Shape and topology optimization of structures built by additive manufacturing

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CMAP, École Polytechnique

CMM, Santiago de Chile, December 1-22, 2022

Outline of the course

- 1 - Introduction: a review of additive manufacturing
- 2 - Parametric optimization and the adjoint method
- 3 - Geometric optimization and Hadamard method
- 4 - Topology optimization and the level set method
- 5 - Typical constraints from additive manufacturing
- 6 - Optimization of lattice materials
- 7 - Coupled shape and laser path optimization

A "hot" topic with a lot of room for new ideas and modeling...

Outline of the first chapter

Chapter 1 - **Introduction: a review of additive manufacturing**

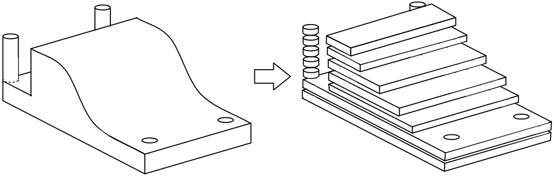
- I - Principles of additive manufacturing
- II - What can be achieved ?
- III - Some failures of additive manufacturing
- IV - Models of the manufacturing process
- V - Conclusion and perspectives

SOFIA

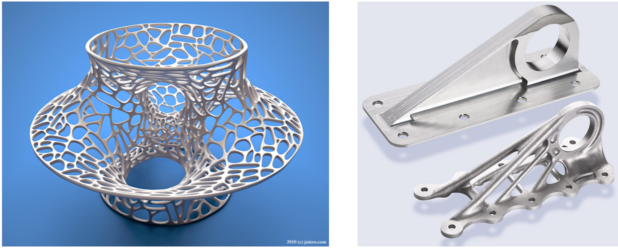
Sofia project: Add-Up, Michelin, Safran, ESI, etc. (2016-2022)

I - Principles of additive manufacturing

- Structures built layer by layer



- No topological constraints on the built structures

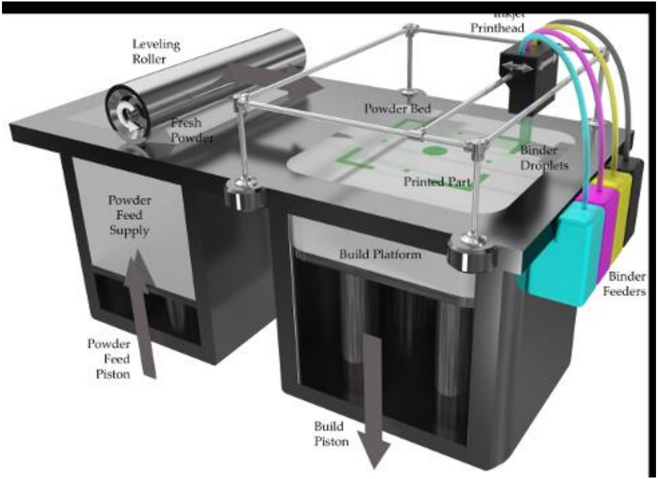


Additive manufacturing (a.k.a. 3-d printing)

