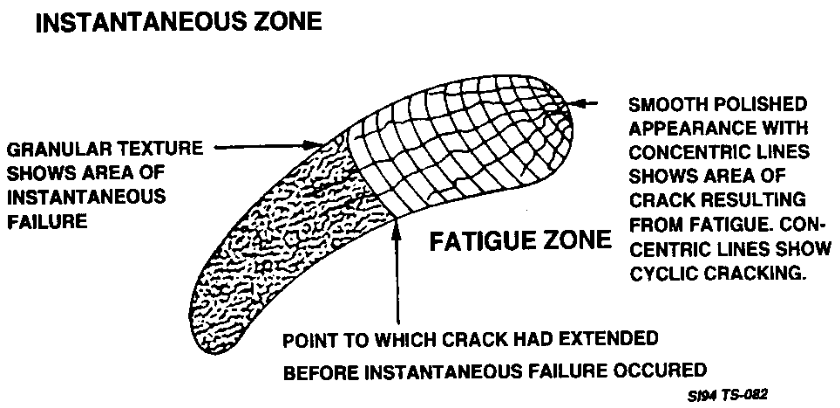
Stress Concentration

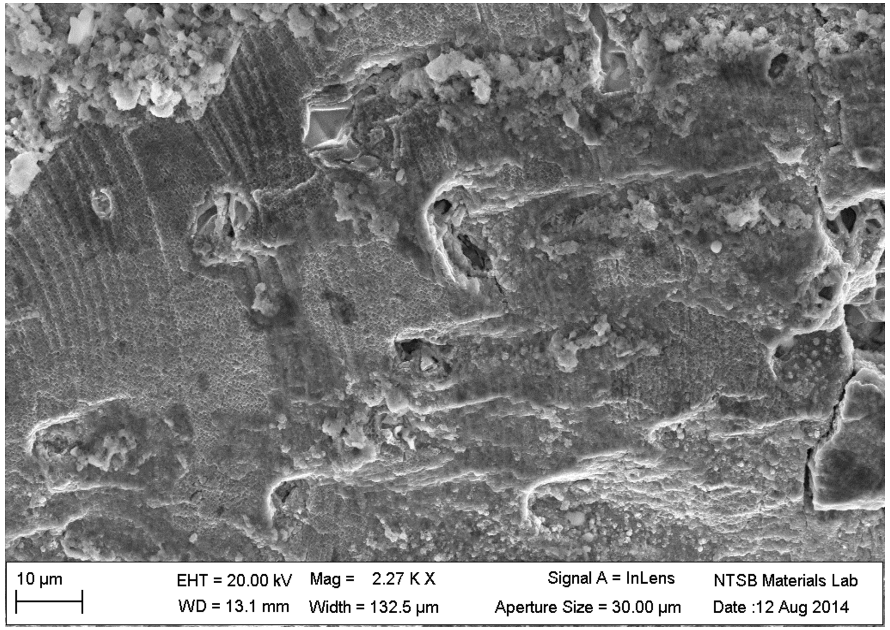
- $K = Y(\frac{a}{w})\sigma\sqrt{\pi a}$
  - K = stress concentration
  - a = crack length
  - w = width
  - Y = shape factor (1.12)
- Fracture/Yield Criteria
  - $\sigma_{CRIT} \leq \frac{K_{Ic}}{Y\sqrt{\pi a}}$



Fatigue Cracking

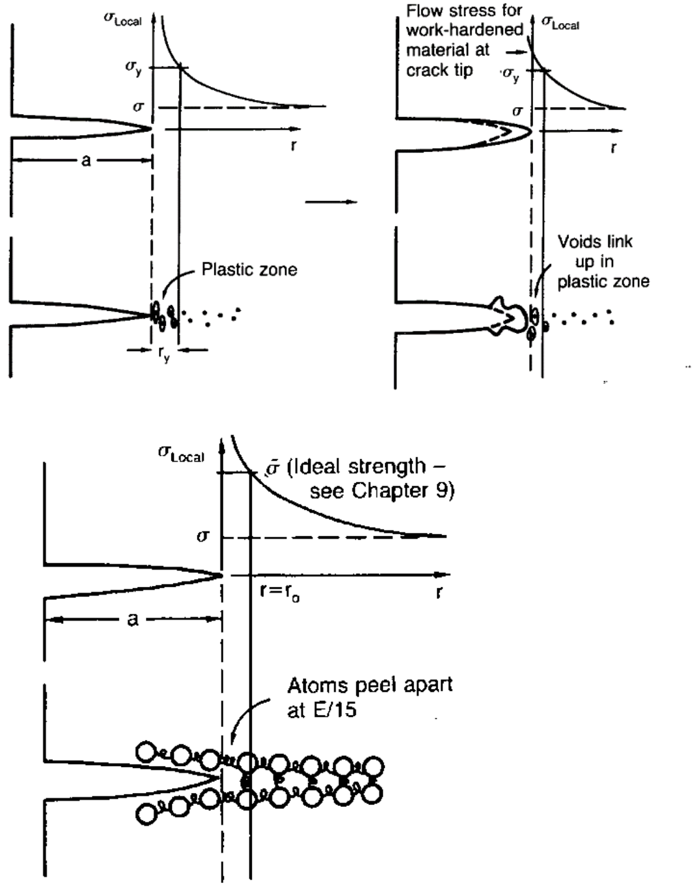
- Local stress concentration (plastic zone) breaks small amount of material
- Continues as loading cycles
- Remaining material cross-section fractures at material tensile strength





Fatigue Mechanism

- **Initiation**
  - Crack starts on active slip planes
  - Crack initially follows planes, but changes at continuities



M.F. Ashby, D.R. Jones. *Engineering Materials 1, 2nd Ed.* Oxford, UK: Butterworth Heinemann (1997)

Fatigue Cracking

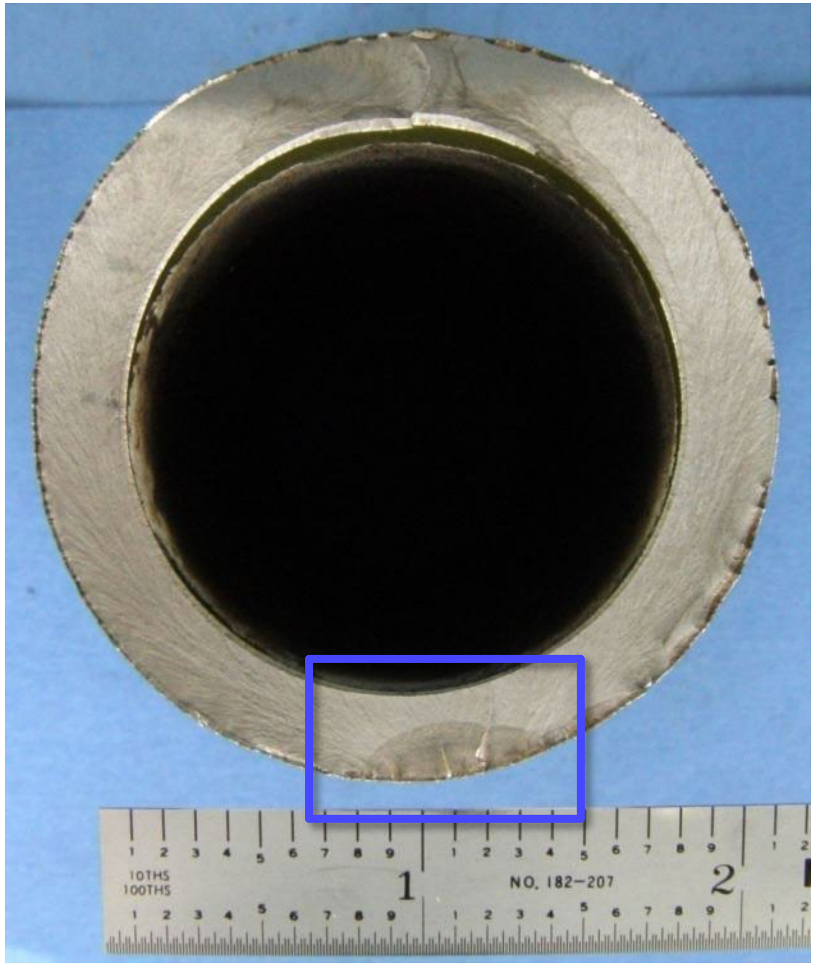
A fracture surface that is smoother and possibly discolored
Ratchet marks when multiple origins are present

Fatigue Cracking

A fracture surface that is smoother and possibly discolored

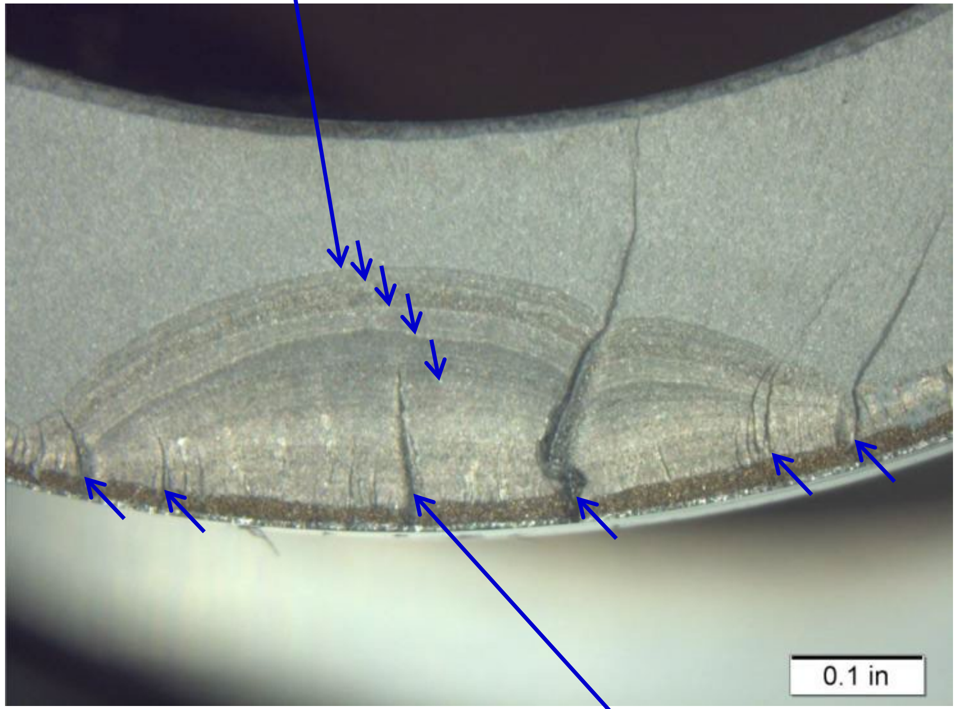
Fatigue banding pattern with smoothly curving crack arrest positions

