Rapid and differentiable macroscopic modeling of the cold spray process

Sergio Garcia Castro

Mines Paris – PSL

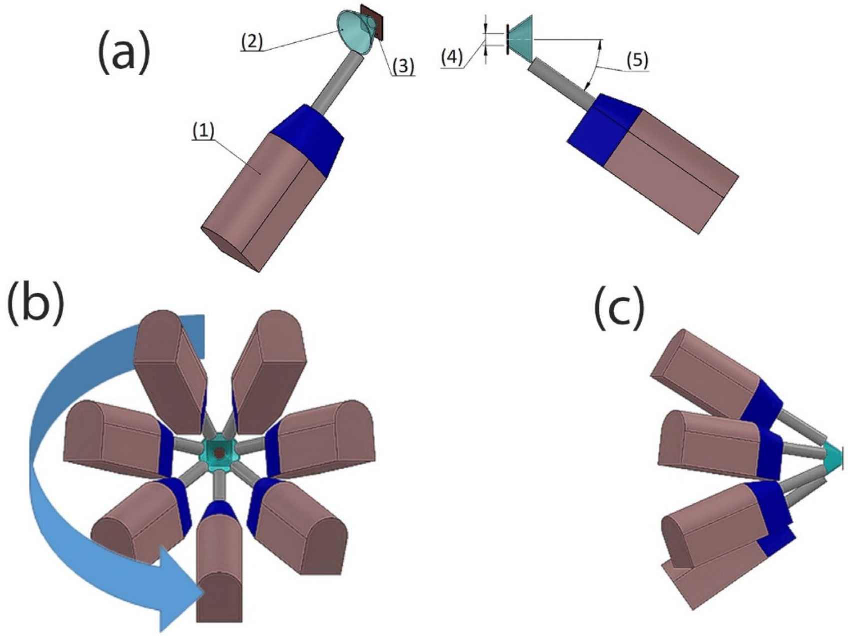
Macroscopic model

- No CFD
- No particle impact
- Only mass deposition at the part scale

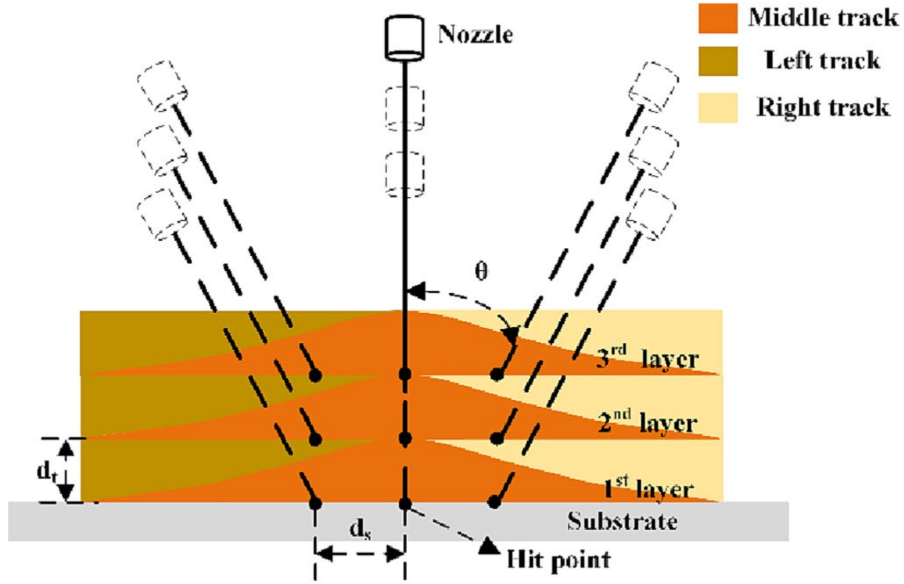
Why do we need a macroscopic model?

- Optimal control of coating thickness
- Optimal repair
- Optimal additive manufacturing

Why do we need a macroscopic model?



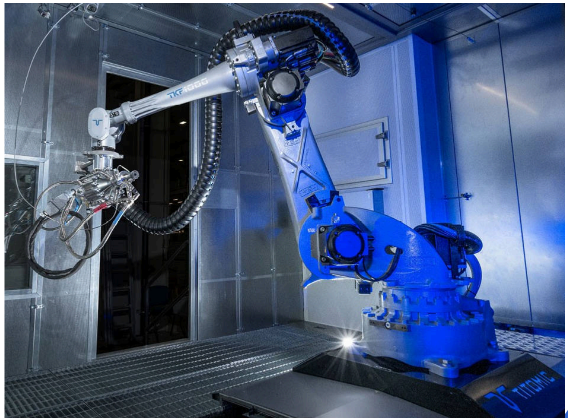
R.F. Vaz et al., Metal Knitting: A New Strategy for Cold Gas Spray Additive Manufacturing, Materials 2022, 15(19), 6785



W. Li et al., General-purpose numerical deposition modeling methodology based on mesh geometry reconstruction strategy in cold spray additive manufacturing system, Surface & Coatings Technology 464 (2023) 129563

What type of models?