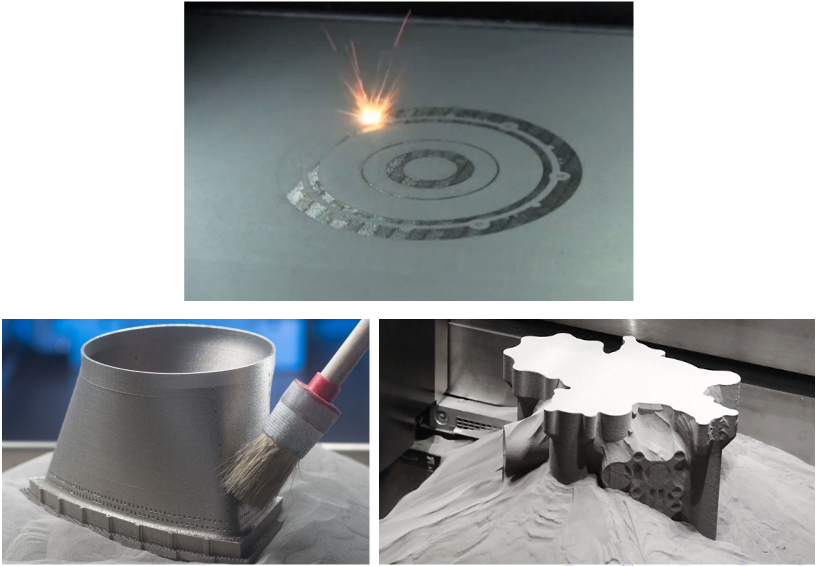
- Various materials: plastic, polymer, metal, ceramic...
- We focus on metallic additive manufacturing.
- Various processes: wire, direct energy deposition (DED), layer by layer...
- We focus on powder bed techniques (layer by layer).
- Very easy process for building ! A simple STL file (STereoLithography) is enough for the machine (through a slicing process).

Metallic additive manufacturing

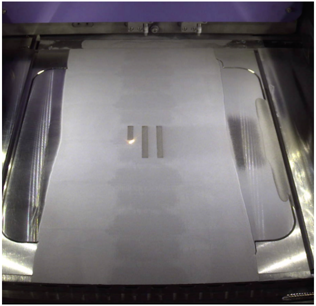
Metallic powder melted by a laser or an electron beam.



Metallic additive manufacturing

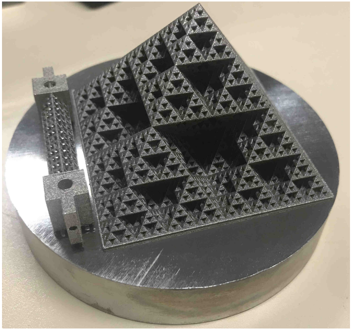


AddUp machine at LURPA (thanks to C. Tournier)

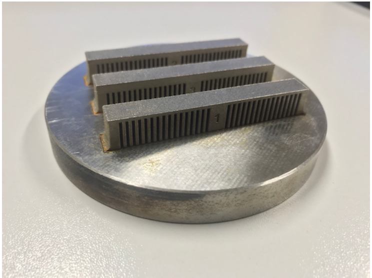


II - What can be achieved ?

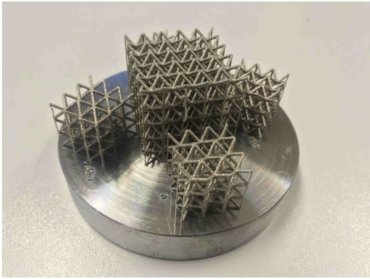
- Very different from classical techniques (molding, milling)
- No topological constraints on the built structures
- Very complicated structures: new applications, new designs
- Lattice (porous) materials
- Functionally graded materials



Examples from LURPA (thanks to C. Tournier)



comb-shaped structure



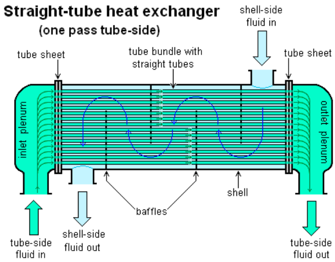
lattice structure

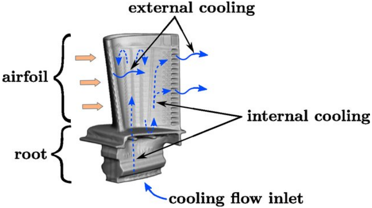
Examples from SAFRAN (thanks to M. Bihr)

Academic example (MBB beam and its support)

Multi-physics applications (F. Feppon, Safran)

New multi-physics designs can be built. For example:





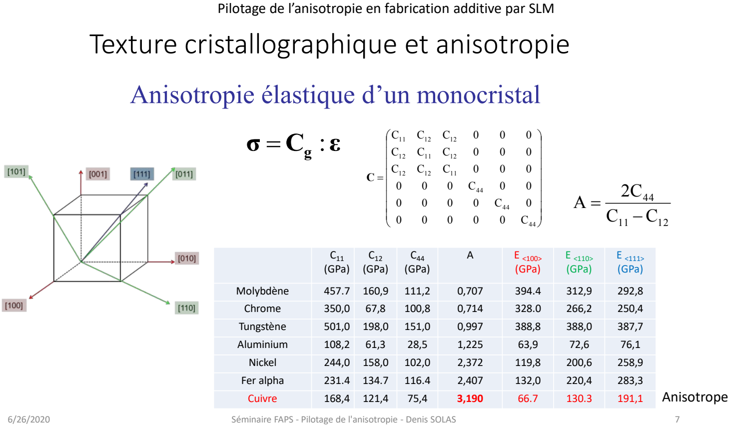
heat exchanger turbine blade with internal cooling

Lattice structures

3-d printing enables structures made of composite materials (called lattice materials).

Functionally graded materials

Work of Denis Solas, ICMMO, Orsay, Paris-Saclay.



Pilotage de l'anisotropie en fabrication additive par SLM

Texture cristallographique et anisotropie

Anisotropie élastique d'un monocristal

$$\boldsymbol{\sigma} = \mathbf{C_g} : \boldsymbol{\varepsilon}$$

$$\mathrm{C} = \begin{pmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{pmatrix}$$

$$A = \frac{2C_{44}}{C_{11} - C_{12}}$$

	C_{11} (GPa)	C_{12} (GPa)	C_{44} (GPa)	A	$E_{<100>}$ (GPa)	$E_{<110>}$ (GPa)	$E_{<111>}$ (GPa)
Molybdène	457.7	160,9	111,2	0,707	394.4	312,9	292,8
Chrome	350,0	67,8	100,8	0,714	328.0	266,2	250,4
Tungstène	501,0	198,0	151,0	0,997	388,8	388,0	387,7
Aluminium	108,2	61,3	28,5	1,225	63,9	72,6	76,1
Nickel	244,0	158,0	102,0	2,372	119,8	200,6	258,9
Fer alpha	231.4	134.7	116.4	2,407	132,0	220,4	283,3
Cuivre	168,4	121,4	75,4	**3,190**	66.7	130.3	191,1

Anisotrope

6/26/2020

Séminaire FAPS - Pilotage de l'anisotropie - Denis SOLAS

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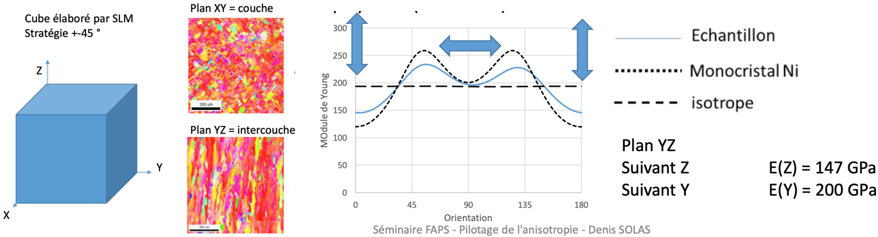
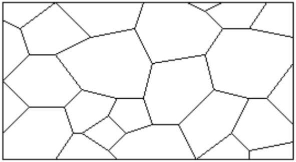
Functionally graded materials



Séminaire FAPS - Pilotage de l'anisotropie - Denis SOLAS



Polycristal

Functionally graded materials

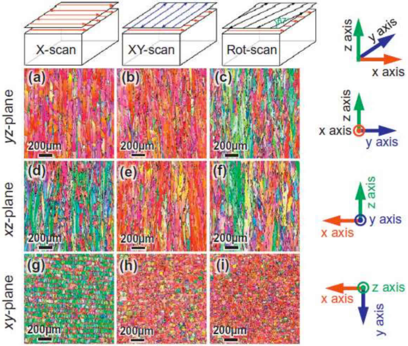
Work of Denis Solas, ICMMO, Orsay, Paris-Saclay.

