UNIVERSITÀ DI PAVIA

WORKSHOP INDAM

Istituto Nazionale di Alta Matematica

# Additive Manufacturing: from object reconstruction to component production. A world full of geometrical and modeling challenges!!


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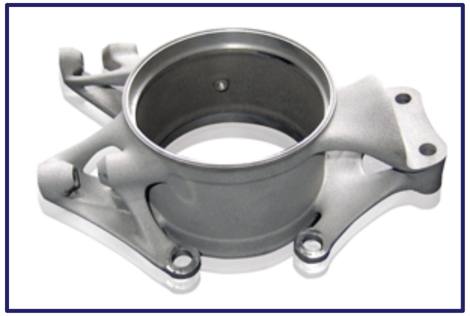
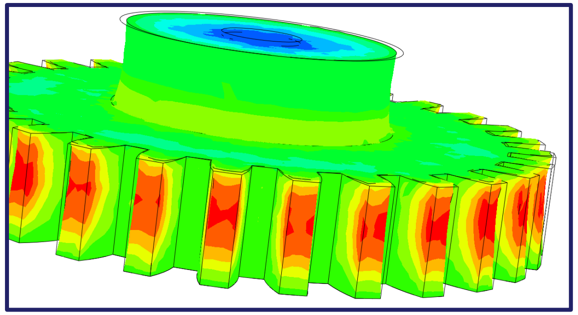
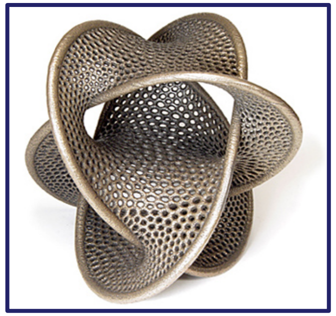





# Presentation outline

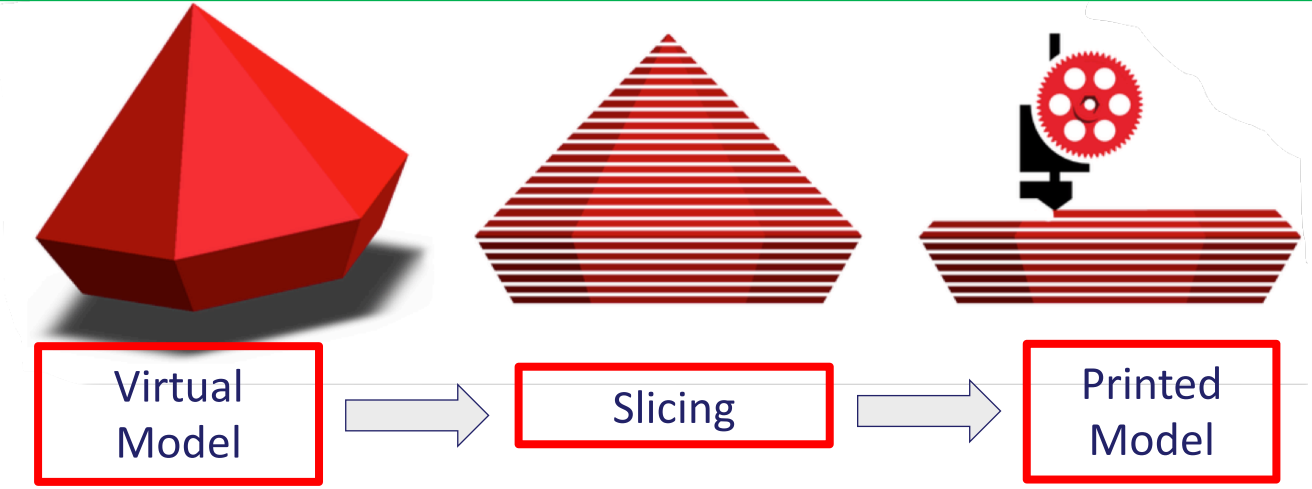


- **Introduction**
  - AM - 3DP: technologies, materials, advantages, open problems
- **Design for additive**
  - Phase-field topology optimization: gradient material
  - Adaptive isogeometric analysis
- **Process simulations**
  - Immersed boundary approach
    - Melt pool: high fidelity simulations
    - Part-scale: low fidelity simulations
  - Two-level method
- **Product simulations**
  - Lattice components
  - Industrial components
- **Future activities & directions**
- **Conclusion**

# AM – 3DP: a quick introduction



- **Additive manufacturing (AM)** also known as **3D printing (3DP)**
- Different from traditional subtractive (machining / milling) or molding manufacturing




**Some AM key-words !!**

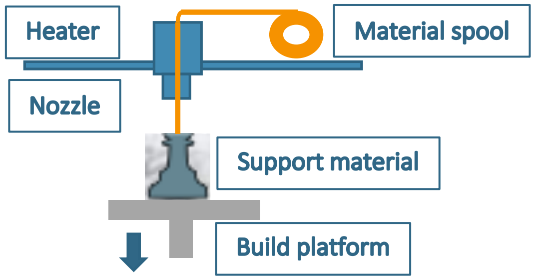
- **Native digital technology**
  - ✓ Technology which was born digital
- **Democratic technology**
  - ✓ Wide machine cost range
  - ✓ Democratic manufacturing & production
- **Material-dependent technology**
  - ✓ many different technologies & materials
  - ✓ 7 classes of processes (ASTM/ISO)
    - Material extrusion
    - Vat Photo Polymerization
    - Material jetting
    - Powder bed fusion
    - Directed energy deposition
    - Binder jetting process
    - Sheet lamination

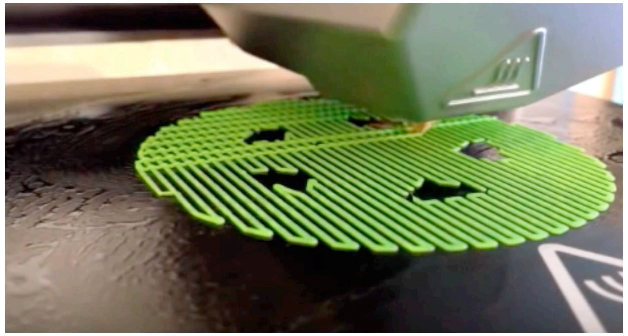
# AM – 3DP: 7 classes of processes (ASTM/ISO)



## Material extrusion
## FDM *(Fused Deposition Modeling)*

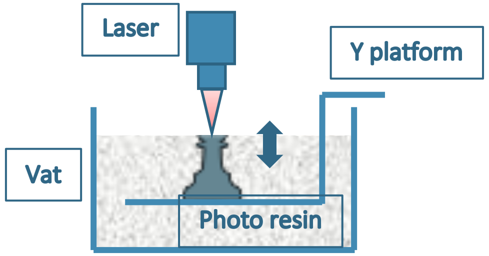
- Material: **thermoplastic filaments** (PLA, ABS, HIPS,TPU, TPE, PETG, Nylon, reinforced materials)
- Curing: **temperature gradient**

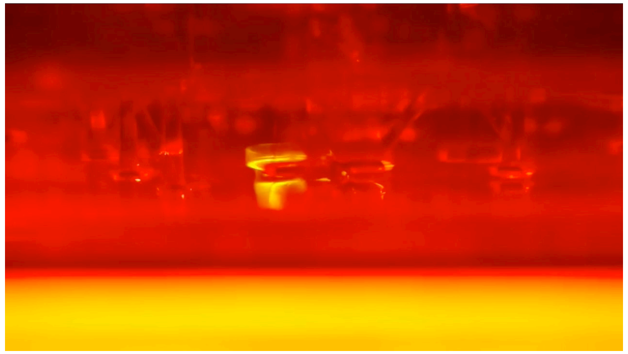


## Vat Photo Polymerization
## SLA *(stereolithography)*

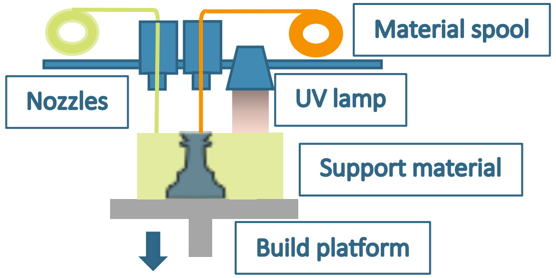
- Material: **photo-polymeric resins**
- Curing: **UV laser**

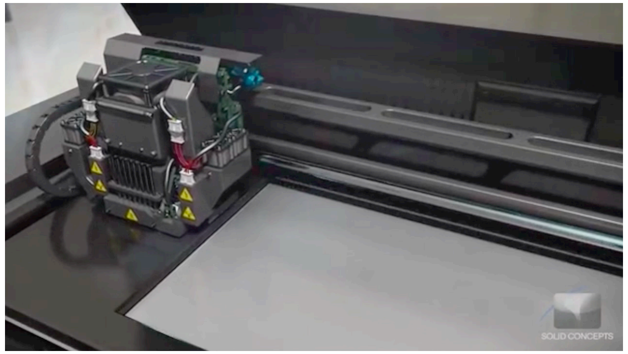


## Material Jetting

- Material: **photo-polymeric resins**
- Curing: **UV lamp**
- Possible debinding and sintering step



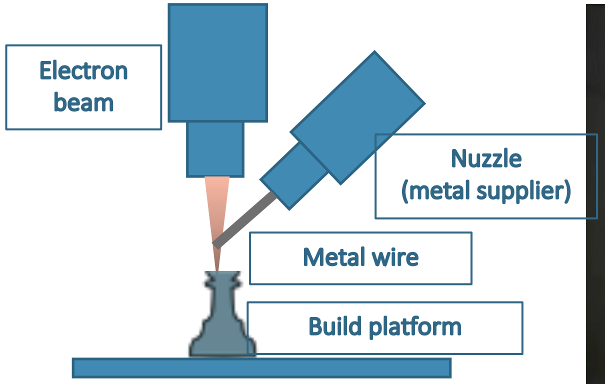



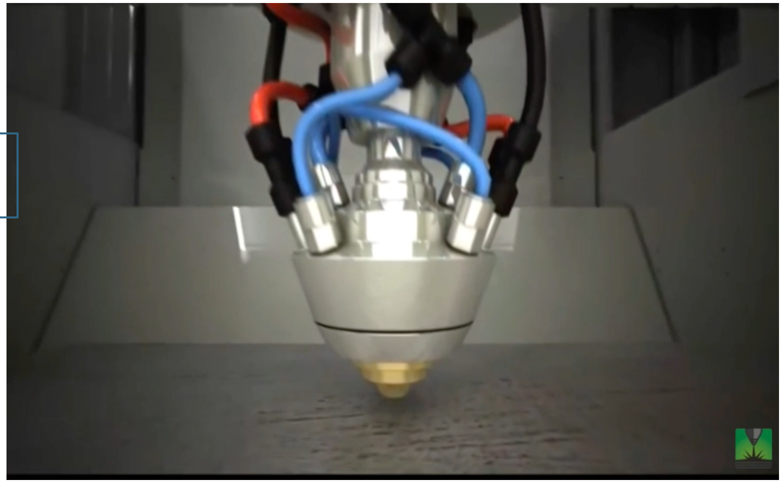
# AM – 3DP: 7 classes of processes (ASTM/ISO)



**Directed energy deposition** (DED)

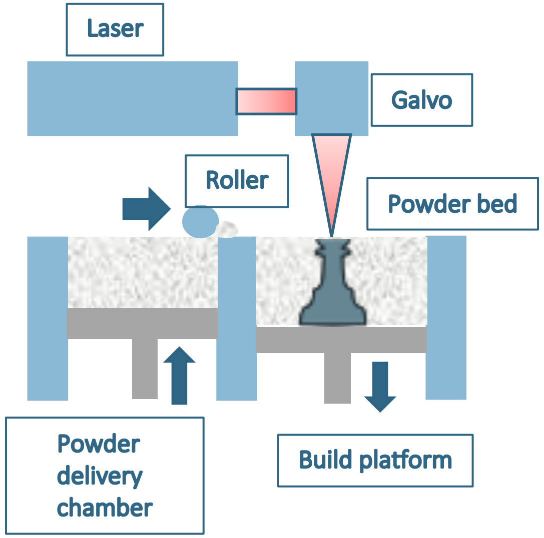
- Material: **metal alloys** (Ni, Co, Fe, Al, steel)
- Curing: **laser, electron beam, arc**



**Power bed fusion**

- Material: **metal alloys** (Ni, Co, Fe, Al, steel), **ceramics**
- Curing: **$CO_2$ laser, electron beam**



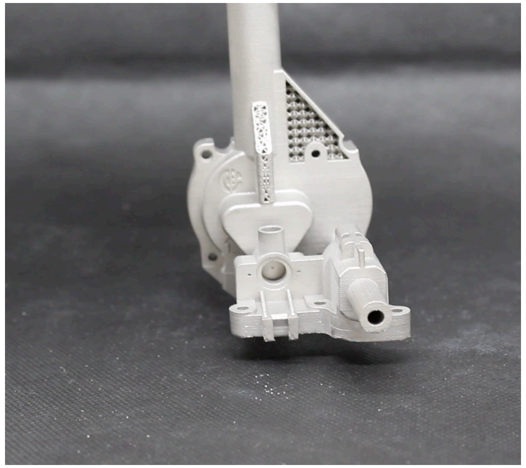

Courtesy of Renishaw Inc.

