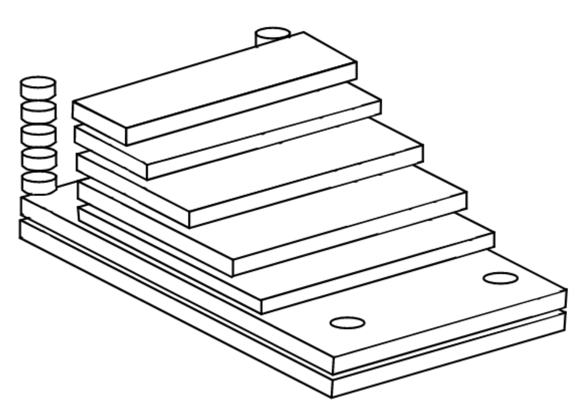
PATH OPTIMIZATION FOR THE LASER POWDER BED FUSION ADDITIVE MANUFACTURING PROCESS

Mathilde BOISSIER[1,2], Grégoire ALLAIRE[1], Christophe TOURNIER[2]
[1] CMAP, Ecole Polytechnique, France [2] LURPA, ENS Paris-Saclay, France

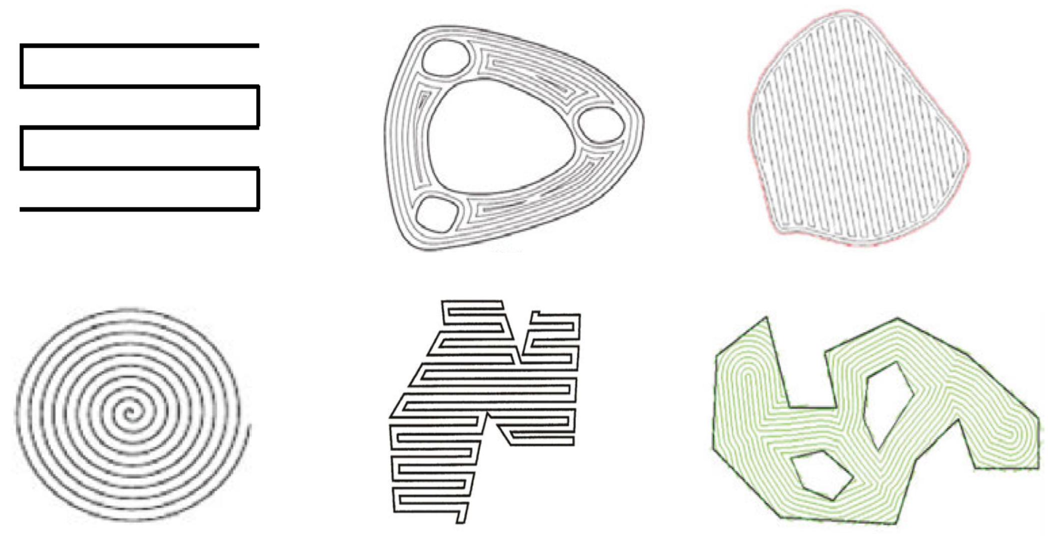
CONTEXT

Decomposition in layers

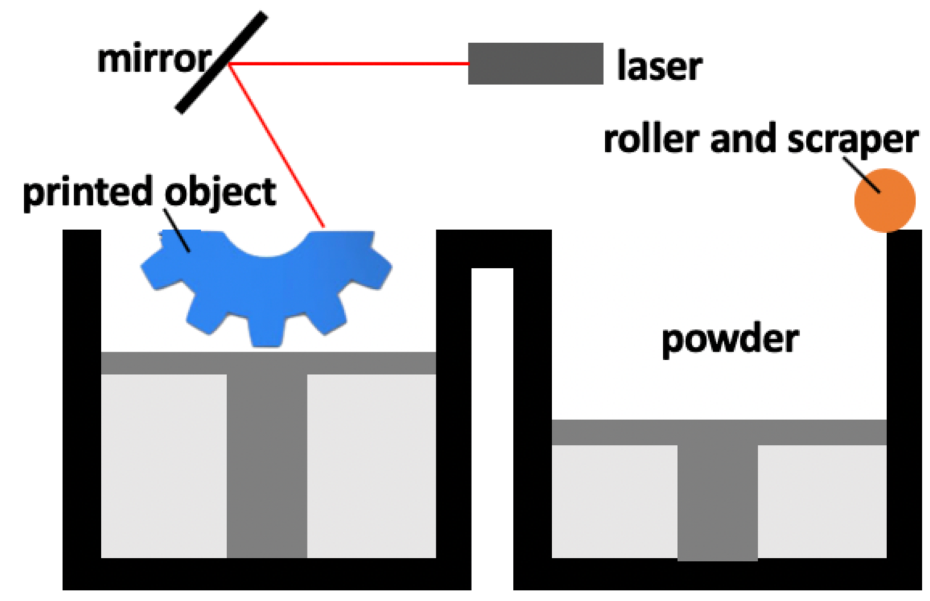


G. Allaire and al., Shape optimization of a layer-by-layer mechanical constraint for additive manufacturing, C. R. Math. Acad. Sci. Paris 355 (2017) 699–717

