Lecture 19
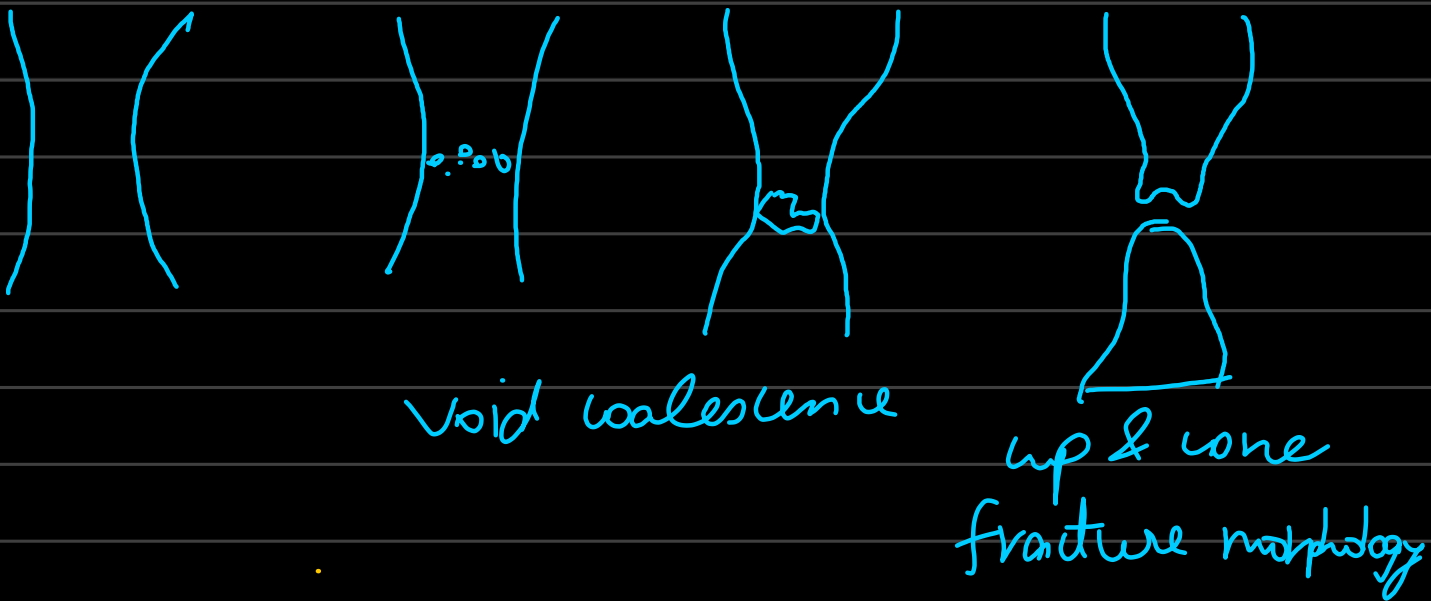
Fatigue:

→ On macroscopic scale, fatigue fracture surface looks like a brittle fracture.

Ductile fracture mechanism:
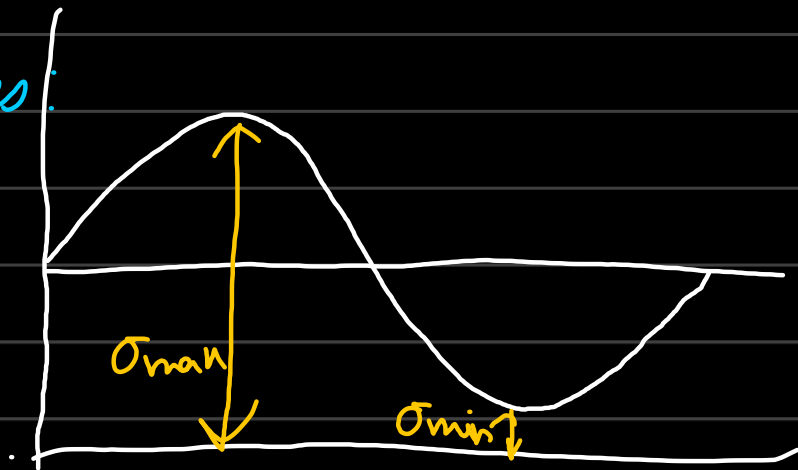

void coalescence

cup & cone
fracture morphology

Factors governing fatigue:

↳ yield stress (σ_y) is macroscopic yield stress

↳ At microscopic scale, yielding starts before (σ_y) leading to slip.

