SANKET SIR

ANURAG

TOM-2

Strain controlled fatigue → Strength, stress, load

Fatigue Test

↳ Continuous stress & time.

↳ Cycling Nature of stress :- stress keeps changing over time
i.e we will take about no. of cycles (stress) and time

•) Fatigue Failure :- The failure of the material under the action of fluctuating stress with time is called as fatigue failure.

•) "Repetition of Load" ≈ Not a dynamic test which is "Rate of Load".
therefore neither static nor dynamic.

•) Continuous cycle of stress with time is not giving plastic deformation here.
They are catastrophic in nature (Brittle), bcz

→ The cracks generated are very fine & cannot be determined.

characterised by
It needs ↓

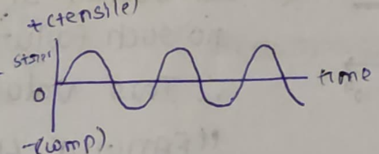
•) → High amount of Tensile stress → to propagate the crack

→ High cyclic stress → appreciable variation in stress → crack generation/initiation

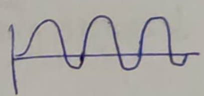
→ Temperature & corrosion also affects it.

→ Large no. of cycles.

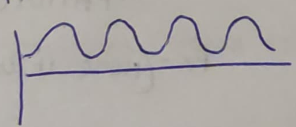
typical Variation :-



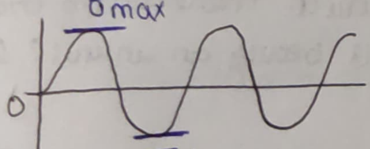
also



only tensile



Terms



$$\sigma_{mean} = \frac{\sigma_{max} + \sigma_{min}}{2}$$

σ_r (Range of stress) $= \sigma_{max} - \sigma_{min}$

~~When~~

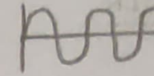
σ_a (Alternate stress) amplitude $= \dfrac{\sigma_r}{2} = \dfrac{\sigma_{max} - \sigma_{min}}{2}$

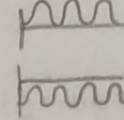
$R =$ Stress Ratio $= \dfrac{\sigma_{min}}{\sigma_{max}}$

$A =$ Amplitude Ratio $= \dfrac{1-R}{1+R} = \dfrac{\sigma_{max} - \sigma_{min}}{\sigma_{max} + \sigma_{min}}$

$$= \frac{\sigma_r}{2\sigma_{mean}}$$

$$= \frac{\sigma_a}{\sigma_{mean}}$$

when $\sigma_{max} = \sigma_{min}$ → Completely Reverse Stress cycle. 

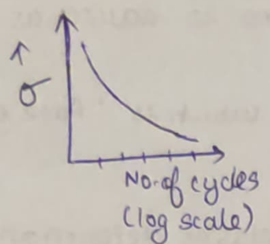
$\sigma_{min} = 0$ → Repeated stress cycle 

Amplitude constant

any other than these will be fluctuating or random stress cycle!

REPRESENTATION OF FATIGUE

↳ S-N Diagram



LCF (Low Cycle Fatigue) → $\leq 10^4 - 10^5$

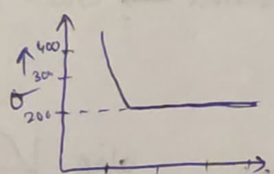
HCF (High Cycle Fatigue) → $\geq 10^5$

- we check fatigue at different stages using stress

stress $\propto \frac{1}{\text{No. of cycles}}$

(x) This Diagram is observed mostly in Non-Ferrous materials

(x) But when it is Ferrous or mild steel (carbon containing basically) is



← can sustain infinite no. of cycles no such failure occuring.
∴ This value of stress is called as "FATIGUE LIMIT" OR "ENDURANCE LIMIT"

Ex:- (Here it is 200MPa)

ENDURANCE LIMIT :- The stress range below which there is no crack growth and the materials bears an infinite life of stress cycles.

FATIGUE STRENGTH :- Maximum stress the material can withstand, after this material fails.