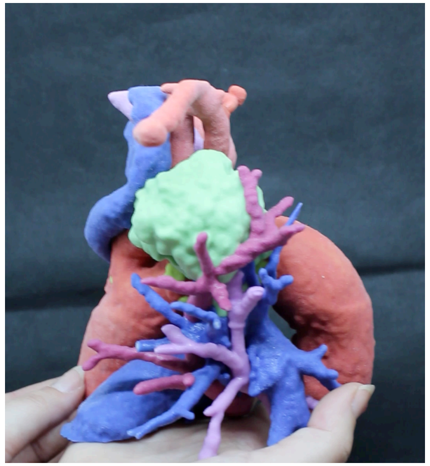
# AM: advantages / disadvantages / impact



## Advantages

- Produce complex geometries: close to free-form flexibility
- Produce single device made of multiple components (assembling more parts into a single one)
- Combine different devices and geometries in a single printing batch
- Green technology: reduced waste
- Accelerate design-testing-production process chain (even in our labs)

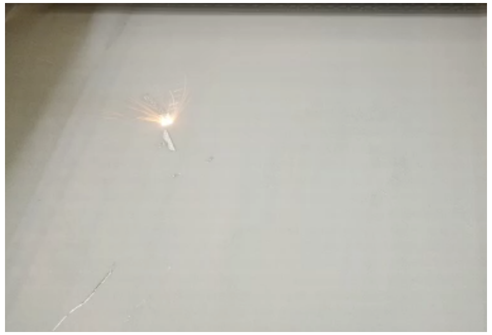


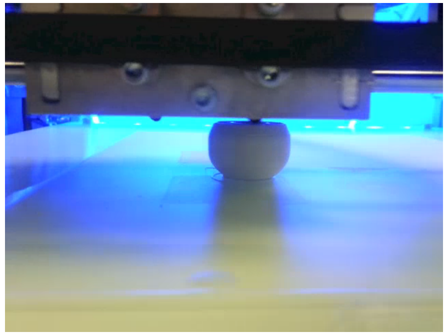


## Disadvantages

- Need of support materials (technology dependent)
- Very localized physics (multi-scale problem, technology dependent)

- Low speed (still a limitation)
- High cost (still a limitation)
- Interaction with further production steps (subtractive or finishing)





## Economics (Impact)

- Still production on low volumes: from prototypes to small batches (10.000 components)
- Entire supply chain will be radically changed
- Expected reduction of energy consumption from 5% up to 27% in many sectors

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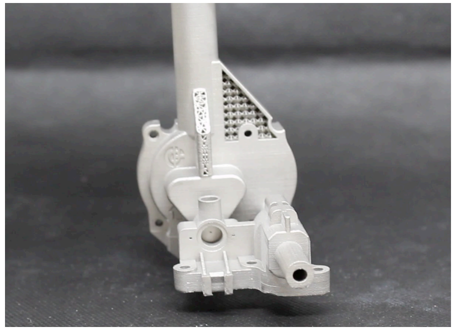
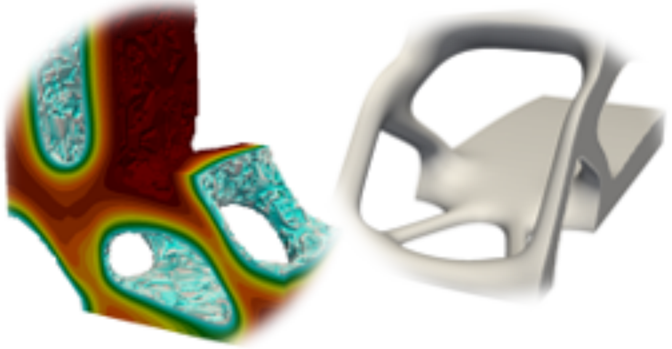
**Design for additive: challenges**

- **Close-to-freeform** flexibility requiring **novel design approaches**
- **Topology** and **shape optimization** as tools for **design**, focusing on product functionality and production constraints



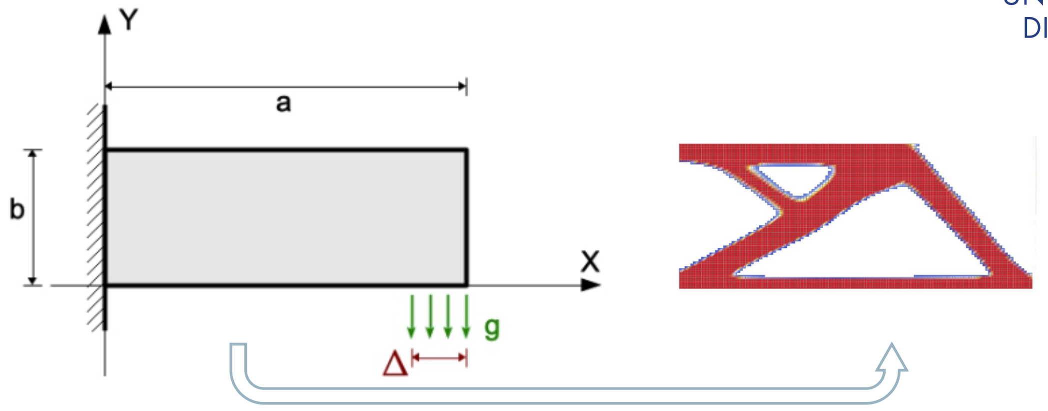


# Phase-field topology optimization (PF top-opt)



## Topology optimization: goal

- Optimal distribution of given amount of material
- Minimize structure compliance (i.e., maximize stiffness)




## Phase-field Method:

- No filtering methods required (cfr. SIMP approaches)

Limit discussion to for linear elastic problems
Introduce standard elastic problem in a domain $\Omega$

$$\begin{aligned} \mathrm{div}[\mathbb{C}\,\boldsymbol{\varepsilon}(\mathbf{u})] = \mathbf{b} \quad & \text{in} \quad \Omega \\ \mathbf{u} = \mathbf{0} \quad & \text{on} \quad \Gamma_D \\ [\mathbb{C}\,\boldsymbol{\varepsilon}(\mathbf{u})] = \mathbf{t} \quad & \text{on} \quad \Gamma_N \end{aligned}$$

**Objective**

Minimize structure compliance:

$$\int_{\Omega} \mathbf{b}\cdot\mathbf{u}\, d\,\Omega + \int_{\Gamma_N} \mathbf{t}\cdot\mathbf{u}\, d\,\Gamma$$

properly distributing material in $\Omega$

## Introduce description of meso-structure (variable density, lattice):

- Obtain a graded design, i.e., structure with varying density

**Acknowledgments: M.Carraturo, E.Rocca, A.Reali** (UniPV & IMATI-CNR), **E.Bonetti** (Università di Milano & IMATI-CNR), **D.Hömberg** (WIAS Institute Berlin)

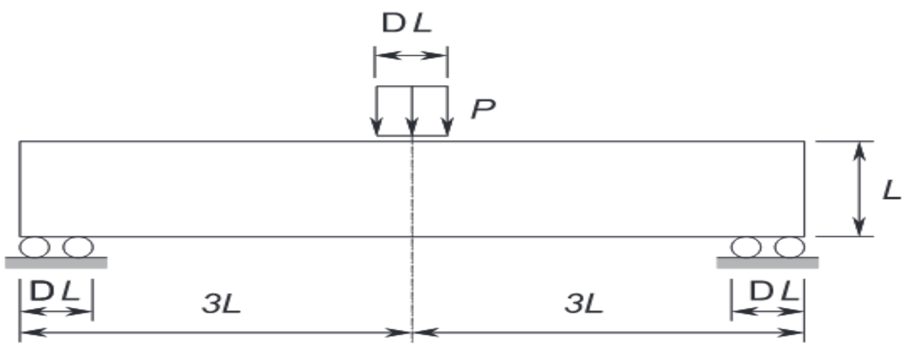
**Publications:**

- Carraturo, Rocca, Bonetti, Hömberg, Reali, FA. *Graded-material design based on phase-field and topology optimization*. Computational Mechanics, Vol. 64, 1589–1600 (2019)
- FA, Bonetti, Carraturo, Hömberg, Reali, Rocca. *A phase-field based graded-material topology optimization with stress constraint*. *M3AS*, Vol. 30 (08), 1461–1483 (2020)

# Phase-field gradient top-opt: MBB example



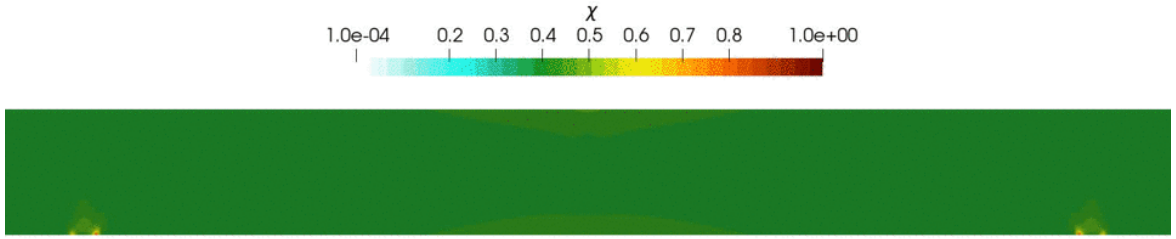
- **Messerschmitt-Bölkow-Blohm (MBB) beam**
  - Applied force = 25 N
  - Material: RGD851 rigid polymer from Stratasys (E=2.3 GPa and v=0.3)
  - 3D printer machine: Stratasys Objet 260 Connex 3
  - Volume fraction = 0.6
  - Mass fraction = 0.4




Messerschmitt-Bolkow-Blohm GmbH;Paytenet al.1998; Bulmanet al.2001

- **Results**
  1. Black-and-white structure indicates material presence
  2. Density continuously re-distributed within material region

$\chi$

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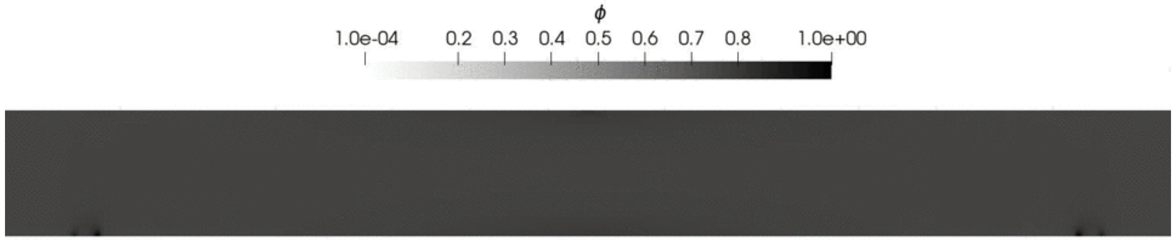


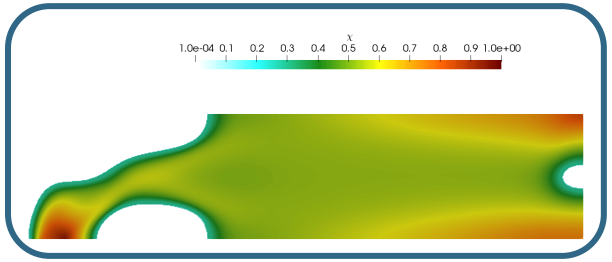

**Acknowledgments: G.Alaimo, M.Carraturo, E.Rocca, A.Reali** (UniPV & IMATI-CNR)

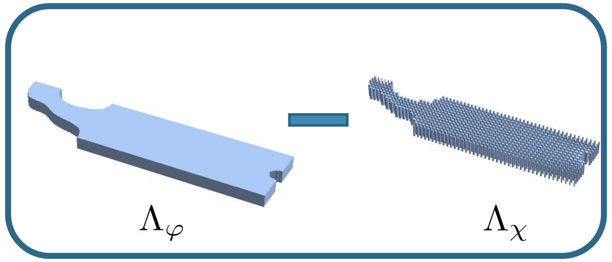
**Publications:** Alaimo, Carraturo, Rocca, Reali, FA. *Functionally graded material design for plane stress structures using phase field method*, II International Conference on Simulation for Additive Manufacturing - Sim-AM 2019

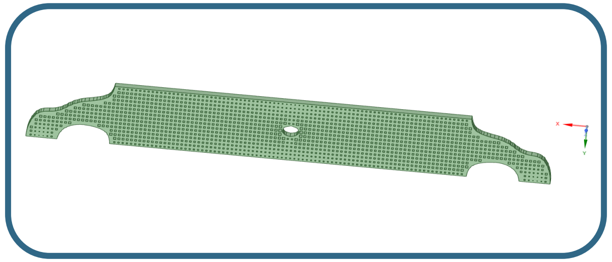
# Phase-field gradient top-opt: numerics, 3D printing & experiments

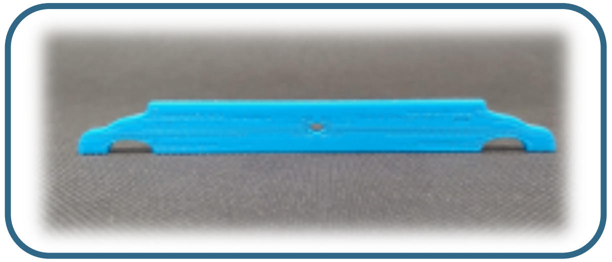


**Objective:** evaluate optimized versus uniform (**same weight**) specimen in terms of max. displacements

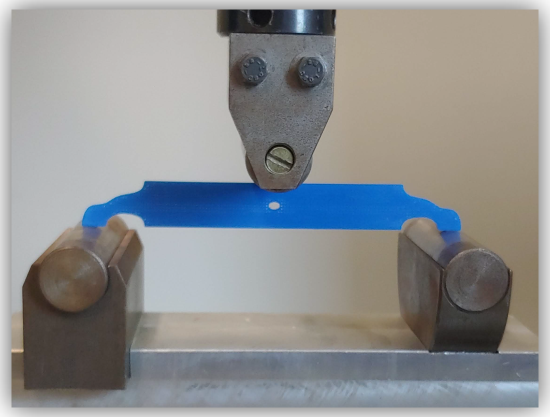


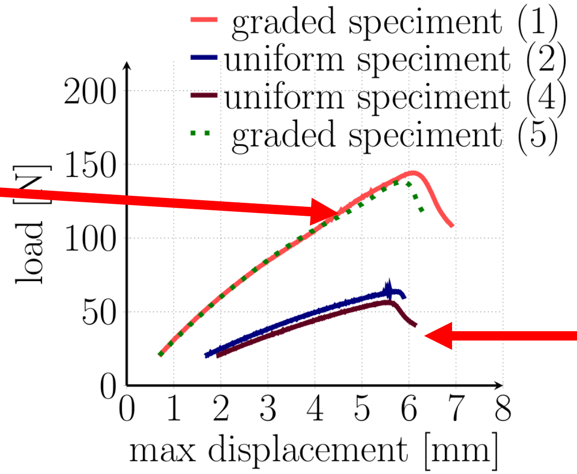



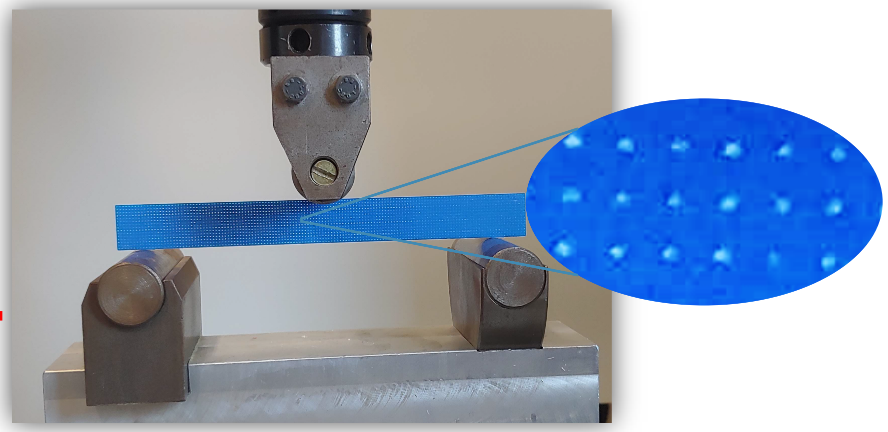





Discrete map of field variables → Generate 3D virtual model → 3D printing





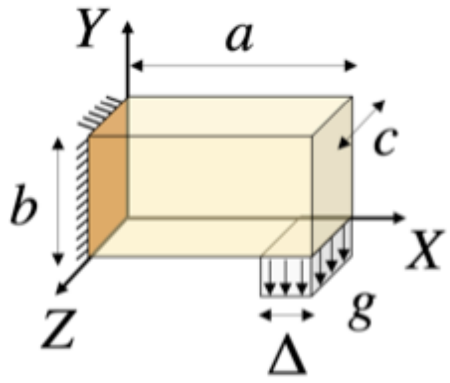
**Results:** for the same load, we observe a **reduction of 50%** as max. displacement

