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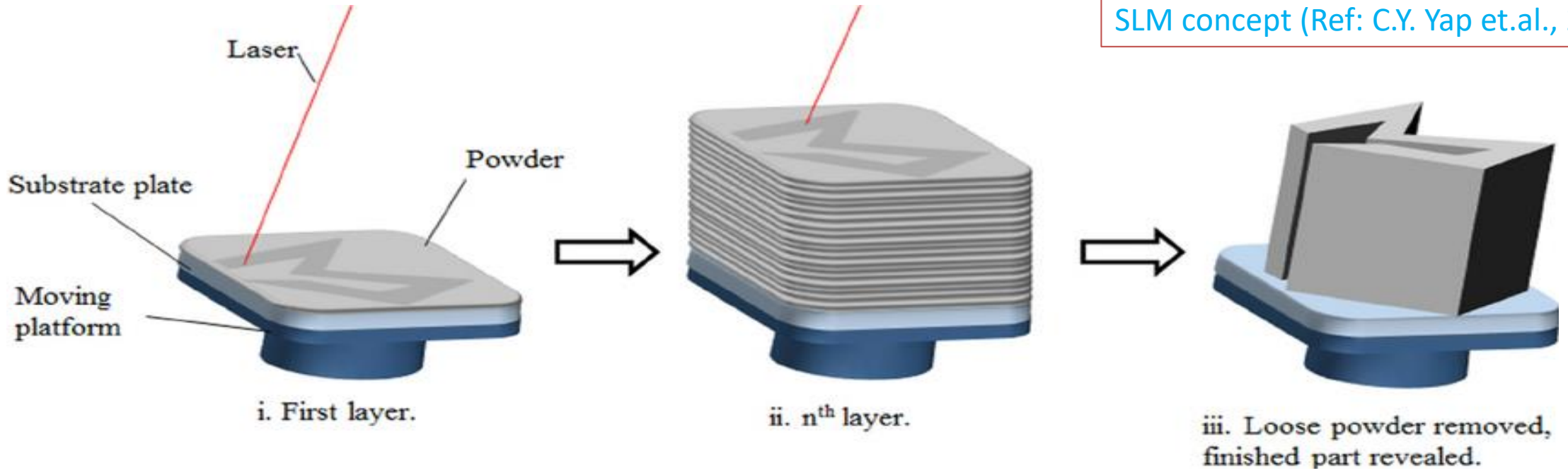


**NUS**  
National University  
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**COMSOL  
CONFERENCE  
2019 BOSTON**

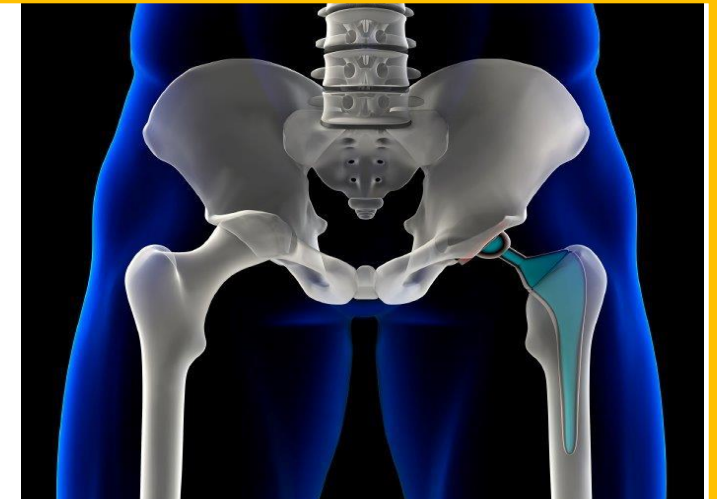
Finite elements modelling and simulation tools to investigate Selective Laser Melting process and materials 3D-printed.

# Introduction to SLM process

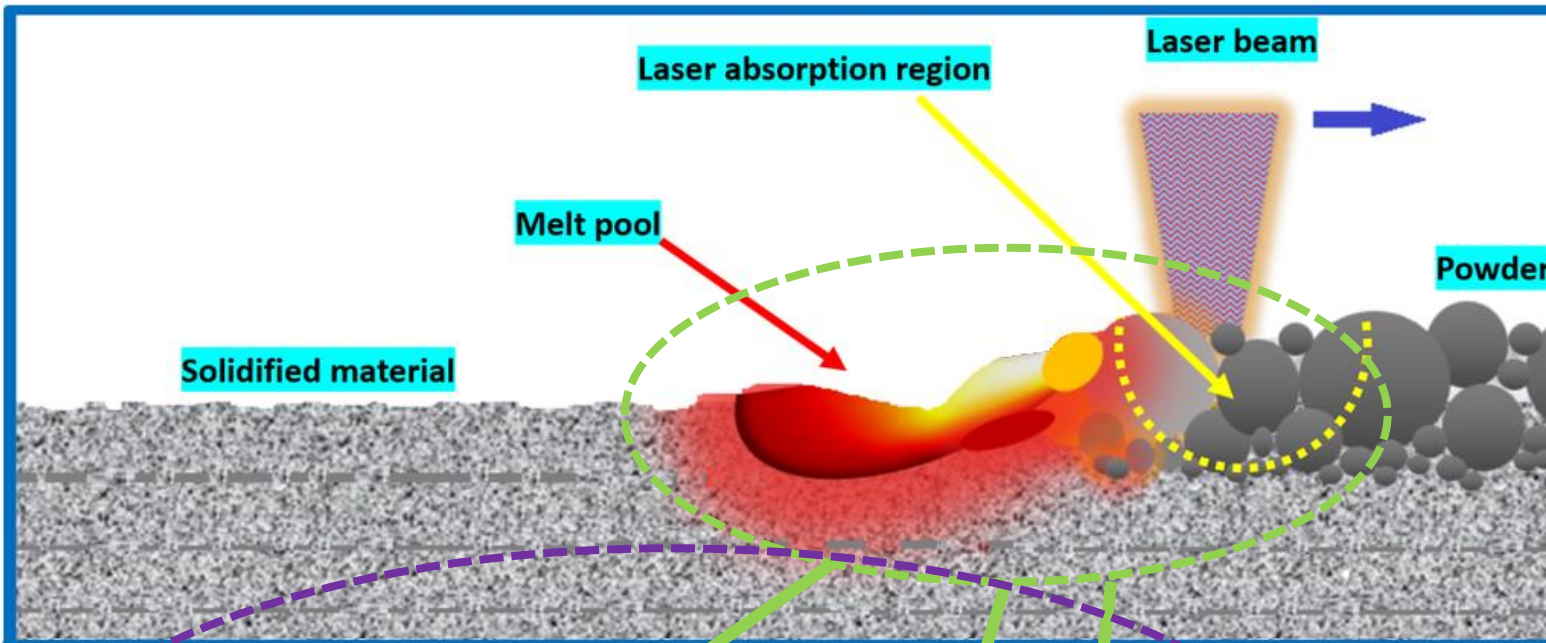


SLM concept (Ref: C.Y. Yap et.al., 2005)