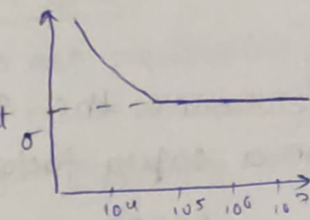
FATIGUE LIFE :- Number of Cycles

for strength look y-axis

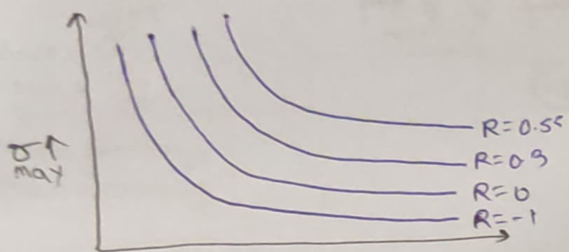
STRAIN AGEING :- In steels, C & N are present as interstitial solute atoms which occupies certain sites. Now the Dislocations moving normally are pinned by these C & N atoms thus the stress required increases resulting increase in strength.

THIS IS THE REASON FOR THIS CURVE

Endurance limit curve



Effect of Stress Ratio on S-N curve

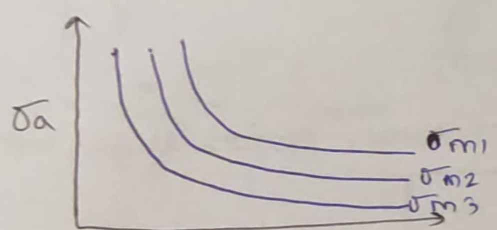


at a fixed cycle (x axis point)

$\uparrow$ Stress ration = $\uparrow$ Endurance Limit

$\uparrow$ Fatigue stregth

Effect of Mean stress on S-N curve



$\boxed{\sigma_{m3} > \sigma_{m2} > \sigma_{m1}}$

$\uparrow$ Meanstress = Alternating stress $\downarrow$

bcz of internal structural changes, these trends are encountered.

Goodman Diagram [σ_r vs mean stress]

Given by
- Goodman
- Gerber
- Soderberg

$$\sigma_a = \sigma_e \left[1 - \left(\frac{\sigma_m}{\sigma_u} \right) \right]^x$$

σ_a = Alternating stress

σ_e = Endurance limit

σ_m = mean stress

σ_u = ultimate Tensile str.

x = 1 → Goodman

2 → Gerber

1 → Soderberg

but in Soderberg we use yield stress σ_0 ✓ σ_u ✗.

→ If $\sigma_e = 500$, will keep a $\boxed{\text{factor of Safety}}$

if factor of safety = 2 ∴ need to use 250 now

Q) A steel bar is subjected to a fluctuated axial load that varies from a maximum of 300 kN tension to a minimum of 110 kN compression. The Mech. properties of steel: UTS = 1090 MPa

Yield str = 1010 MPa

Endurance limit = 510 MPa

Determine the steel bar diameter to give infinite fatigue life based on a safety factor of 2.5.

Soln:- $A = \frac{\pi D^2}{4}$ $\quad \sigma_a = \sigma_e \left[1 - \left(\frac{\sigma_m}{\sigma_u} \right)^x \right]$ $\quad \frac{max + min}{2 (A)}$ $\quad \frac{N}{mm^2} = MPa$

$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2 (A)}$ $\quad \sigma_u$ = UTS

σ_e (safety factor) $= \frac{510}{2.5} = 204$

?

Strain Controlled fatigue:- Amplitude, strain constant

Now static load is not applied (Tensile (+) → Compression (−) → Tensile (+) etc.) ⇒ Trans half

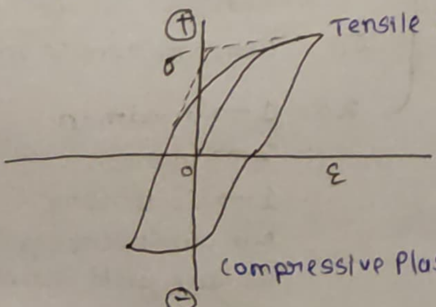


Fig:- cyclic stress-strain diagram

HYSTERESIS LOOP

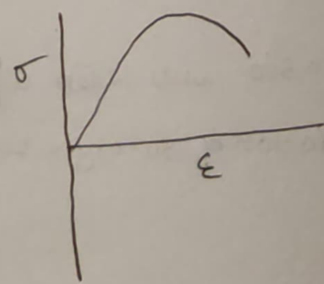
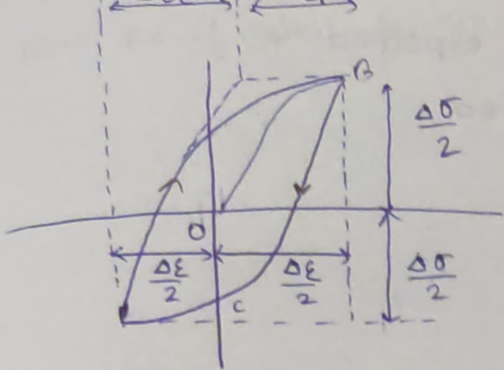


Fig:- Tension i.e Monotonic s-s diagram



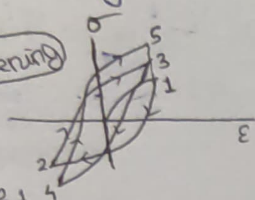
Heigh $= \Delta\sigma$
width $= \Delta\varepsilon$
width will be dependent on the level of cyclic strain

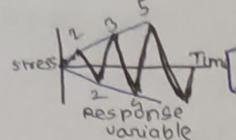
Now what happens in next cycle?

