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Virtual Modeling and Additive Manufacturing for Advanced Materials

IB melt pool: experimental validation of thermal model (AMBench2018)

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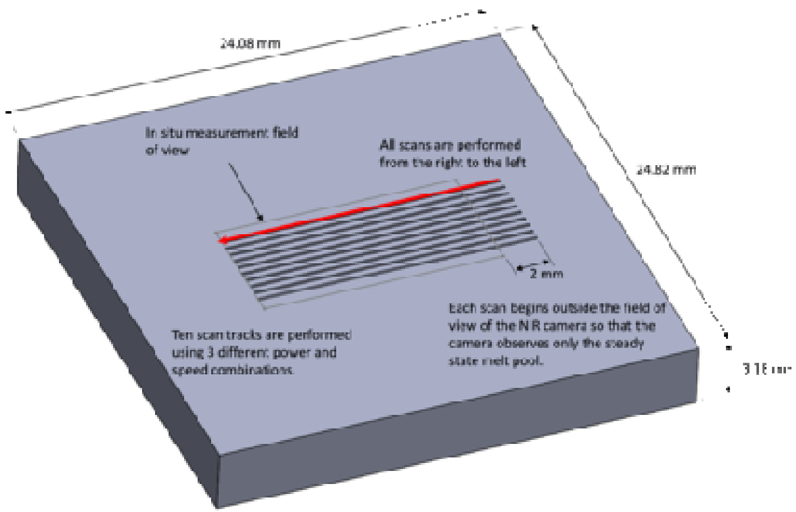
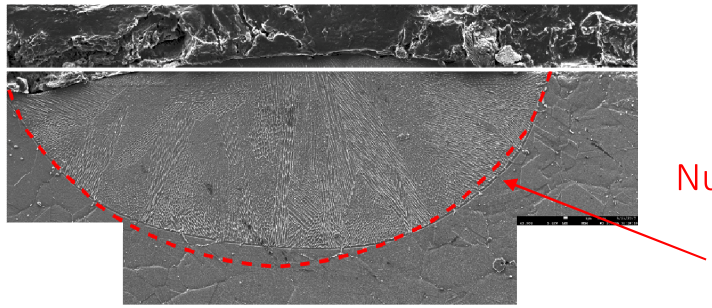
- Material: INCONEL 625
- No powder involved
- Adjacent, independent laser scans using 3 different combinations of power and speed



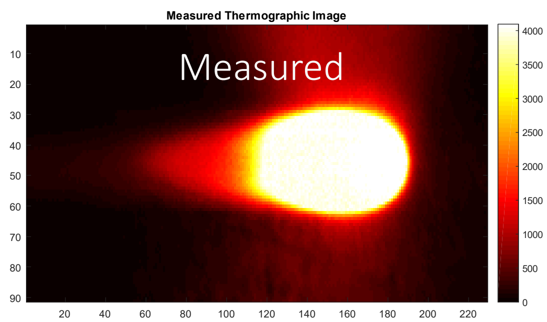
Source: https://www.nist.gov/ambench/amb2018-02-description

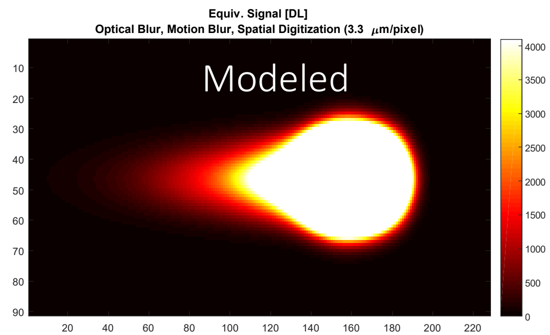
- *Ex-situ* measurements of the melt-pool cross section



Numerical result

- *In-situ* measurements of the melt-pool length.





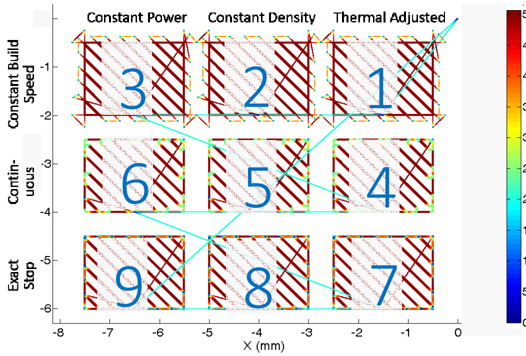
Acknowledgments: Brandon Lane, Ho Yeung (NIST), **Kollmannsberger** (TU Munich), **M.Carraturo, A.Reali** (UniPV & IMATI-CNR)

Publications: Kollmannsberger, Carraturo, Reali, FA. *Accurate Prediction of Melt Pool Shapes in Laser Powder Bed Fusion by the Non-Linear Temperature Equation Including Phase Changes* Integrating Materials and Manufacturing Innovation, 8, 167-177 (2019)

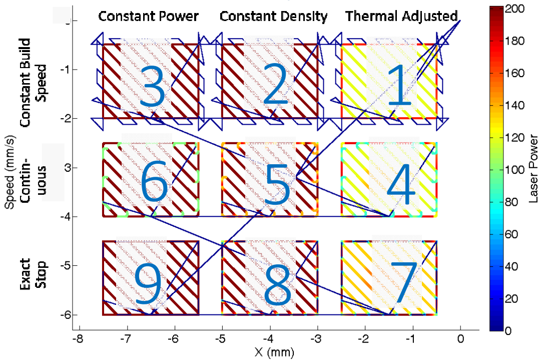
IB melt pool: effect of scanning strategies

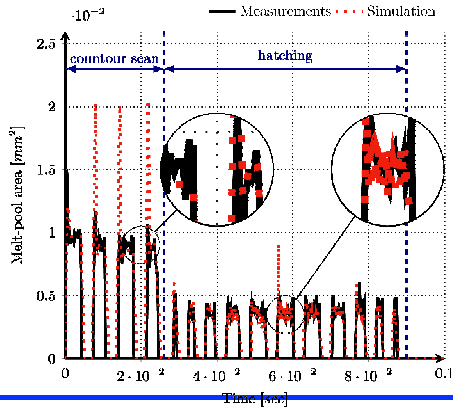
- **Objective:** Estimate the influence of different laser power and speed control modes on Residual Stress
- **Method:**
  - **Nine different scan strategies** printed on a bare Inconel 625 plate
  - **Thermal model validated** wrt melt-pool area of the first scan strategy measured **using high-speed thermal camera**
  - RS magnitude and distribution compared to find the strategy minimizing Residual Stress

Laser power

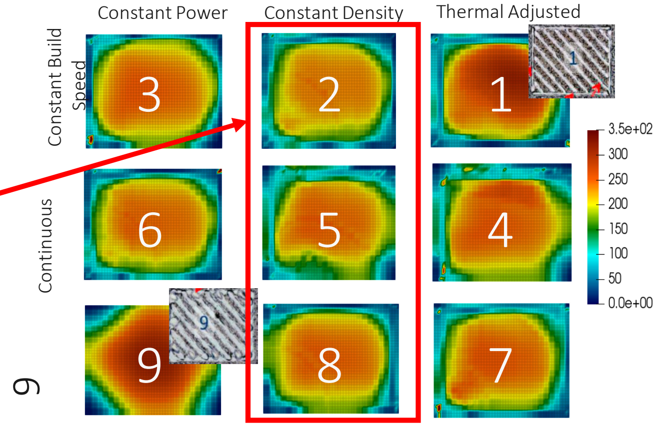


Laser speed





Lower RS are obtained for scan strategy with constant density power



The different combinations of power and speed control modes allow to achieve different results in terms of melt-pool variations, surface topography, and RS

Acknowledgments: **B.Lane, H.Yeung** (NIST), **Kollmannsberger** (TU Munich), **M.Carraturo, A.Reali** (UniPV & IMATI-CNR)

Publications: Carraturo, Lane, Yeung, Reali, FA *Numerical evaluation of advanced laser control strategies Influence on residual stresses for laser powder bed fusion systems*. Integrating Materials and Manufacturing Innovation, 2020.

