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Numerical Modeling of Powder Flow during Coaxial Direct Laser Metal Deposition – Comparison between Ti-6Al-4V Alloy and Stainless Steel 316L

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Projet ANR ASPECT (réf: ANR-09-BLAN-0014-02)

Université de Bretagne-Sud

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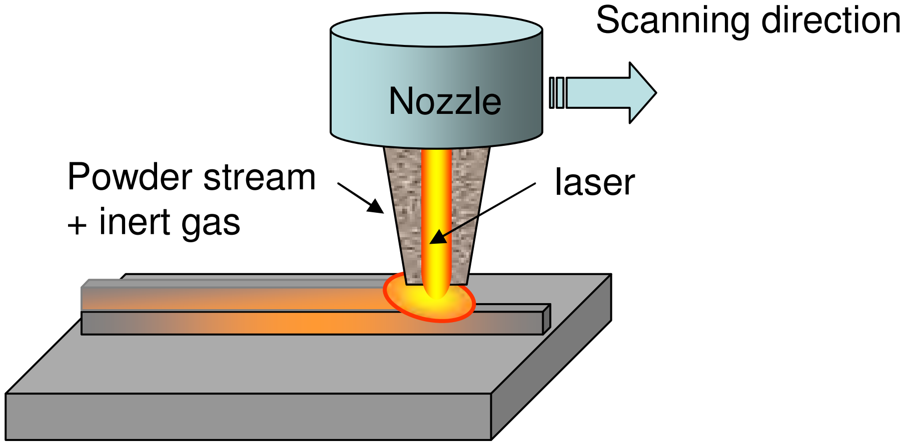
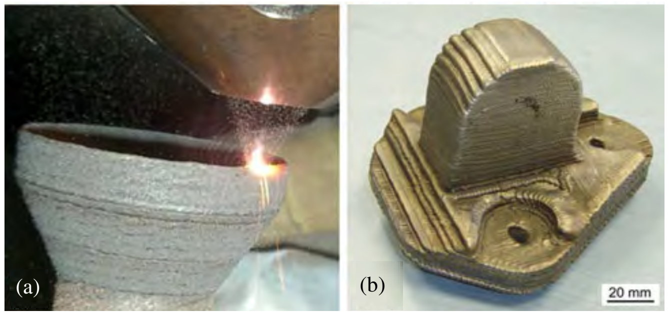
Laboratoire d'Ingénierie des MATériaux de Bretagne

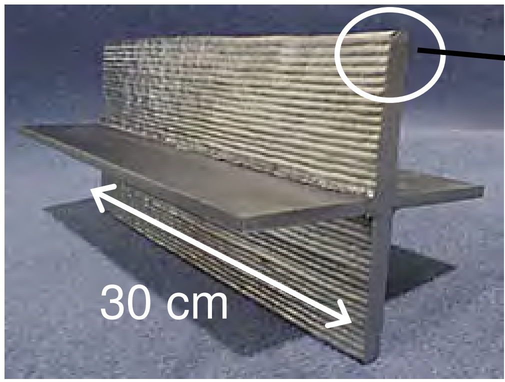
Direct Metal Laser Deposition (DMLD)



Coaxiale nozzle (AILU©)



