Additive Manufacturing – Module 9

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Powder Processes

Advanced Manufacturing | Modeling | Materials

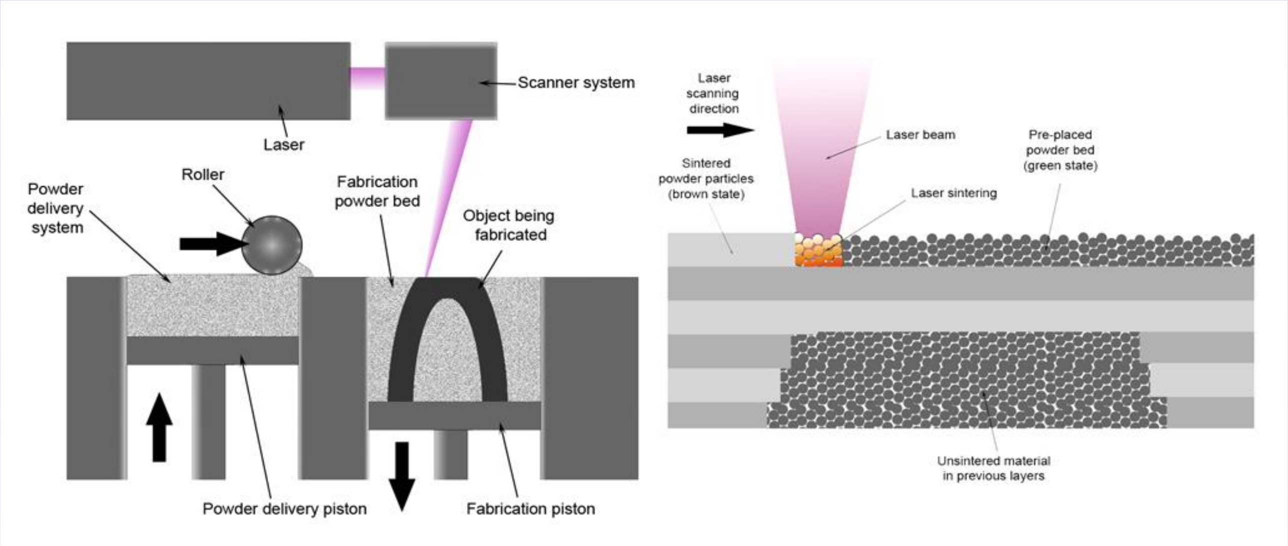
Classification

- **Powder-bed Processes**
  - **Solid state sintering**
  - **Chemical induced binding**
  - **Liquid phase sintering (Partial melting)**
    - **Different binder and structure materials**
      - Separate structure and binder grains
      - Composite grains
      - Coated grains
    - **No binder materials**
      - Single phase partial melting
      - Multiphase partial melting
  - **Full melting**
    - Single component single material
    - Single component alloyed materials
    - Fusing powder mixture

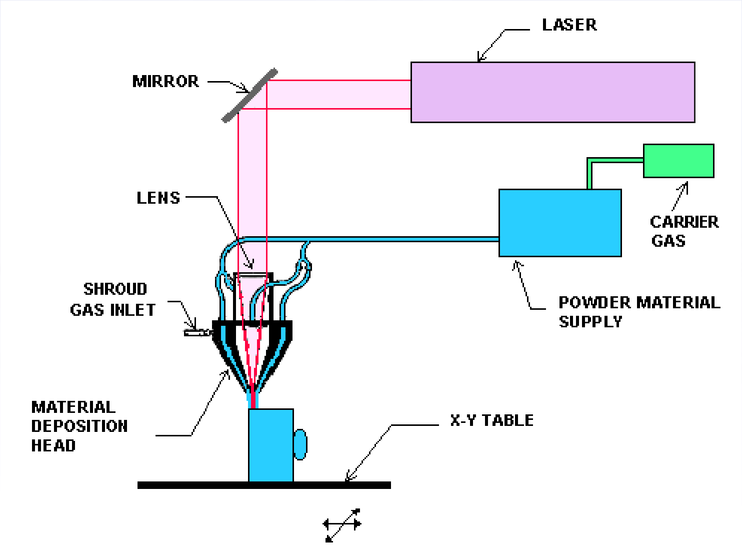
Kruth, Mercelis, Froyen, Rombouts, “Binding Mechanisms in Selective Laser Sintering and Selective Laser Melting,” Proc. Solid Freeform Fabrication Symposium, Austin, TX, Aug. 2-4, 2004.

Powder Processes

Processes



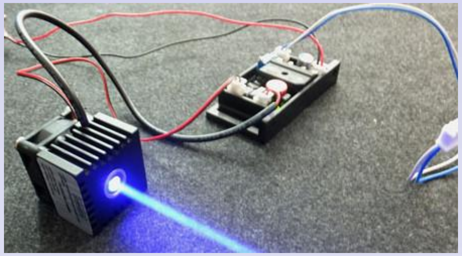
Selective Laser Sintering/Melting, Electron Beam Melting



Laser Engineered Net Shaping /Direct Metal Deposition

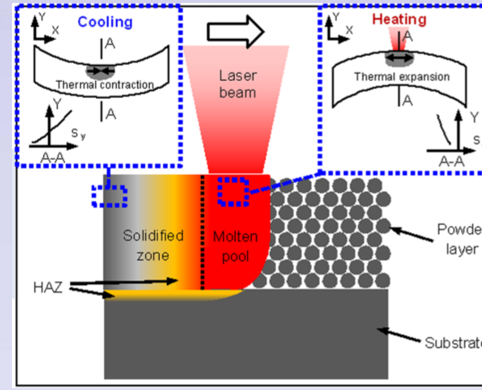
Powder Processes

Complexities

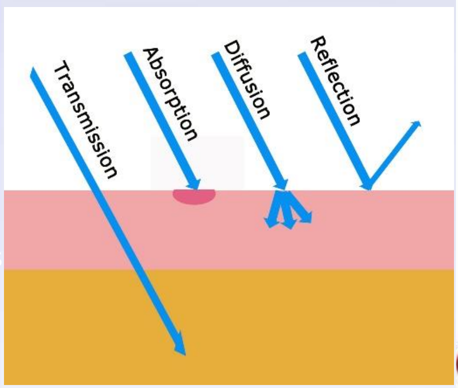


High power energy source: LASER

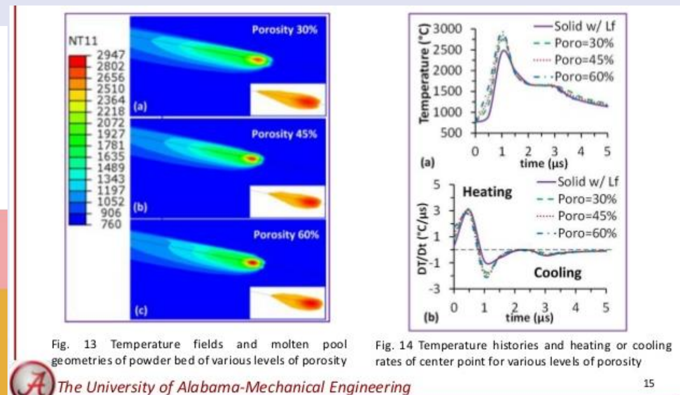
Powder: properties and manufacturing



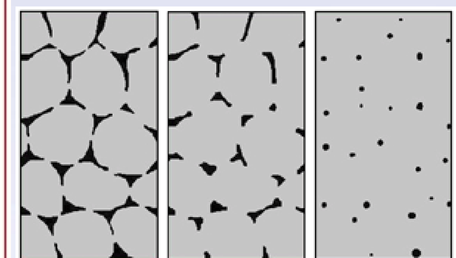
Thermal expansion and internal stress



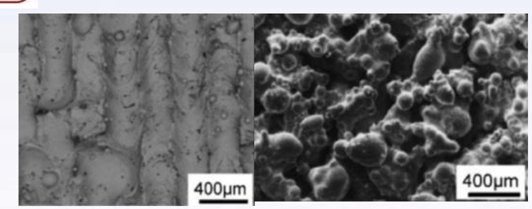
Energy absorption



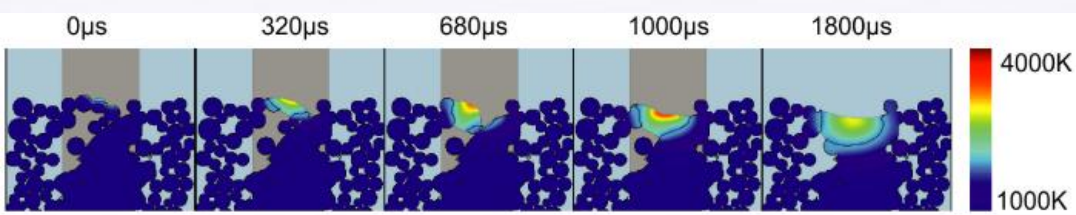
Heat transfer (heat and reheat)



Sintering kinetics



Phase transformation

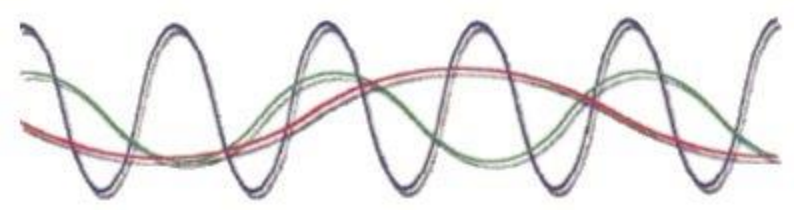


Wetting dynamics: interaction between melts and powder particles

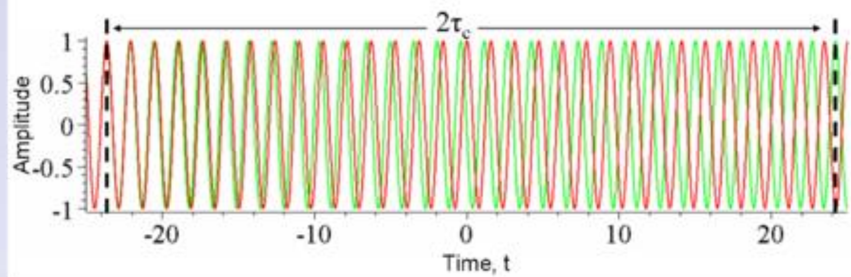
Powder Processes

LASER

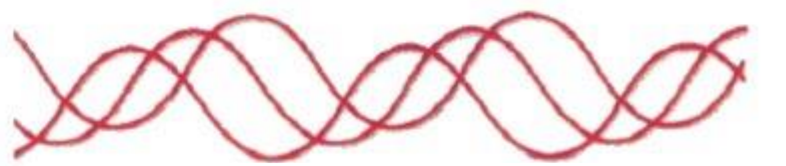
- **Light Amplification by Stimulated Emission of Radiation**



Sunlight (many different colors)

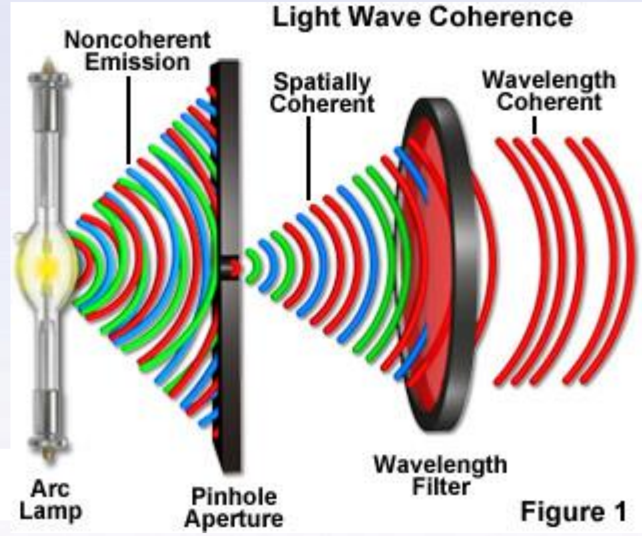


Temporal coherent (red)/incoherent (green)



LE LED: Monochromatic and non-coherent

LASER: Monochromatic, coherent and directional



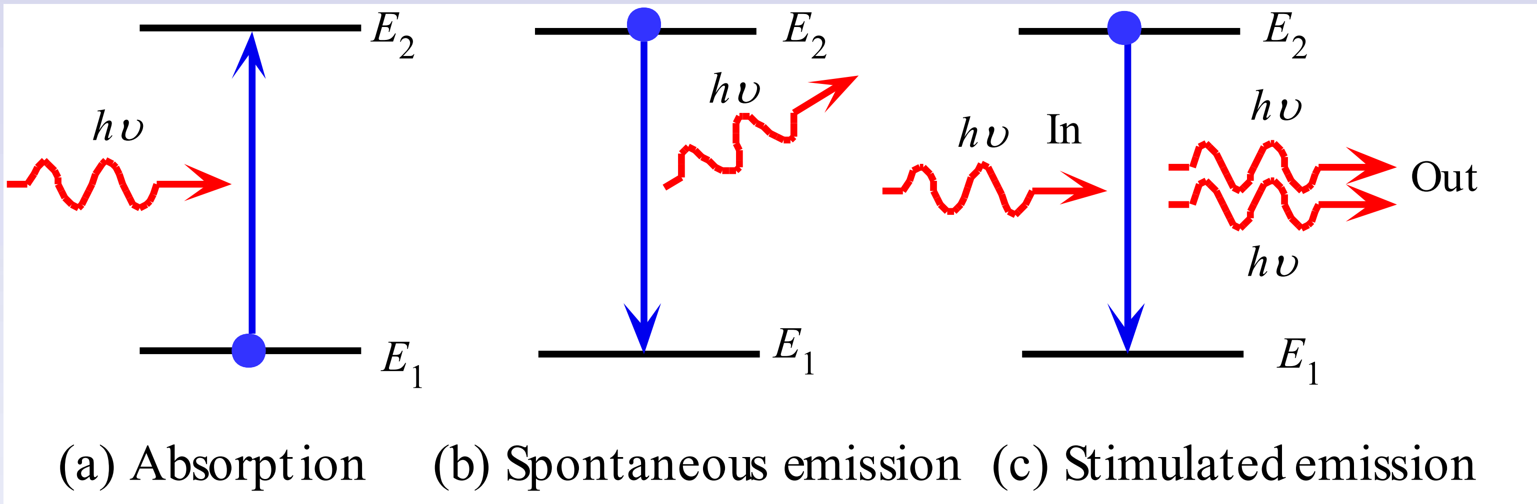
Spatial coherent

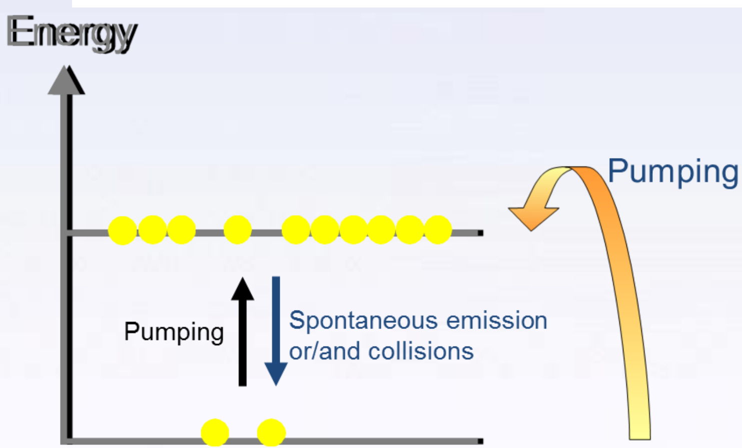
- **Monochromatic (single frequency)**
- **Coherent (spatial and temporal)**
- **Directional (focused)**

Powder Processes

LASER

- **Stimulated emission**





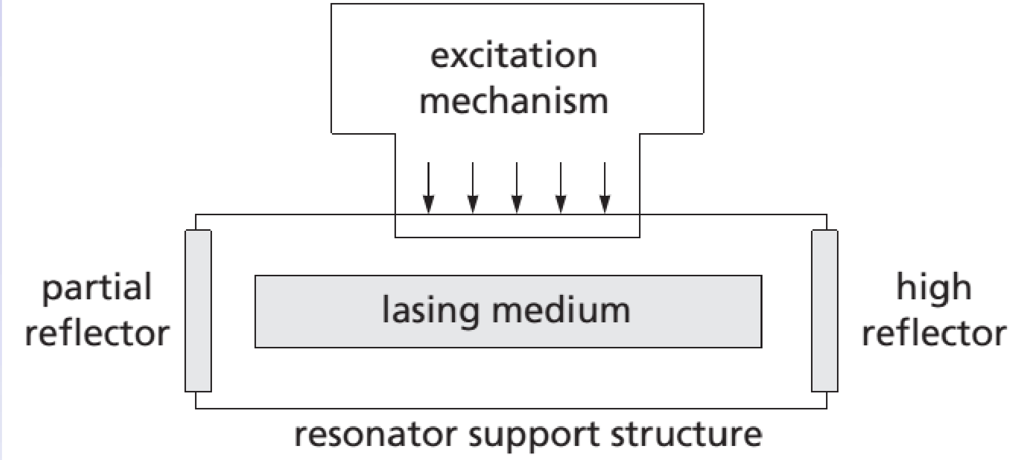
Population inversion

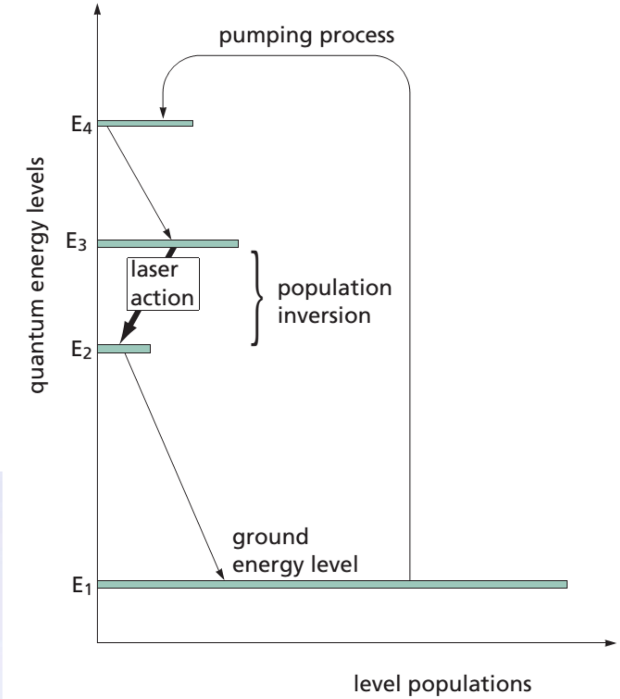
Four essential components of LASER

- **Energy source (pumping)**
- **Lasing medium (gain energy)**
- **Optical resonator**
- **Output coupler**

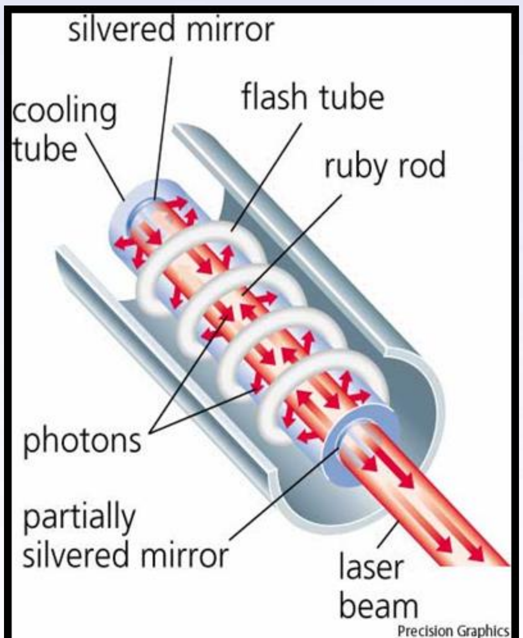
Powder Processes

LASER





A four level laser pumping system



First Ruby Laser 1960 by Theodore Maiman in Hughes Lab

Powder Processes

Powder processes
Overview
Laser
Laser - Matter
Powder
Heat transfer
Residual stress
Sinter
Phase change
Wetting
SLS
P-S-P relation

