

# Lecture 14

## Sintering

$$\sigma_1 = \frac{4\gamma}{D} \quad \begin{matrix} \text{surface energy} \\ \{ \text{surface tension} \} \end{matrix}$$

$$\sigma_2 = \gamma \left[ \frac{2}{D} - \frac{4D}{\kappa^2} \right] \quad \begin{matrix} \text{compressive stress} \\ \text{being exerted due to} \\ \text{necking} \end{matrix}$$

$\Delta\sigma = \sigma_1 - \sigma_2 \rightarrow$  this triggers atomistic mechanisms of diffusion.  
stress gradient hence sintering takes place.

$$\sigma_2 \propto \frac{1}{X}, \quad \sigma_2 \propto \frac{1}{D}$$

$\rightarrow$  As sintering progresses :  $X \uparrow$  ses  $\sigma_2 \downarrow$  ses  
 $\Leftrightarrow \Delta\sigma \downarrow$  ses

Kinetics of Sintering:

## \* Evaporation & Condensation:

Indicated by diff in radius of curvature.



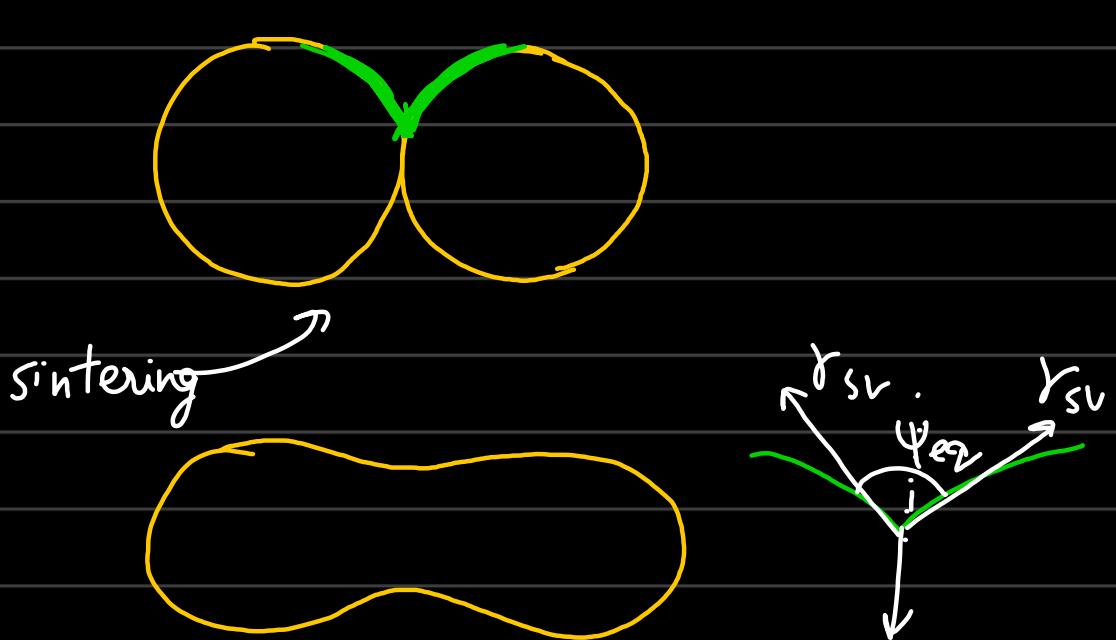
$$r=+ve \Rightarrow \Delta P = +ve$$

{ partial pressure gradients analogous to  
stress gradient }

↳ mass transport from here

$$r=0 \Rightarrow \Delta P = 0$$

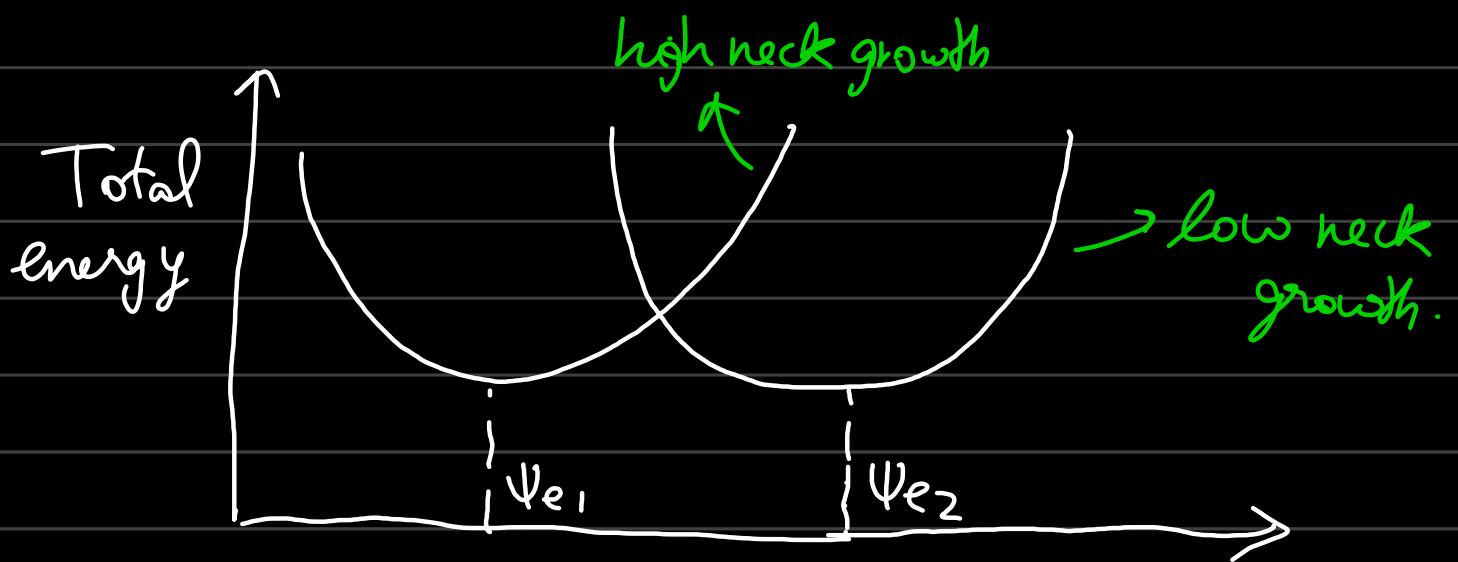
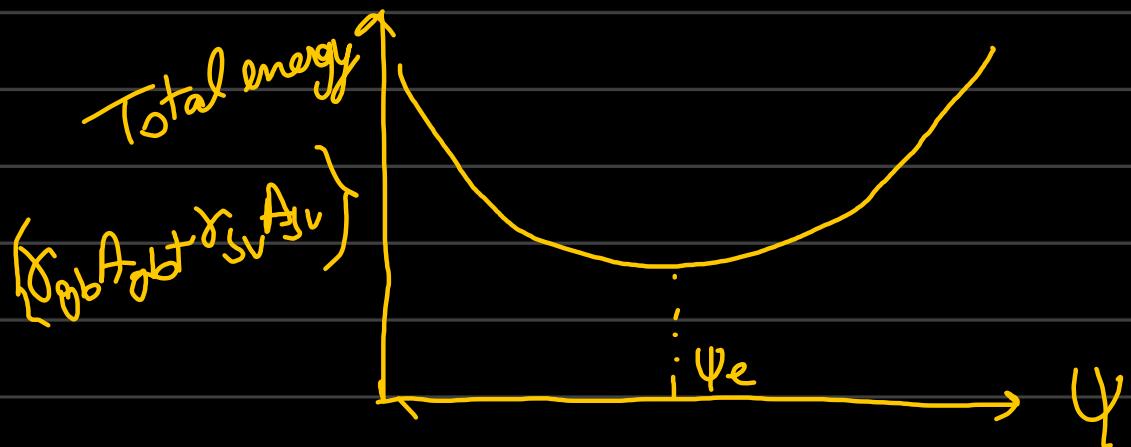
$$r=-ve \Rightarrow \underline{\Delta P} = -ve$$



