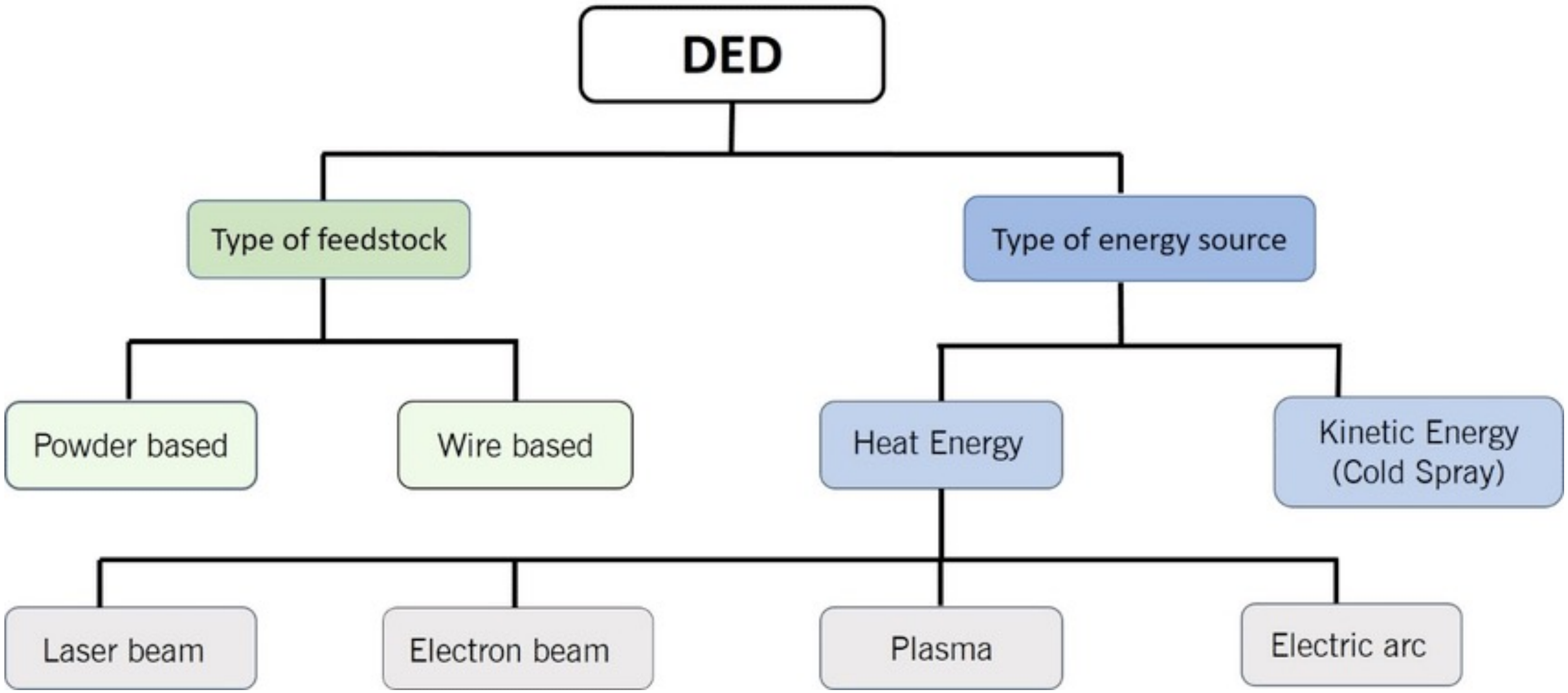
# Directed Energy Deposition

# OUTLINE

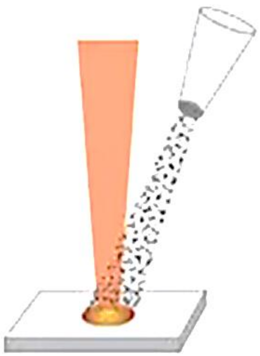
- Directed Energy Deposition
- Mechanism of Laser DED
- Power Attenuation
- Applications

# Directed Energy Deposition

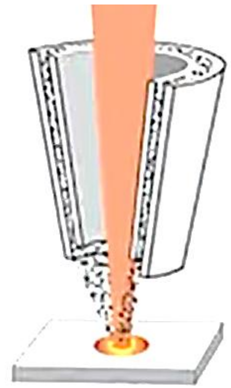



- Directed Energy Deposition (DED): AM process using focused thermal energy.
- Energy Sources: Laser (L-DED), Electron Beam (EB-DED), Plasma/Electric Arc (WAAM).
- Feedstock: Powder or wire.
- Applications: Repair, remanufacture, feature addition, large parts.

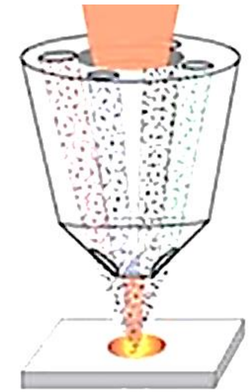
# Powder Feeding Nozzle



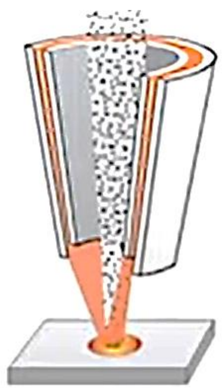
Lateral Feed



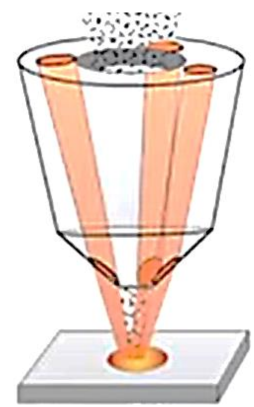
Continuous Feed



Discrete Coaxial



Central feed with annular laser

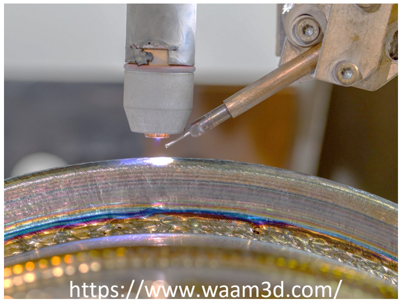


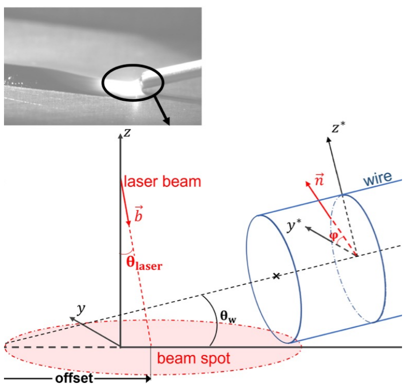
Central feed with discrete feed

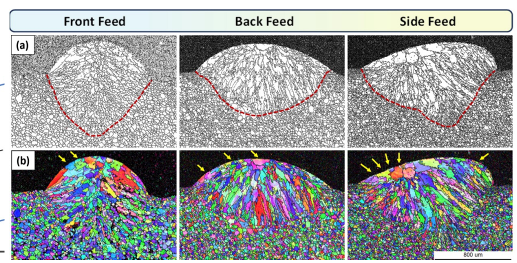
# Powder DED

# Variants of Laser Wire DED (WLDED)

## Lateral wire feeding



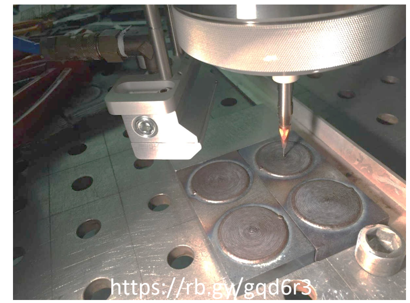



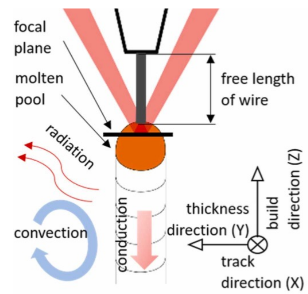

Abadi et. al. (2023)

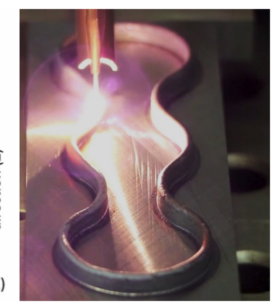
Aditya et. al. (2025)