Since plastic deformation is not reversible, and some dimensional changes have occured.
cyclic Hardening or cyclic softening takes place..

Fig:-

cyclic Hardening



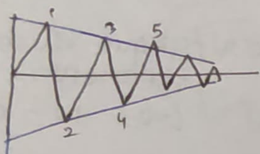


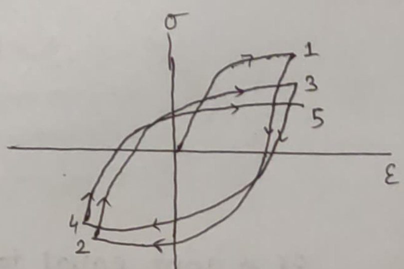
3 above 1
5 above 1
⇓
stress increasing
strain decreasing

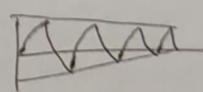
Cyclic Hardening :- Stress increasing every next cycle

Cyclic Softening :- stress decreasing every next cycle.

cyclic softening







The cycle stress strain curve may be described by a power curve

$$\boxed{\Delta\sigma = K'.(\varepsilon_p)^{n'}}$$

n' = cyclic strain hardening exponent
K' = cyclic strength coefficient

Now

$$\Delta\varepsilon = \Delta\varepsilon_e + \Delta\varepsilon_p$$

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2}$$

For elastic, $\frac{\sigma}{\varepsilon} = E$

& $\Delta\sigma = K'.(\varepsilon_p)^{n'}$

$$\boxed{\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \frac{1}{2}\left(\frac{\Delta\sigma}{K'}\right)^{1/n'}}$$

- This is the form of eq. for the cyclic s-s curve that is usually given
- For metals n' varies b/w 0.10 – 0.20.
  In general monotonic, metals with high strain hardening exponents (> 0.15) undergo cyclic hardening
  similarly n (< 0.15) → cyclic softening
- Cyclic hardening is to be expected when the ratio of monotonic UTS to the 0.2% offset yield strength is greater than 1.4

- when the ratio is less than 1.2, cyclic softening is expected
  B/w 1.2 – 1.4 ⇒ large changes in hardness expected.
- LCF → $< 10^4 - 10^5$
  HCF $> 10^6 - 10^7$
-

Coffin Manson Relation

LCF is related to this.

$$\boxed{\frac{\Delta \varepsilon_p}{2} = \varepsilon_f' (2N)^c}$$

$\frac{\Delta \varepsilon_p}{2}$ = Plastic strain amplitude

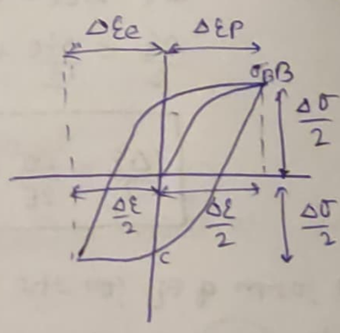
$2N$ = no. of strain reversals to failure
(1 cycle = 2 Reversals)

c = fatigue ductility exponent
(−0.5 to − 0.7)

ε_f' = fatigue ductility coefficient defined by strain intercept at $2N = 1$

ε_f' is appr equal to true fracture strain
(ε_f for many metals)

Q) For the cyclic S-S curve, $\sigma_B = 75$MPa & $\varepsilon_B = 0.000645$. If $\varepsilon_f = 0.30$ and $E = 22 \times 10^4$ MPa (for elastic)
determine (a) $\Delta \varepsilon_e$ & $\Delta \varepsilon_p$
(b) No. of cycles to failure



From fig

$\sigma_B = 75$MPa

$\sigma_B = \Delta\sigma/2$

$\Delta\sigma = 150$MPa

$\Delta \varepsilon_e = \frac{\Delta \sigma}{E} = \frac{150 \text{ MPa}}{22 \times 10^4 \text{ MPa}} = 6.8 \times 10^{-4}$

