3D printing & poroelastic media

Features, artifacts and the bigger picture

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Material Extrusion

3D PrintingS

Material Extrusion

FDM
Fused Deposition Modelling

Robocasting

CFF
Composite Filament Fabrication

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(Masked) Stereolithography

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Ranges/precision

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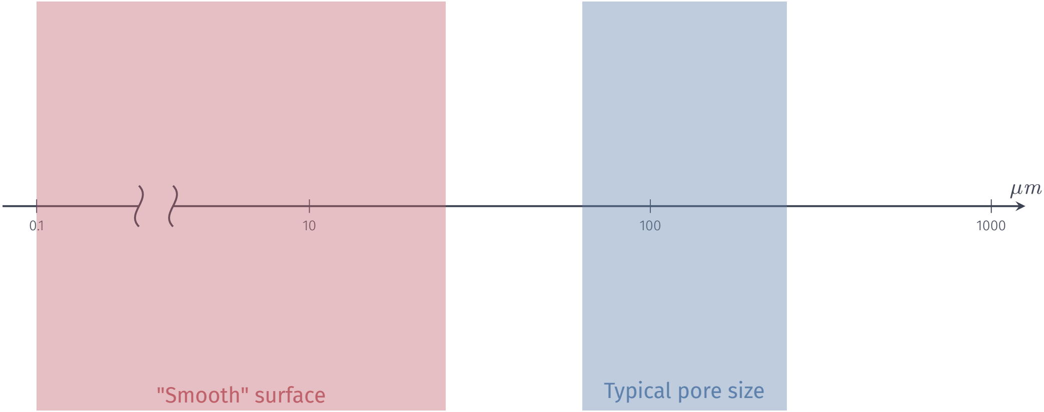

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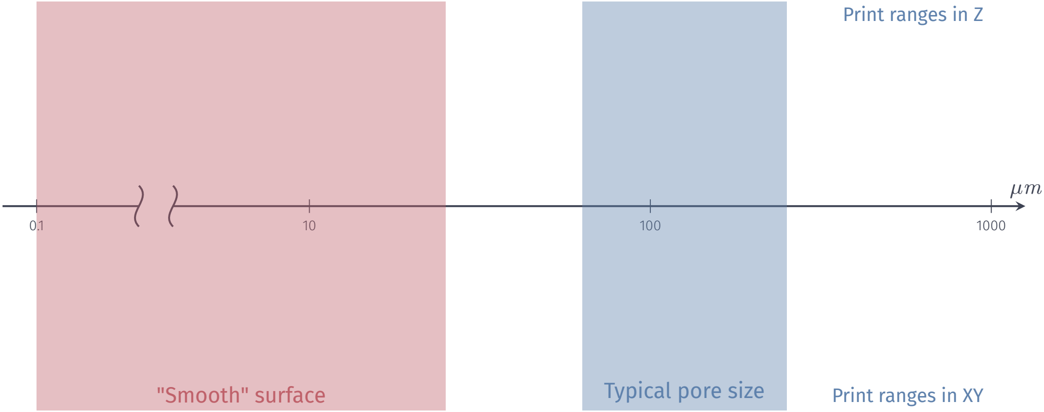

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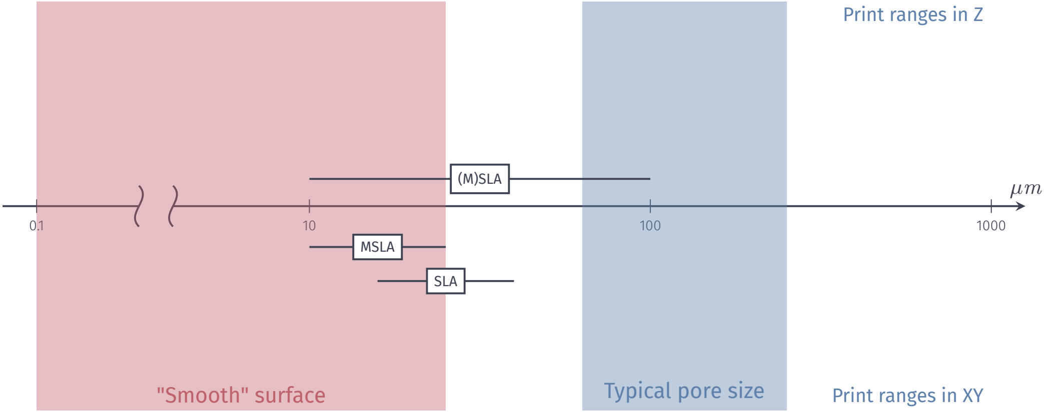

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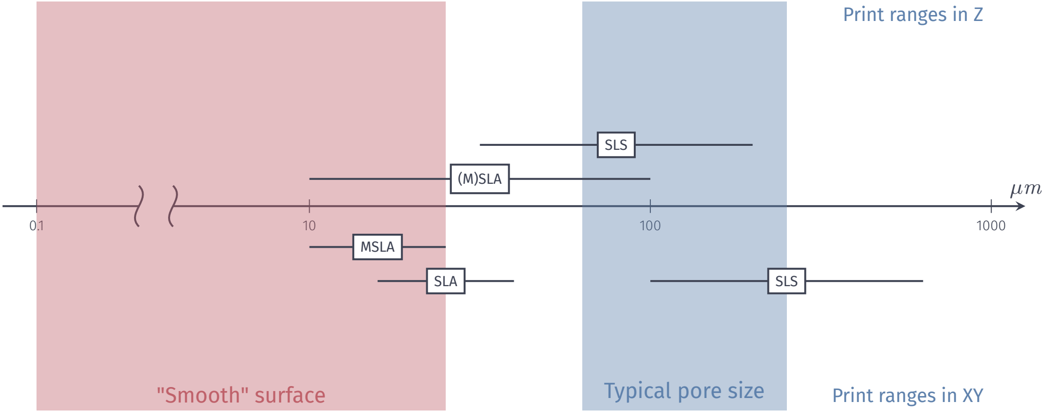

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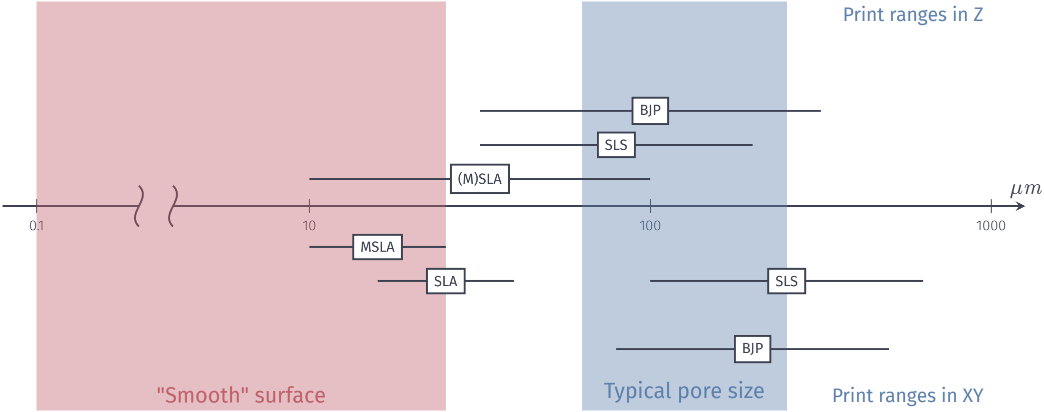

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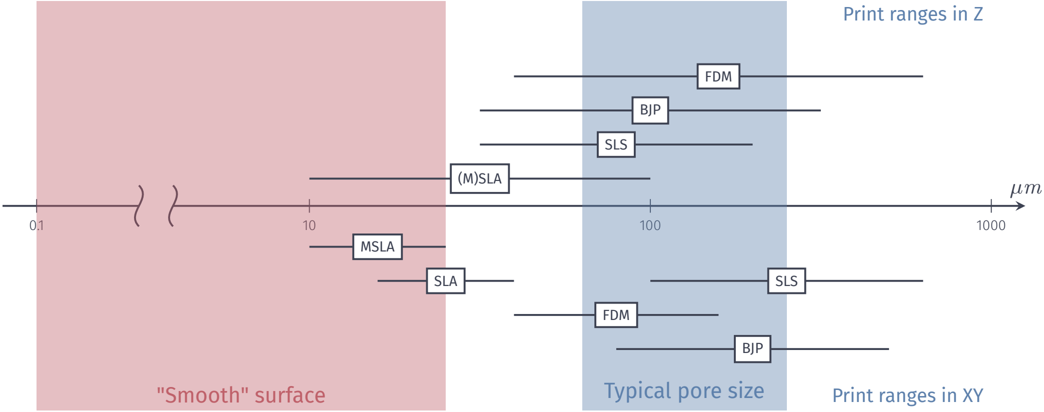

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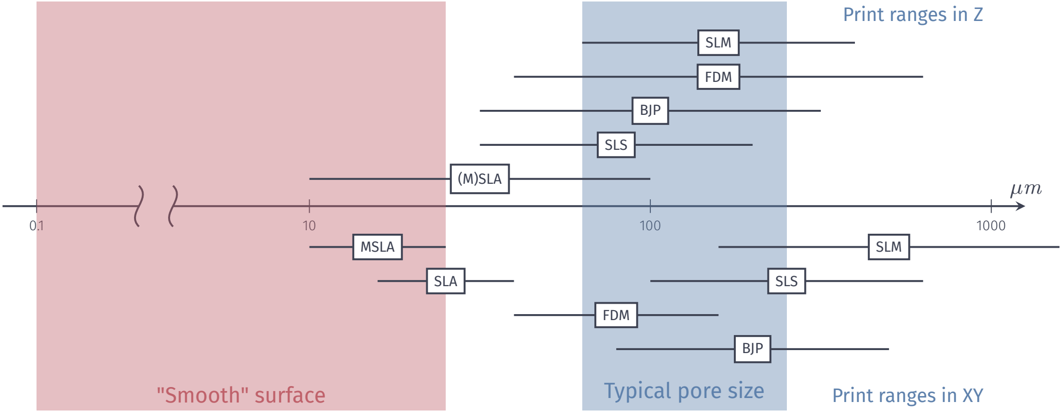

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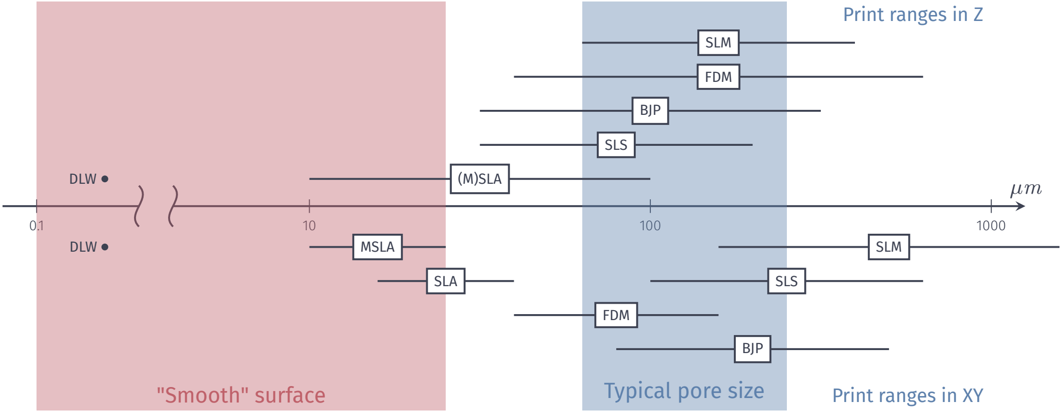
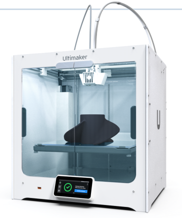


The Fab' Four

Filament Deposition Modelling

- Cheap, thermoplastics
- Almost unlimited size
- Common, reliable



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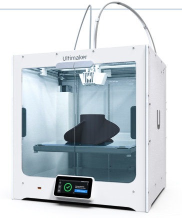

(Masked) Stereolithography

- "Traditional", n-strategies
- Resin, photopolymers
- Getting *much* cheaper
- Post-processing

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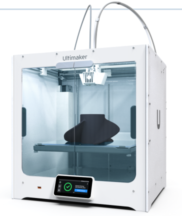

Selective Laser Sintering

- Aggregates, no hull
- Industrial grade
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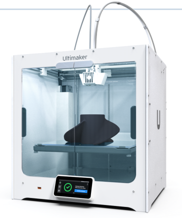

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(Masked) Stereolithography

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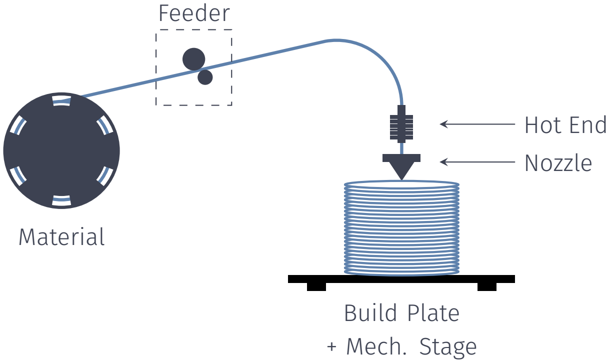
Selective Laser Melting

- Mostly metal, no hull
- Expensive, lost powder
- Complex post-processing

What if we dig deeper ?

