Tutorial 5

① Cu FCC $R = 1.278\ \mathring{A}$, $A_{Cu} = 63.54\ g/mol$

$\rho = ?$

$$\rho = \frac{n \times A_{Cu}}{V \times N_A}$$

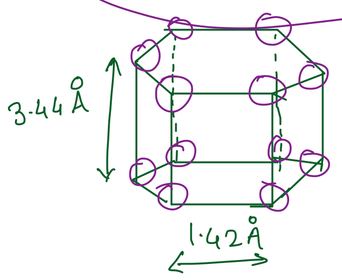
$V = a^3$ FCC $a\sqrt{2} = 4R$

$$\boxed{\rho = 8.93\ gm/cc}$$

② Graphite C-C bonds $1.42\ \mathring{A}$

C-C layer $3.44\ \mathring{A}$

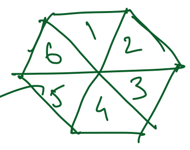
Calculate $\rho = ?$ → Similar to HCP but $n = 2$



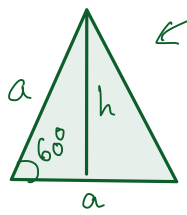
$$\rho = \frac{n \times A_c}{V_c \times N_A}$$

Volume = Area of base × height

$= 6 \times \frac{1}{2} \times b \times h \times c$



$= 6 \times \frac{1}{2} \times a \times \frac{a\sqrt{3}}{2} \times c$



$\sin 60 = \frac{h}{a} = \frac{\sqrt{3}}{2}$

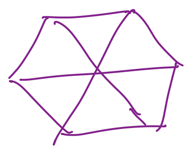
$\rho = 2.211\ gm/cc$

③ In HCP $c = 4.94\ \mathring{A}$ $A_{Zn} = 65.37\ g/mol$

$V = ?$ & $\rho = ?$

$V = 6 \times$ area of base × height

$= 6 \times \frac{1}{2} \times a \times \frac{a\sqrt{3}}{2} \times c$



$V = \frac{3a^2\sqrt{3}}{2}c$ → $\frac{c}{a} = \sqrt{\frac{8}{3}}$

$$\boxed{V = 1.174 \times 10^{-22}\ cm^3}$$

$$\rho = \frac{n \times A}{V_c \times N_A}$$

$$\boxed{\rho = 5.546\ gm/cc}$$

④ Ti BCC ; $a = 3.32\ \mathring{A}$

880°C cool ↓

HCP ; $a = 2.956\ \mathring{A}$, $c = 4.683\ \mathring{A}$

% Change in the volume ?

$V_{BCC} = \frac{a^3}{2} = ?$

$V_{HCP} = \frac{V}{6} = \frac{6 \times \frac{1}{2} \times a \times \frac{a\sqrt{3}}{2} \times c}{6}$

$= \frac{1}{6} \times \frac{3\sqrt{3}}{2} a^2 c$

$= ?$

% change in volume $= \frac{V_{BCC} - V_{HCP}}{V_{BCC}}$

$= 0.0322$

$= 3.22\%$

⑤ Fe $A_{Fe} = 56.05\ g/mol$

BCC ; $R = 1.258\ \mathring{A}$

↓ 910°C

FCC ; $R = 1.298\ \mathring{A}$

$a\sqrt{2} = 4R$

$a\sqrt{3} = 4R$

$V = \frac{a^3}{2}$ BCC

$V = \frac{a^3}{4}$ FCC

① % change in volume ?

② % linear change ?

$\frac{a_1 - a_2}{a_2}$

⑦ Largest atom in the interstitial void of FCC Nickel without distortion ?

⇒ In FCC largest void is octahedral

$\frac{R_c}{R_a} = 0.414$ → without

0.732 → with

$R_c\ (R_{void}) = 0.414 \times R_{Ni}$

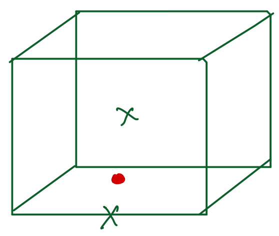
$R_c = \_\_\_\_$

⑧ Largest void in BCC. located at $(0, \frac{1}{2}, \frac{1}{4})$

(with or without distortion?)

Tetrahedral void

Octahedral → $(\frac{1}{2}, \frac{1}{2}, 0)$. $(\frac{1}{2}, 0, 0)$



① $\frac{R_{void}}{R_{atom}} = 0.29$ → 0.225 - 0.414

$$\boxed{R_{void} = 0.29 \times R_{atom}}$$

② $\frac{R_{void}}{R_{atom}} = 0.414$

⑨ FCC Al

$\rho = 2700\ kg/m^3$; $A_{Al} = 26.98\ gm/mol$

$a = ?$

$d_{atom} = ?$

$$\rho = \frac{n \times A_{Al}}{N_A \times V_c}$$

$V_c(a^3) = \_\_\_\_$

$a = \_\_\_\_$

$a\sqrt{2} = 4R$

$R = \_\_\_\_$

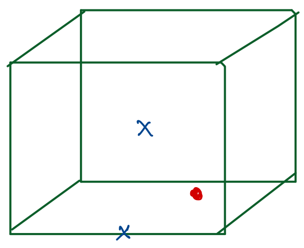
$d = \_\_\_\_$

Tutorial 6

(1) FCC lattice → $(\frac{1}{2},0,0)$, $(0,\frac{1}{2},0)$, $(0,0,\frac{1}{2})$ etc

Find atomic radius of largest interstitial void ?