IB thermo-mechanical part-scale model

- Heat transfer equation

$$\rho c\dot{T} - \nabla(k\nabla T) = Q \quad \text{in} \quad \Omega$$

$Q = \frac{\eta P}{HAV}$ (heating)

$Q = 0$ (cooling)

- Thermal problem Initial conditions

$$T(\mathbf{x}, t) = T_0 \quad \text{at} \quad t = 0$$

- Thermal problem boundary conditions

$$k\nabla T(\mathbf{x}, t) \cdot \mathbf{n} = q^s + q^p \quad on \quad \Gamma_N$$

q^s conduction through the upper layer

q^p conduction through the powder

- Mechanical equation

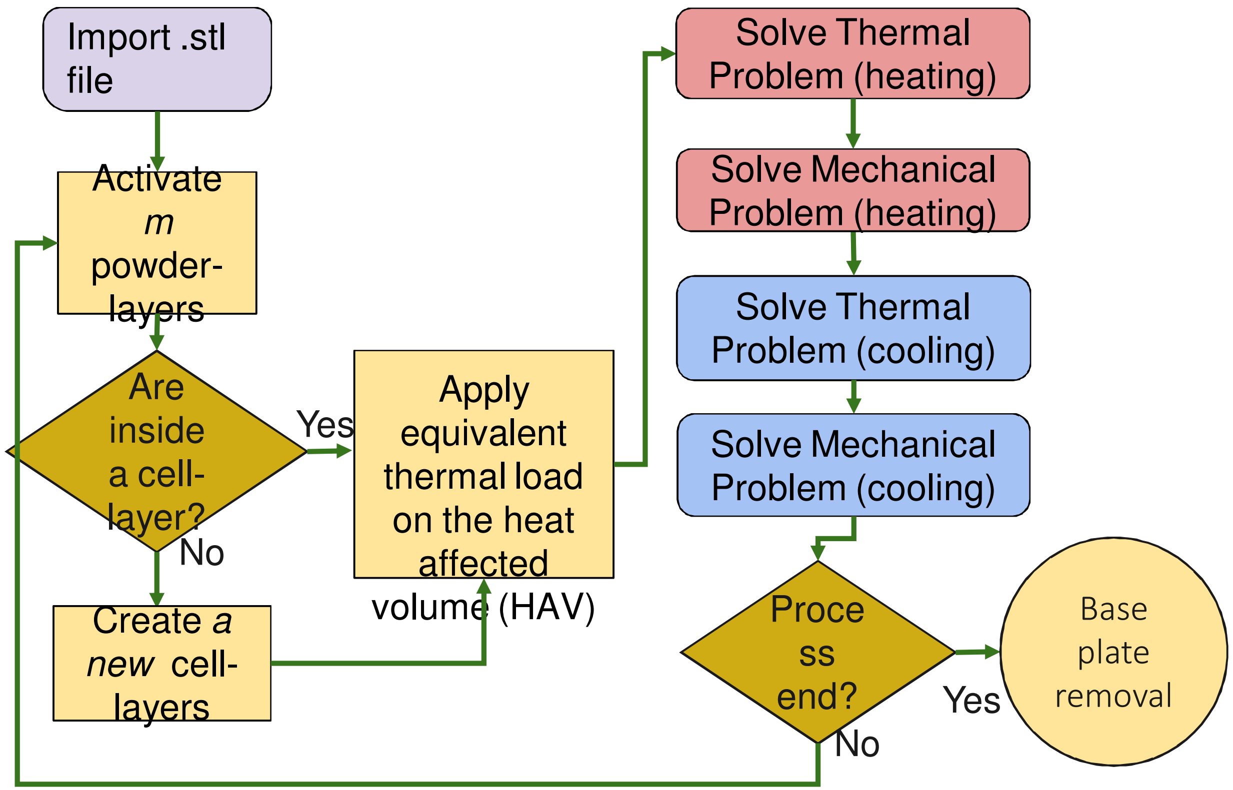
$$\nabla\boldsymbol{\sigma} = \mathbf{0}$$

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{th} + \boldsymbol{\varepsilon}^{el} + \boldsymbol{\varepsilon}^{pl}$$

$$\boldsymbol{\varepsilon}^{th} = \alpha^{th}\Delta T\mathbf{I}$$

$$\boldsymbol{\varepsilon}^{pl} = \dot{\gamma}\frac{\partial\Phi}{\partial\boldsymbol{\sigma}}$$

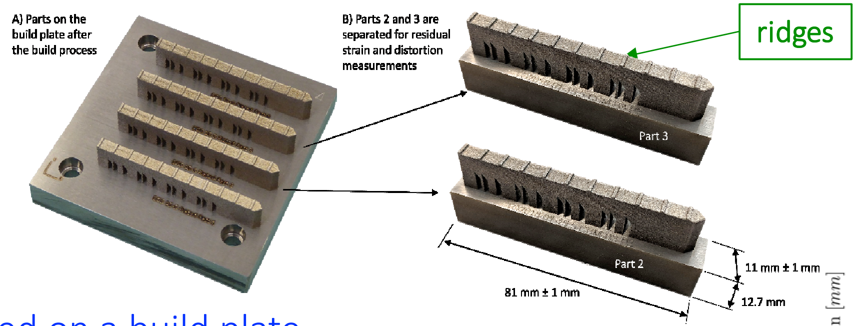
$$\Phi = \sigma_{vm} - \sigma_y(\gamma, T) \le 0$$



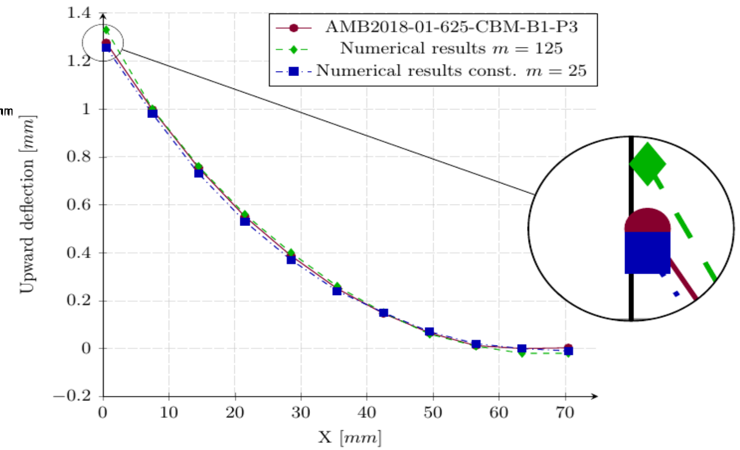
Publications Carraturo, Jomo, Kollmannsberger, Reali, FA, Rank, *Modeling and experimental validation of an immersed thermo-mech. part-scale analysis for LP-BFP*. Additive Manuf. 36 (2020)