Fatigue Crack Example



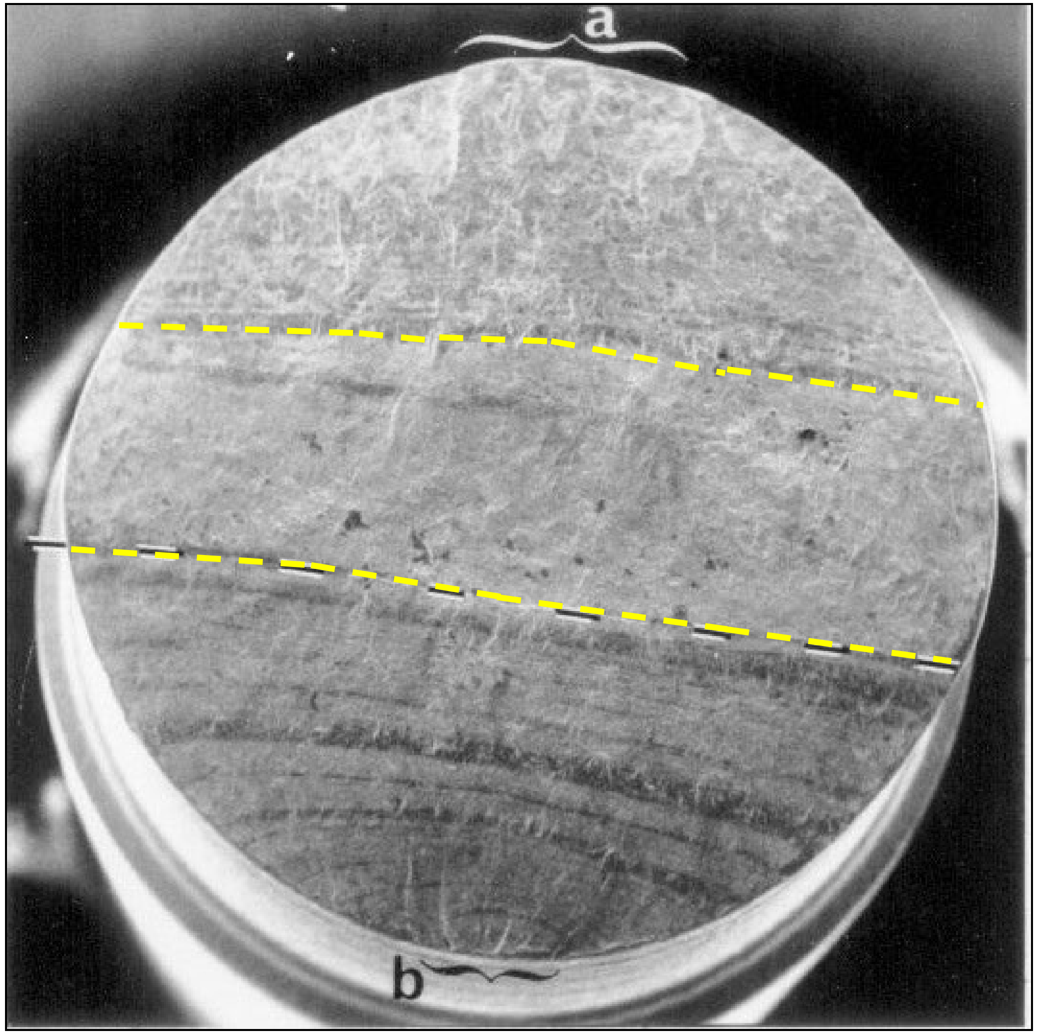
Landing Gear

Crack arrest marks

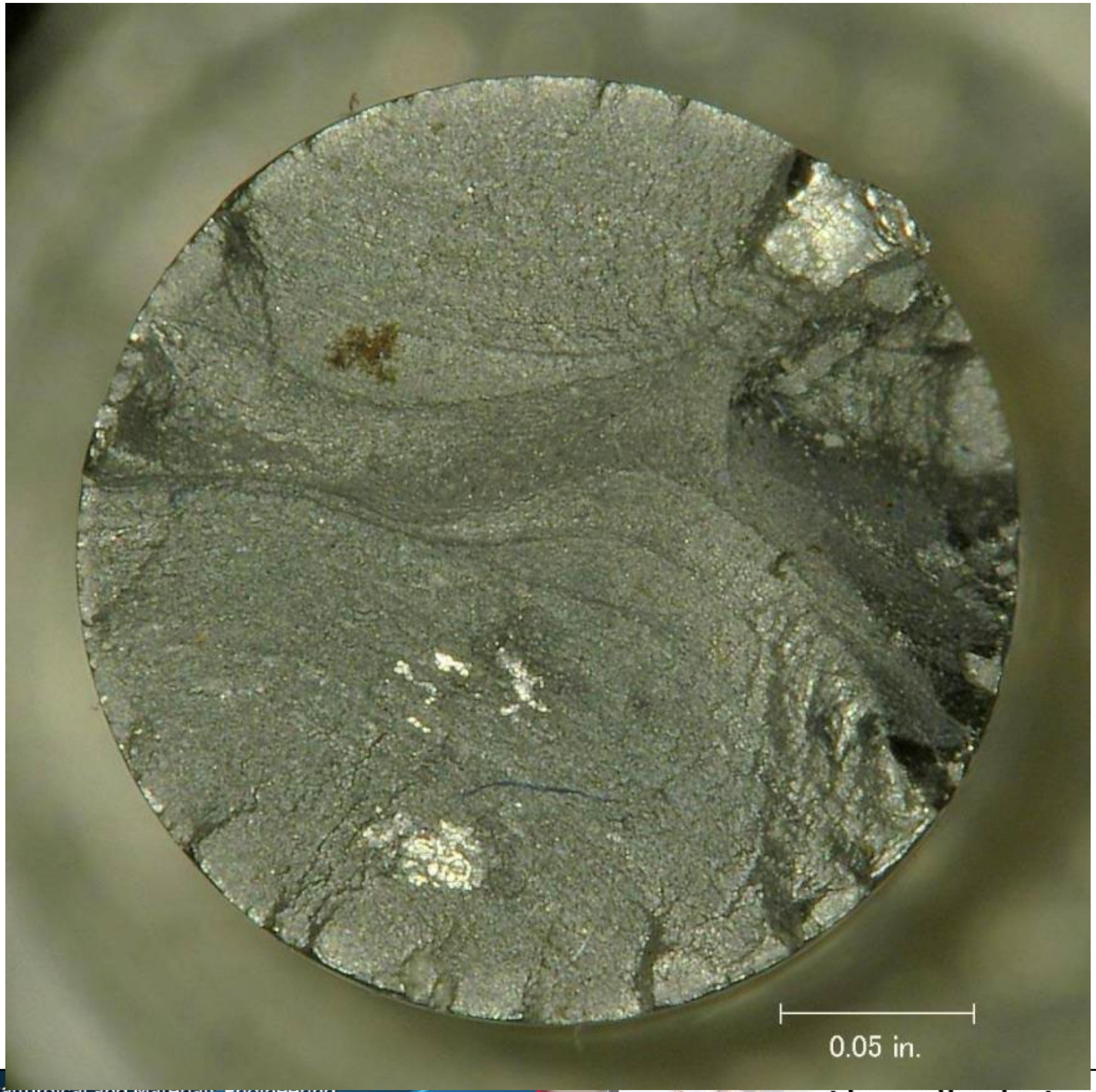


Ratchet marks

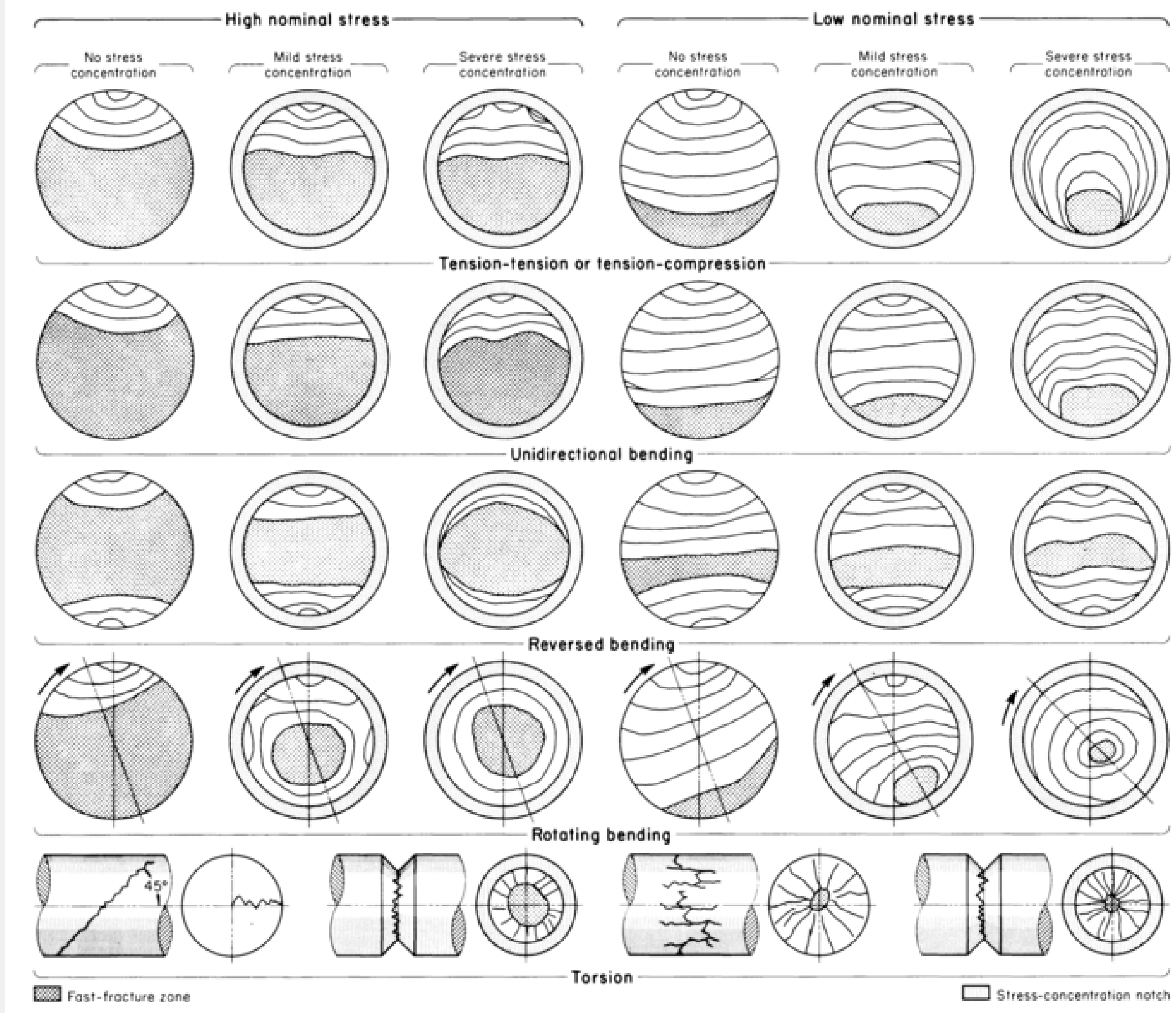
Fatigue - Reverse Bending



Fatigue - Reverse Bending



Fatigue Master Chart



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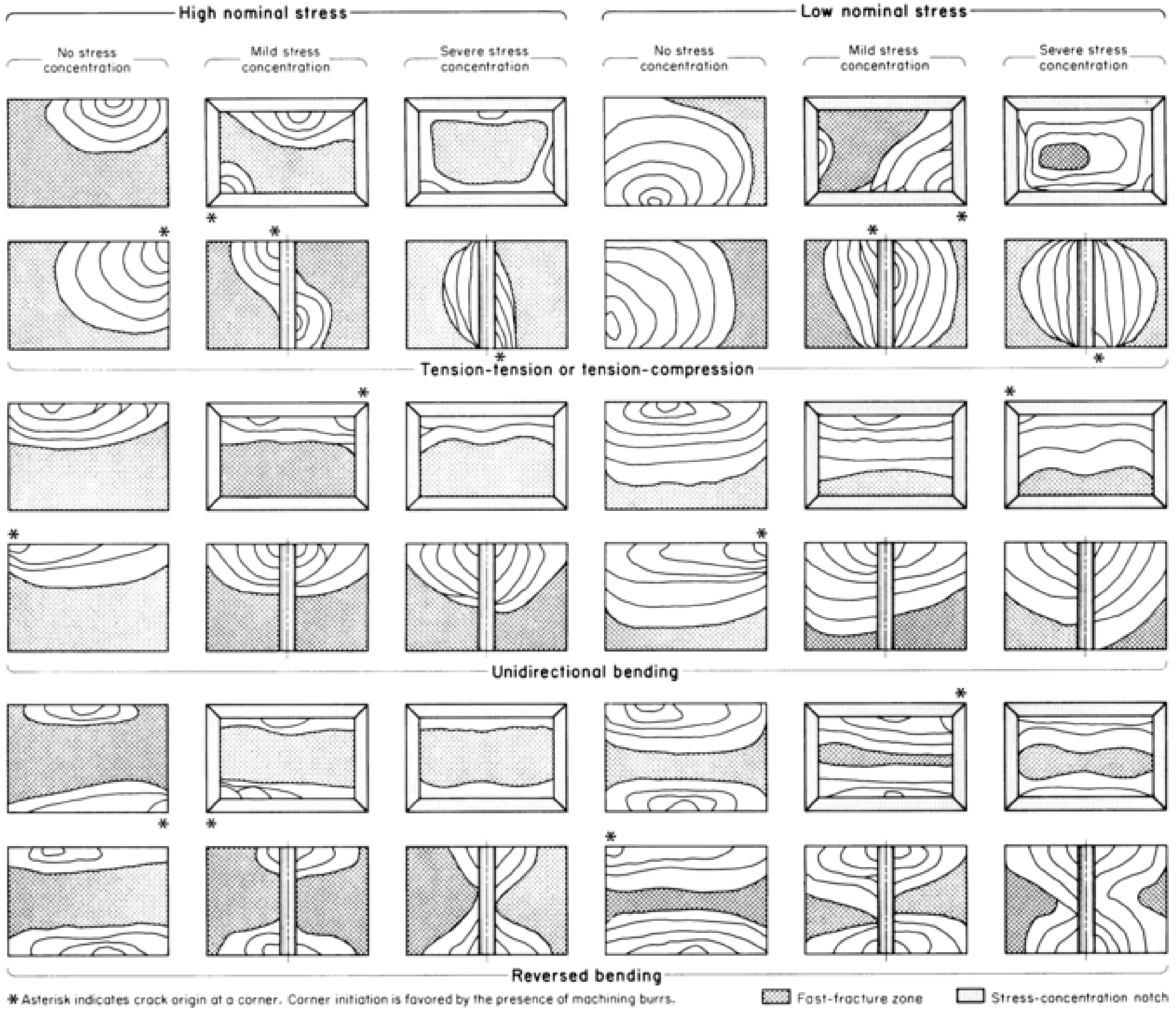
Fatigue Master Chart



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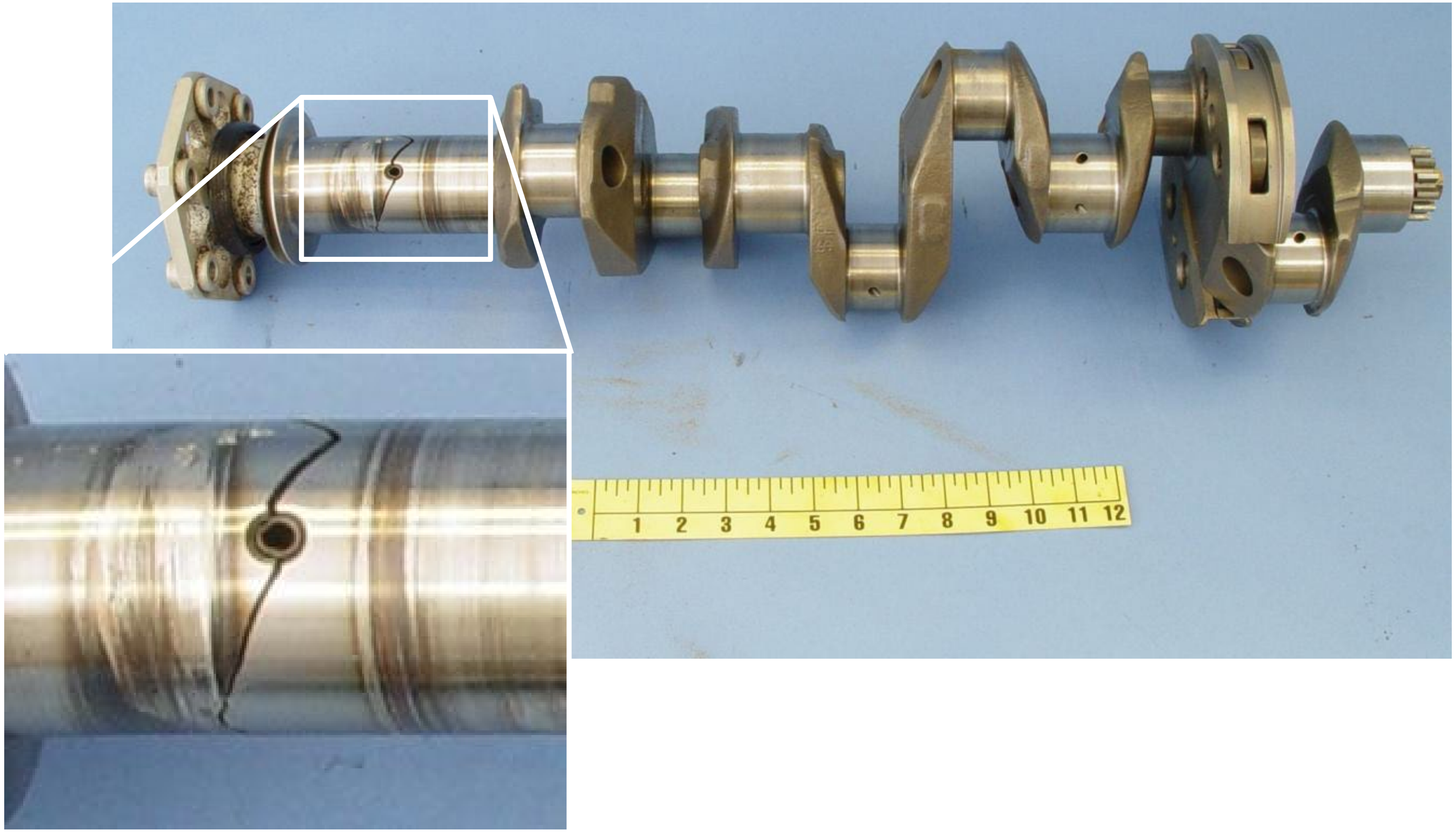
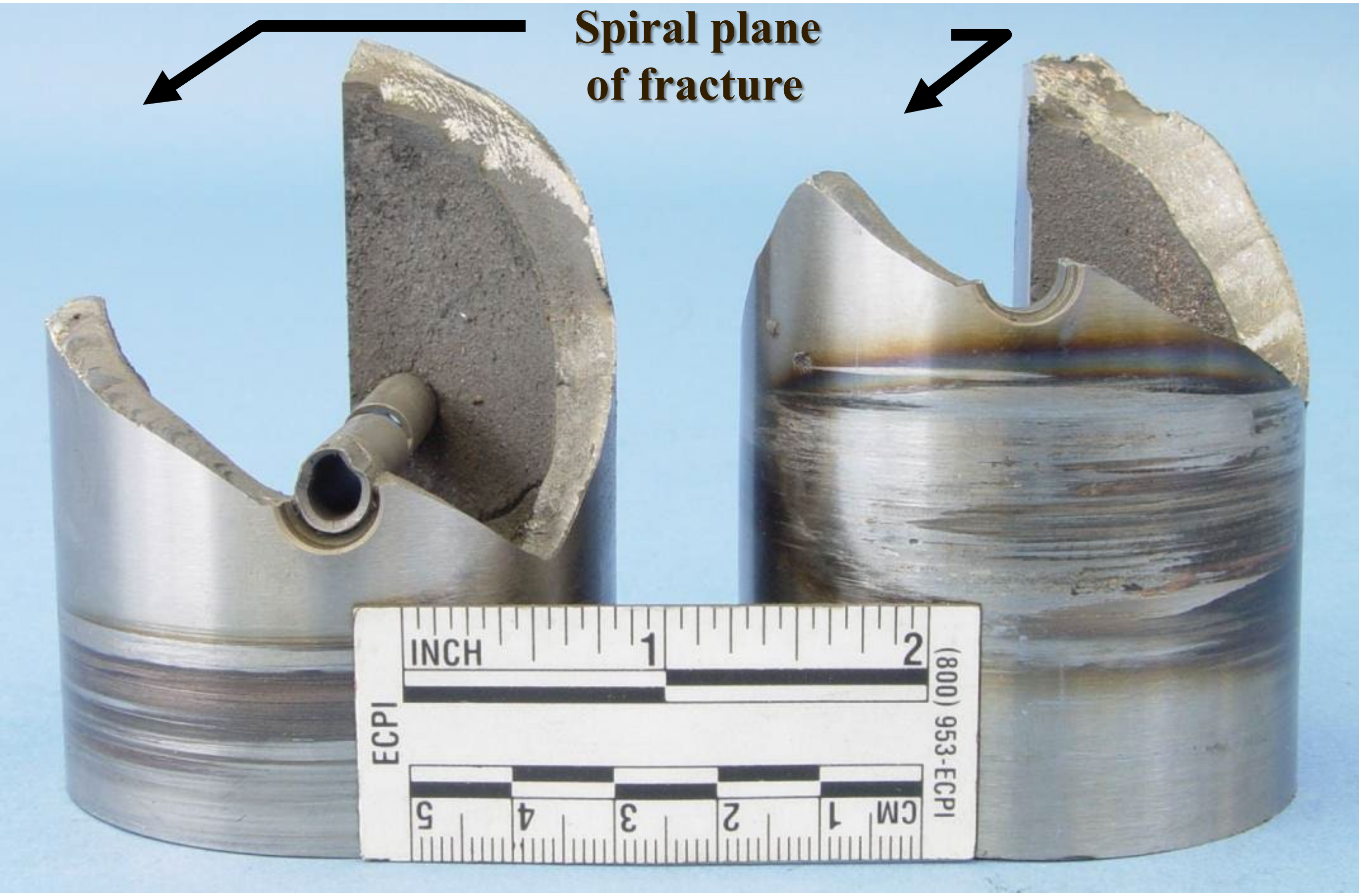
Fatigue – Torsion