Non-uniform heat input & difficult free form deposition

## Coaxial wire feeding



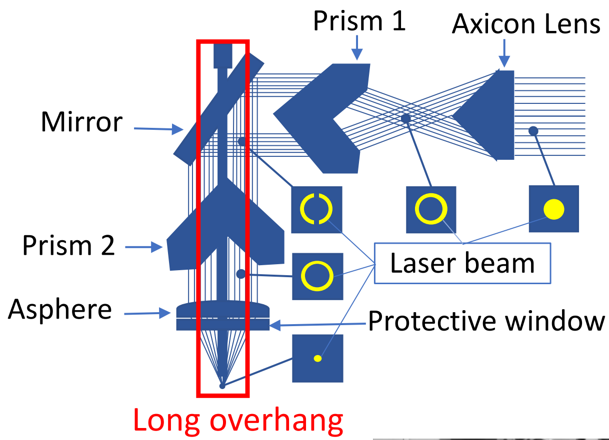
Odermatt et. al. (2022)

https://shorturl.bz/tyz

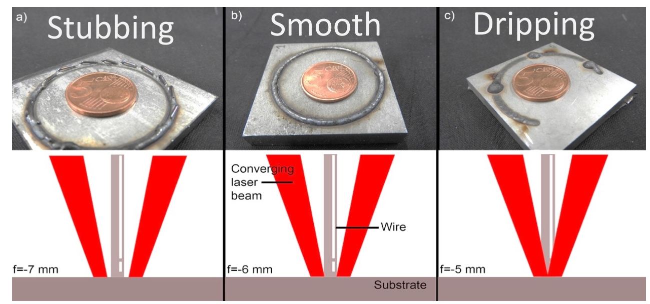
Uniform heat input & easy free form deposition

**Coaxial wire laser DED offers uniform and higher-quality deposits during free form deposition**

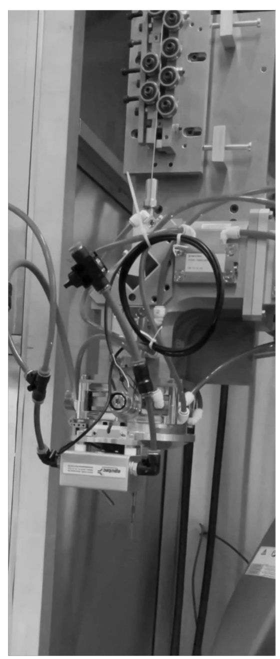
# Wire DED

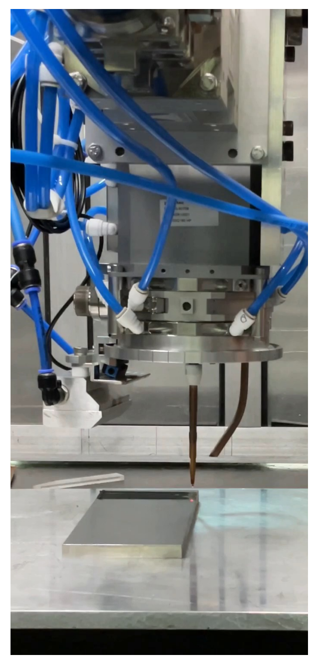



**Coaxial wire feeding**




Motta et. al. (2018)





# Comparison with AM Processes

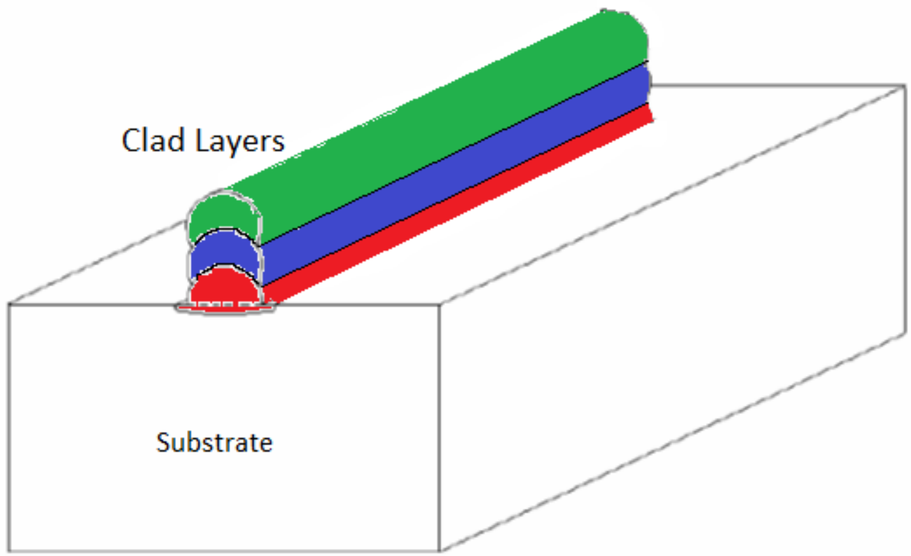
- Deposition Rate: DED Medium–High, PBF Low, Binder Jetting High.
- Accuracy: DED Moderate, PBF High, Binder Jetting Moderate.
- Surface Finish: DED Rough, PBF Smooth, Binder Jetting Rough.
- Build Size: DED Large, PBF Small–Medium, Binder Jetting Large.
- Applications: DED repair/FGMs, PBF precision parts, Binder Jetting prototyping.

# Comparison with AM Techniques

- Deposition Rate: L-DED medium, PBF low, WAAM high.
- Accuracy: L-DED moderate, PBF high, WAAM low.
- Surface Finish: L-DED rough, PBF smooth, WAAM rough.
- Materials: L-DED broad range, PBF powders, WAAM wires.
- Applications: L-DED repair/large, PBF precision, WAAM large.

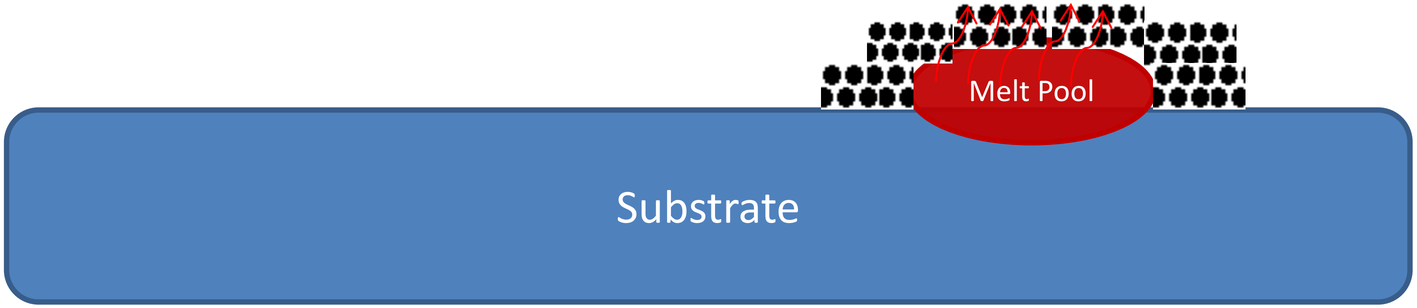
# INTRODUCTION

- Fuse with laser beam another material - of desired properties - on substrate material
- Metallurgical Bonding at surface
- Minimal dilution between material layers



# Process Mechanism

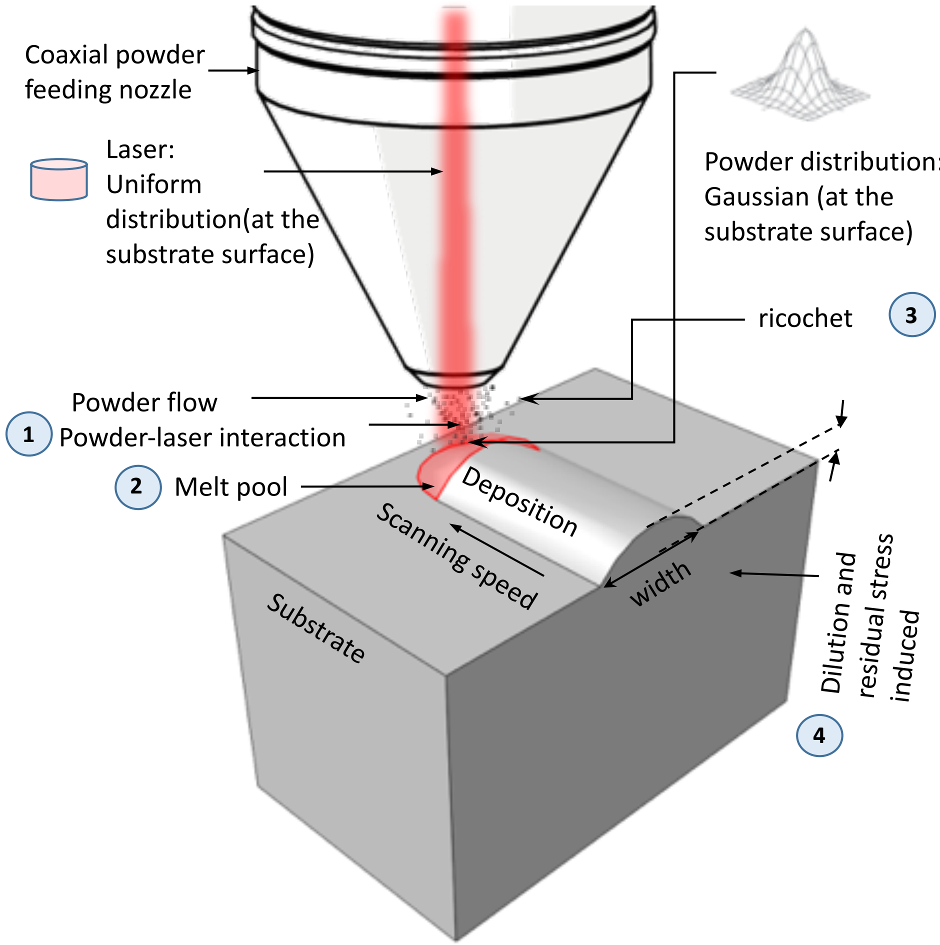
- Melt pool formation and fusion by moving Laser beam
- Surface tension gradient drives molten material flow
- Substrate & Clad material gets mixed in molten state at the interface forming metallurgical bond
- Physical Phenomena's  occurring
  - Heat transfer, momentum, and continuity