Material extrusion

Material extrusion



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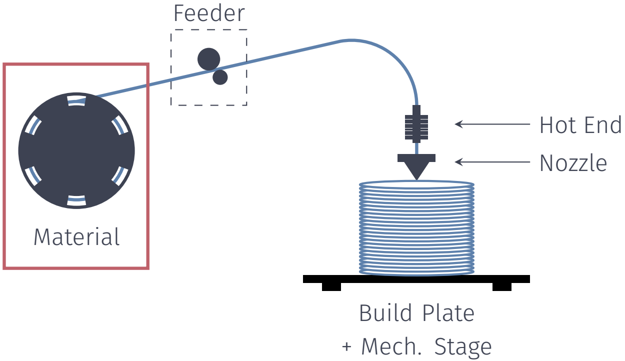

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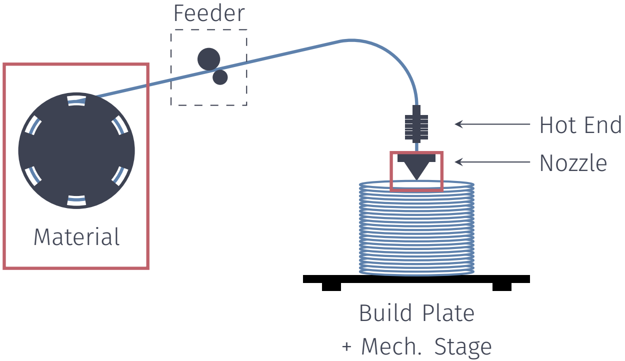

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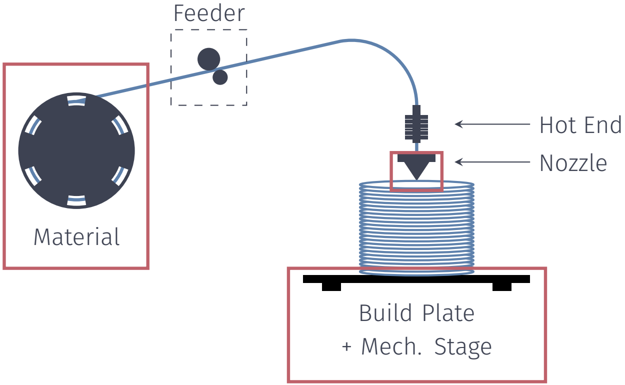

Material extrusion - Material

Wide range

- All thermoplastics, some others (lignin, slurries)
- Limitations: reaching T_g (glass transition), controlled cooling → dimensions gradient

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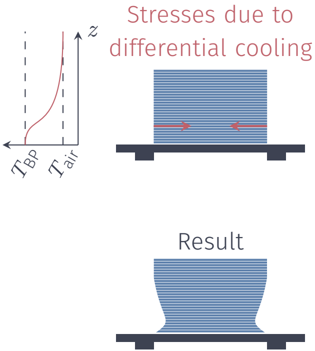

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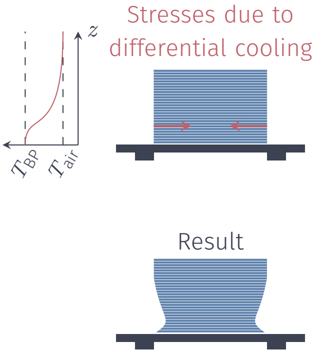
- Mixing thermoplastic with particles (wood, metal, microfibers, etc...)



Stresses due to differential cooling

Result

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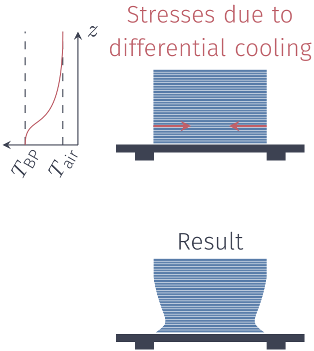
- Extruding fibers along with the filament → CFF



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- Limitations: reaching T_g (glass transition), controlled cooling → dimensions gradient

Options

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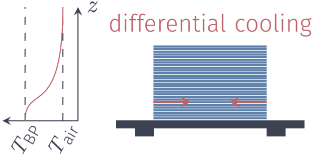
- Extruding fibers along with the filament → CFF
- Mixed extrusion/dual extrusion
- Using chemically/thermally reactive embeddings

Stresses due to differential cooling



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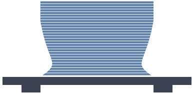

Material extrusion - Nozzle

Key component yet...

- Only a few sizes (in µm): 800, 400, 200
- Micro-notches included → micro-grooves
- Age badly...
- Defects have an acoustic impact
  (cf. PhD thesis Jean Boulvert)

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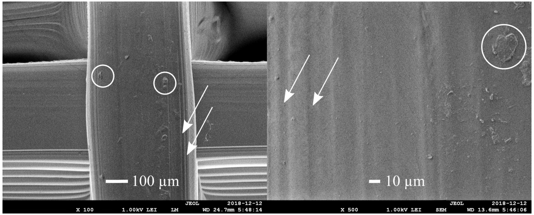

↑ SEM images of FDM printed filaments. Circle: defects, Arrows: micro-grooves.

All images courtesy of Jean Boulvert, from his PhD thesis.

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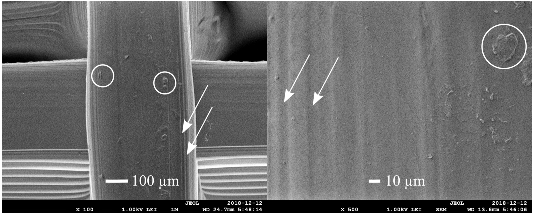

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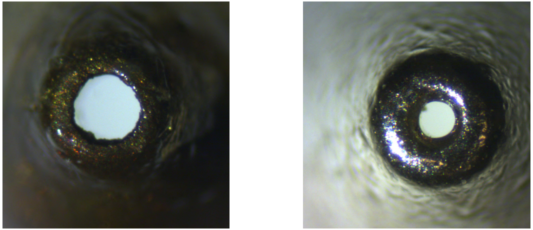
↓ Brand new nozzles in close-up. Left: 400µm, right: 200µm.



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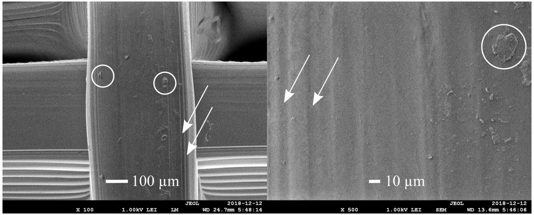
Options

- Custom nozzles
    - Electro-erosion
    - Micro watercut patterns
- Option from the free hardware community (directional, etc.)



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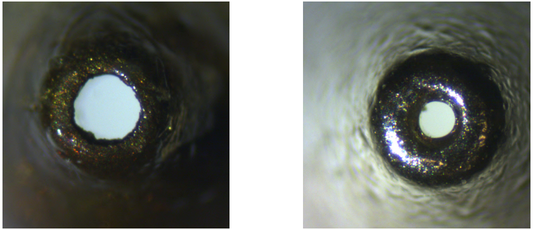

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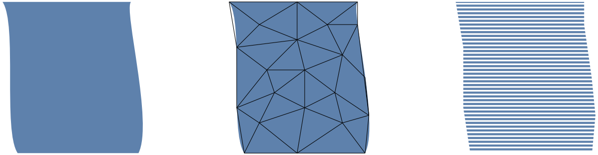
Material extrusion - Slicing feats



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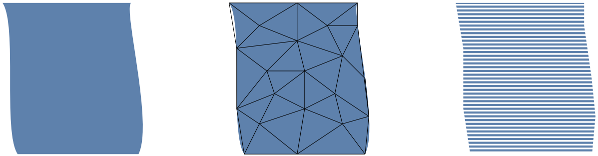

Slices in Z, grids in XY

- Controlled porosity "by design"
- One-step production of metaporous media
- Property gradients
- Optimisation

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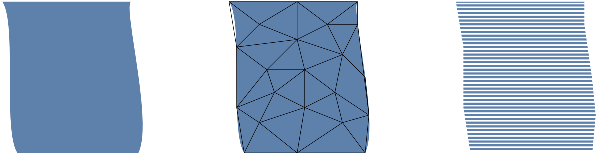

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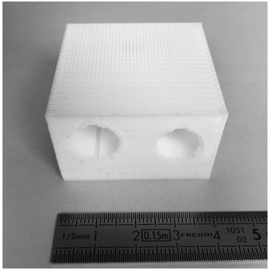

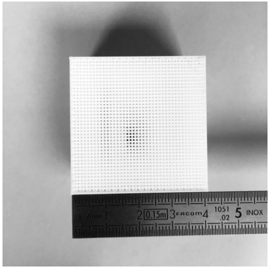

Images from Cavalieri et al. J. Appl. Phys. 129, 115102 (2021), 10.1063/5.0042563

Material extrusion - Layers

Layer-wise effects

Material extrusion - Layers

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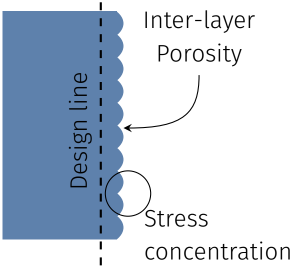
- Rough surfaces $\simeq 1/3$ nozzle width



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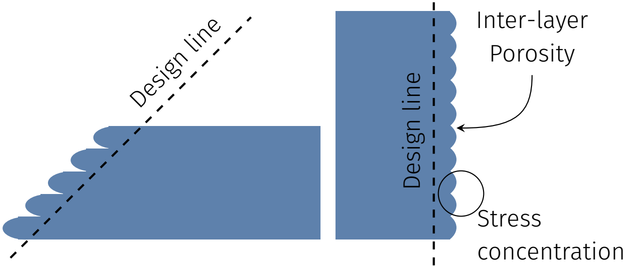
Layer-wise effects

- Rough surfaces $\simeq 1/3$ nozzle width
- Staircases



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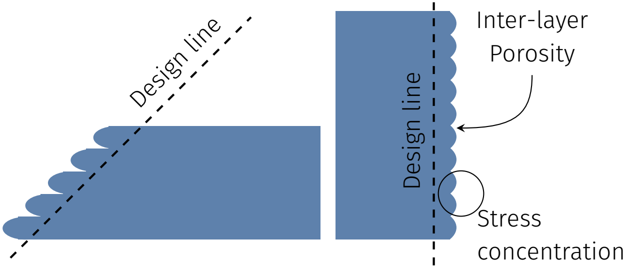
Machine side solutions

- Edge oversampling
- Heat smoothing



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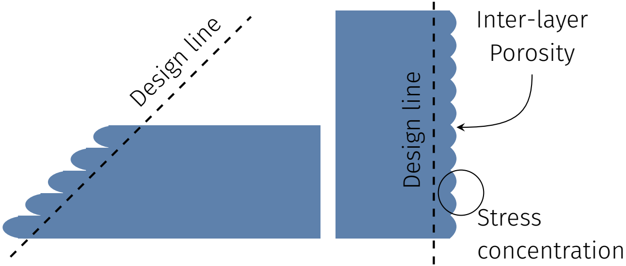
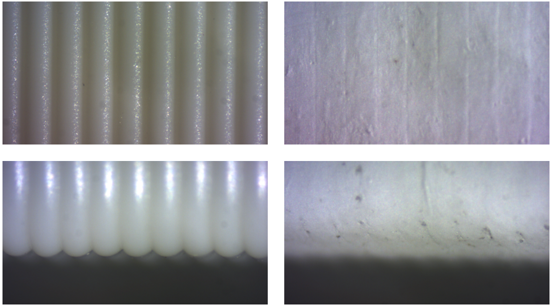
Post-processing solutions

- Coating (boring though...)
- Polishing (tumbling, convex shapes only)
- Chemical surface treatments

ASA print @ 200µm layer height. →
Left: reference.
Right: After 1'30" in Acetone.