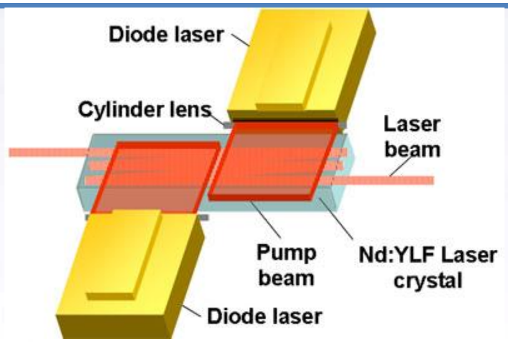
LASER

Lasing materials

- Certain crystals (solid state laser): ruby, sapphire, Nd:YAG, glass (or fiber) etc., typically doped with ions.
  - High power weapon
- Gas (laser): CO_2, Helium/Neon, metal vapor, etc.
  - CO_2 laser can produce ~100 kW for welding, cutting, etc.
- Liquid dye (dye laser): rhodamine (orange), fluorescein (green), etc.
  - Wide range of wavelength
- Semiconductor (laser diode): gallium arsenide (GaAs), indium gallium arsenide (InGaAs), or gallium nitride (GaN).
  - Most common laser
  - Apps; barcode reader, fiber optic communication, laser pointer, DVD recording, laser printing/scanning

Pumping methods

- Optical pumping (e.g., arc, external laser)
- Direct electron excitation
- Atom collision
- Chemical process



Diode-pumped solid-state laser

Powder Processes

LASER

Operation (Both have been used in SLS)

- **Continuous wave (CW) operation**: output power steady over long timescales, need high gain lasing medium
- **Pulsed operation** (refer to anything non-continuous wave, high peak power)
  - Q-switching: build up energy by holding up lasing
  - Mode-locking: pico/femo second pulse, extremely high peak power, by coupling laser cavity phase with light wave phase
  - Pulsed pumping: use pulsed energy source for pumping

Excimer	193-248nm	Pulsed	10's of Watts
Nd-YAG	1064 nm	CW or Pulsed	kW
CO_2	10600 nm	CW or Pulsed	kW
Cu-Vapor	534 nm	Pulsed	10's of Watts
Ti-Sapphire	700-1000 nm	CW or Pulsed	10's of Watts

Important commercial lasers

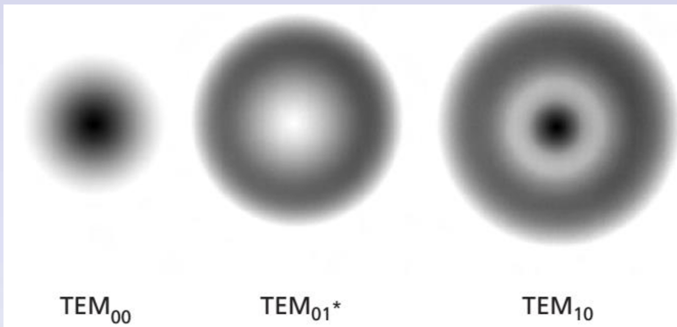
Powder Processes

LASER

Characteristics	Nd-YAG laser	He-Ne laser	CO_2 laser	Semiconductor (Ga-As) laser
Type	Doped insulator laser(solid state laser)	Gas laser	Molecular gas laser	Semiconductor laser
Active medium	Yttrium Aluminium Garnet ($y_3Al_5O_{12}$)	Mixture of Helium and Neon in the ratio 10:1	Mixture of CO_2, N_2 and Helium (or) water vapour	P-N junction diode
Active centre	Neodymium(Nd^{3+} ions)	Neon	CO_2	Recombination of electrons & holes
Pumping method	Optical pumping	Electrical pumping	Electric disharge method	Direct pumping
Optical resonator	Ends of the rods polished with silver and two mirrors. One of them is to totally reflected and the other is partially reflecting	Pair of concave mirrors	Metallic mrror of gold (or) silicon mirrors coated with aluminium	Junction of diopdes-polished
Power output	$2 * 10^4$ watts	0.5-50 mW	10 k W	1 m W
Nature of output	Pulsed	Continuous waveform	Continuous (or) pulsed	Pulsed (or) continuous wave form
wavelength	1.064 μm	6328 A^0	9.6 μm &10.6 μm	8400A^0 - 8600A^0

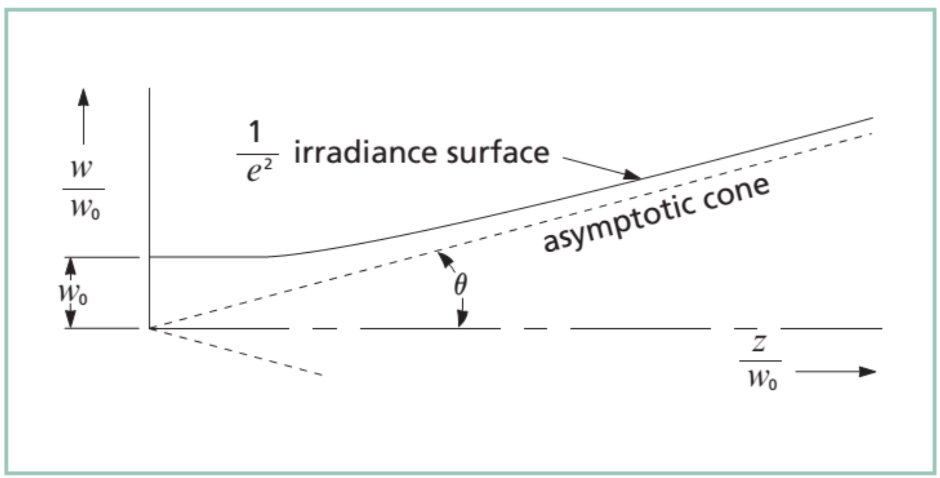
LASER

Propagation



$$I(r) = I_0 e^{-2r^2/w^2} = \frac{2P}{\pi w^2} e^{-2r^2/w^2}$$

Traverse mode: Gaussian beam (lowest order mode), need mode control

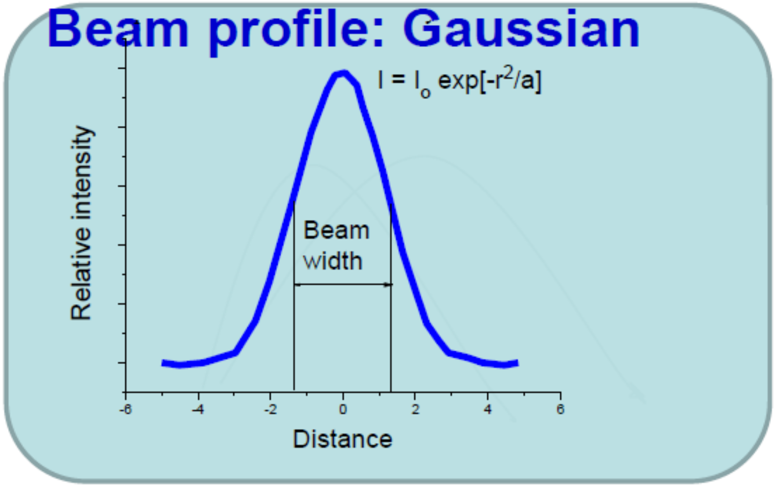


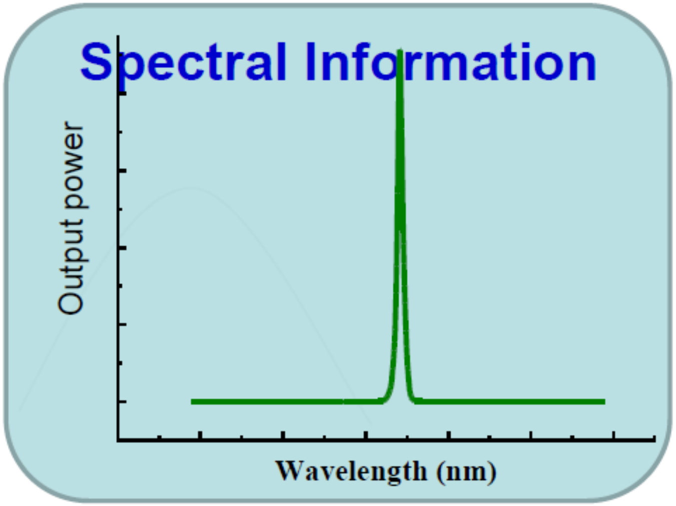
$$R(z) = z\left[1 + \left(\frac{\pi w_0^2}{\lambda z}\right)^2\right]$$

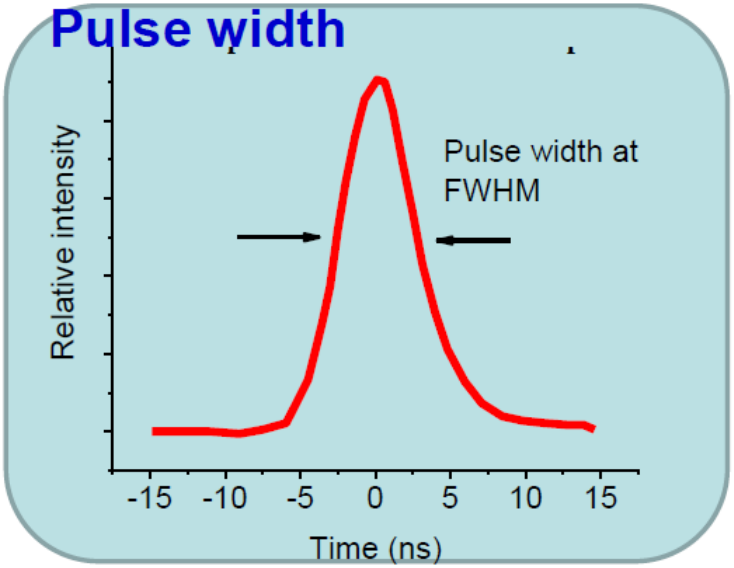
Need to characterize beam spot size and traverse mode

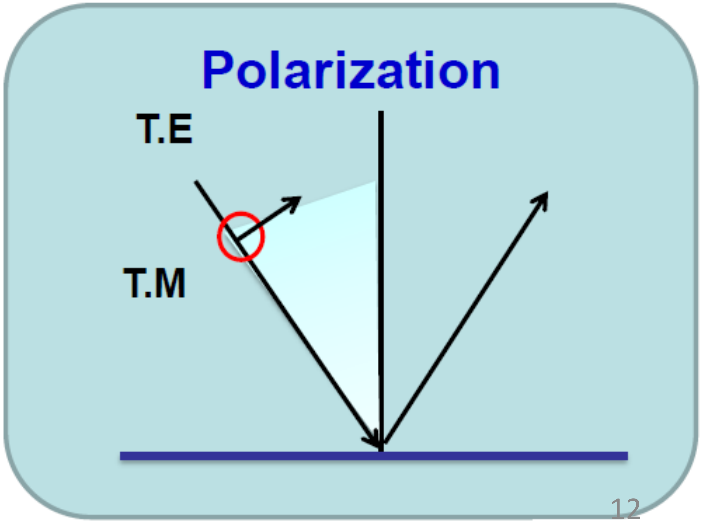
LASER – Material interaction

- **Laser parameters**







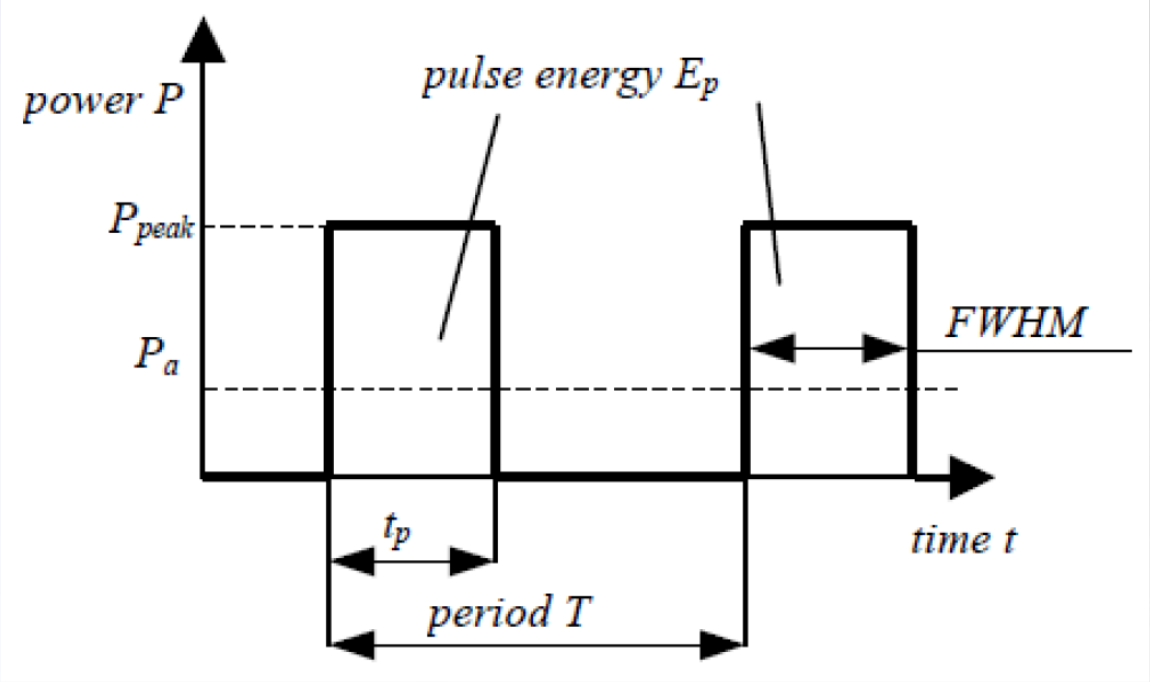


Credit: Dr. Mool C. Gupta at University of Virginia

Powder Processes

LASER – Material interaction

Laser parameters



P_a = Average power
A = Spot area
E_p = Peak energy

Repetition rate: $f_p = \frac{1}{T}$

Peak power: $P_{peak} = \frac{P_a}{t_p f_p}$

Intensity: $I = \frac{P_{peak}}{A} = \frac{E_p}{At_p}$

Peak energy: $E_p = Pdt = P_{peak} \cdot t_p$

Credit: Dr. Mool C. Gupta at University of Virginia

Powder Processes

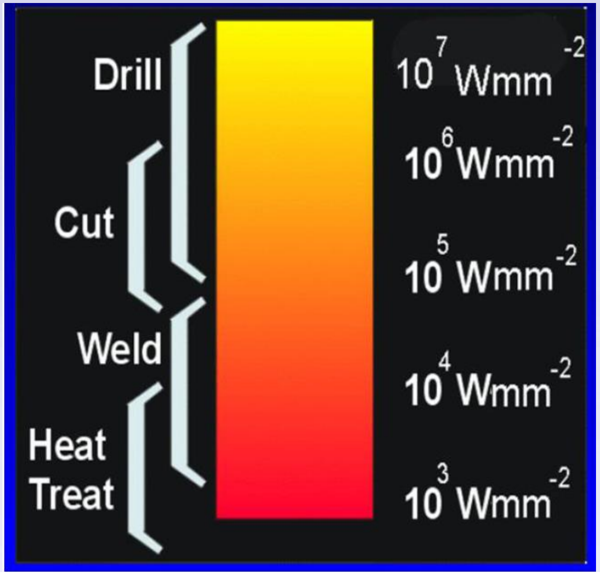
Powder processes
- Overview
- Laser
- Laser - Matter
- Powder
- Heat transfer
- Residual stress
- Sinter
- Phase change
- Wetting
- SLS
- P-S-P relation

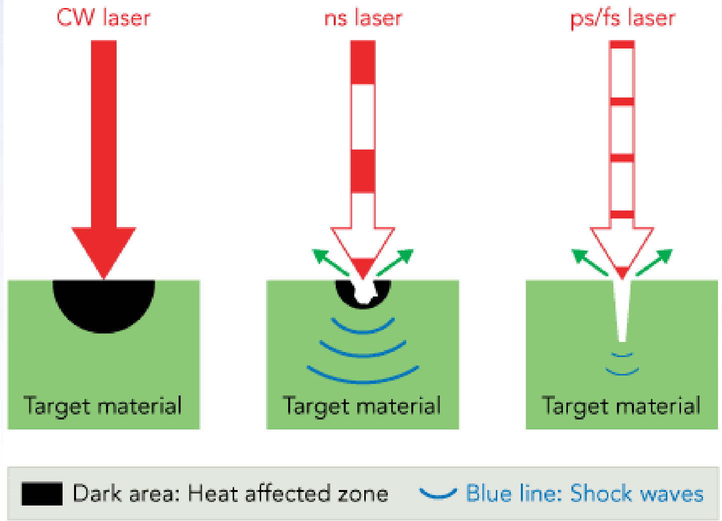
LASER – Material interaction

- **Laser parameters**

- **Continuous wave (CW): Important parameter is the power in Watts between 100W and 20kW for materials processing**

- **Pulsed -Important parameters are Joules per Pulse and number of Pulses per Second**
  - **Energy per pulse: 1mJ -1kJ**
  - **Pulse length: 1ms -1ns-100 fs**
  - **Pulse repetition rate: 0.1/s to 1 MHz**





Laser ablation

Credit: Dr. Mool C. Gupta at University of Virginia

LASER – Material interaction

- **Material properties**

- **Reflectivity**
- **Thermal Conductivity**
- **Specific Heat**
- **Latent Heat**

- **The lower these parameters the more efficient the process since less energy is required to melt the material.**

- **Beer Lambert's Law: relates the attenuation of light to the properties of the material through which the light is traveling**

$$I = I_0 \exp(-4\pi\alpha d/\lambda)$$

- **Where α = extinction coefficient;**
- **λ = wavelength;**
- **I = intensity at depth d**
- **I_0 = intensity at the surface**

Credit: Dr. Mool C. Gupta at University of Virginia

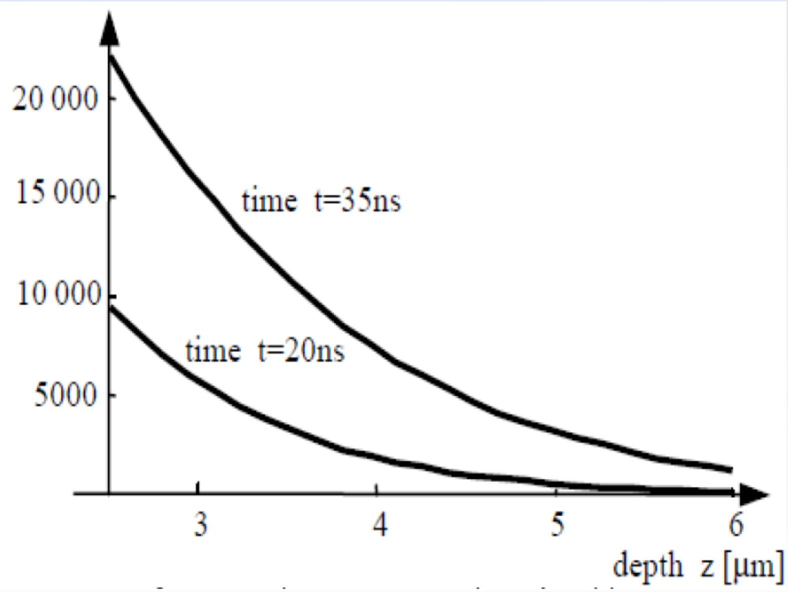
Powder Processes

LASER – Material interaction

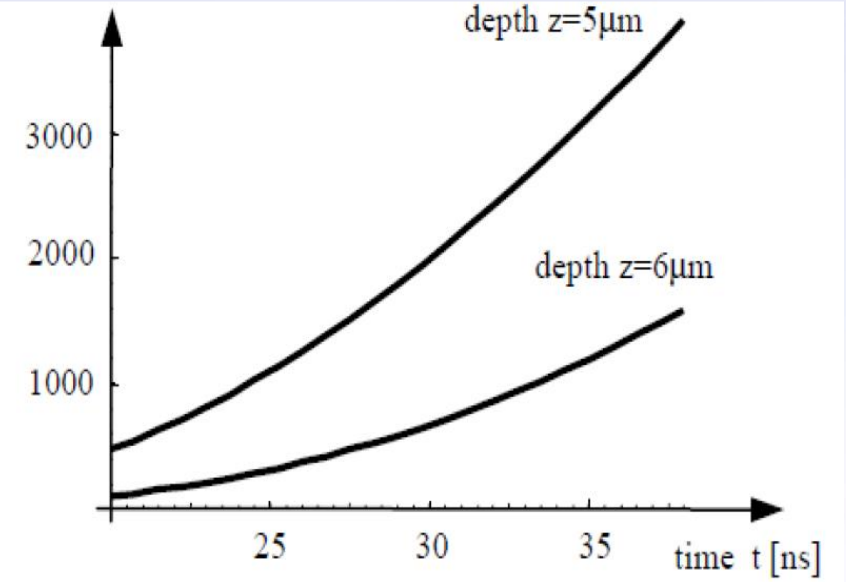
- **Temperature Distribution**

$$\rho c_p \frac{\partial T}{\partial t} - k\frac{\partial^2 T}{\partial z^2} = AI(r)e^{-\alpha z}$$