$\frac{\Delta \varepsilon_e}{2} = \frac{\Delta \varepsilon}{2} \Rightarrow \Delta \varepsilon = 2\Delta \varepsilon_e = 2 \times (0.000645)$

Now $\Delta \varepsilon = \Delta \varepsilon_e + \Delta \varepsilon_p$

$\Delta \varepsilon_p = \Delta \varepsilon - \Delta \varepsilon_e =$
$= 6.082 \times 10^{-4}$

Now no. of cycles, by Coffin Manson

$$\Delta\varepsilon_P/2 = \varepsilon_f'(2N)^c \qquad c=-0.6$$

$$\frac{6.082\times10^{-4}}{2} = 0.30(2N)^{-0.6} \qquad \varepsilon_f' = \varepsilon_f = 0.30 \text{ [most of the time]}$$

$$2N = 97000$$

$$\boxed{N = 48500} \longrightarrow \text{cycles.}$$

CREEP ⇒ It is a time dependent deformation of material under the application of stress at high temperature

Time
Stress
Temperature

creep → $f(\sigma, T, t)$
Tensile → $f(\sigma, \varepsilon)$

Low temp vs High Temp

what happens at High Temp? ⇒

DEFORMATION OCCURENCE →

1. introduction of new slip system at a particular plane & direction
 slip system ↑, deformation ↑
2. dislocation climb :- at RT dislocations strikes the grain boundaries & cannot deform
 While at high temp, these energised dislocations climb & increases deformation
3. grain boundary sliding :- it increases the deformation.
4. Diffusion :- it increases at higher temperature

•) also we know $\sigma > Y.S \Rightarrow$ Plastic deformation ⟶ Room Temperature
but at High Temp, the stress level required decreases. need not to be high. (Reasons above)
basically stress can be $\sigma > Y.S$ or $\sigma < Y.S$ anything)

But what exactly is High Temperature?

High temperatures can be different for ceramics or rubber,
THIS IS Defined using ~~BOILING~~ MELTING POINT called Homologus temperature

(T_H) Homologus temperature (High Temp condn)

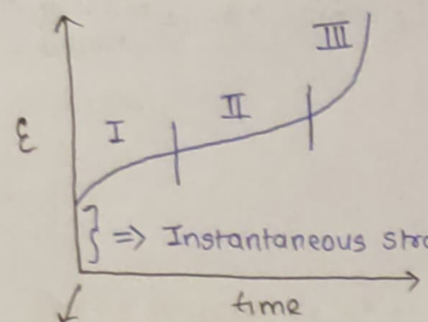
$$\boxed{\frac{T}{T_m} > 0.5}$$

T = operating temperature
T_m = melting temperature

•) Creep test can go on for years, gives idea about the life of the materials ultimately giving us cost idea, while tensile doesn't focus on time.

$\underset{\text{sudden}}{E} + \underset{\text{transient}}{K} + \underset{\text{viscous}}{K}$

Creep Curve – by Andrade



} => Instantaneous strain / Sudden strain

at a particular
σ = 1000 MPa
T = 800°C

creep rate :- $\frac{\text{Strain}}{\text{per unit time}}$

I → transient stage creep
II → Steady stage creep
III → accelerated / tertiary creep

why it shouldn't start from zero / origin?

ANS :- Scale is for number of years. strain gets accumulated in a short amount of time at the starting of creep test. (Although very less)
↳ due to sudden action / start of the test.

I Transient stage

- Here the creep rate decreases.

example: if first 5 min elongation 2mm and next five minutes results in 1mm → creep rate decreases