↳ This slip does not lead to any gross damage to material/component.

→ In cyclic loading leads to reversal of slip directions.

→ Formation of intrusions where cracks are formed.

↳ due to further loading, local stress amplication takes place.

→ fracture toughness is a better criteria of merit

↳ in presence of crack in material, fracture toughness is better criteria to classify materials.

ii) Purely tensile cycles:

σ_{max}

σ_{min}

Fatigue data: S-N curve: → each plot is a constant for σ_m, R or A.
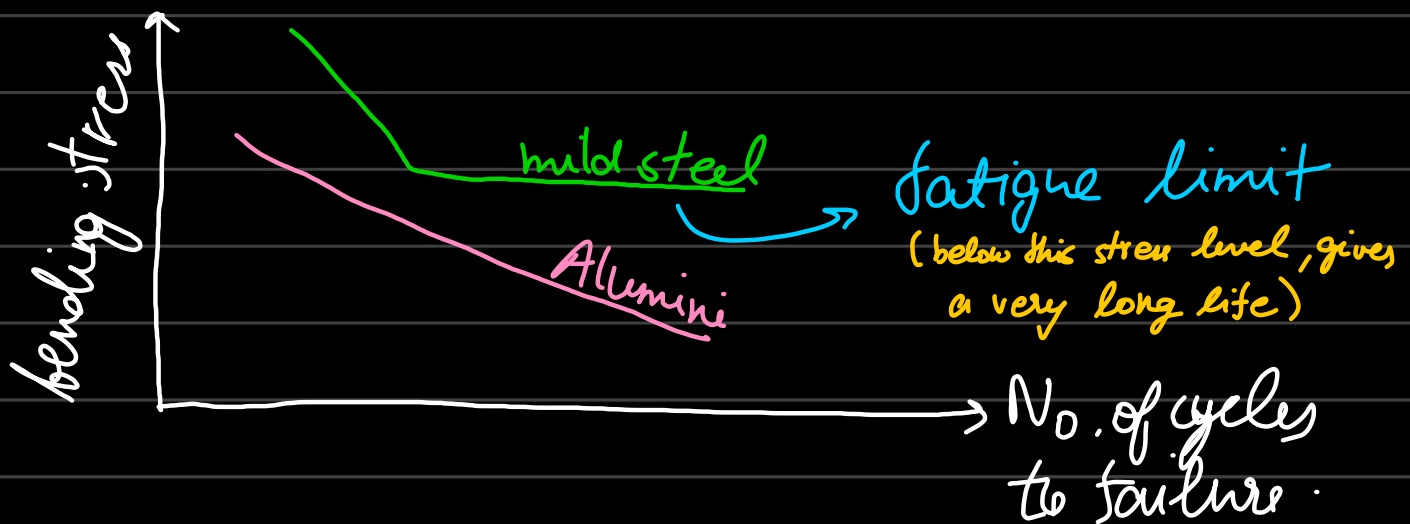
σ_{max}
σ_{min}
σ_a

no. of cycles till fracture.

→ Most fatigue experiments are performed at $\sigma_m = 0$; $R = -1$

High cycle fatigue: $N > 10^5$ cycles → lower than σ_y

Low cycle fatigue: $N < 10^4$ or 10^5 cycles. ↳ higher than σ_y

☆ if magnitude of stress increases, the fatigue life decreases.

bending stress (y-axis)

mild steel

Alumini

fatigue limit
(below this stress level, gives a very long life)

→ No. of cycles to failure.