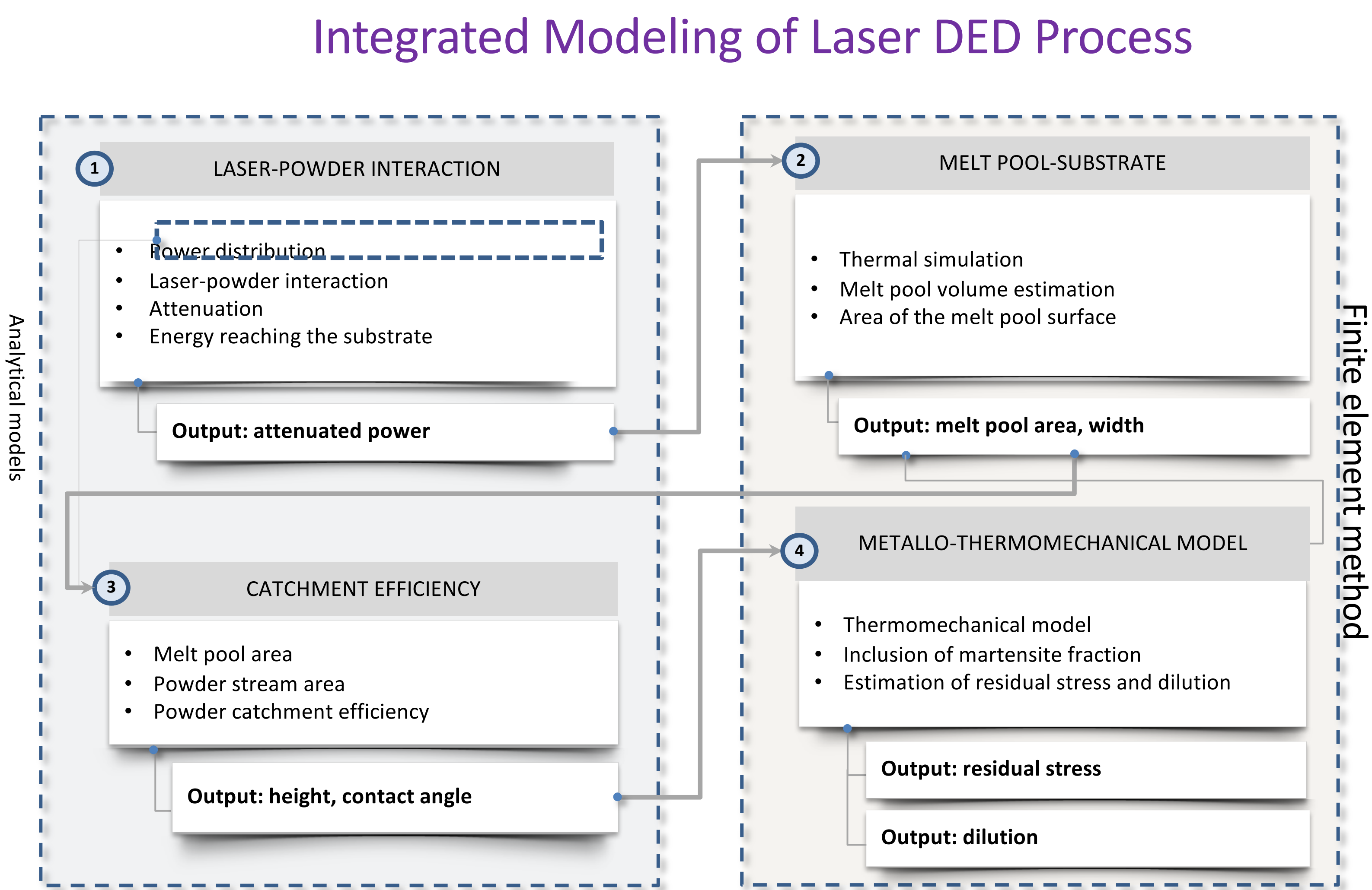


# PROCESS MECHANISM

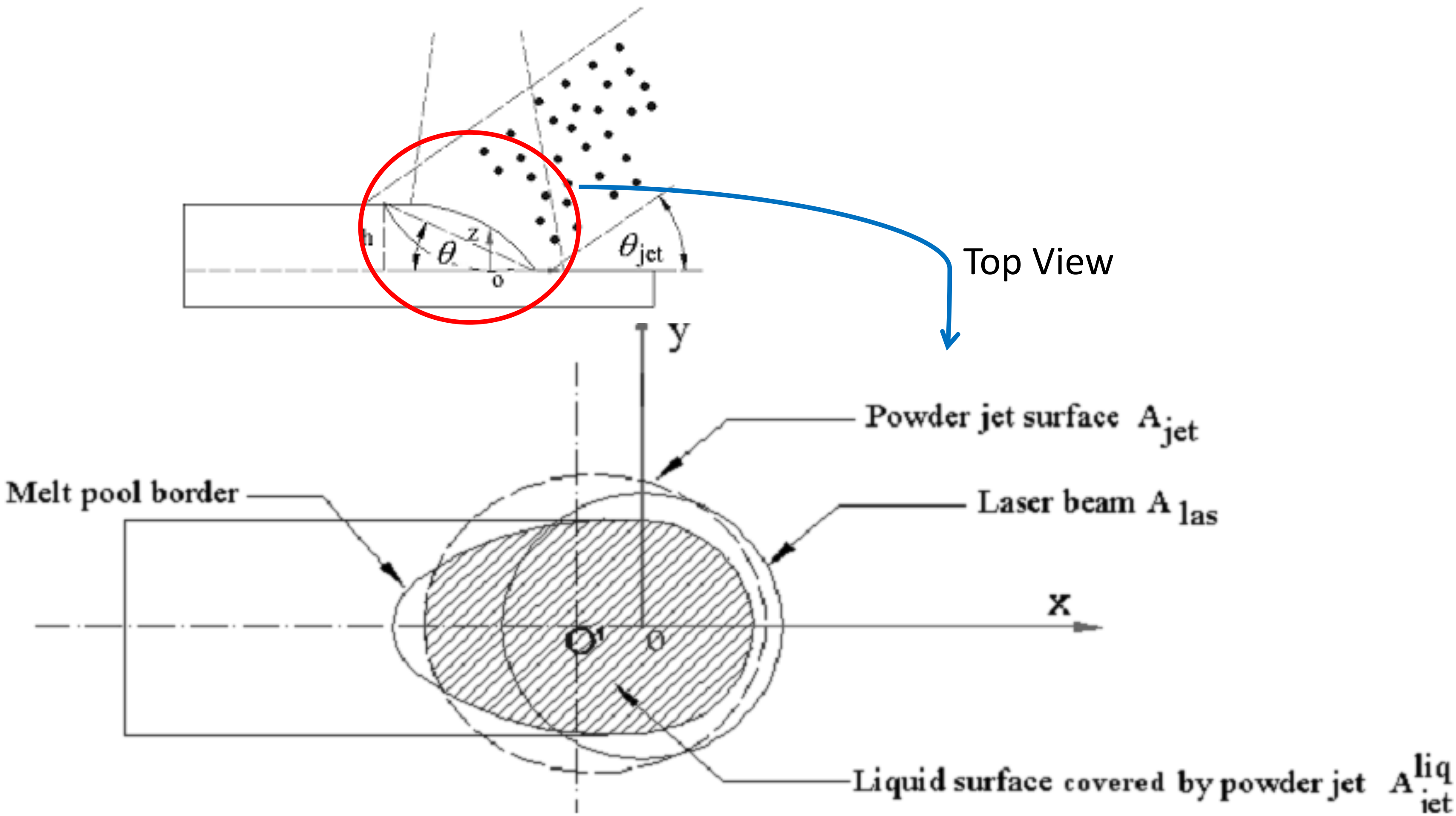
- High cooling rate ( quenching )
  - Formation of fine-grained microstructures OR meta-stable phases
- Supply of clad material to the substrate
  - Pre-Placed: prior clad deposition ( aka laser sintering)
    - Melt-pool formed on top of clad layer and then proceeds downwards to the substrate
  - In-situ feeding: powder injection gun (coaxial OR lateral)
    - Melt-pool formation first occurs at substrate in which clad powder is being fed
    - On their way through the laser beam particles are preheated (Power Attenuation)