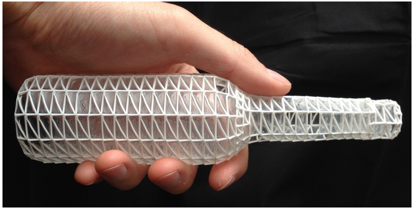


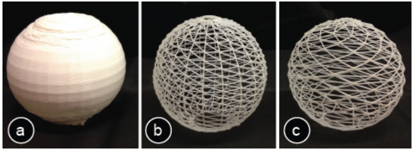


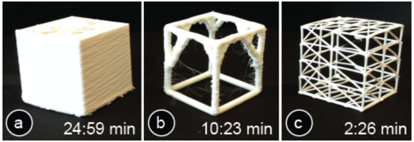
Material extrusion - Rethinking control

Possibility to draw mid-air

- Move-pause strategy
- Much faster than layer-wise wireframing
- Single-filament struts much stronger that layered ones







Images from Müller et al. UIST '14, 273–280, 2014, 10.1145/2642918.2647359.

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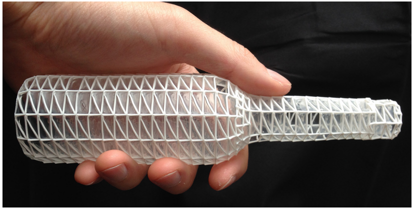
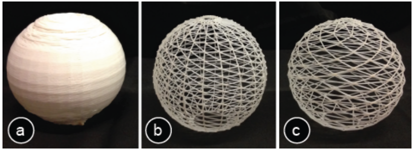
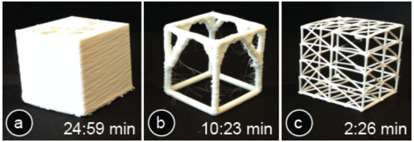


In acoustics

- Create strong flexion planes
- Complex 3D systems without layers
  → vibrations/mechanical applications





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Material Extrusion - Embed-in-print

Stop and go

- Add external components during print
  - Metal inserts → cf part 2
  - Membranes/Textile
  - Electronics

Images from Rivera et al., CHI '17 Conf. Human Fact. Comp. Sys., 497–508, 2017, 10.1145/3025453.3025460

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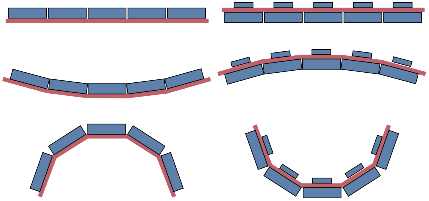

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An example with fabric
Reconfigurable parts beyond machine capabilities

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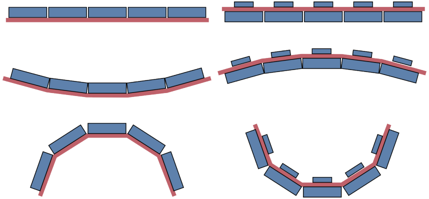

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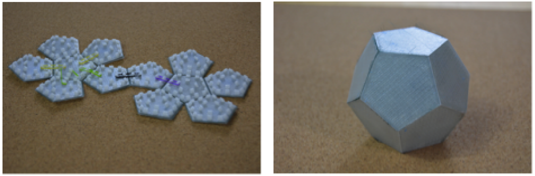

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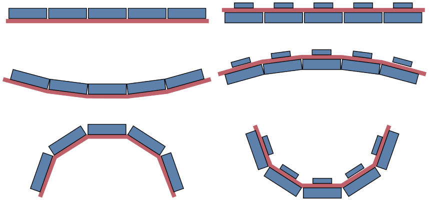

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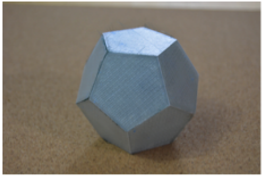

An example with steel beads

See part 2

Images from Rivera et al., CHI '17 Conf. Human Fact. Comp. Sys., 497–508, 2017, 10.1145/3025453.3025460

(Masked) Stereolithography

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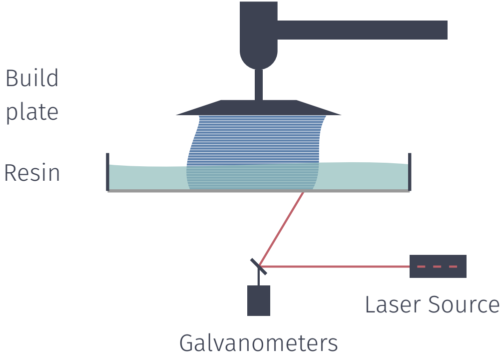

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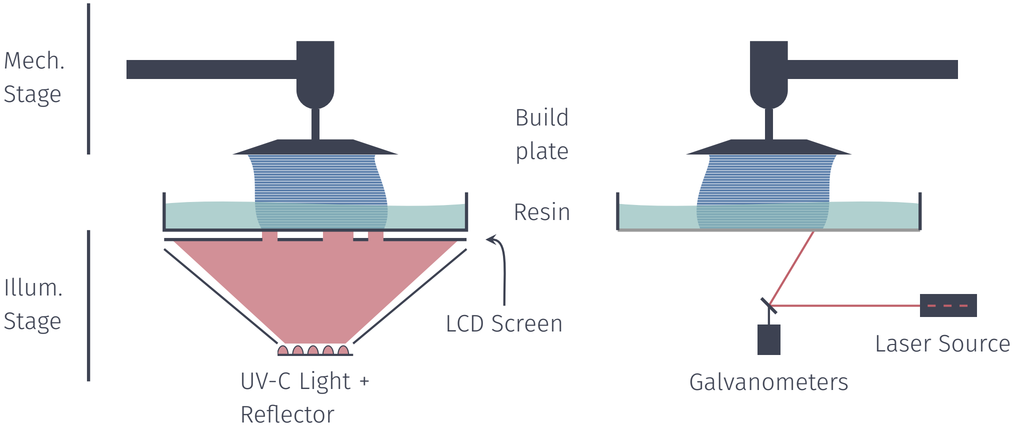

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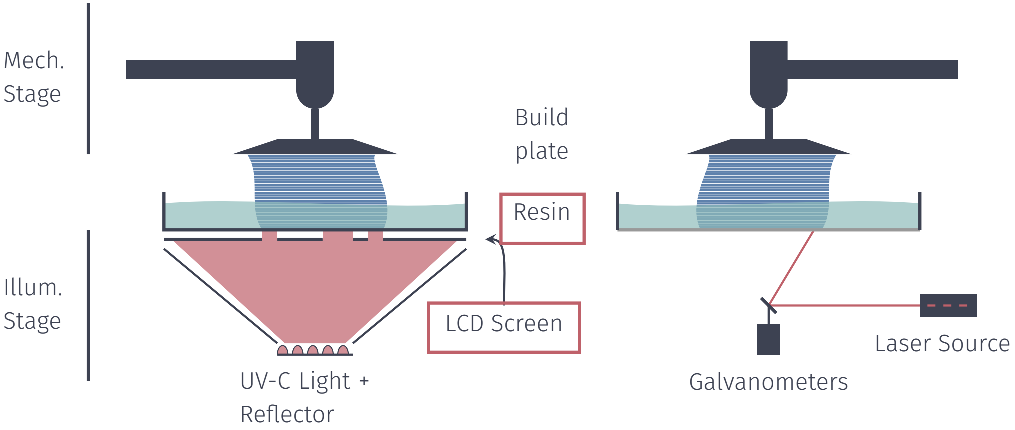

MSLA - Material

monomers + oligomers + photoinitiator

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$$\underbrace{\text{monomers} + \text{oligomers}}_{\text{polymerise to a solid}} + \text{photoinitiator}$$

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Polymers

- Commercially: acrylate resins, added components (flexible, ABS-like, functionnalisation)
- Needs an alcohol or water wash
- Midrange viscosity

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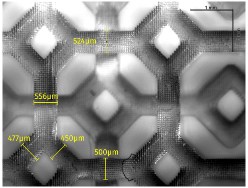
Photoinitiator

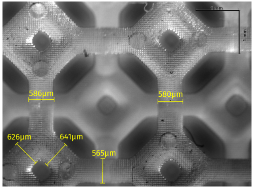
- Specific wavelength (SLA) or wideband (MSLA, UV)
- Compromise:
    - Too much: fast but not enough long polymers
    - Too little: slow/too incomplete polymerisation
- Makes resin unstable once out

MSLA - Material - Lower viscosity

Pretty good results but can we improve?

- Cylindrical struts ∅500µm
- Beware of printing direction





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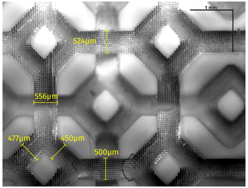
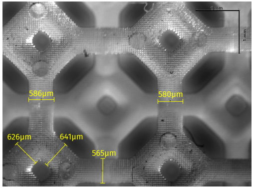
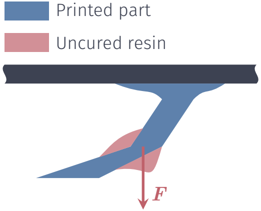
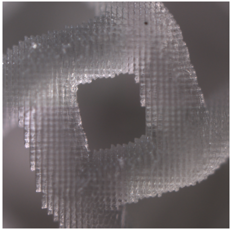




Low viscosity resin

- Lower surface tension
- Less added weight
- Better flow and easier clean up
- Work with chemists!


🟦 Printed part
🟥 Uncured resin



MSLA - Anti-aliasing & Voxel edges

Using a LCD screen as mask

- Resolution is key
- XYZ staircase effects (aliasing)
- Partly compensated by antialising algorithms

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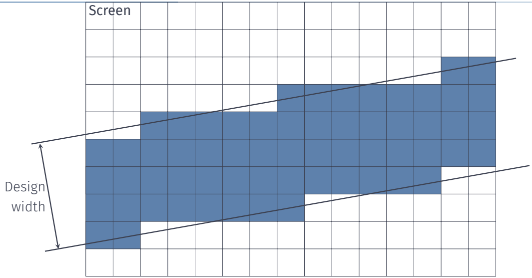

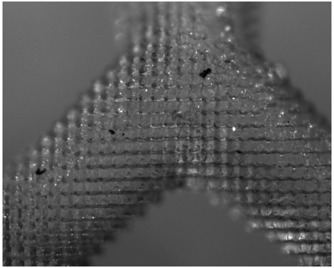

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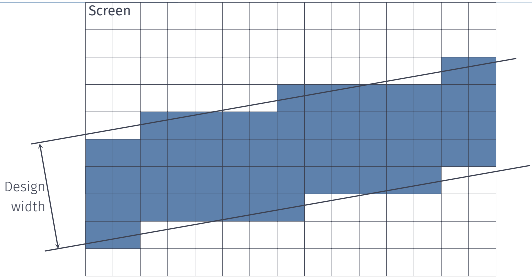

Using a LCD screen as mask

- Resolution is key
- XYZ staircase effects (aliasing)
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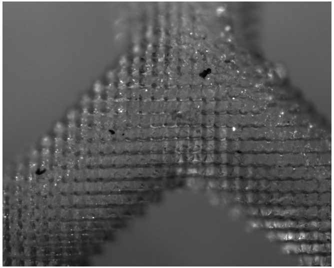
Pixel edge effect

- Edges are more transparent
  → more polymerized
- Isopropanol wash might take the center of voxels away