* Fatigue failure occurs due to microscopic plasticity (which can occur below the yield stress) and damage accumulation with time.

Stages of Fatigue Failure:

i) **Crack initiation:**

ii) **Stage-I crack growth:**
  ↳ growth of crack along planes of high shear stress.

iii) **Stage II : crack growth:**
  ↳ crack growth along directions of maximum tensile stress
  ↳ crack propogation is trans-granular.

iv) **Ductile failure:**
  ↳ reduction in load bearing area (due to crack propogation) leads to ultimate failure.

Crack initiation
  ↳ Crack growth
      ↳
          ↳ Failure

Slip & fatigue crack initiation:

→ Specimen subjected to uniform loading dislocations moving on parallel slip planes.

⤷ give rise to slip lines on surface

→ equivalent slip on all grains (uniform)

⤷ In fatigue loading some grains show slip but others may not.
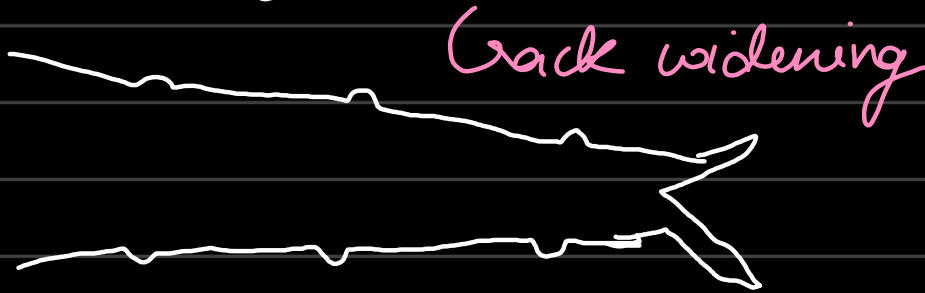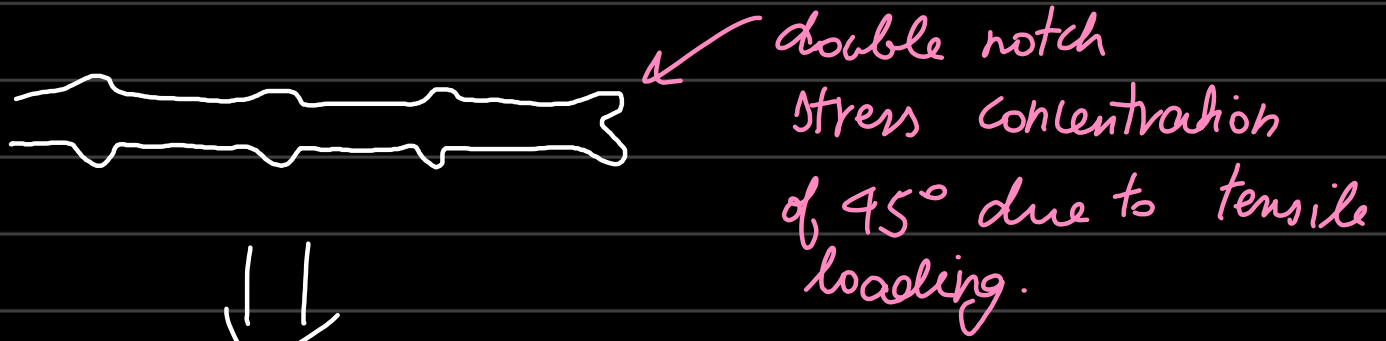
Fatigue crack propagation:

Slip-band crack growth:

⤷ formations of the intrusions.
⤷ thought of crack deepening.

Striations: each striation produced by one cycle of stress.

⤷ only in Stage II of crack growth.

⤷ if absent does not imply fatigue crack propagation was absent ⤷ difficult to observe.

double notch stress concentration of $45°$ due to tensile loading.

Crack widening

Crack tip extension & blunting.