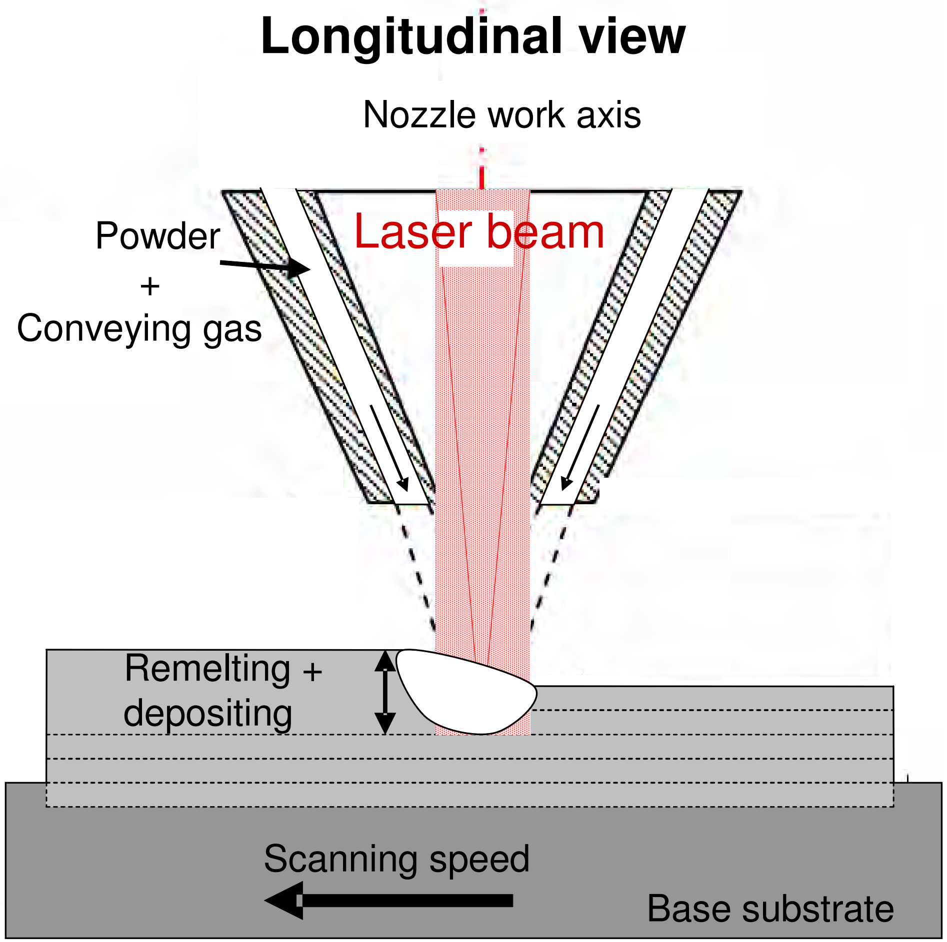
Manufacturing of complex shapes
(Kovalev et al., 2010)



Stiffener in aerospace

⚠ Surface finish with waviness

Schematic of the DMLD process:



Powder flow model

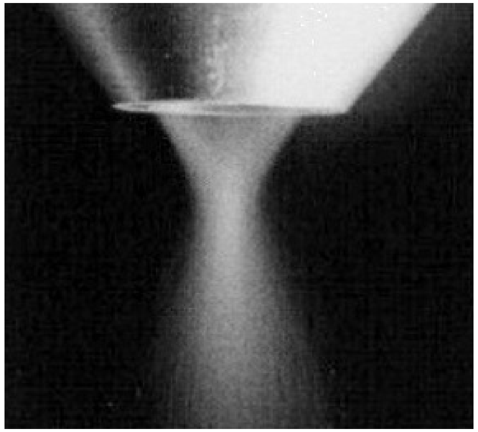
- Powder concentration
- Particle heating

⇩

3D heat and fluid flow model

- Melt pool dimensions
- free surface shape => waviness

Gas flow model :

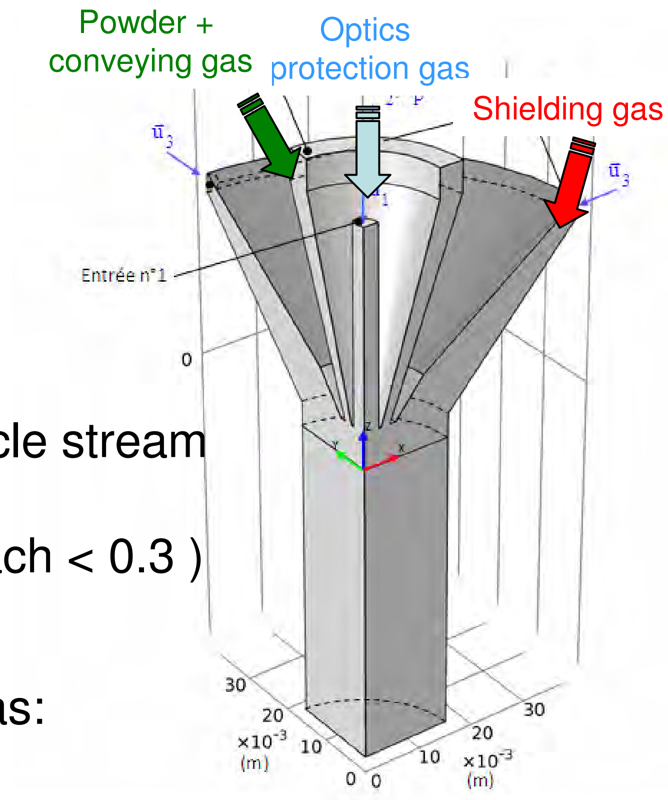


Input data:

- geometry of the nozzle
- inlet gas flow rate
- Argon properties

Assumptions:

- gas flow independent of particle stream (weak fraction of particles)
- weakly compressible gas (Mach < 0.3)
- stationary calculation



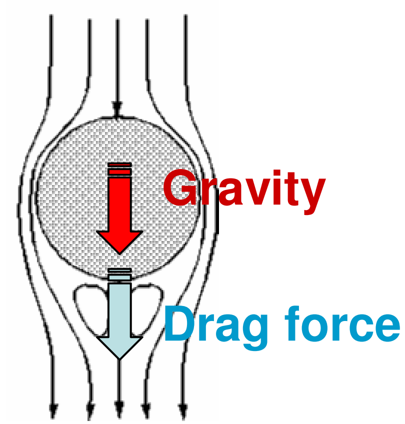
3D Turbulent k-ε model with weakly compressible gas:

$$\rho\frac{\partial\vec{U}}{\partial t} + \rho\vec{U}\cdot\vec{\nabla}\vec{U} + \vec{\nabla}\cdot\overline{(\rho\vec{u}'\otimes\vec{u}')} = \vec{\nabla}\cdot\left[-pI+\mu\left(\vec{\nabla}\vec{U} + \left(\vec{\nabla}\vec{U}\right)^T\right)-\frac{2}{3}\mu\left(\vec{\nabla}\vec{U}\right)I\right] + \vec{F}$$

stationary

Powder stream model:

Assumptions:
- Lagrangian description
- No collision between particles
- Non-spherical particles (shape factor 0.8)
- Ti-6Al-4V or 316L alloy
- Size distribution [45 - 75 µm] with Normal low



Force equilibrium:

$$\frac{d\left(m_p \vec{u}_p\right)}{dt} = \vec{F}_D + \vec{F}_g$$

$$\vec{F}_D = \frac{18\,\mu}{\rho_p d_p^2} \frac{C_D\ Re_p}{24} \left|\vec{u} - \vec{u}_p\right|$$

$$\vec{F}_g = m_p \frac{\left(\rho_p - \rho_f\right)}{\rho_p} \vec{g}$$

$$Re_p = \frac{\rho\, d_p \left|\vec{u} - \vec{u}_p\right|}{\mu}$$

Calculation with « Particle tracing module », computation time: 1 h

Thermal model:

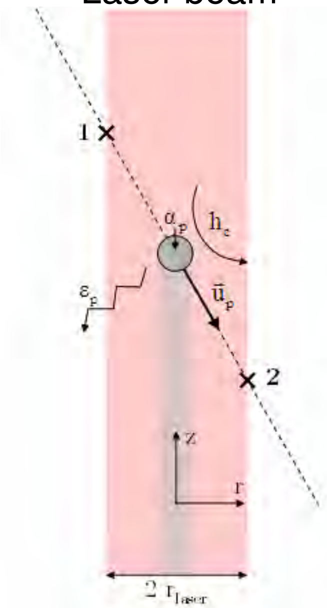
Assumptions:

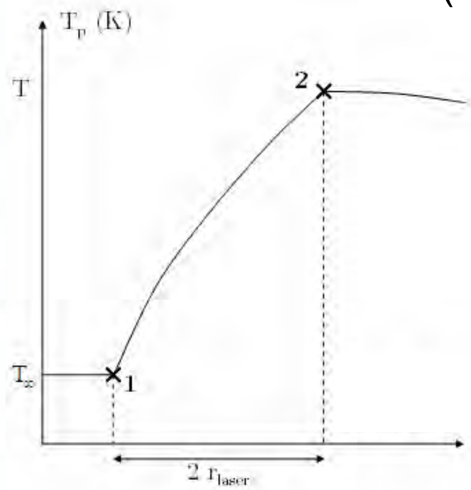
- isothermal particles (Biot number < 0.1)
- No shadow effect between particles
- No evaporation, no attenuation for the laser beam

$$m_p c_p^*(T)\frac{dT_p}{dt} = I_l \eta_p \pi r_p^2 - h\left(T_p - T_\infty\right)4\pi r_p^2 - \varepsilon\sigma\left(T_p^4 - T_\infty^4\right)4\pi r_p^2$$

h → f(Re, Pr)