SLM applications ...flexibility in design



# Introduction to SLM process



❑ Difficult / impossible to measure accurately some process parameters with currently available technologies

❑ Expensive experiment: try-and-error method is not favored

❑ **Simulation is an important tool**

Model of laser absorption

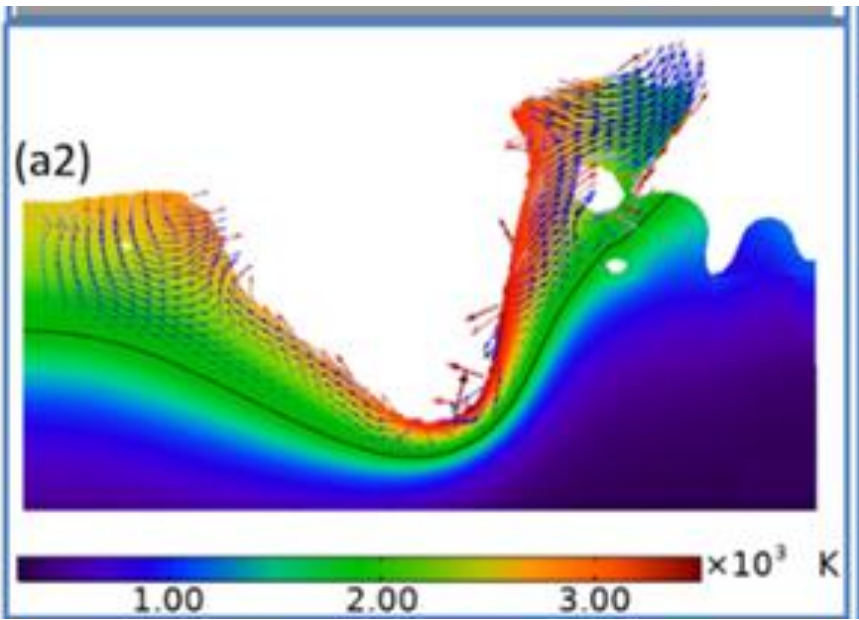
Model of T-profile estimation

Model of mass transfer

The use of the simulation model in real engineering situation

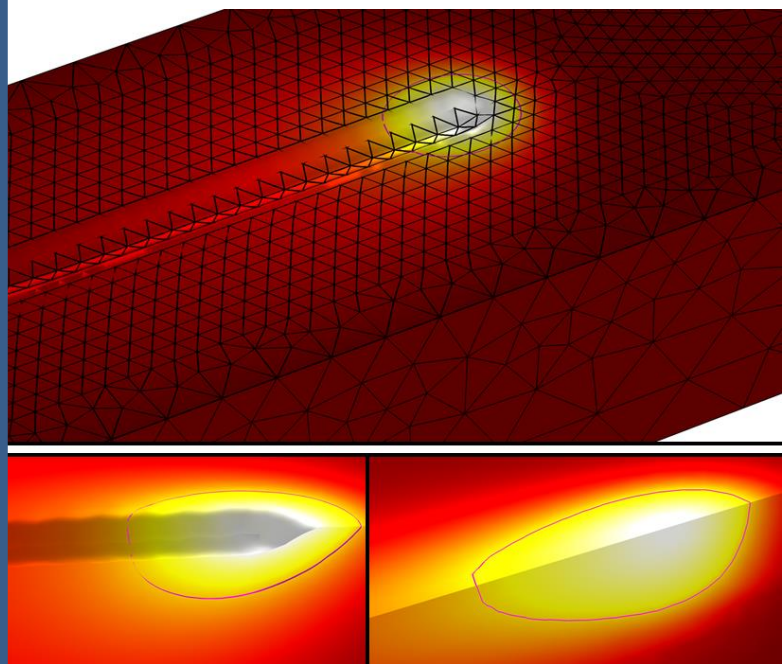
# Introduction: Different levels of approximation

Approximate the granular nature of powder



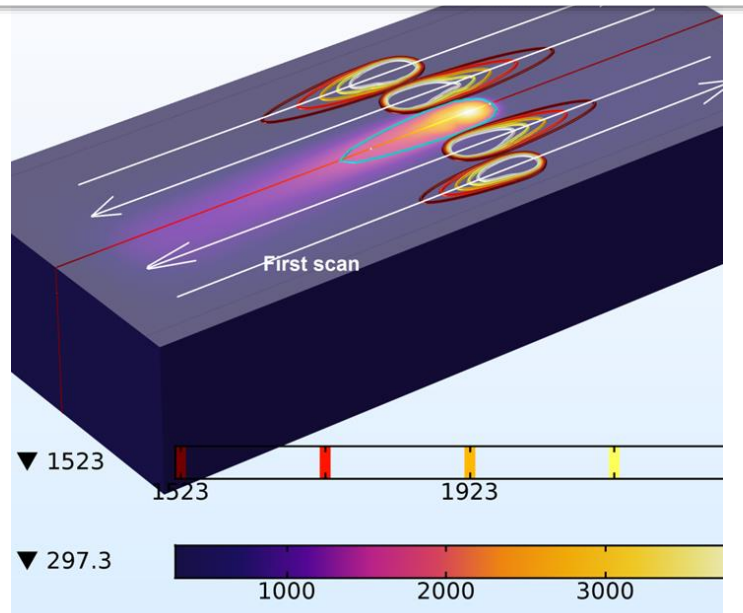
- High computation cost/time
- Differ from real powder bed
- Particular case
- Good for studying porosity or roughness of printed parts

Deformed geometry-moving mesh



- High computation cost/time
- Generalized study
- Good for studying roughness of printed parts