(with or without distortion ?) $R_{FCC} - 1.292\,Å$



O.V. $(\frac{1}{2},0,0)$ & $(\frac{1}{2},\frac{1}{2},\frac{1}{2})$

T.V. $(\frac{1}{4},\frac{1}{4},\frac{1}{4})$

Ratio of R_c/R_a

T.V. → 0.225 − 0.414

O.V. → 0.414 — 0.732

without   with

$\frac{R_c}{R_a} = 0.414$ $R_c = 0.414 \times (1.292\,Å)$

$R_c =$ ______

(2) 1 Slip band width, $w = 300\,nm = 3000\,Å$

SC crystal $a = 3\,Å$

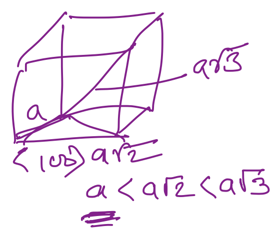
How many dislocations have slipped out ?

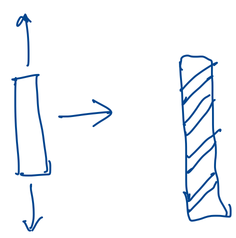
→ $\frac{\text{Width of slip band} - \text{No. of dislocation}}{\text{No. of dislocation}}$

$\vec{b} = \langle 100 \rangle$

$= a$

$= 3\,Å$



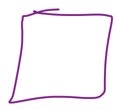


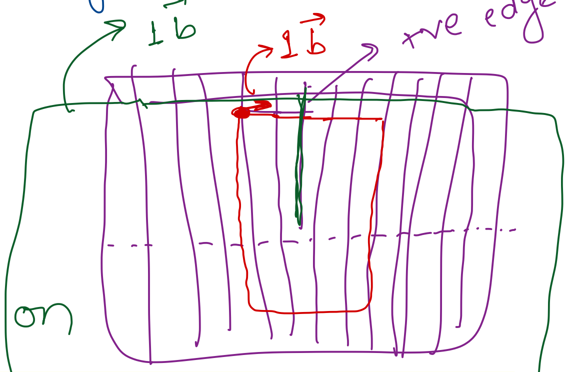
$\frac{3000\,Å - 3\,Å}{3\,Å}$

$= \underline{999}$ dislocation

$\frac{3000}{3} = 1000$

(3) Does Burgers vector change with the size of Burgers circuit ?





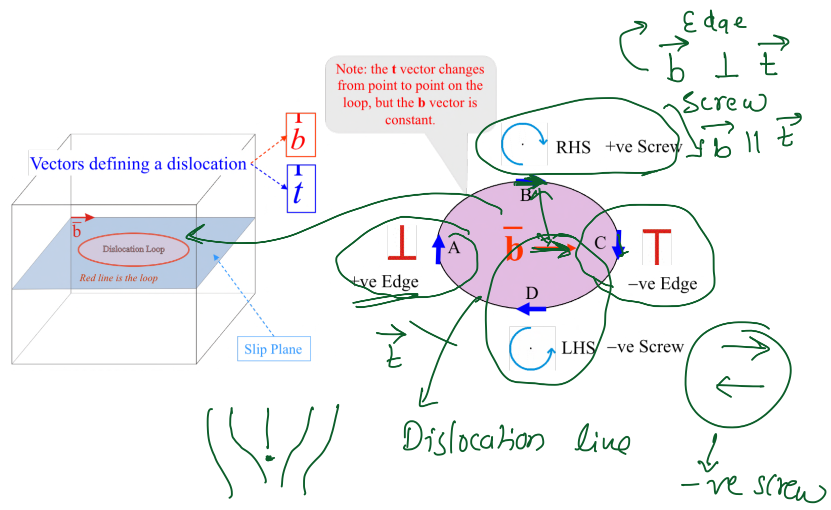
NO. It depends on no. of dislocations & not on circuit

(4) Direction of dislocation line

Burgers vector

Positive edge / Negative edge

positive Screw / Negative screw



(5) Al crystal, $\rho = 10^{10}\,m^{-2}$, $\mu = 25.94\,GN/m^2$

$E = ?$

→ $\boxed{E = \frac{1}{2}\mu b^2}$ $b = ?$

→ $\boxed{\rho = \frac{1}{\ell^2}}$; ℓ = length of dislocation line

$\ell =$ ______ m

$\boxed{\tau = \frac{\mu b}{\ell}}$;