DISLOCATION HARDENING

II Steady stage

- Steady creep state, almost stable or constant

SOFTENING STARTS

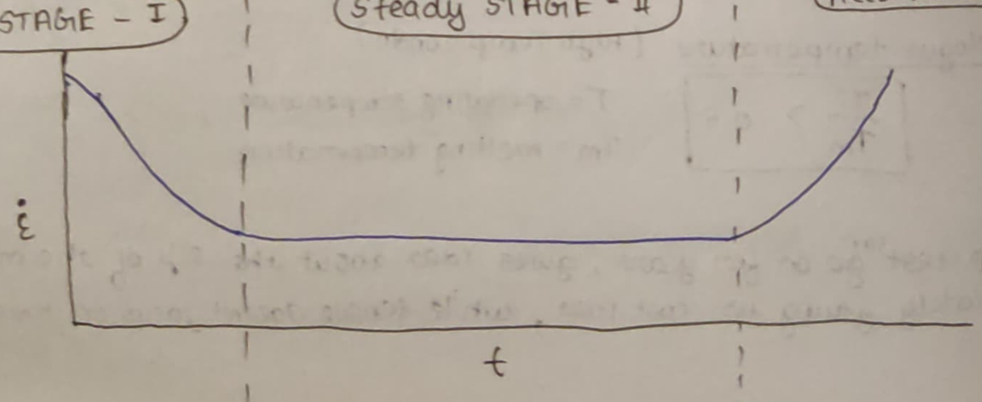
III Accelerated Stage

- Here the creep rate increases. SOFTENING DOMINATES

For Sudden strain, it can be
1) Elastic → recoverable with load
2) Anelastic → recoverable with time (Not load)
3) Plastic → not recoverable at all

- Subtracted from final value.

TRANSIENT STAGE – I | Steady STAGE – II | ACCELERATED STAGE



why decreasing in 1st stage ?

⇒ due to dislocation hardening, sudden start makes the dislocation moves in a random fashion and create obstacle for each other, Therefore no smooth movement causing dislocation hardening

⇒ Not helping much in the deformation ∴ curve decreases

2nd stage

⇒ After some random movement. Dislocation hardening is balanced by the softening process.

3rd stage

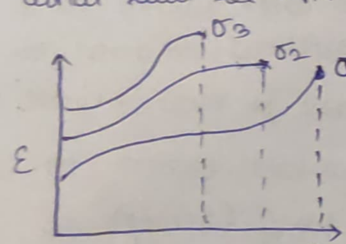
⇒ The time is large to reach this, therefore the decrease in cross section decreases. Softening dominates here
(Recovery, Recrystallisation, Coarsening of precipitates, vacancy concn ↑)
Eventually knacking leads to failure.

- we will report steady state creep rate for comparing $\dot{\varepsilon}_{ss}$

Effect of Strees and Temperature

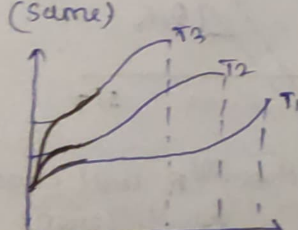
① what will be the variation for $\sigma_1 = 50$ MPa, $\sigma_2 = 100$ MPa, $\sigma_3 = 200$ MPa [T=constant here]

$\sigma_1 < \sigma_2 < \sigma_3$



② what will happen if we increase temperature (same) [Stress constant here

$T_1 < T_2 < T_3$



bcz softening process starts & leads to failure earlier & rupture time decreases

(*) [but the curves will start from same point]

CREEP DEFORMATION V/S STRESS RUPTURE TEST
↳ how much strain it can bear ↳ How much stress it can bear

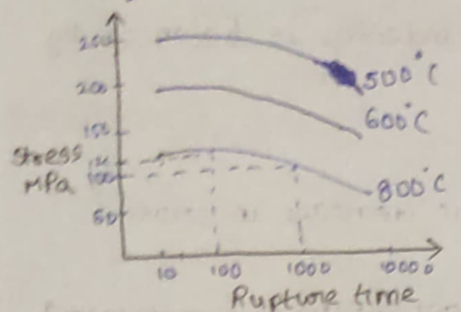
- Creep deformation curve need not be done completed
  ↳ purpose → upto how much time it can bear strain

- To know the stress level we will do STRESS RUPTURE TEST (it can withstand)

- CDT uses lower value of stresses while stress rupture test uses ↑ value of stress
- Strain developed in stress rupture test is high (as much as 50-60%) while CDT (2%)
- ~~Stress~~ ↑ Stress rupture have ↑ elongation & less time (usually 1000 hr) while CDT (10000 hrs)

- Stress rupture test has to be taken to the last i.e fracture point.
- Easy to measure dimensional changes in stress rupture test (due to ↑ strain) but in CDT we need highly precised instruments.
- Structural changes are visible quickly in stress rupture test than in CDT.