Choice of building parameters : laser path, speed, power



Building process



Evaluation of the process

drawbacks in the item's quality (thermal expansion, residual stresses, …)

evaluation of the process's speed (kinematics)

2D MODEL

Constraints to satisfy :

- change of state $\forall x \in \Sigma, \exists t \;\; such\ that \;\; T(t,x) > T_\Phi$
- thermal expansion $\forall x \in \Sigma, \forall t, \quad T(t,x) < T_M$

Source :

$Q(t,x) = Pe^{-\delta(x-u(t))^2}$

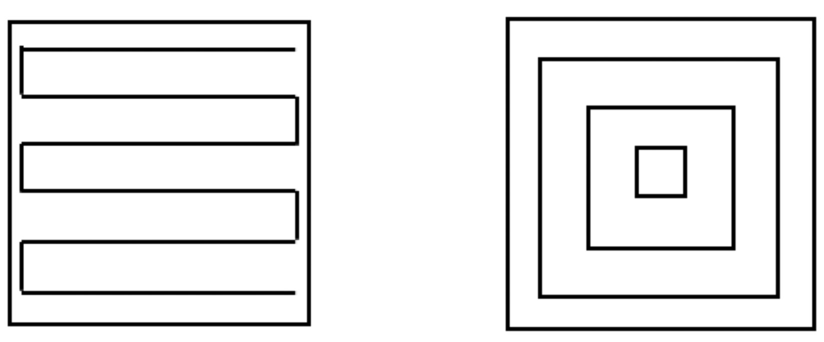
$$\begin{cases} \dot u(t) = v(t)\tau(t) & t \in (0,t_F) \\ u(0) = u_0 \end{cases}$$

Heat Equation :

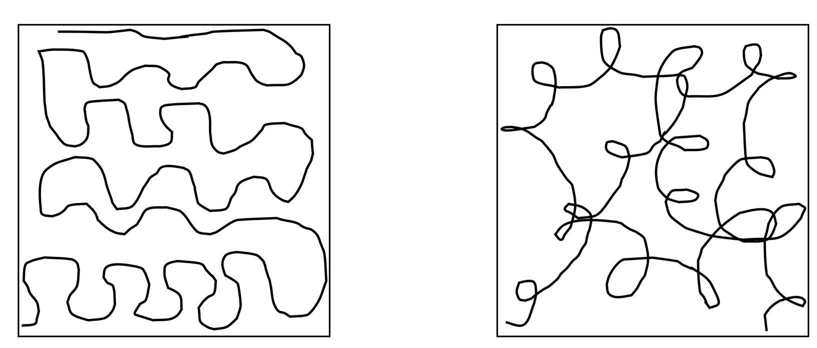
$$\begin{cases} \rho c_p \partial_t T - \nabla\cdot(\lambda\nabla T) + \dfrac{\lambda_{sol}}{L\Delta Z} T = \dfrac{Q}{L} & (t,x) \in (0,t_F)\times\Sigma, \\ \lambda\nabla T\cdot n = 0, & (t,x) \in (0,t_F)\times\partial\Sigma \\ T(0,x) = T_{init}(x), & x \in \Sigma \end{cases}$$

OBJECTIVE

Existing laser paths based on predefined patterns.



Why are these patterns chosen? Are they optimal? Why not these?



Optimize the laser path to improve both the mechanical and kinematic properties of the process, without basing it on any pattern.