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$$

Crack growth rate: $\dfrac{da}{dN} = A\,\sigma_a^{m}\,a^{-n}$

→ crack length.

alternating stress.

$$\frac{da}{dN} = B\,\varepsilon^{q}$$

↓ total strain
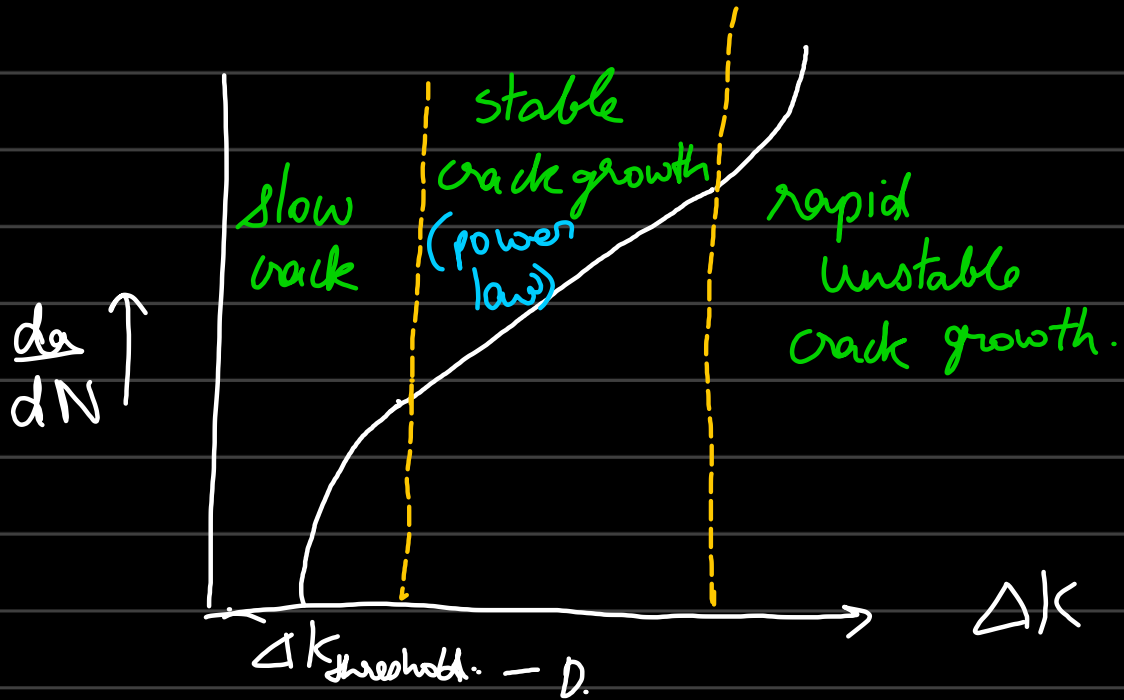
Fatigue crack propagation — Stage II

Crack growth rate $= f(\Delta K)$

$$\Delta K = K_{max} - K_{min} = \sigma_{max}\sqrt{\pi a} - \sigma_{min}\sqrt{\pi a}$$
$$= \sigma_r \sqrt{\pi a}$$

→ In compression, K is not defined

$$K_{compression} = 0$$

da/dN ↑

slow crack

stable crack growth (power law)

rapid unstable crack growth.

→ ΔK

$\Delta K_{threshold} - D.$

$$\Delta K = K_{max} - K_{min}$$

$$K_{max} \approx K_{IC}$$

$$|\sigma_{max}| = |\sigma_{min}|$$

$$R = -1$$

$$R = 0 \qquad \sigma_{min} = 0$$

Boundary conditions.

When $N = N_f$; $a = a_f$

$$\frac{da}{dN} = A(\Delta k)^P = A\left(\leftrightarrow \sigma_r \sqrt{\pi a}\right)^P$$

$$= A(\leftrightarrow)^P (\sigma_r)^P (\pi a)^{P/2}$$

$$a_f = \frac{1}{\pi}\left(\frac{K_C}{\sigma_{max} a}\right)^2$$

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

$\downarrow$

no. of cycles
to failure.