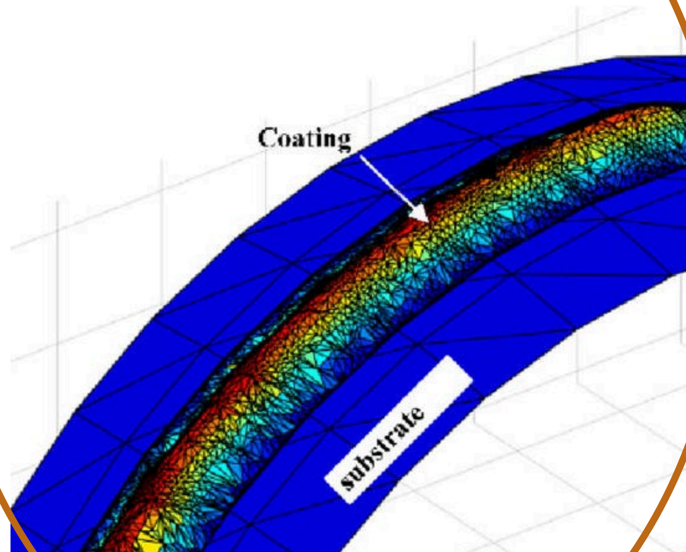
Tool Path
Cold Spray parameters
Materials
...



Forward model

Backward model

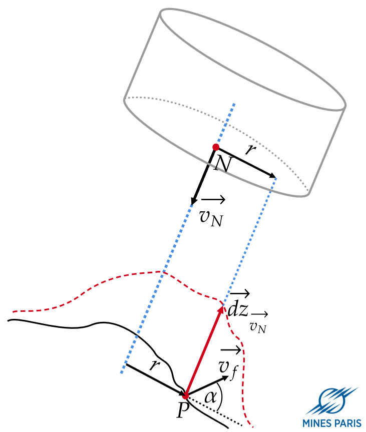
Cold Spray Deposition



Forward Model

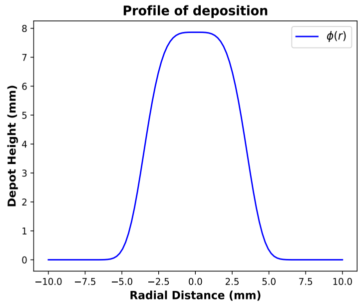
Deposit Thickness Increment

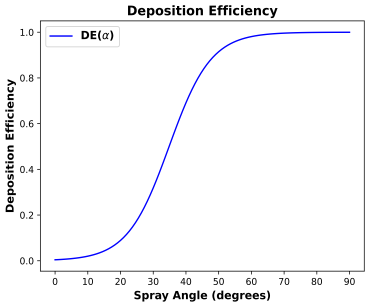
$$\vec{dz}_{\vec{v}_N}(r) = -DE(\alpha)\phi(r)dt \cdot \frac{\vec{v}_N}{\|\vec{v}_N\|}$$



Forward Model

where, $\phi(r) = Ae^{-\left(\frac{r}{2\sigma}\right)^{2n}}$ and $DE(\alpha) = \frac{1}{1+e^{-a(\alpha-b)}}$:



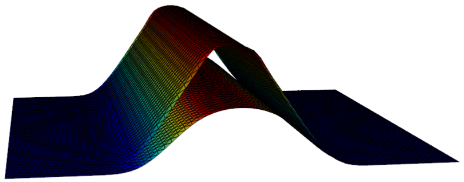


Parameters A, σ, n, a, and b fitted experimentally.

Code Implementation

Key Features

- Built with PyTorch & PyTorch3D for mesh handling
- Ensures mass conservation.
- Achieves 1.5 $\times$ real-time simulation.



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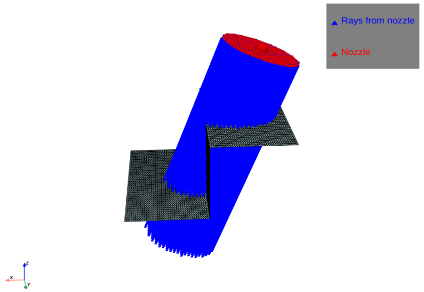
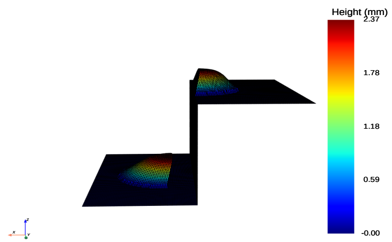
Shadow Effect

- **Shadow Effect:**



- **Modeling Approach:** Ray-tracing technique originating from the nozzle.