Pilotage de l'anisotropie par SLM

➡ Choix de la stratégie

Materials and Design 140 (2018) 307–316

Puissance = 200 W
Vitesse = 800 mm/s
Ecartement = 80 µm
Epaisseur couche = 40 µm



Functionally graded materials

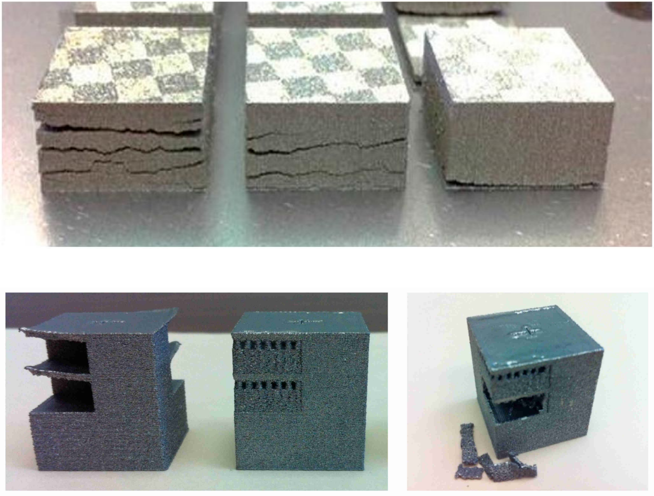
- One can optimize the material properties (anisotropy) by controlling the laser path, its speed and power.
- PhD thesis of Mathilde Boissier (co-supervised with C. Tournier, LURPA): simultaneous optimization of the path and of the shape
- PhD thesis of Abdelhak Touiti (co-supervised with F. Jouve, LJLL): simultaneous optimization of the anisotropy and of the shape

III - Some limitations of additive manufacturing

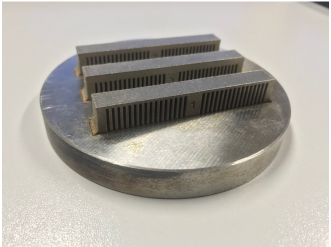
- A very large amount of energy is deposed on the structure: residual thermal stresses.
- Large thermal deformations, thermal fracture.
- Defect, porosities
- Separating a built part from the baseplate is tricky.
- Slow process, not for large series production.

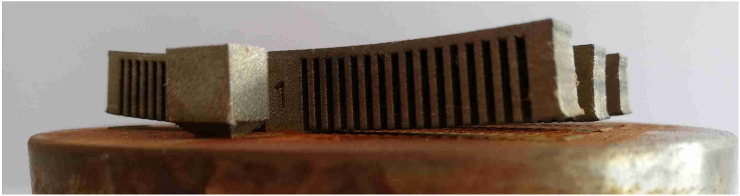
Some failures of additive manufacturing

Thermal stresses and deformations:



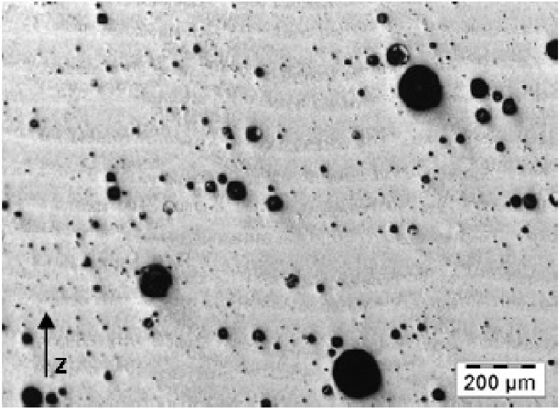
Other failure: residual stresses





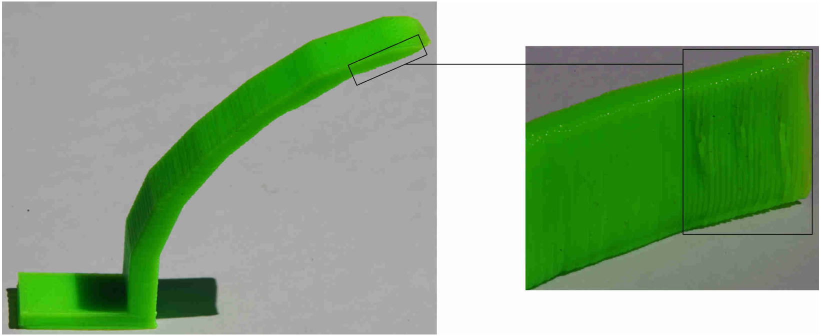
Strong deformation after separation from the baseplate

