AdMoRe
H2020 – MSCA-ITN 675919

Parametric numerical solutions and evaluation of part distortion in additive manufacturing processes

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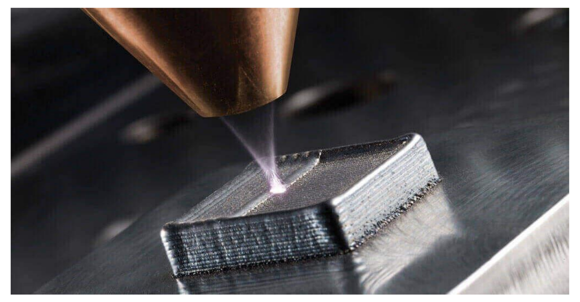
CONCLUSIONS

- This work shows a simplified parametric modeling and its subsequent parametric solution for evaluating parametrically the manufactured part distortion.
- The involved parameter are the ones parametrizing the process trajectories, the thermal shrinkage intensity and anisotropy and the deposited layers.
- The resulting simulation tool allows evaluating in real-time the impact of the parameters on the part distortion and proceed to the required distortion compensation.

1. PROBLEM

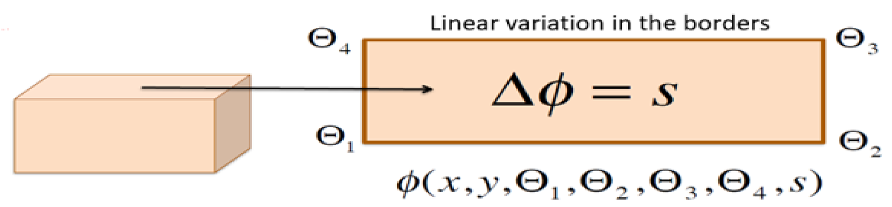
- Additive Manufacturing (AM): technologies that build 3D objects by adding layer-upon-layer of material.



- **Challenges**: the study of the interactions at the scale of the particle and the prediction of the mechanical state of the final part.
- **Main difficulties**: multiple scales, the multiple and complex physics involved and the strong dependency on the (extremely long) process trajectory.
- Standard numerical simulation tools (FEM, FDM, FVM, discrete models, …) are not efficient (very large systems and prohibitive simulation times).
- Parametric analysis for optimizing processes or for performing simulation-based real-time control can not be performed.

2. PARAMETRIC TRAJECTORIES

- Creating offline the parametric solution of the process, the part distortion, for any possible process trajectory (or better to a restricted family of them).



Domain

$$\Omega = [0,L] \times [0,H]$$

Boundary condition

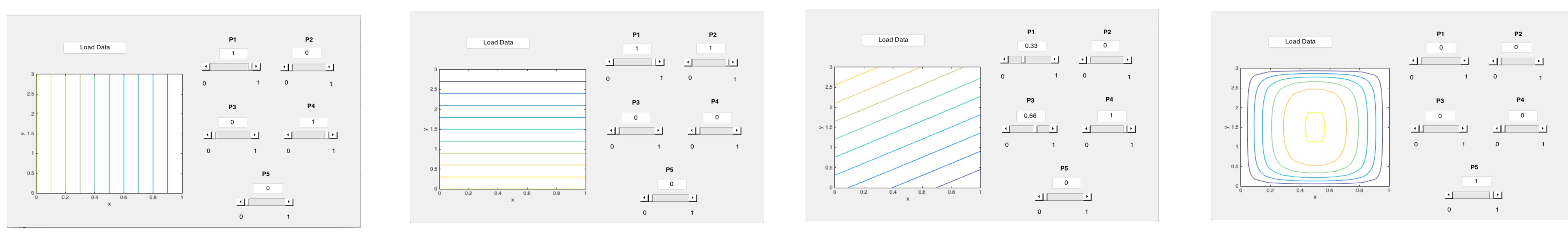
$$\begin{cases} \phi(x,y=0) = \Theta_1 + (\Theta_2-\Theta_1)\frac{x}{L} \\ \phi(x,y=H) = \Theta_4 + (\Theta_3-\Theta_4)\frac{x}{L} \\ \phi(x=0,y) = \Theta_1 + (\Theta_4-\mu_1)\frac{y}{H} \\ \phi(x=L,y) = \Theta_2 + (\Theta_3-\Theta_2)\frac{y}{H} \end{cases}$$

- Parametric trajectories $\phi(x,y,\Theta_1,\Theta_2,\Theta_3,\Theta_4,s)$ computed by solving five boundary value problems.

$$K\Phi = F \begin{cases} \Phi^1 = K^{-1}F^1 \text{ with } F^1 \leftarrow \Theta_1 = 1, \Theta_2 = \Theta_3 = \Theta_4 = s = 0 \\ \Phi^2 = K^{-1}F^2 \text{ with } F^2 \leftarrow \Theta_2 = 1, \Theta_1 = \Theta_3 = \Theta_4 = s = 0 \\ \Phi^3 = K^{-1}F^3 \text{ with } F^3 \leftarrow \Theta_3 = 1, \Theta_1 = \Theta_2 = \Theta_4 = s = 0 \\ \Phi^4 = K^{-1}F^4 \text{ with } F^4 \leftarrow \Theta_4 = 1, \Theta_1 = \Theta_2 = \Theta_3 = s = 0 \\ \Phi^5 = K^{-1}F^5 \text{ with } F^5 \leftarrow s = 1, \Theta_1 = \Theta_2 = \Theta_3 = \Theta_4 = 0 \end{cases}$$