Indirect modelling of volume shrinkage and mass transfer without geometry change

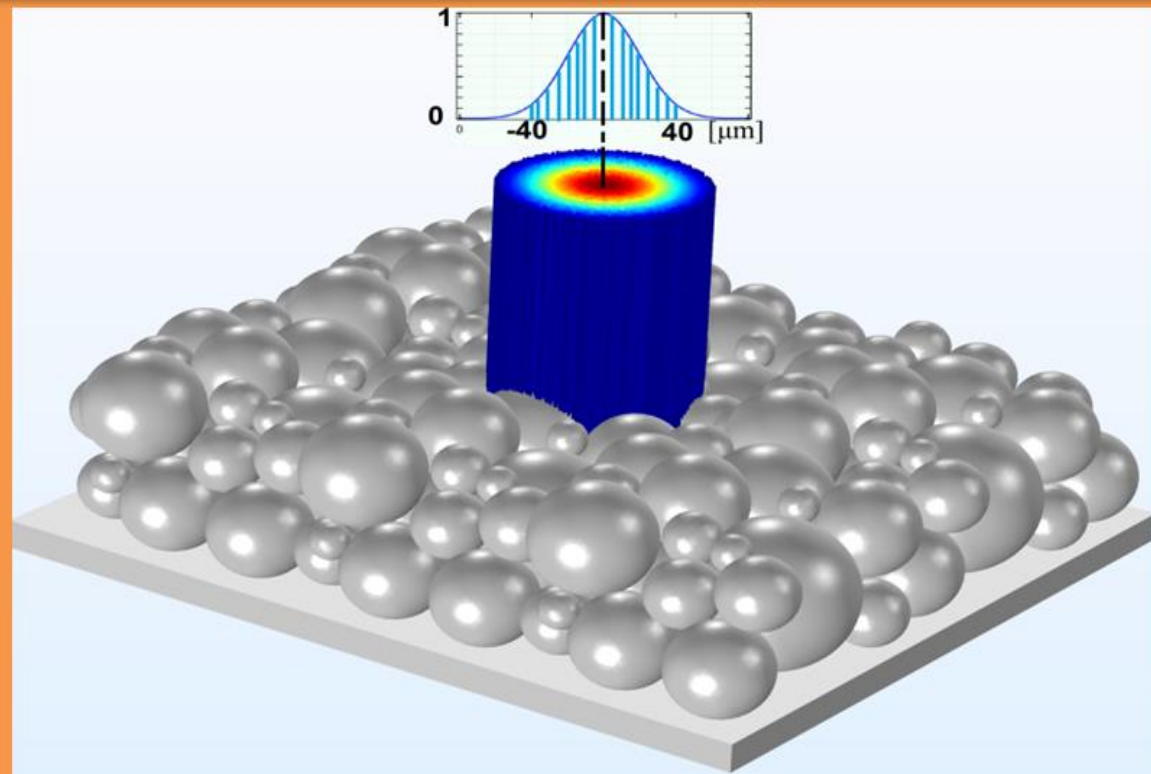


- Low computation cost/time
- Generalized printing quality
- Melt pool size, cooling curve, scanning patterns, multiple layers...
- Adjust the size of powder layer and printed layer

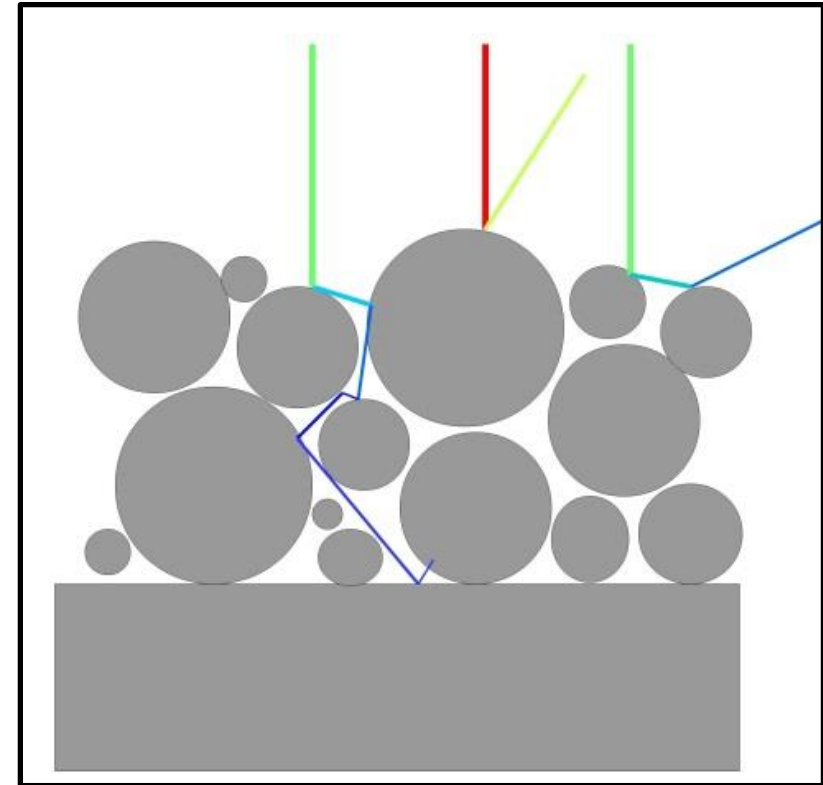
**Simulated temperature-profile is comparable in the 3 approximations**

# 1. Laser absorption: Ray-tracing

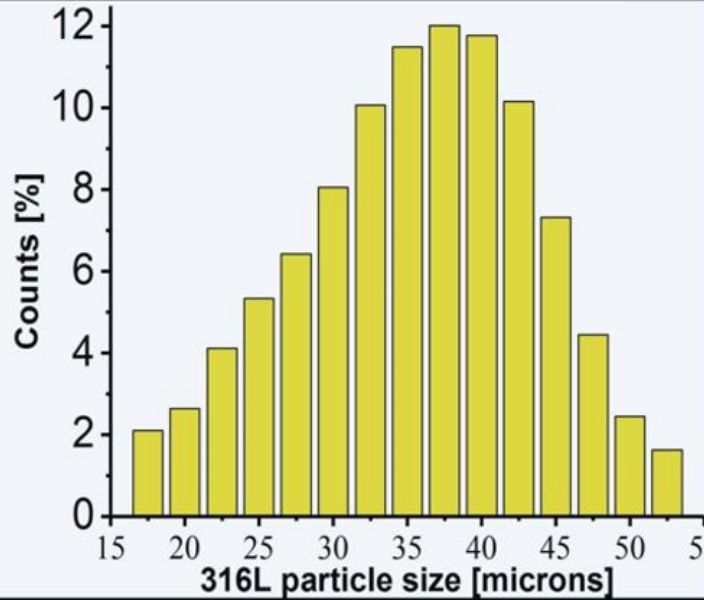
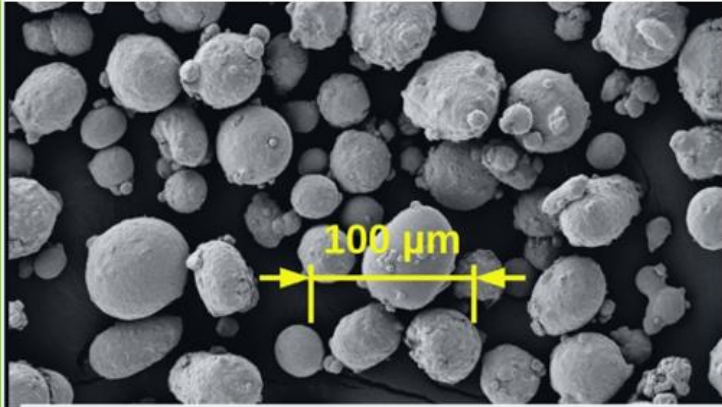
Real powder, real static beam