Other failure:porosities



pores in a 3D-printed aluminum alloy
(source: Inside Metal Additive Manufacturing)

Other failure: overhang limitation



The angle between the structural boundary and the build direction has an impact on the quality of the processed shape.

Overhang limitation

Example of a bad 3-d printing due to overhangs.

Constraints in Additive Manufacturing

Constraints are required to avoid failures in the fabrication process

- almost horizontal **overhang** surfaces cannot be built
- metal melting → large temperatures → **thermal residual stresses** and thermal deformations
- deformations of the structure may stop the powder deposition system
- minimal time (or energy) for completion
- removing the powder (no closed holes)
- bad metallurgical properties (for example, porosities)

How to avoid failures in additive manufacturing ?

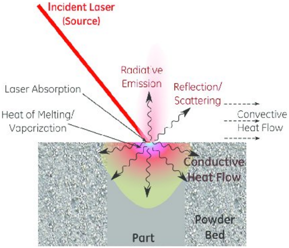
Numerical simulations are required for predicting the success or the failure of the process.

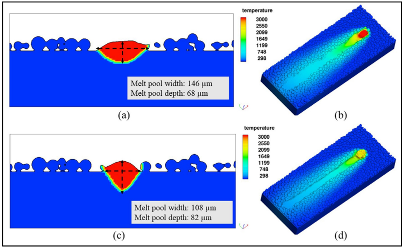
What do we need ?

- good models at different length-scales
- multi-physics models
- model reduction and/or HPC
- optimization

and new ideas !

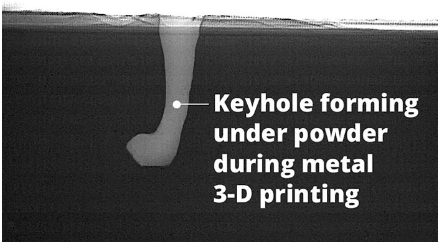
IV - Models of the manufacturing process

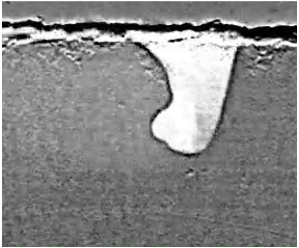




Microscopic model: heat exchange, phase change, fluid mechanics in the melt pool, granular media for the powder coating...
(Spears & Gold, 2016)

Microscopic models





For example: to simulate the "keyhole" phenomenon.

Macroscopic models

Microscopic models are too computationally intense to be used in optimization loops.

Macroscopic models ignore small details and a lot of physics...
but they are useful for quick prediction and optimization !

Two examples:

- thermo-mechanical model
- inherent strain model

Thermo-mechanical model

Heat equation:

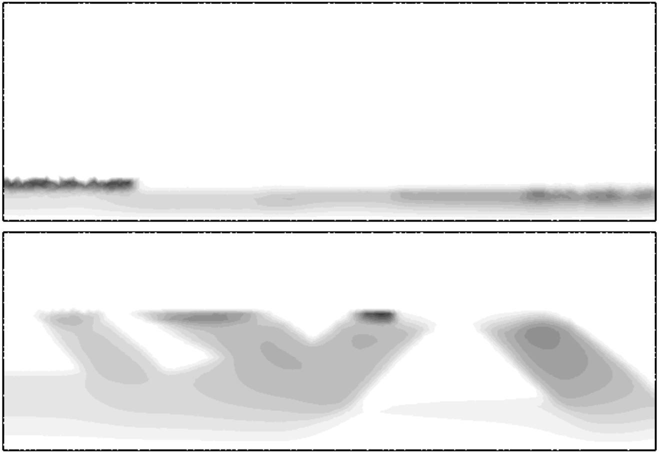
$$\begin{cases} \rho \dfrac{\partial T}{\partial t} - \mathrm{div}(\lambda \nabla T) = Q(t) & \text{in } (0, t_F) \times D \\ T = T_{init} & \text{on } (0, t_F) \times \Gamma_{base} \\ \lambda \nabla T \cdot n = -H_e(T - T_{init}) & \text{on } (0, t_F) \times (\partial D \setminus \Gamma_{base}) \\ T(t = 0) = T_{init} & \text{in } D \end{cases}$$