# Integrated Modeling of Laser DED Process




Integrated Modeling of Laser DED Process
Analytical models
1
LASER-POWDER INTERACTION
Power distribution
Laser-powder interaction
Attenuation
Energy reaching the substrate
Output: attenuated power
3
CATCHMENT EFFICIENCY
Melt pool area
Powder stream area
Powder catchment efficiency
Output: height, contact angle
2
MELT POOL-SUBSTRATE
Thermal simulation
Melt pool volume estimation
Area of the melt pool surface
Output: melt pool area, width
4
METALLO-THERMOMECHANICAL MODEL
Thermomechanical model
Inclusion of martensite fraction
Estimation of residual stress and dilution
Output: residual stress
Output: dilution
Finite element method

# POWER ATTENUATION




*Geometric characteristics process zone(Toyserkani et al., 2005)*

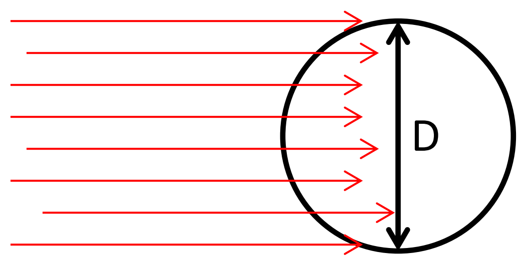
# POWER ATTENUATION

- Energy absorbed by particle along its path
  - Spherical, Size>>Penetration depth

$$E_{absorbed} = E_{incident} - E_{reflected} - E_{transmitted}$$

$$E_{absorbed} = Absorptivity \times E_{incident}$$

$$E_{absorbed} = Absorptivity \times A_{proj} \times I(x,y,z) \times \Delta t$$



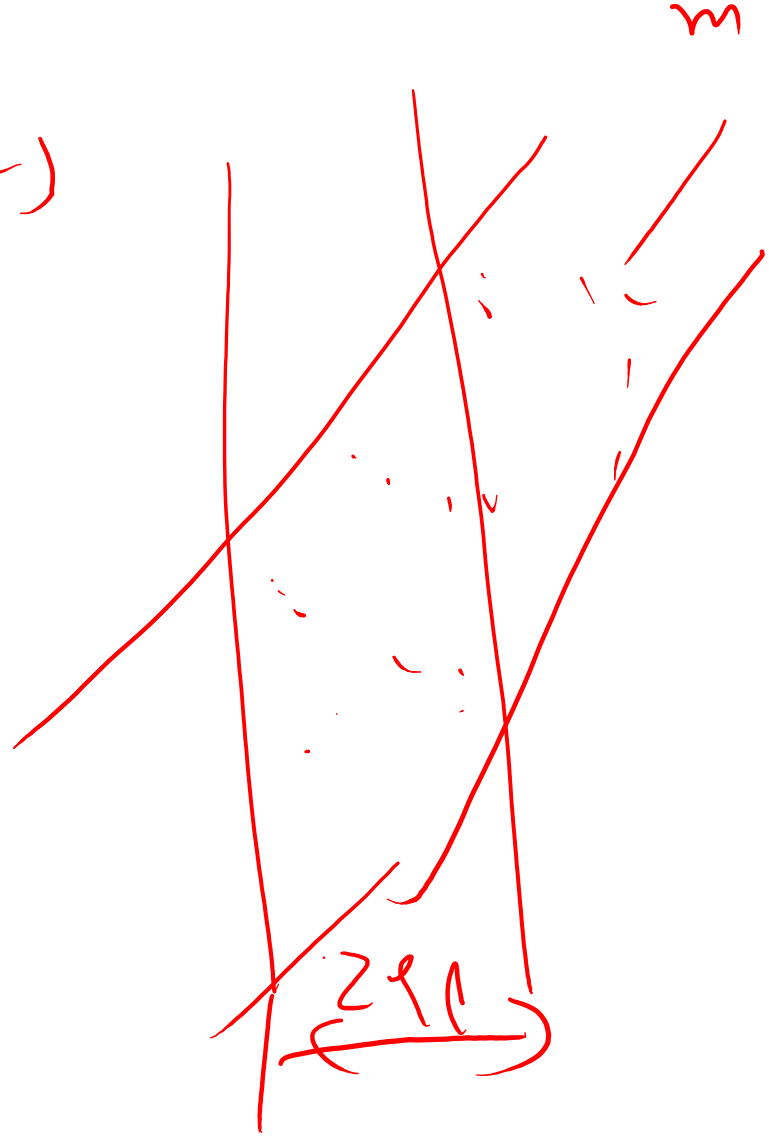

*Clad particle Projected Area*

# Power Attenuation

- Laser power absorption can be attributed to following phenomena (figure 1):
- Laser beam power reaching directly to the substrate (P1)
- Pre-heating of powder particles entering the beam (P2)
- Fraction of laser beam reaching directly to the substrate gets reflected and comes in contact with the powder particles, and fraction of that will get absorbed (P3)