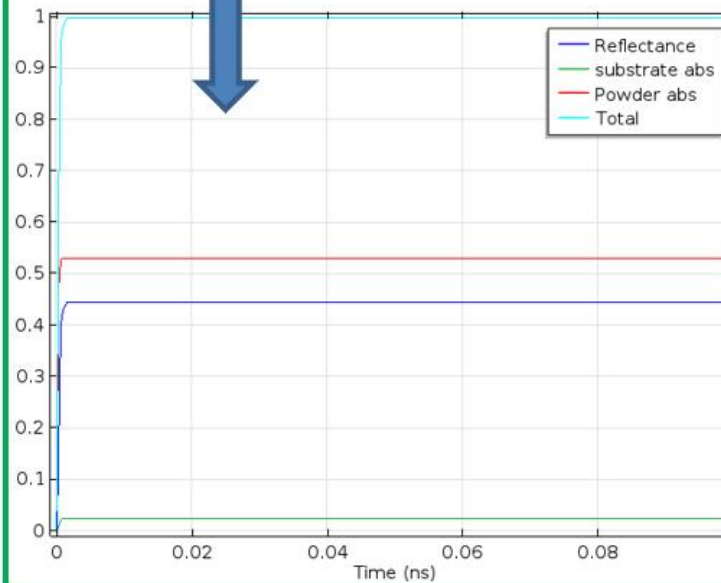
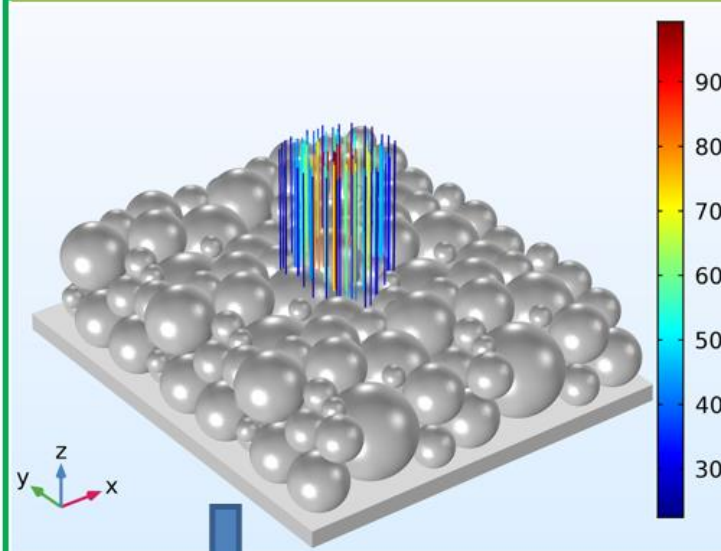
Illustration



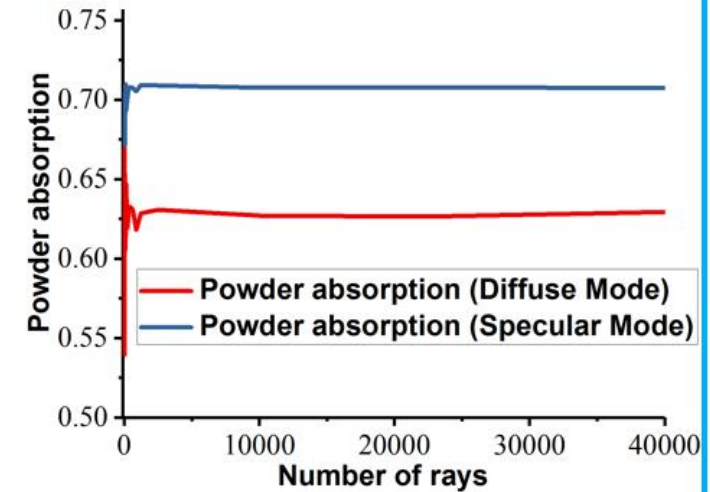
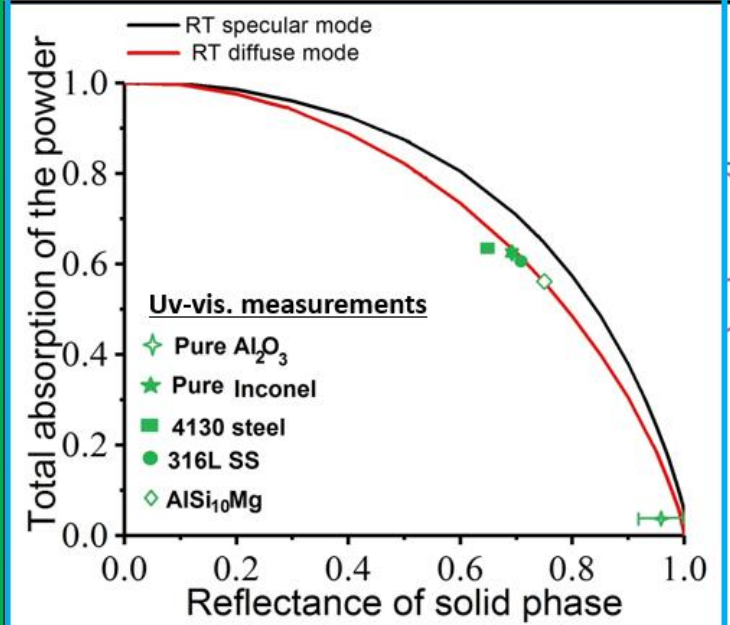
### Powder data