Direct Sound Printing

Sonochemical process

- Provide energy to initiate polymerisation *via* cavitation
- Allows printing PDMS and biotissues
- Potential for incision-free reconstructive surgery

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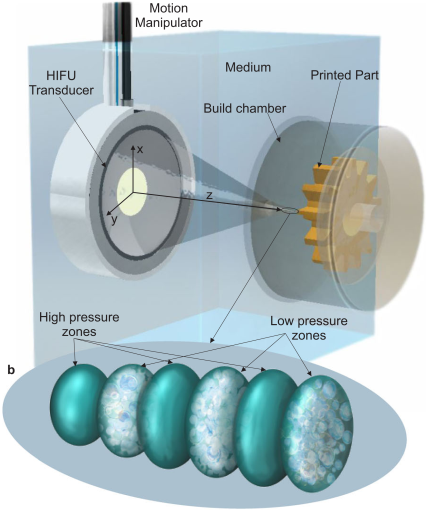

Images from Direct sound printing Habibi et al.Nature Communications **13** 1800, 2022, 0.1038/s41467-022-29395-1

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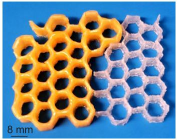

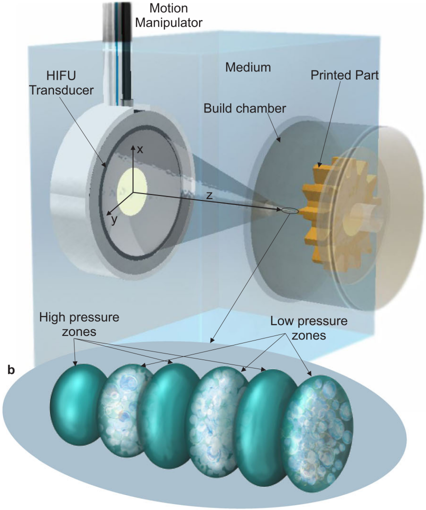

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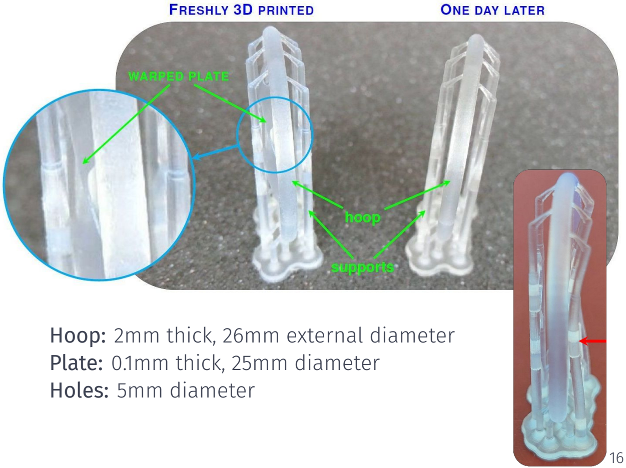
MSLA - Post-processing and deformation

Residual stresses post-curing

Print → Wash residual → UV Curing



Hoop: 2mm thick, 26mm external diameter
Plate: 0.1mm thick, 25mm diameter
Holes: 5mm diameter

Images by T. G. Zieliński, IPPT-PAN. Unpublished.

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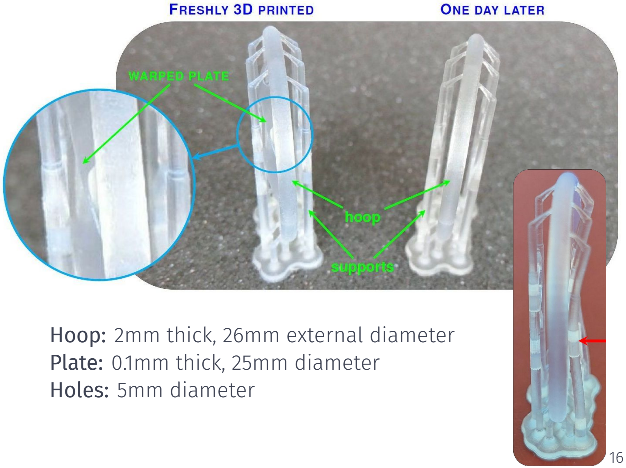
Slight shrinking all through

- residual stresses
- dimensional/geometric discrepancies
- Thick parts: cracks
- Thin parts: tension



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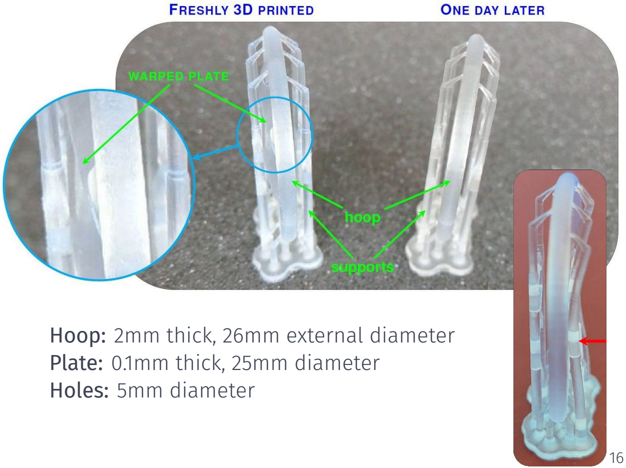
Workarounds

- Annealing (relieves stresses) @ 60-70°C for 5-10min
- Heat-up during curing (60°C)



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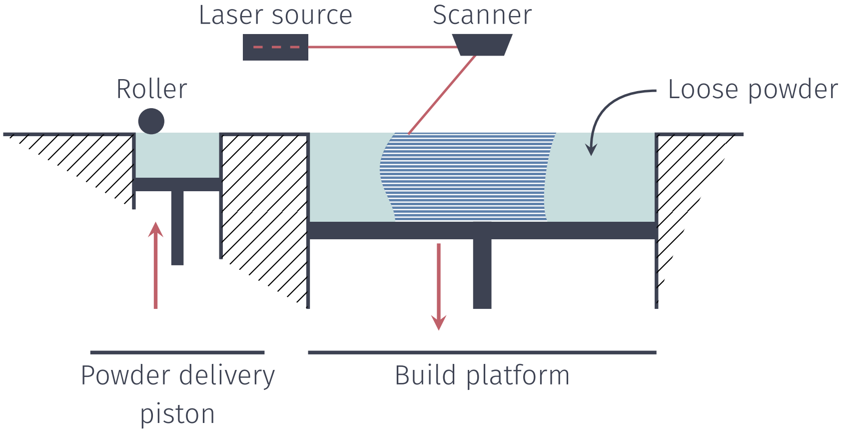
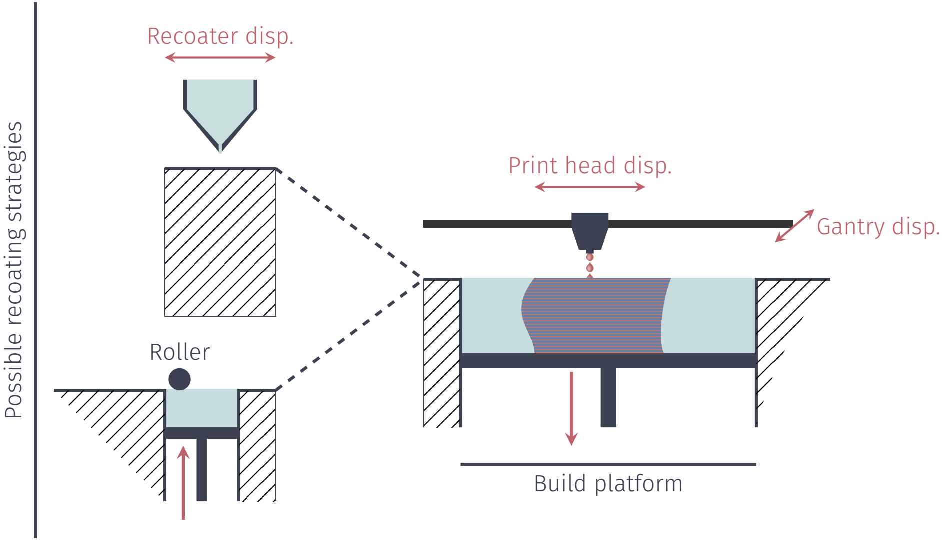
Power bed fabrication

Powder bed & Laser



Binder jetting



Binder Jetting - Material & Binder

Powder

- Any powder !
- Classical: plastics, metal, nylon
- But also : wood, gypsum

Grain size, geometry, distribution are important!

Images from Mostafaei et al., Prog. Mat. Sci **(13)** 100707, j.pmatsci.2020.100707.

Binder Jetting - Material & Binder

Powder

- Any powder !
- Classical: plastics, metal, nylon
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Grain size, geometry, distribution are important!

Binder

- Polymers + solvent
- Monomer
- Addition of dispersive/wetting agent
- Possibility for a flexible matrix

Images from Mostafaei et al., Prog. Mat. Sci **(13)** 100707, j.pmatsci.2020.100707.

Binder Jetting/SLS - Post processing

In all cases: powder removal

- Inherently abrasive though
- Difficult to empty hollow parts
- More in part 2

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Depending on material and applications

- Annealing/Sintering/Densifying
- Chemical infiltration

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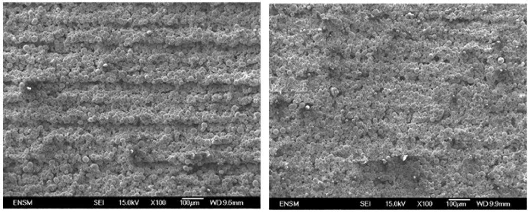
Impregnation/coating

BJP parts are inherently porous



Thinly coat the surface with an impervious layer

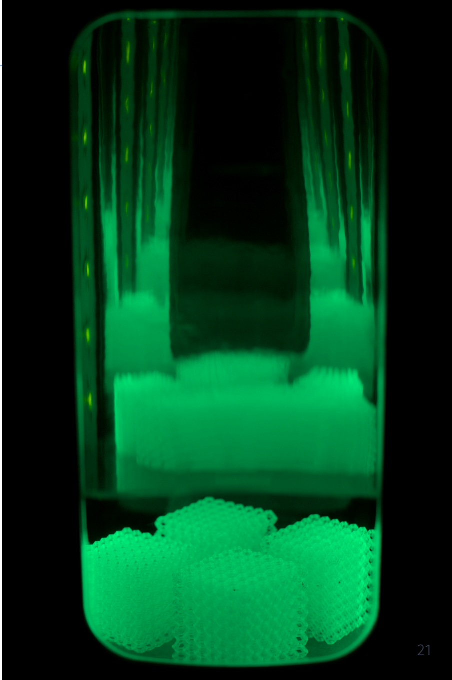
Example in part 2

How to get the most out of these techniques ?