$$P_1 = ?$$

$$P_1 = \beta_s (P - P_{att})$$

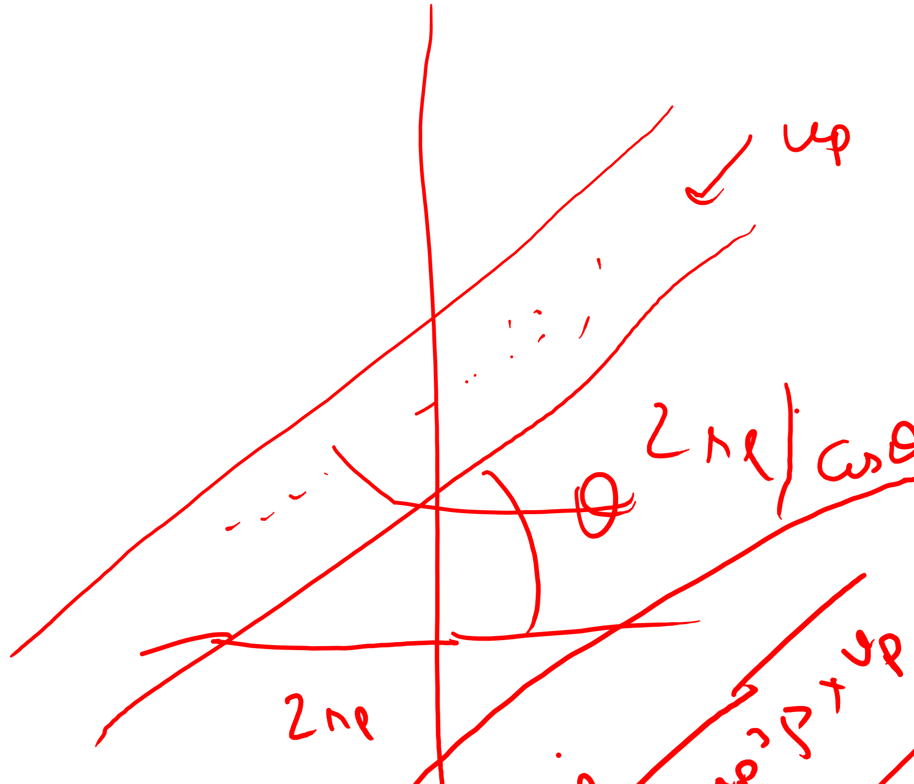


$n$ = no. of particles / length

$\dot{m} = \rho \times \frac{4}{3} \pi r_p^3 \cdot n \times u_p$

$$n = \frac{\text{no. of particles}}{l}$$

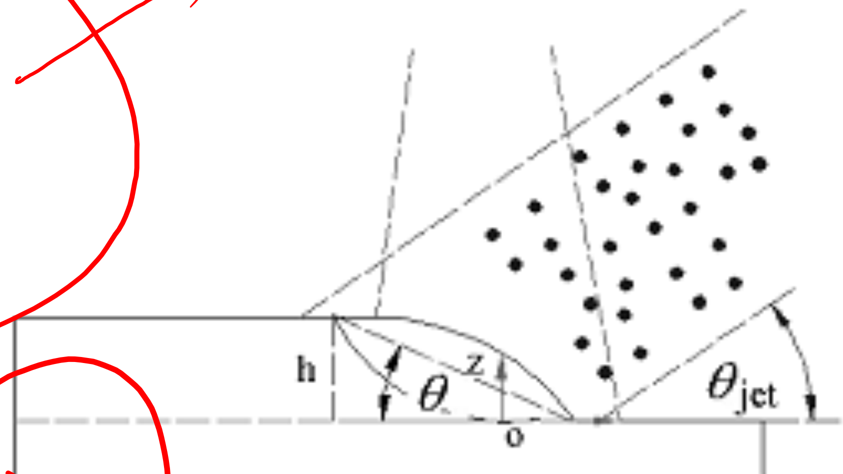
$$n \times \frac{2 r_l}{\cos\theta} \times \frac{\pi r_p^2}{\pi r_l^2}$$




$$\dot{m} = \rho \, \frac{4}{3} \pi r_p^3 \times u_p \times n$$

$$n = \frac{\dot{m}}{\frac{4}{3} \pi r_p^3 \rho \times u_p}$$

# Power Attenuation




$$\frac{P_{atten}}{P_{laser}} = \frac{\dot{m}}{4/3\,\pi r_p^3 \times \rho \times v_p} \times \frac{2 r_l}{\cos\theta} \times \frac{\pi r_p^2}{\pi r_l^2}$$

$$\frac{P_{att}}{P_{laser}} = \frac{\dot{m}_p}{2\rho r_l r_p v_p \cos\theta_{jet}}, if\ r_{jet} < r_l$$

$$= \frac{\dot{m}_p}{2\rho r_{jet} r_p v_p \cos\theta_{jet}}, if\ r_{jet} \geq r_l$$

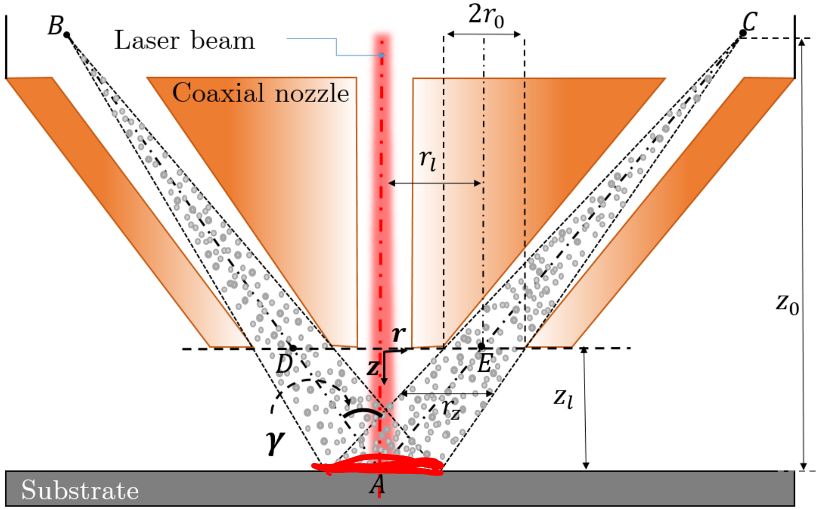
$$\frac{P_{atten}}{P} = \frac{3\dot{m}}{2\pi \rho r_l r_p v_p \cdot \cos\theta}$$

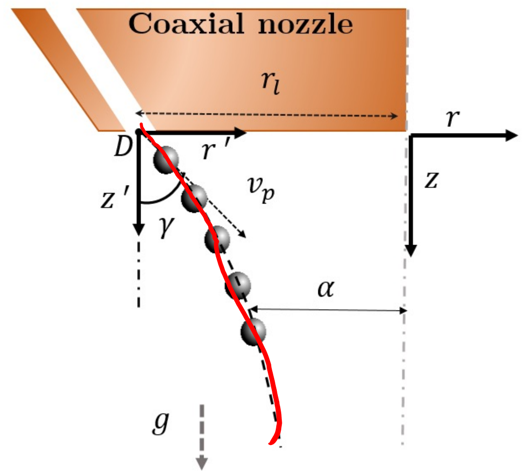
$\beta_1 = (P - P_{atten})\beta_3$

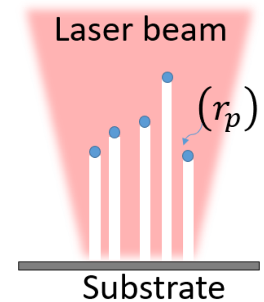
$\beta_2 = P_{atten} + \beta_p$

$\beta_3 = (1-\beta_3)(P - P_{atten}) + \beta_p \left(\frac{P_{atten}}{P}\right)$

# Powder flux modeling of Laser DED Process



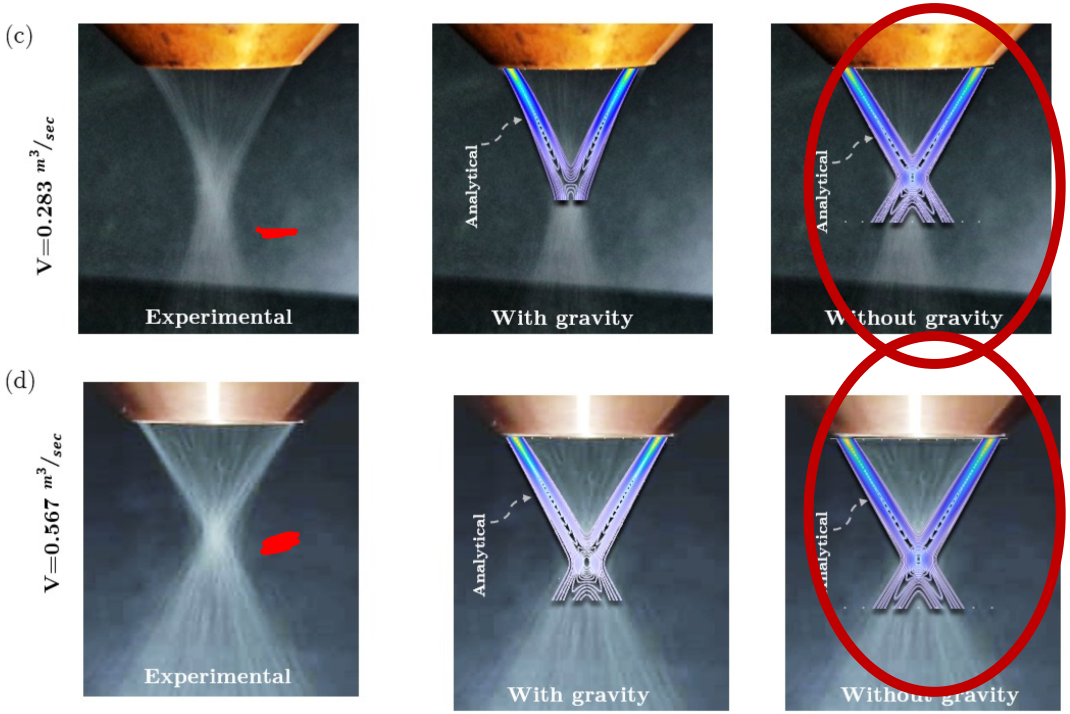

$$z' = r' \cot\gamma + \frac{g(r')^2}{2{v_p}^2 \sin^2\gamma}$$

$$r' = \frac{v_p^2 \sin^2\gamma}{g}\left[\cot\gamma - \sqrt{\cot^2\gamma + {2gz' \operatorname{cosec}^2\gamma}/{v_p^2}}\right]$$