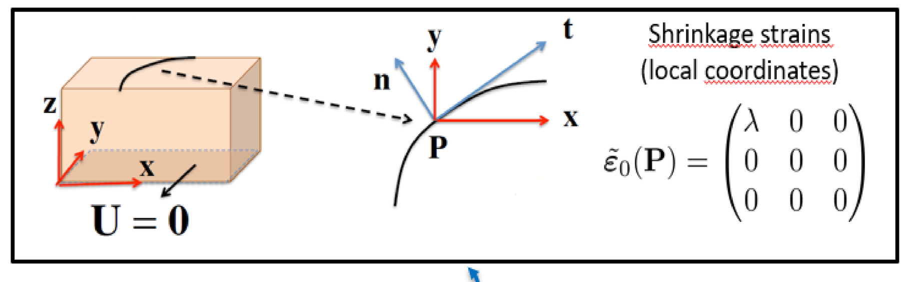
$$\Phi(\Theta_1,\Theta_2,\Theta_3,\Theta_4,s) = \sum_{i=1}^{4} \Theta_i \Phi^i + s\Phi^5$$

Parametric isocurves = Parametric trajectories



3. PARAMETRIC THERMO-MECHANICAL MODEL

- Thermal shrinkage: as soon as layers are assumed deposited at a certain temperature, the cooling process occurs, and being the thermal shrinkage constrained by the already solid part, residuals stress are induced.
- Model: thermal shrinkage follows the deposition trajectory



Shrinkage stresses

$$\varepsilon_0(\mathbf{P}) = \mathbf{R}^T \tilde{\varepsilon}_0(\mathbf{P}) \mathbf{R} \Rightarrow \sigma_0(\mathbf{P}) = \mathbb{C}\,\varepsilon_0(\mathbf{P})$$

Rotation matrix — Hooke's tensor

- Parametrized thermal shrinkage: shrinkage stresses depend parametrically on the trajector (that controls its anisotropy).
- Parametric equation (virtual work principle): solved by using the Proper Generalized Decomposition (PGD).

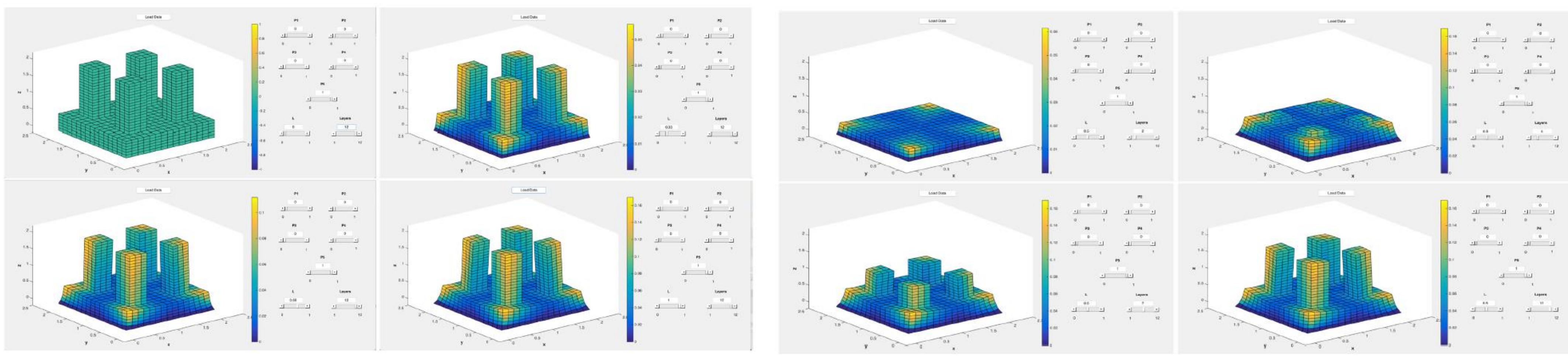
$$\phi(x,y,\Theta_1,\Theta_2,\Theta_3,\Theta_4,s) = \sum_{i=1}^{4} \Theta_i \phi^i(x,y) + s\phi^5(x,y)$$

$$\mathbf{n} = \frac{\nabla\phi}{\|\nabla\phi\|}; \quad \nabla\phi = \begin{pmatrix} \frac{\partial\phi}{\partial x} \\ \frac{\partial\phi}{\partial y} \end{pmatrix} = \begin{pmatrix} \sum_{i=1}^{4} \Theta_i \frac{\partial\phi^i(x,y)}{\partial x} + s\frac{\partial\phi^5(x,y)}{\partial x} \\ \sum_{i=1}^{4} \Theta_i \frac{\partial\phi^i(x,y)}{\partial y} + s\frac{\partial\phi^5(x,y)}{\partial y} \end{pmatrix}$$

$$\mathbf{t} = \begin{pmatrix} -n_y \\ n_x \end{pmatrix}$$

$$\mathbf{R}(x,y,\Theta_1,\Theta_2,\Theta_3,\Theta_4,s) \Rightarrow \sigma_0(x,y,\Theta_1,\Theta_2,\Theta_3,\Theta_4,s,\lambda) = \mathbb{C}\left(\mathbf{R}^T \tilde{\varepsilon}_0 \mathbf{R}\right)$$

$$\int_\Omega \varepsilon^* : (\sigma - \sigma_0)\ d\mathbf{x} = 0 \Rightarrow \mathbf{u}(\mathbf{x},\Theta_1,\Theta_2,\Theta_3,\Theta_4,s,\lambda) \approx \sum_{i=1}^{M} X_i(\mathbf{x})\Lambda_i(\lambda)S_i(s)\prod_{j=1}^{4}\Psi_i^j(\Theta_j)$$



4. DISTORTION COMPENSATION

1. Evaluate the distortion for a choice of the parameters.
2. Apply that displacement field with opposite sign to the target configuration.
3. The final geometry after shrinkage should almost correspond to the target one.