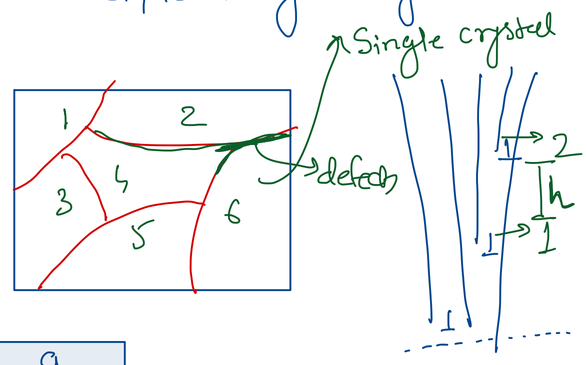
For perfect crystal $\boxed{\tau = \frac{\mu}{6}}$ $\therefore \frac{b}{\ell} = \frac{1}{6}$

→ $b = \frac{\ell}{6}$ = ______ µm $1\,N = \frac{1\,J}{1\,m}$

$E = \frac{1}{2}\mu b^2$ = ______ $\frac{J}{m}$

(7) $\theta = 1^\circ$; FCC, $a_{Cu} = 3.62\,Å$

Distance between two neighbouring edge dislocations = ?



$\frac{b}{h} = \tan\theta$

$h = ?$

$b = \frac{1}{2}\langle 110 \rangle$

$= \frac{1}{2}a\sqrt{2}$ $\boxed{b = \frac{a}{\sqrt{2}}}$ $b =$ ______ Å

$h = \frac{b}{\tan\theta}$ = ______ Å

(8) FCC Iridium $a = 3.62\,Å$

$\theta_1 = 1^\circ$ → $h_1 = \frac{b}{\tan\theta_1}$ = ______ Å

$\theta_2 = 3^\circ$ → $h_2 = \frac{b}{\tan\theta_2}$ = ______ Å

Spacing between dislocations $= h_1 - h_2 =$ ______ Å

(9) Positive edge dislocation

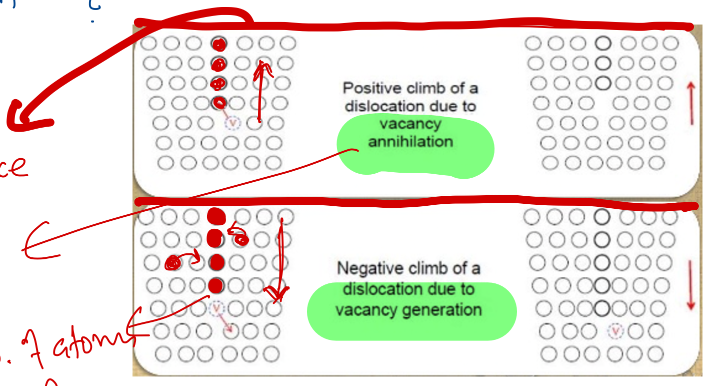
length 1 mm] in Polonium → SC

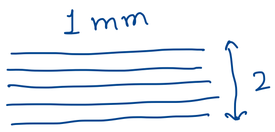
Climbs down by 2 µm]   R → 1.7 Å

(1) Vancancies created or lost ?

(2) How much ?

→





Affected area $= 1\times10^{-3} \times 2\times10^{-6}$

$= 2 \times 10^{-9}\,m^2$

No of vacancies created

$= \frac{\text{No. of atoms in unit cell} \times \text{Affected area}}{\text{area of unit cell}}$

S.C. n = 1 $a = 2R$ | SC

$= \frac{1 \times 2\times10^{-9}}{3.4\times10^{-10} \times 3.4\times10^{-10}}$ = ______

⑥ $E_a = 1.4$ eV , Frenkel defect in ionic solids

$\dfrac{n_{(20^\circ C)}}{n_{(300^\circ C)}}$ for 1 gm of crystal

→

Metals	$n = N\exp\left(\dfrac{-\Delta H_f}{RT}\right)$ ΔH_f = Enthalpy kJ/mol R = gas constant = 8.314 J/mol T = Temp in kelvin	$n = N\exp\left(\dfrac{-E_a}{KT}\right)$ E_a = activation energy K = Boltzmann's constant = 8.625×10^{-5} eV/K
Ionic Solids	$n = N\exp\left(\dfrac{-\Delta H_f}{2RT}\right)$	$n = N\exp\left(\dfrac{-E_a}{2KT}\right)$

Defects formed in pairs always

$$n = N\exp\left(\frac{-E_a}{2KT}\right)$$

$$\frac{n_1}{n_2} = \frac{\exp\left(\frac{-E_a}{2KT_1}\right)}{\exp\left(\frac{-E_a}{2KT_2}\right)}$$