Get the most out

Closer to the machines

- Understand the process to use side effects
- Huge literature on optimised prints



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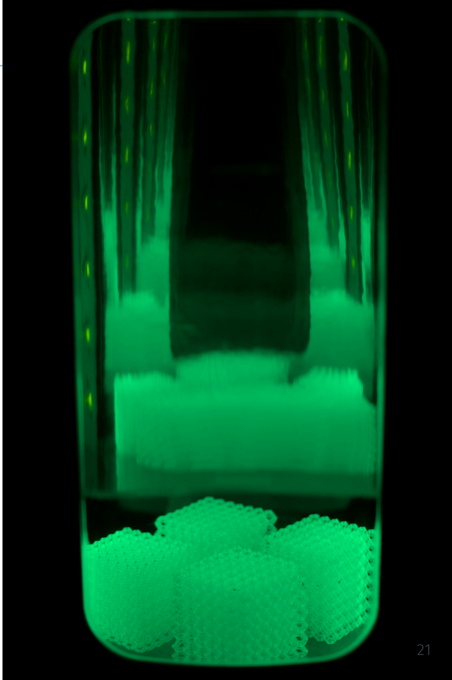
Closer to the material

- Different materials give different possibilities
- Think about post-processing early on



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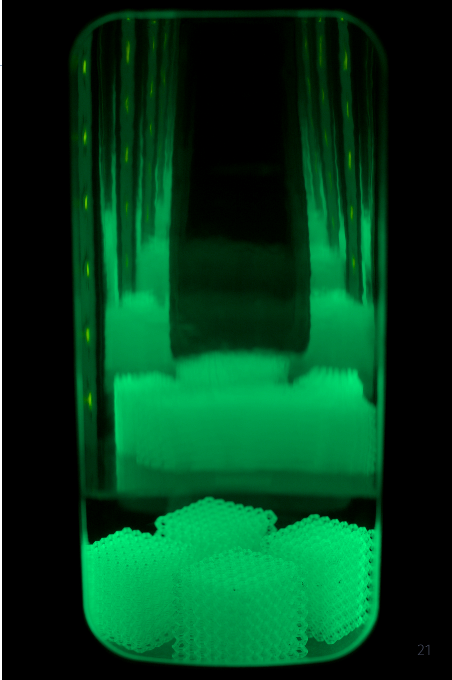
Beyond usage

- Start from consumer-grade machines:
  Cheaper, Reliable, Not so protected
- Checkout community mods & tests



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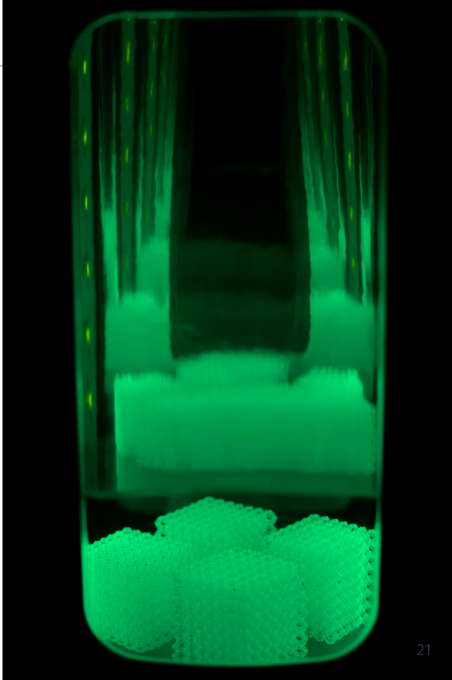
Brands

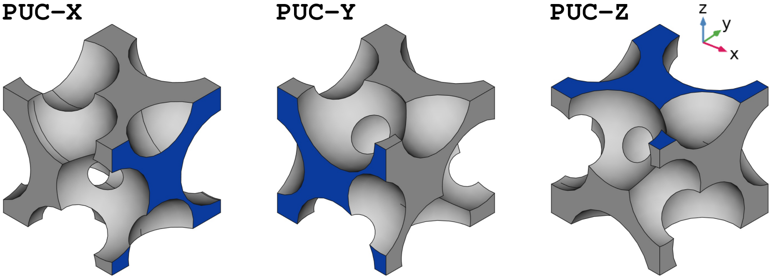
- Speed: Bambulab, Zortrax
- Tweaks: Ultimaker, Eleegoo, Creality



Acoustic Applications

Tomasz G. Zieliński

Reproducibility of 3D printed acoustic materials



Periodic Unit Cell (PUC)

- a cube with a periodic arrangement of four spherical pores of different sizes
- cell size (edge length): 5 mm
- three orientations: X, Y, Z

ROUND ROBIN STUDY

involving 12 laboratories

Additive Manufacturing 36 (2020) 101564

Contents lists available at ScienceDirect

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ELSEVIER

Reproducibility of sound-absorbing periodic porous materials using additive manufacturing technologies: Round robin study

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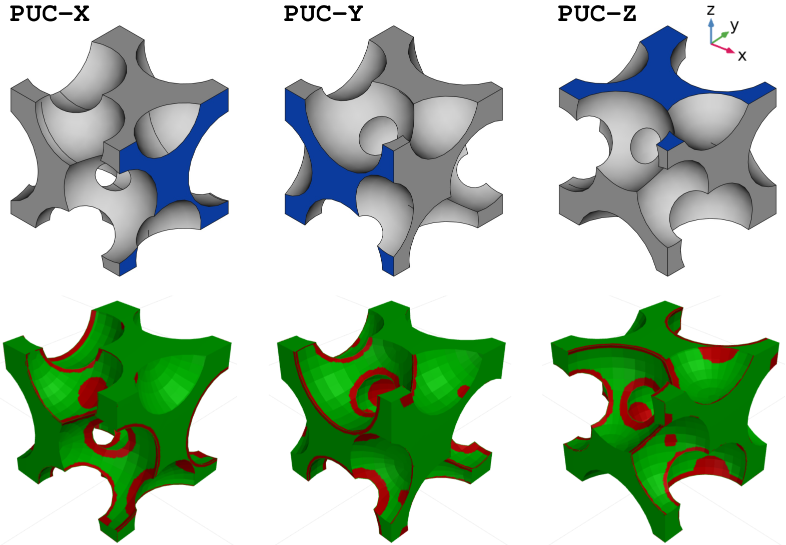
ARTICLE INFO

Keywords:
Porous materials
Designed periodicity
Additive manufacturing
Sound absorption

ABSTRACT

The purpose of this work is to check if additive manufacturing technologies are suitable for reproducing porous samples designed for sound absorption. The work is an inter-laboratory test, in which the production of samples and their acoustic measurements are carried out independently by different laboratories, sharing only the same geometry codes describing agreed periodic cellular designs. Different additive manufacturing technologies and equipment are used to make samples. Although most of the results obtained from measurements performed on samples with the same cellular design are very close, it is shown that some discrepancies are due to shape and surface imperfections, or microporosity, induced by the manufacturing process. The proposed periodic cellular designs can be easily reproduced and are suitable for further benchmarking of additive manufacturing techniques for rapid prototyping of acoustic materials and metamaterials.

Reproducibility of 3D printed acoustic materials



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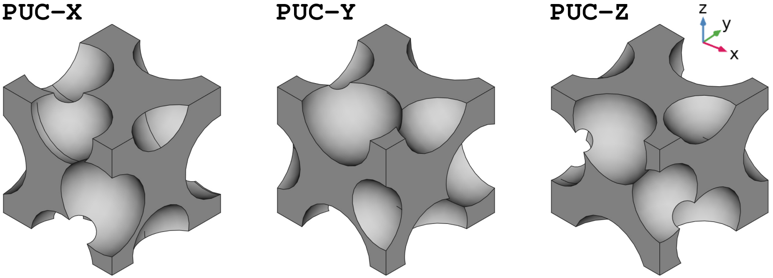
PUC cannot be 3D printed correctly using FDM !!!

Reproducibility of 3D printed acoustic materials



Periodic Unit Cell (PUC)

- a cube with a periodic arrangement of four spherical pores of different sizes
- cell size (edge length): 5 mm
- three orientations: X, Y, Z
- **pore diameters reduced by 10%**

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Sound absorption

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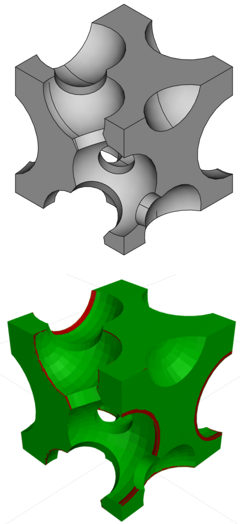
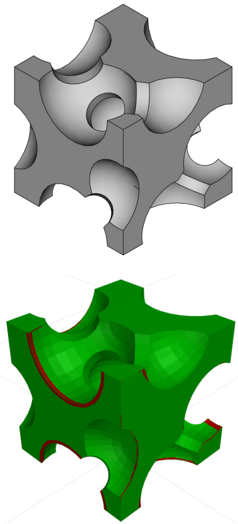
The purpose of this work is to check if additive manufacturing technologies are suitable for reproducing porous samples designed for sound absorption. The work is an inter-laboratory test, in which the production of samples and their acoustic measurements are carried out independently by different laboratories, sharing only the same geometry codes describing agreed periodic cellular designs. Different additive manufacturing technologies and equipment are used to make samples. Although most of the results obtained from measurements performed on samples with the same cellular design are very close, it is shown that some discrepancies are due to shape and surface imperfections, or microporosity, induced by the manufacturing process. The proposed periodic cellular designs can be easily reproduced and are suitable for further benchmarking of additive manufacturing techniques for rapid prototyping of acoustic materials and metamaterials.

Reproducibility of 3D printed acoustic materials

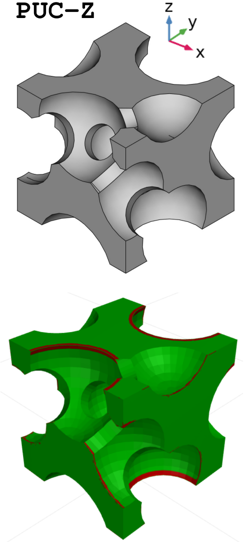
PUC-X



PUC-Y



PUC-Z



ROUND ROBIN STUDY
involving 12 laboratories

Additive Manufacturing 36 (2020) 101564

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

Reproducibility of sound-absorbing periodic porous materials using additive manufacturing technologies: Round robin study

Tomasz G. Zieliński[a,*], Kamil C. Opiela[a], Piotr Pawłowski[a], Nicolas Dauchez[b], Thomas Boutin[b], John Kennedy[c], Daniel Trimble[c], Henry Rice[c], Bart Van Damme[d], Gwenael Hannema[d], Rafał Wróbel[e], Seok Kim[f], Shahrzad Ghaffari Mosanenzadeh[f], Nicholas X. Fang[f], Jieun Yang[g], Baltazar Briere de La Hosseraye[g], Maarten C.J. Hornikx[g], Edouard Salze[h], Marie-Annick Galland[h], René Boonen[i], Augusto Carvalho de Sousa[i,j], Elke Deckers[i,j], Mathieu Gaborit[k,l], Jean-Philippe Groby[l]

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ARTICLE INFO

Keywords:
Porous materials
Designed periodicity
Additive manufacturing
Sound absorption

ABSTRACT

The purpose of this work is to check if additive manufacturing technologies are suitable for reproducing porous samples designed for sound absorption. The work is an inter-laboratory test, in which the production of samples and their acoustic measurements are carried out independently by different laboratories, sharing only the same geometry codes describing agreed periodic cellular designs. Different additive manufacturing technologies and equipment are used to make samples. Although most of the results obtained from measurements performed on samples with the same cellular design are very close, it is shown that some discrepancies are due to shape and surface imperfections, or microporosity, induced by the manufacturing process. The proposed periodic cellular designs can be easily reproduced and are suitable for further benchmarking of additive manufacturing techniques for rapid prototyping of acoustic materials and metamaterials.