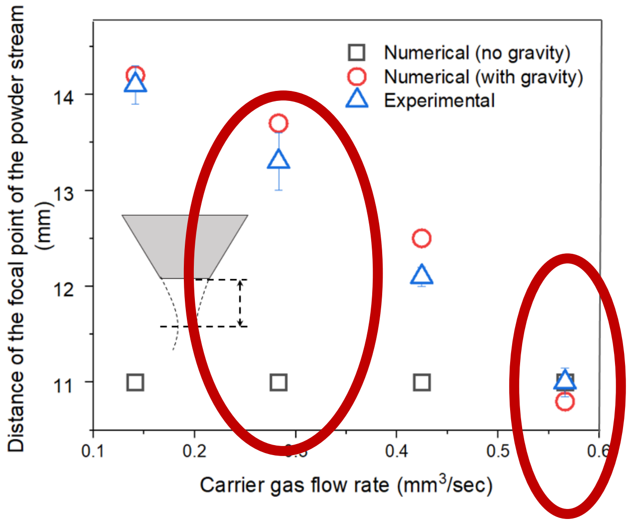
$$\alpha = r_l + \frac{v_p^2 \sin^2\gamma}{g}\left[\cot\gamma - \sqrt{\cot^2\gamma + {2gz \operatorname{cosec}^2\gamma}/{v_p^2}}\right]$$

$$J = \left[\frac{\dot{m}}{\pi r_z^2} \exp\left(-\frac{2(\alpha - r)^2}{r_z^2}\right) + \frac{\dot{m}}{\pi r_z^2} \exp\left(-\frac{2(\alpha + r)^2}{r_z^2}\right)\right]$$