Always in Kelvin

$\dfrac{\exp a}{\exp b} = \exp(a-b)$

$$= \exp\left[\frac{-E_a}{2K}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

$$= \exp\left[\frac{-1.4 \text{ eV}}{2\times8.625\times10^{-5}\ \frac{\text{eV}}{K}}\left(\frac{1}{293} - \frac{1}{573}\right)\right]$$

$$= \exp(-13.56)$$

$$\boxed{\frac{n_1}{n_2} = 1.2\times10^{-6}}$$

$\left(\frac{1}{2},\frac{1}{2},\frac{1}{2}\right), \left(\frac{1}{2},0,0\right)$ without with

FCC → O.V. → 0.414 – 0.732 $\dfrac{R_c}{R_a}$

FCC → T.V. → 0.225 – 0.414

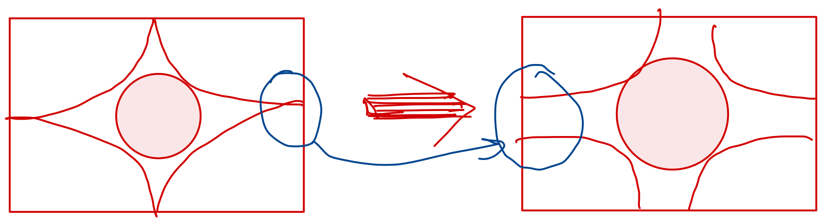
↳ $\left(\frac{1}{4},\frac{1}{4},\frac{1}{4}\right)$