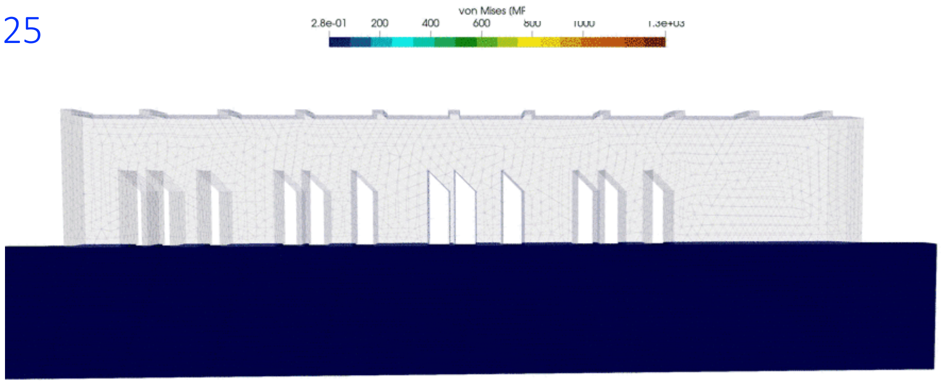
Experimental Validation

- Problem setup:
  - Part height: 12.5 mm
  - # total powder layers: 625
  - Layer thickness: 20 μm
- Experimental setup:
  - 4 cantilever beams are printed on a build plate using Inconel 625 using an EOS M270.
  - Part deflection after support removal is measured at the eleven ridges
- Simulation setup:
  - 2 FCM discretization with agglomerated layers of 2.5 mm and 0.5 mm thickness, respectively 125 and 25 powder layers / agglomerated layer
- Numerical results:
  - **Max. deflection relative error < 5%**
  - **Almost perfect correlation** with experimental measurements (~99%)



Source: https://www.nist.gov/ambench/amb2018-01-description

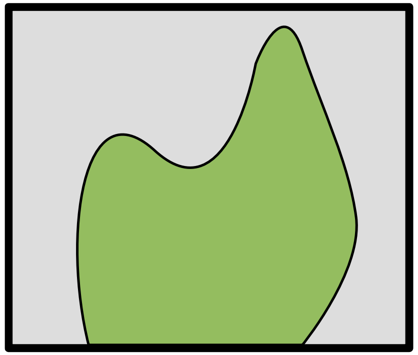




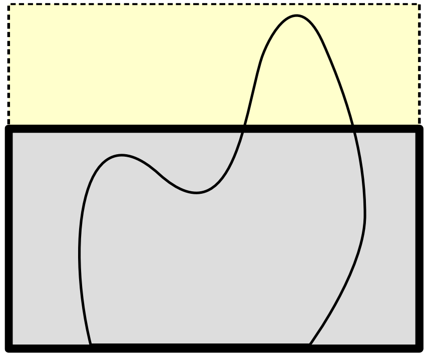
Publications: Carraturo, Jomo, Kollmannsberger, Reali, FA, Rank, *Modeling and experimental validation of an immersed thermo-mechanical part-scale analysis for LP-BFP*. Additive Manuf., 36 (2020)

AM: toward a two-level method

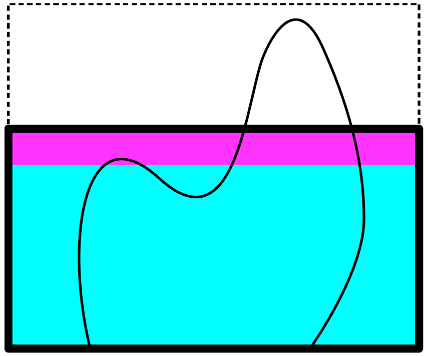
Physical domains



Final physical domain Ω
Green: component to be printed

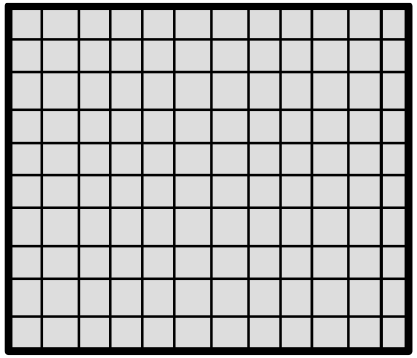


Physical domain Ω @ t
Gray: active domain
Yellow: dormant domain

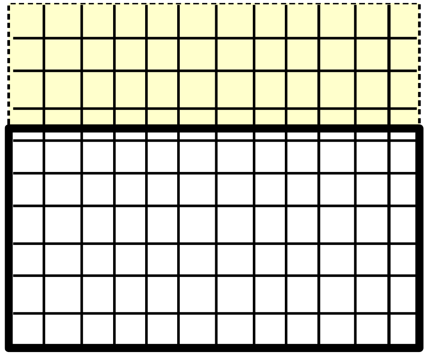


Different scales @ t:
Cyan: coarse-scale region Ωt+
Magenta: fine-scale region Ωt-.

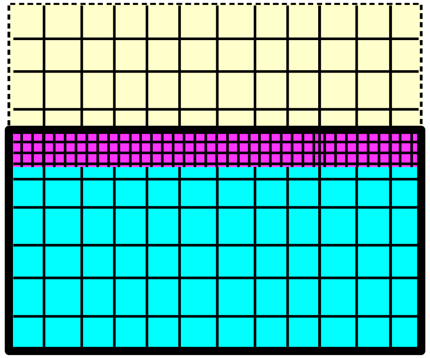
Computational grids



Global coarse mesh:
- resolves coarse scale
- covers entire domain



Global coarse mesh @ t
- fixed throughout simulation
- dormant region: numerically as an artificial domain



Full discrete problem @ t
- fine local mesh covers fine-scale region
- coarse global mesh covers entire domain

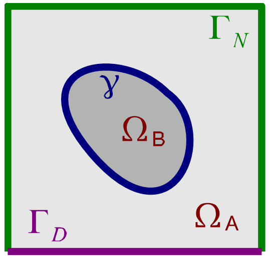
AM: toward a two-level method

- GOAL: approach problems with small portion featuring a significantly more complex physics
  - Additive manufacturing / Fluid flow with immersed membranes
- IDEA: avoid adaptivity, computationally attractive, difficult to generate, possibly with preconditioning issues
  - DIFFICULTIES: problems with time-dependent evolution of region requiring fine mesh

- ORIGINAL TOY PROBLEM: steady thermal problem
- Two regions, Ω_A and Ω_B with different thermal properties

$$
\begin{aligned}
&\nabla \cdot (\kappa \nabla T) = f && \text{in} \quad \Omega_A \,\&\, \Omega_B \\
&T = T_D && \text{on} \quad \Gamma_D \\
&\kappa \frac{\partial T}{\partial n} = q && \text{on} \quad \Gamma_N
\end{aligned}
$$

$$
\kappa = \begin{cases} \kappa_A & in \quad \Omega_A \\ \kappa_B & in \quad \Omega_B \end{cases}
$$

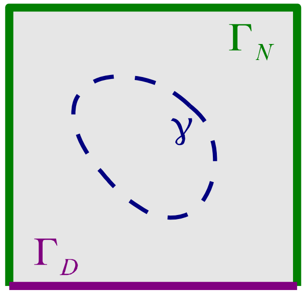


- continuity condition on γ / initial condition
- piecewise heat conductivity β
- Extension to transient & phase transition problems

As in Fat Boundary Method, split original problem into two subproblems (Global & Local)