- **ρ is density; c_p is specific heat; k is thermal conductivity; I(r) radial distribution; A absorptivity (0<A<1)**



Temperature VS depth



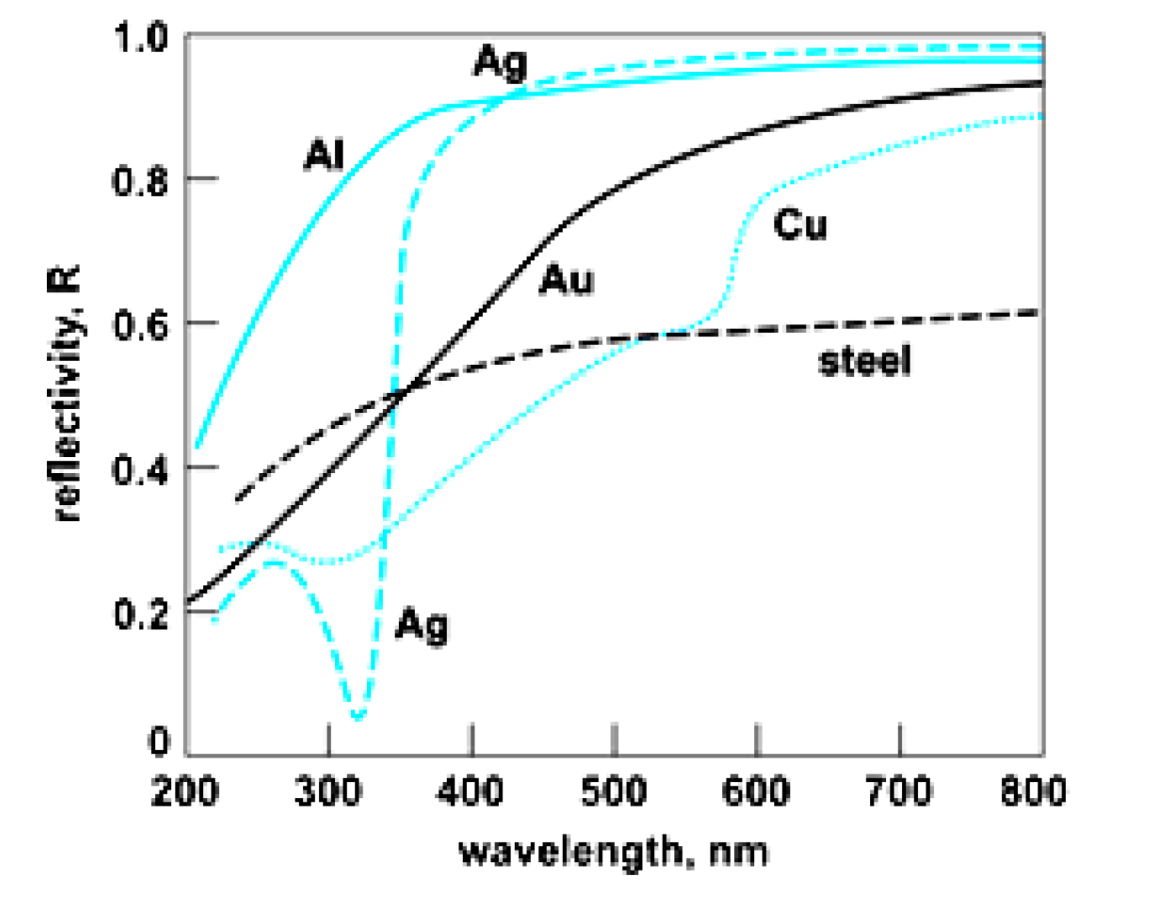
Temperature VS time

Credit: Dr. Mool C. Gupta at University of Virginia

Powder Processes

LASER – Material interaction

- Reflectivity change with wavelength

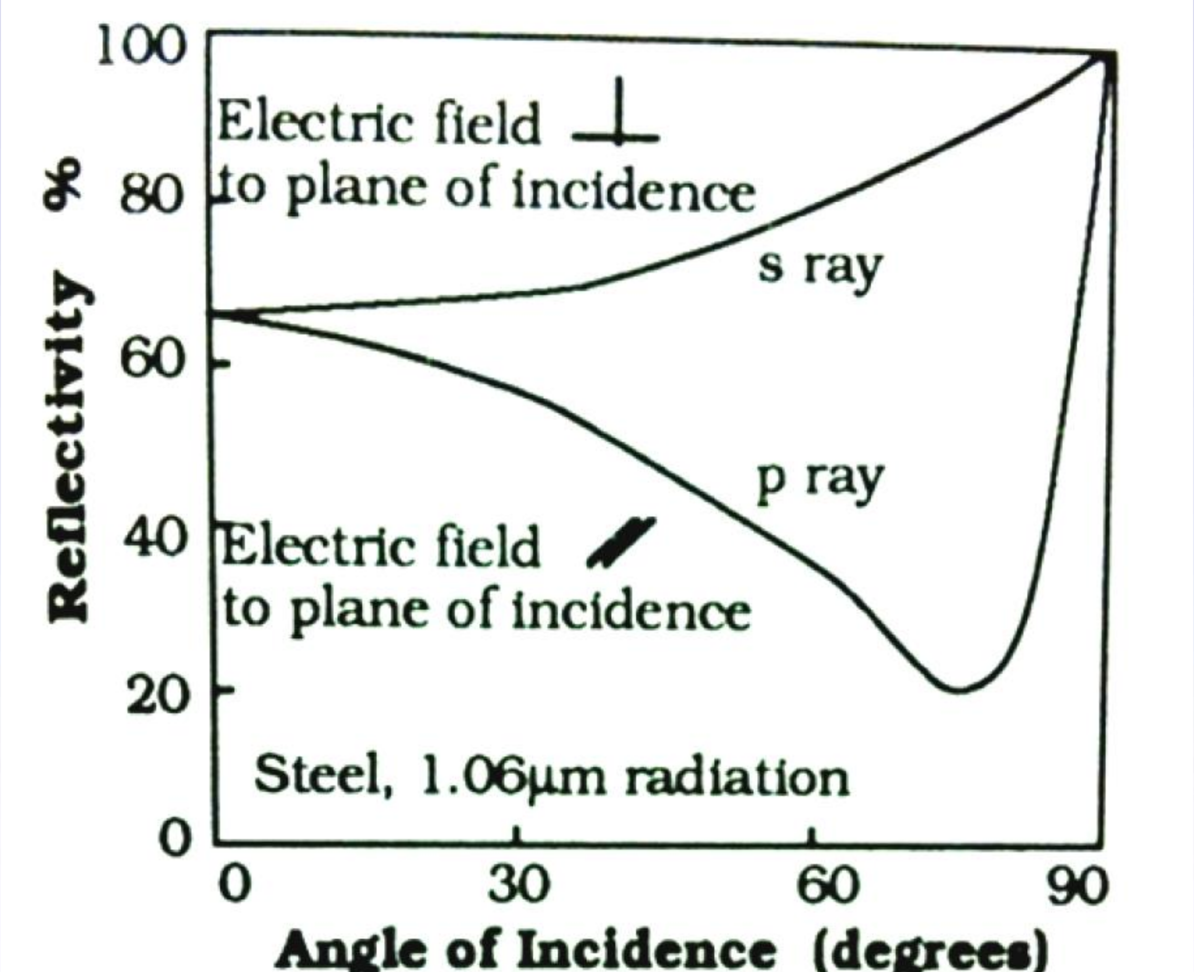


Credit: Dr. Mool C. Gupta at University of Virginia

Powder Processes

LASER – Material interaction

- **Reflectivity change incident angle**



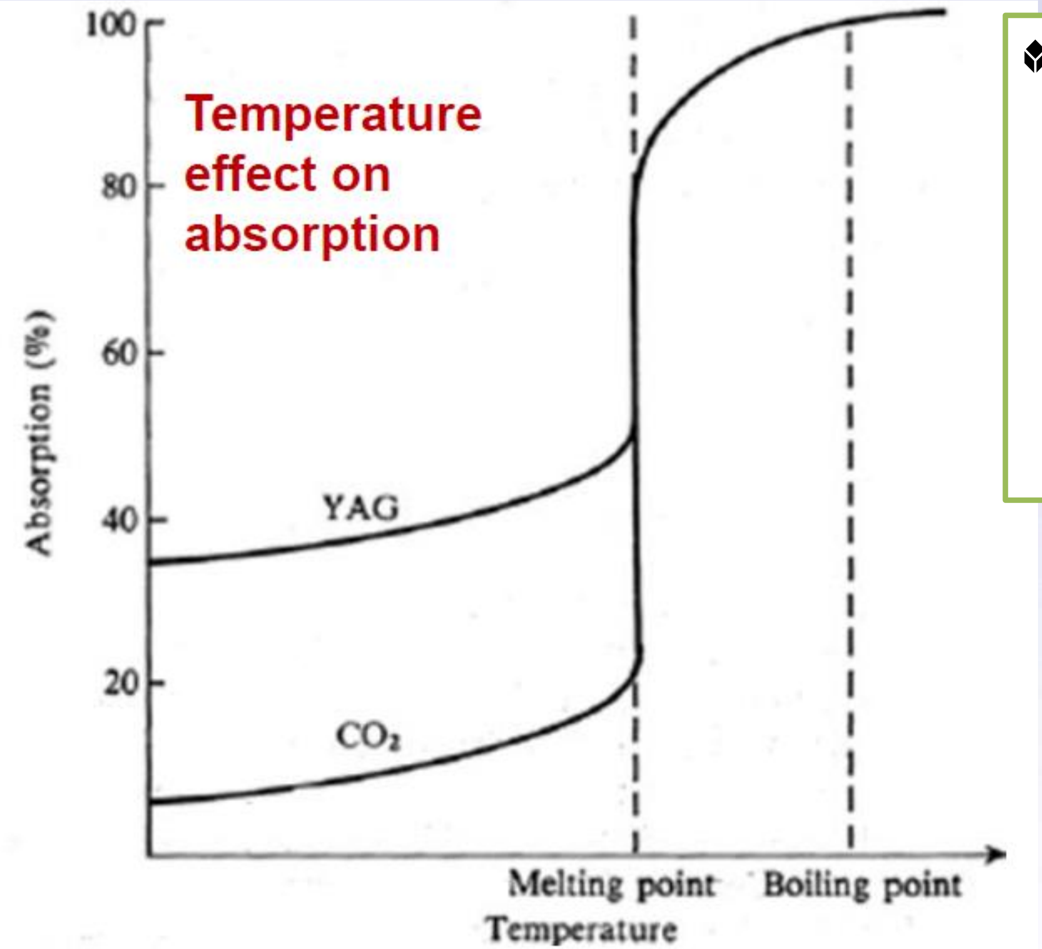
Reflectivity of steel to polarised 1.06 micron radiation

Credit: Dr. Mool C. Gupta at University of Virginia

Powder Processes

LASER – Material interaction

- **Temperature effect on absorption**



- **Absorption and reflectivity are very temperature dependent, often undergo significant changes when material melts, e.g., silicon, steel becomes highly reflective on melting**

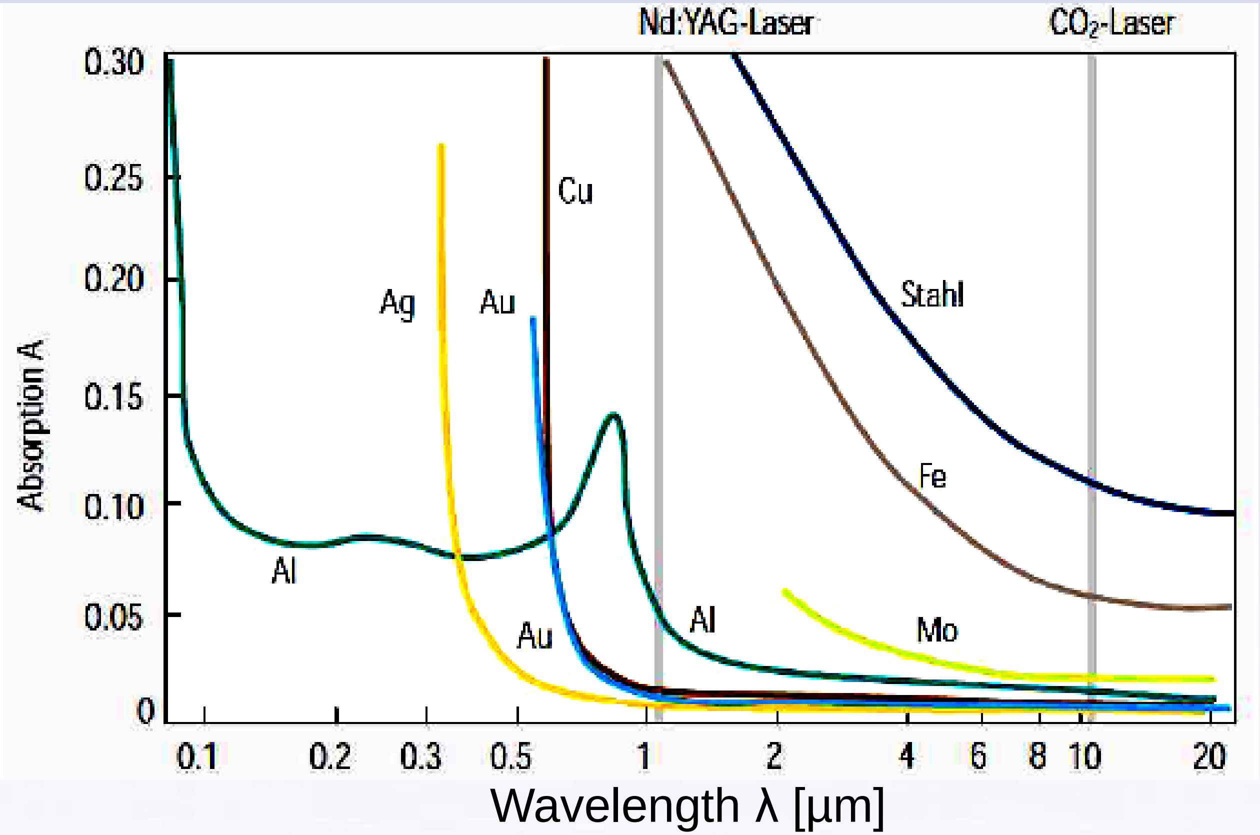
Schematic variation of absorption with temperature for a typical metal surface for both the YAG and CO2 laser wavelength

Credit: Dr. Mool C. Gupta at University of Virginia

Powder Processes

LASER – Material interaction

- **Absorption change with wavelength**



Credit: Dr. Mool C. Gupta at University of Virginia

Powder Processes

Powder – dream powder

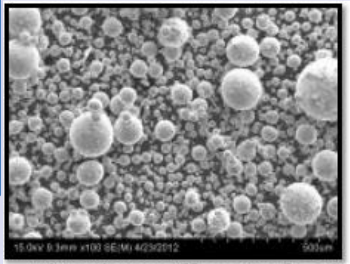
- **Perfect sphere = Minimum surface area**
  - **Low risk of fire/explosion**
  - **Maximum powder lifetime (e.g., low oxidation)**

- **High flowability (ASTM B213)**
  - **Improves powder feeding**
  - **Smooth powder layer**

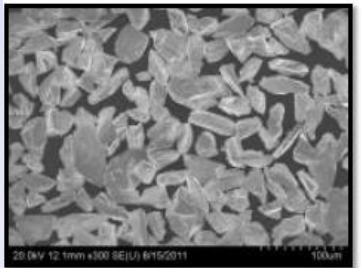
- **High apparent density (ASTM B212)**
  - **Improves sintering density**
  - **Improves heat conduction**
  - **Rule of thumb: > 50% bulk density**

- **No internal porosity inside the particles**
  - **Pores tend to survive into built parts**

- **No particles smaller than 10 um**
  - **Reduce unhealthy dust**
  - **Reduce risk of fire**



Titanium Alloy (Spherical)



Tantalum (Angular)

Credit: Dr. Francisco Medina @ ARCAM

Powder Processes

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Laser
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Residual stress
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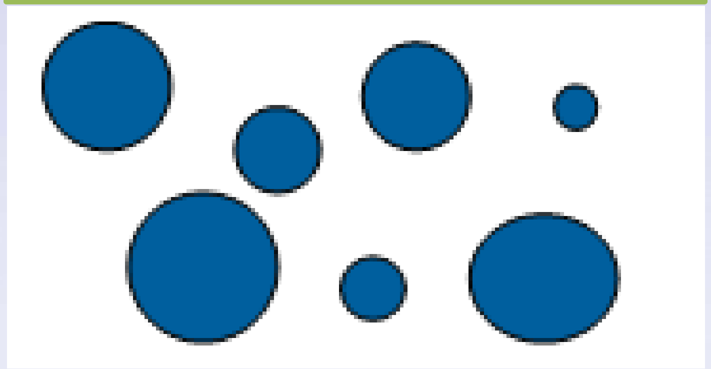
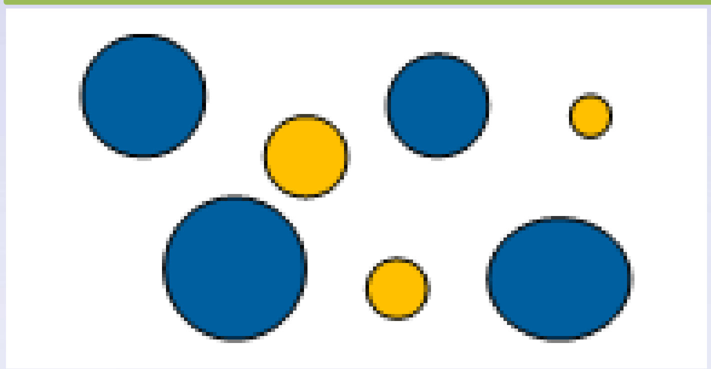
Powder

Pre-alloyed powder
- **All particles have identical chemical composition**



Blended powder
- **A mix of powders with different chemical composition**

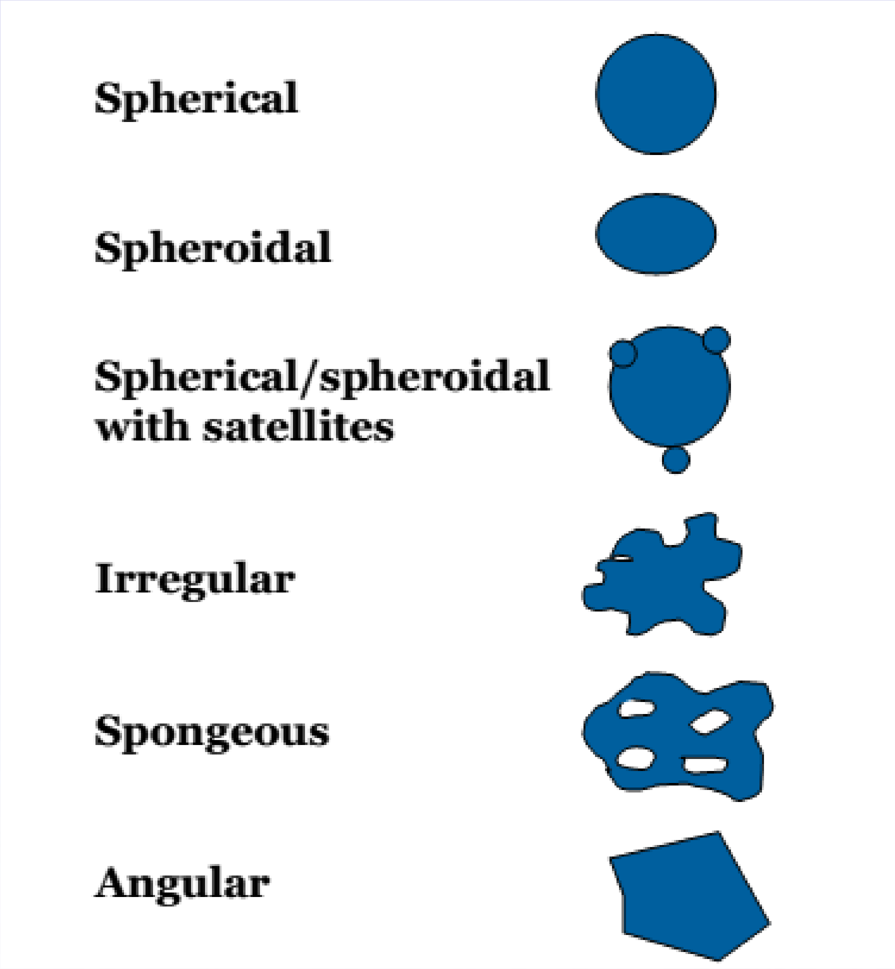


- **Pre-alloyed powder is preferred**
- **Blended powder has some risks:**
  - **Powder segregation due to different density, size, or shape**
  - **Exothermic reactions, e.g., Ti+Al**
  - **Excessive evaporation due to different melting points**
  - **Inhomogeneity in final part**

Credit: Dr. Francisco Medina @ ARCAM

Powder Processes

Powder



Good!