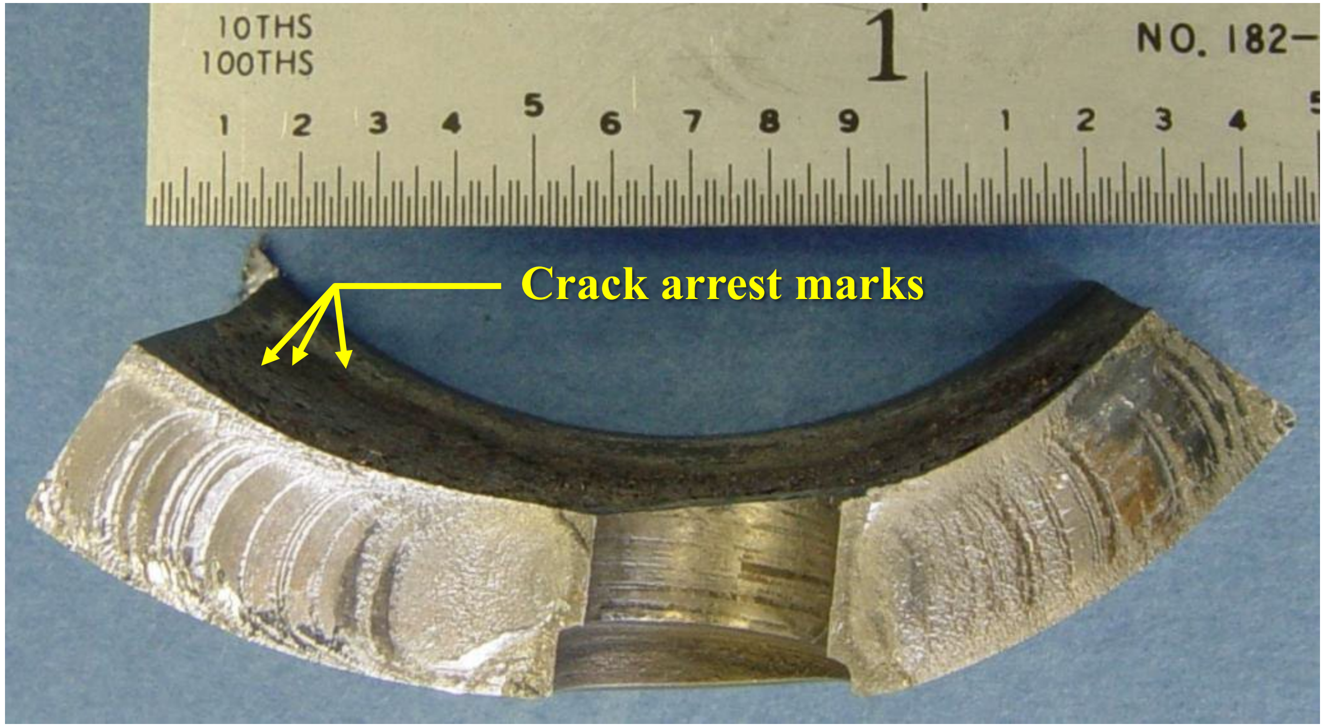


Fatigue – Torsion



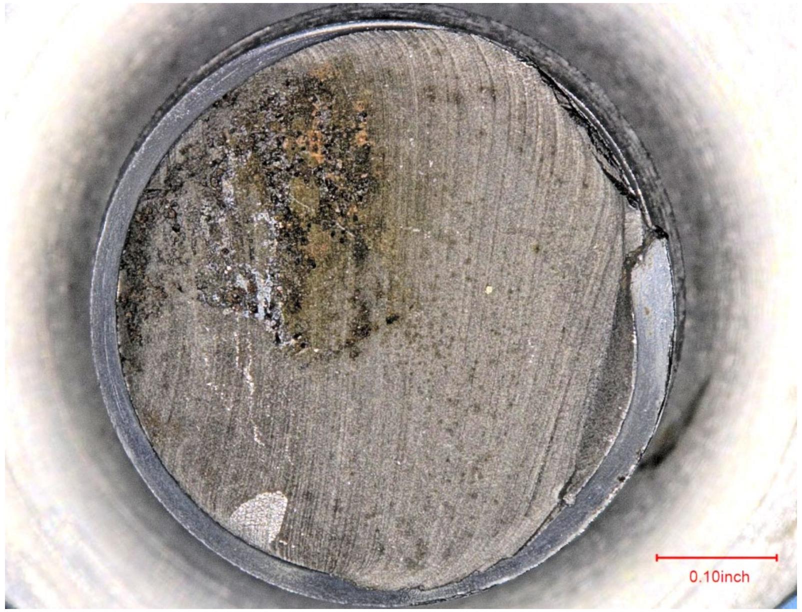
Crankshaft Main Bearing

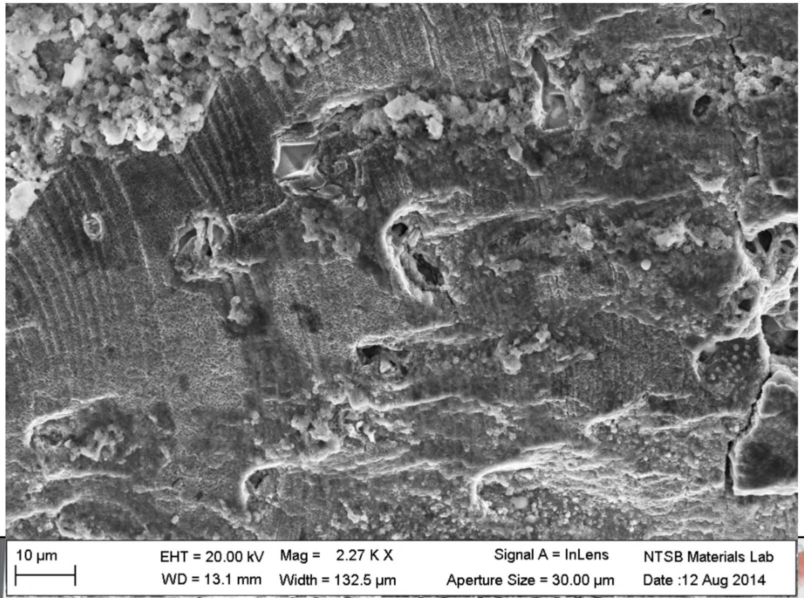
Fatigue – Torsion



Some Notes on Fatigue Terminology

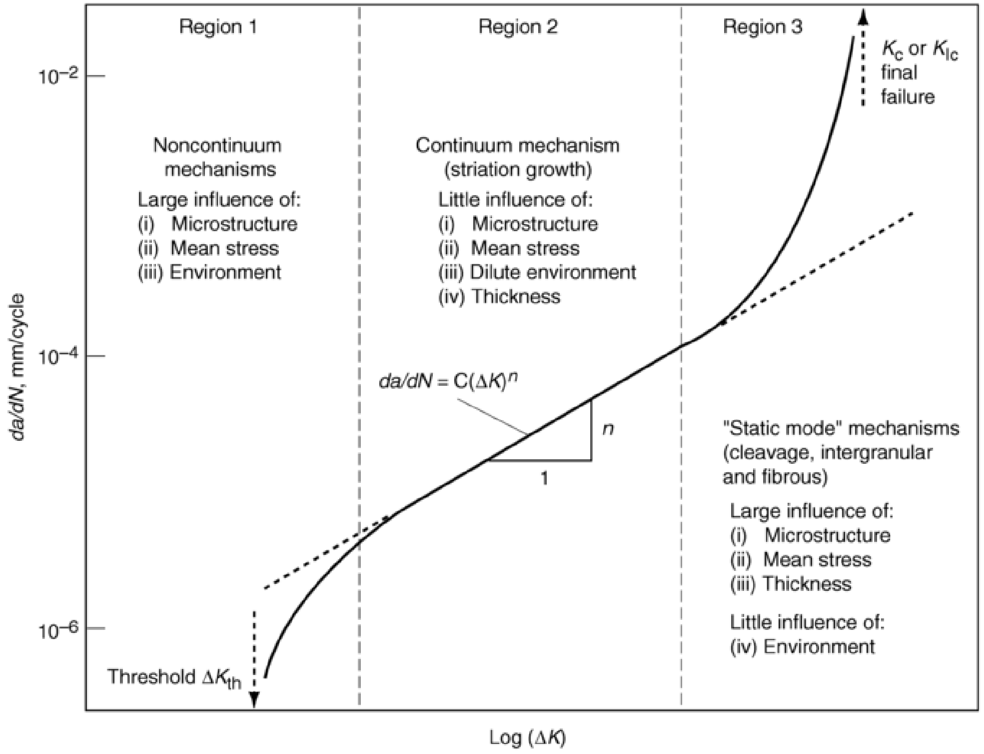
- **Crack Arrest (Beach) Marks**
  - Macroscopic
  - Visible
  - From change in crack growth rate (velocity)
- **Striations**
  - Microscopic
  - Only seen with an SEM or similar
  - From an increase in crack front after each individual stress cycle





Fatigue Crack Growth

- **Region I – Initiation**
  - Crack initiates at a stress concentration site
  - $\Delta K = K_{th}$
- **Region II – Steady state**
  - $\frac{da}{dN} = C(\Delta K)^n$
  - Paris–Erdoğan equation
- **Region III – Final Fracture**
  - $\Delta K \approx K_C$



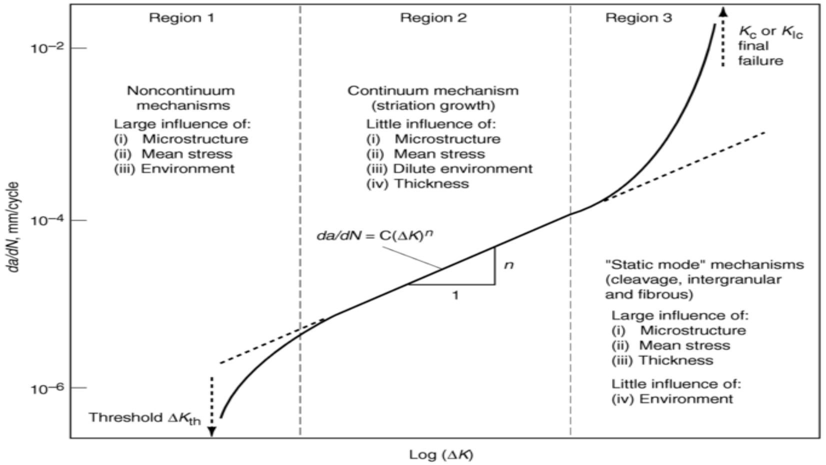
R.O. Ritchie, *Metals Science*, (1977) pp. 368-391

Factors Leading to Crack Initiation

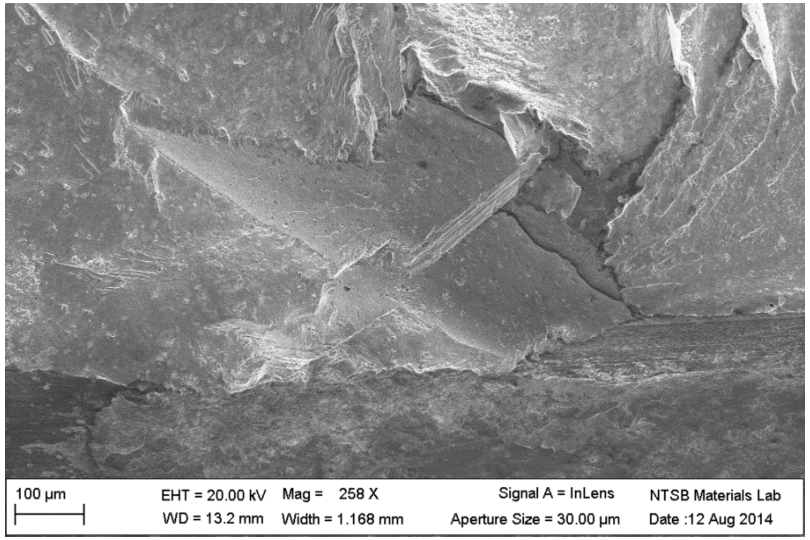
- Stress amplitude
  - High amplitude = shorter initiation time
- Specimen geometry
  - Stress concentrations at sharp corners
- Environment
  - Vacuum vs. atmosphere
- Temperature
  - Can increase slip, but also reduce brittle behavior
- Surface roughness
- Residual stress
- Phase/chemical composition
- Surface treatments (surface hardness)
- Corrosion
  - Pitting
  - Oxide film compromised

Region 1 Fatigue

- The initial stage of fatigue crack growth on slip planes
  - Creates faceted surface morphology with slip bands
  - Occurs on planes with highest shear stress (CRSS)
- Typical in lower-stress, high cycle fatigue
- Features
  - Faceted
  - Do not exhibit striations
  - Common in Ni-superalloys

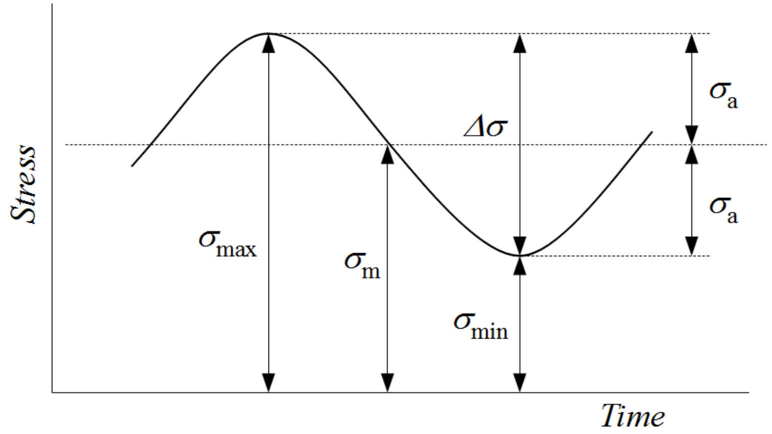


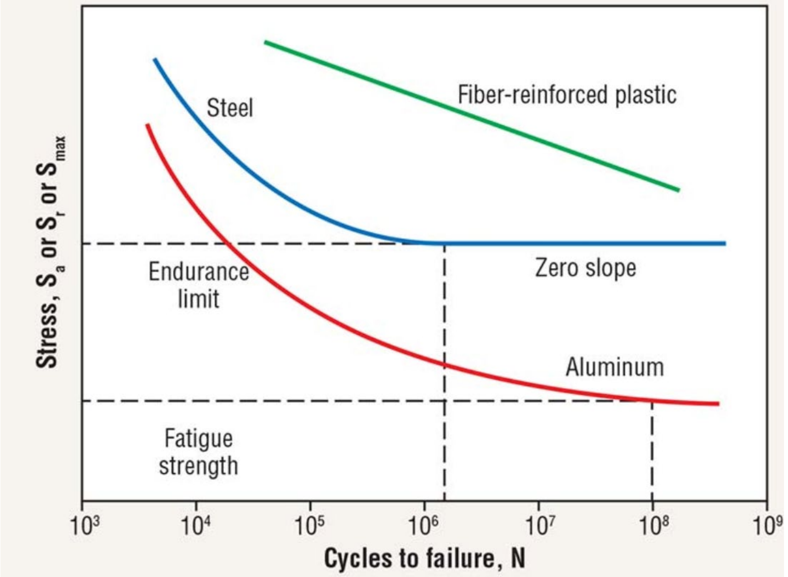
R.O. Ritchie, *Metals Science*, (1977) pp. 368-391



Some Fatigue Analysis

- **Mean stress**
  - $\sigma_M = \frac{\sigma_{MAX}+\sigma_{MIN}}{2}$
- **Stress range**
  - $\Delta\sigma = \sigma_R = \sigma_{MAX} - \sigma_{MIN}$
  - $\sigma_a = \frac{\sigma_{MAX}-\sigma_{MIN}}{2}$
- **Alternating stress**
  - $\sigma_a = \sigma_e[1 - \left(\frac{\sigma_M}{\sigma_{UTS}}\right)^x]$
    - **x = 1 for Goodman (notched)**
    - **x = 2 for Gerber (ductile)**
- **R ratio**
  - $R = \frac{\sigma_{MIN}}{\sigma_{MAX}}$
- **A ratio**
  - $A = \frac{\sigma_a}{\sigma_M} = \frac{1-R}{1+R}$

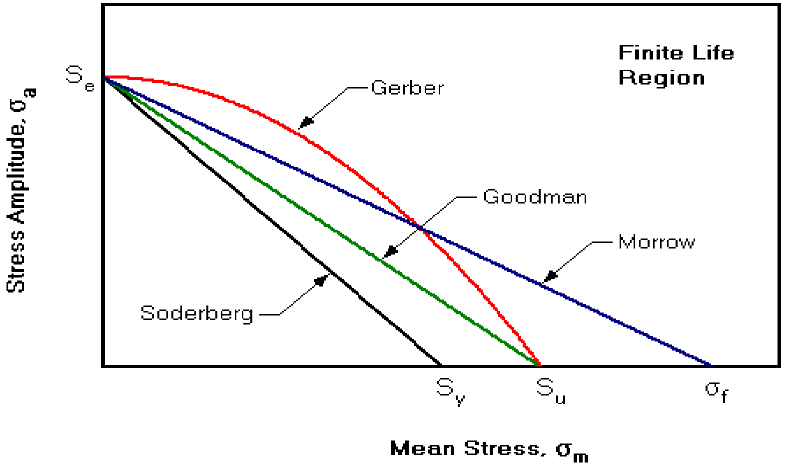




Richard Gedney "Stress-Life Fatigue Testing Basics" IndustrialHeating.com Nov 2018

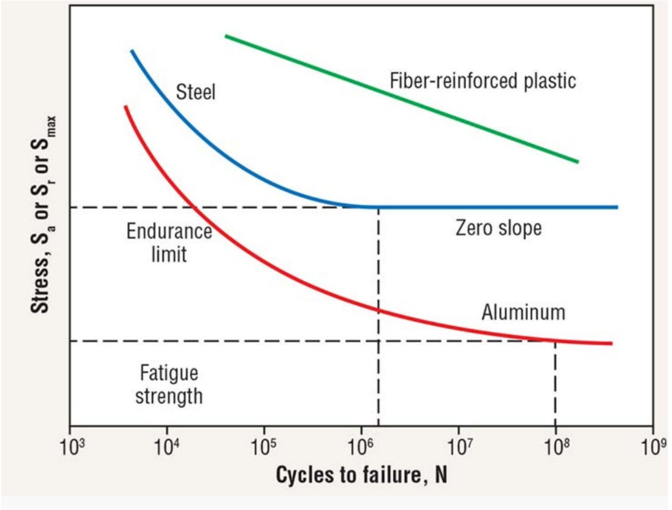
Some Fatigue Analysis

- **Goodman Relationship**
- $\frac{\sigma_a}{\sigma_e} + \frac{\sigma_M}{\sigma_{UTS}} = 1$
- **Gerber Relationship**
- $\frac{\sigma_a}{\sigma_e} + (\frac{\sigma_M}{\sigma_{UTS}})^2 = 1$
- **Morrow Relationship**
- $\frac{\sigma_a}{\sigma_e} + \frac{\sigma_M}{\sigma_f} = 1$
- **Soderberg Relationship**
- $\frac{\sigma_a}{\sigma_e} + \frac{\sigma_M}{\sigma_Y} = 1$