Thermoelastic quasi-static equation:

$$\begin{cases} -\mathrm{div}(\sigma) = 0 & \text{and } \sigma = \sigma^{el} + \sigma^{th} \quad \text{in } (0, t_F) \times D, \\ \sigma^{el} = Ae(u) & \text{and } \sigma^{th} = K(T - T_{init})\,\mathrm{Id}, \end{cases}$$

Material parameters ρ, λ, A, K are different for solid or powder.
Source term $Q(t) =$ beam spot, traveling on the upper layer.
Weak coupling: **first**, solve the heat equation, **second**, solve thermoelasticity.

Path of the source term $Q(t)$



▸ path

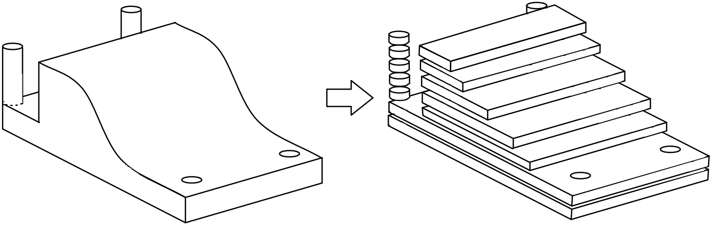
Inherent strain model

- Simplified engineering model, issued from welding.
- No heat equation !
- Inherent strain ε^{inh} tabulated from experiments.

Thermoelastic quasi-static equation:

$$\begin{cases} -\operatorname{div}(\sigma) = 0 & \text{and } \sigma = \sigma^{el} + A\varepsilon^{inh} \quad \text{in } (0, t_F) \times D, \\ \sigma^{el} = Ae(u) & \\ +\text{boundary conditions} & \text{and layer by layer process} \end{cases}$$

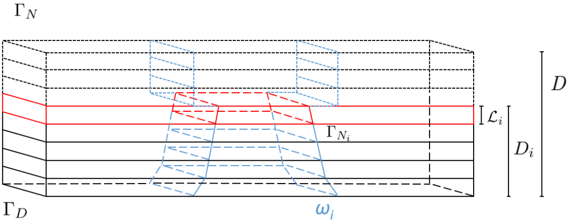
Macroscopic models: layer by layer process



Additive manufacturing involves a layer by layer process.

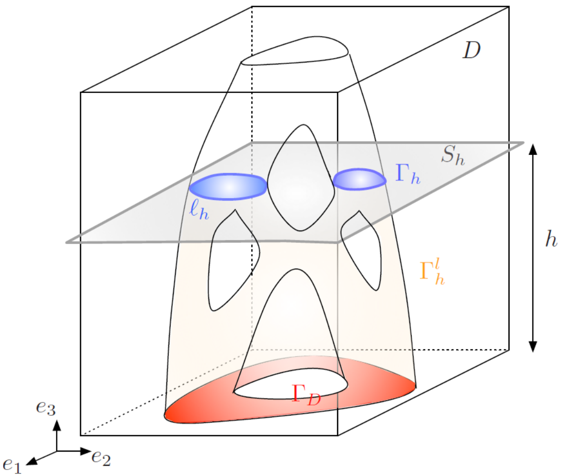
We must take this process into account.