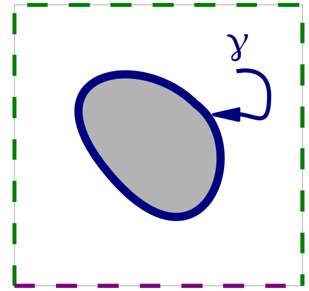
Global problem in Ω_+

$$
\begin{cases} \Omega_+ = \Omega_A \cup \Omega_B \\ \kappa_+ = \kappa_A \ \text{ in } \ \Omega_+ \end{cases}
$$



Local problem in Ω_-

$$
\begin{cases} \Omega_- = \Omega_B \\ \kappa_- = \kappa_B \ \text{ in } \ \Omega_- \end{cases}
$$



Acknowledgments: A.Viguerie, S.Bertoluzza, FA (UniPV & IMATI-CNR),

Publications:

- Viguerie, Bertoluzza, FA. *A Fat boundary-type method for localized nonhomogeneous material problems* Computer Methods in Applied Mechanics and Engineering, 364, 2020
- Viguerie, FA. *Numerical solution of additive manufacturing problems using a two-level method,* International Journal for Numerical Methods in Engineering, 2020 (accepted)

AM: toward a two-level method

- Since $\Omega_- \subset \Omega_+$, in Ω_- we have two distinct functions at the same time, a local one and a global one

- Theorem: Two level formulation (Ω_+ & Ω_-) is equivalent original formulation (Ω_A & Ω_B)

✓ Use two-level formulations to derive a two-level iterative method
✓ Solve iteratively until convergence is reached

Step k (iterate until convergence)

k.1 Obtain temperature distribution T^-_{k+1} by solving on subdomain Ω_-

$$-\nabla \cdot (\kappa_- \nabla T^-_{k+1}) = f \quad \text{in} \quad \Omega_-$$
$$T^-_{k+1} = T^+_k \quad \text{on} \quad \gamma$$

k.2 Obtain temperature distribution $\tilde{T}^+_{k+1}$ by solving on the entire domain Ω_+

$$-\nabla \cdot \left(\kappa_+ \nabla \tilde{T}^+_{k+1}\right) = f\Big|_{\Omega_+ \setminus \Omega_-} + (\kappa_+ - \kappa_-)\frac{\partial T^-_{k+1}}{\partial n} \quad \text{in} \quad \Omega_+$$
$$\tilde{T}^+_{k+1} = T_0 \quad \text{on} \quad \Gamma_D \qquad \& \qquad \kappa_+ \frac{\partial \tilde{T}^+_{k+1}}{\partial n} = \tilde{q} \quad \text{on} \quad \Gamma_D$$

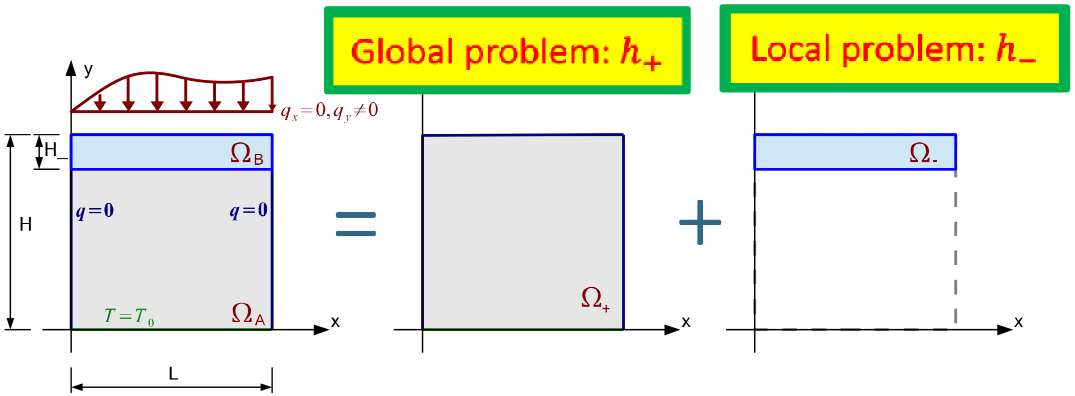
k.3 Perform relaxation step to obtain a temperature distribution T^+_{k+1}

$$T^+_{k+1} = \theta \tilde{T}^+_k + (1-\theta) T^+_k \quad \text{with} \quad \theta \in (0,1]$$

✓ Under-relaxation needed, as iterative algorithm may suffer instability ($\kappa_- >> \kappa_+$)
✓ Convert in weak form and discretize in the FE spirit (P_2 piecewise quadratic FE)

Two-level method: linear steady thermal problem

Linear steady thermal problem with Ω unit square and Ω_B top rectangle



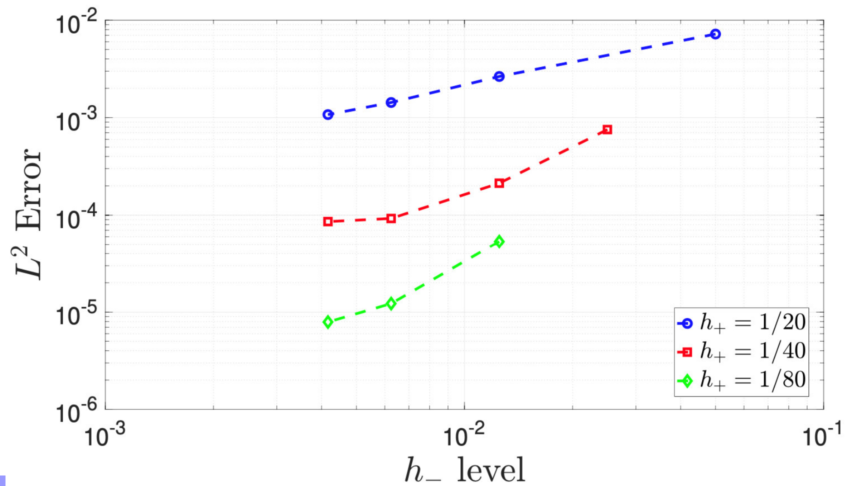
$$H = 1.0,\ L = 1.0,\ H_- = .05,\ \kappa_+ = 1.0,\ \kappa_- = 20.0,\ T_0 = 20$$

$$q = 2000 \exp\left(-\frac{(.1 - x)^2}{.0004}\right) \qquad H_-/H = 5\% \qquad \kappa_+/\kappa_- = 5\%$$

GOAL: investigate error in terms of global mesh size h_+ vs local mesh size h_-
IDEA: for different levels of h_+, observe error when refining h_-

Compute solutions for three global uniform meshes: h_+= 1/20, 1/40, 1/80
Plot error wrt reference solution (u_{ref} on a single fine uniform mesh with h = 1/500)

- For each curve the rightmost point corresponds to the solution obtained without using the two-level algorithm
- Refinement of local mesh h_- reduces error for each level of h_+
- Refine the local mesh to gain accuracy
- Accuracy improvements are not less pronounced as we refine global mesh