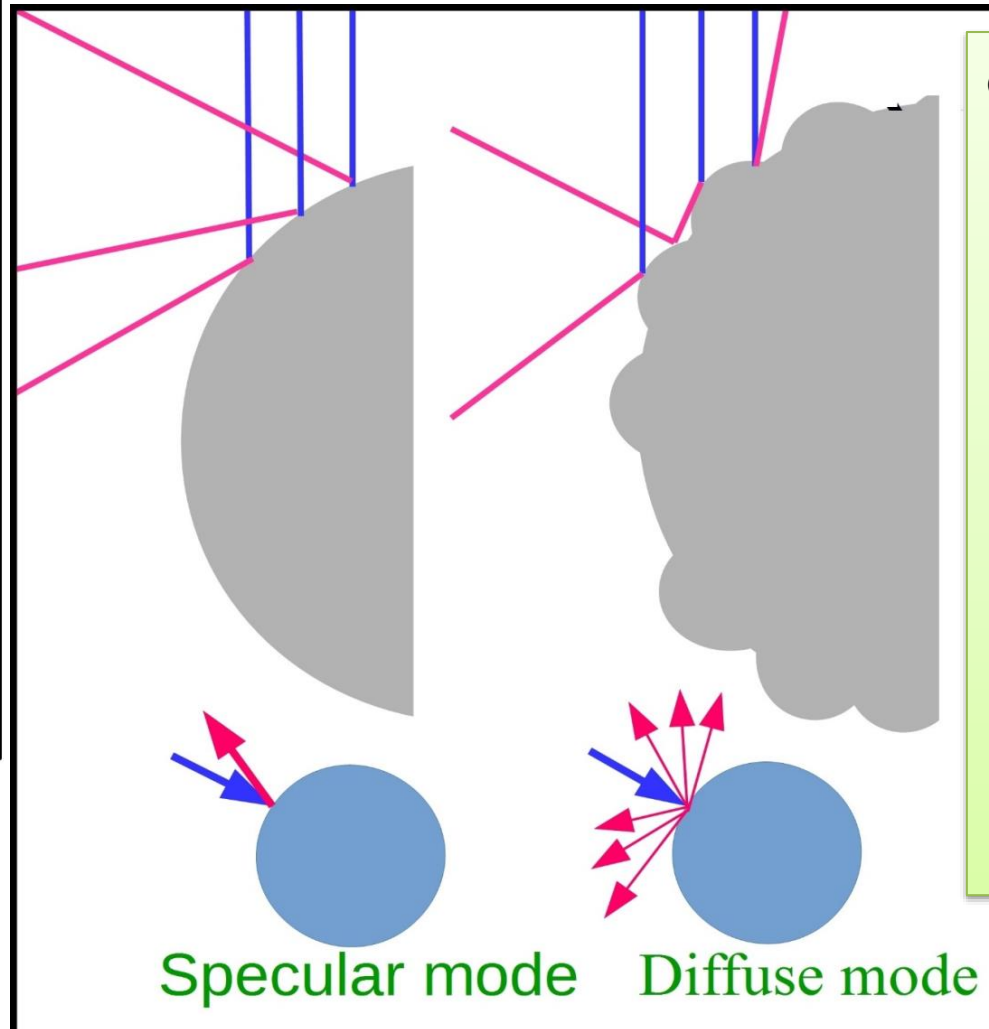
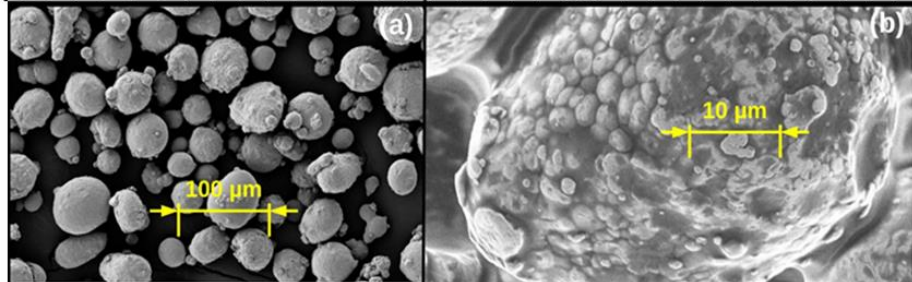
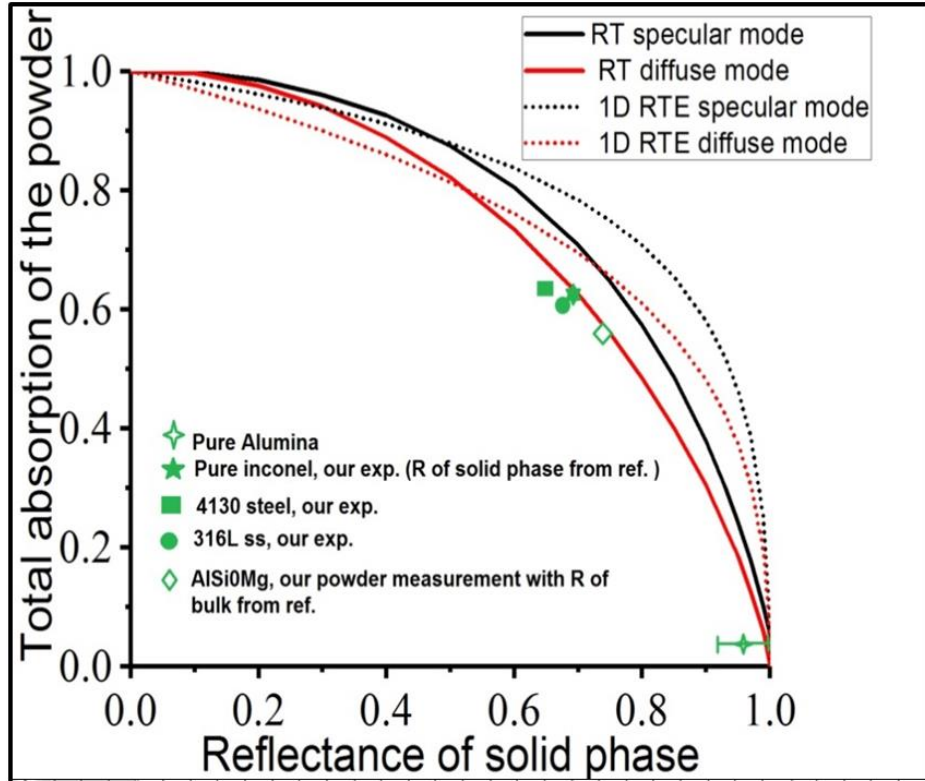
### Absorption from COMSOL ray-tracing



### Results and stability



# Ray-tracing vs analytical solution of the Radiation Transfer Equation (RTE)



Comparison of total absorption obtained by RT, 1D-RTE and experiment: High resolution SEM image of commercial powder used in SLM reveals **non-mirror-like** surface of powder particles justifying the **deviation from specular reflection**

## 2. Model of T-profile estimation

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u \cdot \nabla T - \nabla(k \nabla T) = Q \quad \text{Heat transfer}$$

$$k \left[ \frac{\partial T}{\partial z} \right]_{z=H} = \varepsilon \sigma (T_o^4 - T^4(x, y, H, t)) + h(T_o - T(x, y, H, t))$$