Laser beam

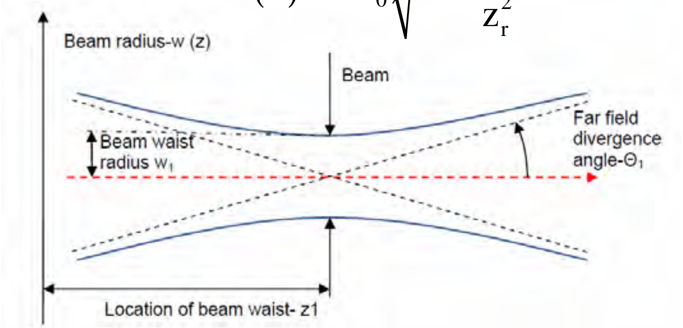




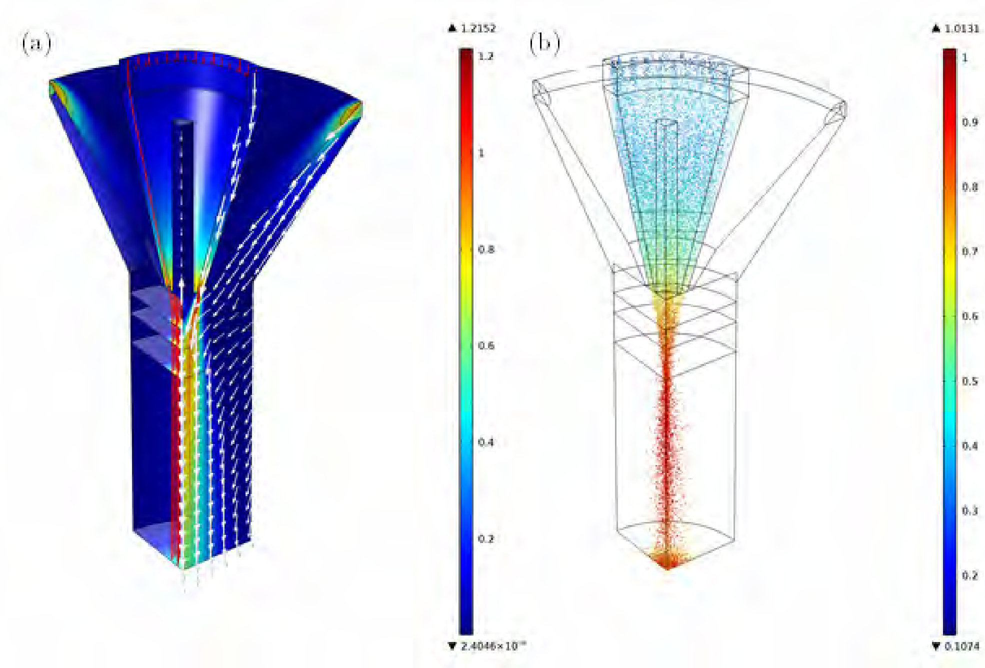
Gaussian distribution

$$I_{laser}(x,y,z) = N_{laser}\frac{P_{laser}}{\pi\, w(z)^2}\exp\left(-N_{laser}\frac{\left(x^2+y^2\right)}{w(z)^2}\right)$$

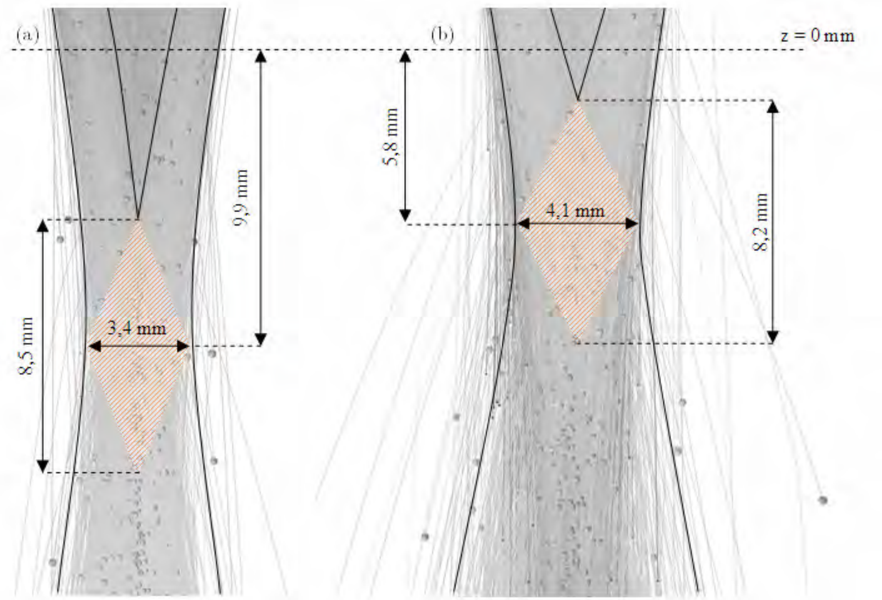
$$w(z) = w_0\sqrt{1+\frac{z^2}{z_r^2}}$$