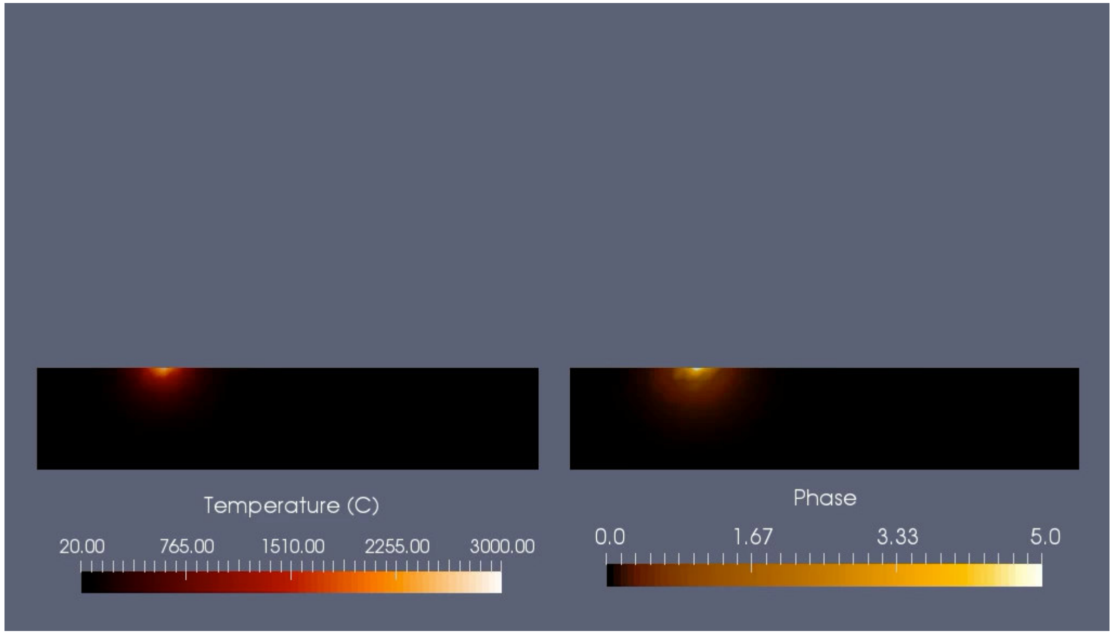


AM: toward a two-level method

Unsteady non linear thermal problem with moving heating source (heating/cooling)
Evolving domain, i.e. domain changes in time

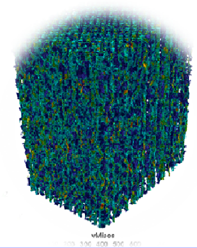
Temperature profile

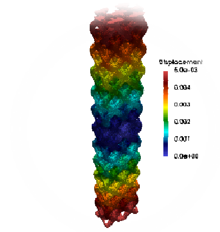
Material profile
Black: powder
Yellow: solid



Product simulation challenges

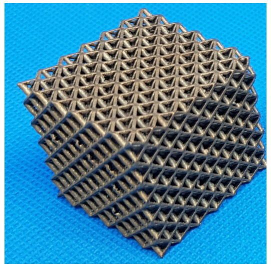
- **Quality control** of the final parts
- Material characterization
- **Mechanical properties** of the printed part



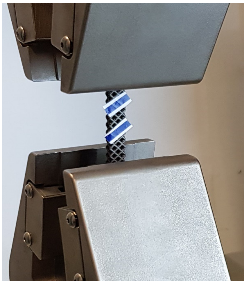


LPBF Product simulations: lattice components

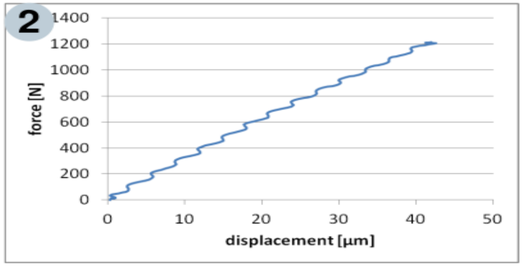
MOTIVATION:
- **lattice structure very appealing** in terms of lightness
- AM lattice structures with **long/expensive mechanical characterization procedure**



3D printed lattice

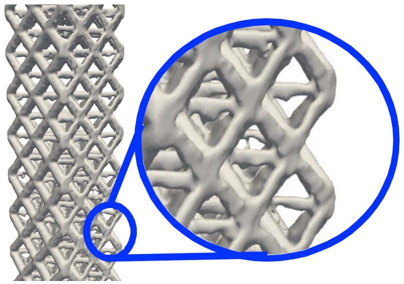


Experimental campaign

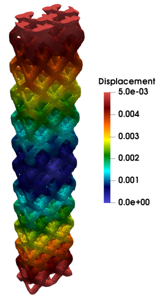


Lattice mechanical properties

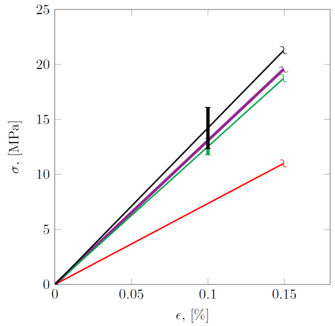
Numerical characterization of lattice structures as an effective and reliable alternative



CT-scan



Numerical analysis



Numerical characterization

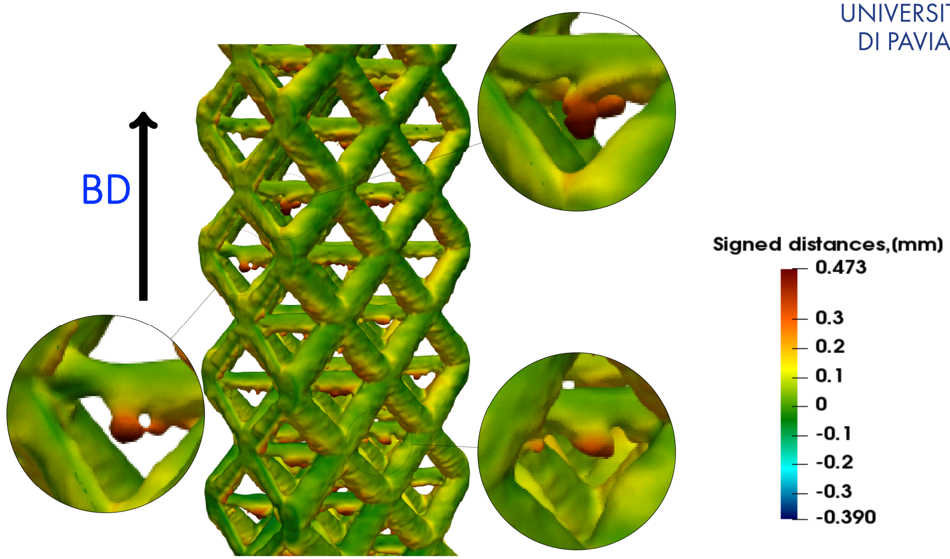
Aalto University

Acknowledgments: **N. Korshunova, S. Kollmannsberger, E. Rank** (TUM) **J. Niiranen, S.B. Hosseini** (Aalto Uni) **G.Alaimo, M.Carraturo, A.Reali** (UniPV & IMATI-CNR)

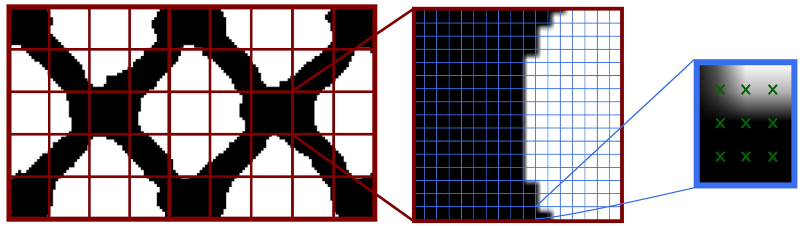
Publications: Korshunova, Alaimo, Hosseini, Carraturo, Reali, Niiranen, FA, Rank, Kollmannsberger, *Tensile and bending behavior of additively manufactured octet-truss structures* (in preparation)