STEADY CASE (source applied on the whole path : heating thread)

Optimization problem

$$\min_\Gamma J(\Gamma) = \int_\Gamma ds$$

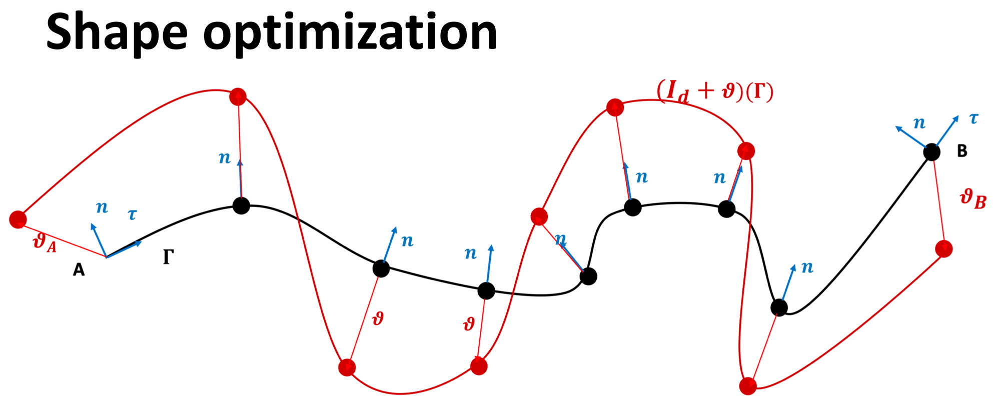
under the constraints :

$$\begin{cases} C_\Phi(\Gamma) = \displaystyle\int_\Sigma [(T_\Phi - T)^+]^2 dx = 0 & (T > T_\Phi), \\ C_M(\Gamma) = \displaystyle\int_\Sigma [(T - T_M)^+]^2 dx = 0 & (T < T_M). \end{cases}$$

and T solution of :

$$\begin{cases} -\nabla\cdot(\lambda_{pow}\nabla T) + \dfrac{\lambda_{sol}}{L\Delta Z}T = \dfrac{P}{L}1_\Gamma, & x \in \Sigma, \\ \lambda_{pow}\nabla T\cdot n = 0 & x \in \partial\Sigma. \end{cases}$$

Shape optimization



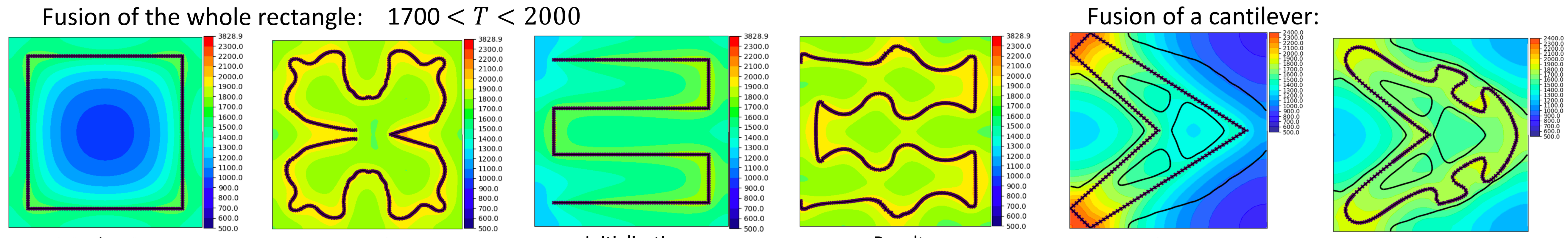
$$J(\Gamma) = \int_\Gamma f(s)ds$$

$$J'(\Gamma)(\vartheta) = \int_\Gamma [\partial_n f + \kappa f]\vartheta\cdot n\, ds + f(B)\vartheta(B)\cdot\tau(B) - f(A)\vartheta(A)\cdot\tau(A)$$

Results (Values from *L. Van Belle, Analyse, Modélisation et Simulation de l'apparition de contraintes en Fusion Laser Métallique, Lyon, INSA, Nov. 2013*)

Fusion of the whole rectangle: $1700 < T < 2000$

Fusion of a cantilever:



Initialisation Result Initialisation Result Initialisation Result

Future work

- Adding constraints
- Allow for splitting a path and gathering paths
- 3D optimization: consider the evolution of the path depending on the layer

UNSTEADY CASE (source moving along the path)

Assumptions

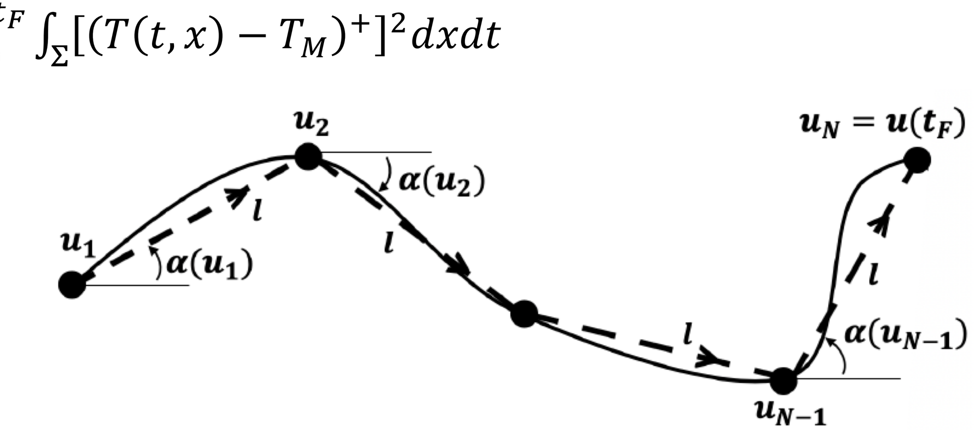
- fixed velocity V (constant along the path)
- fixed power P (constant along the path)