Gas flow and powder stream



Powder focus plane



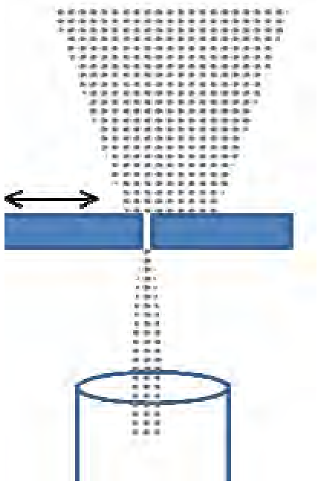
Ti-6Al-4V alloy
ρ ≈ 4200 kg/m^3

316L stainless steel
ρ ≈ 7500 kg/m^3

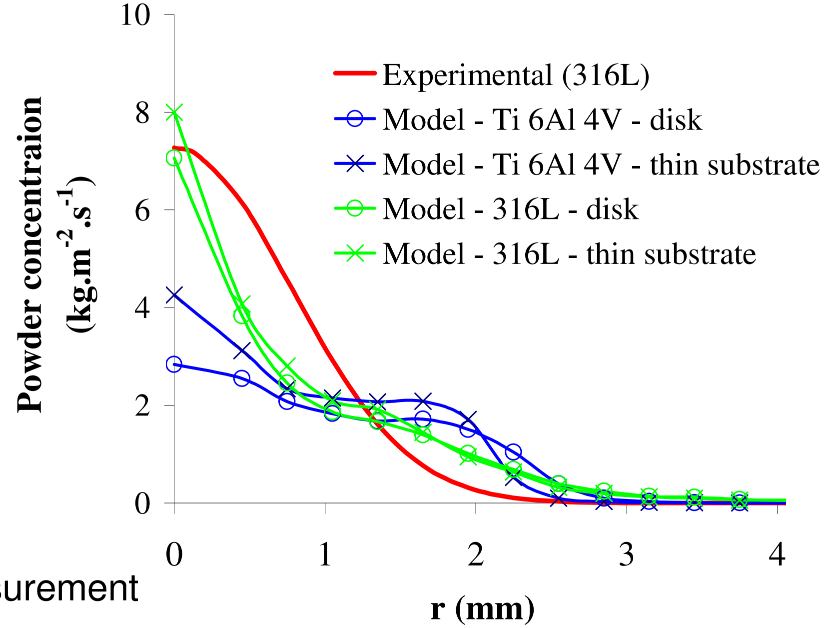
- ✓ Powder focus plane lower with titanium alloy than strainless steel
- ✓ Results in good agreement with measurements