LPBF product simulations: lattice components

- As-manufactured vs as-designed components
  - **LPBF processes:** introduces defects on the geometry, e.g., geometric defects due to lack of fusion defects
  - Influence of defects on 3D printed mechanical properties cannot be neglected (Maconachie 2019)
  - **As-manufactured geometrical model** of the part should be used for a reliable numerical analysis of the product
  - **Computed tomography (CT)**: optima choice for acquisition of as-manufactured geometry of 3D printed parts



- Immersed Numerical Analysis of CT-scan
  - **CT-scan images:** very large and usually unaffordable high computational cost to generate a conforming mesh
  - **As-designed (CAD) models:** not reliable for numerical analyses
  - **Finite Cell Method:** possible solution to compute directly on CT-scan images obtaining reliable numerical results with a reasonable computational cost



LPBF lattice components: three-point bending test validation

Objective: compare experimental vs predicted response

Experimental settings

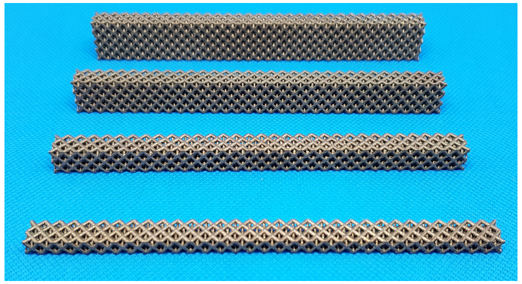
- Uniaxial test
- Three-point bending test
- Four octet-truss structures with varying thickness

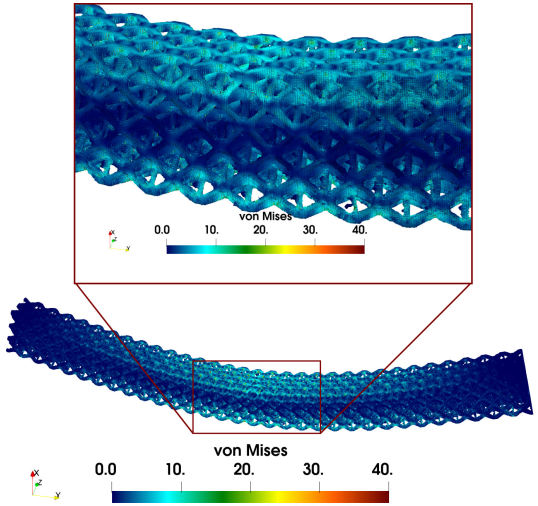
Comparison

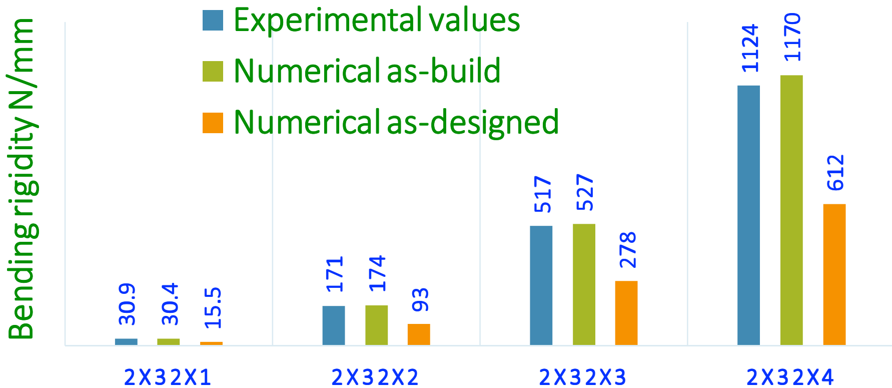
- **CAD-based model** (commercial codes)
- **CT-based model** (using FCM)
- **Experiments**

Results:

- **CT-based model:** well capture experimental data
- **CAD-model:** also for bending rigidity - values approx. 45% lower than experimental data



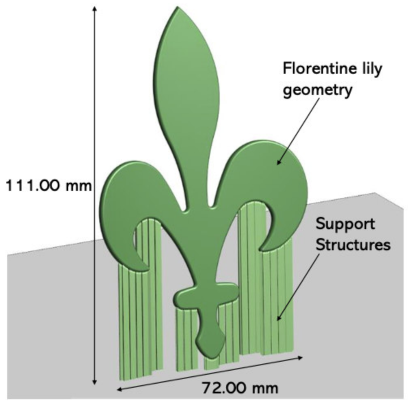


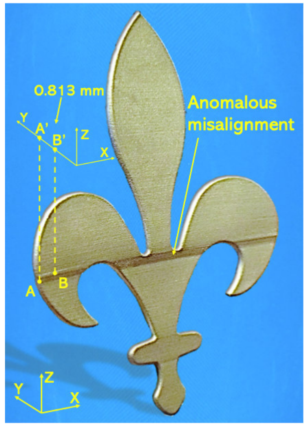


LPBF product simulations: industrial components

Coffee machine components (La Marzocco)

- Redesign & optimization: performance improvements
- Distortion predictions: geometrical accuracy improvements





AM coffee machine: redesign and optimize

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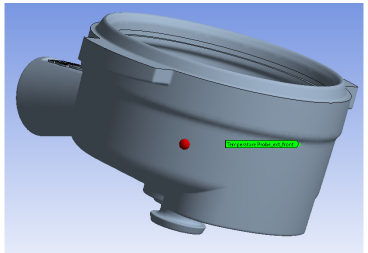
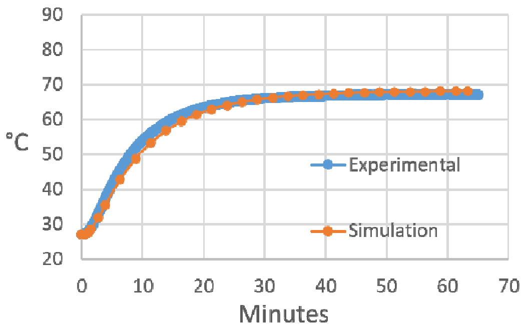
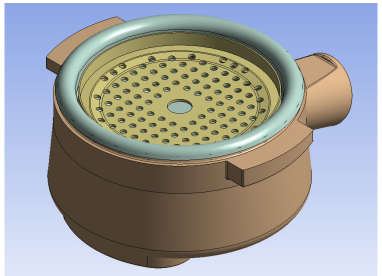
Original design

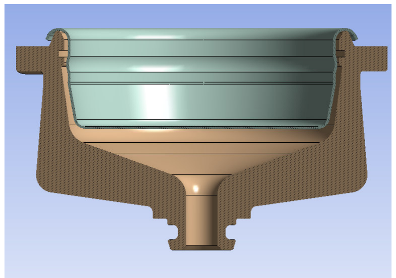


Model parameter fitting

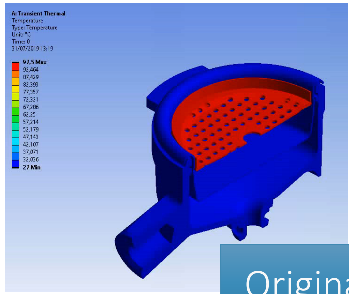


Optimization of new design

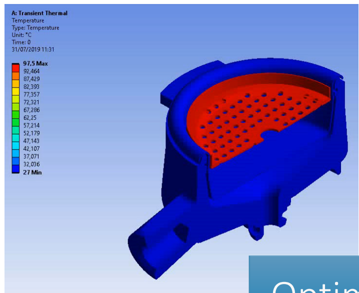




Simulation & validation

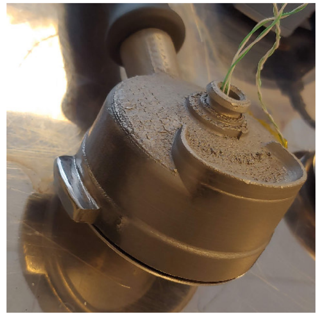


Original



Optimized

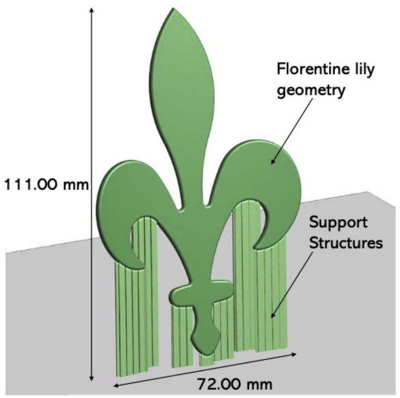
Additively manufactured & experimental validation