Differentiable Code

- Code is differentiable.
- Enables optimization by minimizing loss:

$$L(p) = \|\text{Mesh}_{\text{simulation}}(p) - \text{Mesh}_{\text{target}}\|.$$

- Gradient $\nabla L(p)$ is easily computed.
- Used for model calibration and tool path planning.

Model Calibration

- **Recall:** $\phi(r) = Ae^{-\left(\frac{r}{2\sigma}\right)^{2n}}, \quad DE(\alpha) = \frac{1}{1+e^{-a(\alpha-b)}}$
- Calibrated using optimization methods.
- Profile parameters: 1 pass line deposition at 90° (experimentally measured).
- Deposition efficiency parameters: 10 pass line deposition at 90° (experimentally measured).

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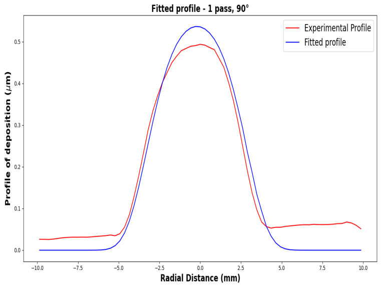
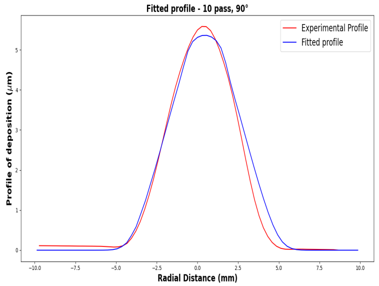
Model Calibration



(a) 1 pass calibration



(b) 10 passes calibration

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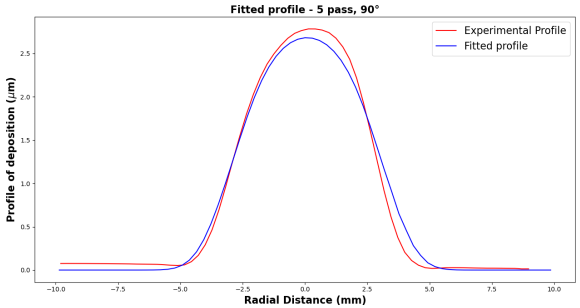
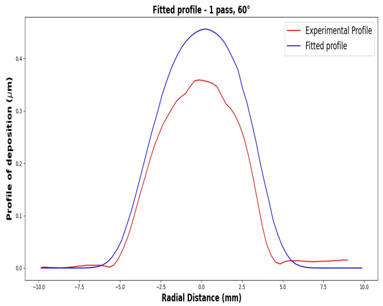
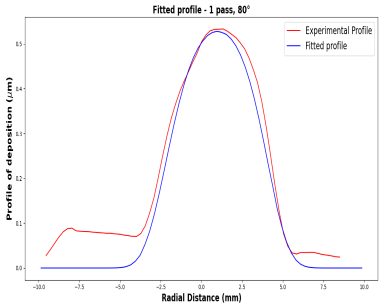
Model Validation

- Model validation done with measurements of:
  - 5 passes at 90°
  - 1 pass at 40°, 50°, 60°, and 80°



Model Validation





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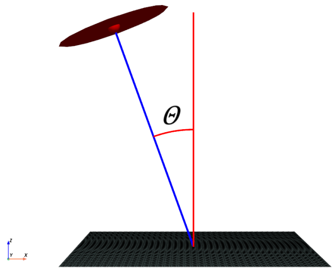
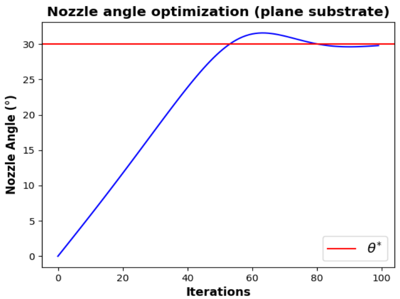
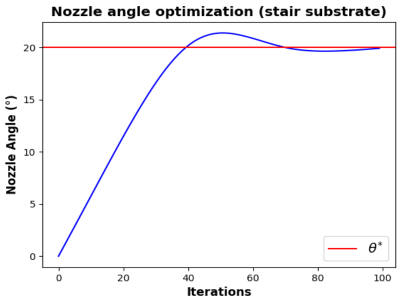
Tool Path Planning

- Target shape: Line deposition with fixed spray angle $\hat{\theta}$ from the z-axis.
- Optimization: Gradient descent to find the optimal angle $\hat{\theta}$.
- Convergence to desired angle $\hat{\theta}$ achieved.



Tool Path Planning





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Conclusion and Perspectives

Areas for Improvement:

- Enhance model calibration with more precise experimental data.
- Introduce additional optimization parameters in the simulation.
- Resolve remeshing challenges during extended spray durations and deposit buildup.