Layer by layer modeling



- Denote by D the building chamber and by Ω the structure to be built.
- In $\mathbb{R}^d$ the vertical direction, e_d, is the building direction (layers are normal to e_d).
- The layer i is built at height h_i.
- When building the ith layer, only the intermediate domain D_i and intermediate shape Ω_i play a role.

Layer by layer modeling



For a final shape Ω, define **intermediate shapes** Ω_i of increasing height h_i

$$\Omega_i = \{x \in \Omega \text{ such that } x_d \leq h_i\} \quad 1 \leq i \leq n.$$

Layer by layer thermoelasticity

Rewrite the thermo-elasticity model in a layer by layer context.

1. Each layer i is built between time t_{i-1} and t_i, $1 \leq i \leq n$.
2. Each layer i at height h_i.
3. Intermediate domains $D_i = \{x \in D \text{ such that } x_d \leq h_i\}$

G. Allaire, L. Jakabcin, *Taking into account thermal residual stresses in topology optimization of structures built by additive manufacturing*, M3AS 28(12), 2313-2366 (2018).

Layer by layer model

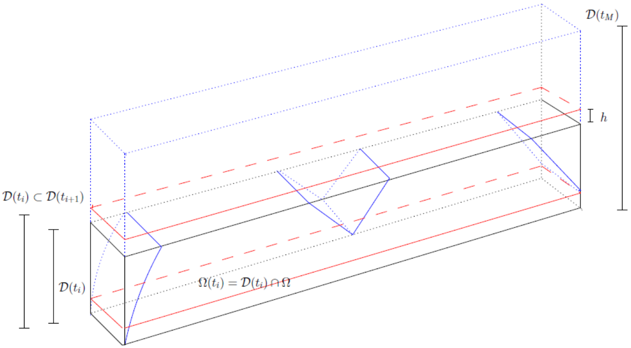
Heat equation:

$$\begin{cases} \rho\dfrac{\partial T}{\partial t} - \mathrm{div}(\lambda\nabla T) = Q(t) & \text{in } (t_{i-1}, t_i) \times D_i \\ T = T_{init} & \text{on } (t_{i-1}, t_i) \times \Gamma_{base} \\ \lambda\nabla T \cdot n = -H_e(T - T_{init}) & \text{on } (t_{i-1}, t_i) \times (\partial D_i \setminus \Gamma_{base}) \\ T(t = t_{i-1}) = T_{init} & \text{in } D_i \setminus D_{i-1} \end{cases}$$

Thermoelastic quasi-static equation:

$$\begin{cases} -\mathrm{div}(\sigma) = 0 & \text{and } \sigma = \sigma^{el} + \sigma^{th} \quad \text{in } (t_{i-1}, t_i) \times D_i, \\ \sigma^{el} = Ae(u) & \text{and } \sigma^{th} = K(T - T_{init})\,\mathrm{Id}, \end{cases}$$

Notations



1. Build chamber D, vertical build direction e_d.
2. Intermediate domains $D_i = \{x \in D \text{ such that } x_d \leq h_i\}$.
3. Final shape Ω and intermediate shapes $\Omega_i = \Omega \cap D_i$.
4. Mixture $D_i = \Omega_i \cup P_i$ of solid and powder.

Layer by layer inherent strain model

1. Powder is neglected and only the intermediate shapes $\Omega_i = \Omega \cap D_i$ are taken into account.
2. The *i*th layer is denoted by $\mathcal{L}_i$.
3. The inherent strain ε^{inh} is applied only in the layer $\mathcal{L}_i$.

The model is

$$\left\{ \begin{array}{rcll} -\mathrm{div}(\sigma_i) & = & 0 & \text{in } \Omega_i, \\ \sigma_i & = & A\left(e(u_i) + \varepsilon_{\mathcal{L}_i}\right) & \text{with } \varepsilon_{\mathcal{L}_i}(x) = \varepsilon^{inh}\chi_{\mathcal{L}_i}(x), \\ \sigma_i n & = & 0 & \text{on } \Gamma_{N_i}, \\ u_i & = & 0 & \text{on } \Gamma_D \cap \partial\Omega_i. \end{array} \right.$$