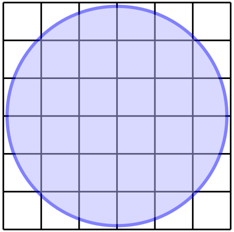
PUC can be 3D printed using FDM technology

Reproducibility of 3D printed acoustic materials

$\varnothing \approx 29\,\text{mm}$

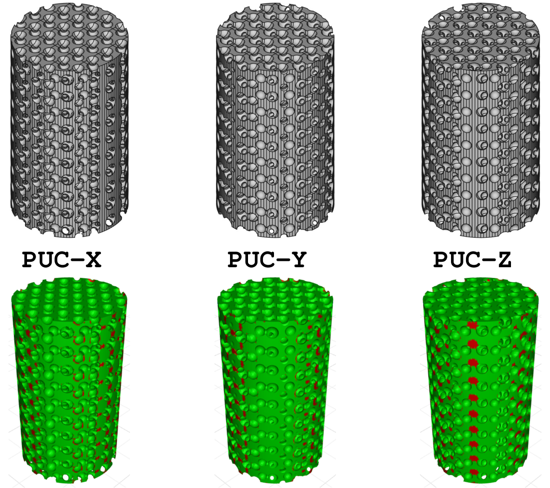
cell size: 5 mm

6×6×10 cells



height: 50 mm

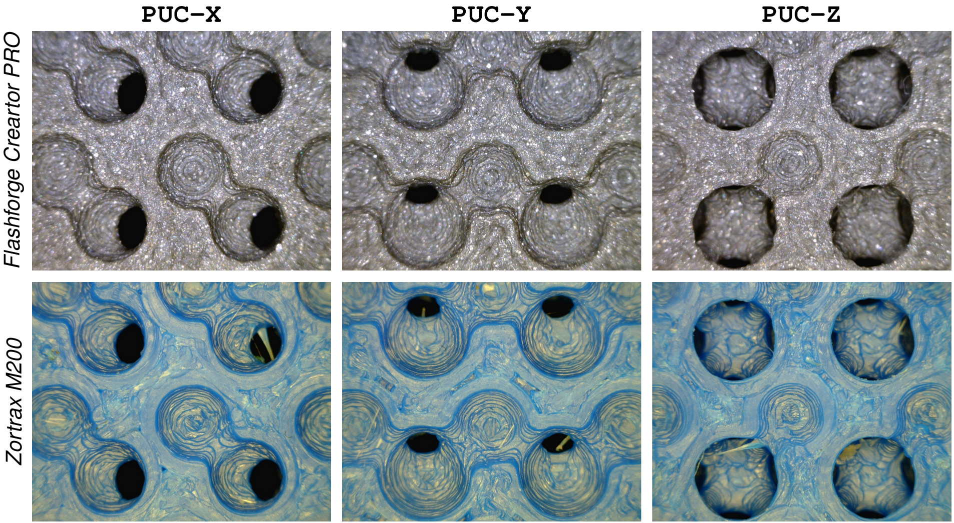
CAD models of POROUS CYLINDERS



Polymer sample

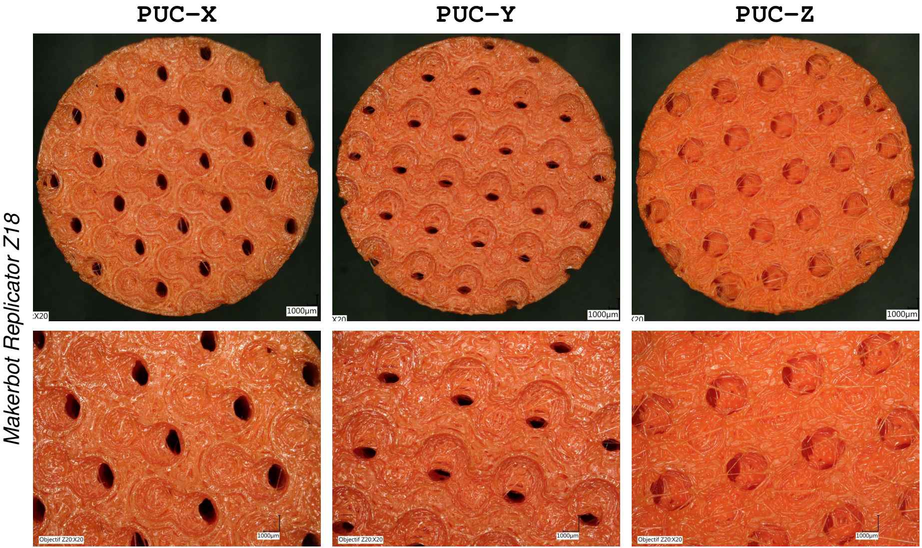
Metal sample wrapped with tape

Reproducibility of 3D printed acoustic materials (FDM samples)



- Technology:
  FDM / FFF
- Material:
  ABS polymer filaments
- Quality:
  good / decent
- Characteristics:
  staircase-type roughness due to the layer height

Reproducibility of 3D printed acoustic materials (FDM samples)


PUC-X

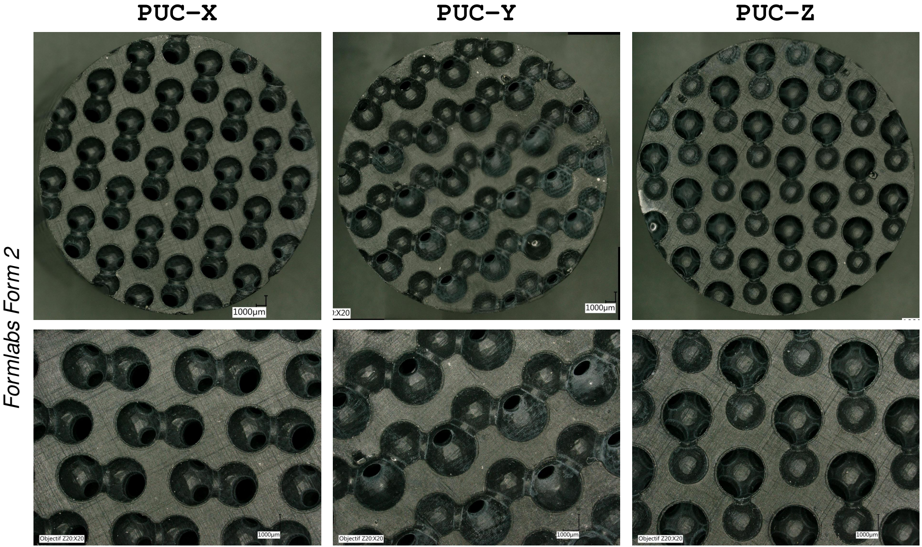
PUC-Y

PUC-Z

Makerbot Replicator Z18

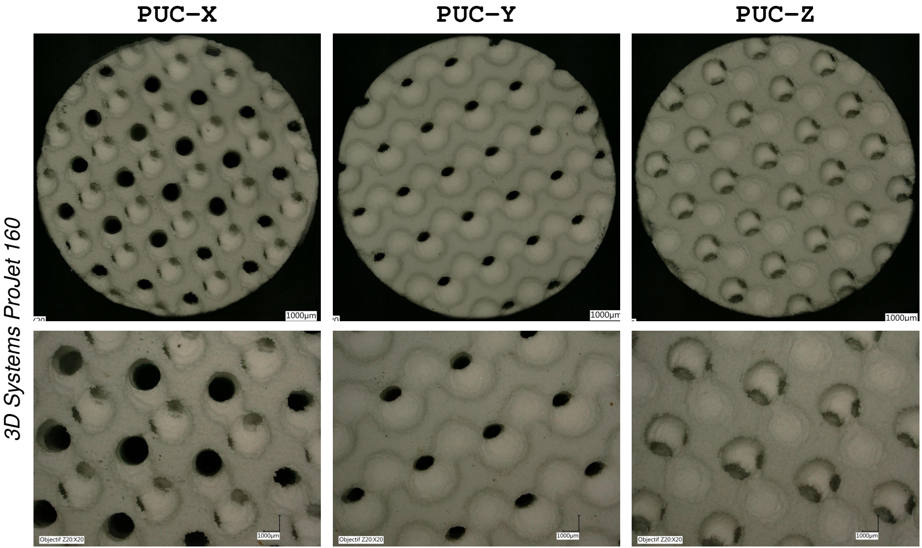
- Technology:
  FDM / FFF
- Material:
  PLA polymer filament
- Quality:
  very bad
- Characteristics:
  fibres in the pores caused by **filament stringing**; surface **roughness**

Reproducibility of 3D printed acoustic materials (SLA samples)



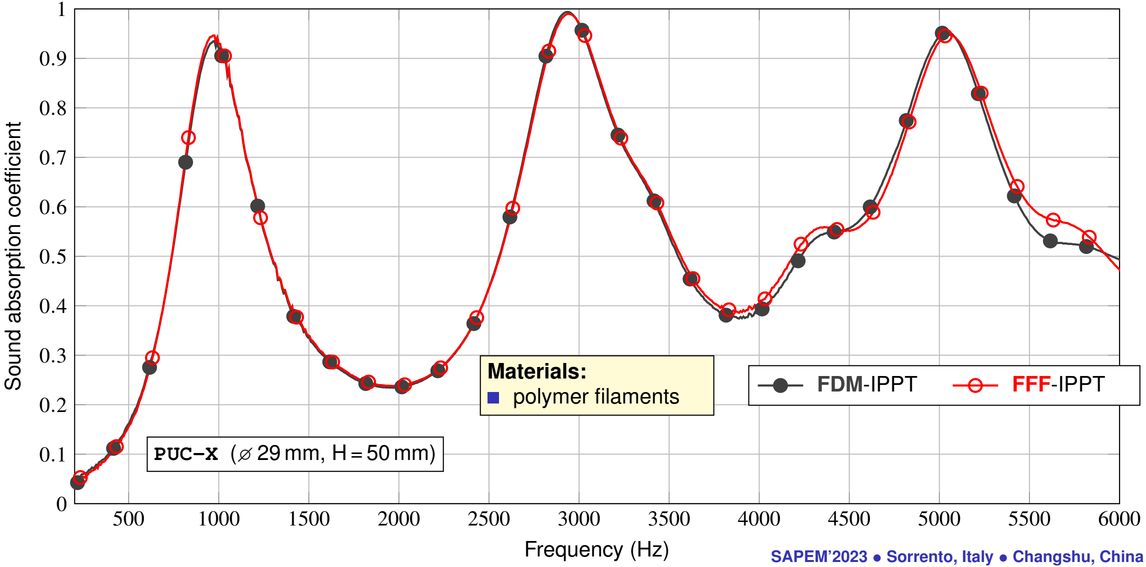
- Technology: **SLA** (vat photo-polymerisation)
- Material: **photopolymer resin**
- Quality: **excellent**
- Characteristics: correct shapes; smooth surfaces

Reproducibility of 3D printed acoustic materials (BJP samples)

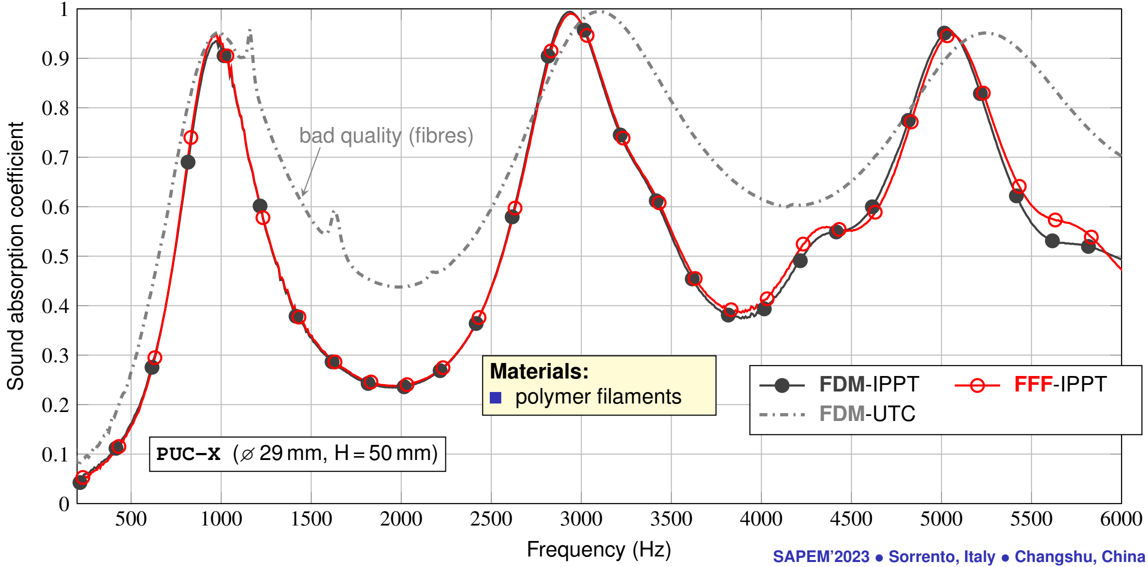


- Technology:
  BJP (powder-bed technique)
- Material:
  gypsum powder + binder
- Quality:
  good (esp. after impregnation)
- Characteristics:
  roughness due to powder grains; **microporosity** (closed by impregnation)