Different powder shapes

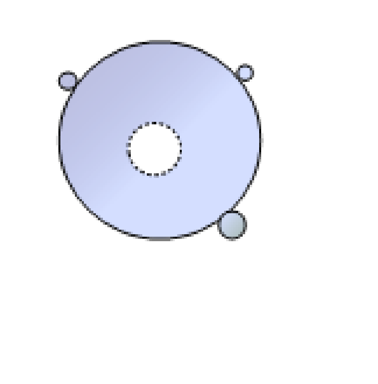
Credit: Dr. Francisco Medina @ ARCAM

Powder Processes

Powder

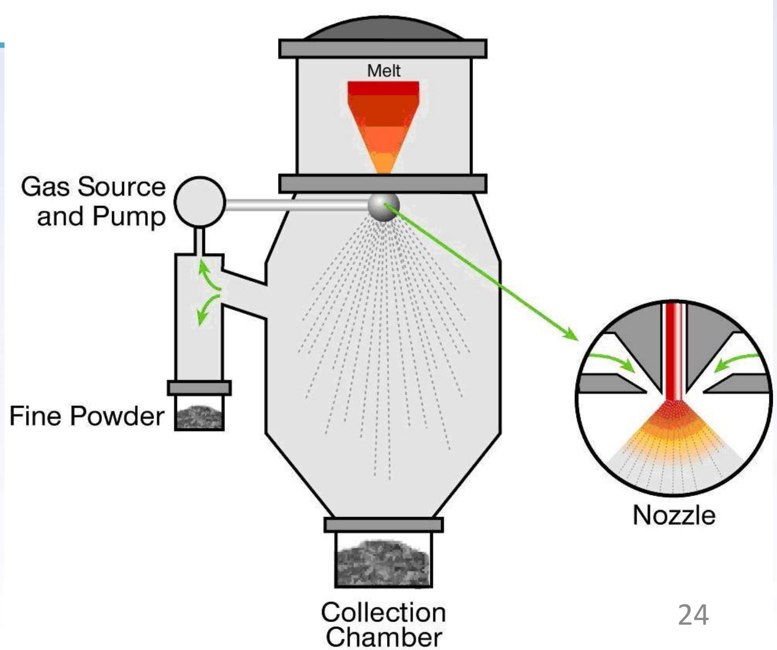
Gas atomization

- **Molten metal converted to droplets by flowing inert gas, e.g., argon or nitrogen**
- **Spheroidal particles with satellites**
  - \+ **Good flowability & density**
  - \+ **High productivity**
  - \+ **Reasonably priced**
  - \- **Satellites**
  - \- **Internal porosity**



Melting method

- **Crucible**
  - \+ **Can use scrap metal**
  - \+ **Easy to tailor chemistry**
  - \- **Possible contamination**
- **Induction coil melting of bars**
  - \+ **Non-contact = high purity**
  - \- **Need solid bars**



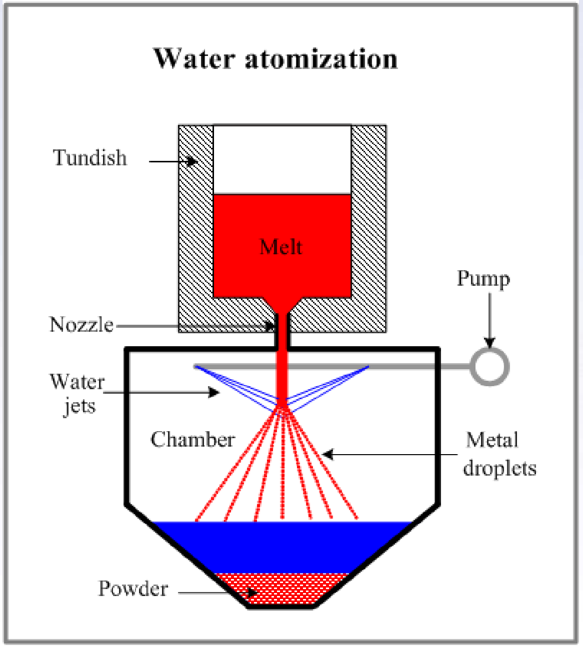
Credit: Dr. Francisco Medina @ ARCAM

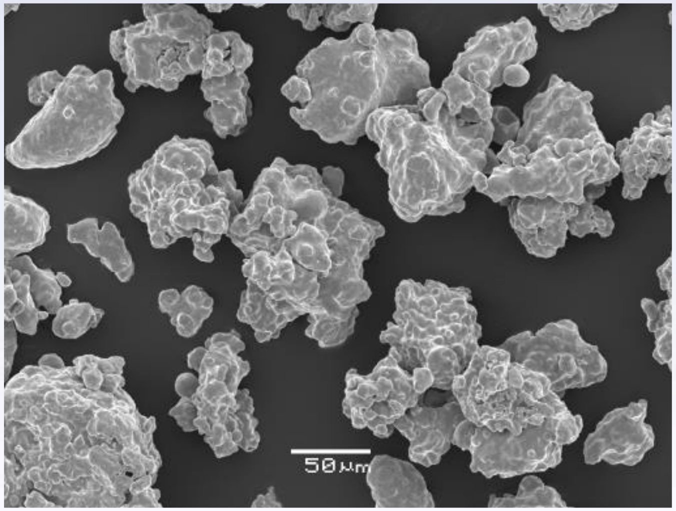
Powder Processes

Powder

Water atomization

- **Molten metal converted to droplets by water jet**
- **Very irregular particles**
  - \+ **High productivity**
  - \+ **Very good price**
  - \- **Poor flowability and density**
  - \- **High risk of oxidation**
  - \- **Unsuitable for reactive metals such as Ti**



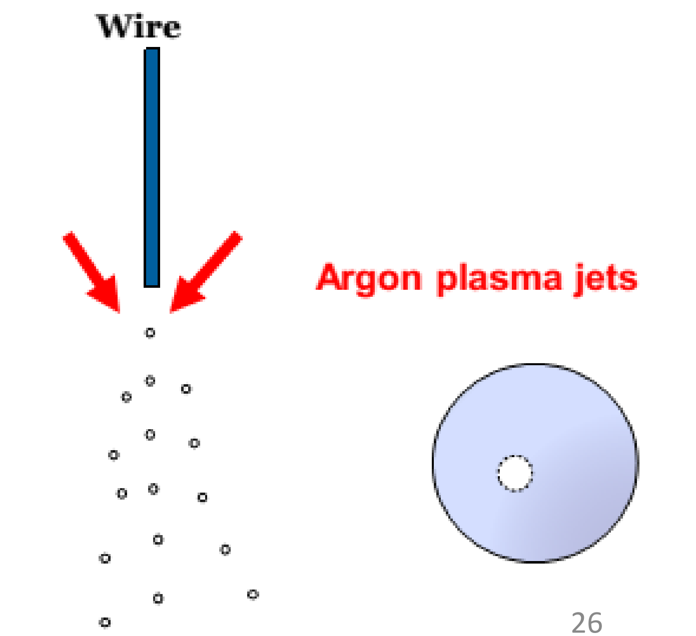


Powder Processes

Powder

Plasma atomization

- **Thin metal wire melted and converted to droplets in argon plasma**
- **Spherical particles without satellites**
  - \+ **Very good flowability and density**
  - \+ **High purity**
  - \- **Some internal porosity**
  - \- **Low productivity**
  - \- **High price**



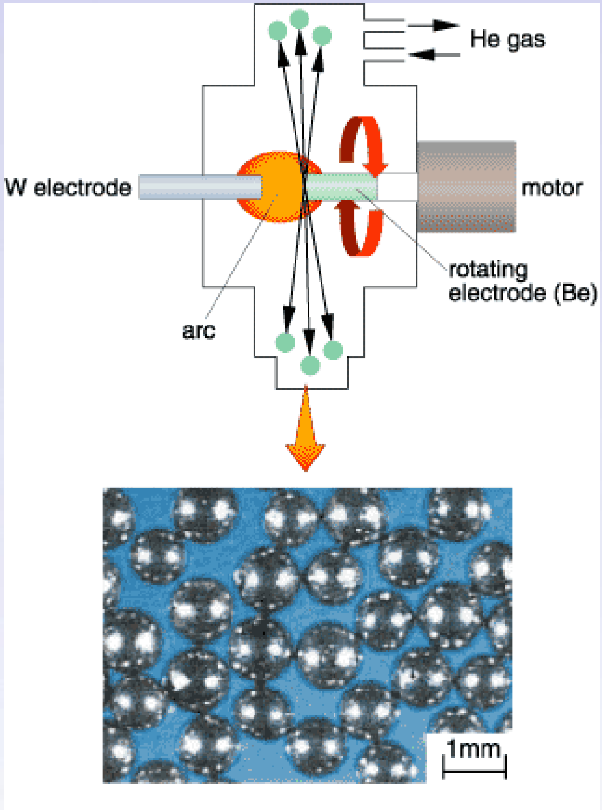
Credit: Dr. Francisco Medina @ ARCAM

Powder Processes

Powder

Centrifugal atomization

- **Plasma Rotating Electrode Process**
- **Spinning metal bar melted by gas plasma**
  - \+ **Perfectly spherical particles**
  - \+ **High density (flow like water)**
  - \+ **No internal porosity**
  - \+ **Non-contact**
  - \- **Poor yield**
  - \- **High price**

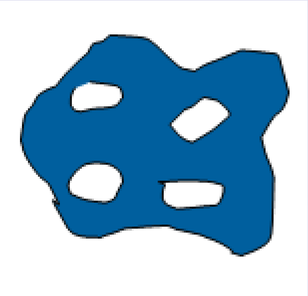


Credit: Dr. Francisco Medina @ ARCAM

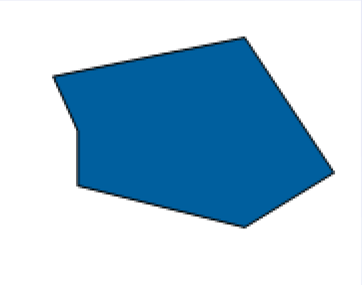
Powder Processes

Powder

Spongeous powders
- **Usually made via chemical methods, e.g., electrolysis**
  - \+ **Low cost**
  - \- **Low flowability & density**
  - \- **Internal porosity**



Angular powders
- **Usually made via mechanical methods, e.g., milling**
  - \+ **Low cost**
  - \- **Low flowability & density**
  - \- **Low purity**

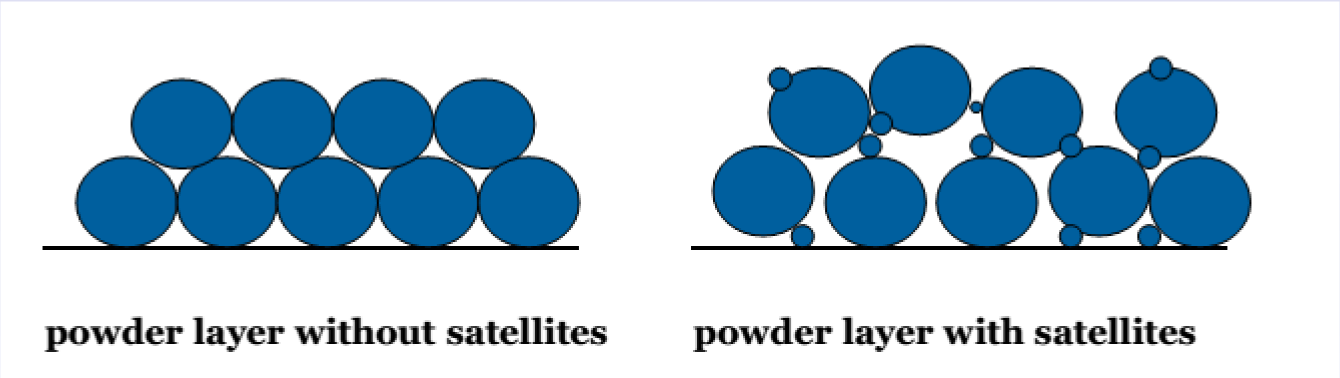


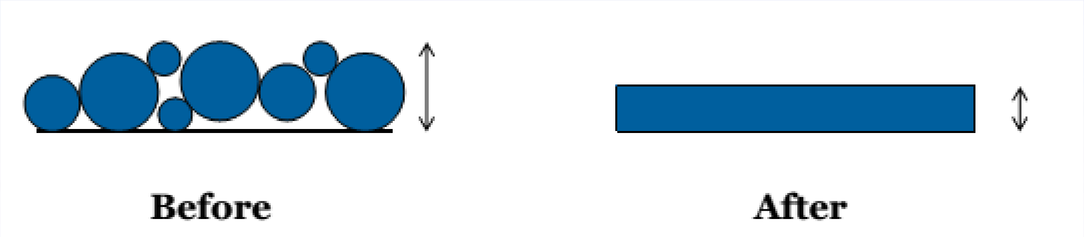
Credit: Dr. Francisco Medina @ ARCAM

Powder Processes

Powder

Satellites
- **Typical for gas atomized powders**
- **Satellites density depends on atomizing parameters**

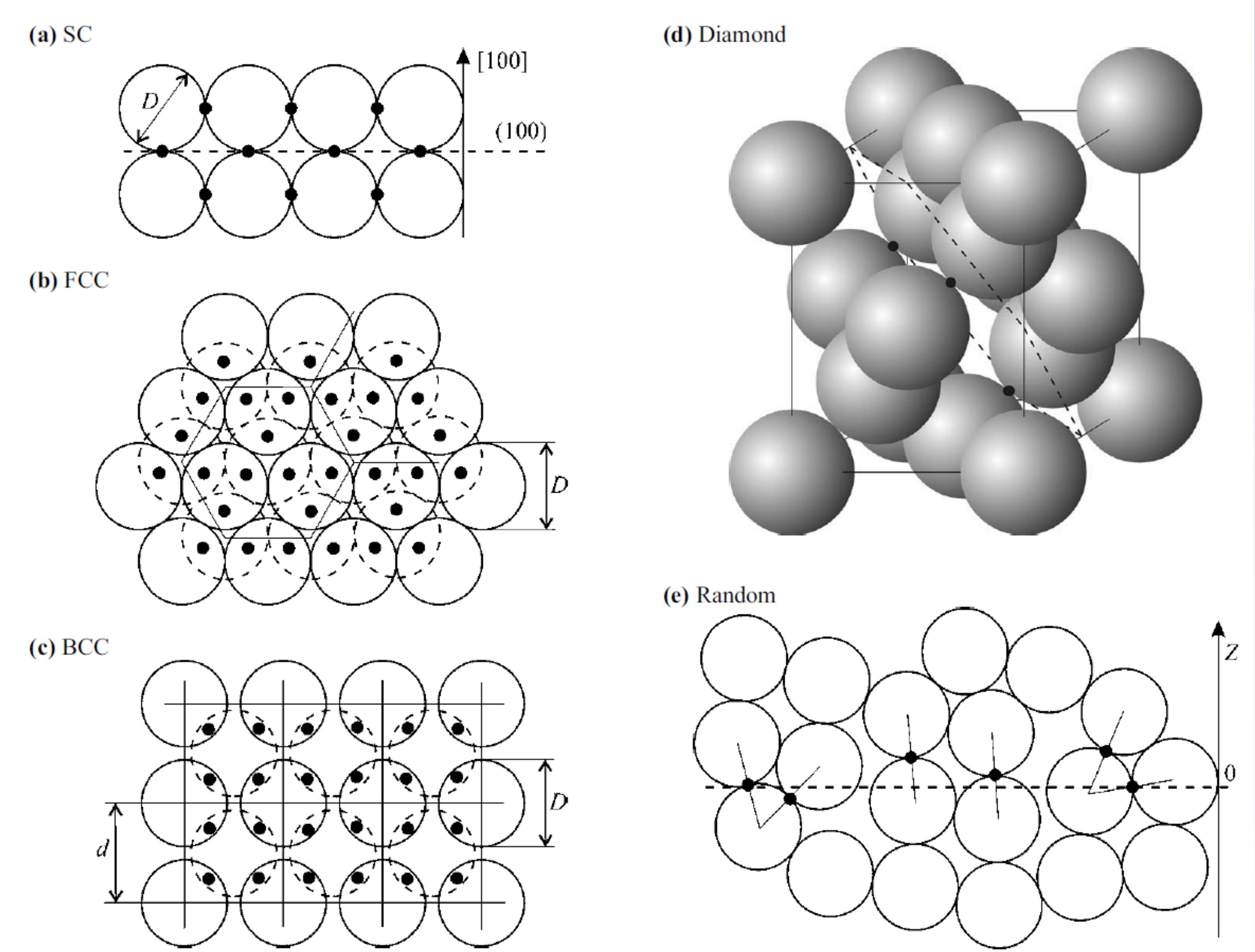




Affecting coating thickness: typically thickness before sintering is 2 – 3X of after sintering

Credit: Dr. Francisco Medina @ ARCAM

Heat transfer



Thermal contacts for different powder packing

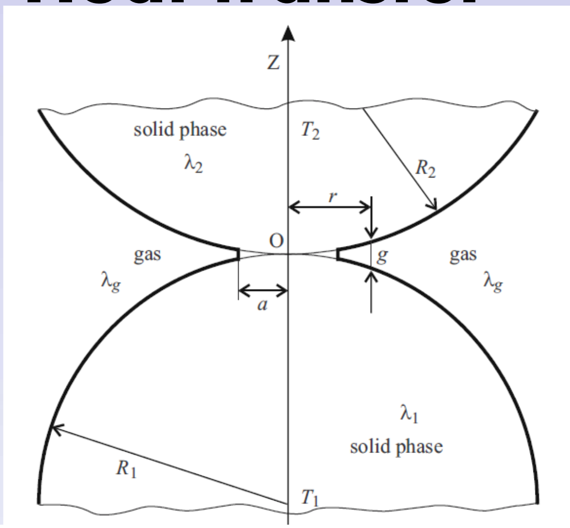
Gusarov, A. V., and E. P. Kovalev. "Model of thermal conductivity in powder beds." *Physical Review B* 80.2 (2009): 024202.