CREEP

(move slowly & carefully in order to avoid
being heard or noticed)

very slow plastic deformation.

time dependent plastic deformation that could
happen under constant load or stress conditions
and is generally represented by strain vs time.

$\hookrightarrow$ the time dependence is governed by first order
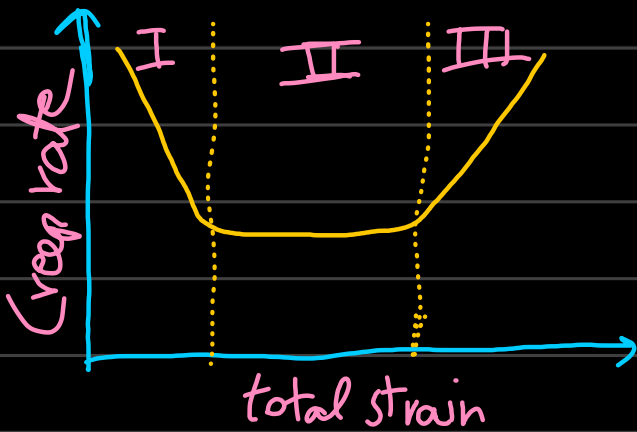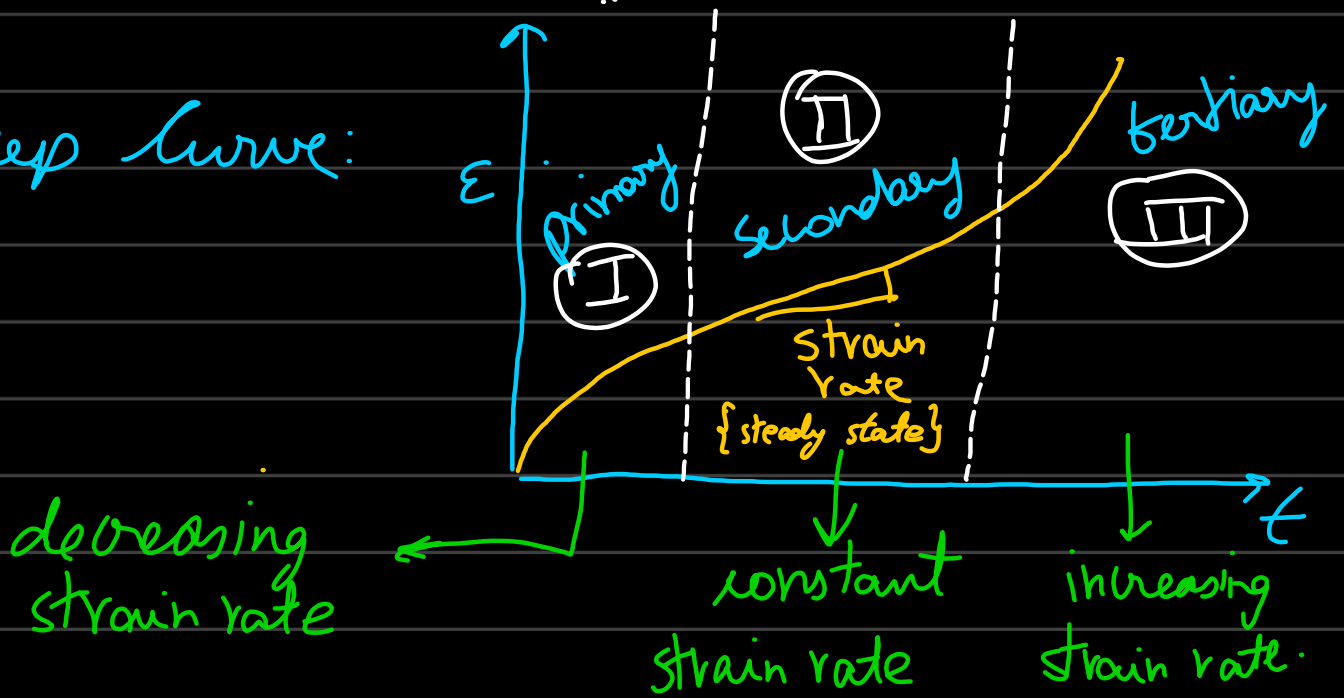kinetics.