$\left(\frac{1}{2},\frac{1}{2},0\right), \left(\frac{1}{2},0,0\right)$

BCC → O.V. → 0.414 – 0.732

BCC → T.V. → 0.225 – 0.414

↓ $\left(0,\frac{1}{2},\frac{1}{4}\right)$



$\dfrac{R_c}{R_a} = 0.225$ Without distortion

$\dfrac{R_c}{R_a} = 0.414$ With distortion

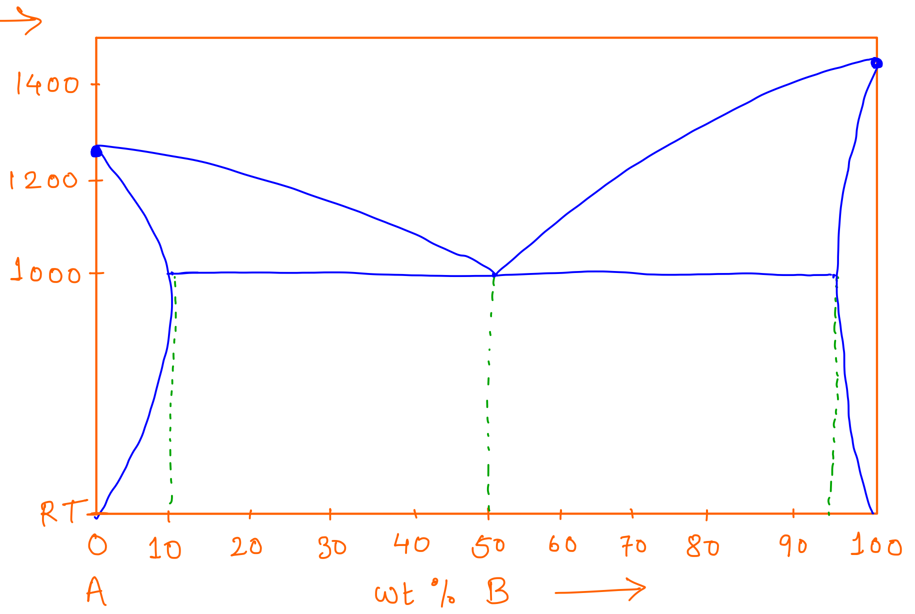
TUTORIAL - 7

① Binary A-B alloy

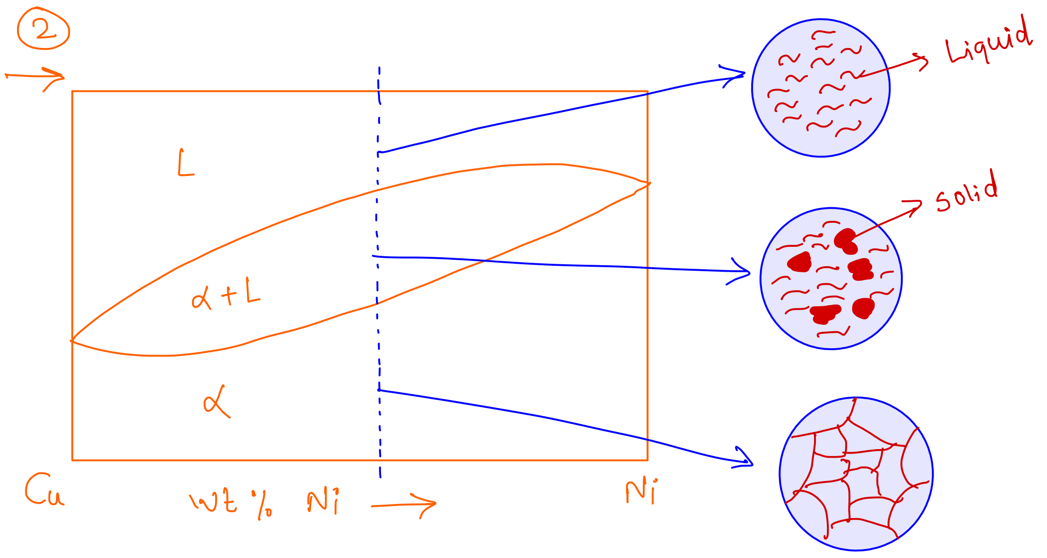
M.P. of A − 1250°C
B − 1250°C

A is 5% soluble in B at invariant temp 1000°C
B is 10% soluble in A
Both solids drops down to zero at RT
Triple point is at 50% of B
Draw the corresponding phase diagram.

→



② →

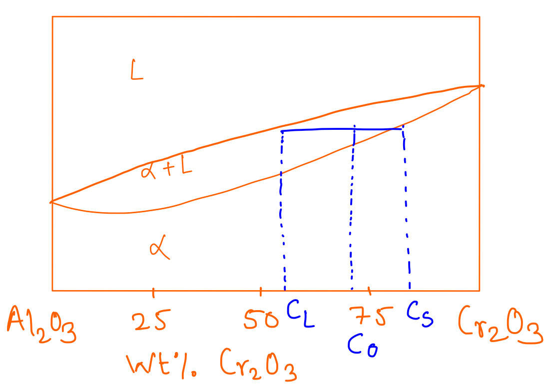


③ Binary phase diagram of $Al_2O_3 - Cr_2O_3$

At 2180°C, % Cr_2O_3 C_L − 57%
C_S − 82%

For 70% Cr_2O_3, find out W_L & W_S respectively.

→



C_L − 57%
C_S − 82%
C_o − 70%

$$\boxed{W_L = \frac{C_S - C_o}{C_S - C_L}} \qquad \boxed{W_S = \frac{C_o - C_L}{C_S - C_L}}$$

④ ⓐ Maximum no. of phases ?
ⓑ Maximum possible degree of freedom ? } In binary system

→ For binary system $P + F = C + 1$

ⓐ For $F = 0$; $C = 2$ ⇒ $\boxed{P = 3}$

ⓑ For $P = 1$; $C = 2$ ⇒ $\boxed{F = 2}$

⑦ A-B alloy is in α+β state. Find volume fractions.
$\rho_\alpha = 10640$ kg/m³ ; $\rho_\beta = 7290$ kg/m³

→ This is like Pb-Sn system
So, $W_\alpha = 67\%$, $W_\beta = 33\%$
For 1 kg ⇒ $M_\alpha = 670$ gm, $M_\beta = 33$ gm

$$V_\alpha = \frac{V_\alpha}{V_\alpha + V_\beta} = \frac{M_\alpha/\rho_\alpha}{\frac{M_\alpha}{\rho_\alpha} + \frac{M_\beta}{\rho_\beta}} = \_\_\_\_\_\_ \%$$

$$V_\beta = \frac{V_\beta}{V_\alpha + V_\beta} = \frac{M_\beta/\rho_\beta}{\frac{M_\alpha}{\rho_\alpha} + \frac{M_\beta}{\rho_\beta}} = \_\_\_\_\_\_ \%$$

⑧ Cu − Ni system
Cu − 68 atomic %
Ni − 32 atomic %
Find the weight fractions.

→

Atomic weight of Cu − 63.54 gm/mol
Ni − 58.69 gm/mol

Weight of Cu atoms
63.54 g/mol = 6.023×10^{23} atoms

wt of 68 atoms $= \frac{63.54}{6.023 \times 10^{23}} \times 68$

$= \_\_\_\_\_\_$ gm

Weight of Ni atoms
58.69 g/mol = 6.023×10^{23} atoms

wt of 32 atoms $= \frac{58.69}{6.023 \times 10^{23}} \times 32$
$= \_\_\_\_\_\_$ gm

$$\text{Wt fraction of Cu} = \frac{\text{wt of 68 Cu atoms}}{\text{wt of 68 Cu atoms} + \text{wt of 32 Ni atoms}}$$

$= \_\_\_\_\_\_ \%$

$$\text{Wt fraction of Ni} = \frac{\text{wt of 32 Ni atoms}}{\text{wt of 68 Cu atoms} + \text{wt of 32 Ni atoms}}$$

$= \_\_\_\_\_\_ \%$

⑥ ASTM 7 → ASTM 14
Find out increase in σ_y of the steel ?