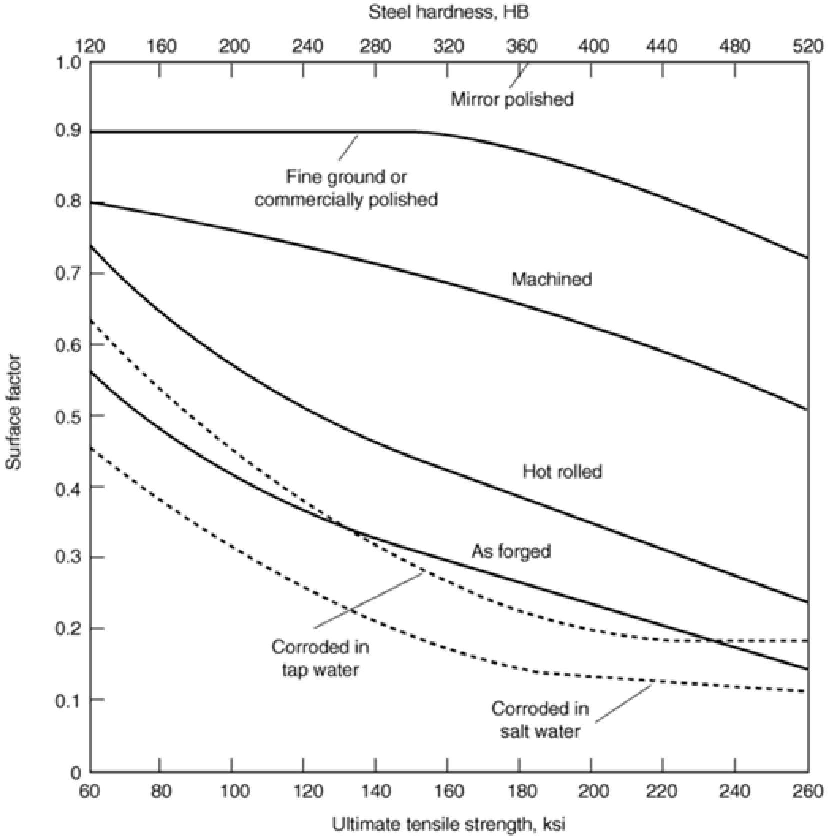


- $\sigma_M = \frac{\sigma_{MAX} + \sigma_{MIN}}{2}$
- $\sigma_A = \frac{\sigma_{MAX} - \sigma_{MIN}}{2}$

Fatigue Limit Knockdowns (Reductions)



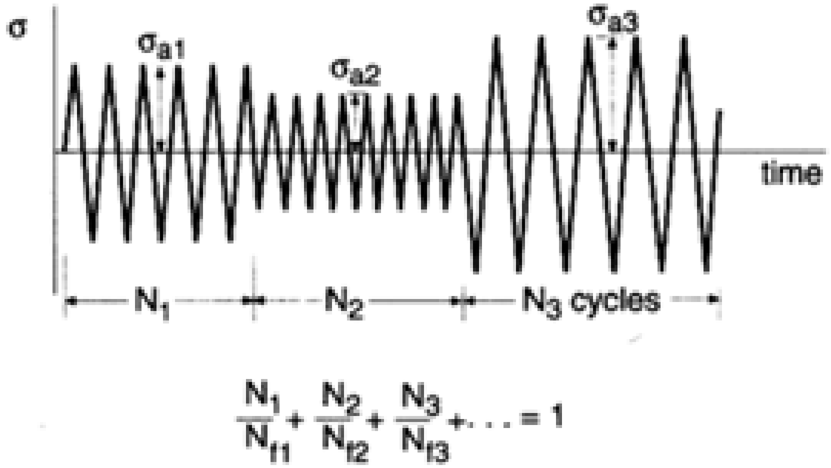
$$C_S = \begin{cases} 1.0 & D \le 10mm \\ 0.9 & 10 \le D \le 50mm \\ 1 - \dfrac{D-0.76}{380} & 50 \le D \le 230mm \end{cases}$$

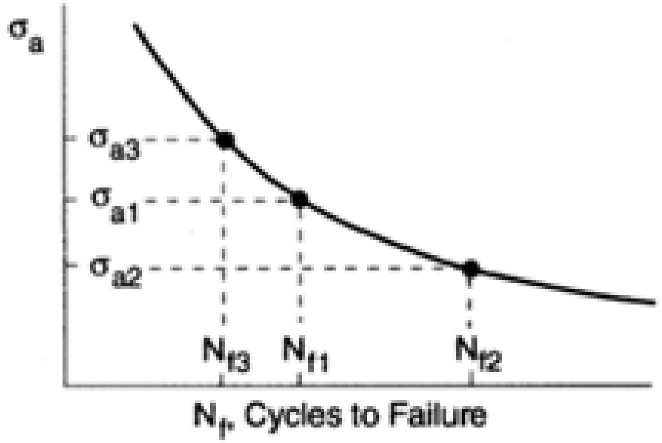


- **Endurance limit from chart: σ'_e**
- **Real endurance limit for design**
  - $\sigma_e = \sigma'_e C_S C_F C_Z$
    - **σ'_e = unnotched fatigue limit**
    - **C_S = size factor (table)**
    - **C_F = surface finish factor (table)**
    - **C_Z = scatter factor (typically 0.81)**

Accumulated Damage – Miner's Rule

- **Palmgren-Miner Rule**
  - $\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \cdots + \frac{n_k}{N_k} = 1$
- **If** $\sum \frac{n_j}{N_j} \geq 1$**, then part fails**





Fatigue Analysis - Assumptions

- **Quick Assumptions**
  - Endurance Limit and Hardness
    - For Hardness < 400 HB:
      - $\sigma_E \approx 0.25$ X (Brinell Hardness) [in ksi]
    - For Hardness > 400 HB:
      - $\sigma_E \approx 100$ ksi
  - Endurance Limit and σ_{UTS}
    - For $\sigma_{UTS} < 200$ ksi
      - $\sigma_E \approx 0.5$ X (σ_{UTS}) [in ksi]
    - For $\sigma_{UTS} > 200$ ksi
      - $\sigma_E \approx 100$ksi

Fatigue Problem #1

- **A plain sided specimen is subjected to $1x10^7$ cycles, at an applied stress range of 200 MPa. Estimate how many further cycles can be applied at a stress range of 500 MPa before failure is predicted to occur.**

Applied Stress Range (MPa)	Cycles to Failure
600	$1x10^4$
500	$2x10^4$
400	$5x10^4$
300	$3x10^5$
250	$3x10^6$
200	$8x10^7$

Fatigue Problem #1

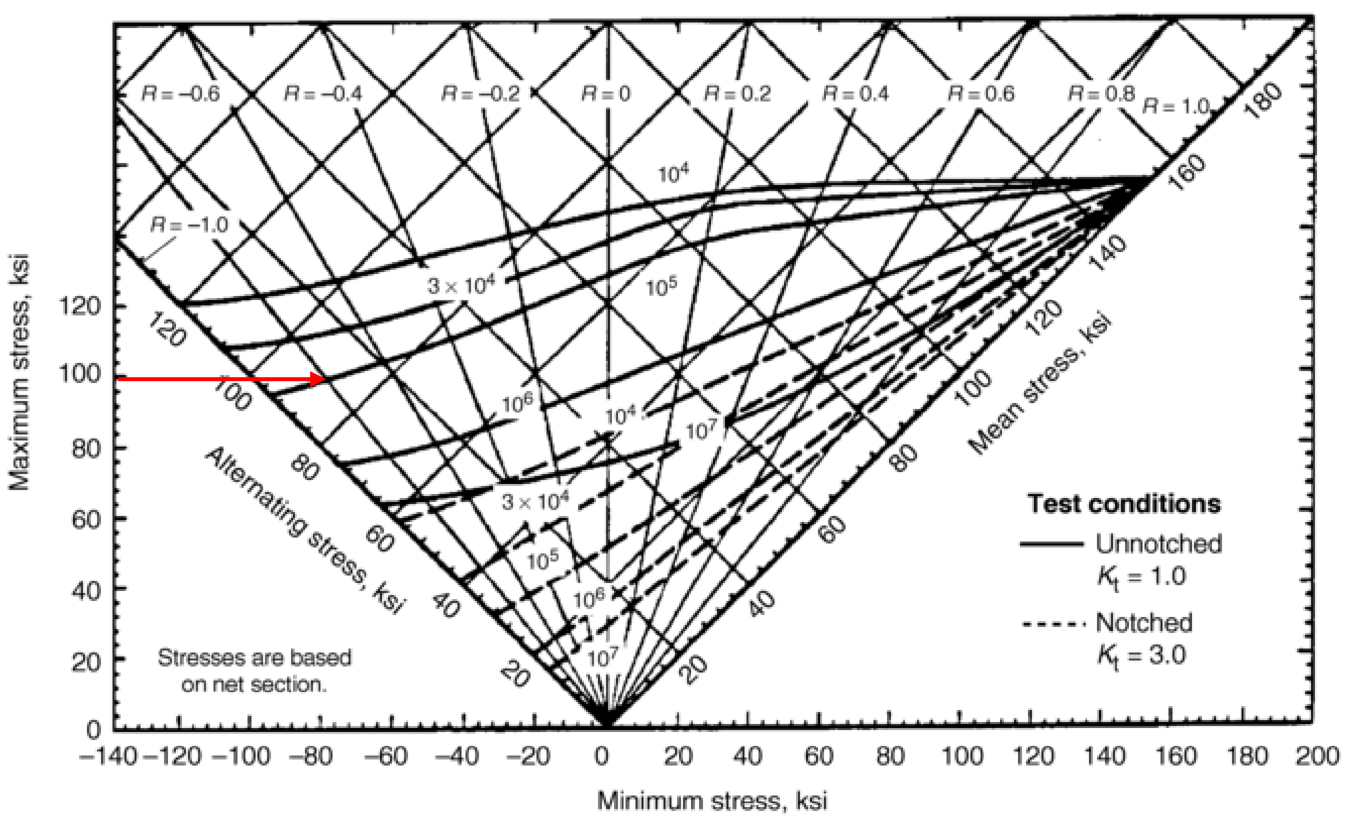
Applied Stress Range (MPa)	Cycles to Failure
600	$1x10^4$
500	$2x10^4$
400	$5x10^4$
300	$3x10^5$
250	$3x10^6$
200	$8x10^7$

- $\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_k}{N_k} = 1$
- $\frac{1*10^7}{8*10^7} + \frac{n_2}{2*10^4} = 1$
- $\frac{1}{8} + \frac{n_2}{2*10^4} = 1$
- $\frac{n_2}{2*10^4} = \frac{7}{8}$
- $n_2 = 1.75 * 10^4\ cycles$

Fatigue Problem #2

- A company is using an unnotched steel bar in a high cycle fatigue environment. The company has the Goodman diagram for the material. With a maximum stress of 100 ksi in complete reverse bending, at what interval should the bar be inspected, assuming inspection at no more than half the expected fatigue life?
  - A) 10000 cycles
  - B) 50000 cycles
  - C) 100000 cycles
  - D) 1500 cycles

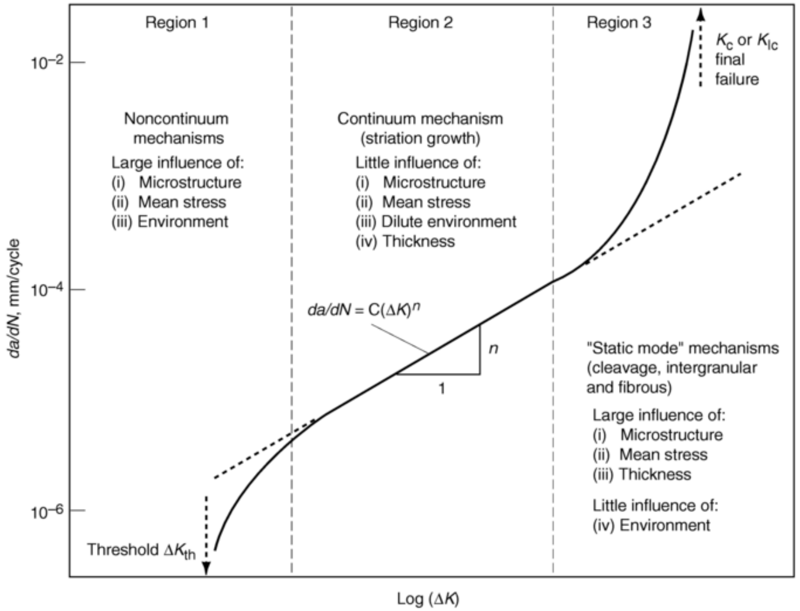
Fatigue Problem #2



MIL-HDBK-5D, Military Standardization Handbook, *Metallic Materials and Elements for Aerospace Vehicle Structures*, 1983, p 5–87

Region 2 Fatigue

- **Paris-Erdoğan Law**
  - **Steady State (Stage II) Fatigue**
  - $\frac{da}{dN} = \frac{A(\Delta K)^p}{(1-R)K_{Ic}-\Delta K}$
    - **p = 3 for steel, 3-4 Al**
    - **A = constant**
    - **R = R-ratio**
  - $N_f = \frac{a_f^{-\frac{p}{2}+1} - a_i^{-\frac{p}{2}+1}}{\left(-\frac{p}{2}+1\right) A \sigma^p \pi^{p/2} Y^p}$



R.O. Ritchie, *Metals Science*, (1977) pp. 368-391

Fatigue Problem #3

- A 7075-T651 plate with a 2 in thickness was inspected with UT and found to have no cracks, but the detection limit is 0.01 mm. The plate had been subjected to alternating tensile stresses of 25 MPa and 125 MPa for 350000 cycles. The plate is to be subjected to alternating tensile and compressive stresses of 250 MPa. How many of the additional cycles can be sustained before failure?
- Assume n = 3.1, and A = 1.8×10^{-10}.
  - A) 3500 cycles
  - B) 19500 cycles
  - C) 310 cycles
  - D) 46000 cycles

p. 12

Alloy	Condition	Ultimate Tensile Strength (UTS)	% Elongation	Fracture Toughness (K_{Ic})	Endurance Limit
		MPa		MPa(m)$^{1/2}$	MPa
AISI-SAE 1020 Steel	Annealed	395	36.5	60	220
AISI-SAE 1040 Steel	Annealed	519	30.2	60	275
AISI-SAE 4130 Steel	Annealed	561	28.2	100	280
AISI-SAE 4130 Steel	WQ&T(425°C)	1282	13.0	45	510
AISI-SAE 4140 Steel	Q&T (650°C)	758	22	65	350
AISI-SAE 4340 Steel	Annealed	745	22.0	100	310
AISI-SAE 4340 Steel	OQ&T(425°C)	1469	10.0	80	560
AISI-SAE 8620 Steel	Annealed	536	31.3	90	280
AISI-SAE 9310 Steel	Annealed	470	17.3	115	375
AISI 304 Stainless Steel	Annealed	515	40	65	170
AISI 304 Stainless Steel	1/2 Hard	1035	7	95	490
AISI 304L Stainless Steel	Annealed	480	40	60	280
AISI 316 Stainless Steel	Annealed	515	40	65	240
AISI 17-4PH Steel	H1150	930	16	180	450
AISI 410 Stainless Steel	Annealed	450	20	70	290
AISI 410 Stainless Steel	Hard	1310	15	50	385
AISI 2205 Duplex Stainless Steel	Annealed	800	22	170	275
1100 Aluminum	O Temper	90	35	32	24
2024 Aluminum	Annealed (O)	185	20	38	90
2024 Aluminum	Aged (T4)	470	20	40	140
2024 Aluminum	Aged (T6)	470	20	40	140
3003 Aluminum	Annealed (O)	110	40	48	50
6061 Aluminum	Aged (T6)	310	17	33	95
7075 Aluminum	Annealed (O)	230	16	37	52
7075 Aluminum	Aged (T6)	570	11	30	160
C10200 (Oxygen-Free Copper)	OS25	235	45	81	75
Cartridge Brass (70Cu30Zn, C26000)	Soft	340	57	72	95
5% Phosphor Bronze (C51000)	Soft	365	50	61	158
5% Phosphor Bronze (C51000)	Hard	560	10	29	240
Inconel 718 (N07718)	Solution Treated and Aged (STA)	1240	12	125	620
Inconel 625 (N06625)	Annealed	930	42.5	200	475
Ti-6Al-4V	Annealed	930	14	95	550
Ti-6Al-4V	Solution Treated and Aged	1170	10	90	625

Fatigue Problem #3

- What do we know?
  - 25 MPa <> 125 MPa, 350000 cycles
    - a_0 = 0.01 mm, a_f = ??
  - -250 MPa <> 250 MPa, N_f = ??
    - a_f = ??, a_c = ??
  - K_{IC} = 29 MPa*$m^{1/2}$
  - n (or p) = 3.1, and A = 1.8×10^{-10} , Y = 1.12

- $N_f = \frac{a_f^{-\frac{p}{2}+1} - a_i^{-\frac{p}{2}+1}}{\left(-\frac{p}{2}+1\right) A \sigma^p \pi^{p/2} Y^p}$

- $350000 = \frac{a_f^{-\frac{3.1}{2}+1} - (1*10^{-5}\ m)_i^{-\frac{3.1}{2}+1}}{\left(-\frac{3.1}{2}+1\right)*1.8*10^{-10}(125-25\ MPa)^{3.1}\pi^{\frac{3.1}{2}}(1.12^{3.1})}$