Now for stress Rupture test



T↑, rupture life ↓

Steady-state eqn

$$\dot{\varepsilon}_{ss} = \underset{\text{constant}}{A} \cdot \underset{\text{stress}}{\sigma^n} \cdot \exp\left[\frac{-Q}{RT}\right]$$

Q → activation energy
T → Temperature (K)

$\frac{Q}{R} = f(\sigma) =$ Parameter

Monkmann-Grant Relation

$$\boxed{\dot{\varepsilon}_{ss} \times t = B}$$

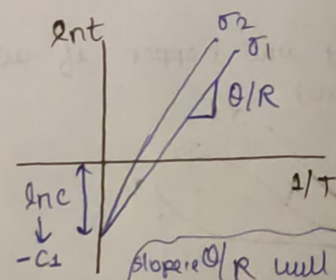
at a particular value of stress

$$t \cdot \exp\left(\frac{-Q}{RT}\right) = C$$

taking log both sides

$$\ln t - \frac{Q}{RT} = \ln C$$

$$\boxed{\ln t = \frac{Q}{RT} + \ln C}$$ →



Slope Q/R will change for different values of stress as $Q/R = f(\sigma) = P$

using $Q/R = P$ $\ln C = -C_1$

$$\ln t = -C_1 + \frac{Q}{RT}$$

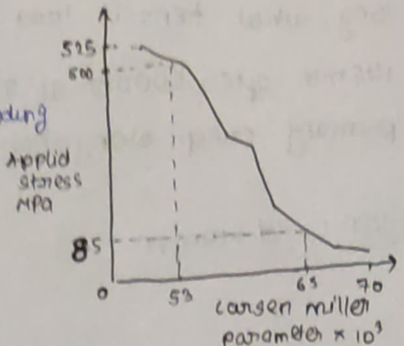
C = larsen miller constant

$$\boxed{\underset{(K)}{T}(\underset{(hrs)}{\ln t} + \underset{46}{C_1}) = P}$$ → Larsen Miller correlation Parameter

Natural log, $C_1 \approx 46-50$

Log $C_1 \approx 18-22$

Q) Determine the stress required for failure of Astroloy in 100000 hours at temperature of 650°C & 870°C.



Soln:- Lets take $C_1 = 46$
we will find the value of P & check its corresponding stress using the graph

$t = 100000$
$T = 650°C = 650 + 273.15 = 923.15\ K$

$T(\ln t + 46) = P$

$P \approx \underline{53} \times 10^3$

$\text{Stress}_{\text{at } P=53} = 500\ MPa$

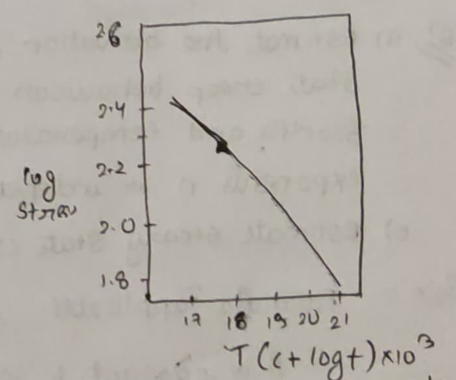
for $T = 870°C = 1143.15\ K$
$t = 100000$

$T(\ln t + 46) = P$

$P = 65$

$\text{Stress}_{\text{at } P=65} = 85\ MPa$

Q) A Larsen Miller plot for some hypothetical metal alloy is shown in the following figure. The value of the parameter C is unknown. However it is known that at a stress level of 125 MPa and at 677°C, rupture occurs at 1000 hr. On this basis, calculate the rupture life time in years at a stress level of 260 MPa and 527°C.



Soln:- at stress level of 125
$\therefore \log(125) \simeq 2.1$
corresponding the value $= 19$ $\quad \underline{P = 19} \times 10^3$

we know $T(\ln t + C) = P$

$T = 677°C = 950.15\ K \quad , \quad P = 19 \times 10^3$

$19000 = 950(C + \log(1000)) = \underline{C = 17}$

Now for $\underline{260\ MPa}$
$\log(260) \approx 2.41 \qquad T = 527°C = 800.15$
corresponing
$P = \underline{\text{to } 17} \times 10^3$

$17000 = 800.15(17 + \log t)$

$t = 2.03$ yrs

Q) For a cylindrical S-590 alloy specimen originally 10 mm diameter and 500 mm long, what tensile load is neccessary to produce a total elongation of 145 mm after 2000 hr at 730°C. Assume that the sum of instantaneous and primary creep elongation is 8.6 mm. Tertiary creep stage was not reached

Given:- $d = 10\,mm$

Q) a) Estimate the activation energy for creep for the S-590 alloy having the steady state creep behaviour shown in fig. Use data taken as a stress level of 300 MPa and temperature of 650°C and 730°C. Assume that the stress exponents n is independent of temperature

b) Estimate steady state creep rate at 600°C & 300 MPa.

stress is diff

A & n calculate separately

Soln :- Formula applicable $\dot{\varepsilon}_{ss} = A\sigma^n \cdot \exp\left[\frac{-Q}{RT}\right]$