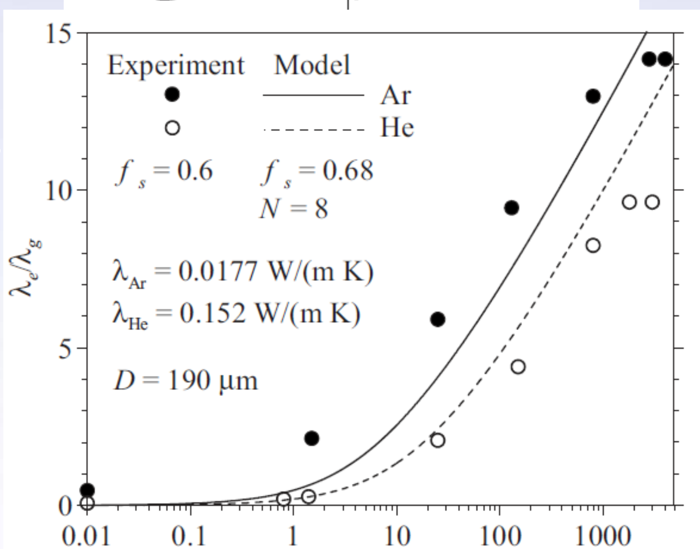
Powder Processes

Heat transfer

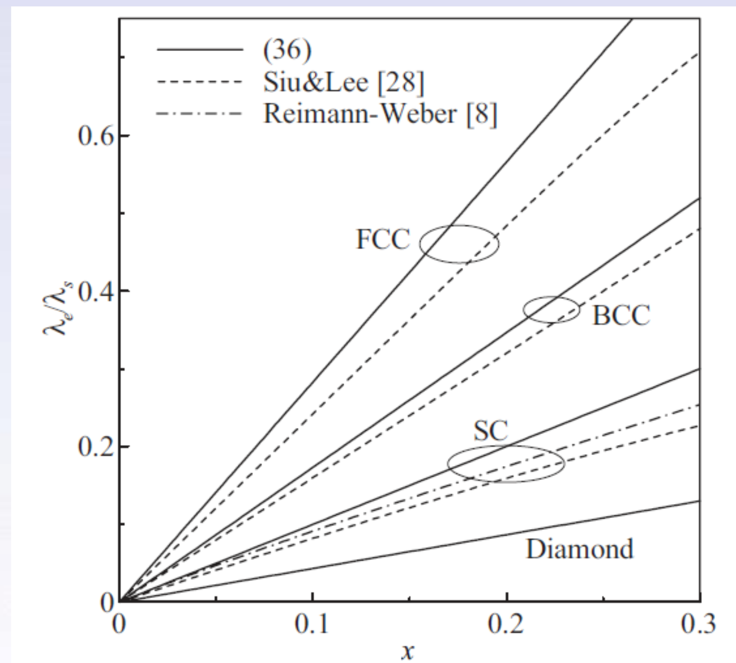
Thought process

- **Study how the thermal conductivity changes for two individual powder particles**
- **Estimate effective thermal conductivity for different packing**





Effective thermal conductivity VS different gas pressure

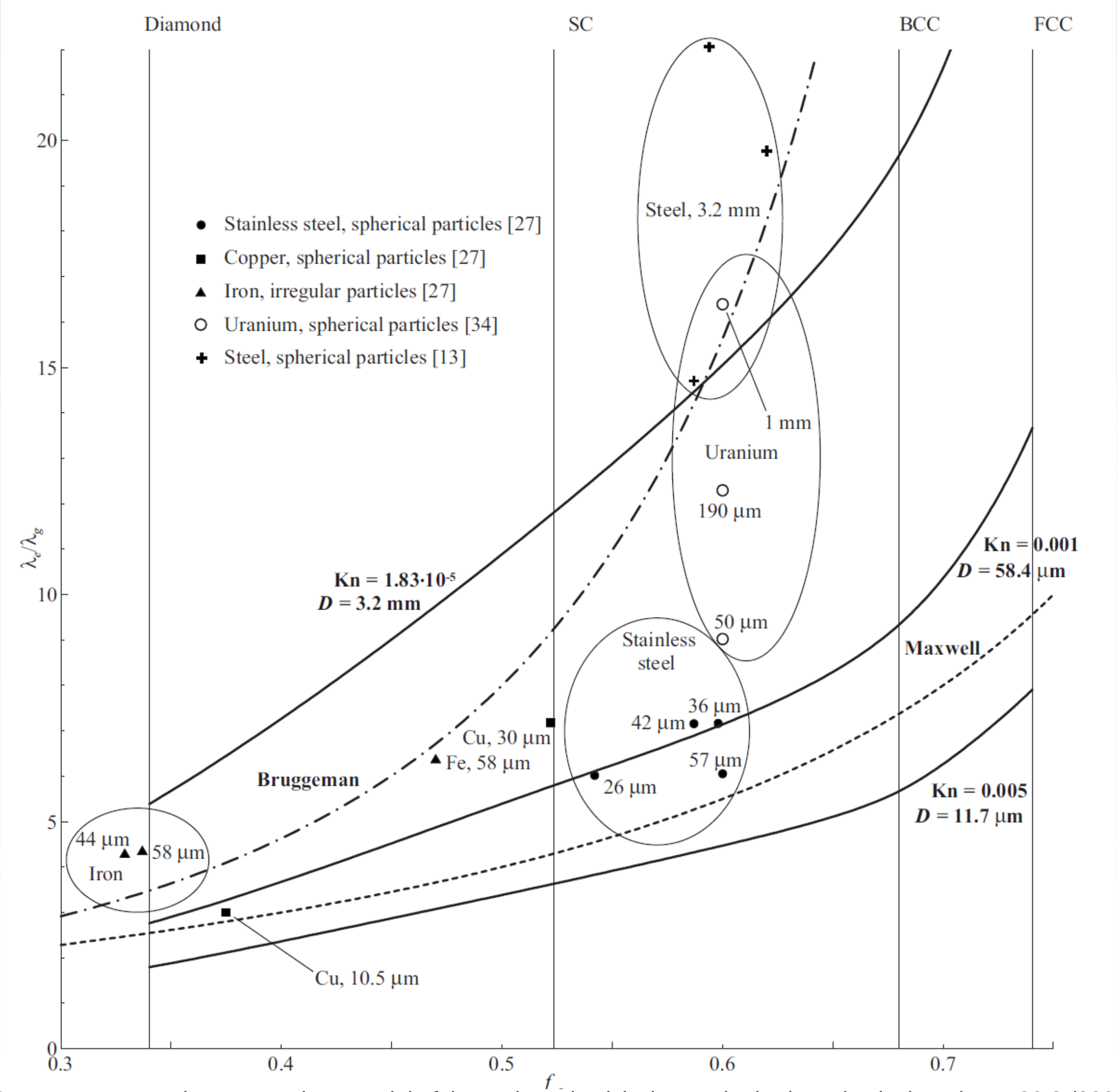


Effective thermal conductivity VS different contact size

Gusarov, A. V., and E. P. Kovalev. "Model of thermal conductivity in powder beds." *Physical Review B* 80.2 (2009): 024202.

Powder Processes

Heat transfer

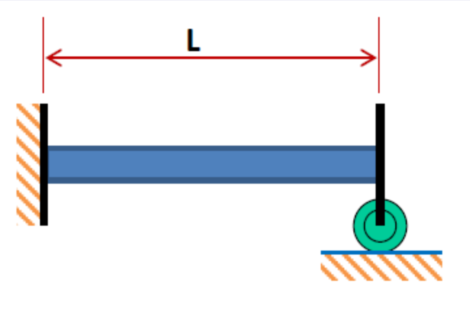


Effective thermal conductivity for different volume fraction (packing)

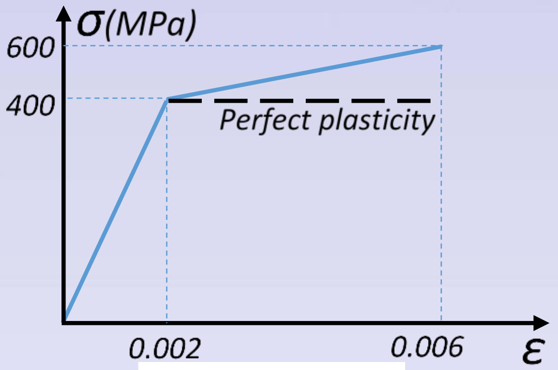
Gusarov, A. V., and E. P. Kovalev. "Model of thermal conductivity in powder beds." *Physical Review B* 80.2 (2009): 024202.

Thermal expansion

- **Origin of residual stress**

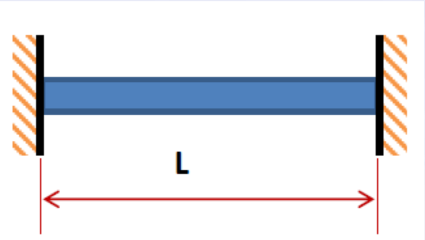


Carbon steel:
- $E = 200$ GPa
- $F_y = 400$ MPa
- $\alpha = 1\times10^{-5}$ /K



Stress-strain curve

- **Case A: The temperature in the steel bar is uniformly risen from 300 to 1,100 K and then cooled back down to 300 K. Will there be any residual stress in the bar?**



- **Case B: risen from 300 to 1,100 K and then cooled back down to 300 K?**
- **Case C: risen from 300 to 450 K and then cooled back down to 300 K?**

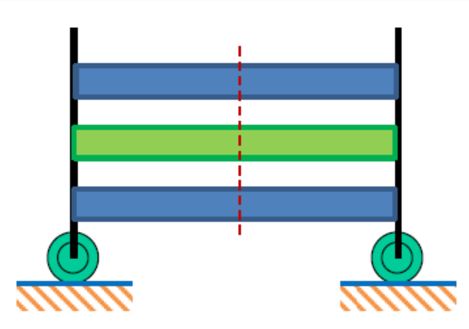
- **Case A: No stress (since no geometric constraints)**
- **Case B: thermal strain (0.008)→ plastic deformation (stress: 900MPa)→ cooling (E*0.008=3200MPa) → residual stress**
- **Case C: thermal strain (0.0015) → elastic deformation → elastic recover → no residual stress.**

Credit: Dr. Wei Zhang @ Ohio State U

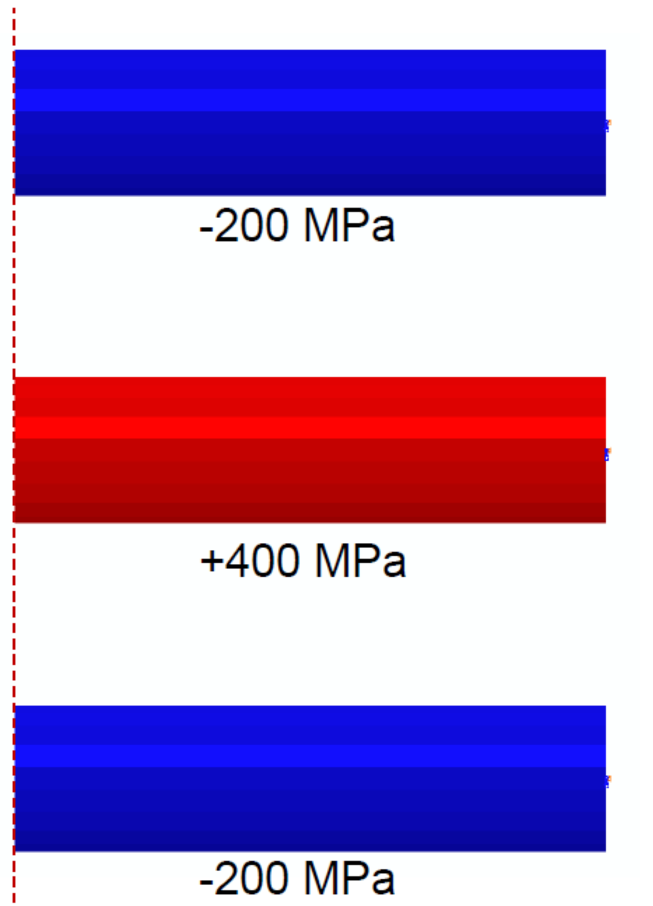
Advanced Manufacturing | Modeling | Materials

Thermal expansion

- Origin of residual stress – three bar problem to approximate layer by layer scanning



- Case A: Temperatures in all three bars are simultaneously risen from 300 to 1,100 K and then cooled down to 300 K?
- Case B: Temperature in the middle bar is risen from 300 to 1,100 K and then cooled down to 300 K? The two side bars are kept at 300 K.

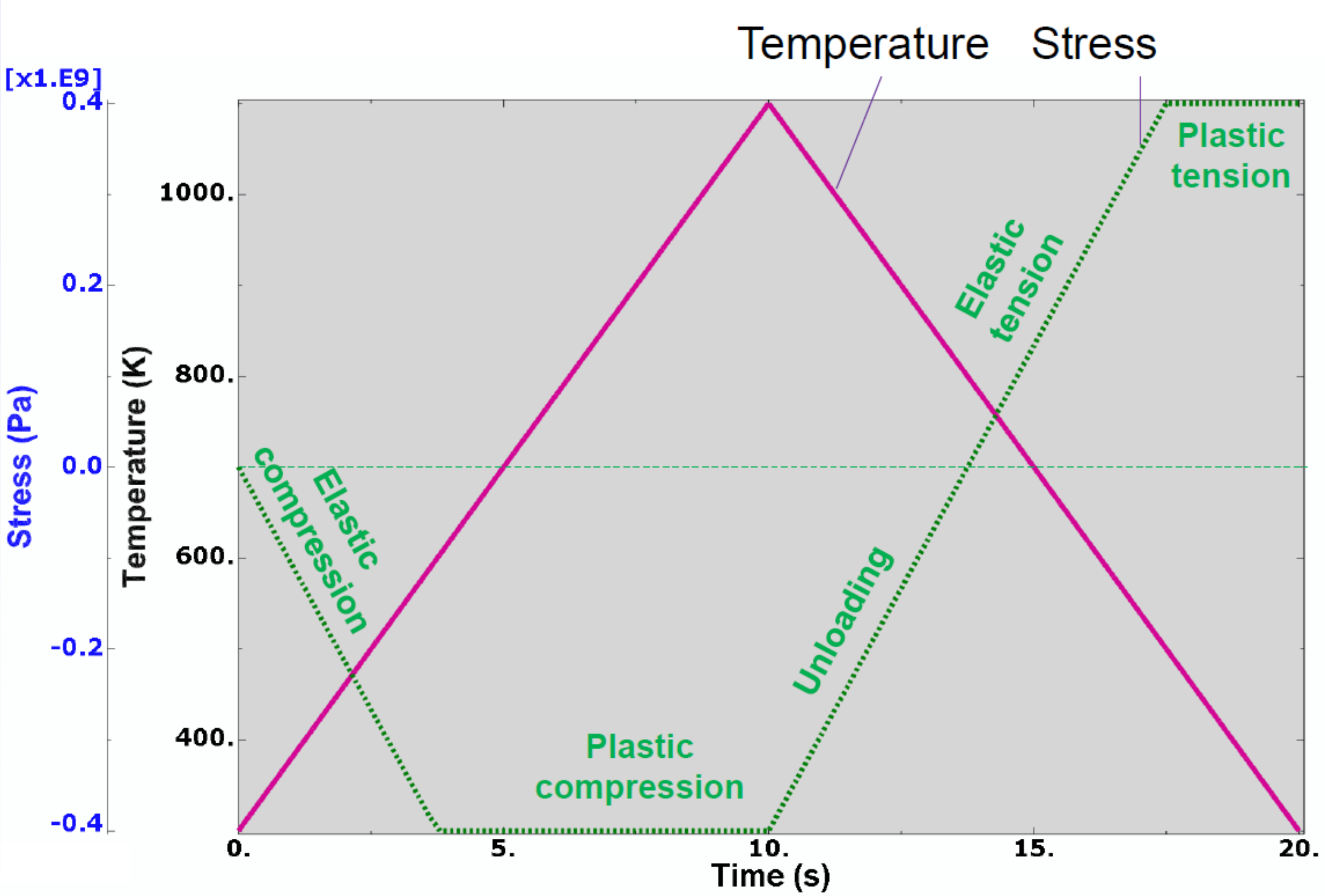


Credit: Dr. Wei Zhang @ Ohio State U

Powder Processes

Thermal expansion

- **Origin of residual stress – three bar problem to approximate layer by layer scanning**



Credit: Dr. Wei Zhang @ Ohio State U

Powder Processes

Thermal expansion

- **Origin of residual stress**

Key factors for residual stress and distortion

- **Thermal expansion**
- **Plastic deformation**
- **Spatially non-uniform distribution of temperature**

- **Modeling**

Continuum mechanics approach:

- Fourier's law of heat conduction for temperature

$$\rho C_P \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right)$$

- Force equilibrium for stress and strain

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z} + F_x = 0$$

Credit: Dr. Wei Zhang @ Ohio State U

Thermal expansion

Measurement of residual stress

Hooke's law of linear elasticity:

$$\sigma_{xx} = (2\mu + \lambda)\varepsilon_{xx} + \lambda \cdot \varepsilon_{yy} + \lambda \cdot \varepsilon_{zz}$$

$$\sigma_{yy} = \lambda \cdot \varepsilon_{xx} + (2\mu + \lambda)\varepsilon_{yy} + \lambda \cdot \varepsilon_{zz}$$

$$\sigma_{yy} = \lambda \cdot \varepsilon_{xx} + \lambda \cdot \varepsilon_{yy} + (2\mu + \lambda)\varepsilon_{zz}$$

- Lamé constants:

$$\lambda = \frac{E\nu}{(1+\nu)(1-2\nu)}$$

$$\mu = \frac{E}{2(1+\nu)}$$

Principle directions assumed and thus zero shear strains.

- ε_{xx}, ε_{yy} and ε_{zz} are normal elastic strains.

$$\varepsilon_{xx} = \frac{d_x - d_0}{d_0}$$

d_x and d_0 are the lattice spacing under stressed and stress-free conditions, respectively.

Neutron diffraction/scattering

Credit: Dr. Wei Zhang @ Ohio State U

Powder processes

Overview

Laser

Laser - Matter

Powder

Heat transfer

Residual stress

Sinter

Phase change

Wetting

SLS

P-S-P relation

Sintering

From Internet

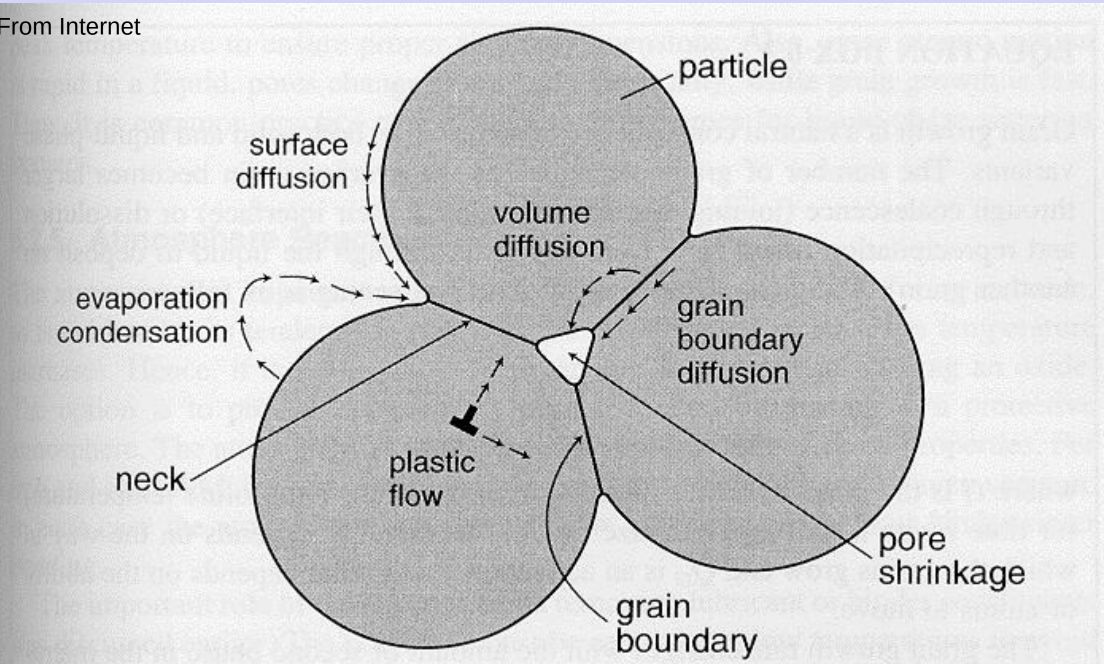


Figure 6.4. A three-particle sketch of sintering, showing the several possible paths of atomic motion involved with particle bonding (neck growth) and pore shrinkage (densification).