$$T(x, y, z, t)|_{t=0} = T_o$$

Mass transfer

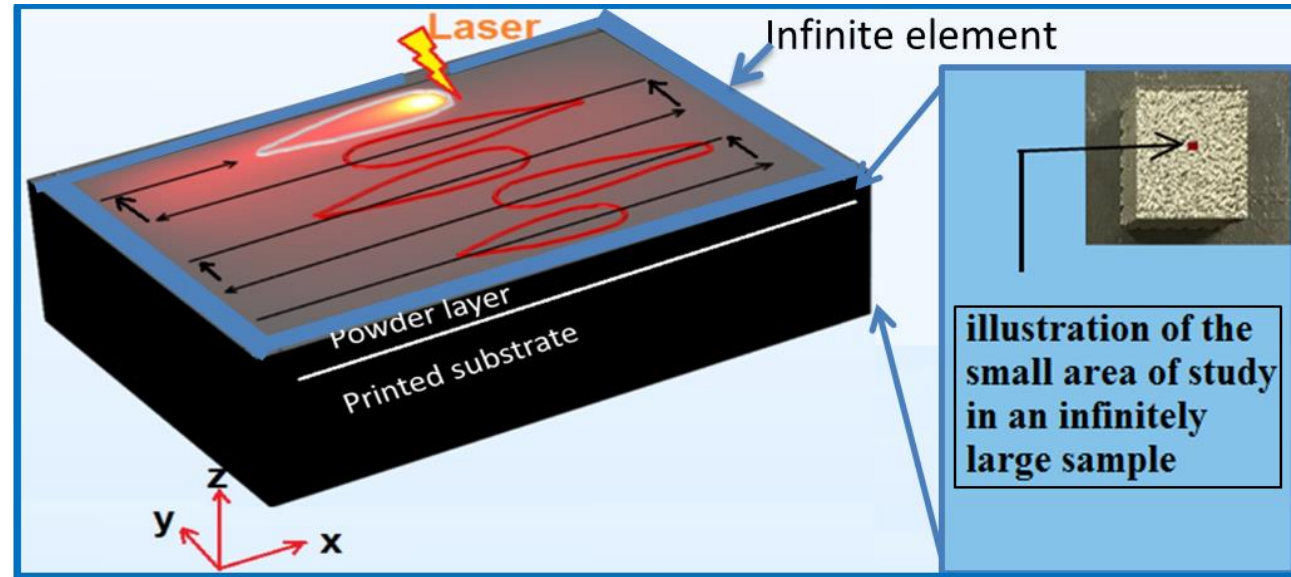
$$\begin{cases} \rho \frac{\partial u}{\partial t} + \rho(u \cdot \nabla)u = \nabla[-P\mathbf{I} + \mu((\nabla u + (\nabla u)^T))] + \rho g + \mathbf{F} \\ \rho \nabla \cdot (u) = 0. \end{cases}$$

Laser energy source from Ray-tracing and distribution

$$Q = (\alpha_A) \frac{2P}{\pi l (\alpha_r r)^2} \exp \left\{ \frac{2[(x-p_1(t))^2 + (y-p_2(t))^2]}{(\alpha_r r)^2} \right\} \times \mathbf{u}(z)$$

From Ray-tracing

- $F^{Marangoni} = \nabla_s \gamma$ ,  $\gamma = \gamma_0 + \frac{d\gamma}{dT} (T - T_{ref})$
- Recoil pressure during vaporization



Note: Immediate coupling of ray-tracing

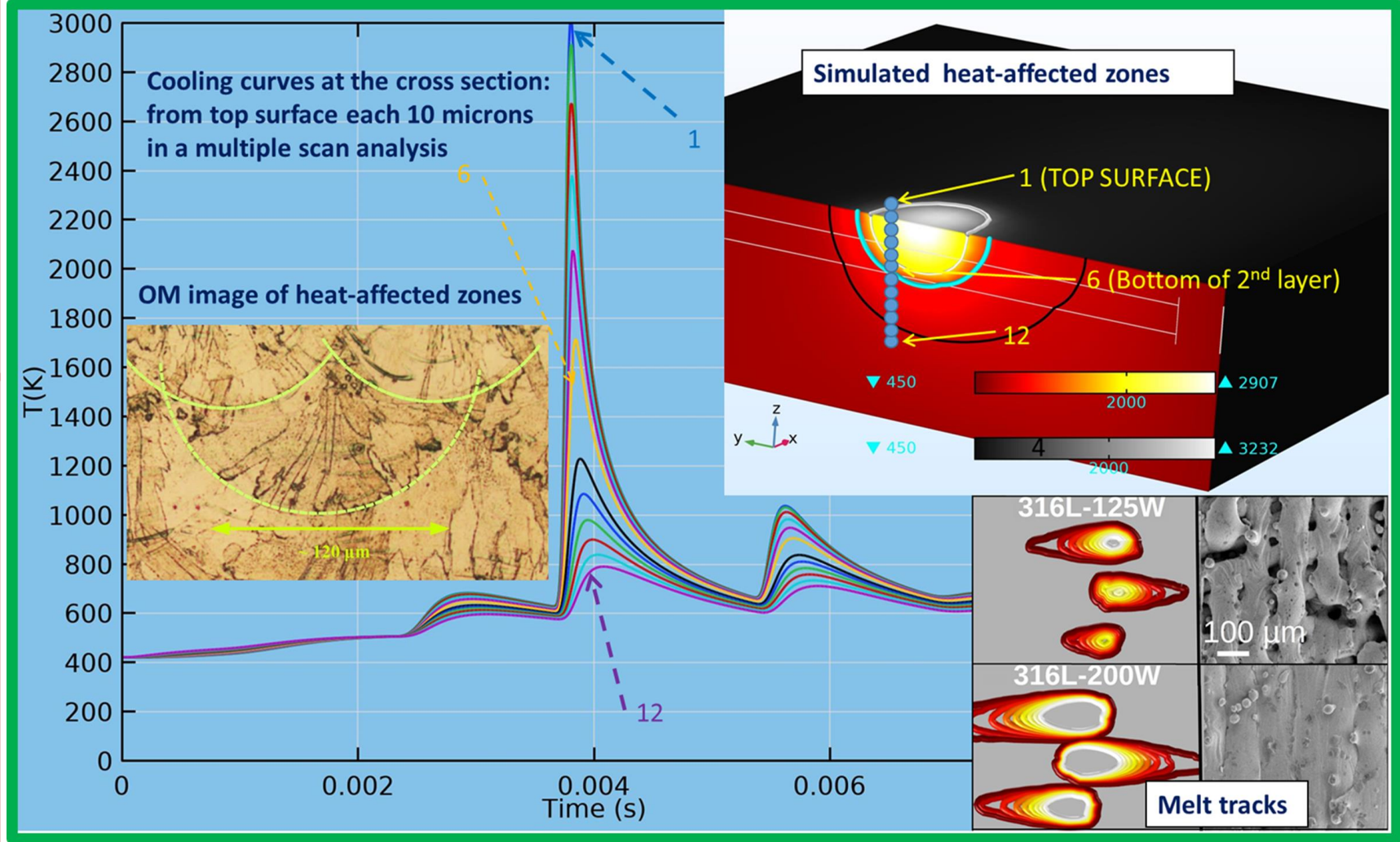
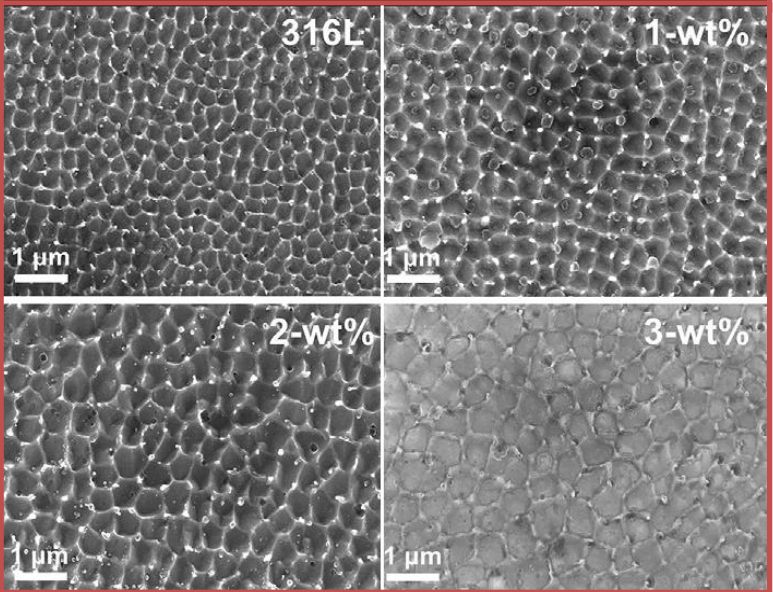
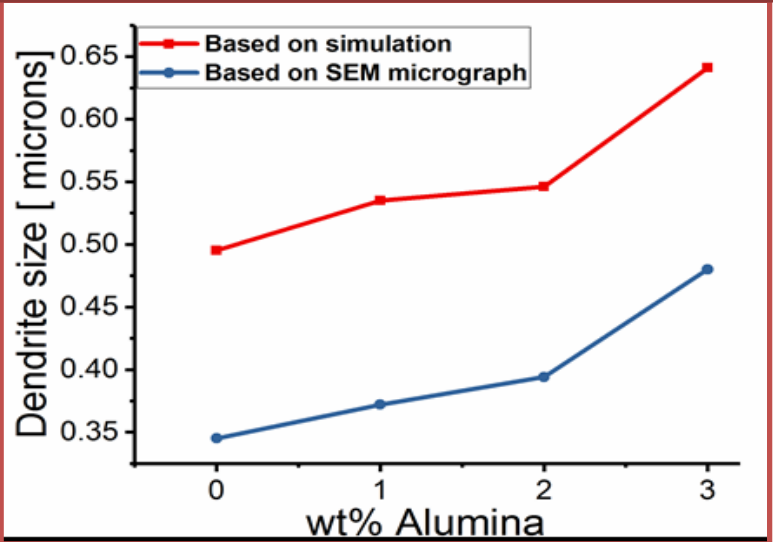