A is constant & so is n → given

Using graph data at 650°C & 300 MPa $\dot{\varepsilon}_{ss_1} = 10^{-4}$

Similarly at 730°C & 300 MPA $\dot{\varepsilon}_{ss_2} = 10^{-2}$

$Q = 453700$

const term $= 4.27 \times 10^{21}$

creep rate $= 3 \times 10^{-6}\,h^{-1}$

∴ The equations are

$$\dot{\varepsilon}_{ss_1} = \underbrace{A\sigma^n}_{B} \exp\left[\frac{-Q_1}{R \times (650 + 273.15)}\right] \quad — (1)$$

$$10^{-4} = B \exp\left[\frac{-Q_1}{8.3174 \times (650 + 273.15)}\right]$$

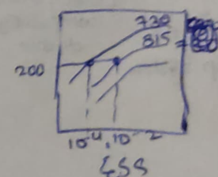
$$10^{-2} = \dot{\varepsilon}_{ss_2} = B \exp\left[\frac{-Q_1}{8.3174 \times (730 + 273.15)}\right] \quad — (2)$$

Q. A cylindrical specimen 13.1 mm in diameter of an S-590 alloy is to be subjected to a tensile load of 27,000 N. At approximately what temperature will the steady state creep be $10^{-3}\ h^{-1}$? Use the data shown. Assume the stress exponent n to be independent of temperature.

$N/mm^2 = MPa$

Soln Load = 27,000 $\quad$ d = 13.1 mm

$$\text{Stress} = \frac{\text{Load}}{\text{Area}} = \frac{271000}{\pi (13.1)^2} \times 4 = 200\ MPa$$



Tms = 770

Now at 200 MPa, two temperature lines can be used ~~730~~ 730°C & 815°C corresponding to 10^{-4} & 10^{-2} steady state creep rate respectively

$$\therefore\ 10^{-4} = (A \times \sigma^n) \times \exp\left(\frac{-Q}{R \times (650 + 273.15)}\right)$$

$$10^{-2} = (A \times \sigma^n) \exp\left(\frac{-Q}{8.314\,(815 + 273.15)}\right)$$

IMPACT TESTING

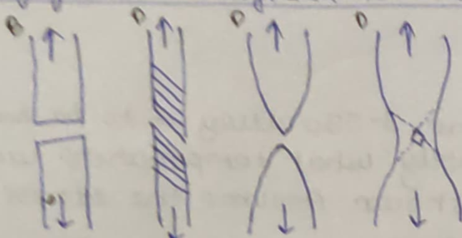
- Done to get the idea about 'FRACTURE' of the material.

FRACTURE :- Separation or Fragmentation of material into several (two or more) parts under the action of stress

types :- Ductile & Brittle Fracture → Based on strain to failure criterion

Ductile	Brittle
after deformⁿ necking	No prior info (sudden)
Appearance of fracture: Fibrous in nature	Granular in nature
Shear crystallographic mode	Cleavage crystallographic mode

Types of fracture subjected to uniaxial tension



(a) (b) (c) (d)

Ex:- (a) BCC, HCP; (b) HCP → due to less no of slip system; (c) ex:- Lead, Gold — completely ductile; (d) Moderately ductile Materials → cup & cone Failure / arrangement (a ductile failure)

a) Brittle fracture of single & polycrystals
b) Shearing fracture in ductile single crystals
c) completely ductile fracture in polycrystals
d) ductile fracture in polycrystals

Need?
- to find brittle fracture
- basically after WW II as ship components failed during winters & when submerged under water

Conditions leading to Brittle Fracture (out of 3, two need to be present)

1. Triaxial state of stress — stress in all 3 axis, stress intensity ↑, Fracture early
2. Low Temperature
3. High strain rate / High rate of Loading

Now in the ship components case Triaxial state of stress & Low T were responsible for brittle fracture.
Triaxial state of stress occurred due to welded joints that are point of crack suspect. Joints are the weakest point and act as STRESS RAISERS.