Mechanisms

- **Surface diffusion** – Diffusion of atoms along the surface of a particle
- **Vapor transport** – Evaporation of atoms that condense on a different surface
- **Volume diffusion** – atoms diffuses through volume
- **Grain boundary diffusion** – atoms diffuse along grain boundary
- **Plastic deformation** – dislocation motion causes flow of matter

Powder Processes

Liquid phase sintering and melting

From Internet

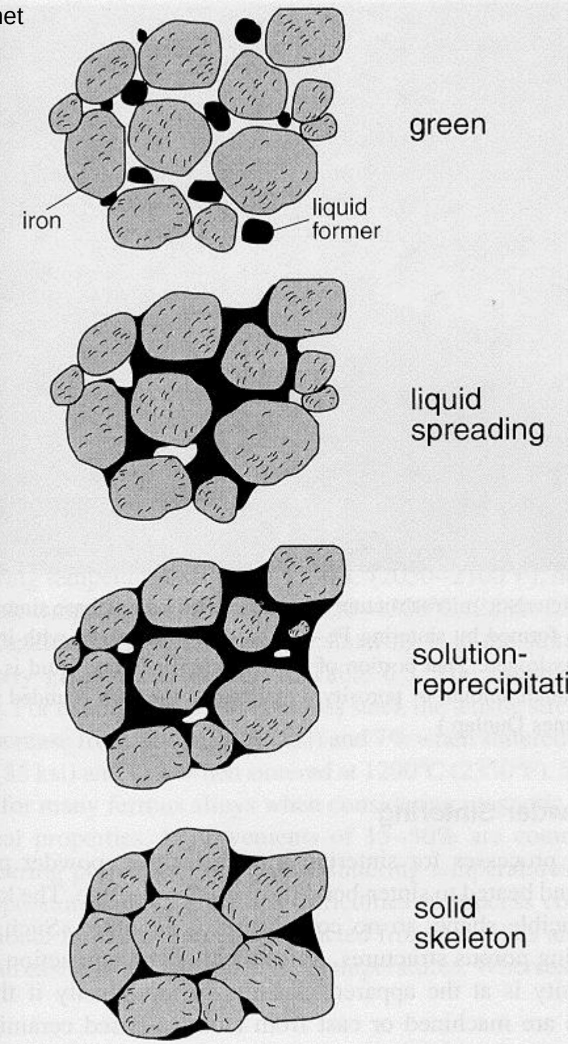
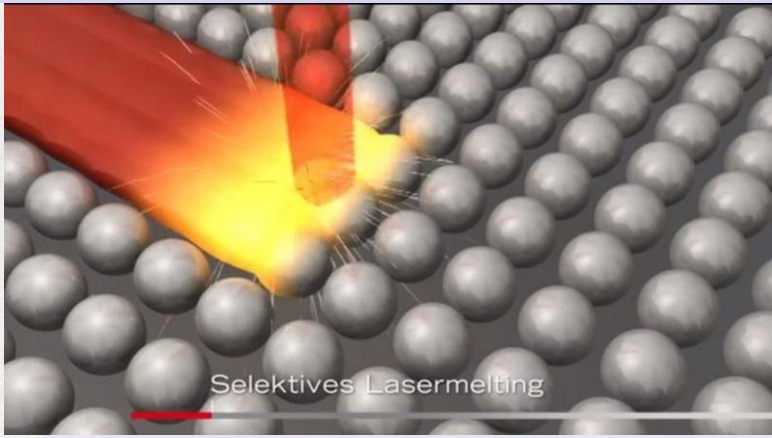
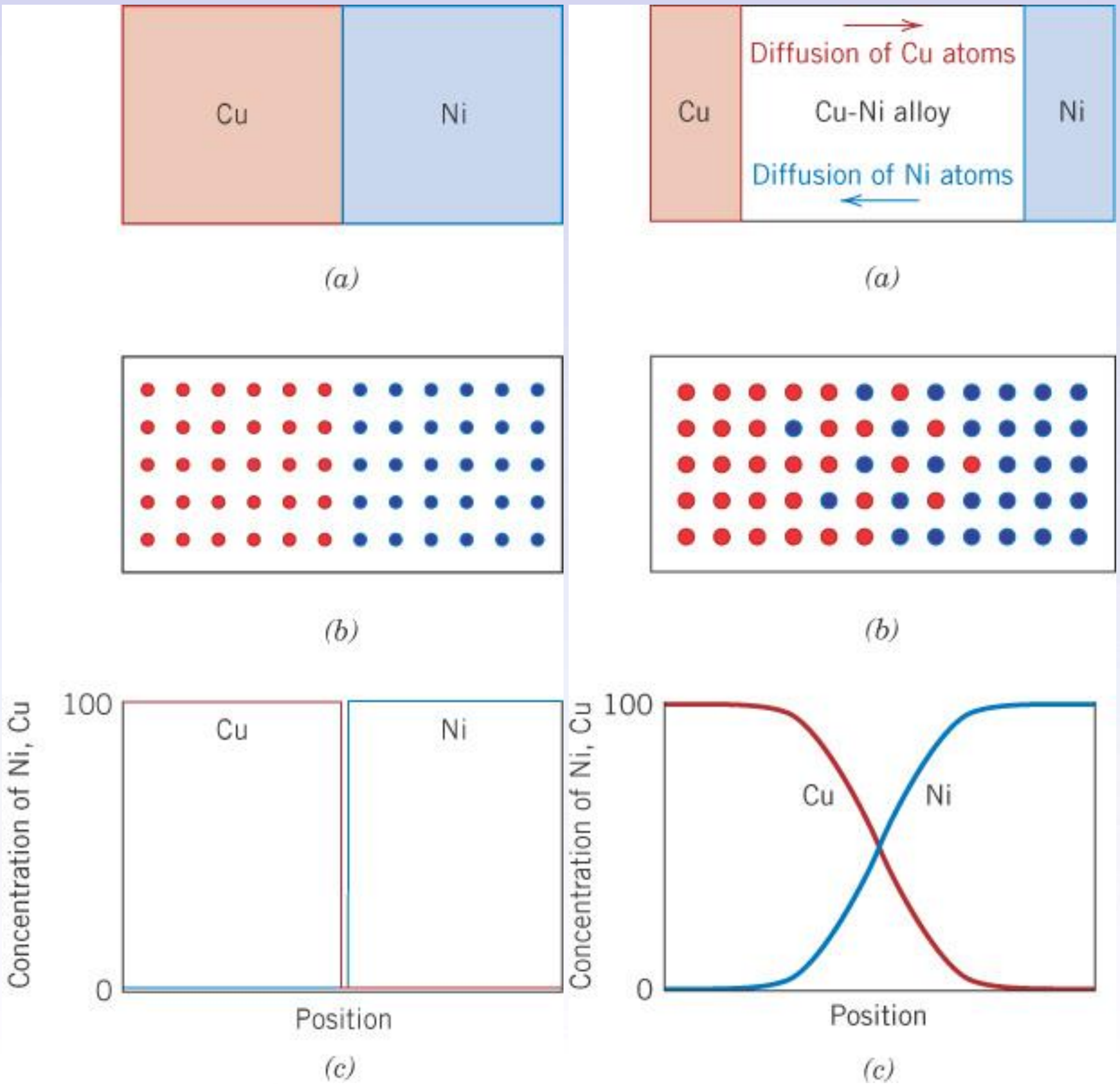


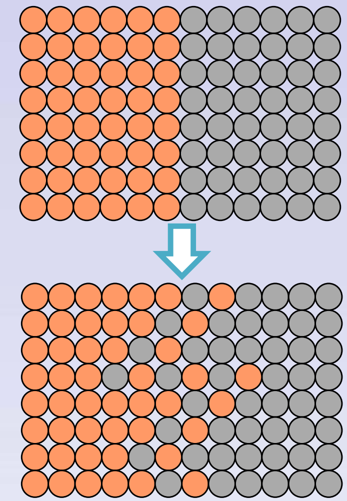
Figure 6.14. Liquid-phase sintering usually involves mixing an iron powder with a liquid forming powder (boride, carbide, phosphide, copper, tin) and heating to a temperature where the liquid forms, spreads, and contributes to particle bonding and densification.



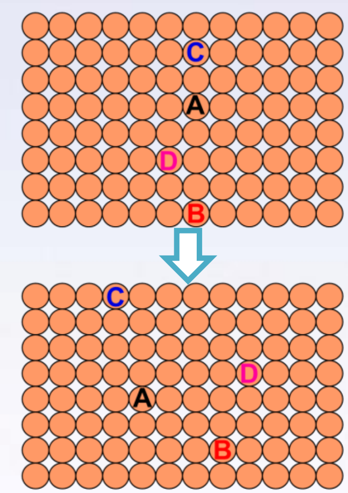
Selective laser melting

Sintering – Diffusion





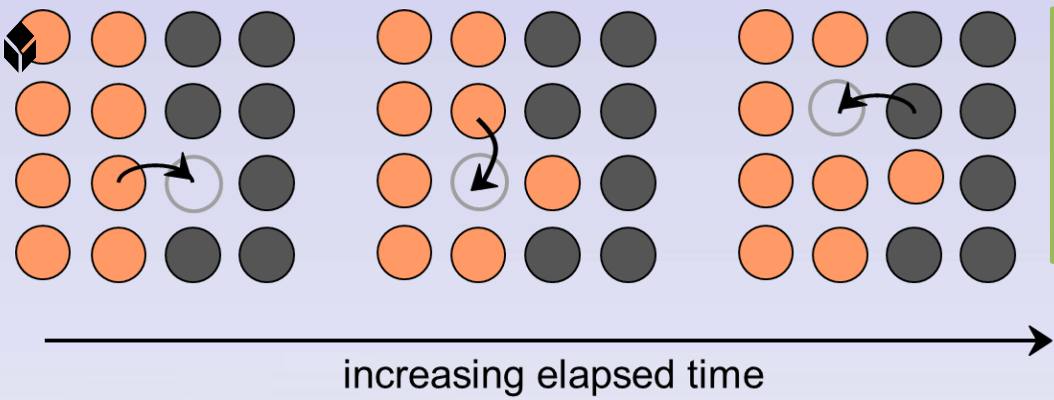
Inter-diffusion



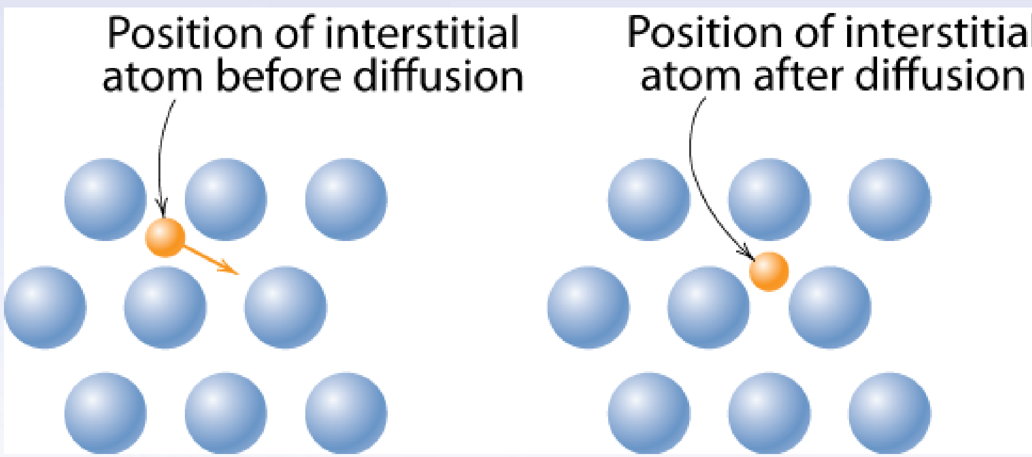
Self-diffusion

Powder Processes

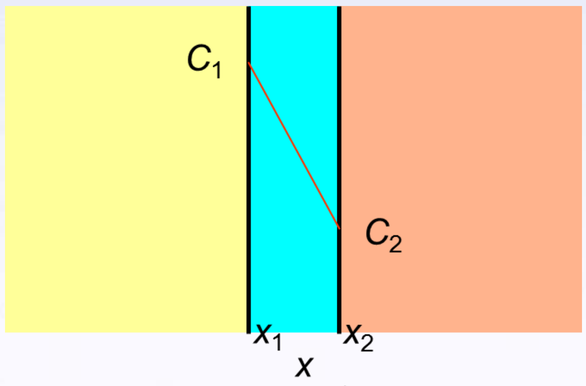
Sintering – Diffusion– Mechanisms



Vacancy Diffusion
- Rate depends on:
- Number of vacancies
- Activation energy



Interstitial Diffusion
- Smaller atoms diffuse between atoms
- More rapid



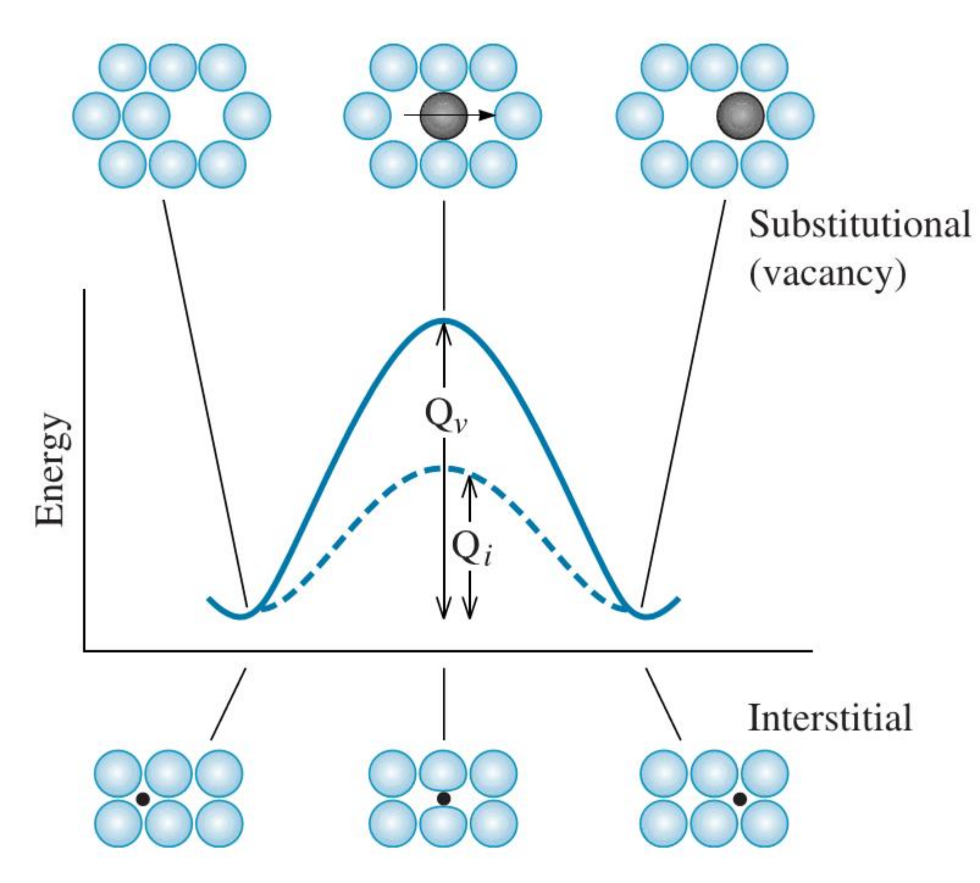
$$j \equiv \text{Flux} \equiv \frac{\text{moles (or mass) diffusing}}{(\text{surface area})(\text{time})} = \frac{\text{mol}}{\text{cm}^2\text{s}} \text{ or } \frac{\text{kg}}{\text{m}^2\text{s}}$$

Fick's first law of diffusion

$$j = -D\frac{dc}{dx}$$

$D \equiv$ diffusion coefficient

Sintering – Diffusion – Activation energy



Arrhenius-type equation

$$D = D_o \exp\left(-\frac{Q_d}{RT}\right)$$

D = diffusion coefficient [m^2/s]

D_o = pre-exponential [m^2/s]

Q_d = activation energy [J/mol]

R = gas constant [8.31 J/mol-K]

T = absolute temperature [K]

Sintering – Diffusion – Flux

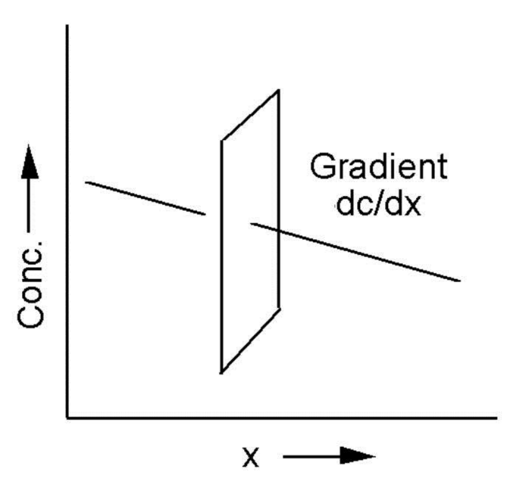
	Thermodynamic Force (Gradient of Potential)				
Flow *J*	**Hydraulic head**	**Temperature**	**Electrical**	**Chemical concentration**	**Stress**
Fluid	Hydraulic conduction *Darcy's law*	Thermo-osmosis Density changes	Electro-osmosis	Chemical osmosis Density change	consolidation
Heat	Isothermal heat transfer	Thermal conduction *Fourier's law*	*Peltier effect*	*Dofour effect*	Fully coupled thermoelastcity Phase change
Current	Streaming current	Thermoelectricity *Seebeck effect*	Electric conduction *Ohm's law*	Diffusion potential and membrane potential	Piezoelectricity
Ion	Streaming current	Thermal diffusion of electrolyte *Soret effect*	Electrophoresis	Diffusion *Fick's law*	Dissolution/ precipitation
Strain	consolidation (change in effective stress) fracture	Thermal expansion Density changes	Piezo-electricity	Dissolution and precipitate Consolidation (double-layer contraction)	Elasticity Viscoelasticity Plasticity Viscous flow Consolidation

Sintering – Diffusion – Flux

Transported quantity	Physical phenomenon	Physical law	Equations	Driving force
Fluid volume flux	Fluid through porous medium	Darcy's law	$q_i = -k_{ij} \frac{\partial P}{\partial x_j}$	Pressure gradient
Mass flux	Diffusion	Fick's law	$j_i = -D_{ij} \frac{\partial c}{\partial x_j}$	Concentration gradient
Electrical current flux	Electricity conduction	Ohm's law	$i_i = -R_{ij} \frac{\partial V}{\partial x_j}$	Electrical potential gradient
Heat energy flux	Heat conduction	Fourier's law	$q_i = -k_{ij} \frac{\partial T}{\partial x_j}$	Temperature gradient
Momentum flux	Viscosity	Newtonian fluid	$\tau_{ij} = -\mu \frac{\partial \rho u_i}{\partial x_j}$	Momentum gradient

Powder processes
Overview
Laser
Laser - Matter
Powder
Heat transfer
Residual stress
Sinter
Phase change
Wetting
SLS
P-S-P relation

Sintering – Diffusion – Flux



$$j = -D\frac{dc}{dx}$$

- Phenomenological (empirical)
- Only applies to neutral non-interacting particles (e.g., H in metals)
- In other cases, D is not a constant
- Physical meaning of D is not clear

Re-examine Fick's law with fundamentals

$$j_i = cv_i \qquad v_i = M\mathbf{F}_i$$

$$\mathbf{F}_i = -\frac{d\mu}{dx_i} \qquad \mu = \frac{\partial G}{\partial N}$$

$$G = G(T,P,N) = U + PV - TS$$

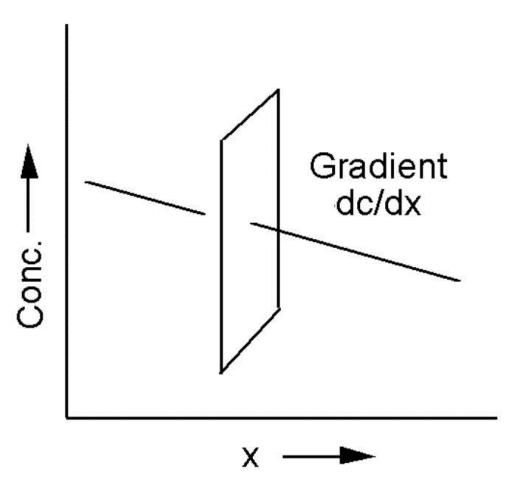
$$U = TS - PV + \mu N$$

$$j_i = -M\nabla\mu$$

- v is drift velocity
- M is mobility (quantifying how hard it is to move something)
- F is force
- G is Gibbs free energy
- U is internal energy
- Conjugate variables: Pressure (P) & Volume (V); Temperature (T) & Entropy (S); Chemical potential (μ) and number (N)

Powder Processes

Sintering – Diffusion – Flux



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- **F is force**
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- **U is internal energy**
- **Conjugate variables: Pressure (P) & Volume (V); Temperature (T) & Entropy (S); Chemical potential (μ) and number (N)**

Sintering – Diffusion – Flux

j $\frac{\partial c}{\partial t}$ $j + \frac{\partial j}{\partial x}$

dx

$$j = -D\frac{dc}{dx}$$

- **Mass conservation:** $\frac{\partial c}{\partial t} + \left(j + \frac{\partial j}{\partial x}\right) - j = \frac{\partial c}{\partial t} - \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) = 0$