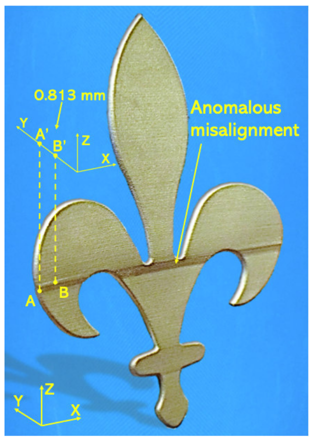


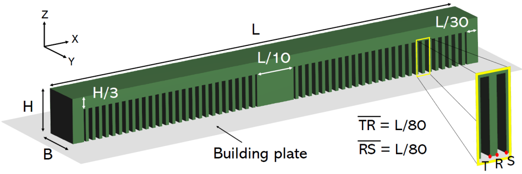
+7°C on the point of measure

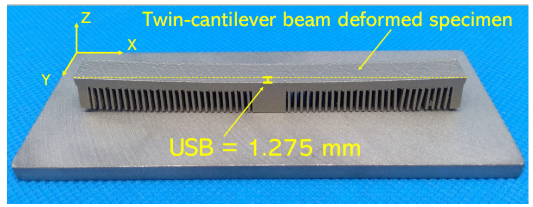
AM coffee machine: distorsion prediction

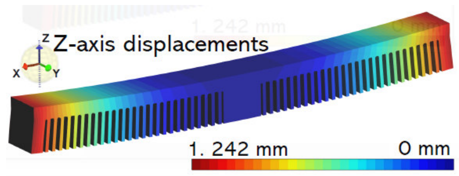
Step 1: evaluation of residual distortion

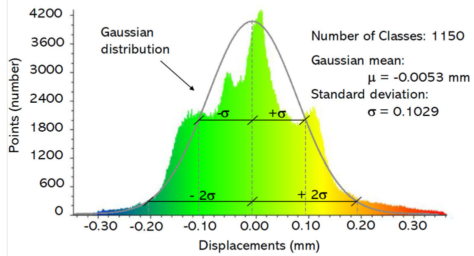


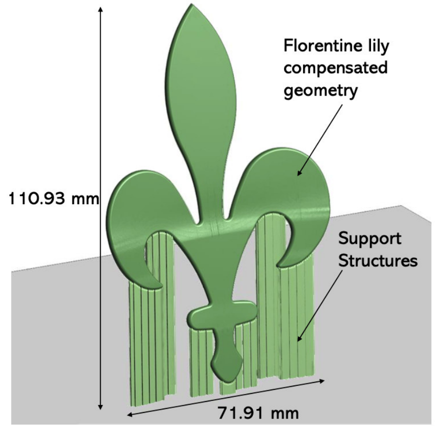


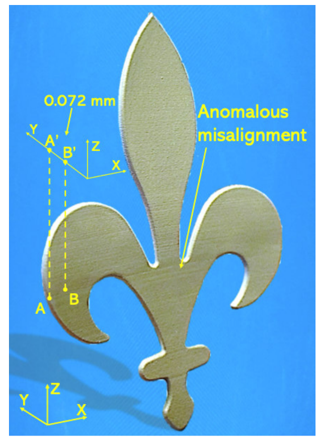




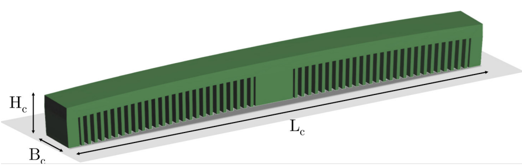


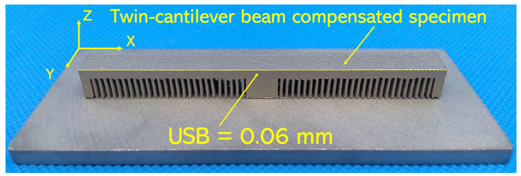






Step 2: compensation

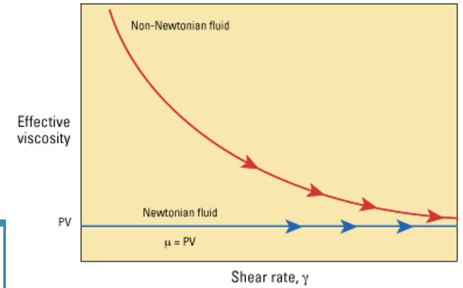




Innovative AM processes and materials

GOAL: combine low-cost AM technologies with chemical/thermal processes to produce metallic (or metal-ceramic) components

Path 1- Extrusion of non-Newtonian fluids (i.e., colloids)

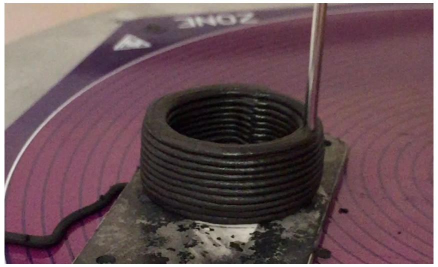


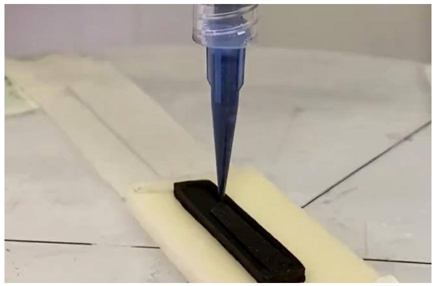
Ste 1. Preparation of precursor material

- Find optimal mix and proportion of ingredients
  - Oxides (powder)
  - Polymeric binder
  - Additives
- Avoid bubbles and contamination during mixing

Step 2. 3D printing

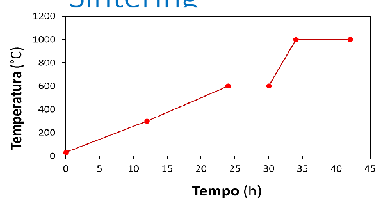
- Design of in-house system

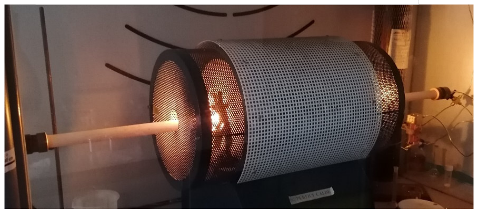


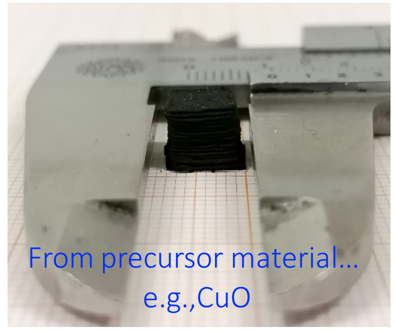


Step 3. Sintering processes

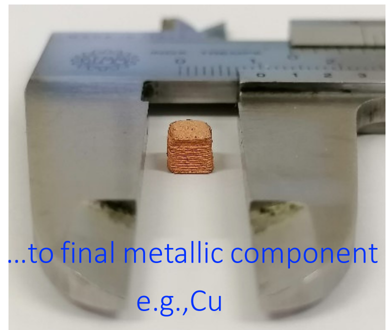
- Find optimal temperature ramps for
  - Solvent evaporation
  - Debinding
  - Sintering