# 3. COMSOL setting

The screenshot displays the COMSOL Multiphysics software interface. On the left is the 'Component 1 (comp1)' tree view, where the 'Heat Transfer in Solids (ht)' node is expanded and highlighted with a red box. Below it, the 'Laminar Flow (spf)', 'Domain ODEs and DAEs (dode)', and 'Multiphysics' nodes are also highlighted with a red box. The central panel shows the 'Study 1/Solut' data set and 'All' time selection. The 'Plot Settings' section is expanded, showing 'x-axis label: Time (s)' and 'y-axis label: T(oC)'. The 'Axis' section shows 'Manual axis limits' with values: x minimum: -1.22263E-4, x maximum: 0.00776, y minimum: 131.59997, and y maximum: 1016.23428. The 'Grid' section is expanded, showing 'Show grid' checked and 'Manual spacing' unchecked with x and y spacing both set to 1. On the right is a 1D line plot of Temperature T(oC) versus Time (s). The plot shows four curves (blue, green, red, cyan) that rise from 150 oC at 0 s to a peak of approximately 375 oC at 0.001 s, then drop to a minimum of about 260 oC at 0.0025 s, followed by a sharp rise to a second peak of about 940 oC at 0.0025 s, and a final peak of about 775 oC at 0.004 s. The plot area is titled 'T(oC)' and the x-axis is labeled 'Time (s)'. At the bottom, there are tabs for 'Messages', 'Progress', 'Log', and 'Evaluation 3D', and the version number 'COMSOL Multiphysics 5.4.0.388' is visible.

# 3. Some examples using SLM simulation

316L-Alumina composite: control of grain size



# 4. COMSOL App – Multiple scanning lines

Untitled.mph - MULTISCAN App

Setting window for input parameters

Equipment parameters

- Laser power: 250 W
- Scanning speed: 1050 mm/s
- Radius of Laser spot size: 40 um
- hatch distance: 110 um
- powder layer thickness: 60.01 um

Kinetic parameters of material

- Latent heat of fusion: 260
- Latent heat of vaporization: 6088.6
- Dynamic viscosity of pure Fe: 0.0043
- Temperature derivative of the surface tension: 0.15
- Average thermal conductivity: 12.2e-6
- Mass of evaporating molecule: 55.845

Optical properties of material

- Powder absorption: 0.623
- Surface emissivity: 0.785

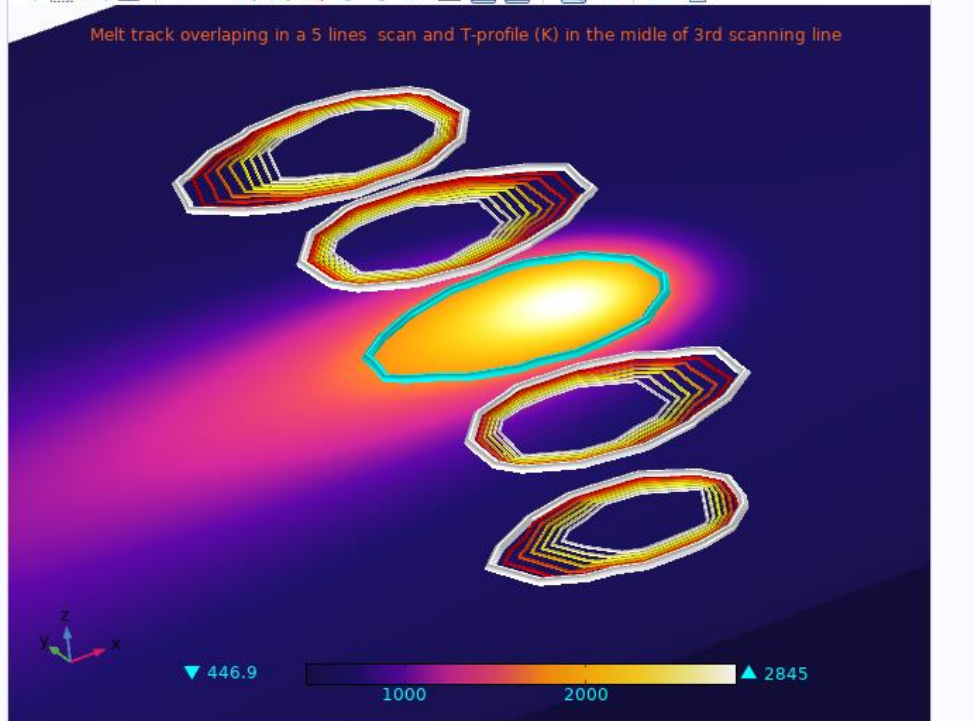
Thermal properties of material

- Melting T: 1450+273[K] K
- Solidous T: 1385+273[K] K
- Evaporization temperature: 3020 K