→

$$\boxed{\sigma_y = \sigma_i + \frac{k}{\sqrt{d}}} \qquad \boxed{1\ \text{MPa} = 1\ \frac{\text{MN}}{\text{m}^2}}$$

$k = 0.74$ MN/m$^{3/2}$
$\sigma_o = 70$ MPa

no. of grains (n) per sq. inch at 100 X

$$n = 2^{N-1}$$

where,
N = Grain index (ASTM) number

$$\text{Area of one grain (A)} = \frac{(1\ \text{inch})^2}{n}$$
(at 100 X)

$$A\ (\text{at } 100\times) = \frac{645\ mm^2}{n}$$

$$\text{Actual grain size} = \sqrt{\frac{\text{Area at } 100\times}{100}}$$

$$= \sqrt{\frac{645}{n \times 10^4}}$$

$$\boxed{\text{Grain size}(d) = \sqrt{\frac{645}{2^{N-1} \times 10^4}}}$$

Now,

$\sigma_y' \rightarrow$ Yield strength for ASTM 7

$\sigma_y'' \rightarrow$ Yield strength for ASTM 14

Increase in Yield strength,

$$\sigma_y'' - \sigma_y' = K\left(\frac{1}{\sqrt{d''}} - \frac{1}{\sqrt{d'}}\right)$$

$$= \underline{\hspace{2cm}}\ MPa$$

5 Grain size changes from 0.04 mm to 0.01 mm

Yield strength changes from 120 MPa to 220 MPa

Calculate σ_y if grain diameter is 0.0159 mm.

$$120\ MPa = \sigma_i + K(0.04 \times 10^{-3})^{-1/2} \quad \text{—— } (1)$$
$$220\ MPa = \sigma_i + K(0.01 \times 10^{-3})^{-1/2} \quad \text{—— } (2)$$

Equation (1) − (2) gives,

$$\boxed{\begin{aligned} \sigma_i &= 20\ MPa \\ K &= 0.633\ MNm^{-3/2} \end{aligned}}$$

Therefore,

Yield strength for the grain diameter of 0.0159 mm is.

$$\sigma_y = \sigma_i + K\frac{1}{\sqrt{d}}$$

$$= 20 + 0.633 \times (0.0159 \times 10^{-3})^{-1/2}$$

$$\boxed{\sigma_y = 179\ MPa}$$

TUTORIAL 8

5 For mild steel

$\sigma_y = 20000$ psi for 0.05 mm grain dia

$\sigma_y = 40000$ psi for 0.007 mm grain dia

Find the grain diameter for $\sigma_y = 30000$ psi.

→ We know that,

1000 psi = 6.895 MPa

→ 20000 psi = 137.9 MPa

40000 psi = 275.8 MPa

$$137.9 = \sigma_i + \frac{K}{\sqrt{0.05}} \quad \text{—— } (1)$$

$$275.8 = \sigma_i + \frac{K}{\sqrt{0.007}} \quad \text{—— } (2)$$

Equation (1) − (2) gives,

$$\sigma_i = 55.5\ MPa$$
$$K = 18.43\ MPa\ mm^{1/2}$$

Therefore, for 30000 psi (206.9 MPa)

$$\sigma_y = \sigma_i + \frac{K}{\sqrt{d}}$$

$$\Rightarrow \boxed{d = 0.0148\ mm}$$

Tutorial 8-9

① FCC lead $a = 0.4949$ nm

has $\frac{\text{one vacancy}}{500 \text{ Pb atoms}}$ & $A = 207.2$ gm

Calculate

① Density

② No. of vacancies per gram ?

→ $\rho = \frac{n \times A}{N_A \times V_c}$ —— ①

$\boxed{\rho = 11.35 \text{ g/cc}}$ Ideal ρ

No of vacancies per unit cell $= \frac{4}{500}$ → $1 - 500$, $? - 4$

No of atoms per unit cell $= \left(4 - \frac{4}{500}\right)$

Density with defects

$\boxed{\rho = 11.32 \text{ g/cc}}$

Now, 207.2 gm $= 6.023 \times 10^{23}$ atoms

1 gm $= 2.9066 \times 10^{21}$ atoms

Thus, if $1 - 500$

$? - 2.9066 \times 10^{21}$

$\boxed{\text{Vacancies} = 5.813 \times 10^{18}}$

---

② Gold $n = ?$; $E_a = 0.98$ eV/atom ; $A = 197$ gm/mol

$\rho = 19.32$ g/cc , $T = 1173$ K

→ $n = N \exp\left(\frac{-E_a}{kT}\right)$

$N = ?$ $\rho = \frac{n \times A}{N_A \times V_c}$ ⇒ $\boxed{\frac{\rho . N_A}{A} = \frac{n}{V} = N}$

$n = \frac{19.32 \times 6.023 \times 10^{23}}{197} \exp\left(\frac{-0.98 \text{ eV}}{8.62 \times 10^{-5} \text{ eV/K}}\right)$