- $= \frac{a_f^{-0.55} - (0.00001)^{-0.55}}{(-0.55)*1.8*10^{-10}(100)^{3.1}\pi^{1.55}(1.12^{3.1})} = \frac{a_f^{-0.55} - 562.341}{-1.315*10^{-3}}$

- $a_f^{-0.55} - 562.341 = -460.25$

- $a_f^{-0.55} = 102.091$

- $a_f = 2.22483 * 10^{-4}\ m$

- $K_{Ic} = Y * \sigma\sqrt{\pi * a_c}$
- $K_{Ic} = 29 = 1.12 * 250\sqrt{\pi * a_c}$
- $1.77245 * a_c^{0.5} = \frac{29\ MPa*m^{0.5}}{1.12*250\ MPa} = 0.10357$
- $a_c^{0.5} = 0.05843324$
- $a_c \ = 3.41444 * 10^{-3}\ m$
  - This is the crack length where we will break

- $$N_c = N_f = \frac{a_f^{-\frac{p}{2}+1} - a_i^{-\frac{p}{2}+1}}{\left(-\frac{p}{2}+1\right) A\sigma^p \pi^{p/2} Y^p}$$

- $$N_c = \frac{(3.41444 * 10^{-3})^{-\frac{3.1}{2}+1} - (2.2483 * 10^{-4}\ m)_i^{-\frac{3.1}{2}+1}}{\left(-\frac{3.1}{2}+1\right) * 1.8 * 10^{-10} (250\ MPa)^{3.1} \pi^{\frac{3.1}{2}} (1.12^{3.1})}$$

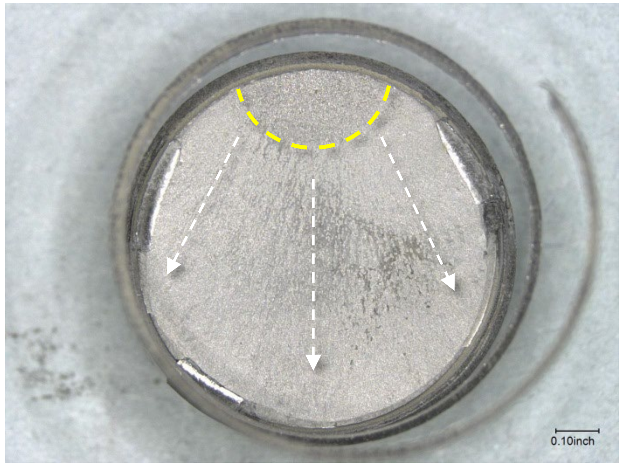
- $$N_c = \frac{22.73392 - 101.503}{(-0.55) * 1.8 * 10^{-10} (250)^{3.1} \pi^{1.55} (1.12^{3.1})} =$$

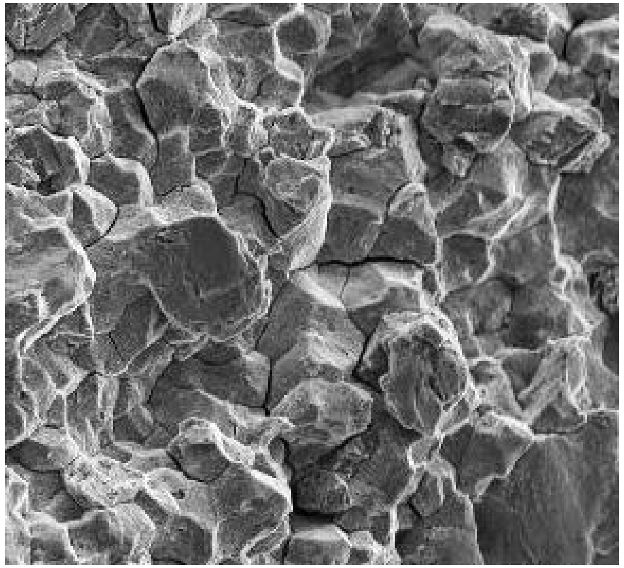
- $$N_c = \frac{-78.769}{-2.251 * 10^{-2}}$$

- $$N_c = 3499.03\ cycles$$

Stress Corrosion Cracking

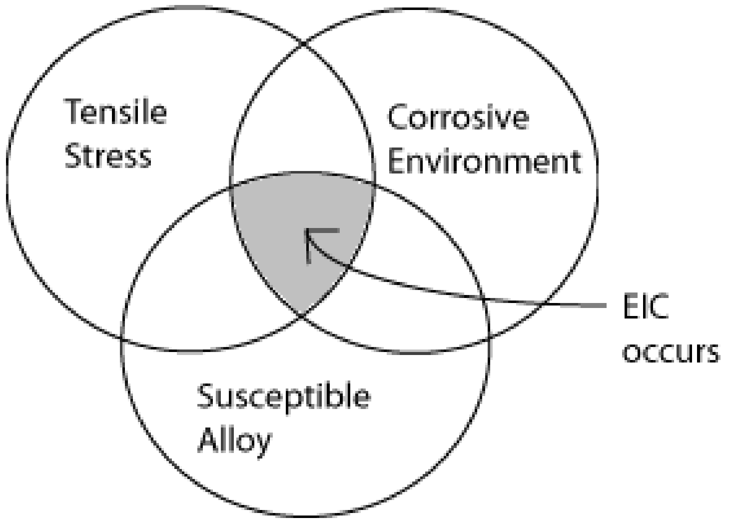
- **Synergistic effect of local corrosion of material under stress**
- **Visually similar to fatigue**
  - **Microscopically very different**
- **Difficult to predict and detect**
- **Certain materials are susceptible in certain environments**





Stress Corrosion Cracking

- **Susceptible Material**
- **Corrosive Environment**
- **Applied stress**



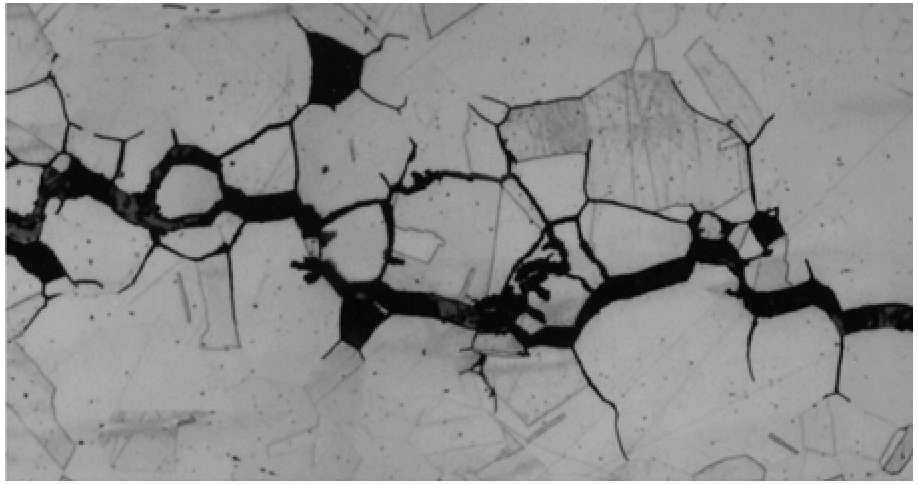
Alloy	K_{Ic} (MN/m$^{3/2}$)	SCC environment	K_{ISCC} (MN/m$^{3/2}$)
13Cr steel	60	3% NaCl	12
18Cr-8Ni	200	42% $MgCl_2$	10
Cu-30Zn	200	NH_4OH, pH7	1
Al-3Mg-7Zn	25	Aqueous halides	5
Ti-6Al-1V	60	0.6M KCl	20

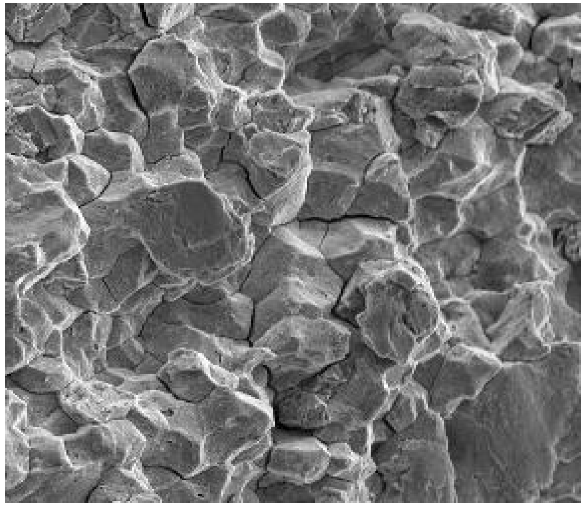
D.H. Herring "Hydrogen Embrittlement", *Wire Forming Technology, Fall 2010*

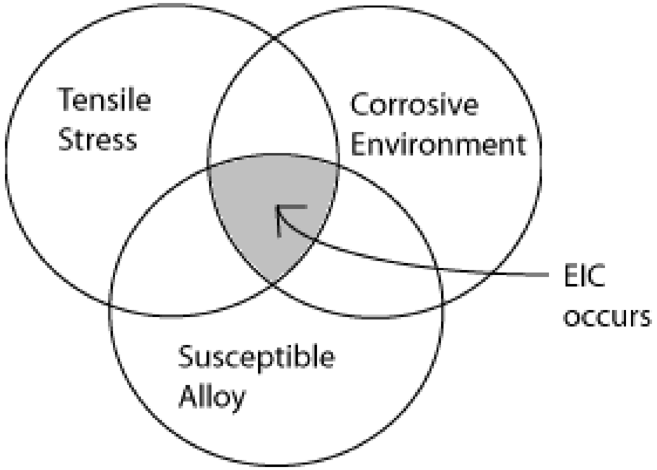
Materials Susceptible to SCC

Chemical Species	Alloys	Temperature of Attack
Chlorides: $Cl_{(aq)}$	• Austenitic stainless steel • High strength steels • High strength aluminums	• Above room T • Room T • Room T
Fluorides: $F_{(aq)}$	• Sensitized austenitic stainless steels	Room T
Fused Chloride Salt	• Titanium alloys • Zirconium alloys	• Above salt T_M • Above salt T_M
Hydroxides: OH^-	• Carbon steel	100°C
Aqueous nitrates	• Carbon steel	100°C
$H_2S_{(g)}$	• HSLA steels	Room T
$N_2O_{4(l)}$	• Titanium alloys	50°C
Ammonia: $HN_{3(g)}$, $NH_4{}^+{}_{(aq)}$	• Copper alloys	Room T
Wet nitrogen oxides	• Copper alloys	Room T

Stress Corrosion Cracking

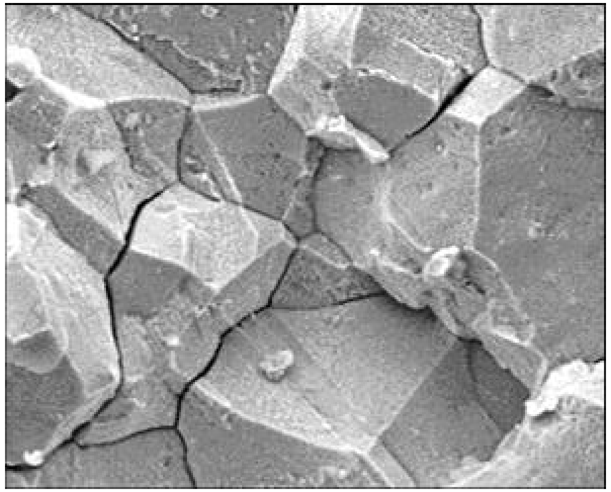


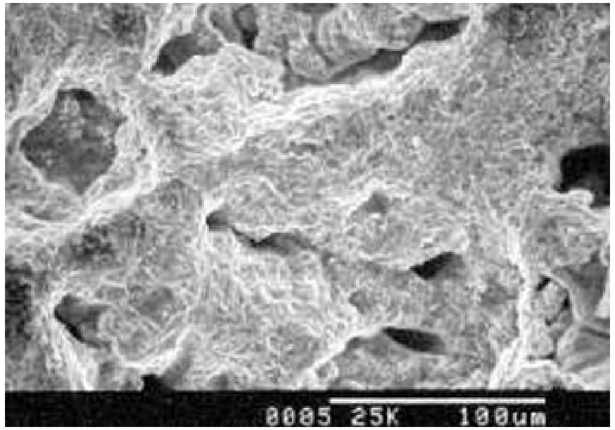




Other Failure Modes

- Environmental Decohesive Rupture
  – Hydrogen embrittlement
  – Heat treating embrittlement
  – Selective corrosion
  – Bulk corrosion
- Thermal Decohesive Rupture
  – Creep
- Mixed Source Failure
  – Corrosion Fatigue
  – Thermomechanical Fatigue

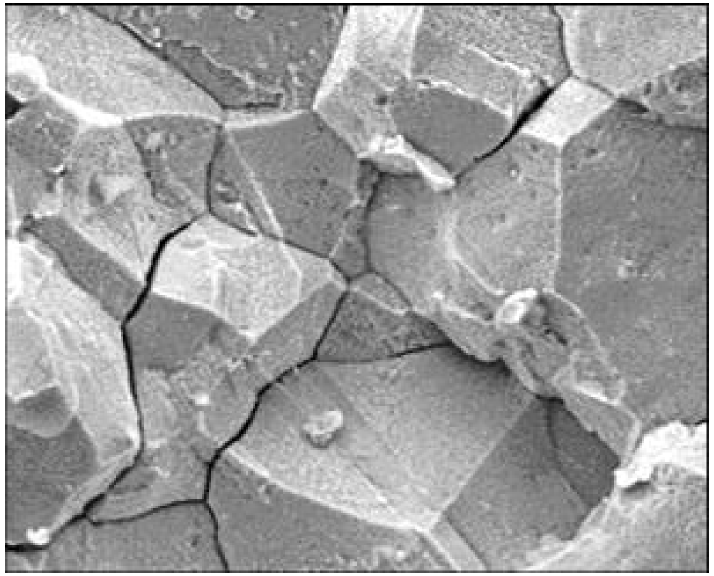




V. Kerlins and A. Phillips, Modes of Fracture, *Fractography*, Vol. 12, *ASM Handbook*, ASM International, 1987

Hydrogen Embrittlement

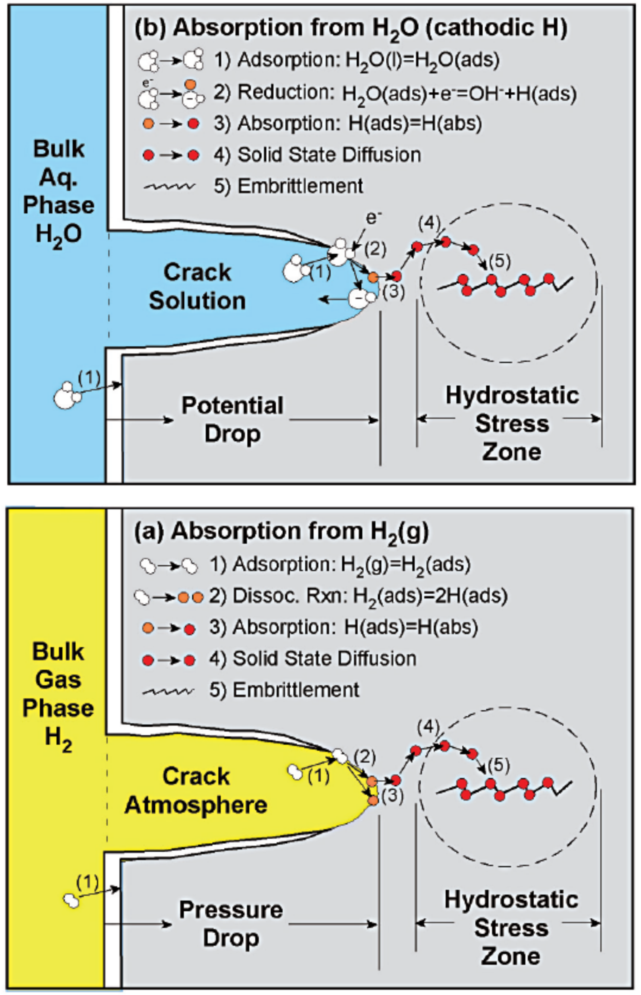
- **Exposure to H or H-generating environments lowers material K_{IC}**
- **Mechanism (debated)**
  - **Porosity from H_2 bubbles**
  - **Hydride formation**
  - **H reaction with alloying elements**
  - **GB pinning**
  - **Interaction with screw dislocation core**
- **Fracture surface is intergranular**



V. Kerlins and A. Phillips, Modes of Fracture, *Fractography*, Vol. 12, *ASM Handbook*, ASM International, 1987

Hydrogen embrittlement

- **Processes introducing H**
  - Electroplating
  - Pickling
  - Arc welding in moisture
  - Galvanic corrosion
- **Susceptible materials**
  - High strength steels (> 30 HRC or 145 ksi/1000 MPa)
  - PH Stainless steel



D.H. Herring "Hydrogen Embrittlement", *Wire Forming Technology, Fall 2010*

Hydrogen embrittlement reduction

- Avoid processes that produce H^+/H_2
- Use substrates/catalysts
- Baking (Bake out)
  - Hold metal at elevated temperature
  - Must be done before material cracks (within 24 hrs.)
- Welding
  - Pre/post-weld HT
  - Low H electrodes
    - Don't use wet electrodes!
- Use low-impurity alloys
- Reduce residual stress

Table 1. Hydrogen Bake-Out Requirements for High Strength Parts.