**Special thanks to:** **G.Alaimo (ProtoLab) & S.Marconi (3D4Med)**

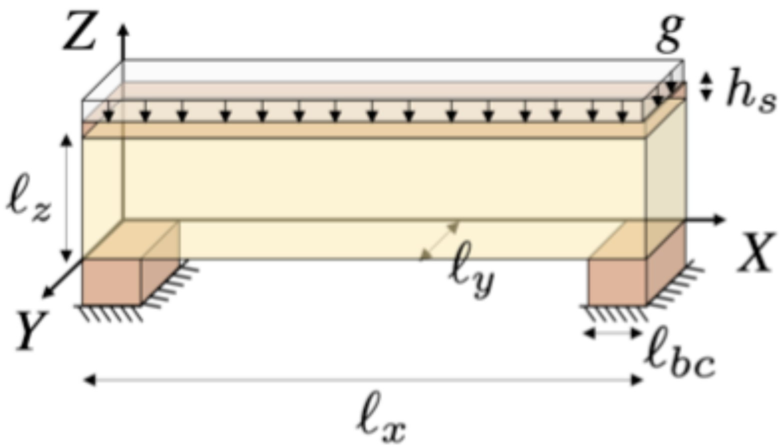
**Acknowledgments:** **G.Alaimo,** M.Carraturo, E.Rocca, A.Reali (UniPV & IMATI-CNR)

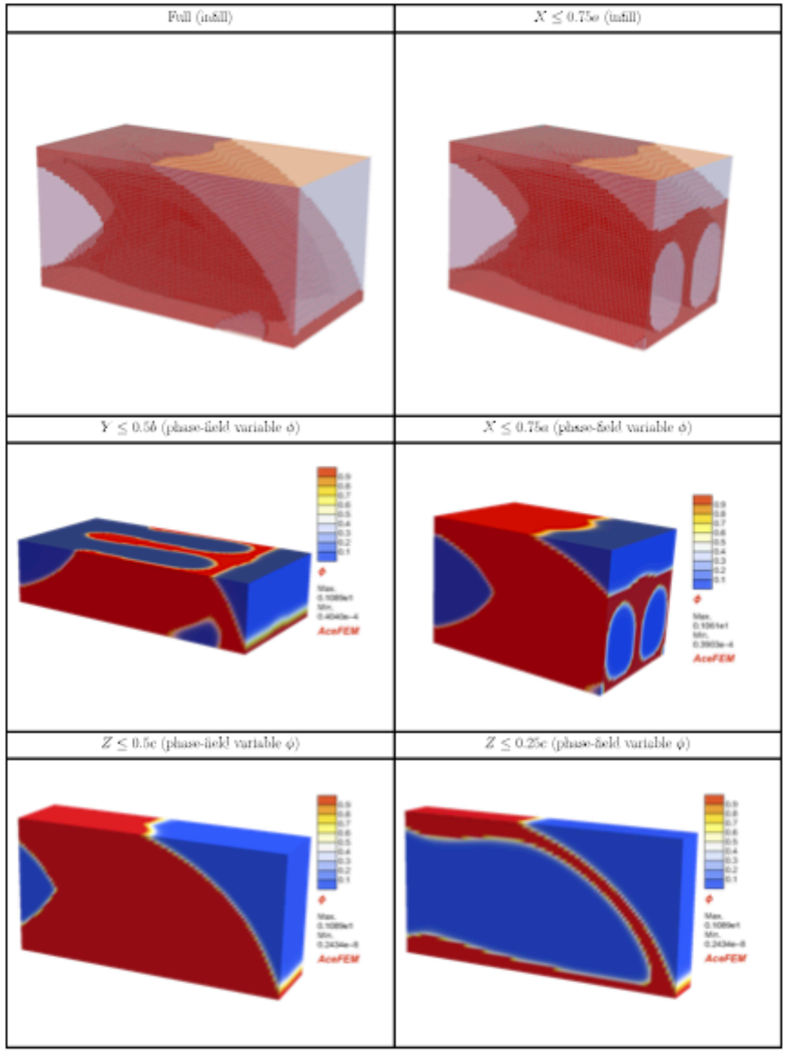
**Publications:** Alaimo, Carraturo, Rocca, Reali, FA *Functionally graded material design for plane stress structures using phase field method*, II Int.Conf. Simulation for AM - Sim-AM 2019

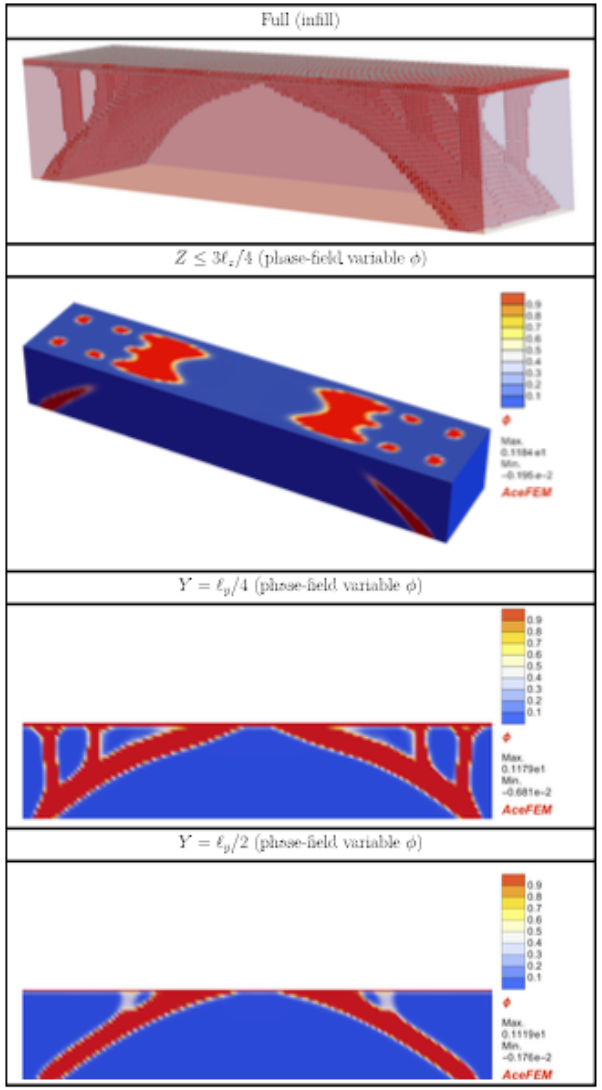
## 3D cantilever




## 3D bridge



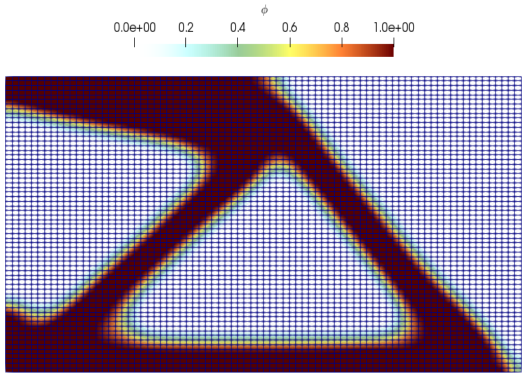



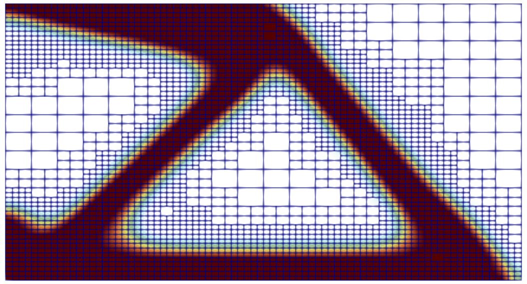



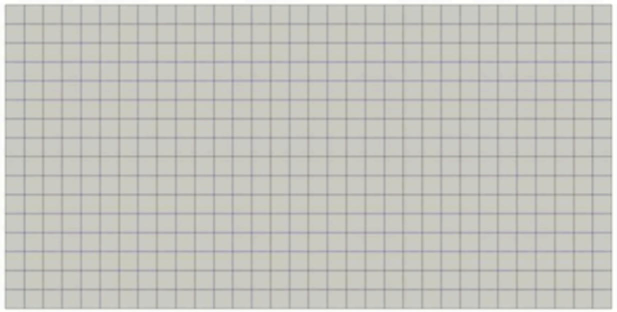
# Phase-field single material top-opt: adaptive isogeometric analysis

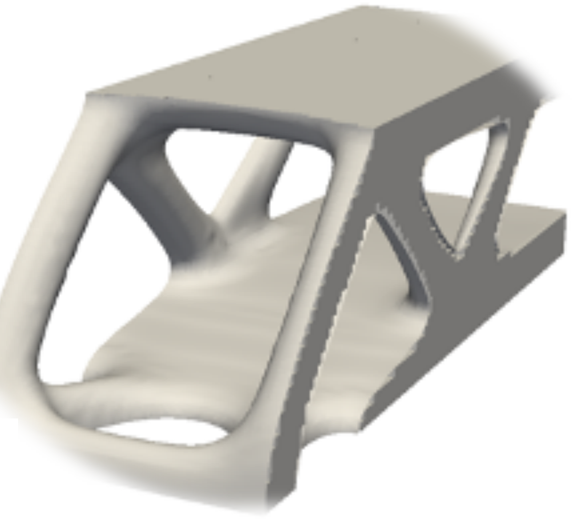
- **Idea:** Approximate mechanical and phase-field solution space using IGA, since higher continuity of IGA basis functions very effective for phase-field methods
- Adaptive Isogeometric Analysis as presented in **Henning et al. 2016** allows to **locally concentrate the computational effort** at the material interface **without any loss of accuracy**
- Single material

Work in progres…







- 60% reduction in terms of DOFs
- 40% less CPU time
- Higher improvement are likely expected for the 3D case…

**Acknowledgments: Markus Kästner, Paul Henning, Leonhard Heindel** (TU Dresden), **M.Carraturo, A.Reali** (UniPV & IMATI-CNR)

**Publications:** Henning, Heindel, Carraturo, Reali, FA, Kästner. *Projection Methods in Adaptive Isogeometric Analysis and its Application to Topology Optimization*, Proceedings in Applied Mathematics and Mechanics (*accepted*).

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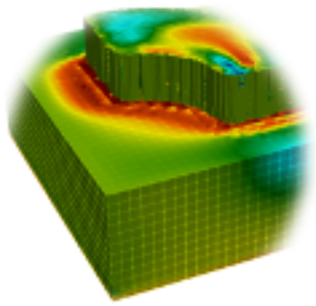
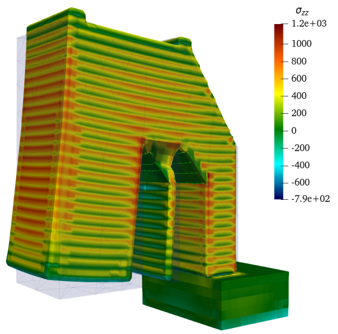
**Process simulations: challenges**

- **Large scale range** both in space and time
- **Complex physical phenomena** to be modeled
- Predict defects due to process



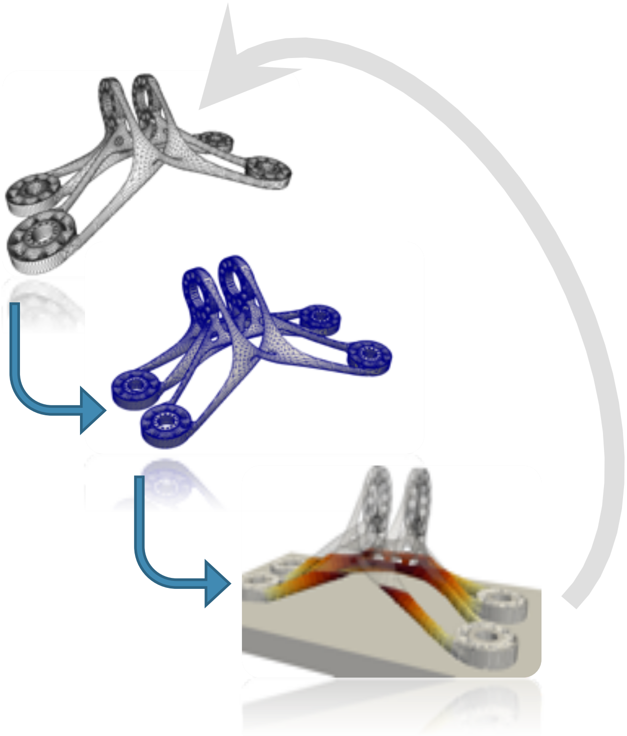


# LPBF-AM process simulations



## Focus on the most industrially relevant technology: laser powder bed fusion for metal components (LPBF)

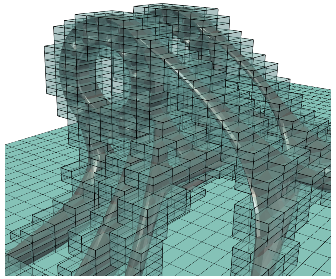
### Standard AM-design process

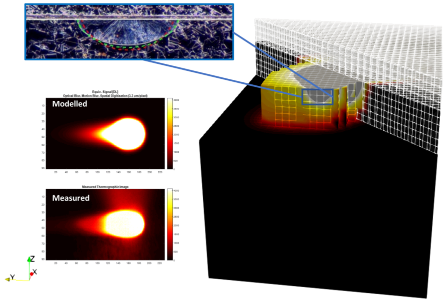


- 3D virtual model is developed within a CAD environment
- Geometry to be repaired
- Conform mesh generated
- Finite element analysis of the process
- To update the geometry, need to go back to CAD software and start procedure once again …

### AM-design-through-analysis

- Thermo-mechanical analyses can be performed directly on CAD models
- STL repair step required only once the final design ready to be printed
- Remarkable computational speed-up for multi-layer high-fidelity analyses of complex geometrical features






**Acknowledgments: Ernst Rank, Stefan Kollmannsberger, John Jomo, Ali Özcan, Nils Zander** (TUM), **M.Carraturo, A.Reali** (UniPV & IMATI-CNR)

**Publications:**

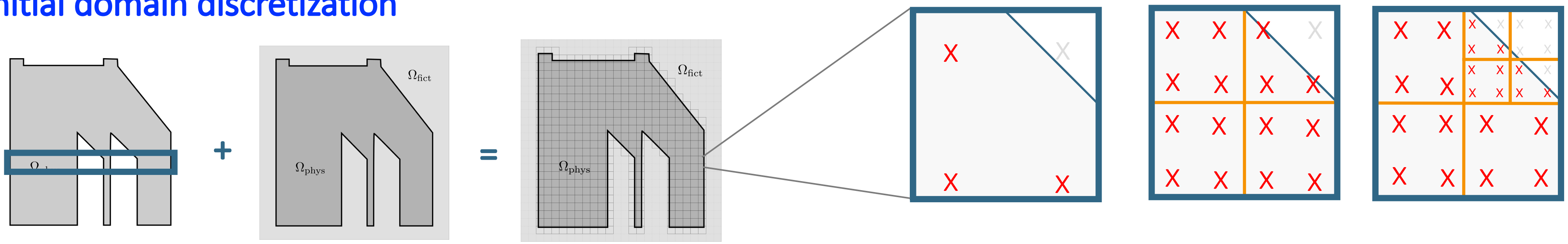
- Kollmannsberger, Özcan, Carraturo, Zander, Rank. *A hierarchical computational model for moving thermal loads and phase changes with applications to selective laser melting.* CAMWA, Vol. 75 (5), 1483-1497 (2018)
- Carraturo, Jomo, Kollmannsberger, Reali, FA, Rank. *Modeling and experimental validation of an immersed thermo-mechanical part-scale analysis for laser powder bed fusion processes.* Additive Manufacturing, Vol. 36, 101498 (2020)