$\boxed{n = 3.65 \times 10^{18} \text{ cm}^{-3}}$

---

③ Aluminum, $E_a = ?$, $n = 7.57 \times 10^{23}$ m^{-3} ; $A = 26.98$ g/mol

& $\rho = 2.62$ gm/cc ; $T = 773$ K

→ $\frac{n}{V} = \frac{\rho \times N_A}{A} = \frac{2.62 \times 6.023 \times 10^{23}}{26.98}$

$N =$ ________ atoms/m^3

Now, $n = N \exp\left(-\frac{E_a}{kT}\right)$

$\ln n = \ln N - \frac{E_a}{kT}$

⇒ $E_a = -kT \ln\left(\frac{n}{N}\right)$

$\boxed{E_a = 0.75 \text{ eV}}$

$\log a - \log b = \log\left(\frac{a}{b}\right)$

(4) Slip plane (111)

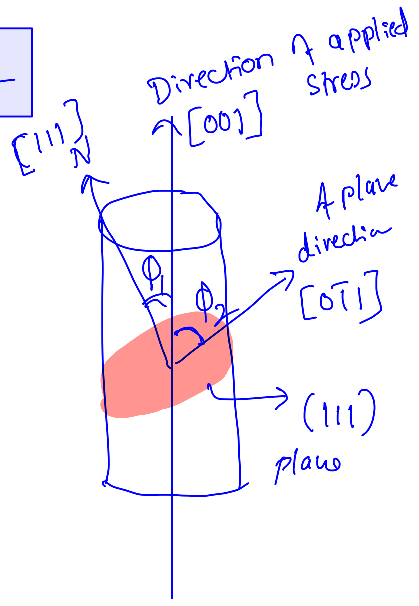
Slip direction $[0\bar{1}1]$

σ 3000 psi along $[001]$

τ_{RSS} along the slip direction ??

→ Schmid's law

$$\boxed{\tau = \sigma \cos\phi_1 \cos\phi_2}$$



Only in cubic,

$(111) \rightarrow$ Normal $[111]$

$(110) \rightarrow$ Normal $[110]$

MI for direction

↓

$[u_1 v_1 w_1]$ $[u_2 v_2 w_2]$

Angle between two directions

$$\phi = \cos^{-1}\left[\frac{u_1 \cdot u_2 + v_1 \cdot v_2 + w_1 \cdot w_2}{\sqrt{(u_1^2+v_1^2+w_1^2)(u_2^2+v_2^2+w_2^2)}}\right]$$

$\phi_1 =$ ________

$\phi_2 =$ ________

$\tau = \sigma \cos\phi_1 \cos\phi_2$

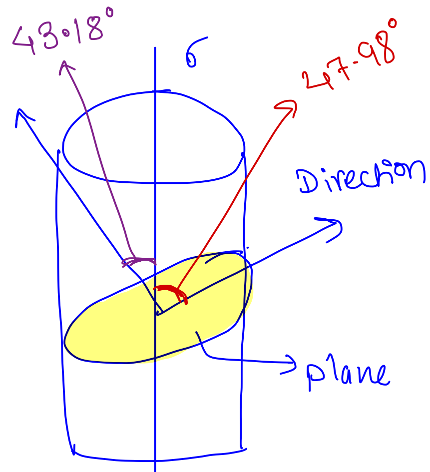
$=$ ________ psi

(6) $\tau_{CRSS} = 20.7$ MPa

Does $\sigma = 45$ MPa cause the single crystal to yield ?

If yes, why ?

If not, how much stress is required ?



→ $\tau_{CRSS} = 20.7$ MPa

If $\tau_{RSS} \geq \tau_{CRSS}$ then & only then plastic deformation.

$\tau_{RSS} = \sigma \cos\phi_1 \cos\phi_2$

$=$ ________

$\geq$ 20.7 MPa

There is plastic deform

(7) $\phi_1 = 28.18°$

$\phi_2 = 62.48°$
$= 72.08°$
$= 81.18°$

(a) which is most favoured direction ?

(b) If $\sigma = 1.95$ MPa find out τ_{CRSS}

→ It will be maximum along the direction with larger value of ϕ_2.

$$\boxed{\tau = \sigma \cos\phi_1 \cos\phi_2}$$

$\cos(62.48°) =$

$\cos(72.08°) =$

$\cos(81.08°) =$

$\tau_{CRSS} = \sigma \cdot \cos\phi_1 \cdot \cos\phi_2$

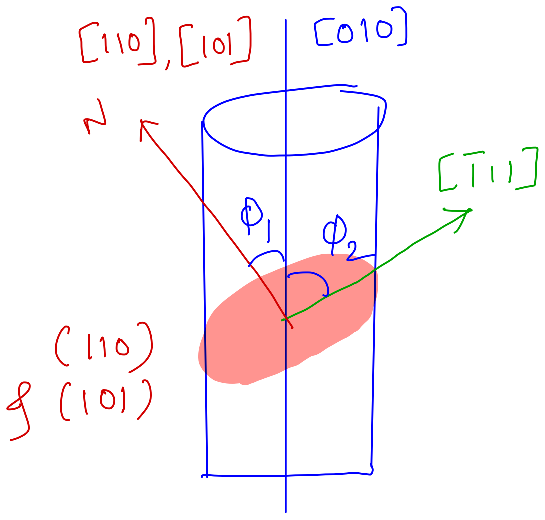
$\tau =$ ________ MPa

(12) $\sigma = 2.75$ MPa

(a) $\tau[(110)\ [\bar{1}11]] = ?$

$\tau[(101)\ [\bar{1}11]] = ?$

(b) Most favourable slip system ??