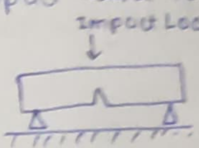
Impact Testing [How the conditions [of brittle fracture] are made]

- 10×10mm Sample
- Small component is attacked by a swinging pendulum or hammer causing High Strain Rate of 10^3 sec or V=50m/s
- A chamber or Furnace is used to maintain the temperature
- We develop NOTCH upto depth of 2mm [best design for generating triaxial state of stress]
  0.25mm root radius of notch
- 45° angle (top)

Now they are two possibilities it can be done

① Charpy V-notch (top view)

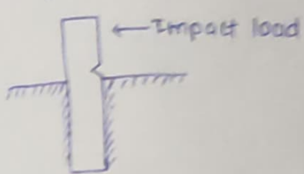
- impact done to opposite side of notch



Reading:- Cv 40J

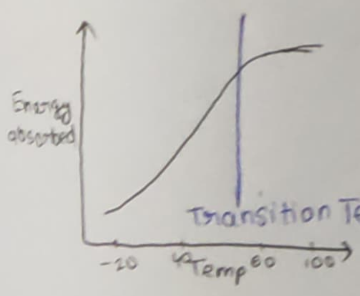
② Izod (side view)

- impact to the same side of notch



- We generally measure the energy absorbed. Higher the energy absorbed ~~greater~~ lesser the rebound height.
  Brittle material will have less energy absorbed, ∴ ~~lesser~~ higher the rebound
  Ductile materials will have more energy absorbed, ∴ less rebound

+ We perform the testing (charpy & Izod) on some range of temperatures to see the Ductile to brittle transition. (as Dislocation hardening ↑ deformn ↓, brittleness ↑)
  ∴ Low T ⟶ prone to Brittleness, ↓ Energy absorbed
  & then we measure the energy absorbed



DBTT = Ductile to brittle Transition Temp

Q) two Material has DBTT 50°C & 20°C, which one to prefer?

Ans:→ 20°C
Now we have more margin of ductility and thus no sudden failure

DBTT
B D

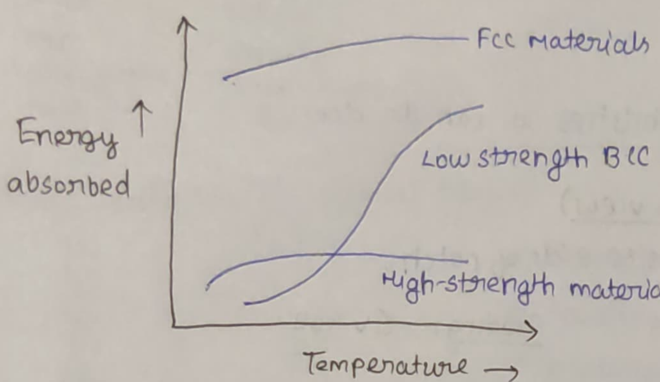
•) Appearance & microstructures can be used to determine brittle or ductile materials or fracture.

cleavage/flat facets structure → Higher reflectivity → bright → BRITTLE

Fibrous / Dimple surface → Higher light absorbivity → dull or Grey → DUCTILE

Bcc v/s FCC v/s High strength Material

Fcc didn't show sudden dip i.e NOTCH CURVE MATERIAL (↑ E absorbed and ductile)
bcc



Advantages [charpy ~~& Izod~~]

1. Easy setup, cheaper & simple to do
2. can be performed over a range of Temperature

Disadvantages [charpy ~~& Izod~~]

1. Energy values can't be used for design considerations.
2. Transition temp varies, graphs will not be sharp always.
3. ~~Sudden~~ Not give idea about crack, crack size & propagation (Flaw size)
4. To perform it again, we need to recreate the NOTCH of same dimensions & conditions thus values are scattered.

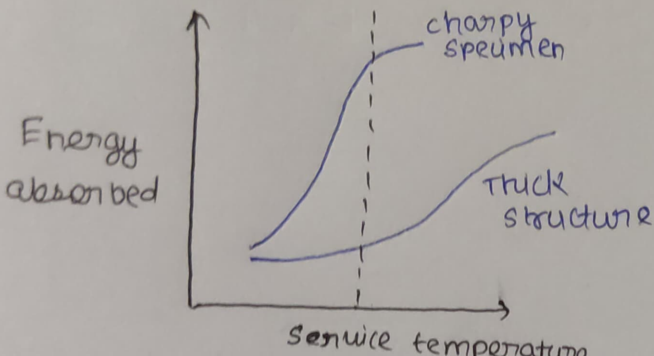
INSTRUMENTED CHARPY TEST

↳ we have load-time moniteration over a range of temperature
↳ get idea about crack initiation & fracture
↳ History is recorded using sensors

MAJOR CHANGES after CHARPY.

why?

↳ sample size was very less ∴ large thickness sample were started to use bcz as we increase thickness, the transition temperature changes composition remain the same



Temperature →

② Drop weight Test