Tensile Strength		Hardness (HRC)	Time (hrs) Post Plate Bake Out at 375º- 430ºF (190º - 220ºC)
MPa	ksi		
1700 – 1800	247 – 261	49 – 51	22+
1600 – 1700	232 – 247	47 - 49	20+
1500 – 1600	218 – 232	45 - 47	18+
1400 – 1500	203 – 218	43 - 45	16+
1300 – 1400	189 – 203	39 – 43	14+
1200 – 1300	174 – 189	36 – 39	12+
1100 – 1200	160 – 174	33 – 36	10+
1000 – 1100	145 -160	31 – 33	8+

Note: Per *ASTM B 850-98 (2009)*, Standard Guide for Post-Coating Treatments of Steel for Reducing the Risk of Hydrogen Embrittlement.

Embrittlements - Steels

- **Blue Brittleness**
  - Occurs in steels worked in 205-305°C (400-700°F). Killing with Al prevents this by tying up N. A rapid form of *strain age embrittlement.*
- **Strain age embrittlement**
  - Occurs in low-C steels when deformed 15% and aged slowly (<200°C). Creates Lüders bans. Kill steel or barely deform (1%) to prevent.
- **Quench-age Embrittlement**
  - Occurs in 0.04-0.12% C steels; quench rapidly from below A_{c1} and let sit.
  - Caused by C atmospheres around dislocations

Embrittlement - Steels

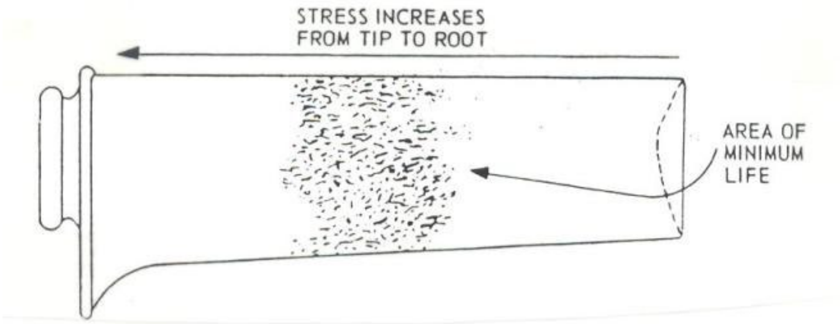
- **Tempered Martensite Embrittlement**
  - (350°C/500°F Embrittlement)
  - Alloyed and mid-C steels
  - Occurs when tempering high-strength alloy steels to 205-370°C (400-700°F).
  - Caused by cementite precipitation on prior austenite grain boundaries and segregation of impurities on prior GB.
- **Temper Embrittlement**
  - Tempering of low alloy steels
  - Occurs when cooling too slow through 300-600°C (570-1110°F).
  - Caused by segregation of Sb, P, Sn, As impurities at GBs; shifts DBT upward.
  - Reverse by re-tempering above critical T range, and cooling more rapidly.
- **Quench Cracking**
  - Cracking during quenching in high hardness, low toughness steels
  - AISI 4340

Embrittlement - Stainless

- <u>Thermal Embrittlement</u>
  - Maraging Stainless Steels
  - Precipitation of TiN/TiC on austenite GB during cooling in 430-815°C (800-1500°F)
  - Reduce time in range and C,N levels
- <u>Sensitization</u>
  - Austenitic and duplex stainless
  - Between 425-815°C (800-1500°F), precipitate $Cr_{23}C_6$ at GB's, pulling Cr out of solution and making GB's anodic to the bulk
  - Rapidly cool, add Ti/Nb to tie up C, use low-C alloys
- <u>475°C/885°F Embrittlement</u>
  - Ferritic Stainless
  - Rapid homogeneous precipitation between 20-120 hrs
  - Increases with C, Cr additions
- <u>Sigma-phase Embrittlement</u>
  - All stainless steels, some superalloys
  - Form FeCr (σ phase) below 500°F at long service times

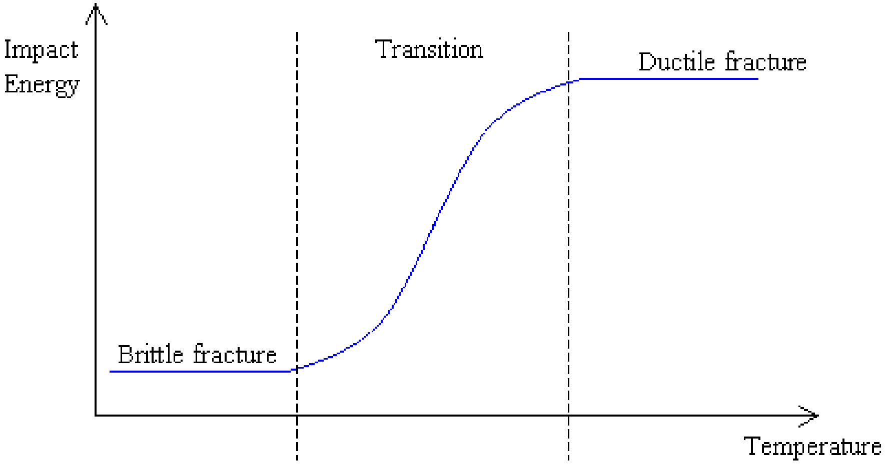
Creep and High Temp Failure

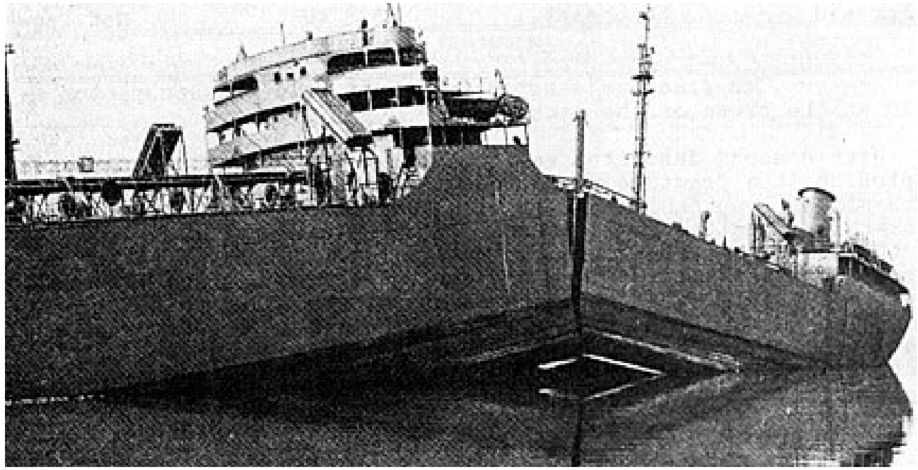
- **Material flows at high temperature under stress**
  - **Fastest at grain boundaries**
- **Most common in turbine components**
  - **Blades**
  - **Discs**
  - **Also stationary parts**
- **A common consequence of compressor stalls**
  - **Overtemperature exposure**



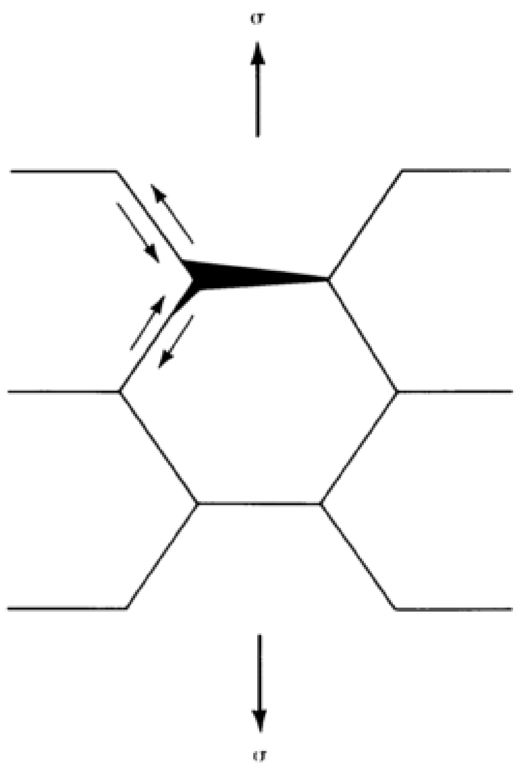
Influence of Temperature / Time on Fracture

- **Atomics in solids aren't stationary**
  - Constantly vibrating due to thermal effects
- **Fracture affected by T and strain rate**
  - Higher temperature = greater vibrations
  - Slower strain rate = more times for atoms to rearrange
- **Ductile to Brittle Transition**
  - Occurs in steels, tungsten
  - Does not occur in Al, Ni, Cu

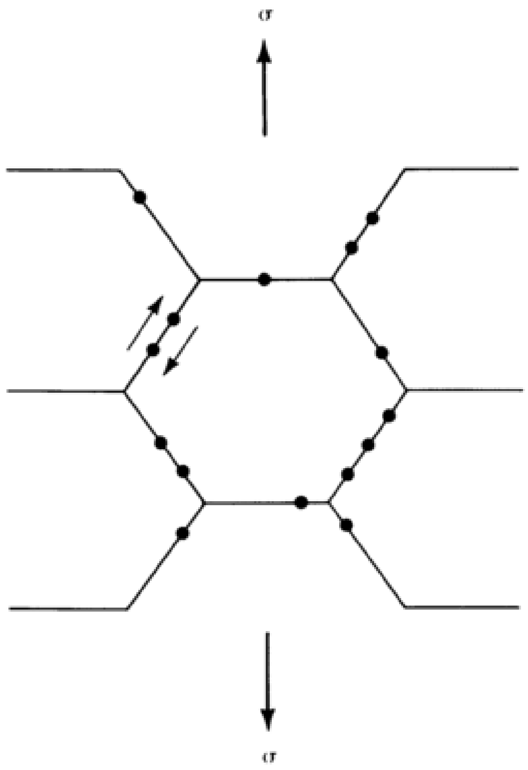




Creep Failures



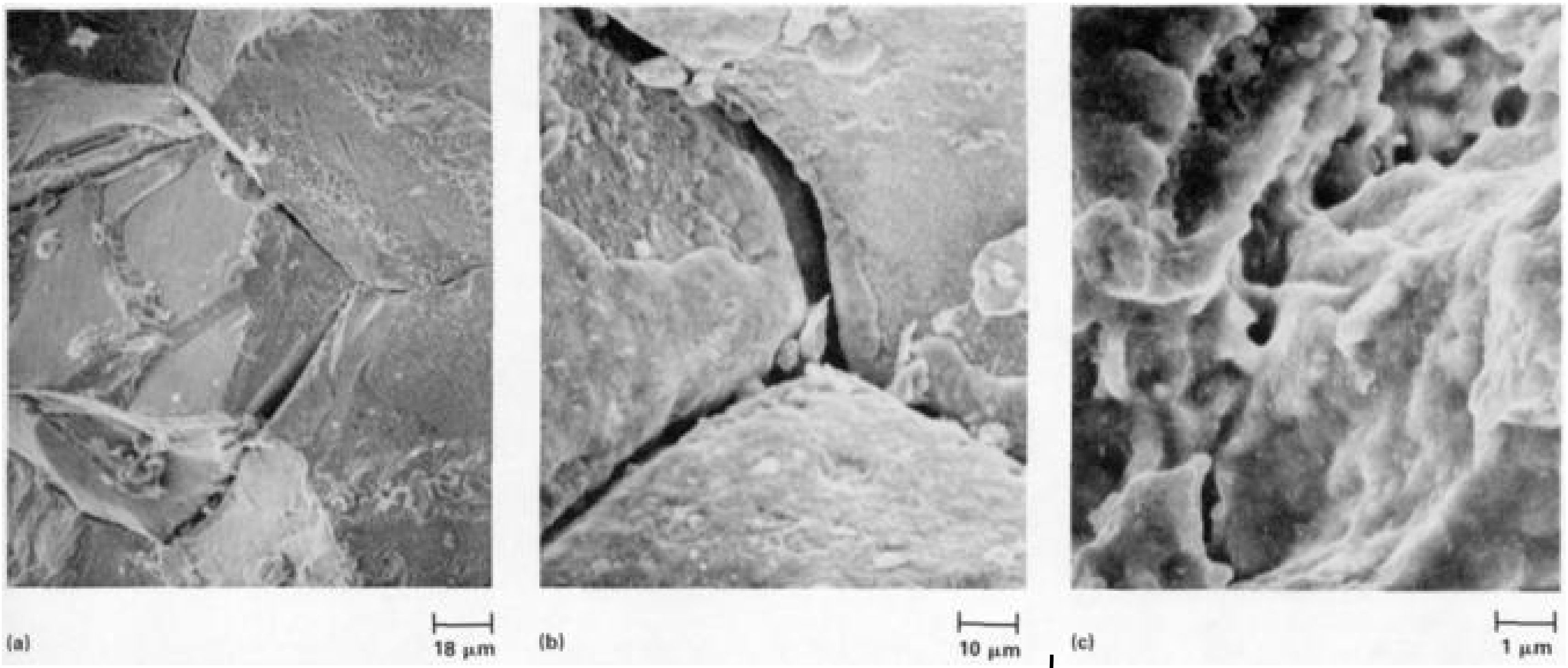
Triple point cracking



Cavitation

V. Kerlins and A. Phillips, Modes of Fracture, *Fractography*, Vol. 12, *ASM Handbook*, ASM International, 1987

Creep Failures



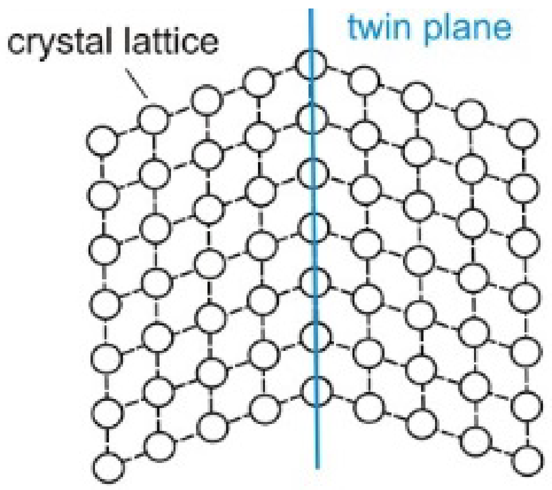
Intergranular triple point wedge cracking

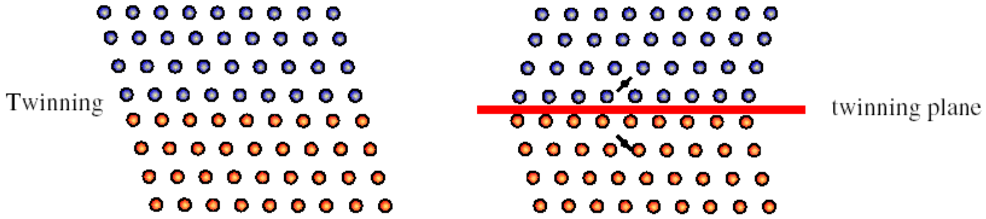
Grain boundary cavitation

K. Sadananda and P. Shahinian, *Met. Sci. J.*, Vol 15, 1981, p 425–432

Twinning

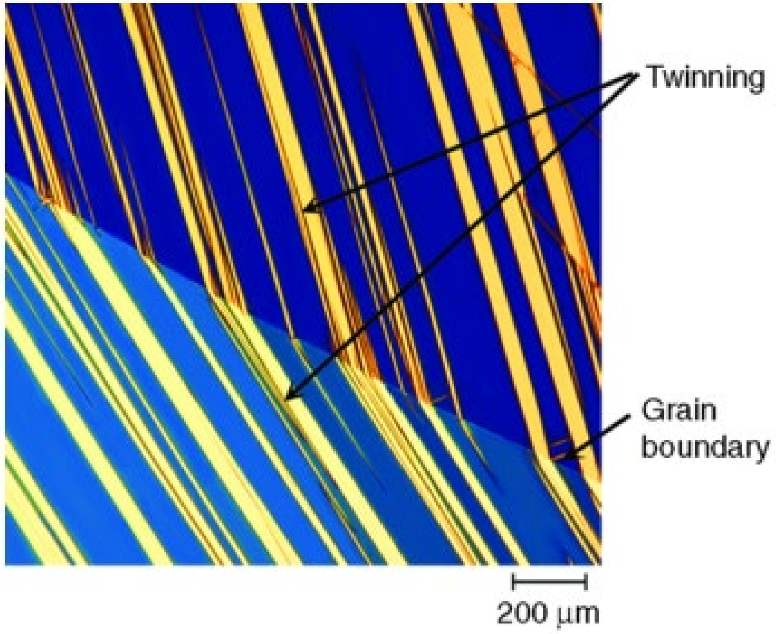
- A shear force that causes atomic displacement
  - $\sigma_{twin} < \sigma_{yield}$
- Atoms on one side of a plane mirror the atoms on the other side
- Occurs on defined planes and directions, dependent on slip system
  - BCC twinning on (112)[111]





Twinning

- **Occur in metals with BCC and HCP structure**
- **FCC metals do not usually deform by mechanical twins**
  - **Do have annealing twins**
- **Shock loading: occur at low T and high shear rates**
- **Slip restricted: conditions where there are few slip systems present**
- **Small gross deformation compared to slip**



P.E. Danielson and R.C. Sutherlin, Metallography and Microstructures of Zirconium, Hafnium, and Their Alloys, *Metallography and Microstructures*, Vol 9, *ASM Handbook*, ASM International, 2004, p. 942–958