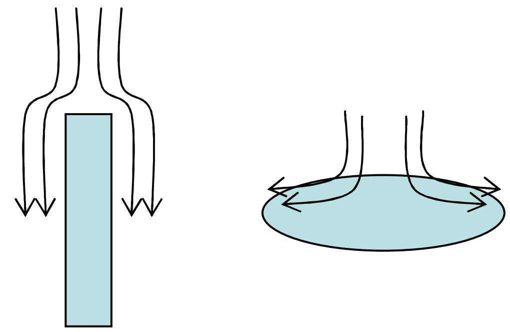
Particle concentration profile

✓ Influence of material, shape of the substrate



Powder concentration measurement

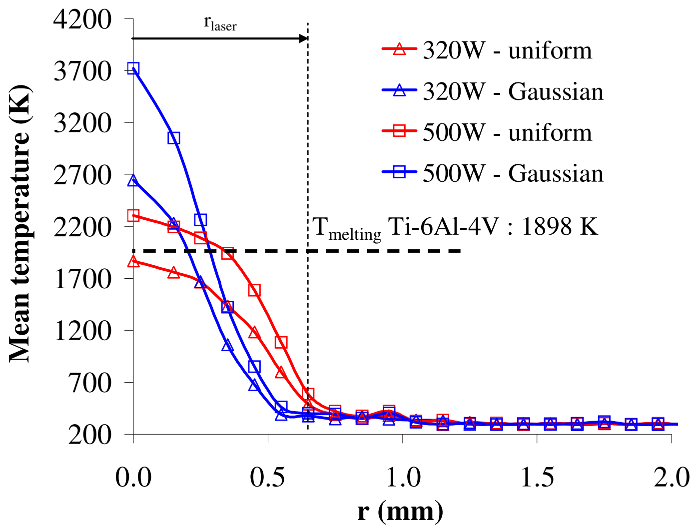




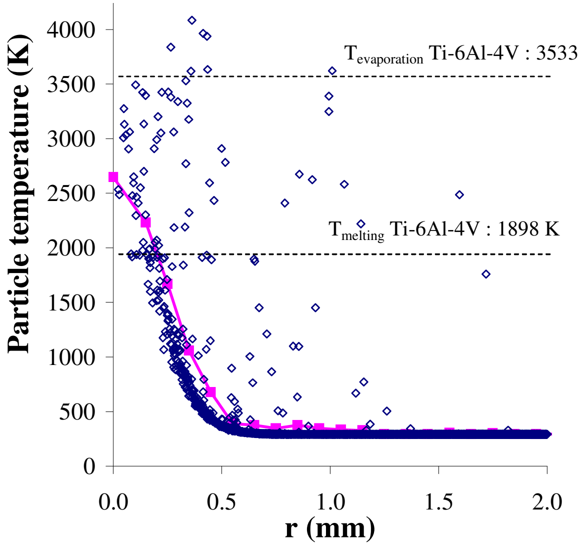
✓ Powder distribution depends on the material
✓ Presence of the substrate need to be modeled
✓ Good agreement between experience and model

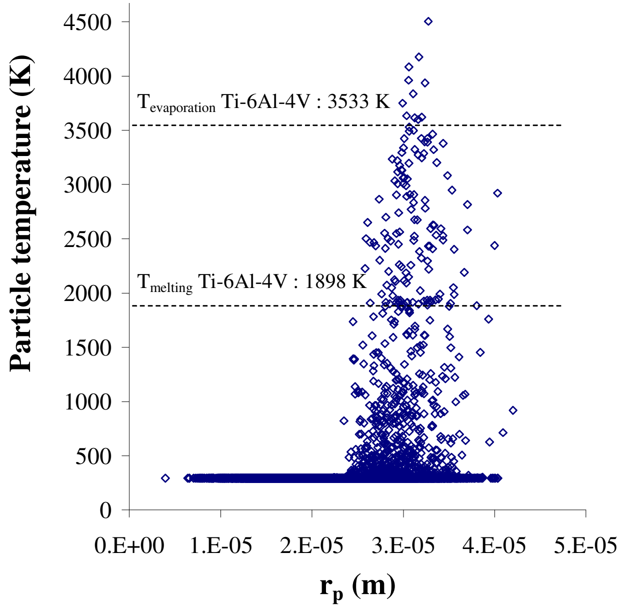
Particle temperature at the substrate surface

✓ Influence of laser power, energy distribution



320 W, Gaussian distribution





✓ Temperature profiles strongly depend on the laser power and energy distribution
✓ Temperature particles depend on particle radius
✓ Small particles stay at room temperature

Conclusion

• Development of a 3D model to describe the dynamic and thermal behavior of the coaxial powder flow for direct laser metal deposition process.

=> Powder focus plane is lower for titanium alloy than stainless steel

=> Increase of the particle temperature with laser power

=> Strong variation of particle temperature with a Gaussian energy distribution

• This model gives information difficult to obtain experimentally and can be used to optimize the operating parameters (optimal focus plane position, particle temperature above the melting point).

• The concentration profile and particle temperature can be used for 3D melt pool model to predict the geometry of the clad.