- **Fick's second law:**

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2}$$

For interacting particles →

$$\frac{\partial c}{\partial t} = M\frac{\partial^2 \mu}{\partial x^2}$$

Powder Processes

Phase transformation

- **Melting: order to disorder**
- **Solidification: disorder to order (more complex)**

Based on Mass transport

PHASE TRANSFORMATIONS

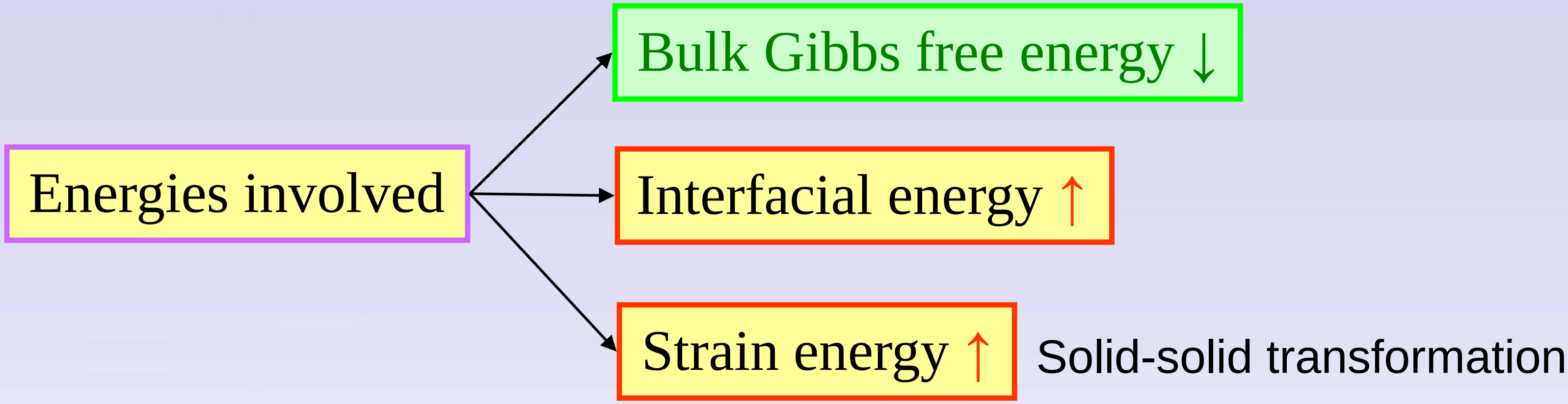
- Diffusional
- Martensitic (Diffusionless)

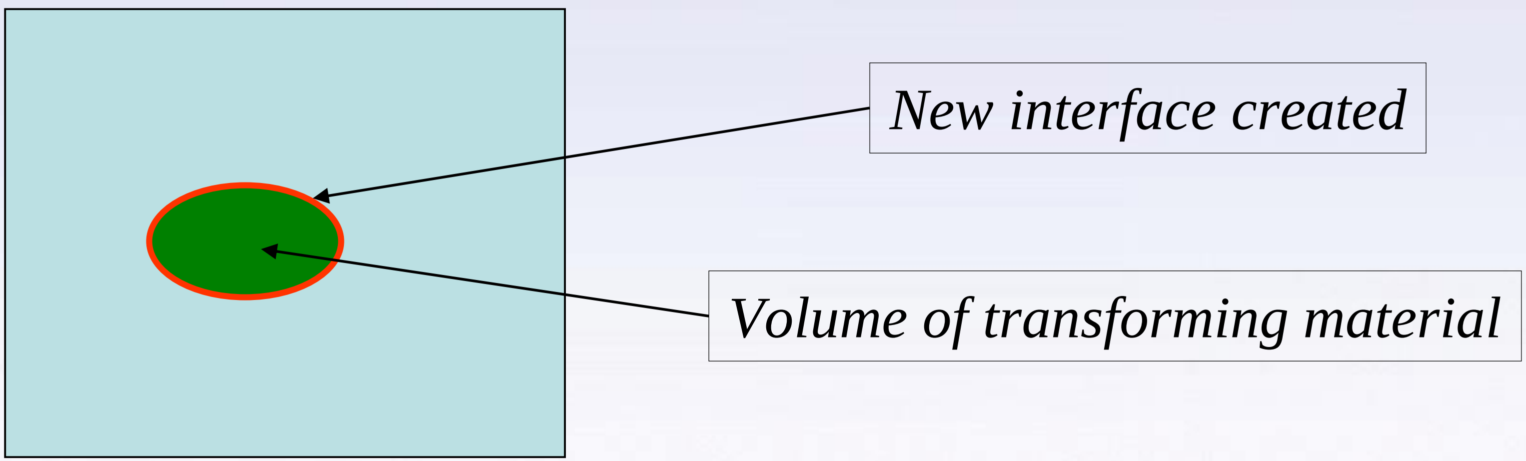
Based on order

PHASE TRANSFORMATIONS

- 1[nd] order — *nucleation & growth*
- 2[nd] order — *Entire volume transforms*

Phase transformation





Powder Processes

Powder processes
- Overview
- Laser
- Laser - Matter
- Powder
- Heat transfer
- Residual stress
- Sinter
- Phase change
- Wetting
- SLS
- P-S-P relation

Phase transformation

Solidification = Nucleation + Growth

Nucleation → Homogenous

Nucleation → Heterogenous

Heterogenous → Liquid to solid: walls, inclusions

Heterogenous → Solid to solid: grain boundaries, inclusions

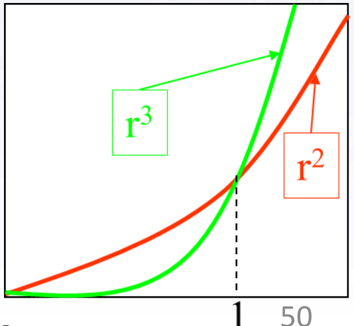
Homogenous nucleation

Free energy change on nucleation = Reduction in bulk free energy + increase in surface energy

$$\Delta G = (\text{Volume}).(\Delta G) + (\text{Surface}).(\gamma)$$

$$\Delta G = \left(\frac{4}{3}\pi r^3\right).(\Delta G_v) + \left(4\pi r^2\right).(\gamma)$$

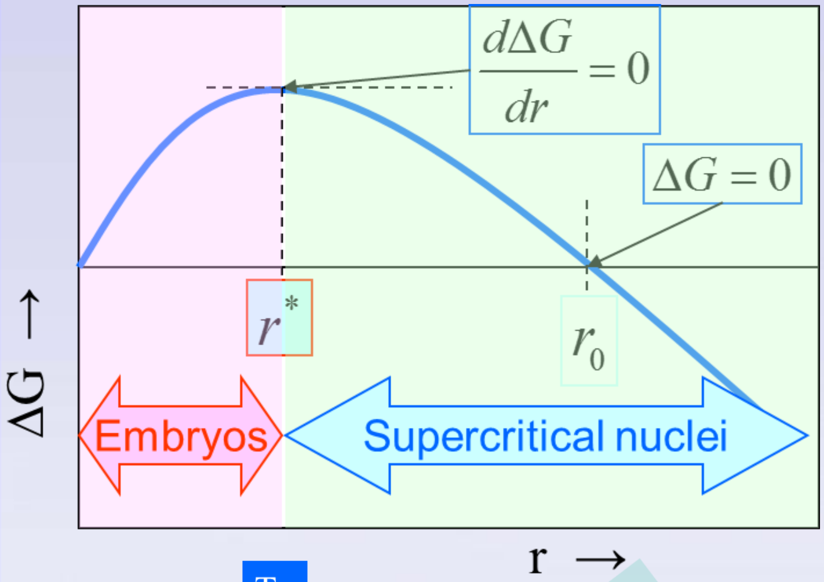
$$\Delta G_v = f(\Delta T)$$



Need to reach a minimum radius for spontaneous growth

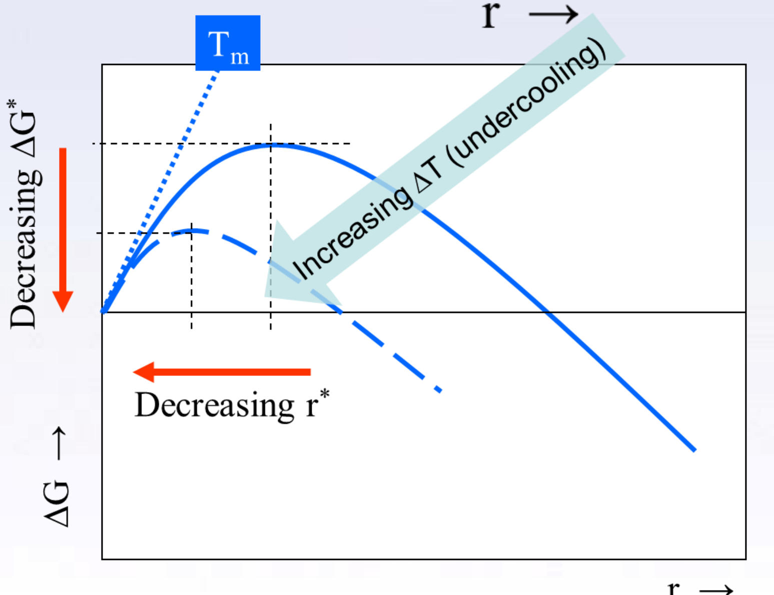
Powder Processes

Phase transformation



$$\frac{d\Delta G}{dr} = 0 \Rightarrow r^* = -\frac{2\gamma}{\Delta G_v}$$

As ΔG_v is –ve, r^* is +ve

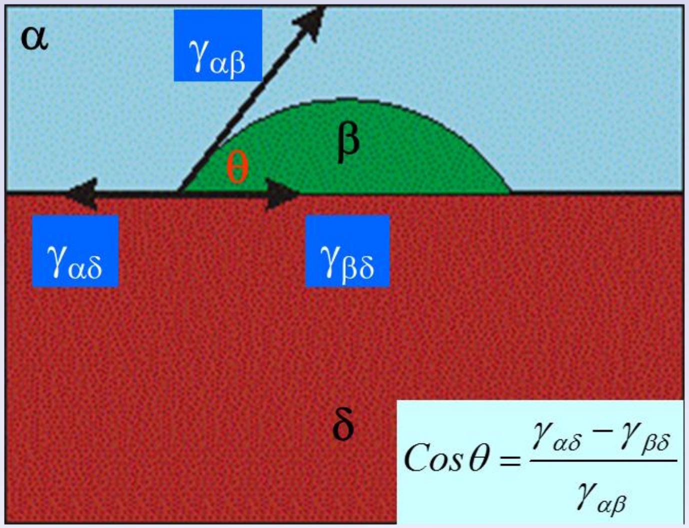


Undercooling reduces critical radius

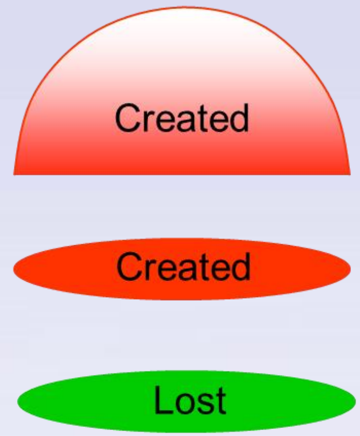
Powder Processes

Phase transformation

Heterogeneous nucleation



Interfacial Energies



$A_{lens}\,\gamma_{\alpha\beta}$

$A_{circle}\,\gamma_{\beta\delta}$

$A_{circle}\,\gamma_{\alpha\delta}$

Surface tension force balance → $\gamma_{\alpha\beta} Cos\theta + \gamma_{\beta\delta} = \gamma_{\alpha\delta}$

$$\Delta G = (V_{lens})\Delta G_v + (A_{lens})\gamma_{\alpha\beta} + (A_{circle})\gamma_{\beta\delta} - (A_{circle})\gamma_{\alpha\delta}$$

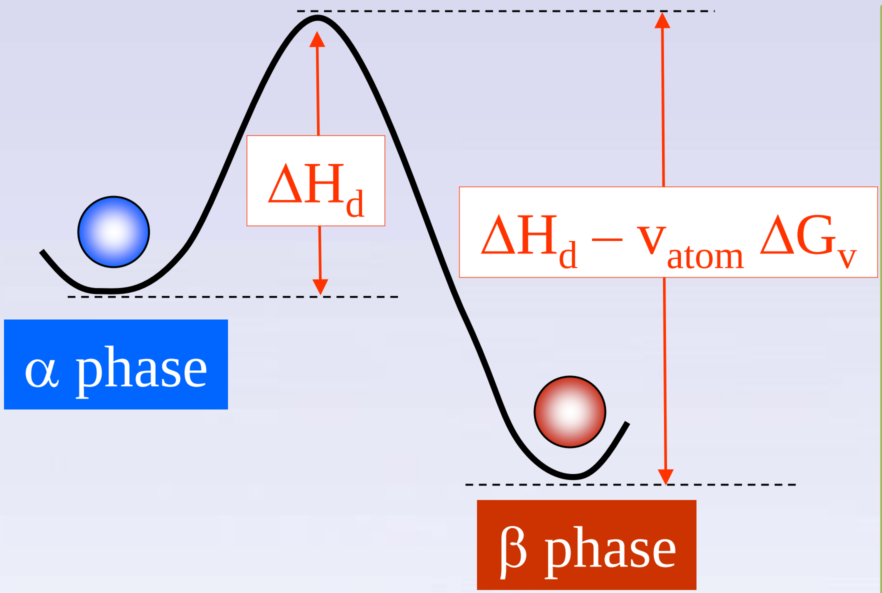
$V_{lens} = \pi h^2(3r-h)/3$ | $A_{lens} = 2\pi rh$ | $h = (1-Cos\theta)r$ | $r_{circle} = r\,Sin\theta$

$$\Delta G^*_{hetero} = \frac{1}{4} G^*_{homo}\left(2 - 3Cos\theta + Cos^3\theta\right)$$

Powder Processes

Phase transformation

- **Growth**



- **At transformation temperature the probability of jump of atom from $\alpha \rightarrow \beta$ (across the interface) is same as the reverse jump**
- **Growth proceeds below the transformation temperature, wherein the activation barrier for the reverse jump is higher**

$$\text{Transformation rate} = f(\text{Nucleation rate, Growth rate})$$

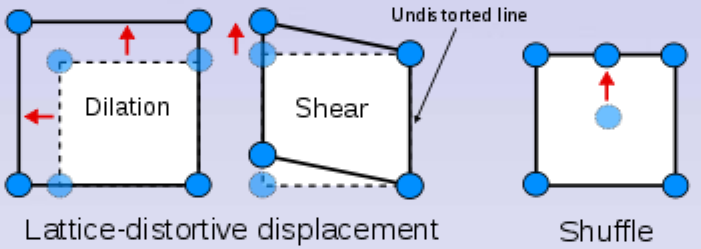
$$T = \frac{dX_\beta}{dt} = f(I, U)$$

$$X_\beta = 1 - e^{-\left(\frac{\pi I U^3 t^4}{3}\right)}$$

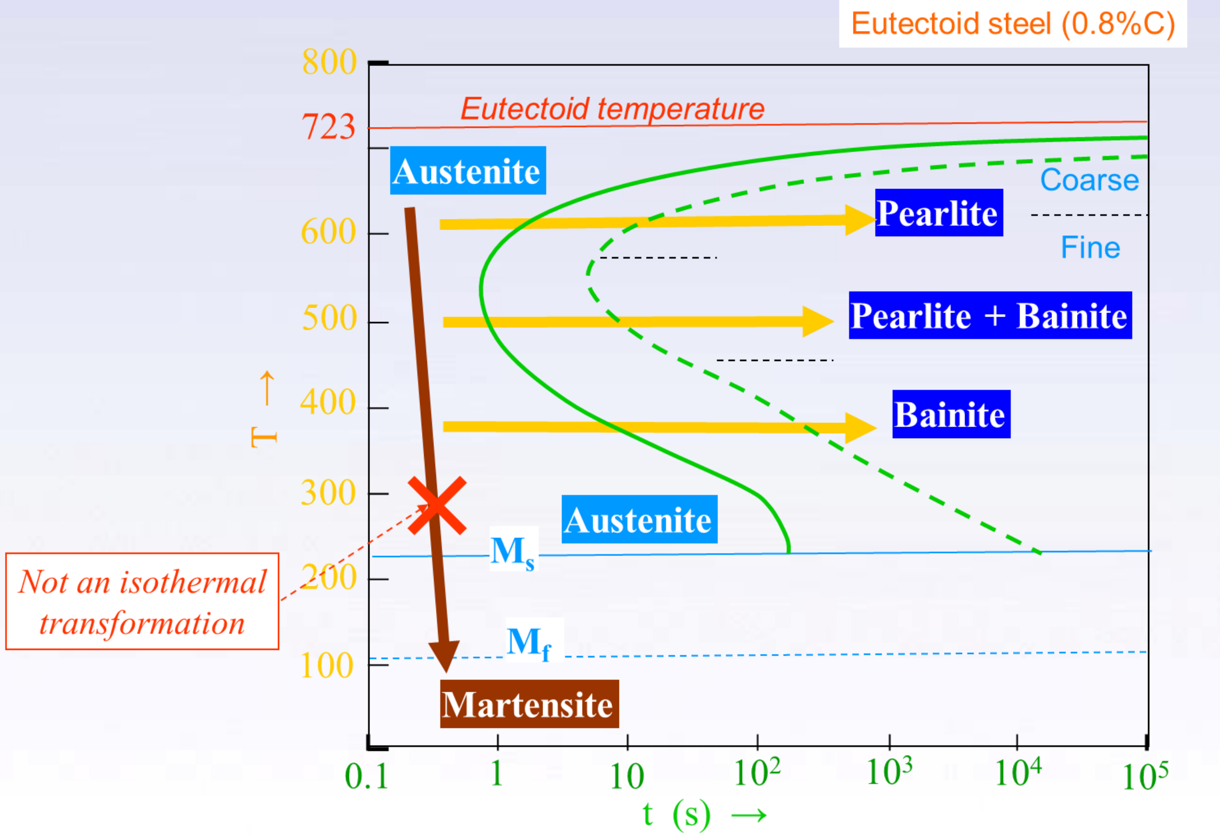
Phase transformation

- **Martensitic transformation**

Military transformation: collective, short distance, usually interatomic



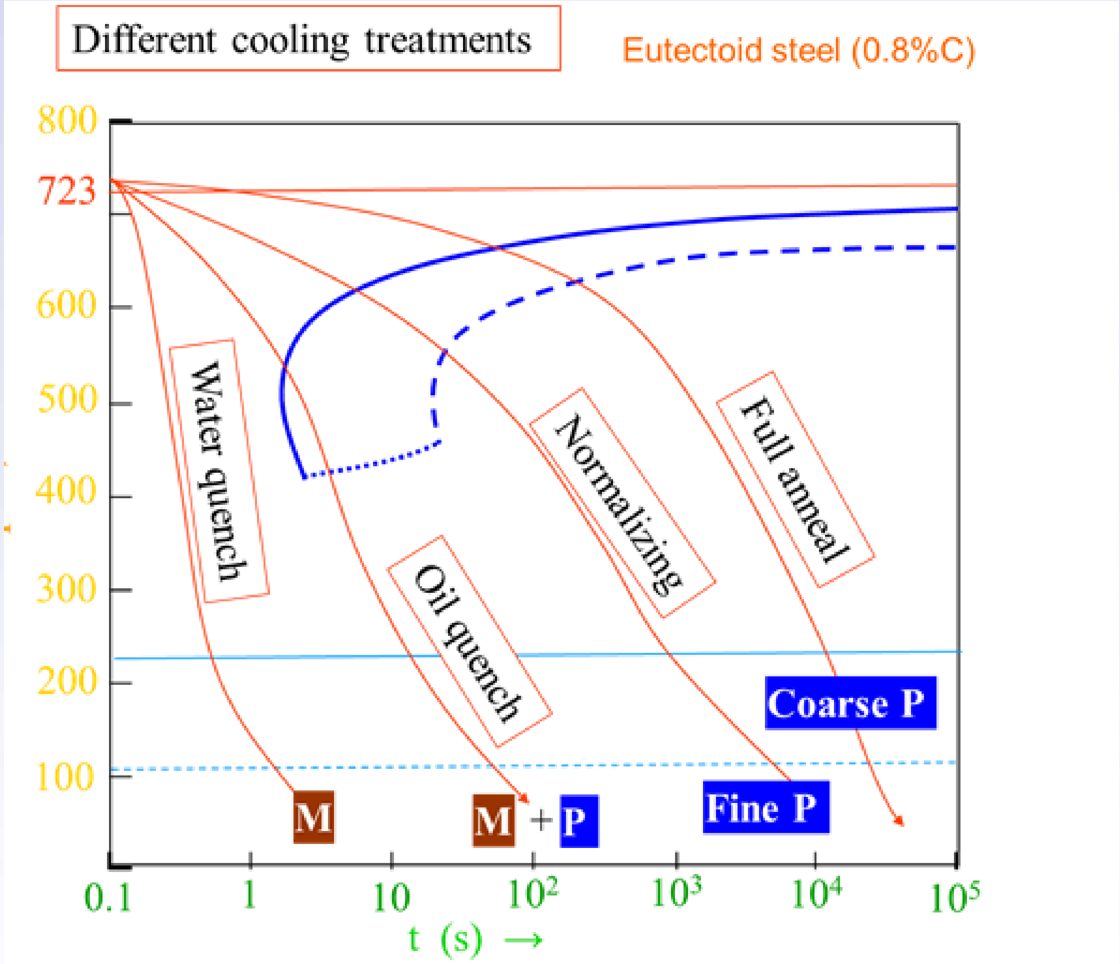
Time- Temperature-Transformation (TTT) Curves – *Isothermal Transformation*