From precursor material... e.g.,CuO



...to final metallic component e.g.,Cu

Acknowledgments: Simone Morganti, Umberto Anselmi Tamburini (UniPV)

Innovative AM processes and materials

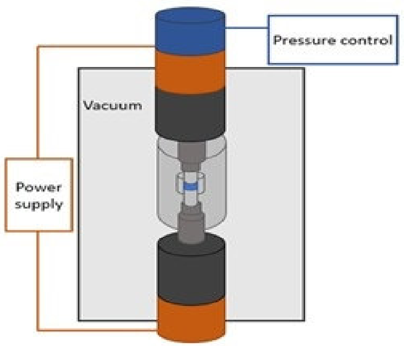
GOAL: combine low-cost AM technologies with chemical/thermal processes to produce metallic (or metal-ceramic) components

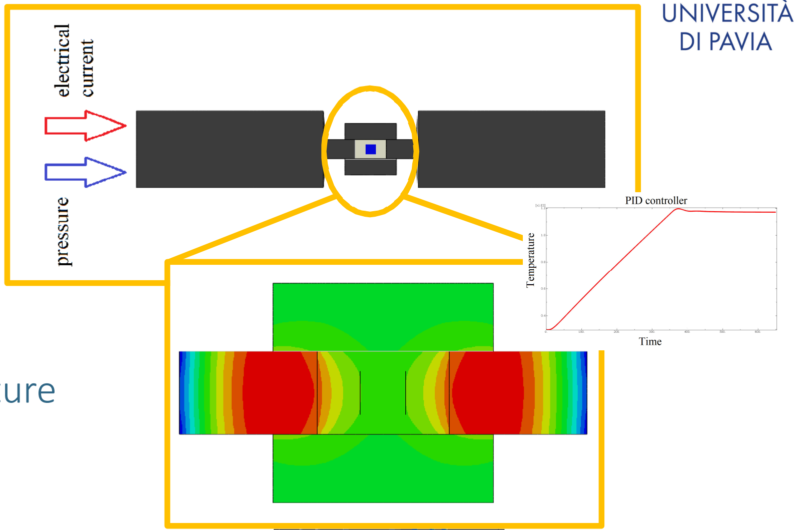
3D Printing

- Design of in-house system

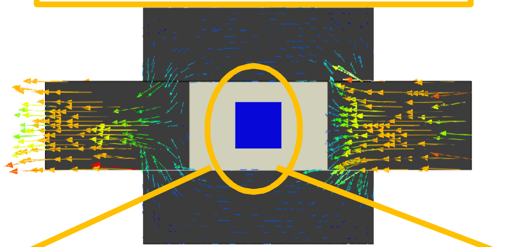
Sintering Processes

- Find optimal temperature ramps for:
  - Sintering with *Spark Plasma Sintering (SPS)* technique
  - No further steps:

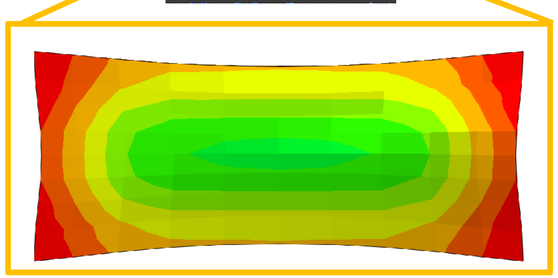




Temperature

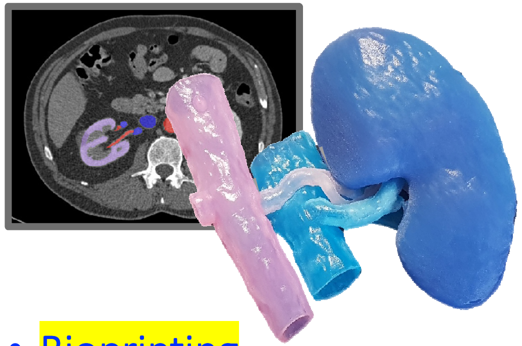


Electric field
Joule effect

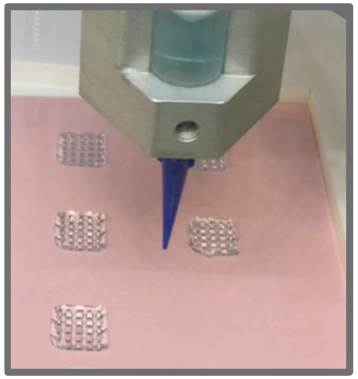


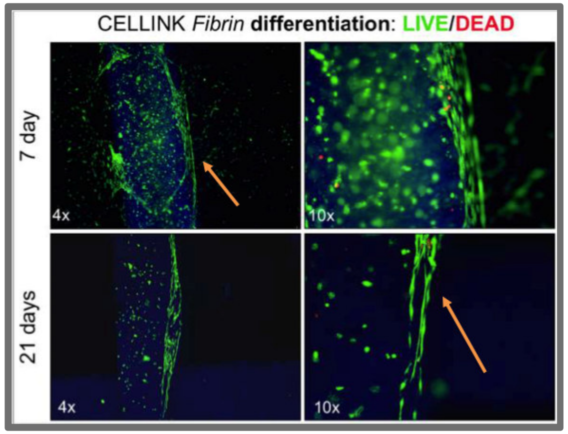
Pressure
Mechanics

- 3D4Med



- Bioprinting

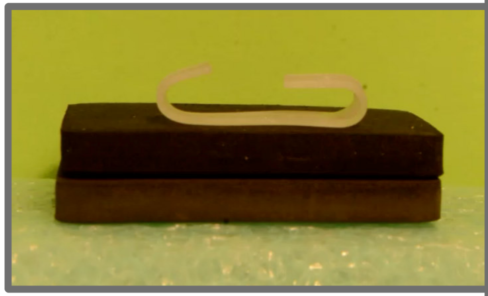


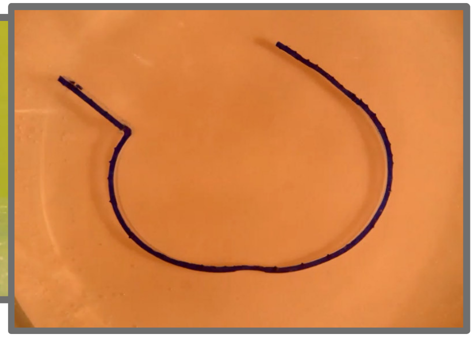


- Concrete 3D printing

ETESIAS

- 4D printing: devices activated by light or temperature





- industrial research: combination additive-subtractive / component simulation & production

Special thanks …

Massimo Carraturo, Stefania Marconi, Gianluca Alaimo, Alessandro Reali, Michele Conti, Simone Morganti, ….

… and all the members of Pavia team !!

3D printing … a real breakthrough technology