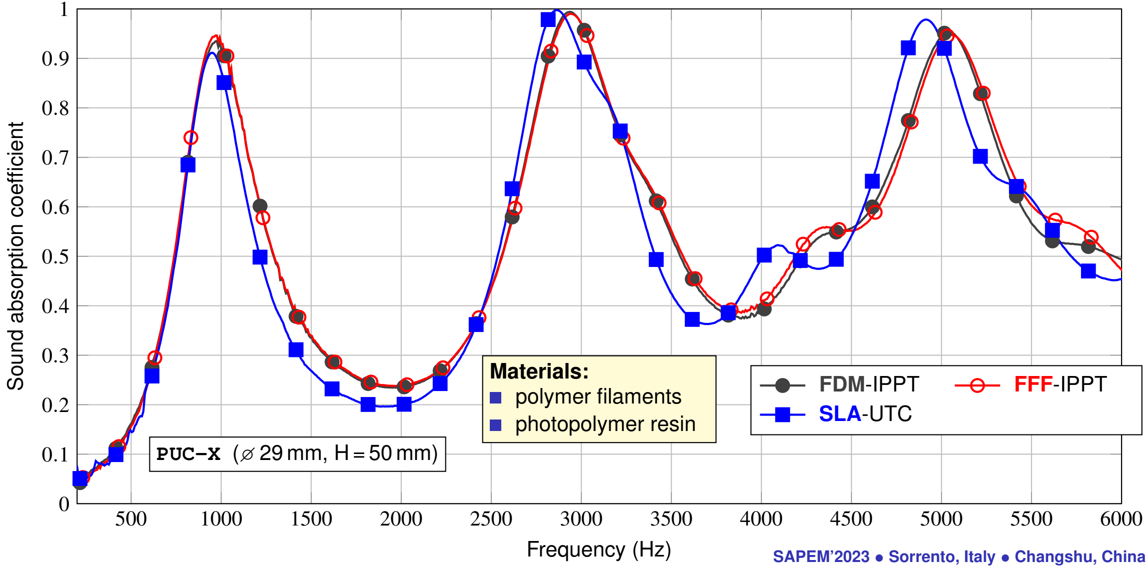
Reproducibility of 3D printed acoustic materials



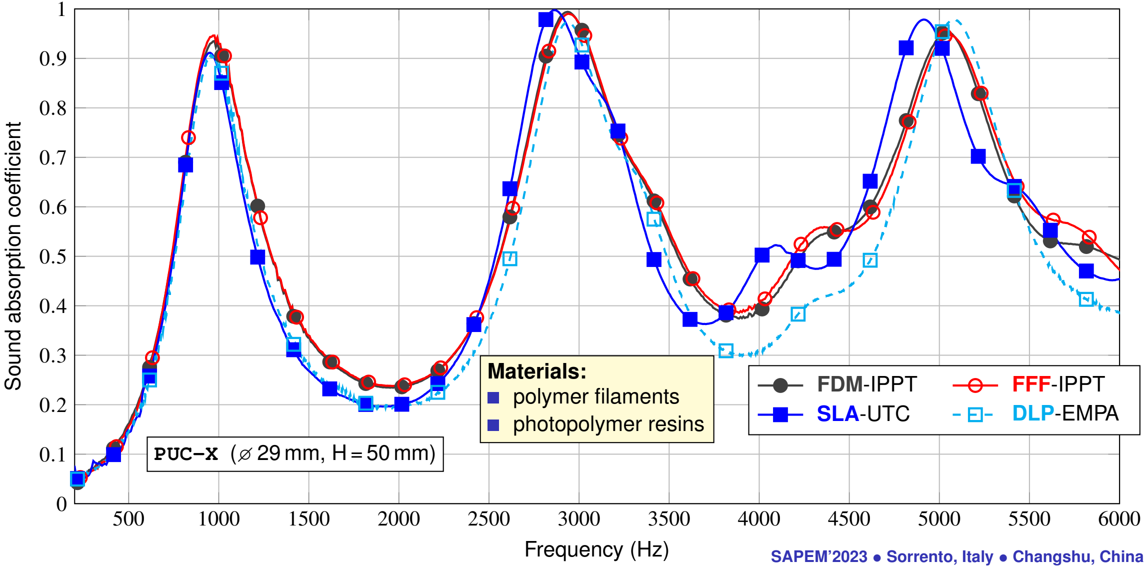
Reproducibility of 3D printed acoustic materials



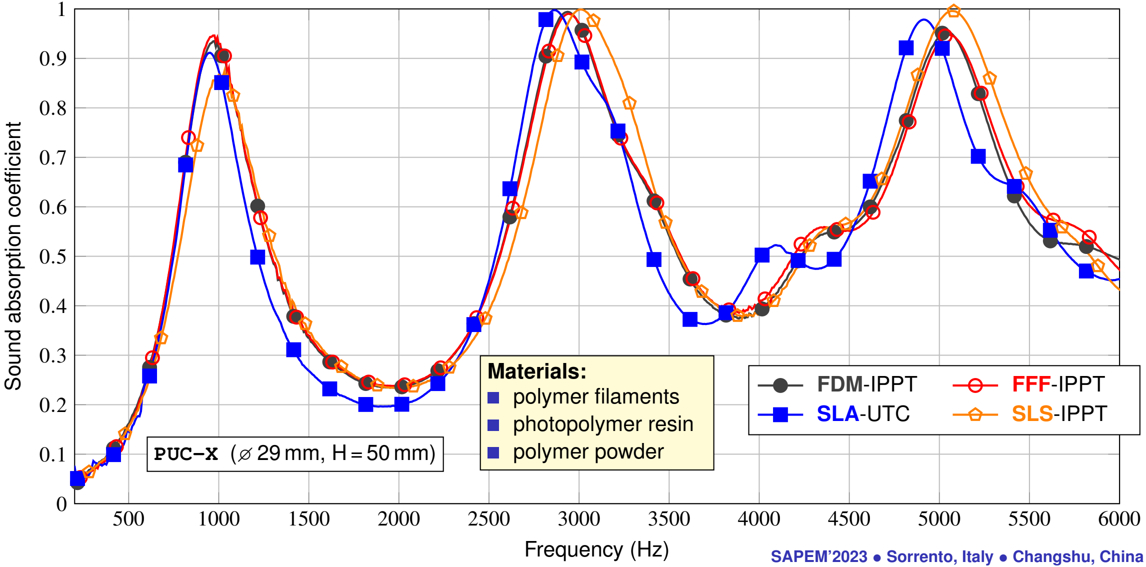
Reproducibility of 3D printed acoustic materials



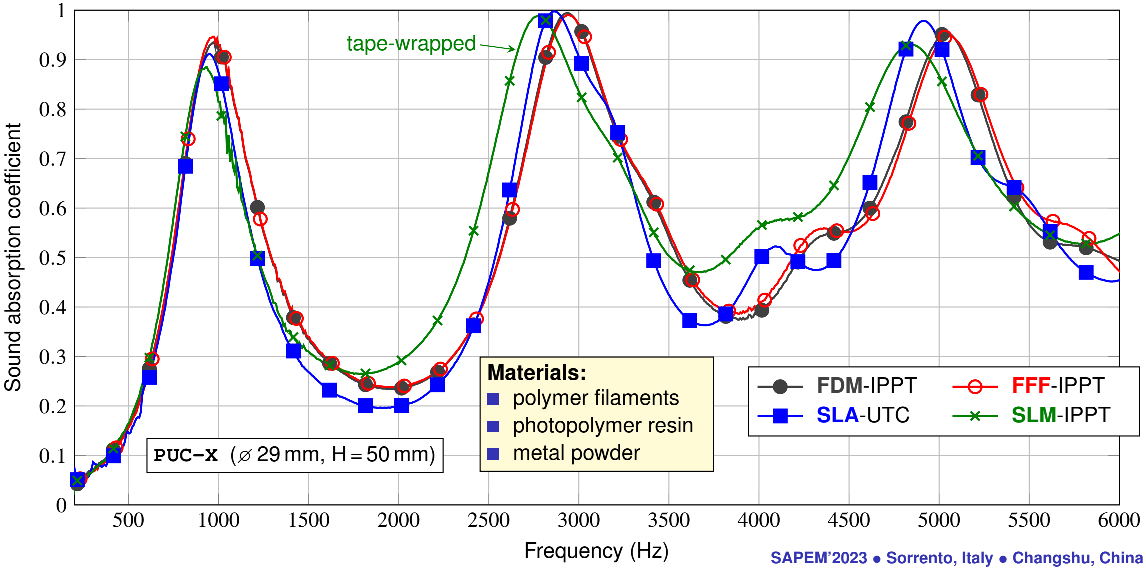
Reproducibility of 3D printed acoustic materials



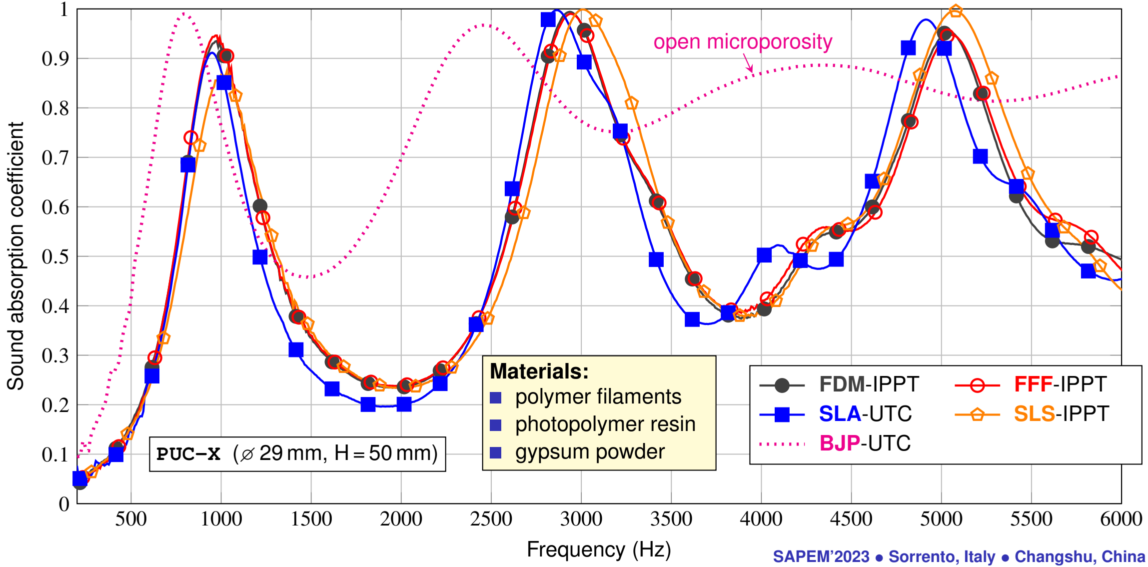
Reproducibility of 3D printed acoustic materials