$\rightarrow$ strain rate : regular tensile test: 10^{-5} to $10^{-1}/s$
regular creep test: 10^{-8} to $10^{-5}/s$.

a) 10 mins to failure in tensile test
at $\dot{\varepsilon} = 10^{-4}/s$

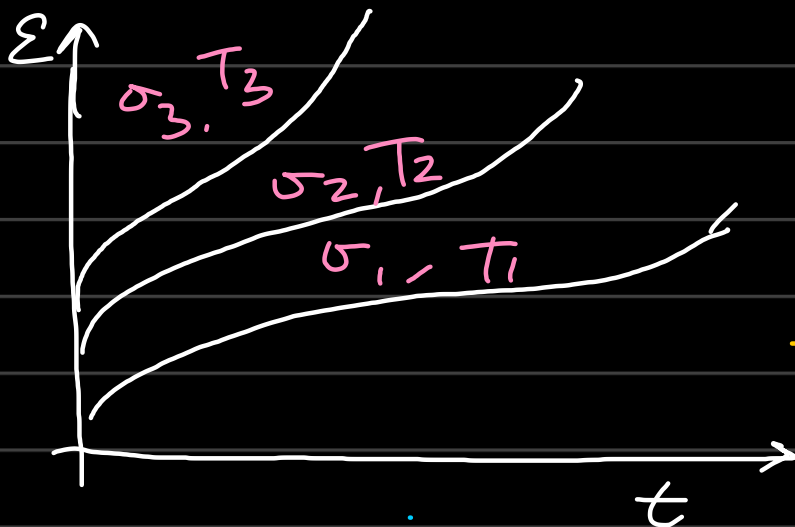t mins to failure in creep test at $\dot{\varepsilon} = 10^{-8}/s$

$t = 10^{4} \times 10 = 10^{5}$ mins

Creep curve:

Primary I · Secondary II · tertiary III

ε (vertical) , t (horizontal)

strain rate {steady state}

decreasing strain rate

constant strain rate

increasing strain rate.

I II III

Creep rate (vertical) · total strain (horizontal)

※ Creep curve in general can be considered as a competition between strain hardening & recovery.
{high temperature deformation}

→ In primary stage : strain hardening > recovery

ε (vertical) · t (horizontal)

σ_3 , T_3

σ_2 , T_2

σ_1 , T_1

$\sigma_3 > \sigma_2 > \sigma_1$

$T_3 > T_2 > T_1$

* Creep tests must be carried out at stresses lower than the critical stress for microstructural change.

* Most important microstructural parameter is grain size.

$$\sigma_y = \sigma_0 + \frac{k_y}{\sqrt{d}}$$

Hall-petch relation

* Equicohesive temperature:
T at which grain interior is as strong as grain boundary.

↳ typically grain boundary strength uses with ↑se in temperature.

fine grains deform more than coarse grains.

* typically : $\dot{\varepsilon} \propto d^{-p}$

Secondary creep:

$$\dot{\varepsilon} \propto A d^{-p} \sigma^n \exp\left(\frac{-Q}{RT}\right)$$

grain size exponent.

→ activation energy for deformation

↓ normal stress

Creep Mechanisms:

Broadly two categories:

i) Diffusion of vacancies based creep

    i) Coble creep $\{n=1, p=3, Q=Q_b)$ $\underline{\underline{n=1}}$

    ii) Nabarro-Herring Creep $\{n=1; p=3; Q=Q_{gb})$

    {Newtonian creep mechanisms}

    iii) Harper-Dorn Creep $\{n=1, p=0; Q=Q_L\}$

ii) Dislocation based creep mechanisms.

    ii) Viscous slide $\{n=3; p=0; Q=Q_L\}$

    iii) Climb

    iv) Power Law Breakdown.

    iii) Grain boundary sliding {GBS}