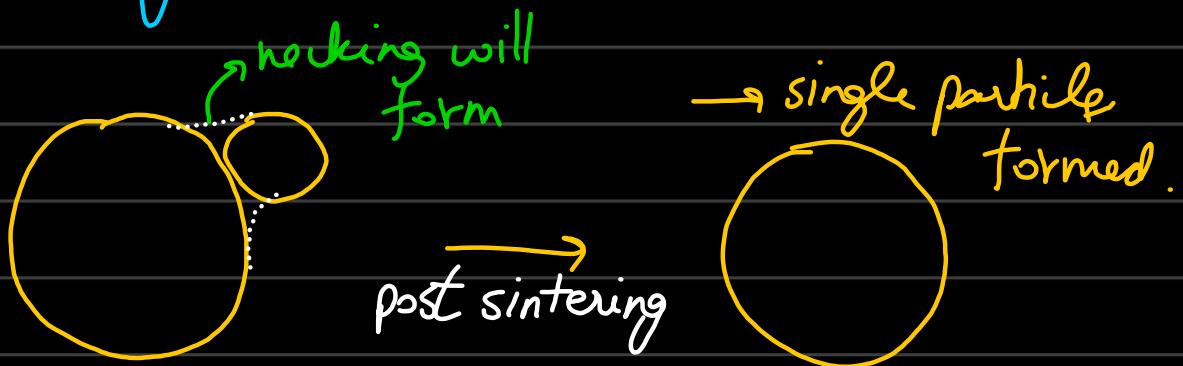
\* Equilibrium achieved when driving

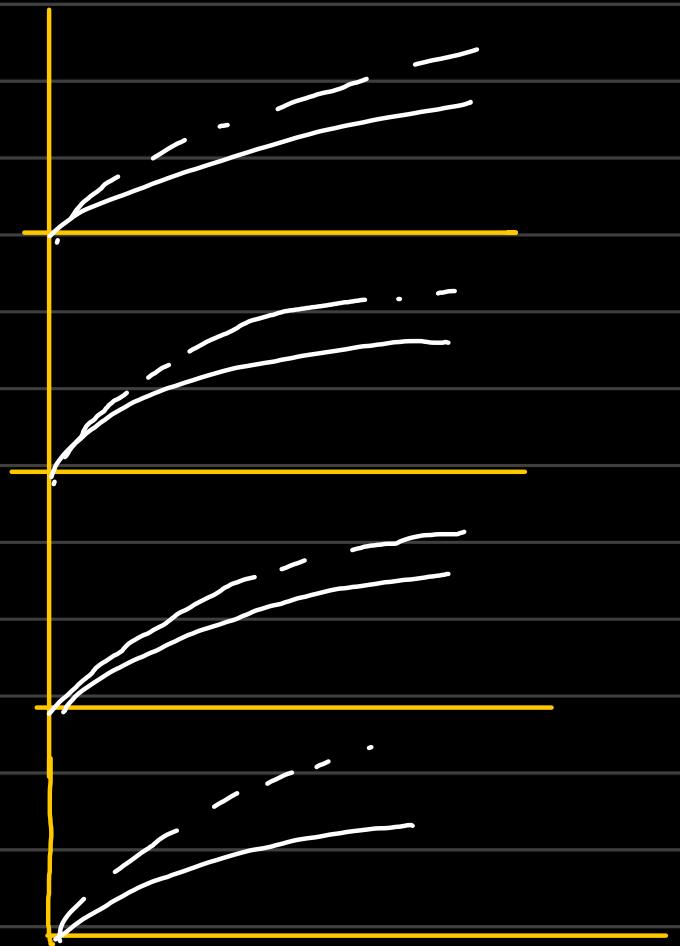
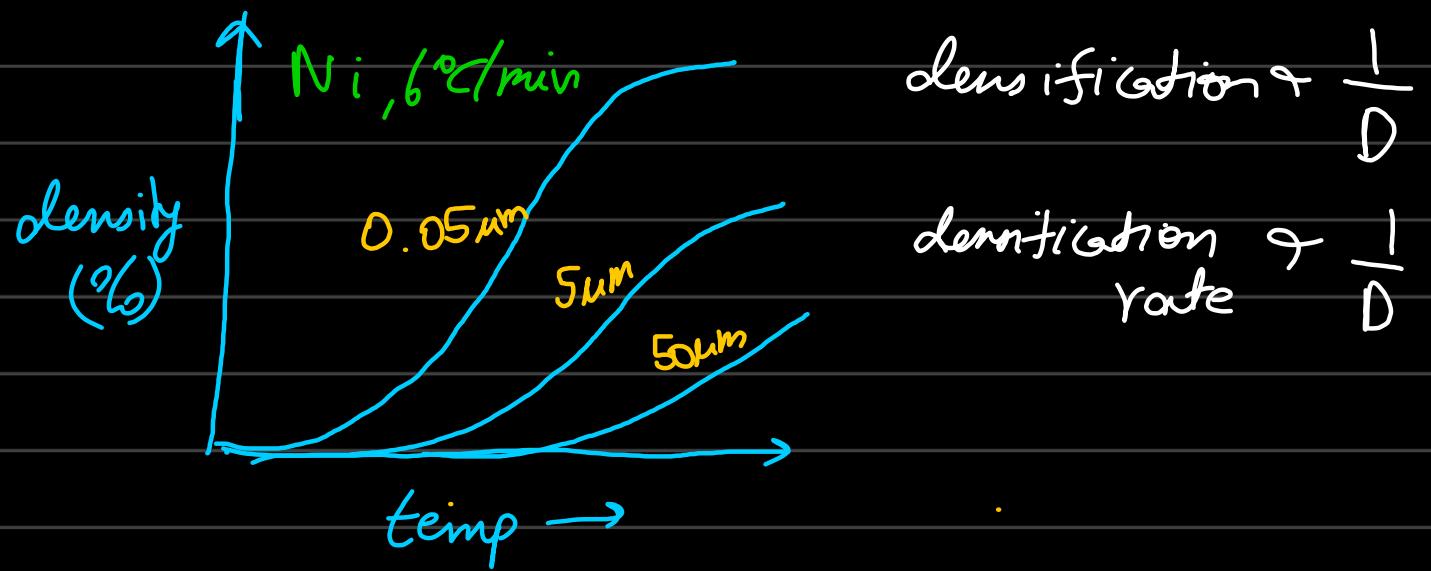
force is minimized at atomistic diffusion ceases.