# Immersed boundary approach for growing domain



## The Finite Cell Method (FCM)

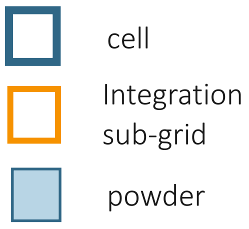
- **Initial domain discretization**



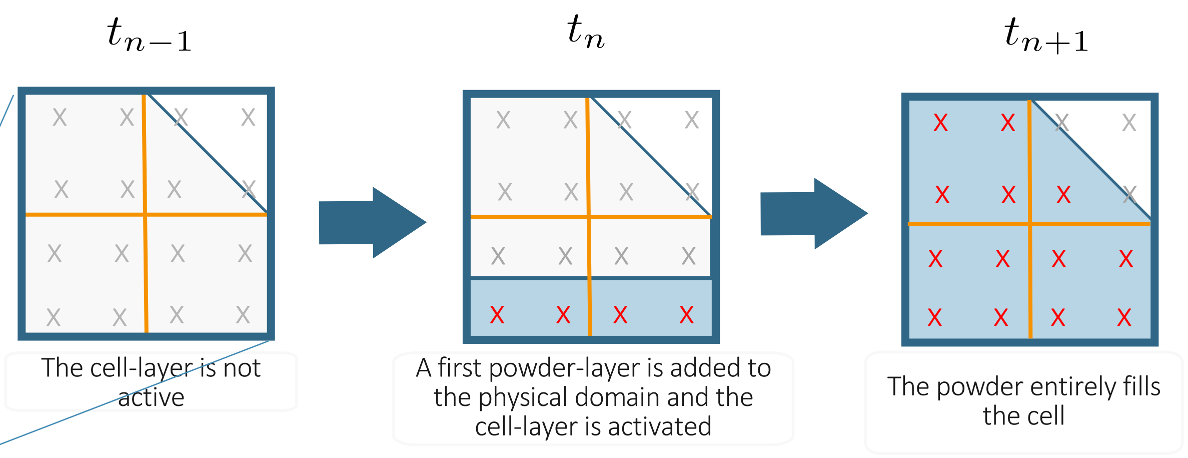

  - **Weak form modified** using a parameter $\alpha$ evaluated at Gauss points
  - Integration points distributed on **sub-cells** to accurately integrate over discontinuities at boundaries

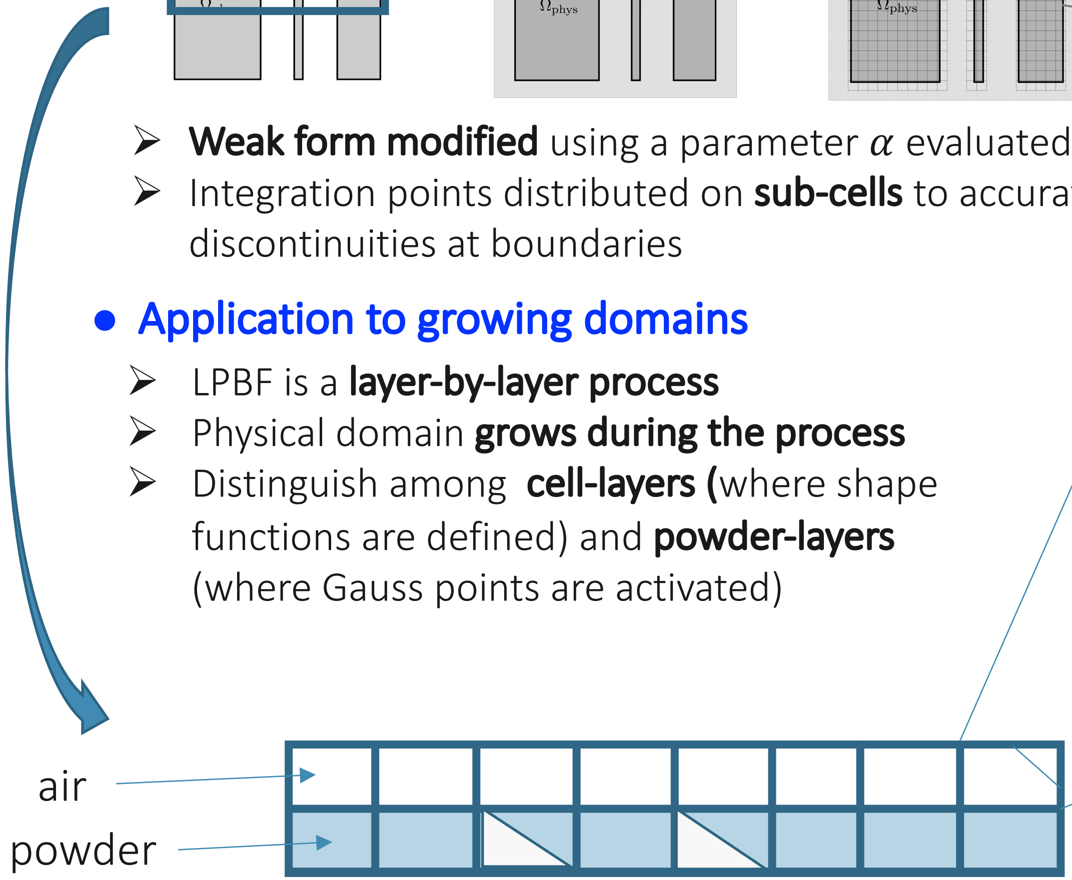
$$\alpha(\mathbf{x})\, a(\mathbf{u},\mathbf{v}) = l\,(\mathbf{v})$$

$$\text{with} \quad \alpha(\mathbf{x}) = \begin{cases} 1: & \forall \mathbf{x} \in \Omega_{phys} \\ 0: & \forall \mathbf{x} \notin \Omega_{phys} \end{cases}$$




- **Application to growing domains**
  - LPBF is a **layer-by-layer process**
  - Physical domain **grows during the process**
  - Distinguish among **cell-layers** (where shape functions are defined) and **powder-layers** (where Gauss points are activated)



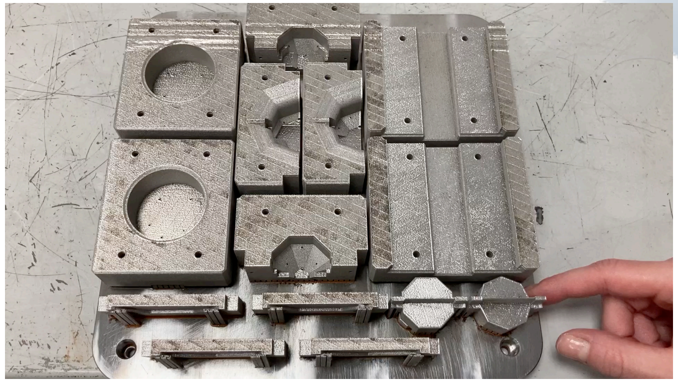



# Immersed boundary approach for growing domain: different scale approaches

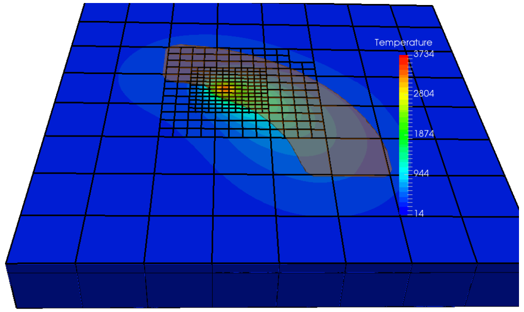


- Due to problem complexity, need to choose a-priori solution scale
- Choose quantities of interested


| Input parameters | Range values |
|---|---|
| Laser power | 100÷1000 [W] |
| Laser speed | 0.2÷1.5 [m/s] |
| Laser spot radius | 25÷100 [μm] |



**Melt-pool analysis**
**High-fidelity simulation**



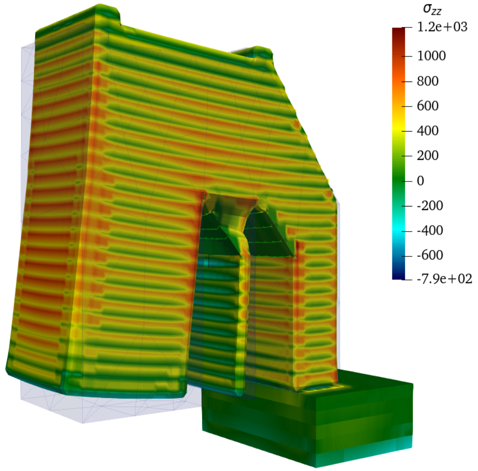

**Objective**

- Predict **temperature and stress state** at the **melt-pool length-scale** (element size ~ 10μm)
- Evaluate melt-pool shape and cooling rate

**Model features**

- **Few laser strokes** can be simulated (10÷100 mm length)
- Powder is included in the model
- Phase-change has to be taken into account

**Part-scale analysis**
**Low-fidelity simulation**




**Objective**

- Predict **part deflection** after base plate removal
- Evaluate **residual stresses** in the final component

**Model features**

- **Complete process** is simulated (including post-processing steps, e.g. part removal)
- Powder modeled as conduction BC, not included in the domain
- Latent heat usually neglected

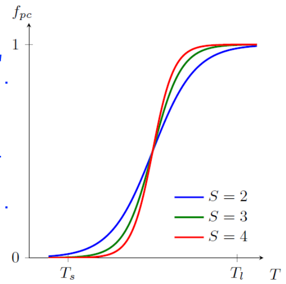
# Immersed boundary for melt pool: thermal problem



- **Heat transfer equation**

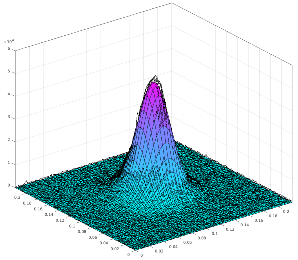
$$\rho c\dot{T} + \rho L\dot{f}_{pc} - \nabla(k\nabla T) = 0 \quad \text{in} \quad \Omega$$

$$f_{pc} = \frac{1}{2}\left[\tanh\left(S\frac{2}{T_l - T_s}\left(T - \frac{T_s + T_l}{2}\right)\right) + 1\right]$$




- **Initial conditions**

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



- **Boundary conditions**

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

Radiation heat flux: $q^s = \sigma\epsilon(T^2 + T_e^2)(T_e^2 - T^2)$

Laser heat source: $q^L = \dfrac{2Q\eta}{\pi\rho^2}\exp\left[-2\left(\dfrac{y - y_0}{r^2} + \dfrac{x - x_0}{r^2}\right)\right]$

Obtained fitting measured data with a gaussian distribution

- **Mechanical equation**

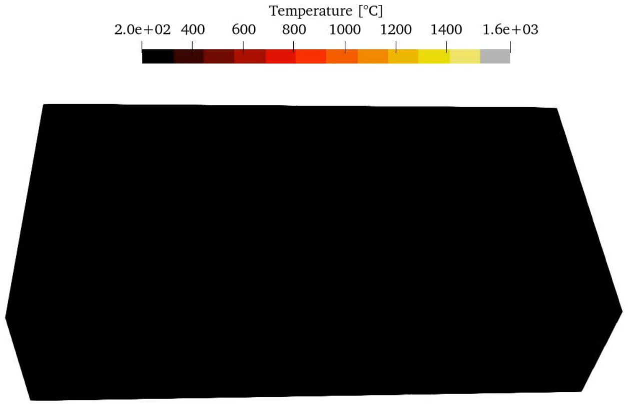
$$\nabla\cdot\boldsymbol{\sigma} + \mathbf{b} = \mathbf{0}$$

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

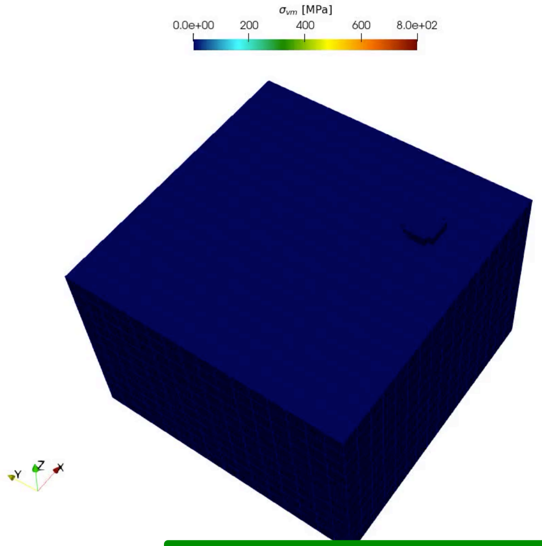
$$\boldsymbol{\varepsilon}^{th} = \alpha^{th}\Delta T\mathbf{I}$$

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

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




Thermal problem




Mechanical problem

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

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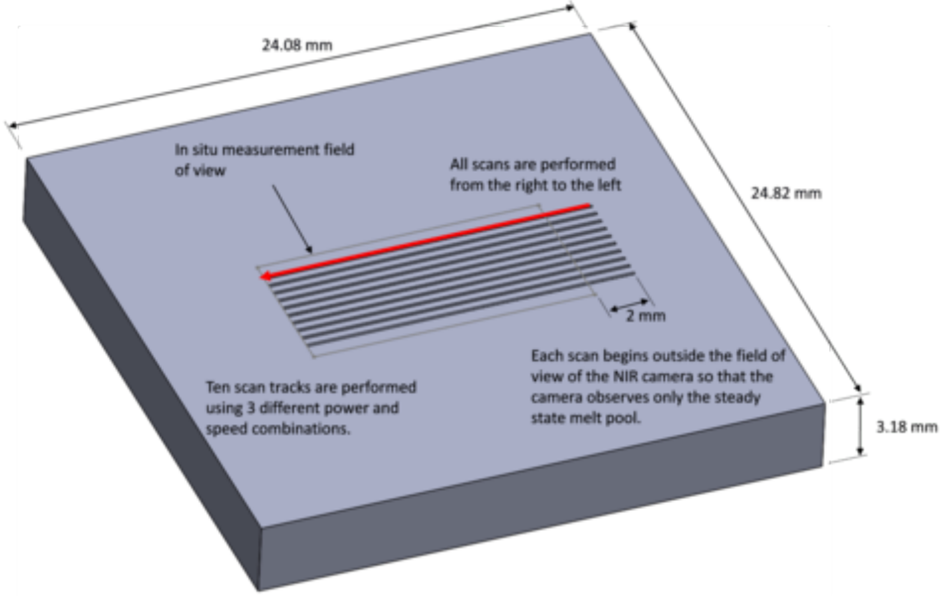
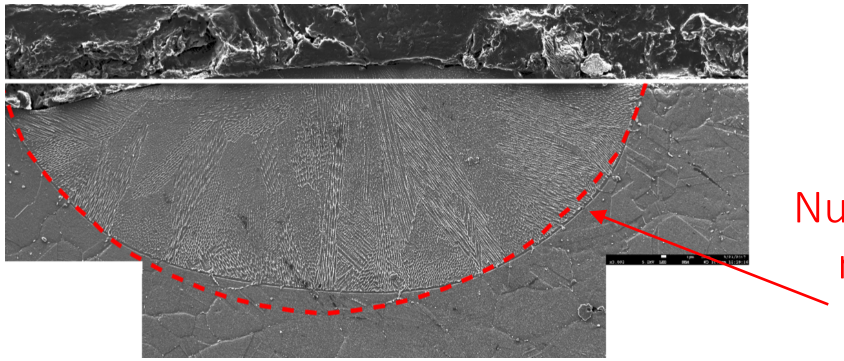
- Material: INCONEL 625
- No powder involved
- Adjacent, independent laser scans using 3 different combinations of power and speed