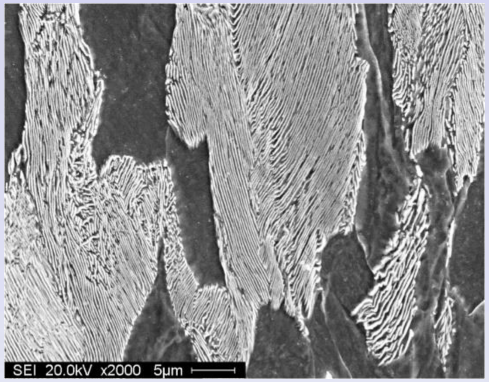


Powder Processes

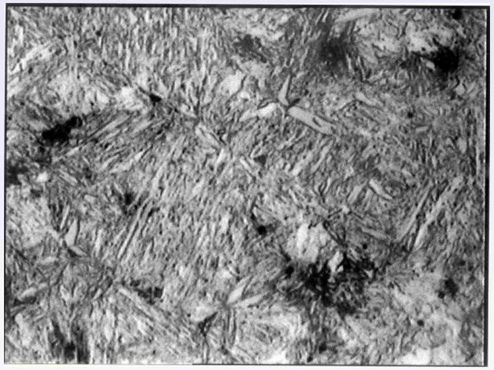
Phase transformation

Martensitic transformation



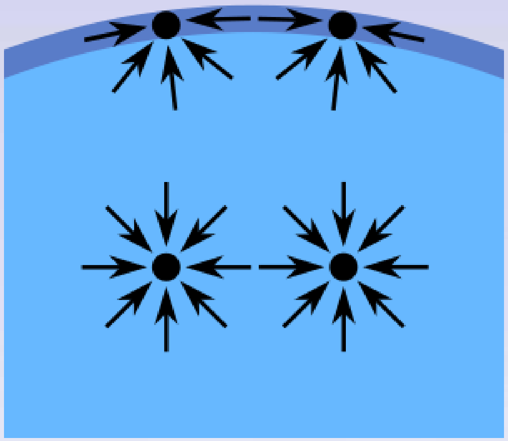


P = Pearlite

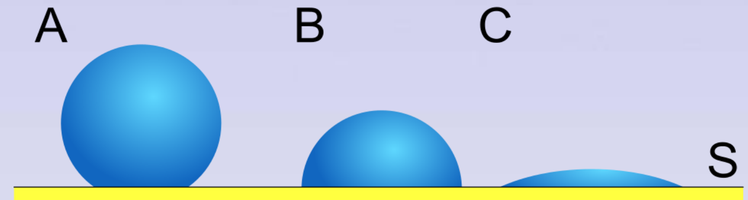


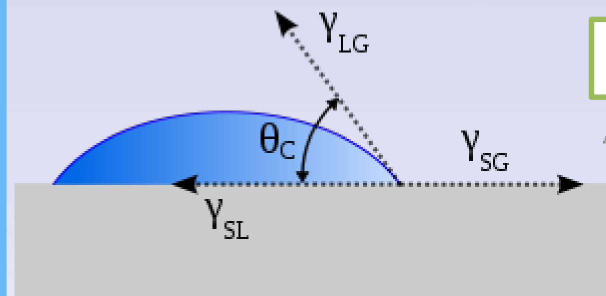
M = Martensite

Wetting



Surface tension

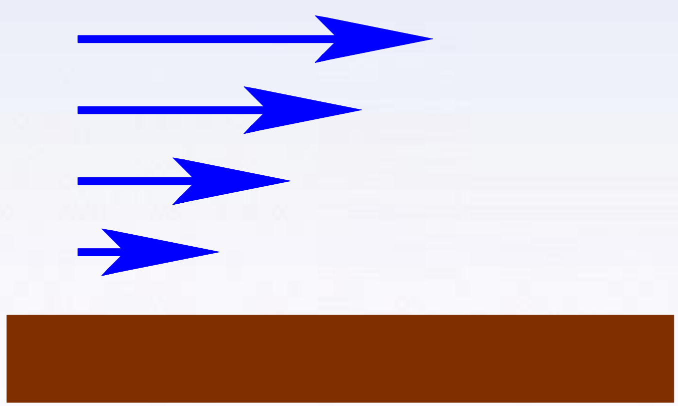




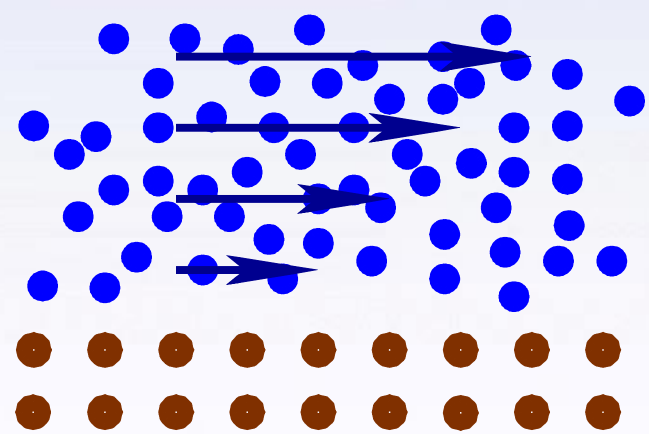
- **Contact angle**

$$\gamma_{SG} = \gamma_{SL} + \gamma_{LG}\cos\theta$$

Continuum picture



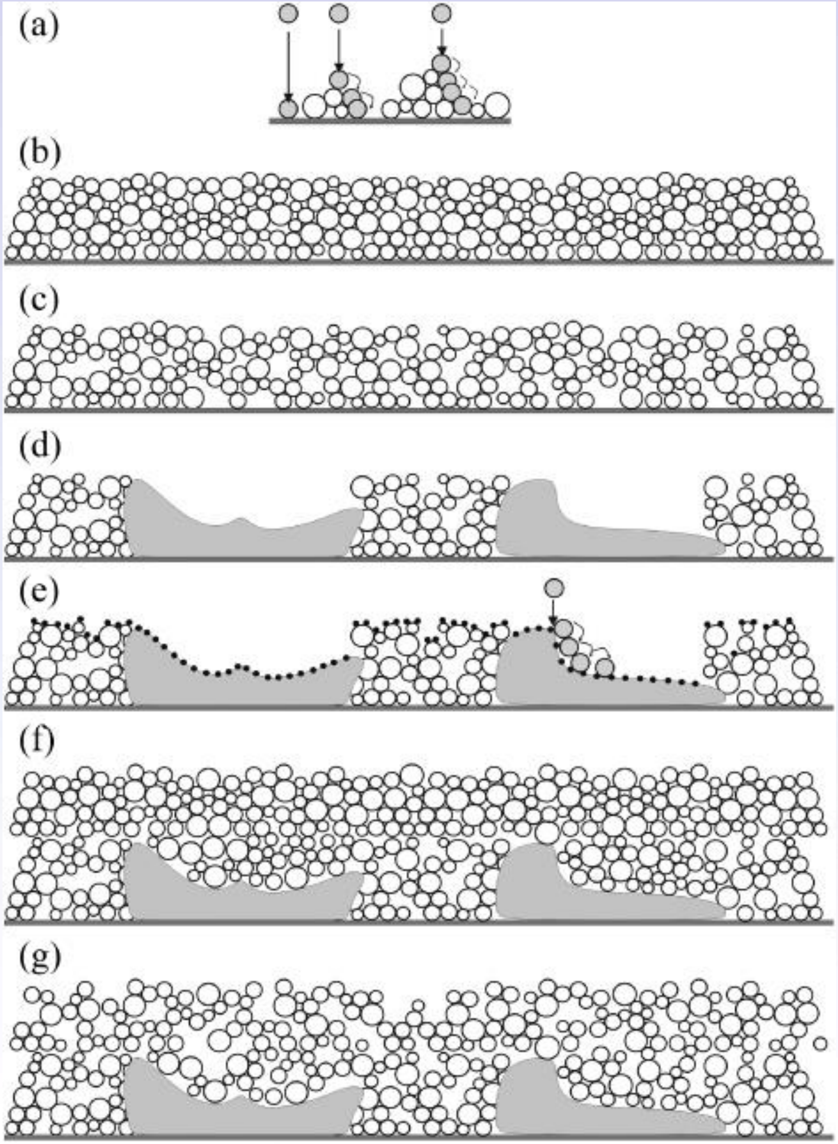
Molecular picture



No-Slip Boundary Condition **breakdown near the wall**

Powder Processes

Wetting



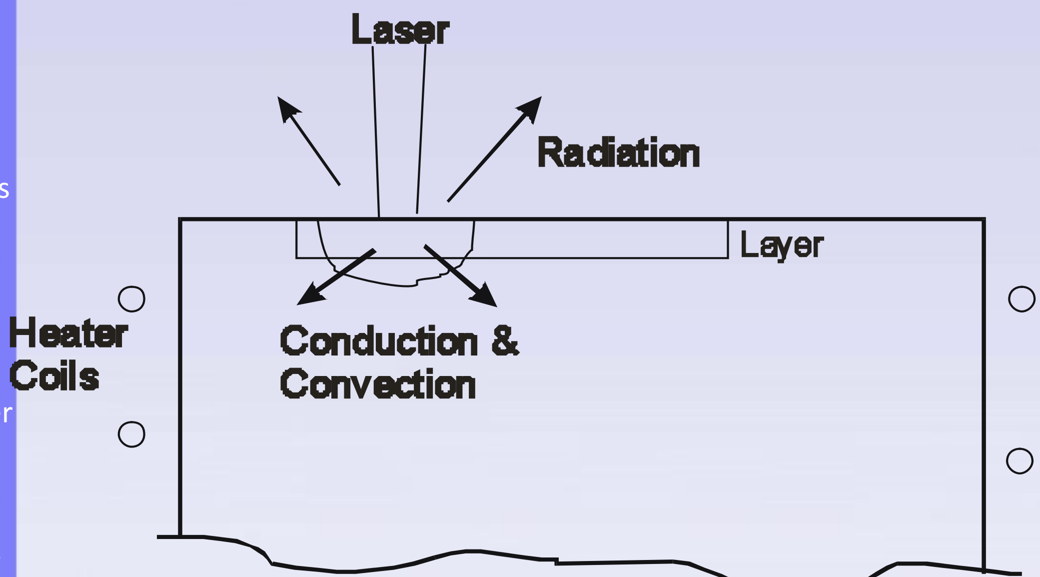
Relevant forces

- **Surface tension**
- **Viscous force**
- **Inertial force**

Need to solve Navier-Stokes Equations with complex geometric boundaries

Powder Processes

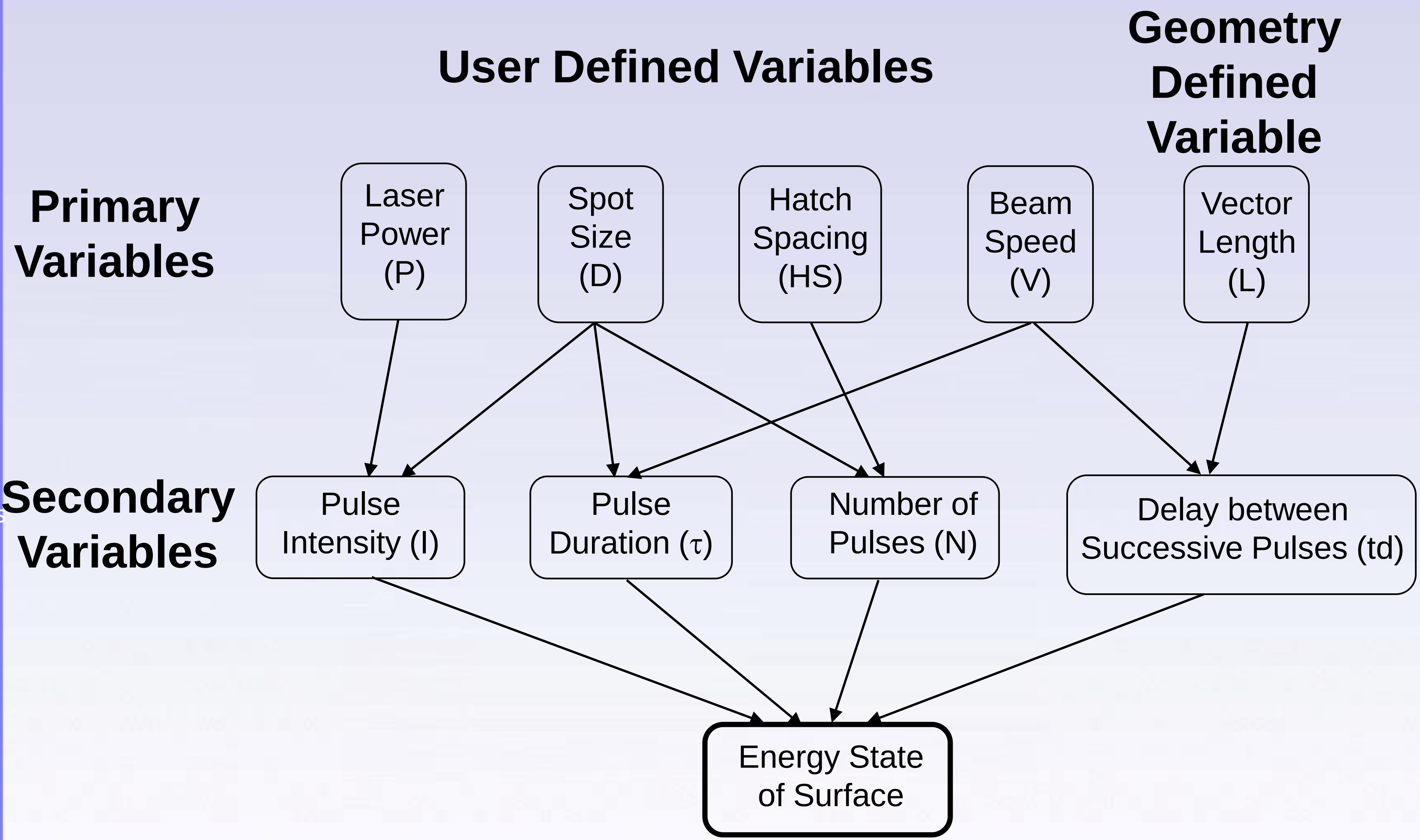
- **Selective laser sintering**



- **Bed is heated to just below powder's melting temperature.**
- **SLS powder beds are porous, powder sizes typically 20-40 mm.**
- **Conduction, convection, and radiation modes of heat transfer.**
- **Material properties (temp. dependent):**
  - **density r [kg/m3]**
  - **specific heat Cp [J/kg K]**
  - **thermal conductivity k [W/m K]**
  - **thermal diffusivity a [m2/s]: a = k / (r Cp)**
- **Couple all the physics together**

Credit: Dr. David Rosen @ Georgia Tech

Selective laser sintering



Credit: Dr. David Rosen @ Georgia Tech

Powder Processes

Powder processes
Overview
Laser
Laser - Matter
Powder
Heat transfer
Residual stress
Sinter
Phase change
Wetting
SLS
P-S-P relation

Properties of sintered structure

From Internet

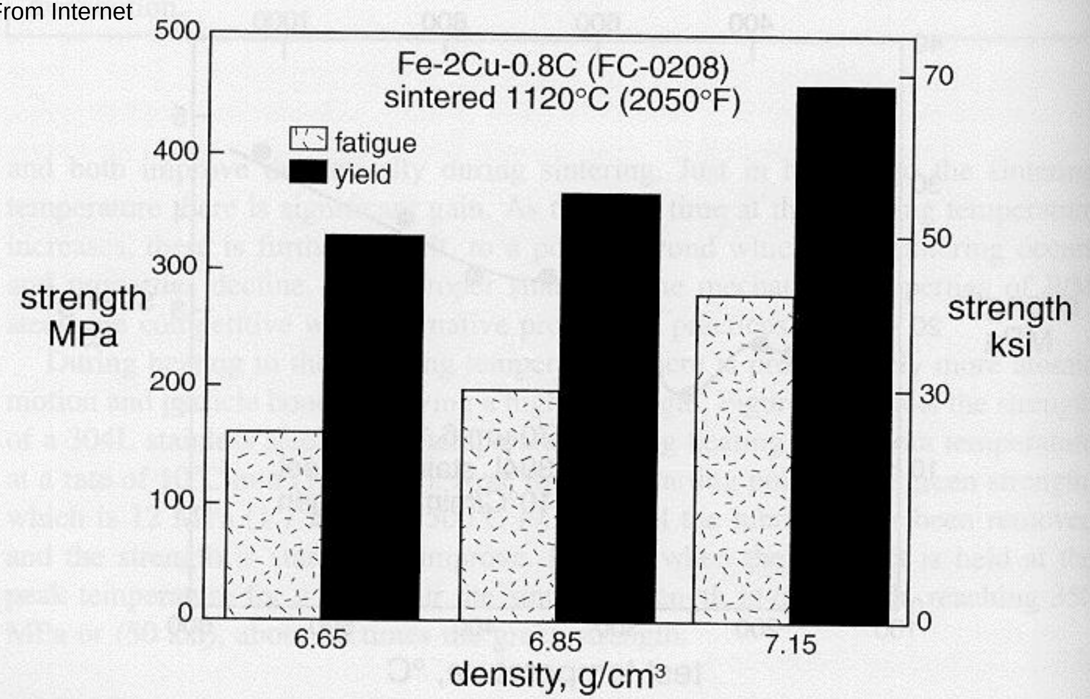


Figure 6.23. Yield and fatigue strength of sintered Fe–2Cu–0.8C (FC-0208) shown as a function of the green density, for a constant sintering cycle of 1120°C (2050°F) for 25 min. (Data from Kevin Christian.)

- **Process – Structure – Property relationship**

- **Question: with the simulation of all the physics coupled together, how to obtain the properties of the part?**


THANK
Y U!

Powder Processes

LASER

LASER	POWER RANGE (W)	WAVE-LENGTH (µm)	TYPICAL INDUSTRIAL APPLICATIONS
CO_2 – Flowing Gas (Continuous Wave and Pulsed)	500 – 45,000	10.6	Cutting, welding, cladding, free forming, and hardening
CO_2 – Sealed (Pulsed)	10 – 1,000	10.6	Micro-welding, cutting, scribing, and drilling
Nd:YAG (Continuous Wave)	1,000 – 5,000	1.06	Welding, cutting, cladding, and hardening
Nd:YAG (Pulsed)	10 – 2,000	0.53 - 1.06	Micro-welding, cutting, drilling, scribing, and marking
Nd:YAG –Diode Pumped (Pulsed)	10 - 500	1.06	Cutting, drilling, scribing, marking, and micro-machining.
Excimer (Pulsed)	0.001 - 400	0.157 – 0.351	Micro-machining, marking, and photolithography

Polymer

Evaluating design

Prototyping Technologies	Base Materials
Selective laser sintering (SLS)	Thermoplastics, metal powders
Fused deposition modeling (FDM)	Thermoplastics, eutectic metals
Stereolithography (SLA)	Photopolymer
Laminated object manufacturing (LOM)	Paper
Electron beam melting (EBM)	Titanium alloys
3D printing (3DP)	Various Materials

https://www.youtube.com/watch?v=p__-QbQbntI

A design of a motion system – motion can be described using kinematic equations when approximated as rigid structures