# Powder Flow Visualization

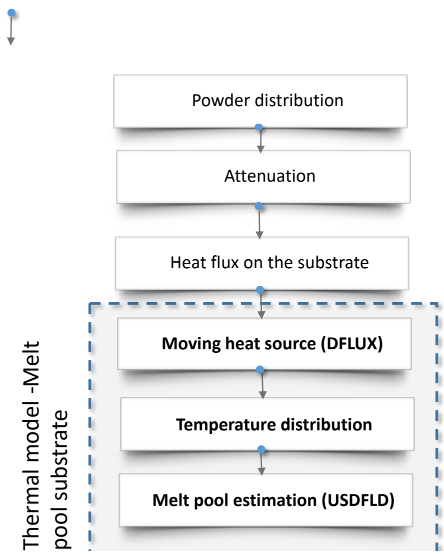


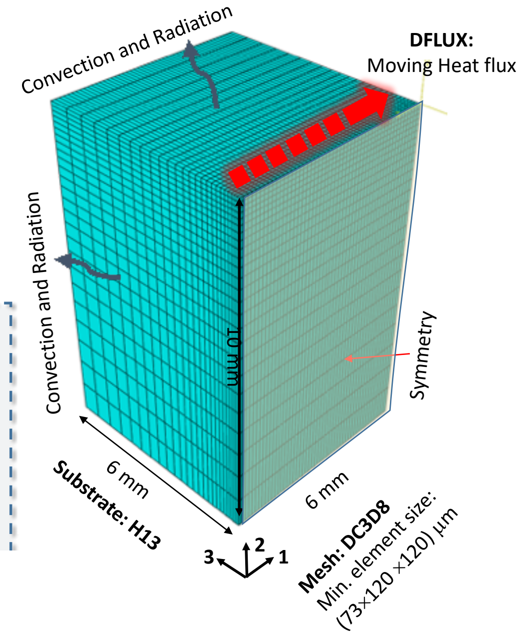

Effect of gravity is prominent at low speeds

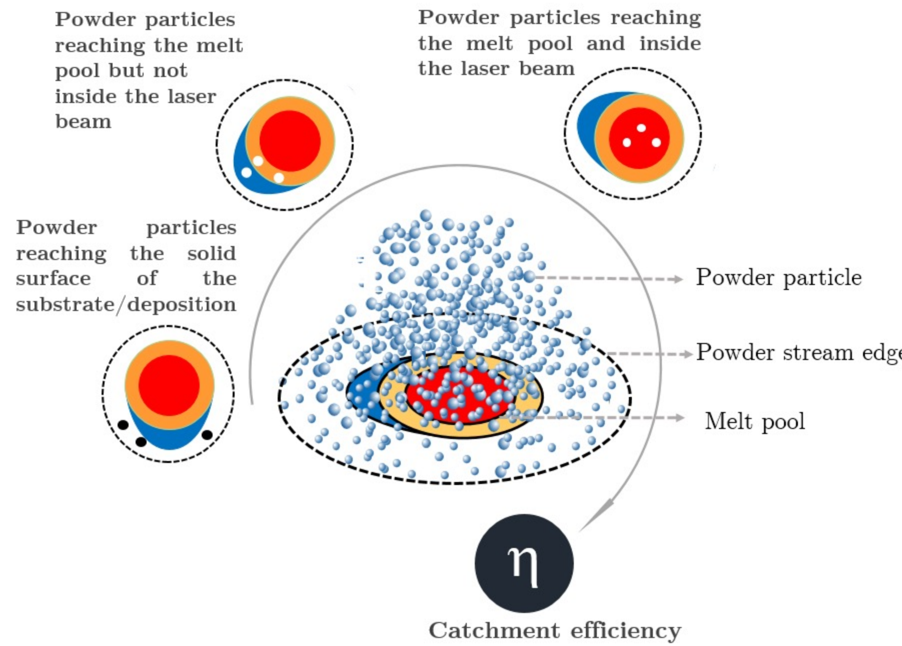


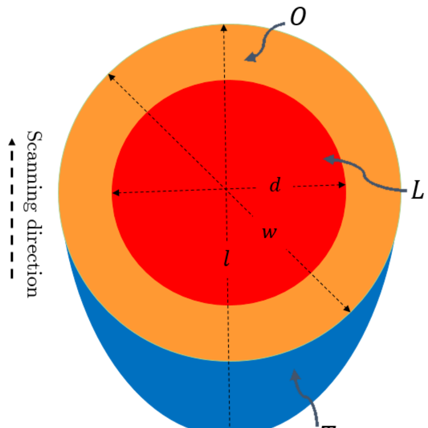

Effect of gravity is countered by increased drag at high speeds

# Melt Pool & Catchment




$$P_a/P = \frac{3}{4r_p\rho_p}\int_0^{z_l}\int_0^{d/2}\frac{J}{v_{pz}}dz\,rdr$$

$$v_{pz} = \frac{V\cos\gamma}{4\pi r_l r_0}\left(\frac{r_0}{r_z}\right)^2$$

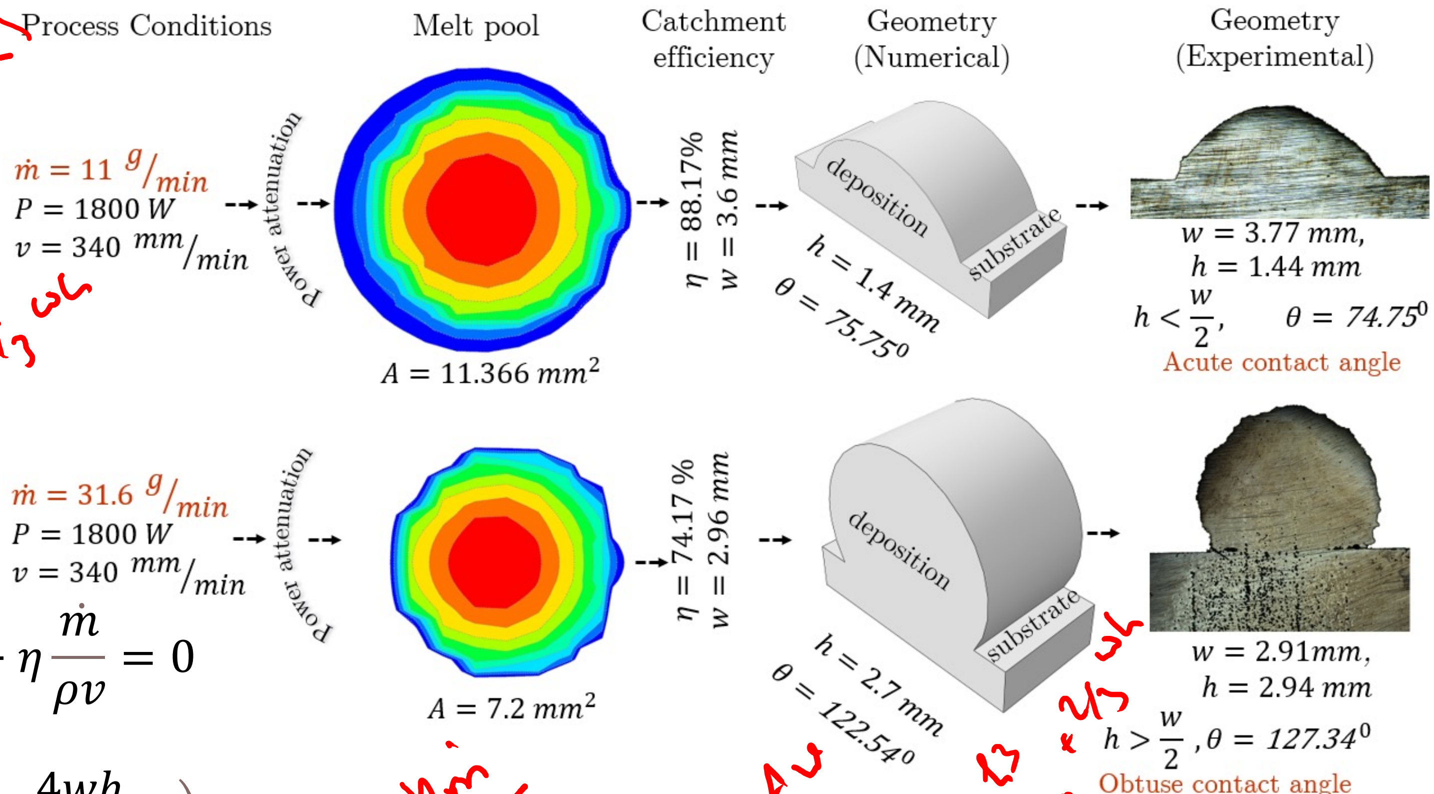
$$A_m = \frac{\pi wl}{4}$$

# Geometry & Contact Angle of Deposition

$\frac{h^3}{2w} + \frac{2}{3}wh$

$\eta \dot{m} = \rho . A . v$

$A = \frac{h^3}{2w} + \frac{2}{3}wh$




$$\frac{h^3}{2w} + \frac{2}{3}wh - \eta\frac{\dot{m}}{\rho v} = 0$$

$$\theta = \pi - sin^{-1}\left(\frac{4wh}{w^2 + 4h^2}\right)$$

$$if\ ^{w}/_{2} \leq h$$

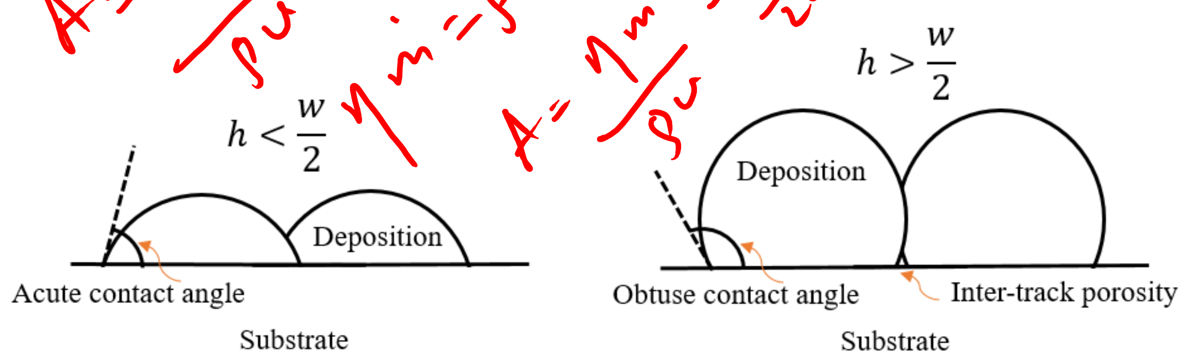
$$else$$

$$\theta = sin^{-1}\left(\frac{4wh}{w^2 + 4h^2}\right)$$

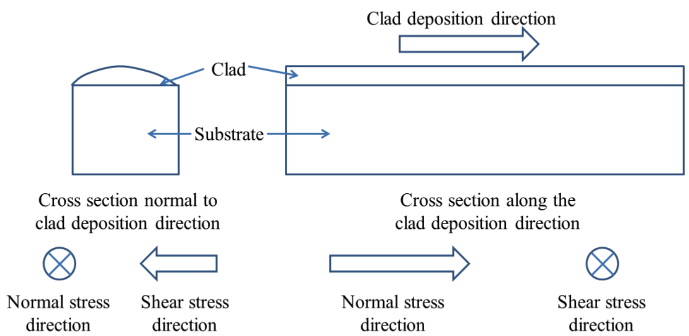
$A = \frac{\eta \dot{m}}{\rho v}$