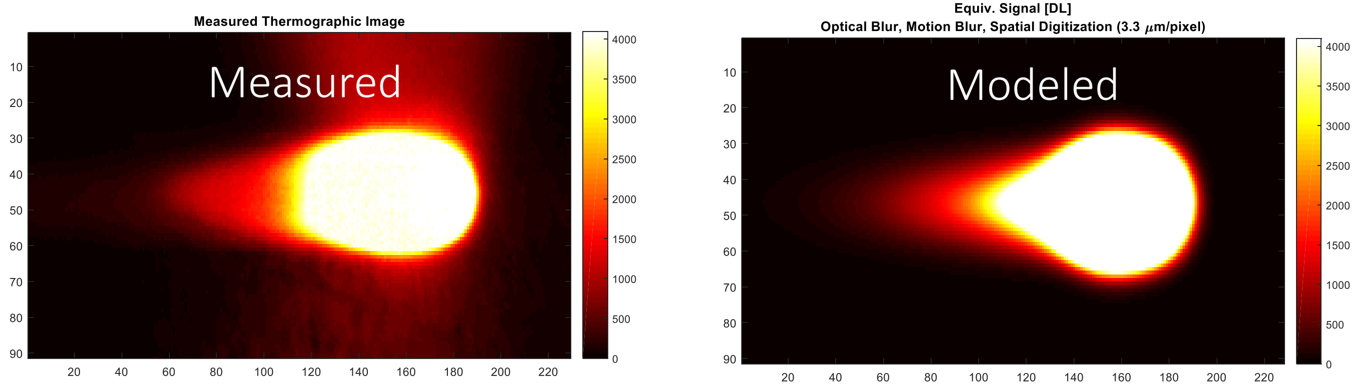



Source: https://www.nist.gov/ambench/amb2018-02-description

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




- *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 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**

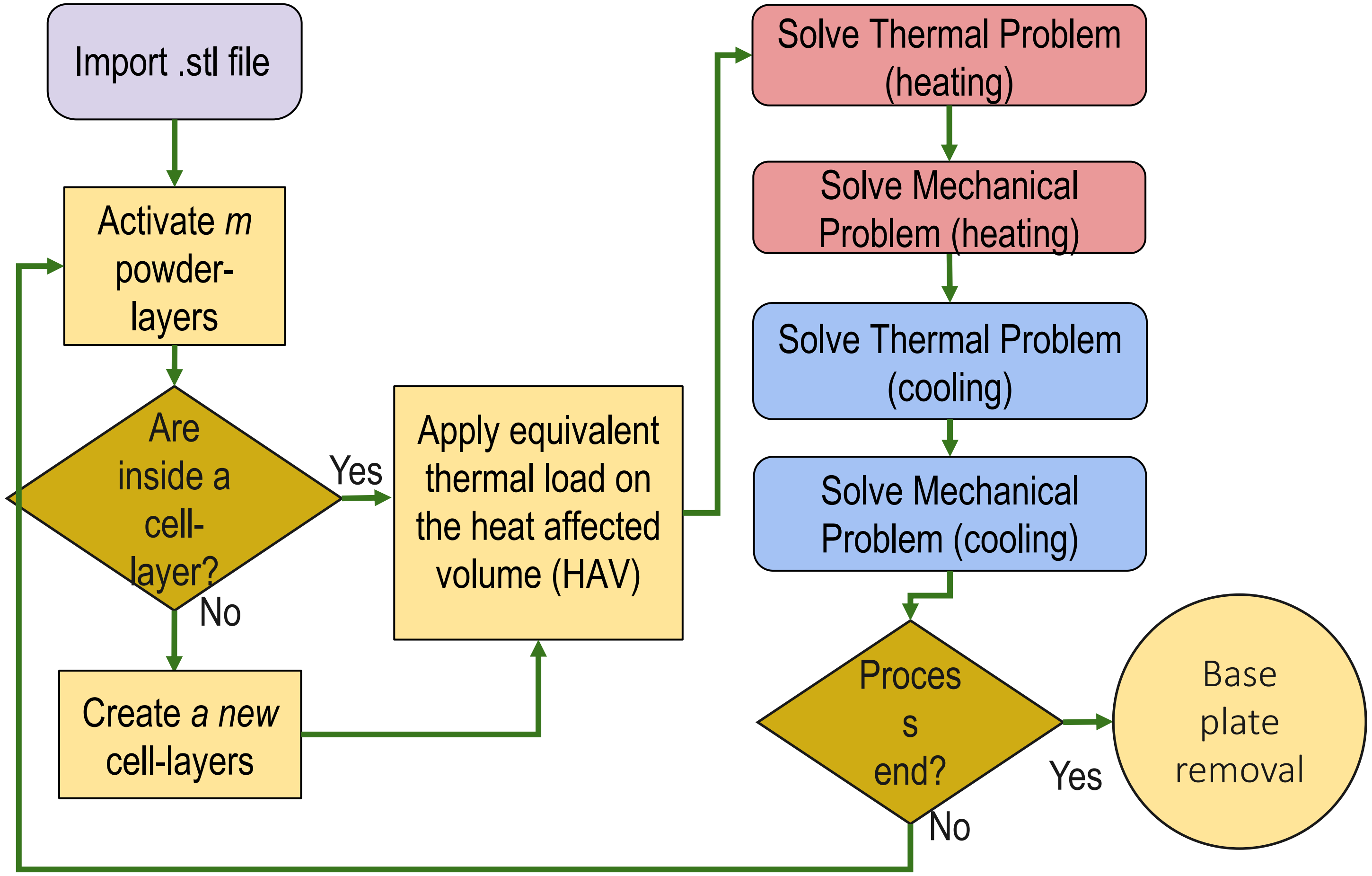
$$\nabla\boldsymbol{\sigma} = \mathbf{0}$$

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

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

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

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

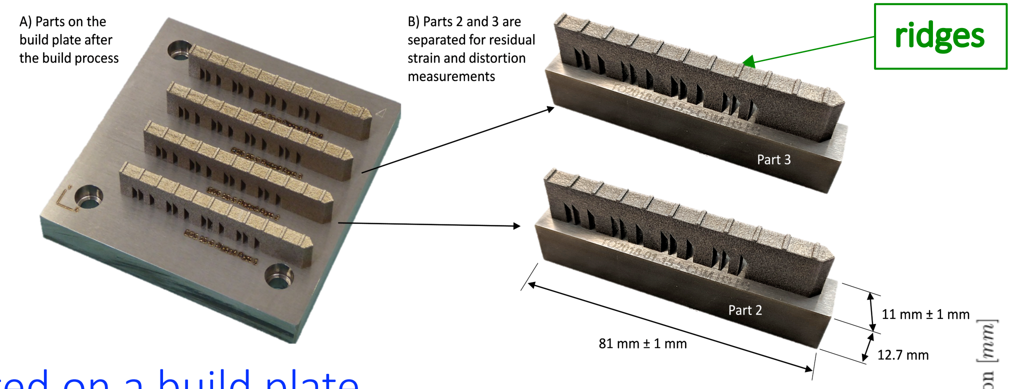



**Publications** Carraturo, Jomo, Kollmannsberger, Reali, FA, Rank, *Modeling and experimental validation of an immersed thermo-mech. part-scale analysis for LP-BFP*. Additive Manuf. 36 (2020)

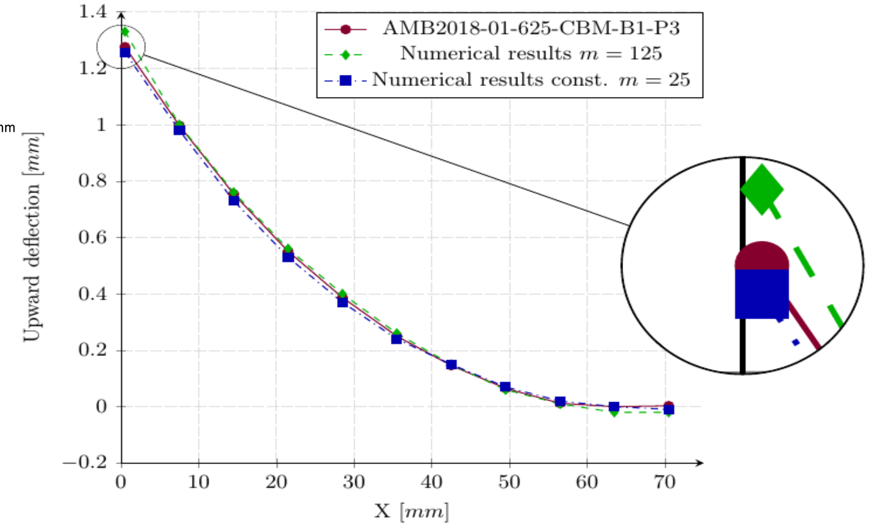
# Experimental Validation

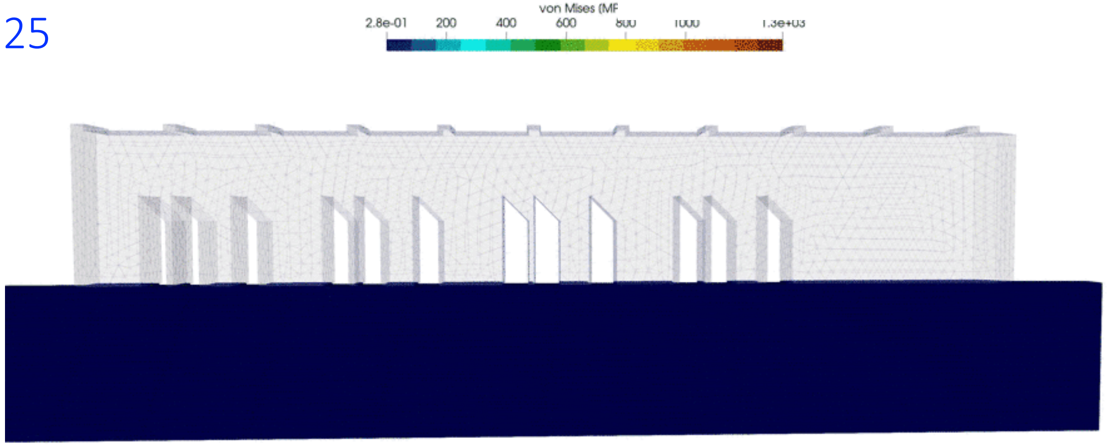


- **Problem setup:**
  - Part height: 12.5 mm
  - # total powder layers: 625
  - Layer thickness: 20 µm
- **Experimental setup:**
  - 4 cantilever beams are printed on a build plate using Inconel 625 using an EOS M270.
  - Part deflection after support removal is measured at the eleven ridges
- **Simulation 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



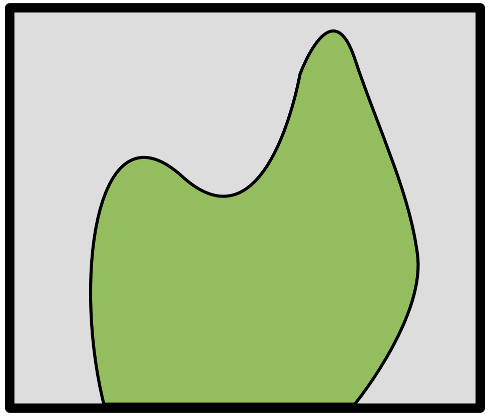



**Publications:** Carraturo, Jomo, Kollmannsberger, Reali, FA, Rank, *Modeling and experimental validation of an immersed thermo-mechanical part-scale analysis for LP-BFP*. Additive Manuf., 36 (2020)

# AM: toward a two-level method

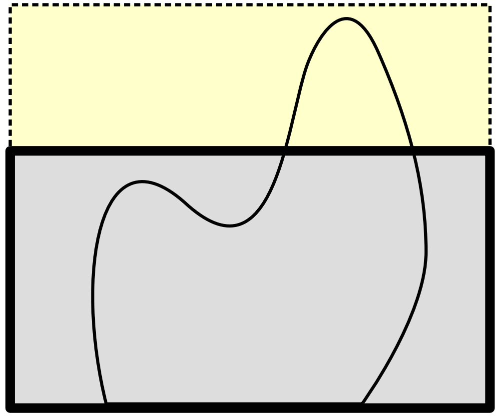


## Physical domains



**Final physical domain Ω**

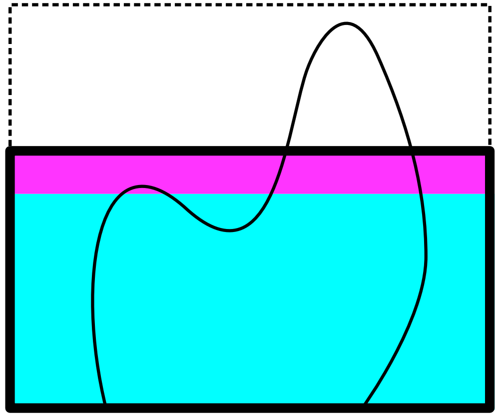
**Green**: component to be printed



**Physical domain Ω @ t**

**Gray**: active domain

**Yellow**: dormant domain

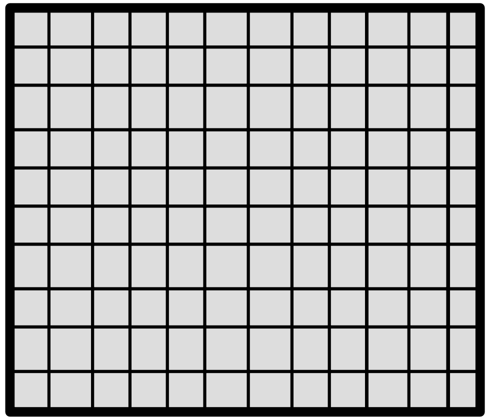


**Different scales @ t:**

**Cyan**: coarse-scale region Ωt+

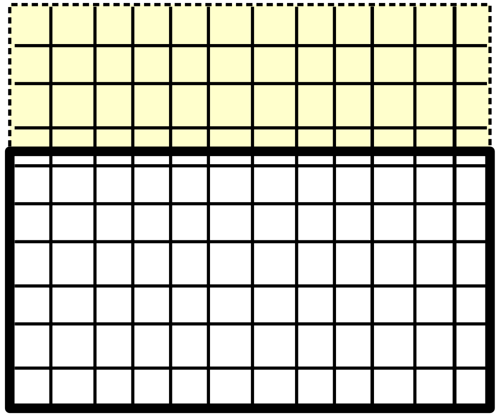
**Magenta**: fine-scale region Ωt-.