Results

Meltpool tracks Cooling curve

Melt track overlapping in a 5 lines scan and T-profile (K) in the middle of 3rd scanning line

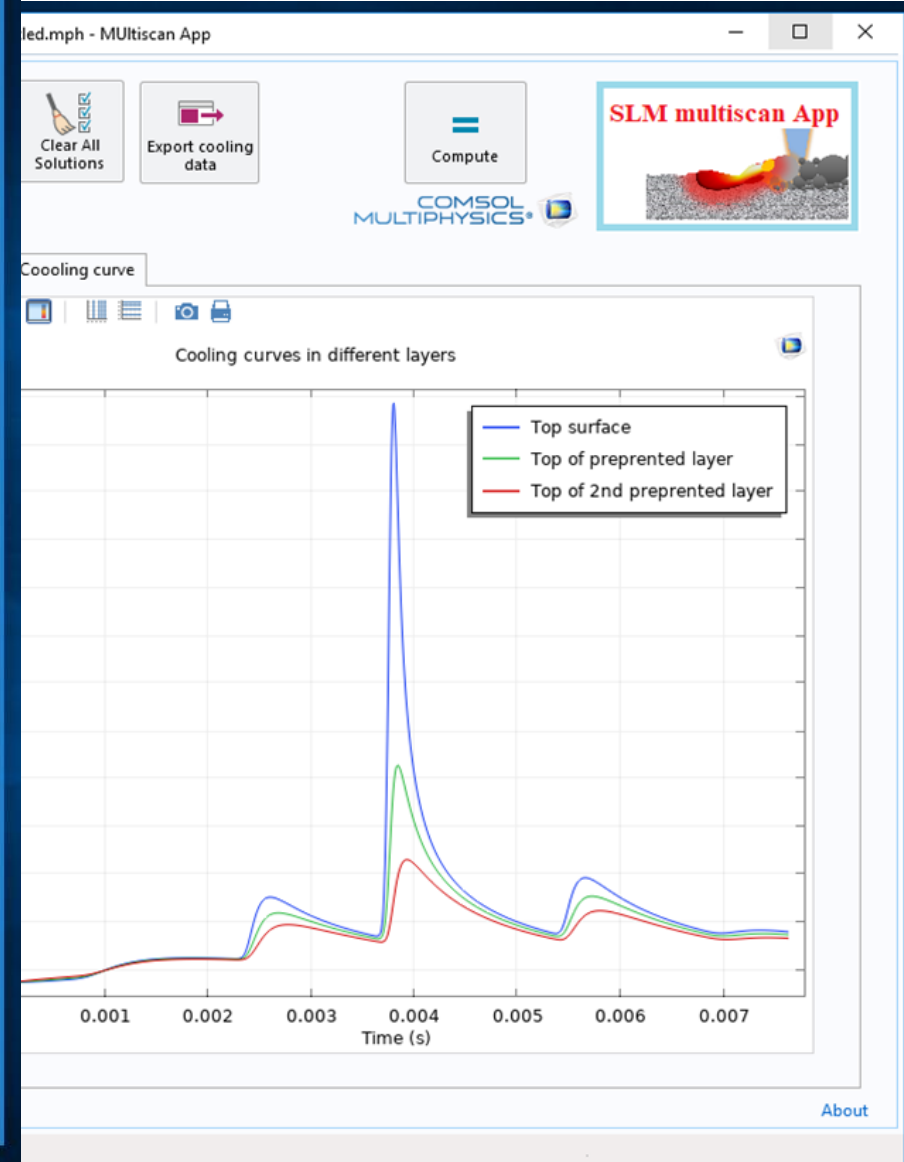


COMSOL MULTIPHYSICS

SLM multiscan App

Reset parameters Clear All Solutions Export cooling data Compute

About



# COMSOL App – Single scan

**Note:** Melt pool size usually increases a bit from 1 to 2<sup>nd</sup> line due to heat accumulation but it normally stabilizes at the 3<sup>rd</sup> line. One should know this while using this single scan model

The screenshot displays the COMSOL App interface for a simulation titled "Untitled.mph - Metal bar laser".

**Parameters setting window:**

- Equipment parameters:**
  - Scanning speed: 750.01 mm/s
  - Radius of the laser spot size: 0.040 mm
  - Laser power: 175.01 W
  - Powder layer thickness: 60 um
- Optical properties of material:**
  - Surface emissivity: 0.43
  - Total powder absorption: 0.63
- Thermal properties of materials:**
  - Melting Temperature: 1450+273[K] K
  - Solidus Temperature: 1380+273 [K] K
  - Evaporization temperature: 3020 K
  - Latent heat of fusion: 260 J/g
  - Latent heat of vaporization: 6088.6 J/kg
  - Mass of evaporating molecule: 55.845 u
  - Thermal conductivity of solid phase: 13.4 W/(m
  - Thermal conductivity of solid phase: 31.1 W/(m
  - Density of solid phase: 7950 kg/m<sup>3</sup>
  - Density of liquid phase: 7311 kg/m<sup>3</sup>
  - Heat capacity of solid phase: 470 J/(kg·K)

**Results:**

- Buttons: Reset parameters, Clear All Solutions, Compute
- Tab: Melt pool and T-profile
- Plot: Temperature profile (K) and melt pool at Time=0.0010027. The plot shows a cross-section of the melt pool with a color scale from 0.5 to 4.5 (multiplied by 10<sup>3</sup> K).

The screenshot displays the COMSOL App interface for the same simulation, showing the velocity field results.

**Results:**

- Buttons: Clear All Solutions, Compute
- Tab: Velocity field
- Plot: Velocity fields and Velocity magnitude (m/s) at Time=0.0010027. The plot shows a cross-section of the melt pool with a color scale from 0 to 2 m/s.

# Summary

- Compared to experimental measurements of laser absorption in commercial powders used in SLM, ray-tracing **diffuse mode gives the best approximation.**
- **The results of T-profile simulation** (overlapping of molten track, molten pool size, cooling information ) **agree with experiment .**
- SLM being a relatively **complex process**, COMSOL Apps is useful for **users without strong background in modelling.**