→

$\phi_1 \{[110] \& [010]\} = 45°$

$\phi_1 \{[101] \& [010]\} = 90°$

$\phi_2 \{[010] \& [\bar{1}11]\} = 54.7°$

$\tau[(101)\ [\bar{1}11]] = \sigma \cos\phi_1 \cos\phi_2$

$=$ ________ MPa

$\tau[(110)\ [\bar{1}11]] = \sigma \cos\phi_1 \cos\phi_2$

$=$ ________ MPa

(b) The most favourable system is with larger τ.

8

$d_o = 12.8$ mm

$\sigma_{Fracture} = 460$ MPa

$\Delta d = 10.7$ mm

True stress = ?

→ $\boxed{\sigma_{True} = \frac{F}{Area}}$ → Actual

$F = ?$

$\sigma = \frac{F}{A}$

$F = \sigma_{Fracture} \times Area$

area $= \pi r^2 = \pi\left(\frac{d}{2}\right)^2$

$= \left[\pi\left(\frac{d_o}{2}\right)^2\right]$

$F = \_\_\_\_$

$\sigma_{True} = \frac{F}{\pi\left(\frac{\Delta d}{2}\right)^2}$

$\sigma_{True} = \_\_\_\_\_\_$ MPa

9

$d_o = 10$ mm

$\Delta d = 2.5$ μm

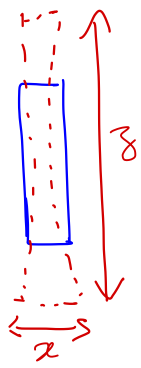
$\nu = 0.34$

$Y = 97$ GPa

$F = ?$

Elastic

→ $\boxed{F = \sigma \cdot A}$



$\nu = \frac{\varepsilon_x}{\varepsilon_z}$

$\varepsilon_z = \frac{\varepsilon_x}{\nu} = \frac{\Delta d}{d \cdot \nu} = 7.35 \times 10^{-4}$

$Y = \frac{\sigma}{\varepsilon} \Rightarrow \sigma = Y \cdot \varepsilon$

$\boxed{\sigma = \_\_\_\_\_\_ \text{ MPa}}$

$F = \sigma\left(\frac{d_o}{2}\right)^2 \times \pi$

$F = \_\_\_\_\_\_$ N

10

$\sigma_y = 275$ MPa

$Y = 115$ GPa

(a) $F = ?$ $A = 325$ mm^2

(b) $l_o = 115$ mm ; $\Delta l = ?$

→ $\sigma_y = \frac{F_{max}}{A}$

$F_{max} = \sigma_y \cdot A$

$\boxed{F_{max} = \_\_\_\_\_\_ \text{ N}}$

$\varepsilon = \frac{\Delta l}{l_o}$

$Y = \frac{\sigma}{\varepsilon}$

$Y = \sigma_y \cdot \frac{l_o}{\Delta l}$

$\boxed{\Delta l = \frac{\sigma_y \cdot l_o}{Y}}$

11

$Y = 110$ GPa

$\sigma_y = 240$ MPa

$F = 6660$ N

$l_o = 380$ mm

$\Delta l = 0.50$ mm

$d_o = ?$

$Y = \frac{\sigma}{\varepsilon}$

$\sigma = \frac{F}{A}$ $A = \pi r^2 = \pi\left(\frac{d}{2}\right)^2$

$\varepsilon = \frac{\Delta l}{l_o}$

→ $Y = \frac{\sigma}{\varepsilon}$

$= \left(\frac{F}{A}\right) \cdot \left(\frac{l_o}{\Delta l}\right)$

$= \frac{F}{\pi\left(\frac{d_o}{2}\right)^2} \cdot \left(\frac{l_o}{\Delta l}\right)$

$A = \pi r^2 = \pi\left(\frac{d}{2}\right)^2$

$Y = \frac{4F}{\pi d_o^2} \cdot \frac{l_o}{\Delta l}$

$d_o^2 = \frac{4 \cdot F \cdot l_o}{\pi \cdot \Delta l \cdot Y}$

$d_o = \sqrt{\frac{4F \cdot l_o}{\pi \cdot \Delta l \cdot Y}}$

$d_o = \_\_\_\_\_\_$ mm