## Computational grids



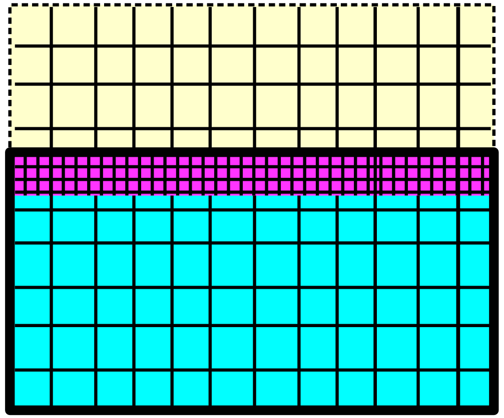
**Global coarse mesh:**

- 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

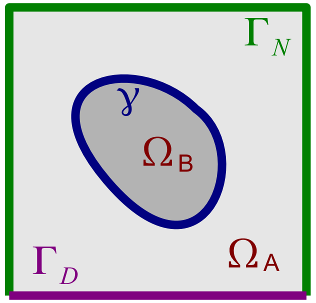


- **GOAL**: approach problems with small portion featuring a significantly more complex physics
  - Additive manufacturing / Fluid flow with immersed membranes
- **IDEA**: avoid adaptivity, computationally attractive, difficult to generate, possibly with preconditioning issues
  - **DIFFICULTIES**: problems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

- **ORIGINAL TOY PROBLEM**: steady thermal problem
- Two regions, $\Omega_A$ and $\Omega_B$ with different thermal properties

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

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

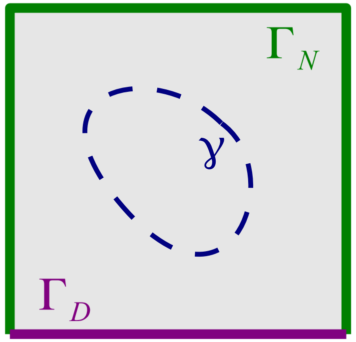



- continuity condition on γ / initial condition
- piecewise heat conductivity β
- Extension to transient & phase transition problems

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

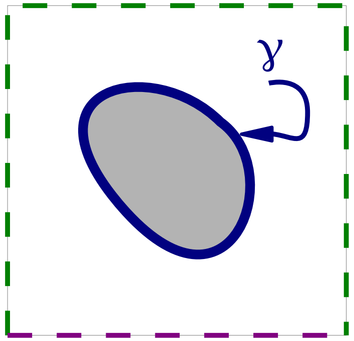
**Global problem** in $\Omega_+$

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




**Local problem** in $\Omega_-$

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




**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 $\Omega_-$ we have two distinct functions at the same time, a local one and a global one

- **Theorem: Two level formulation ($\Omega_+$ & $\Omega_-$) is equivalent original formulation ($\Omega_A$ & $\Omega_B$)**

✓ 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 $\Omega_-$

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

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

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

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

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

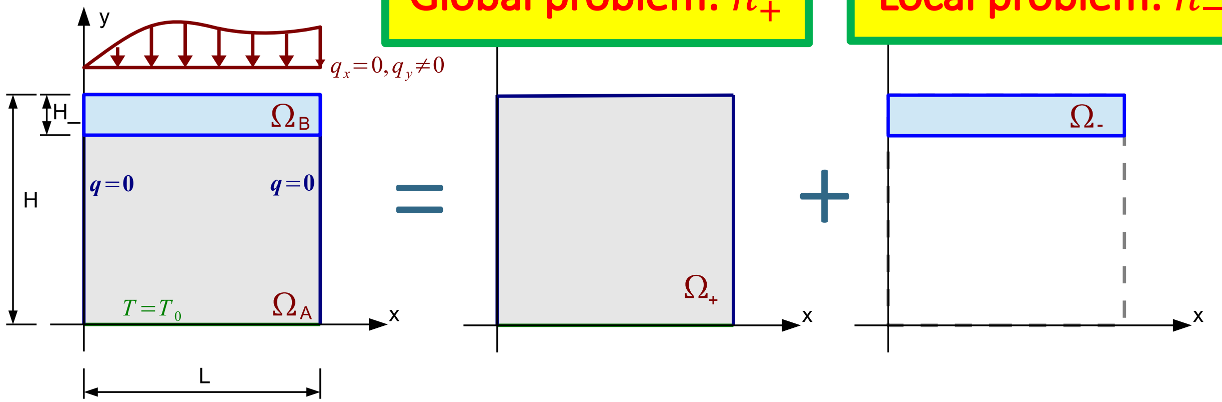
✓ Under-relaxation needed, as iterative algorithm may suffer instability ( $\kappa_- >> \kappa_+$ )
✓ Convert in weak form and discretize in the FE spirit ($P_2$ piecewise quadratic FE)

# Two-level method: linear steady thermal problem



Linear steady thermal problem with Ω unit square and $\Omega_B$ top rectangle

**Global problem: $h_+$** **Local problem: $h_-$**



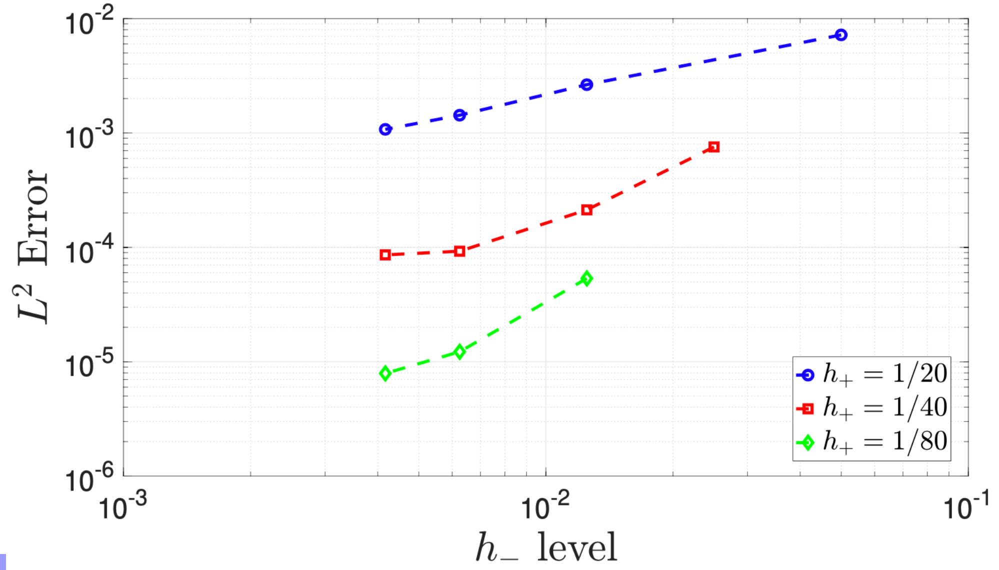

$$H = 1.0,\ L = 1.0,\ H_- = .05,\ \kappa_+ = 1.0,\ \kappa_- = 20.0,\ T_0 = 20$$

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

**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



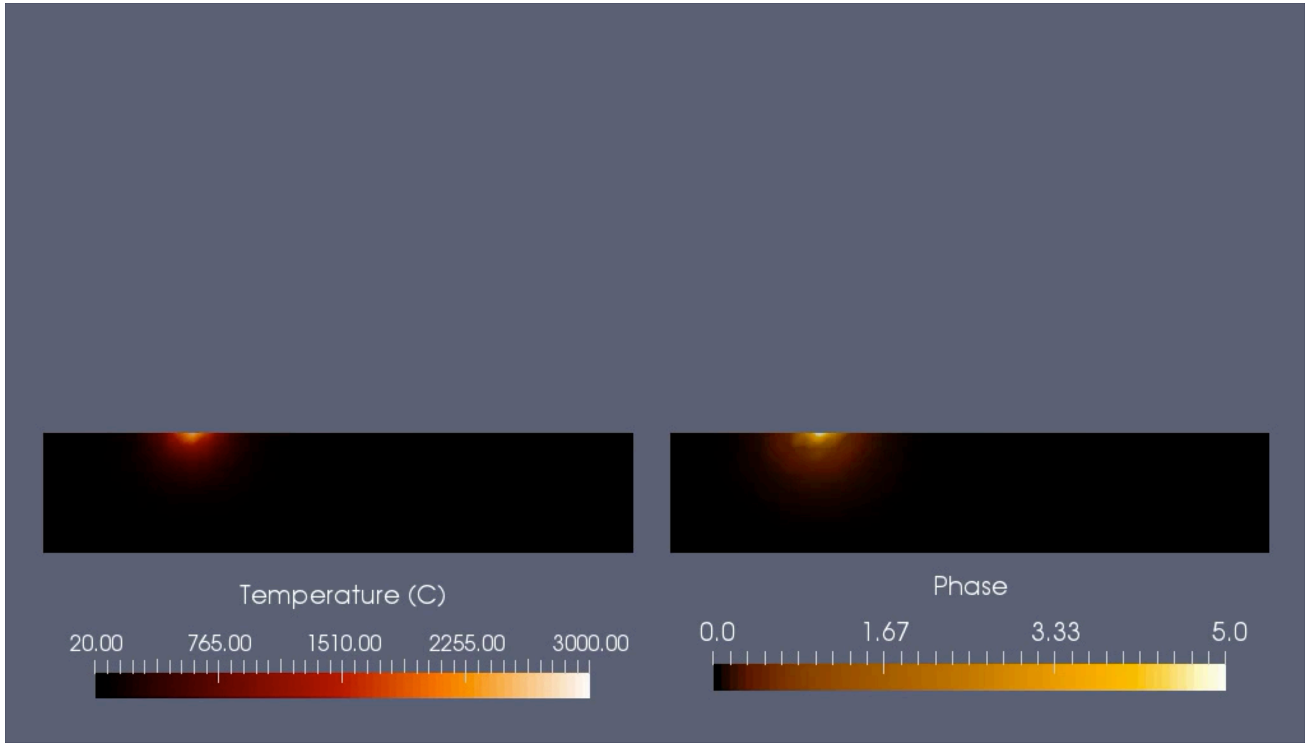
# AM: toward a two-level method



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

Temperature profile

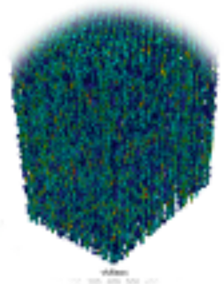
Material profile
Black: powder
Yellow: solid

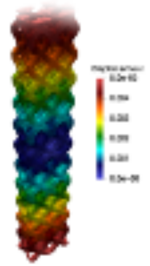


- Introduction
  - AM - 3DP: technologies, materials, advantages, open problems
- Design for additive
  - Phase-field topology optimization: gradient material
  - Adaptive isogeometric analysis
  - Phase-field topology optimization: single material
- Process simulations
  - Immersed boundary approach
    - Melt pool: high fidelity simulations
    - Part-scale: low fidelity simulations
  - Two-level method
- **Product simulations**
  - Lattice components
  - Industrial components
- Future activities & directions
- Conclusion

**Product simulation challenges**

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

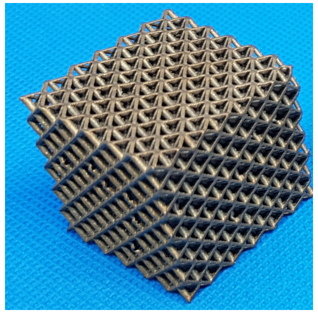




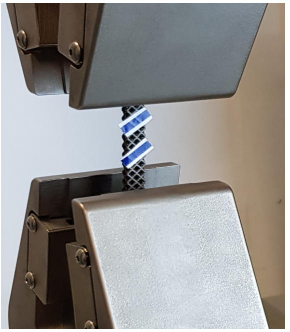
# LPBF Product simulations: lattice components



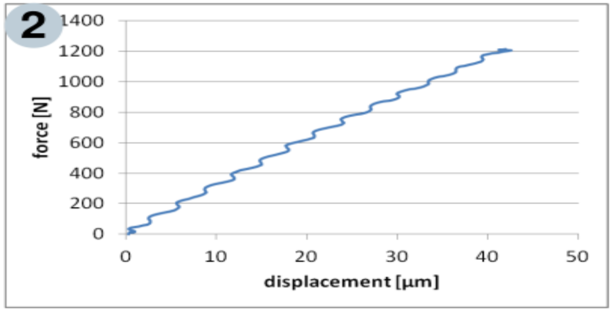
**MOTIVATION:**
- **lattice structure very appealing** in terms of lightness
- AM lattice structures with **long/expensive mechanical characterization procedure**



3D printed lattice

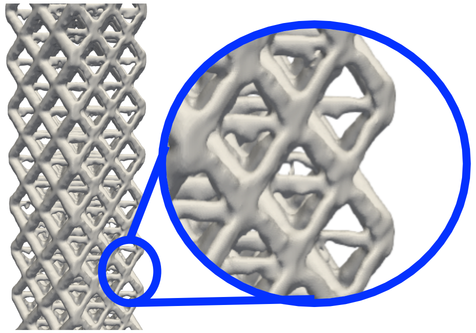


Experimental campaign

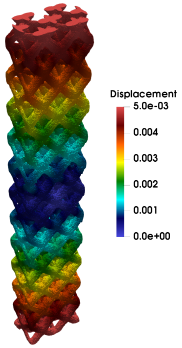



Lattice mechanical properties

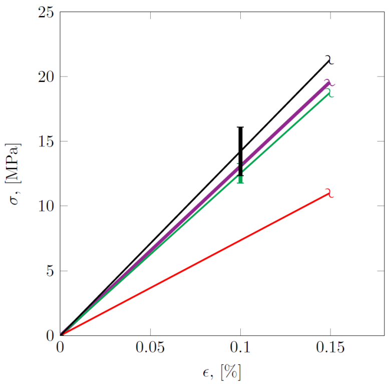
Numerical characterization of lattice structures as an effective and reliable alternative