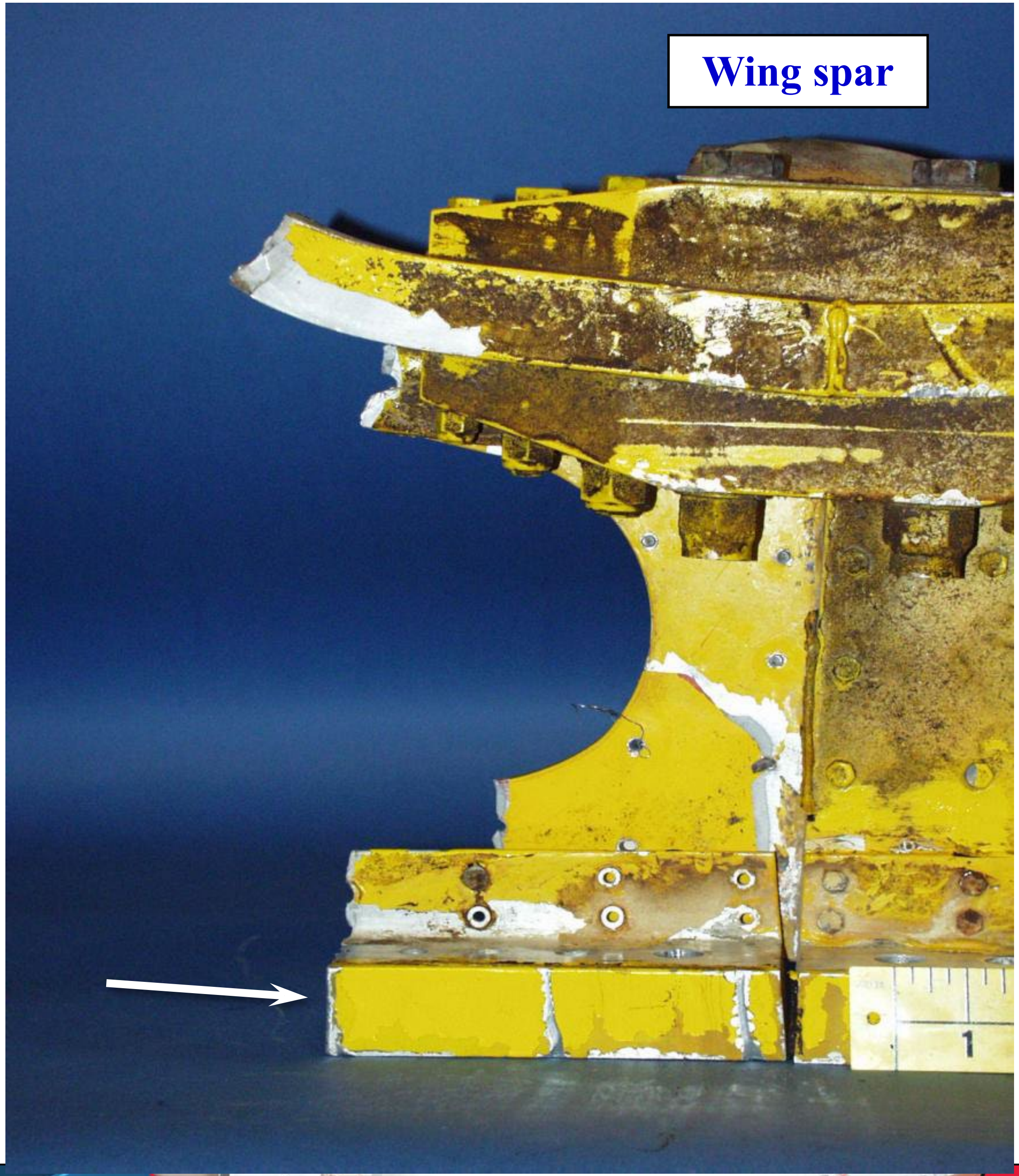
Structural Failure Overview

FRACTURE OF A TENSION MEMBER:

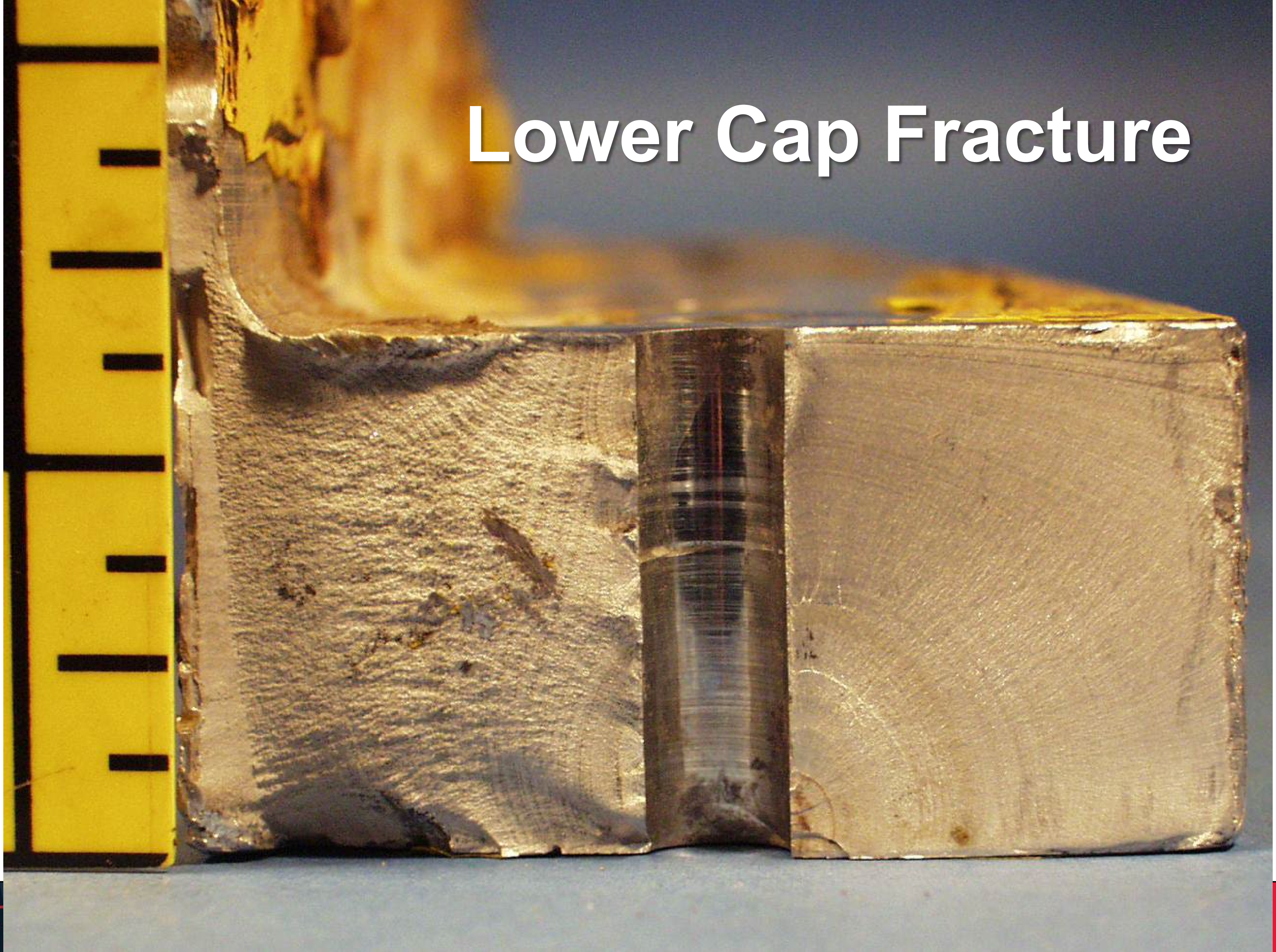
- **Initial fracture**
  - **Little or no bending deformation near fracture.**
  - **Only necking if fracture is ductile overstress**
- **Subsequent fractures**
  - **Substantial out-of-plane bending deformation**
  - **Usually no compression buckling**

Fracture of a Tension Member

- Upper fracture bent upward
- Lower fracture in-plane and flat



Lower Cap Fracture

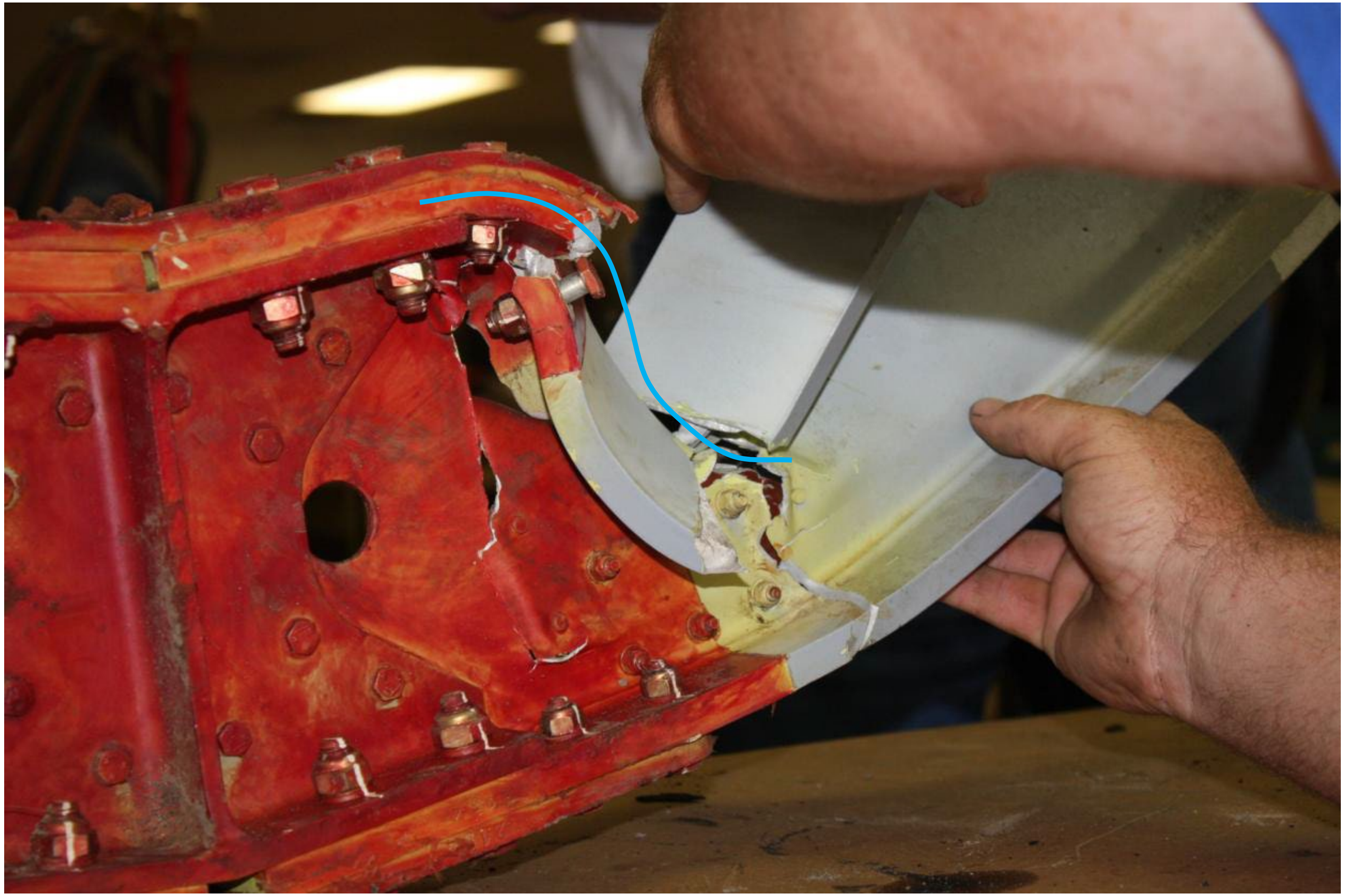


Structural Failure

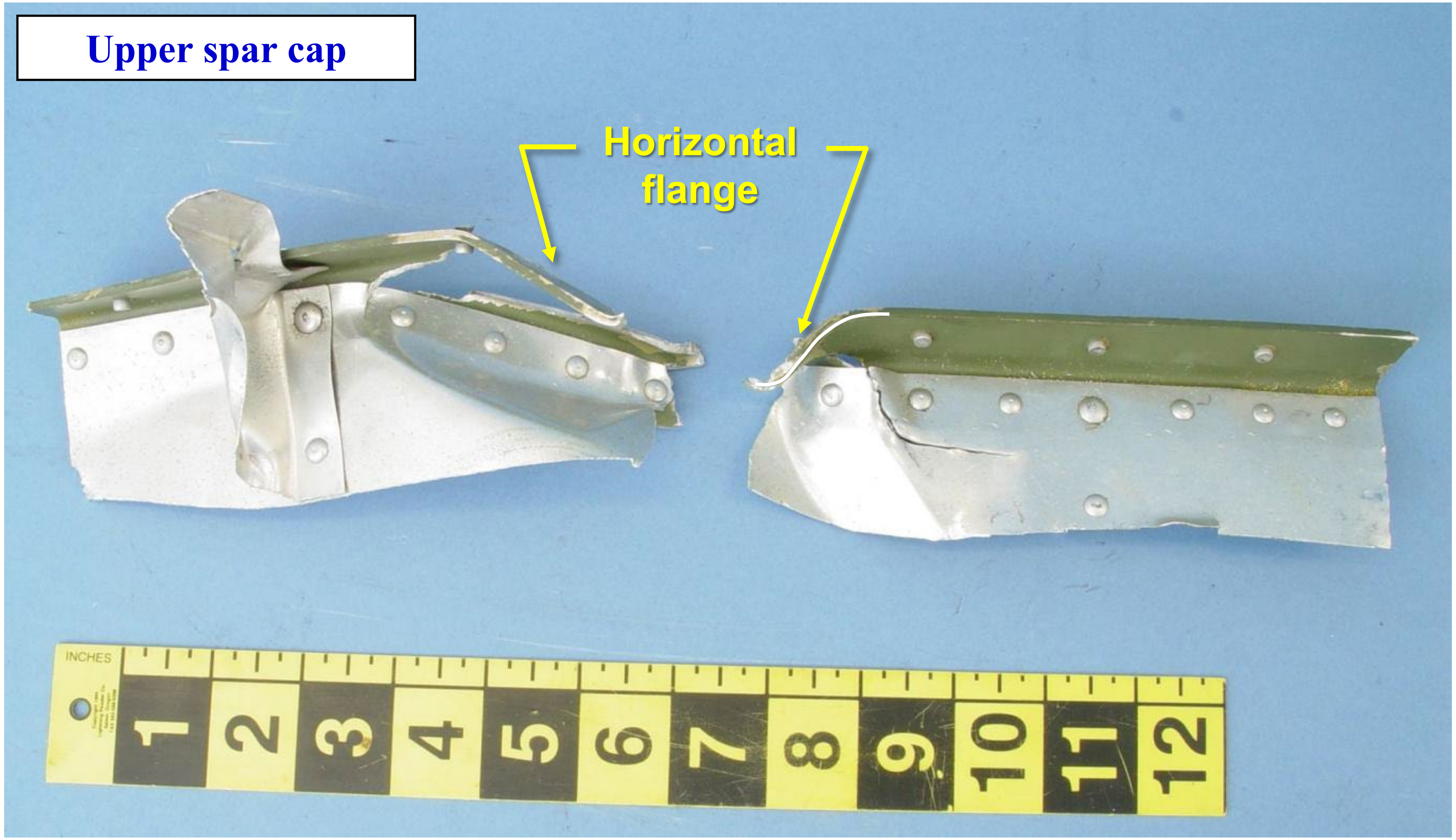
BUCKLING OF A COMPRESSION MEMBER:

- **Initial fracture**
  - **"S" shaped compression buckling deformation**
- **Subsequent fractures**
  - **Substantial out-of-plane bending deformation**
  - **Usually no compression buckling.**
- **If present under bending loads, generally precedes tension fracture.**