Optimal control problem

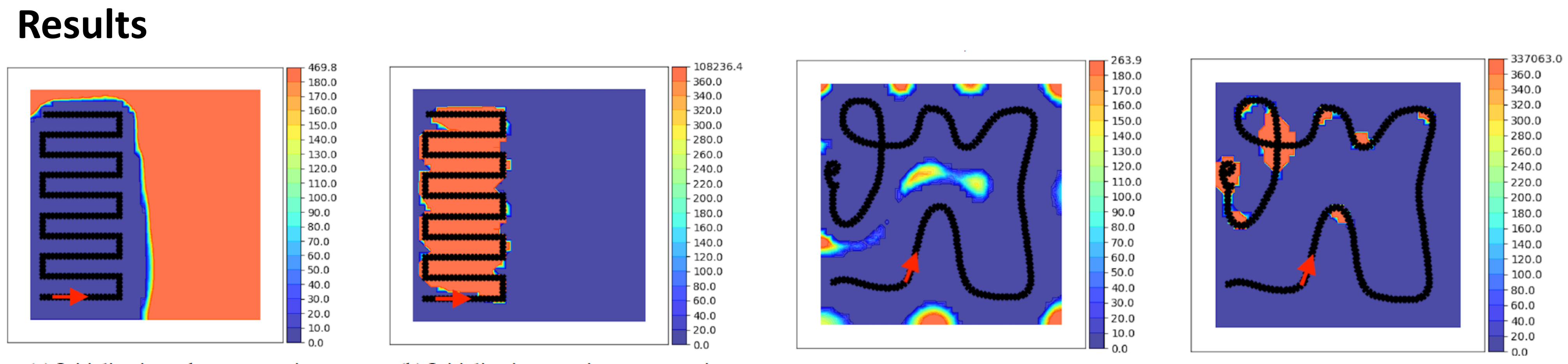
$$\min_\Gamma J(\alpha) = t_F + \int_\Sigma \left[(T_\Phi - ||T(.,x)||_{L^2([0,t_F])})^+\right]^2 dx + \int_0^{t_F}\int_\Sigma [(T(t,x)-T_M)^+]^2 dxdt$$

with T solution of the heat equation, where $Q(t,x) = Pe^{-\delta(x-u(t))^2}$ and

$$\begin{cases} \dot u(t) = (\cos(\alpha(t)), \sin(\alpha(t))) & t \in (0,t_F) \\ u(0) = u_0 \end{cases}$$



Results



(a) Initialization, phase constraint, $L = 0.83m$, $C_\Phi = 4245K^2m^2$

(b) Initialization, maximum constraint, $L = 0.83m$, $C_M = 374K^2m^2s$

(c) Final iteration, phase constraint, $L = 0.86m$, $C_\Phi = 52K^2m^2$

(d) Final iteration, maximum constraint, $L = 0.86m$, $C_M = 72K^2m^2s$

Future work

- Improve the results
- Same work than for the steady case

PERSPECTIVES

- coupling the shape and path optimization
- optimizing a line in a 3D domain

REFERENCES

1. M. Megahed et al. "Metal Additive-Manufacturing Process and Residual Stress Modeling", Integrating Materials and Manufacturing Innovation 5.1 (Dec. 2016), p. 4.
2. G. Allaire and L. Jakabčin. "Taking into Account Thermal Residual Stresses in Topology Optimization of Structures Built by Additive Manufacturing", Mathematical Models and Methods in Applied Sciences 28.12 (2018), pp. 2313–2366.
3. J. L. Lions. Optimal Control of Systems Governed by Partial Differential Equations. Vol. 170. Springer (1971).
4. S. Wendl, H. J. Pesch, and A. Rund. "On a State-Constrained PDE Optimal Control Problem Arising from ODE-PDE Optimal Control", Recent Advances in Optimization and Its Applications in Engineering. (2010), pp. 429–438.