$$\gamma_{gb} = 2\gamma_{sv} \cos\left(\frac{\Psi_e}{2}\right)$$



→ reflecting upon the sintering process which is happening.





# Stages of Sintering:

- i) Initial Stage: Neck formation, pore formation
- ii) Intermediate stage: Pore rounding, grain growth and some densification
- iii) Final stage: Sintering occurs with closed pores.

☞ 
$$\left(\frac{X}{D}\right)^n = \frac{Bt}{D^m}$$
 → initial stage of sintering

constant  
exponents

sintering time.

- \*  $n$  &  $m$  dictated by mechanism.
- \*  $B$  thermally varying constant  
 $B$  can change upon changing mechanism.
- \* The above equation holds true for  $\frac{X}{D} < 0.3$   
for  $\frac{X}{D} \geq 0.3 \rightarrow$  eqn collapses.
- \* Sintering rate can be measured easily in terms of shrinkage rather than neck size reduction

## Intermediate Stages.

→ tetraakisdecahedron. (14-sided)

↳ formation of pore structure network.

↳ highly interconnected cylindrical pores on edges of tetraakisdecahedron.

→ densification takes place by diffusion of vacancies away from pores.

constant  $\propto \frac{1}{\text{grain size}}$ .

$$\rho_s = \rho_I + B_I \ln \left( \frac{t}{t_s} \right)$$

end of stage II

time of start stage II

↓  
fractional density after stage II

↓  
fractional density start stage II

## Final Stage:

↳ characterized by spherical monosized pores at corners at corners of tetraakisdecahedron grains.

↳ pores are closed and isolated.

→ pores grow by Ostwald Ripening

\* If pore has trapped gas, it slows or prevents pore elimination.

↳ Sintering performed in vacuum eliminates this problem.

→ For the final stage of sintering:

$$\frac{\text{densification rate}}{\text{rate}} = \frac{12 D_V \Omega}{K T G^2} \left[ \frac{4\gamma}{dp} - \rho_g \right]$$

volume diffusivity

$d_p$  = size of pore

$\Omega$  = atomic volume

$G$  = grain size

$K$  = Boltzmann const.

$\gamma$  = Solid-vapour Surface energy.

$\rho_g$  = pressure exerted by pore due to gas entrapment.

→ over time  $\frac{dg}{dt} \rightarrow 0$  : saturation in densification.

\* Pores at grain boundary are stable

## Example:

Q)  $P = 10^5 \text{ N/m}^2$ ;  $d_p = 20 \mu\text{m}$

final pore diameter that can be achieved assuming ideal gas law.

$$\gamma = 2 \text{ J/m}^2; D_r = 5 \times 10^{-5} \text{ m}^2/\text{s},$$

$$\Omega = 125 \text{ A}^\circ$$

From ideal gas law:  $P_1 d_1^3 = P_2 d_2^3$

→ Final size attained when  $\frac{dP}{d\zeta} = 0$

$$\frac{4\gamma}{d_p} \geq P_g$$

$$\frac{4\gamma}{d_p} = \frac{P_1 d_1^3}{d_p^{3/2}} \quad dP^2 = \frac{P_1 d_1^3}{4\gamma}$$

$$d_p^2 = \frac{10^5 \times (20 \times 10^{-6})^3}{4 \times 2}$$