CT-scan




Numerical analysis




Numerical characterization

Aalto University

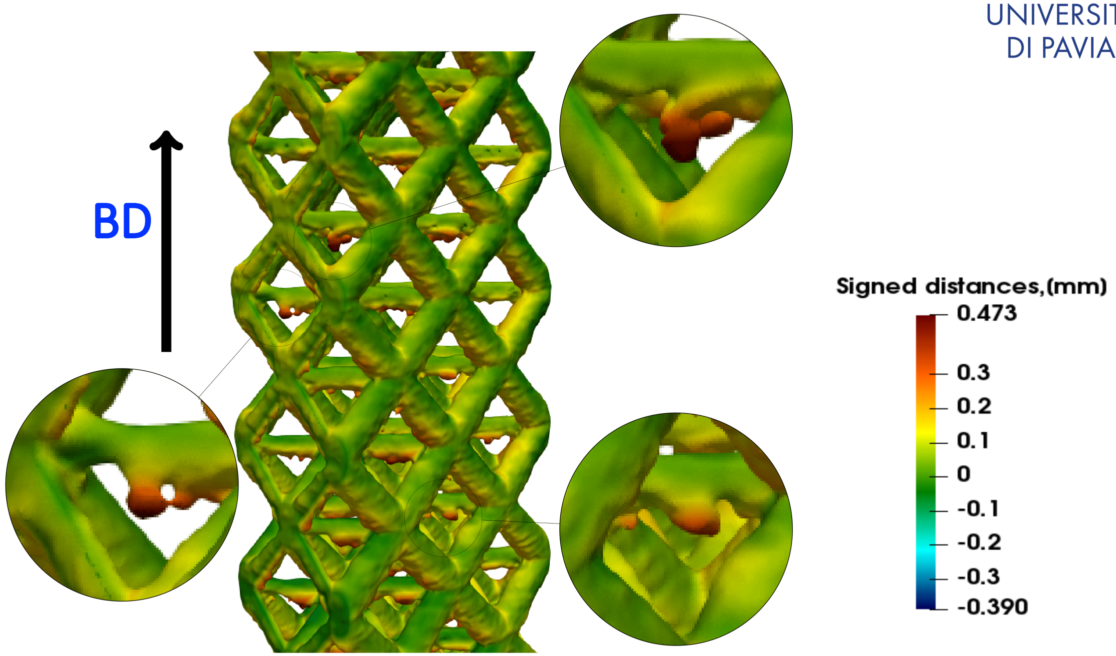
TUM

**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)

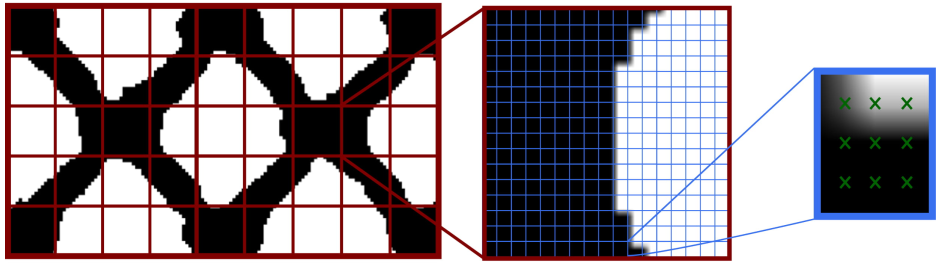
# LPBF product simulations: lattice components



- **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



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# LPBF lattice components: three-point bending test validation

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**Objective: compare experimental vs predicted response**

## Experimental settings

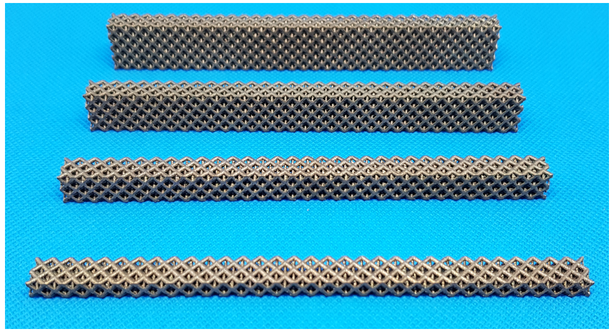
- Uniaxial test
- Three-point bending test
- Four octet-truss structures with varying thickness

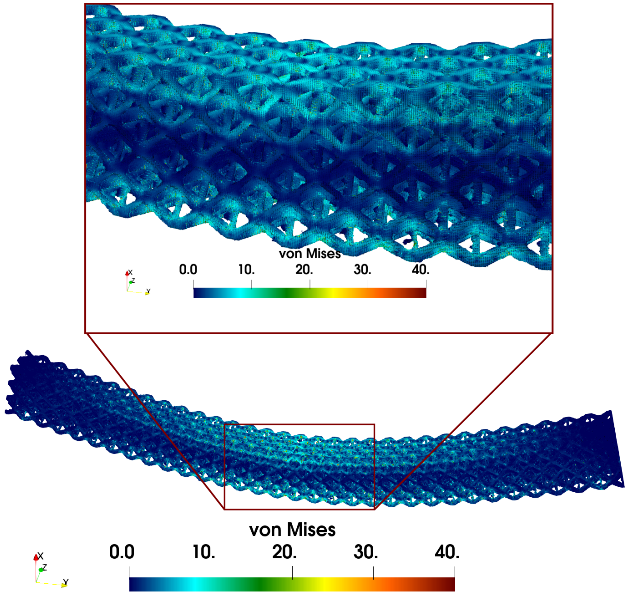
## Comparison

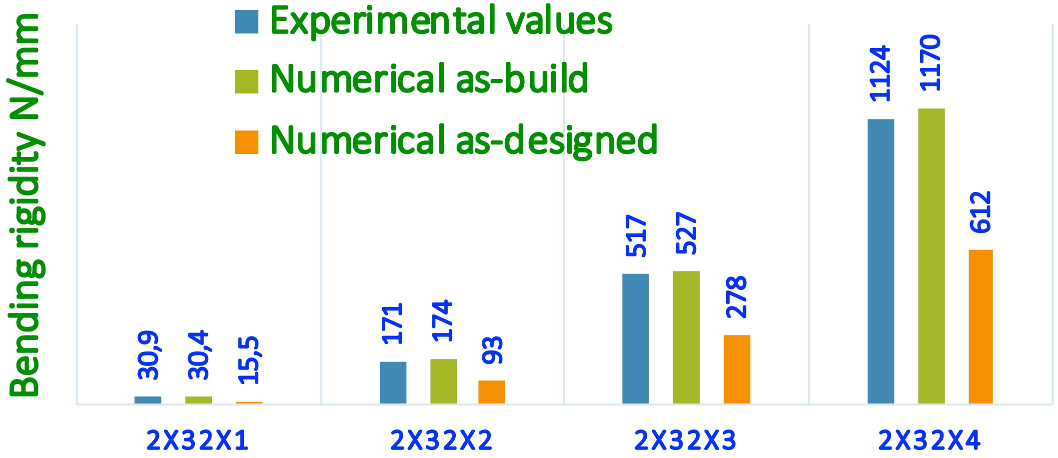
- **CAD-based model** (commercial codes)
- **CT-based model** (using FCM)
- **Experiments**

## Results:

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



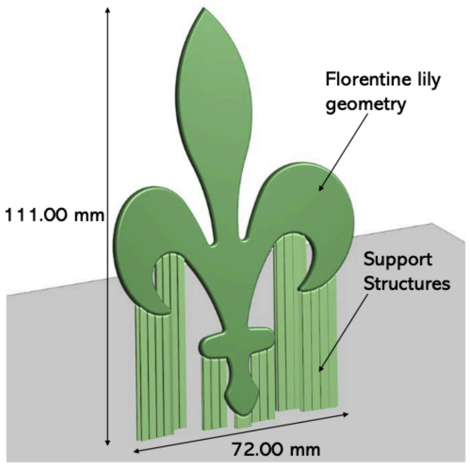


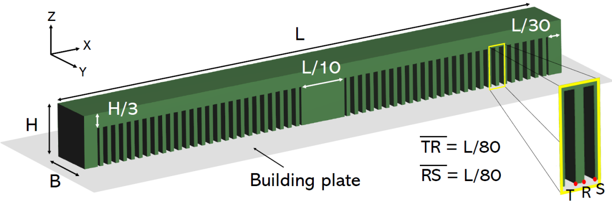



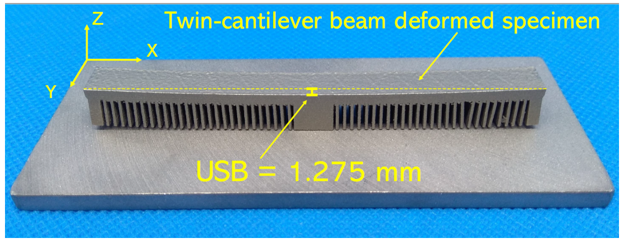
# AM coffee machine: distorsion prediction

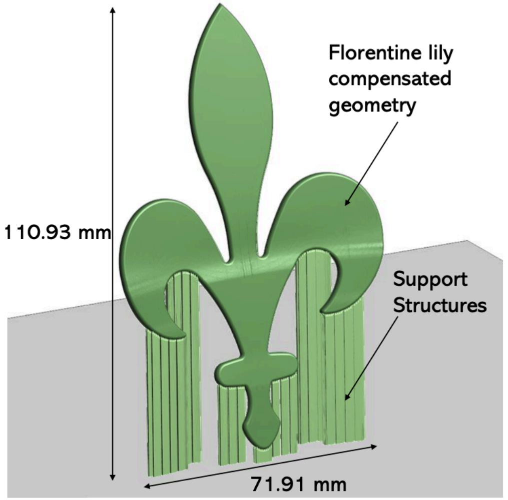


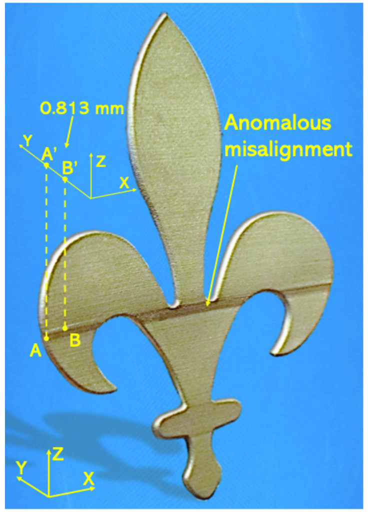
## Step 1: evaluation of residual distortion

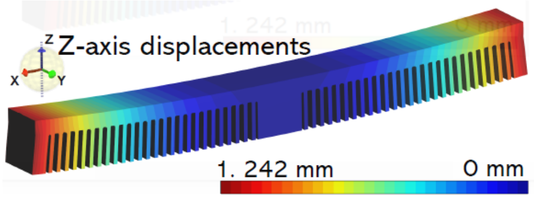


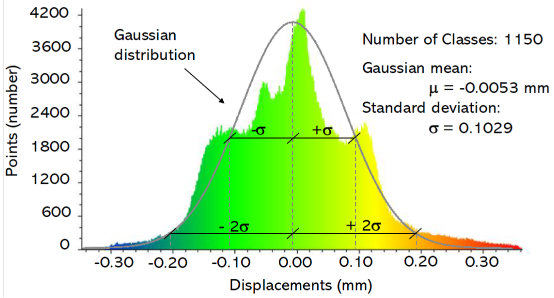



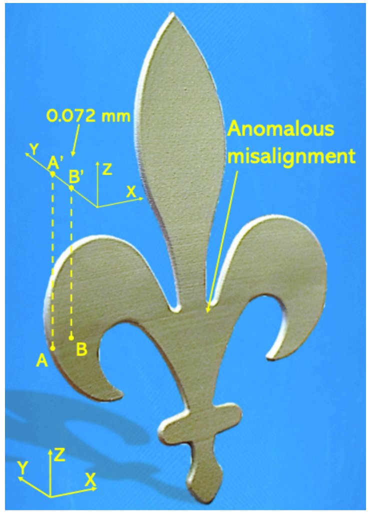



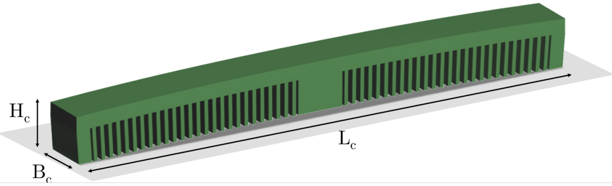



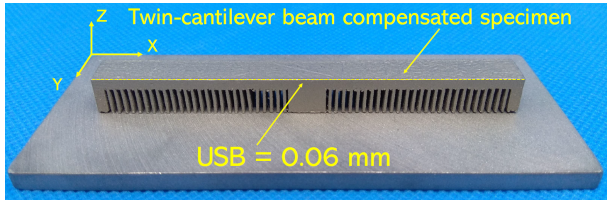




## Step 2: compensation



- Introduction
  - AM - 3DP: technologies, materials, advantages, open problems
- Design for additive
  - Phase-field topology optimization: gradient material
  - Adaptive isogeometric analysis
  - Phase-field topology optimization: single material
- Process simulations
  - Immersed boundary approach
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# UniPV – Additive Manufacturing Laboratories

## HP JET FUSION 580 COLOR

- Technology: Multi Jet Fusion
- Chamber: 332 x 190 x 248 mm
- Materials: PA12 – PA12HR
- Precision: Up to 10 μm


## CONNEX OBJECT 260

- Technology: PolyJet
- Chamber: 255 x 252 x 200 mm
- Materials: Rigid opaque, Vero series, Tango series, Bio-compatible materials
- Precision: Up to 20 μm


## RENISHAW AM400

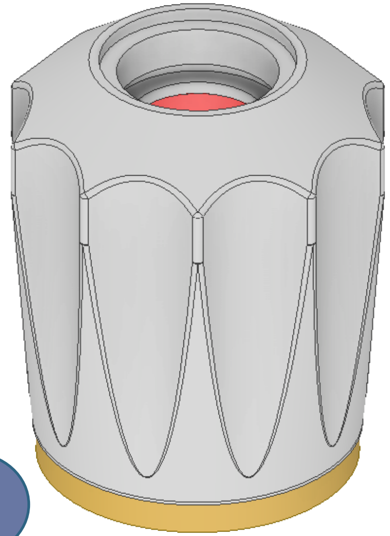
- Technology: Selective Laser Melting
- Chamber: 250 x 250 x 300 mm
- Materials: SS316L, Al12Mg10, Ni625, Ni718, Ti64AlV
- Precision: Up to 50 μm

## DMG MORI CMX 600V

- Technology: CNC
- Chamber: 600 x 500 x 900 mm
- Materials: metals, plastics
- Precision: Up to 2 μm