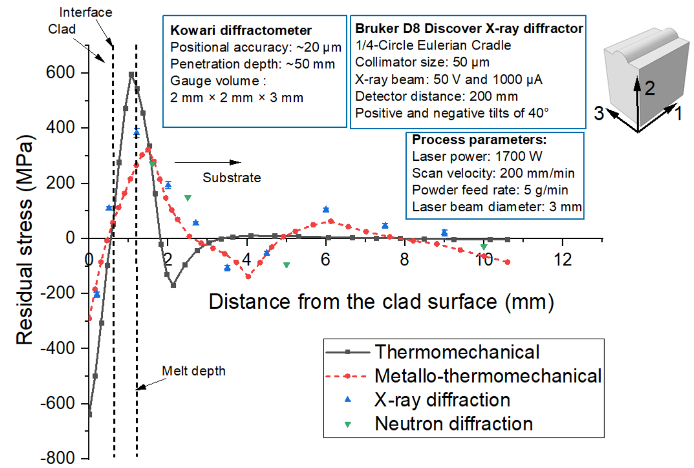
$\eta \dot{m} = \rho A v$

$A = \frac{\eta \dot{m}}{\rho v} = \frac{h^3}{2w} + \frac{2}{3}wh$

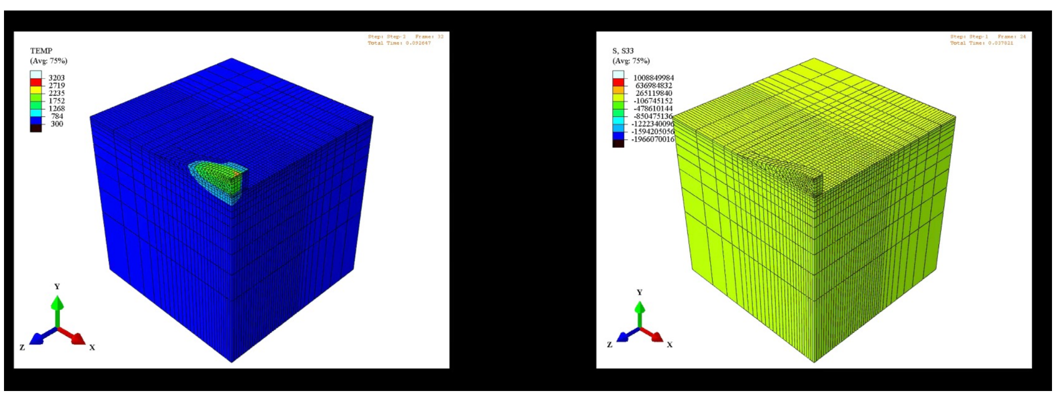


# Residual Stress Evolution



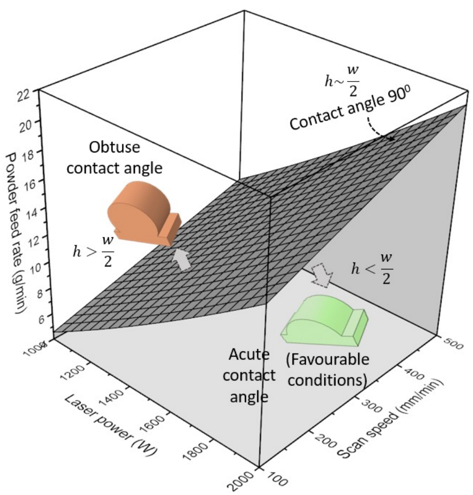



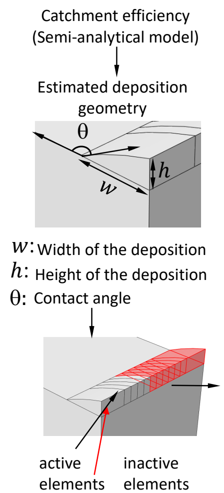

Direction of residual stress measurement

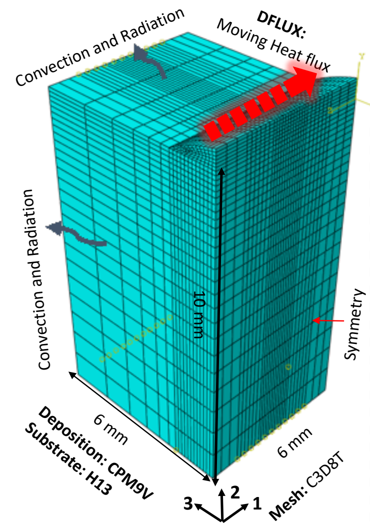


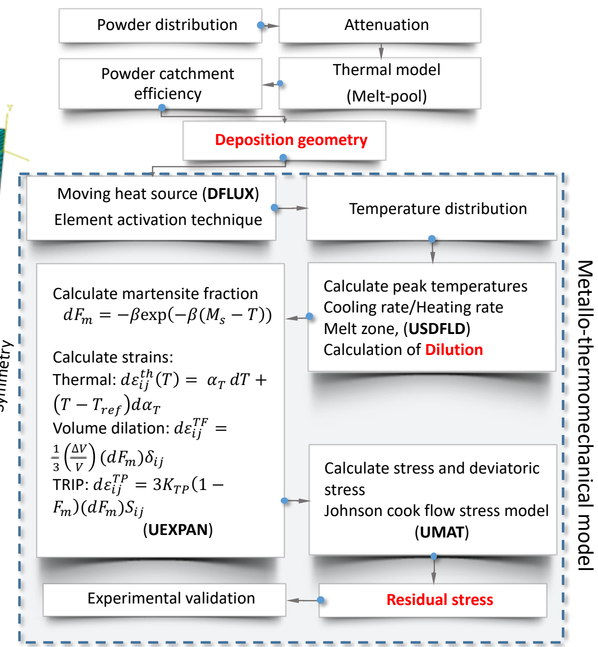
Contour of residual stress along normal direction

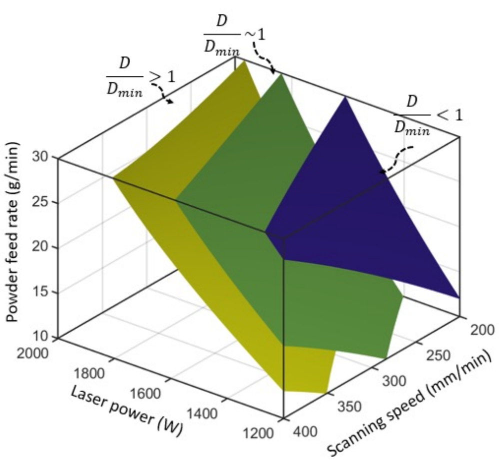
# Process Maps for favorable depositions in single track

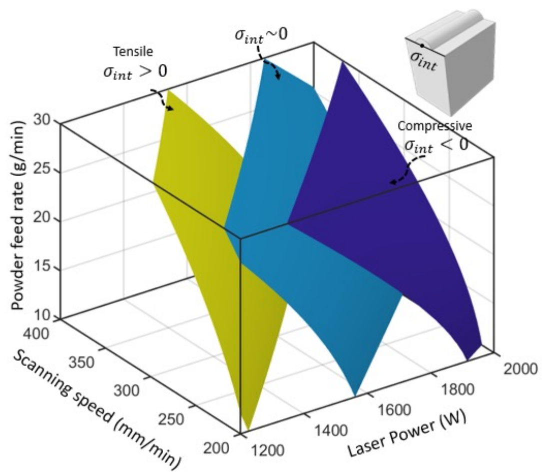


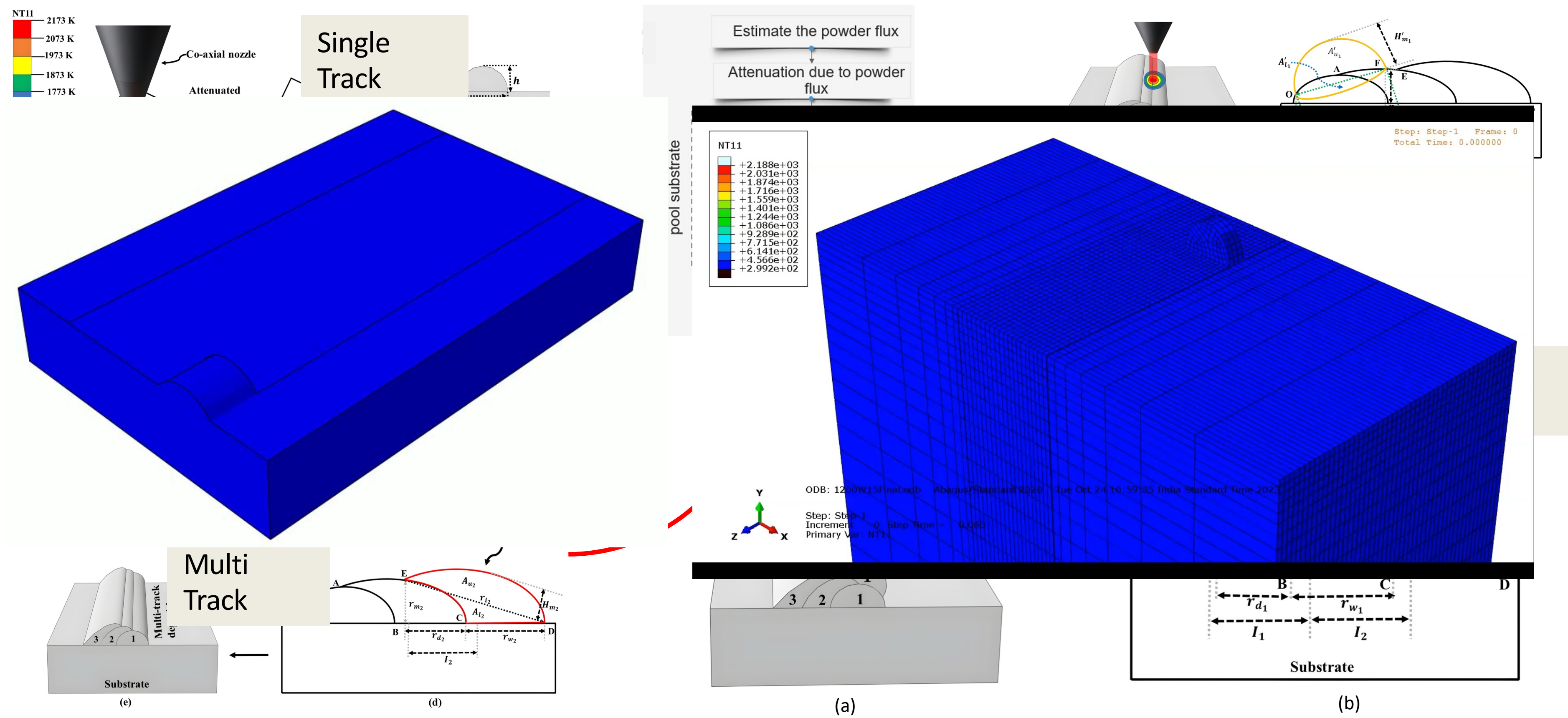




Vundru et al., International Journal of Mech. Sci

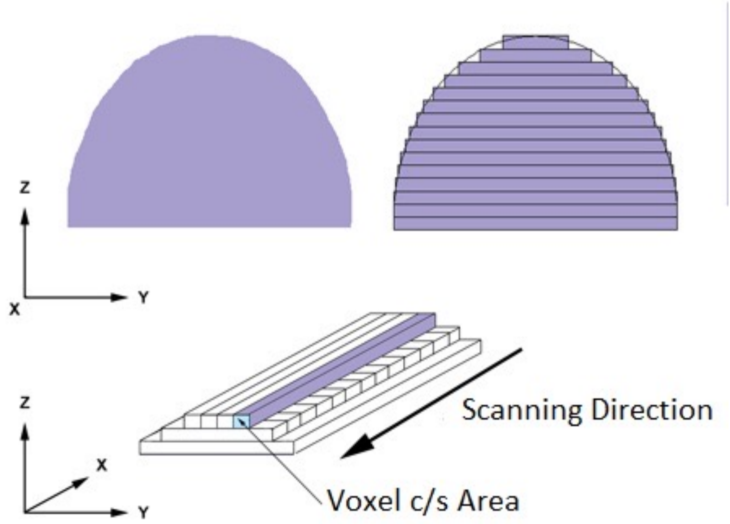
# Analytical-FEM Multi-Track Multi-Layer Deposition



# APPLICATIONS

- Surface properties enhancement
- Component repair
- Rapid prototyping
- Functionally graded components

Parts repair (Toyserkani et al., 2005)




*Rapid prototyping*
http://lastanzadellemeraviglie.nova100.ilsole24ore.com

*Turbine wheels repair(Rombouts et al, 2006)*