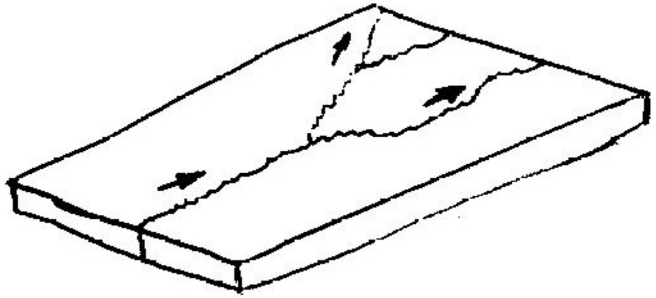
Compression Buckling



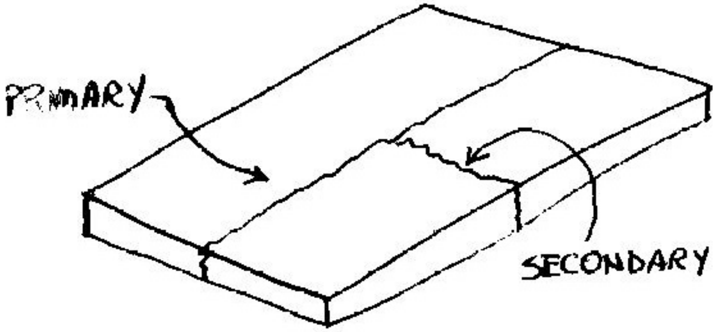
Compression Buckling



Clues to Origin

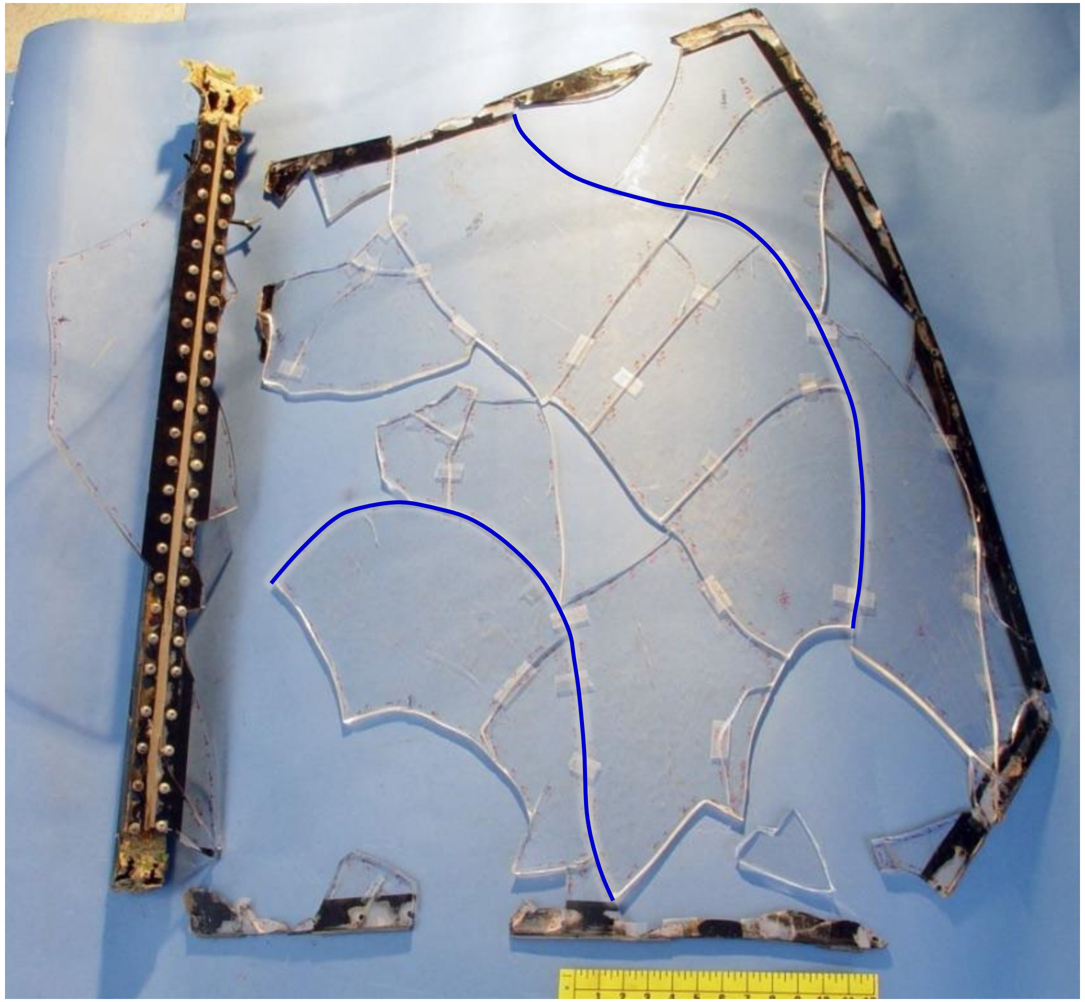


BRANCHING



INTERSECTING

Cracking Sequence Example



Helicopter Windscreen

Practice Questions

I. Structure: C. Fractography

I.C—Q1

Ratchet marks, beach marks, and striations are all characteristic of fatigue. What are the differences between these three features?

(A) There is no difference. All three are analogous and can be used interchangeably.
(B) Ratchet marks are the ligaments between multiple origins, beach marks are macroscopic arrest marks, and striations are microscopic steps left by the progressing crack front.
(C) Ratchet marks indicate high cycles, beach marks are present at the fracture terminus, and striations point towards the crack origin.
(D) Ratchet marks are left by torsional fatigue, beach marks are left by bending fatigue, and striations are due to axial fatigue.

I.C—Q2

One of your clients brings you a 32" 2000 psi API 6A bolted flange for analysis. The flange reportedly failed during hydrostatic testing after being in service for 10 years. The flange is secured to a mating flange by 24 ASTM A193 Grade B7 1-5/8-inch bolts. The fracture surfaces of the bolts appear to be in good condition, and you observe crescent-shaped flat areas of various sizes on each bolt. You determine that it would be beneficial to identify the bolt that failed first. What characteristics would you expect to see in the original bolt failure?

(A) The largest flat area and limited evidence of yielding.
(B) The smallest flat area and visible thread stretch.
(C) The most corrosion within thread roots.
(D) It is not possible to determine the first bolt to fail in a flange.

IV. Performance: F. Failure Analysis

IV.F—Q1

A carbon steel tank was "hydrotested" (pressure tested using water as the pressurizing medium) to 50 psig (345 kPa gage pressure). The tank had work performed on some of the inside baffles prior to testing, and the hydrotest was conducted immediately after the work was finished to make up for some previous lost time on the project schedule. The test lasted for about 4 hours and was conducted at ambient temperature of 70ºF (21C). The tank passed the pressure test. When the test water was drained out of the tank, it was tinted light reddish-brown and contained spots of rusty material along with dark flakes. The water was taken from the municipal water supply, which is chlorinated. High-pressure flexible hoses rated at 180ºF (82ºC) similar to those used in washing machines and dishwashers, only larger, were used to connect the tank to the water supply. Select the most likely cause of the discoloration and foreign material.

(A) The inside walls of the tank corroded during the hydrotest.
(B) The cause of the corrosion was microbial induced corrosion from bacteria in the hydrotesting water.
(C) The connecting hoses deteriorated during the tank fill and released material to the testing water.
(D) The tank was not properly cleaned before hydrotesting, and the observed material was slag, scale, and rust from welding and grinding inside the tank.

IV.F—Q2

You are performing a failure analysis on a section of 8-inch NPS, 0.214-inch wall thickness, API Spec 5L X52 seamless line pipe. There is clear evidence of corrosion in a narrow band along the bottom inside surface of the pipe. The pipe has been in service for 2 years and has reportedly only transported dry produced gas. Which of these four substances must have been present in the pipe for the observed corrosion to occur?

(A) Water
(B) Carbon dioxide
(C) Hydrogen sulfide
(D) Sodium chloride

IV. Performance: G. Fatigue Analysis

IV.G—Q1

Why would carburizing be chosen over through-hardening to improve fatigue resistance in a part?

(A) The soft core will prevent the case from cracking under stress.
(B) A crack which begins in the hard case will be stopped when it reaches the core.
(C) Residual compressive stress in the case improves fatigue life.
(D) The carburizing alloy is cheaper than a through-hardening alloy, since the carbon provides the hardenability.

IV. Performance: P. Wear Mechanisms

IV.P—Q1

In a Power Plant a discovery was made during ultrasonic examination of feedwater piping that locally thinned regions were observed along the pipe ID surface. The piping is 24" OD x 2.0" wall thickness and supplies treated feedwater at 375 deg F and 2,500 psi pressure to a power boiler.

The locally thinned regions were identified as being located adjacent to a tee-section off of a main run of piping and one sharp radius elbow.

Based on the ultrasonic test data, what would be the most probable mechanism for internal wall thinning on the carbon steel feedwater piping?

(A) Erosion
(B) Erosion/corrosion
(C) Defects from pipe manufacturing
(D) Improper UT data

Bonus Fatigue Problem – True σ_E

- Several bars of high strength steel are to be used as leaf-springs. The springs will be subjected to a zero-to-maximum (R=0) three-point flex loading. The bars are as-machined and have a cross sectional area of 0.147 in^2.
- Determine the maximum surface stress that will allow the bars to have infinite life, using the Goodman relationship.

- Selected properties of bars
  - Hardness = 48 HRC / 465 HB
  - Residual surface stress = 0 ksi
  - Surface roughness = 250 μin

Bonus Fatigue Problem – True σ_E

- Fatigue Limit Stress
  - $\sigma_E = \sigma'_E C_S C_F C_Z$
    - σ'_E = unnotched fatigue limit
    - C_S = size factor (table)
    - C_F = surface finish factor (table)
    - C_Z = scatter factor (typically 0.81)

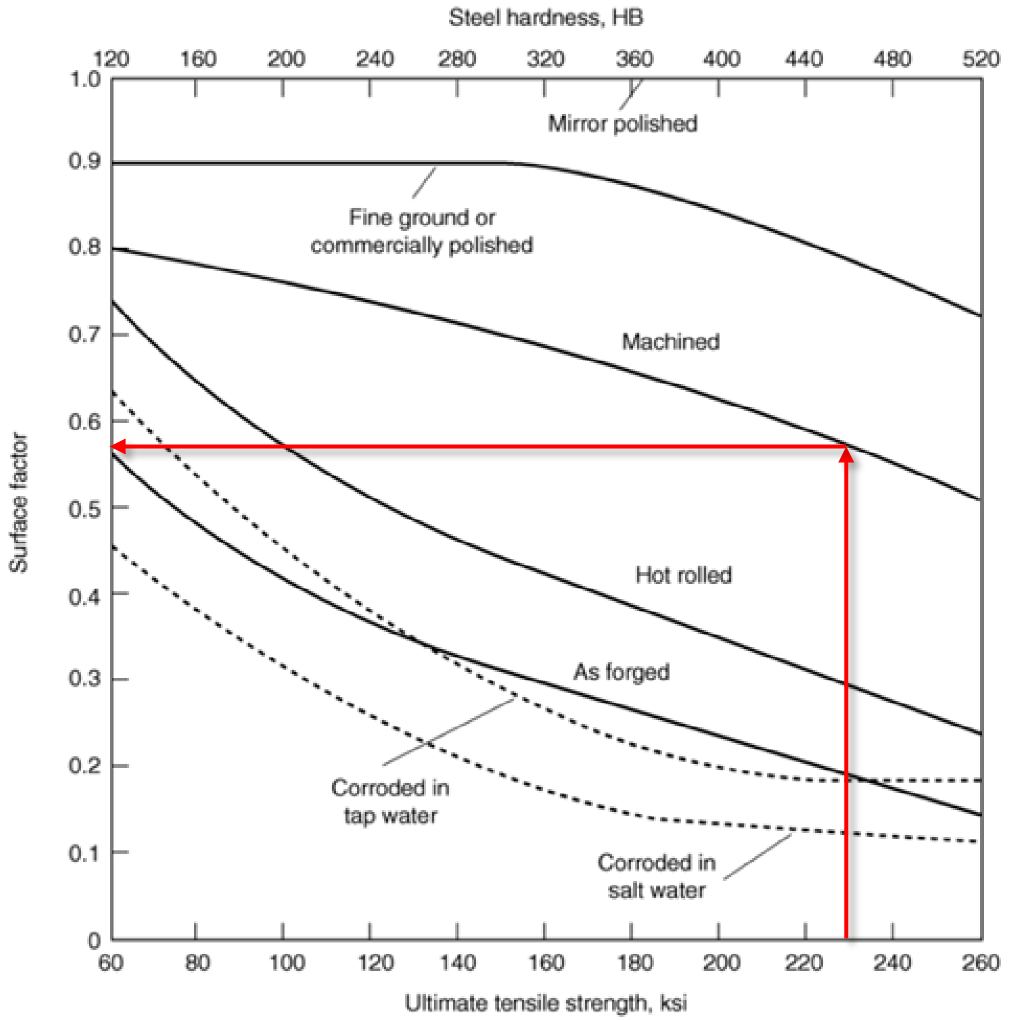
- **As Machined**
  - **Hardness = 48 HRC / 465 HB**
  - **Residual surface stress = 0 ksi**
  - **Surface roughness = 250 μin**
- Quick Assumptions
  - 0.5 Brinell Hardness ≈ σ_{UTS} (in ksi)
    - As HT: (0.5)*(465) = 232.5 ksi = 1603 MPa
  - Endurance Limit and Hardness
    - For σ_{UTS} > 200 ksi
      - $\sigma'_E \approx$ 100 ksi
    - For Hardness > 400 HB:
      - $\sigma'_E \approx$ 100 ksi
      - 100 ksi = 689 MPa

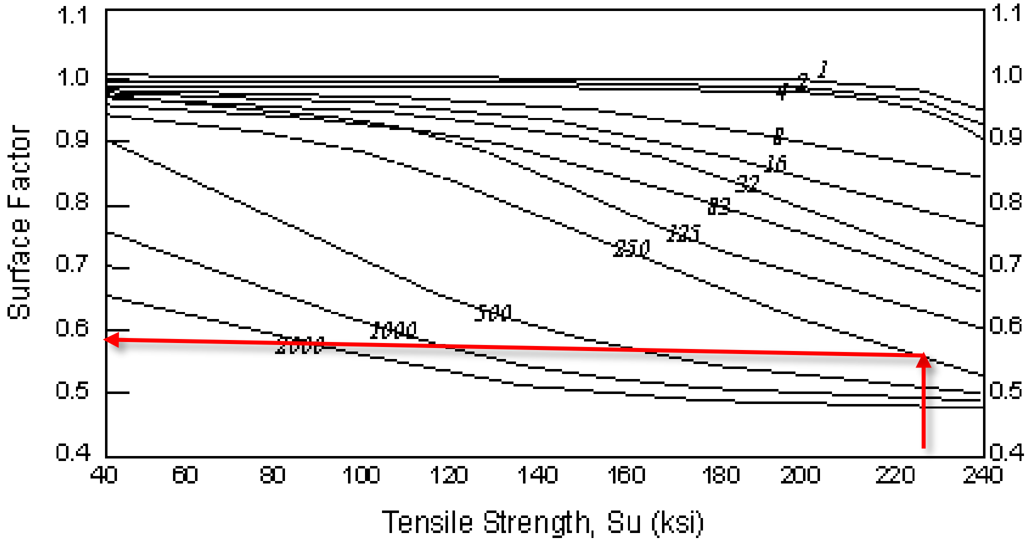
Bonus Fatigue Problem – True σ_E

- **Find diameter**
  - $A = \pi r^2 = \pi (\frac{d}{2})^2 = 0.147\ in^2$
  - $d = 2\sqrt{\frac{A}{\pi}} = 2\sqrt{\frac{0.147\ in^2}{\pi}}$
  - **d = 0.4325 in**
- **Find size factor**
  - $C_S = (\frac{0.43}{0.3})^{-0.107} = 0.962$

$$C_S = \begin{cases} (d/0.3)^{-0.107} & 0.11 \le d \le 2\ in \\ 0.91 d^{-0.157} & 2 < d \le 10\ in \\ (d/7.62)^{-0.107} & 2.79 \le d \le 51 mm \\ 1.51 d^{-0.157} & 51 < d \le 254 mm \end{cases}$$

Bonus Fatigue Problem – True σ_E

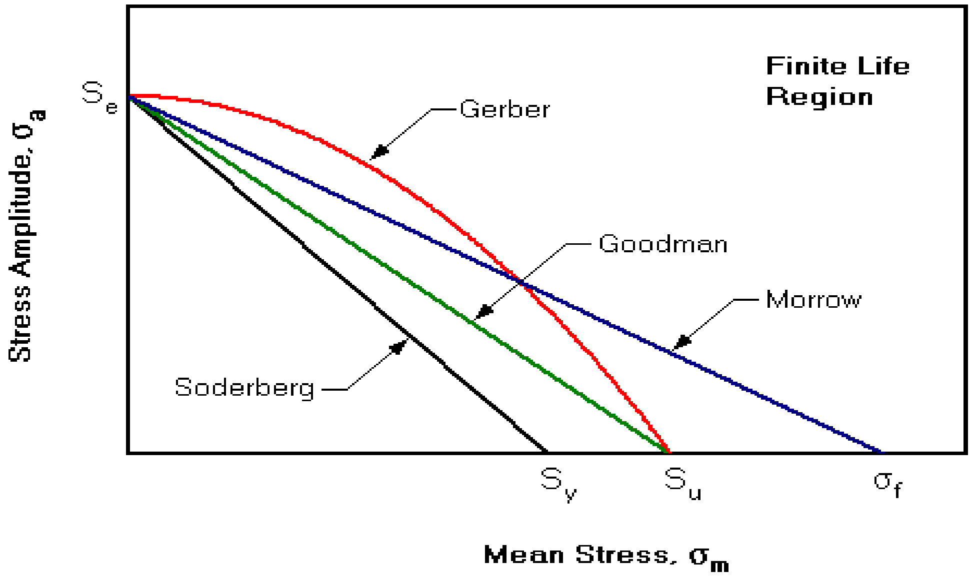




- **As HT**
  - σ_{UTS} **= 232.5 ksi**
  - **Surface roughness = 250 μin**
  - C_F **= 0.58**

Bonus Fatigue Problem – True σ_E

- **Fatigue Limit Stress**
  - $\sigma_E = \sigma'_E C_S C_F C_Z$
  - $\sigma_E^{AM} = (100)(0.962)(0.58)(0.81)$
  - $\sigma_E^{AM} = 45.19$ ksi
- **Goodman Relationship**
  - $\frac{\sigma_A}{\sigma_E} + \frac{\sigma_M}{\sigma_{UTS}} = 1$
  - For R = 0, $\sigma_A = \sigma_M$
  - $\frac{\sigma_M}{45.2} + \frac{\sigma_M}{232.5} = 1$
  - $\sigma_M = 37.84\ ksi$
  - $\sigma_{MAX} = \sigma_A + \sigma_M = 2(\sigma_M)$
  - $\sigma_{MAX} = 75.67\ ksi$



- $\sigma_M = \frac{\sigma_{MAX} + \sigma_{MIN}}{2}$
- $\sigma_A = \frac{\sigma_{MAX} - \sigma_{MIN}}{2}$