# ADDITIVE AND SUBTRACTIVE TECHNOLOGIES

# Example of mixed Additive-Subtractive production

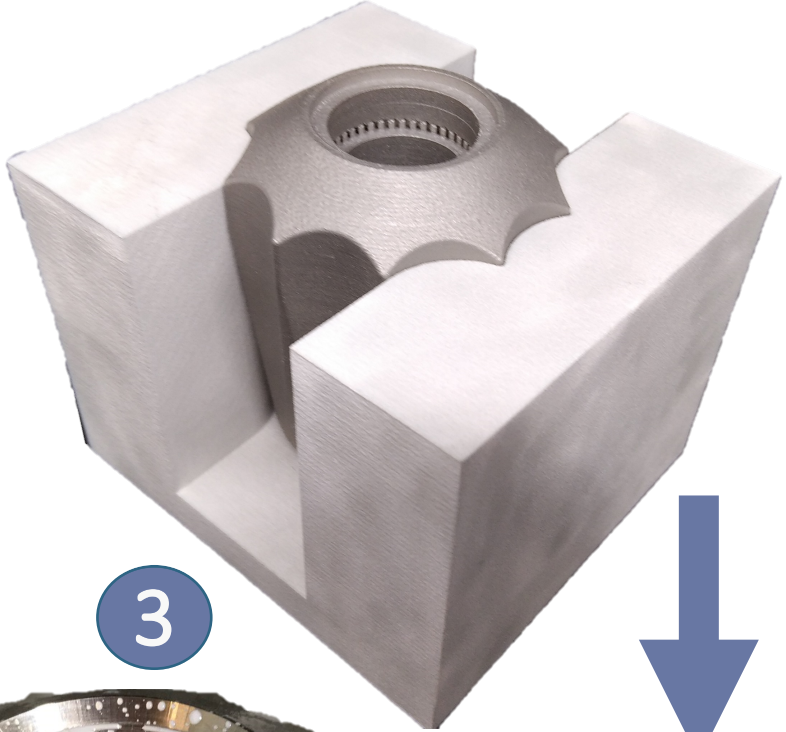


1

Printed with Renishaw AM400


2

Grasping Printed with HP Jet Fusion 580



3

CNC operations realized with DMG Mori CMX600V


4

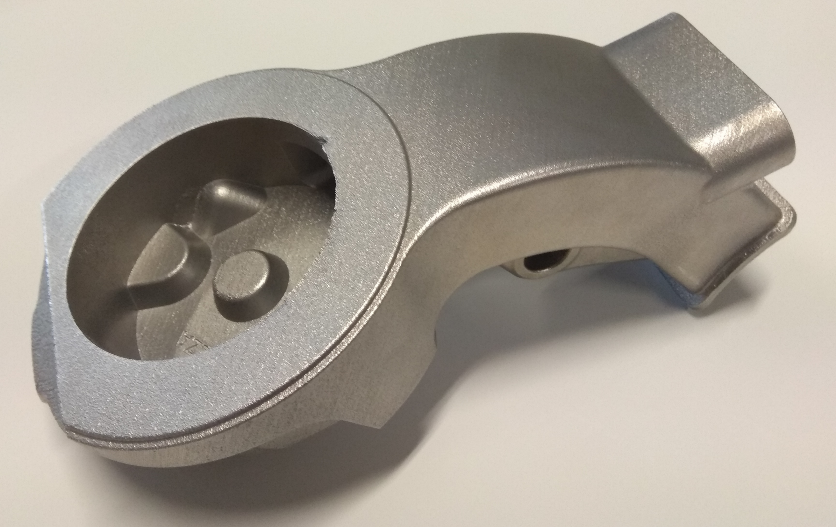
Final Assembling

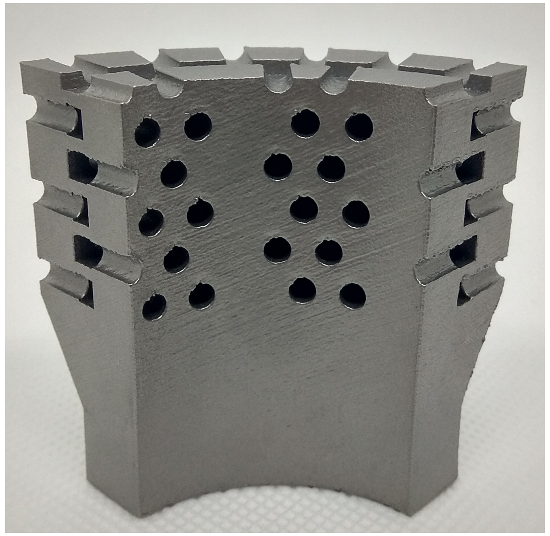
5

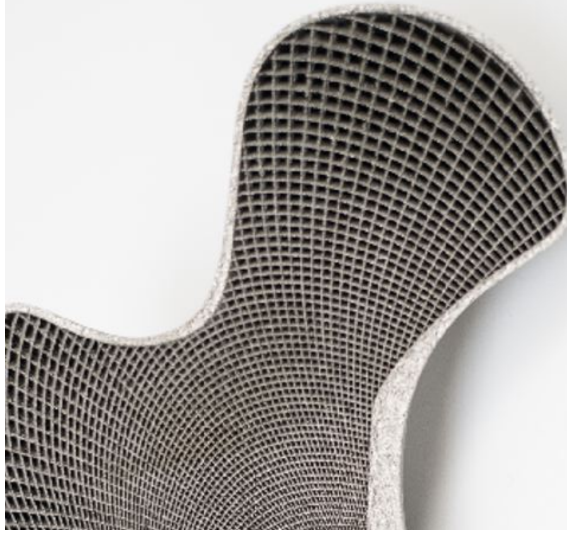
# UniPV – Additive Manufacturing applications

Computational Mechanics & Advanced Materials

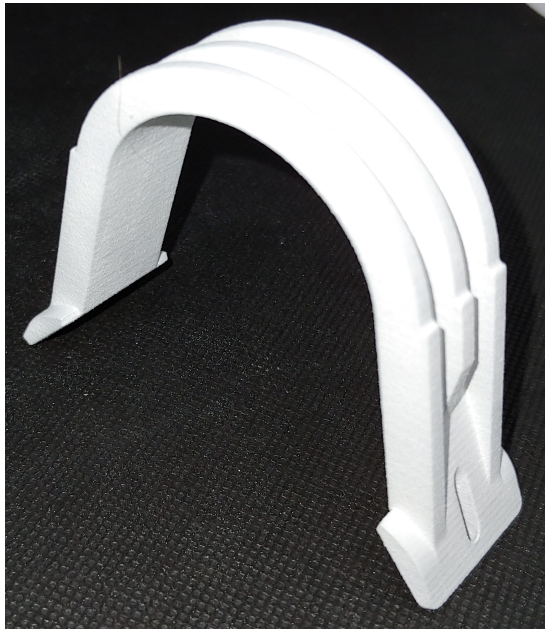
## Metal parts:





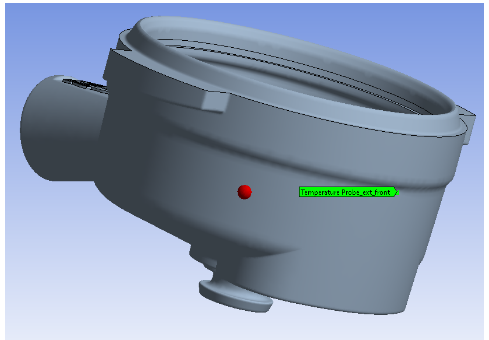
## Nylon PA12 parts:

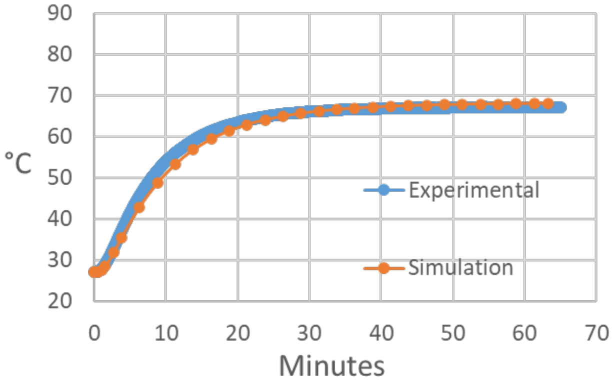
# UniPV – AM redesign and optimize



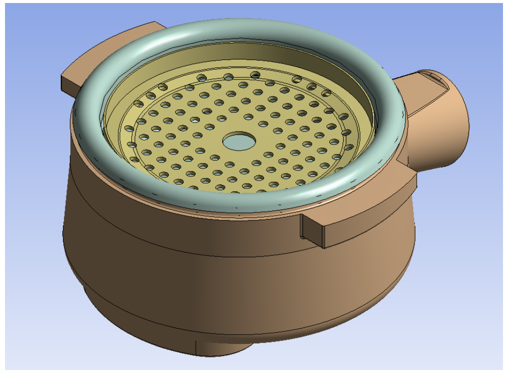
## Original design

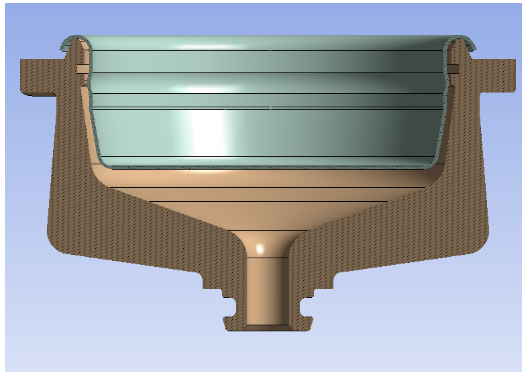


### Model parameter fitting

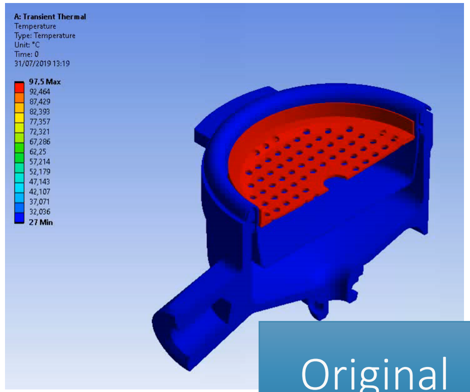



## Optimization of new design

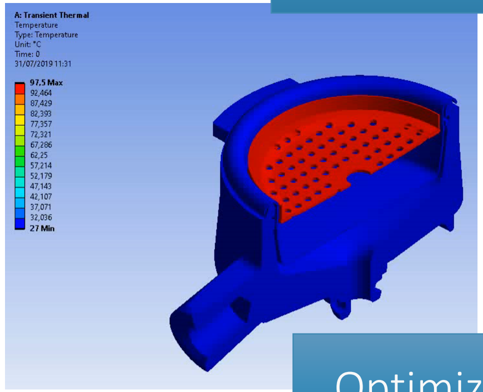




## Simulation & validation

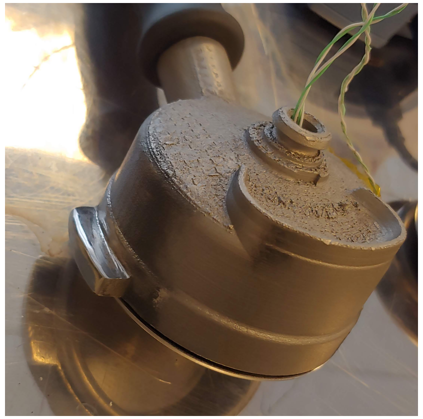


Original



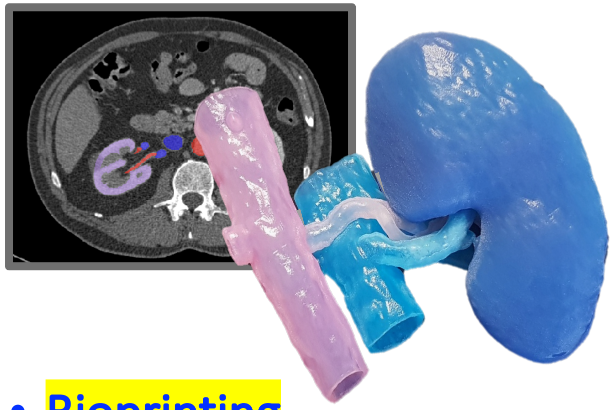
Optimized

## Additively manufactured & experimental validation

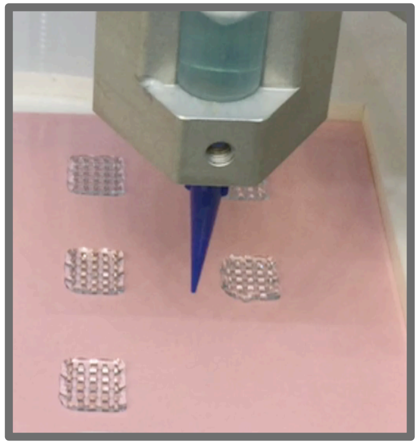


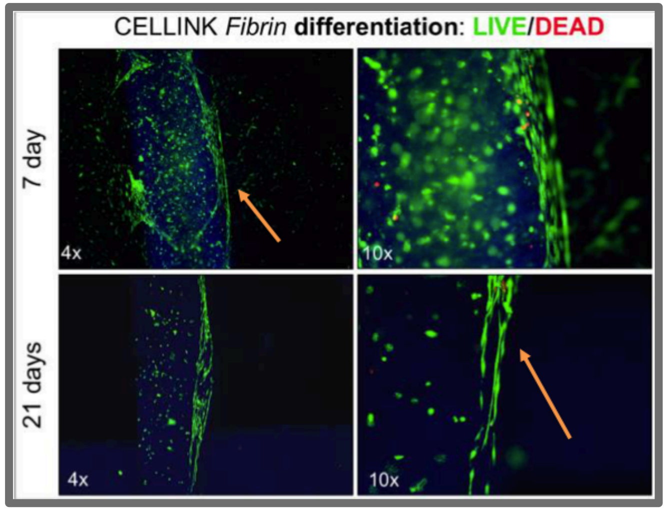
3D@UniPV
Virtual Modeling and Additive Manufacturing for Advanced Materials

- 3D4Med



- Bioprinting

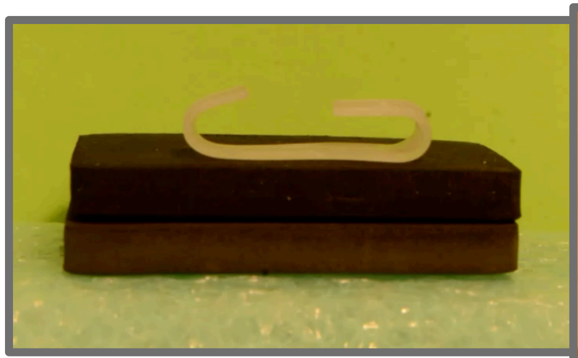


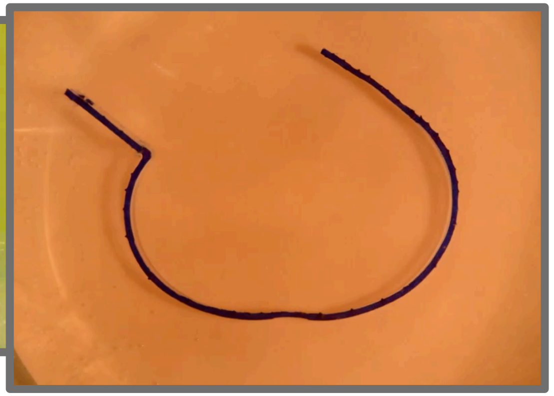



- Concrete 3D printing

ETESIAS


- 4D printing: devices activated by light or temperature





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

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# 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**