Reproducibility of 3D printed acoustic materials

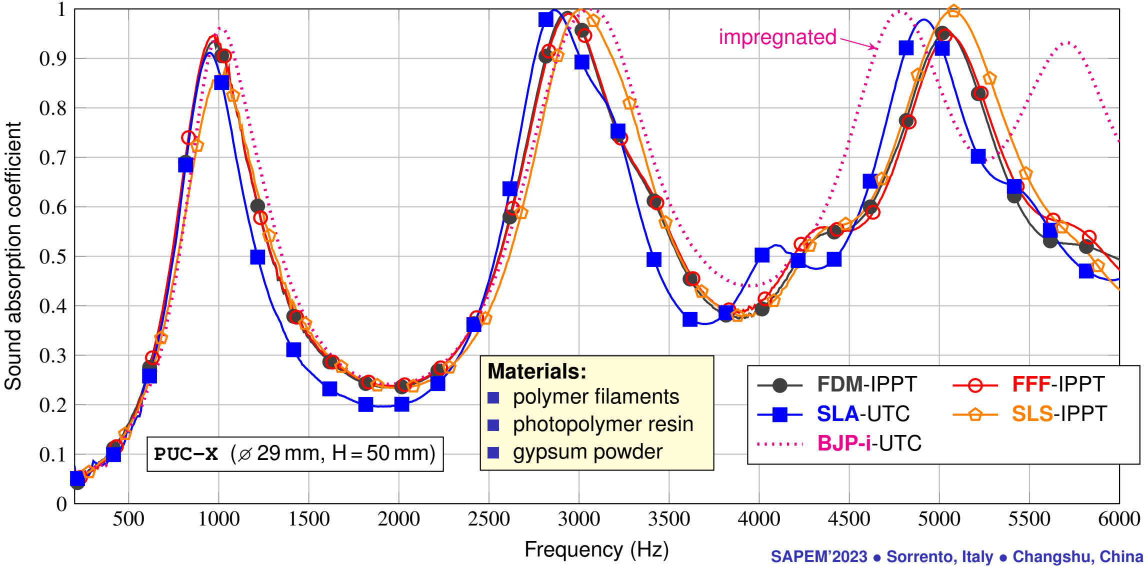


Reproducibility of 3D printed acoustic materials



Materials:
- polymer filaments
- photopolymer resin
- gypsum powder

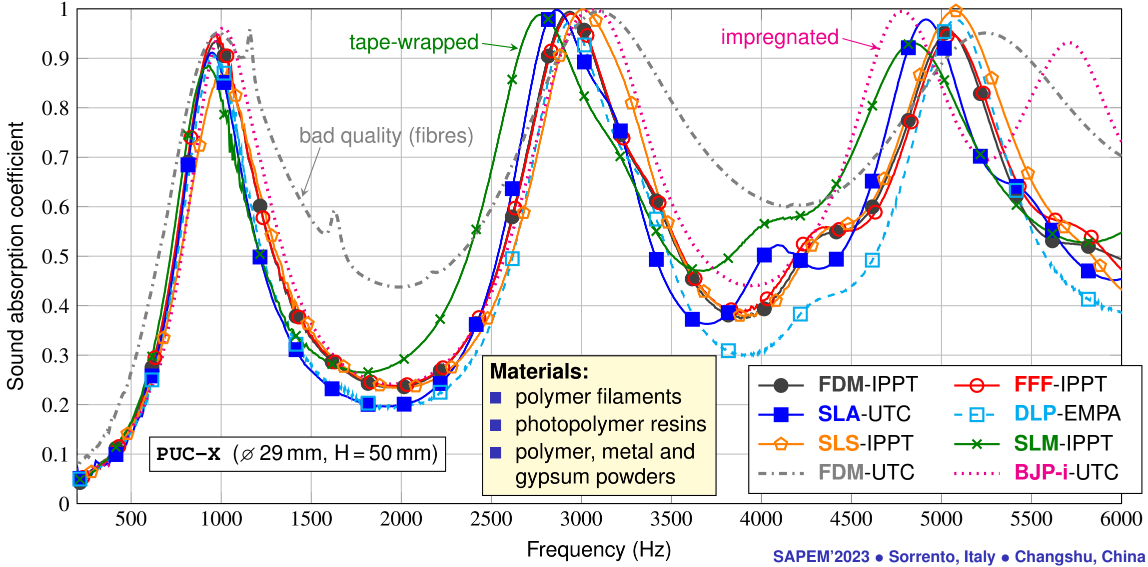
Reproducibility of 3D printed acoustic materials



PUC-X (⌀ 29 mm, H = 50 mm)

Materials:
- polymer filaments
- photopolymer resin
- gypsum powder

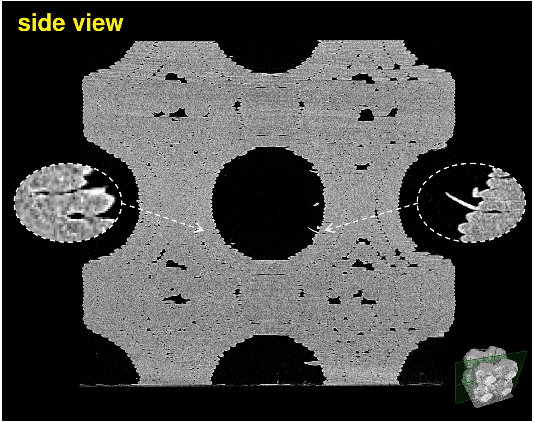
Reproducibility of 3D printed acoustic materials

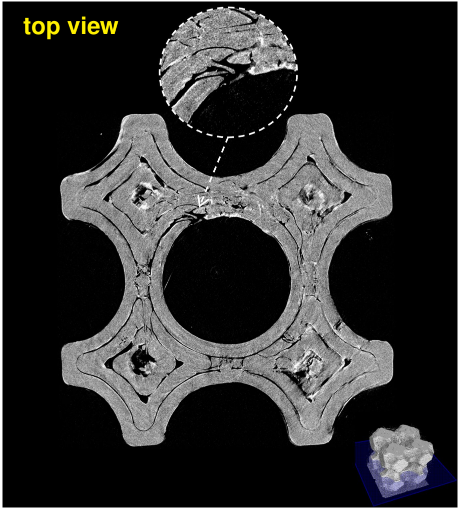


Quality and typical imperfections of 3D printing (CT scans)

FDM

- **staircase** type surface **roughness**
- very **irregular microporosity** (mainly closed)
- thin **fibres** due to **filament stringing**



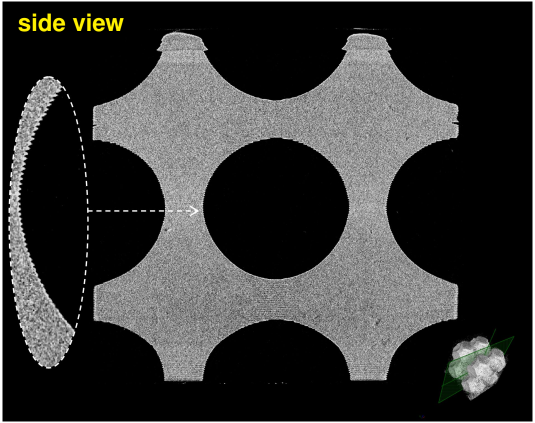


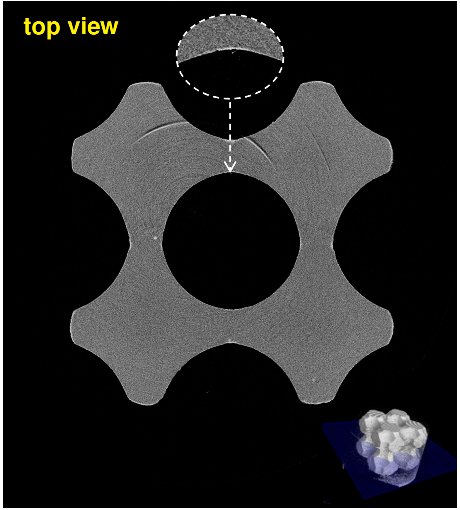
A. CICHON's PhD thesis (2023, Trinity College Dublin)

Quality and typical imperfections of 3D printing (CT scans)

MSLA

- relatively **smooth surfaces**
- virtually **no microporosity**
- overall **high quality** (especially for SLA)



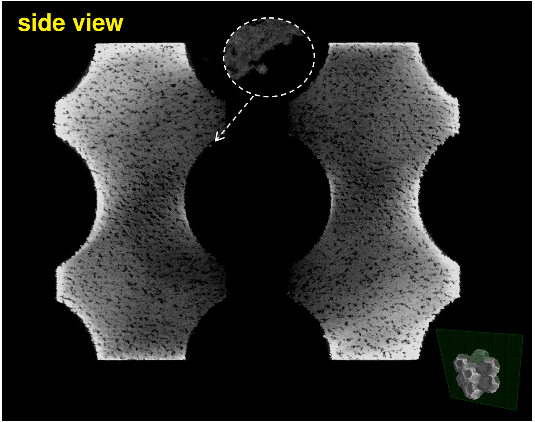


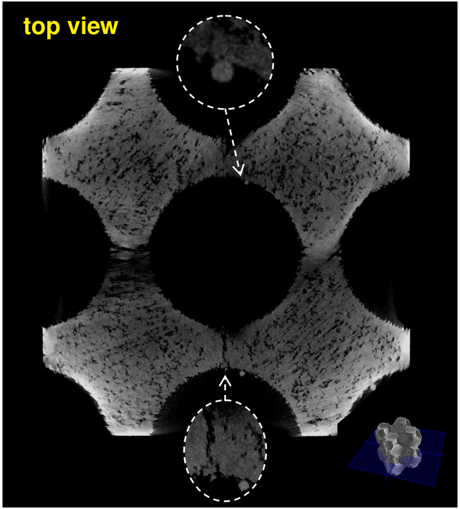
A. CICHON's PhD thesis (2023, Trinity College Dublin)

Quality and typical imperfections of 3D printing (CT scans)

SLM

- **roughness** due to powder grains
- regular (partly) closed or open **microporosity**
- irregular imperfections (e.g. satellite particles)

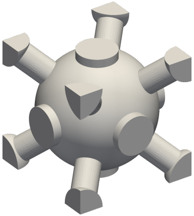




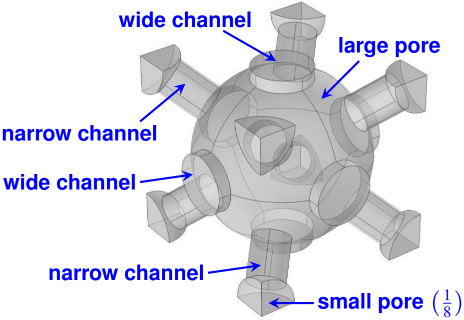
A. CICHON's PhD thesis (2023, Trinity College Dublin)

Example: 3D printed adaptable sound absorber

Pore network



Void diameter [mm]	
large pore:	4.60
small pore:	2.00
wide channel:	1.60
narrow channel:	1.00
Cell size:	5.00



Periodic unit cell contains:

- a single large pore at the centre
- 8 one-eighths of a small pore in the corners
- 4 horizontal and 2 vertical channels which link the large pores (of adjacent cells)
- 8 oblique narrower channels which connect the large pore with the small ones

Composites Part B 187 (2020) 107833

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journal homepage: www.elsevier.com/locate/composites

Microstructural design, manufacturing and dual-scale modelling of an adaptable porous composite sound absorber

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A R T I C L E   I N F O

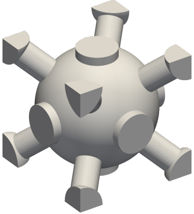
Keywords:
Porous composite
Adaptive sound absorber
Microstructure-based modelling
Additive manufacturing

A B S T R A C T

This work investigates a porous composite with modifiable micro-geometry so that its ability to absorb noise can be accommodated to different frequency ranges. The polymeric skeleton of the composite has a specific periodic structure with two types of pores (larger and smaller ones) and two types of channels (wide and narrow ones), and each of the large pores contains a small steel ball. Depending on the situation, the balls block different channels that connect the pores, and therefore alter the visco-inertial phenomena between the saturating air and solid skeleton which take place at the micro-scale level and are responsible for the dissipation of the energy of acoustic waves penetrating the porous composite. All this is studied numerically using advanced dual-scale modelling, and the results are verified by the corresponding experimental tests of 3D-printed samples. Particular attention is paid to the prototyping and additive manufacturing of such adaptive porous composites.

Example: 3D printed adaptable sound absorber

Pore network



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wide channel:	1.60
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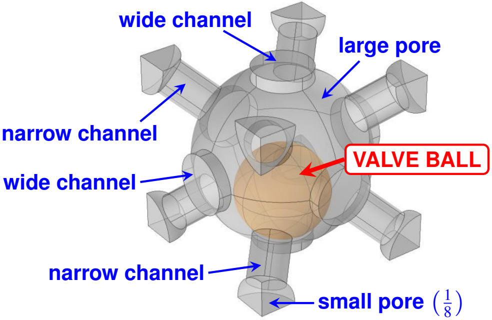
Cell size:	5.00



Periodic unit cell contains:

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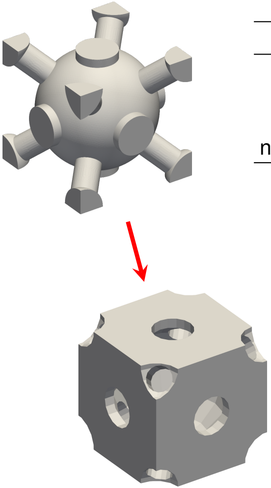
- 4 horizontal and 2 vertical channels which link the large pores (of adjacent cells)
- 8 oblique narrower channels which connect the large pore with the small ones

In the case of a **porous composite** material, a **steel valve ball** is inserted into the large pore. This ball can be moved inside the pore:

- to block certain channels and thus modify the viscous flow in the pore network,
- and change the acoustic wave propagation and absorption on a macroscopic scale.

Example: 3D printed adaptable sound absorber

Pore network



Periodic skeleton cell
(edge length: 5 mm)

Void diameter [mm]	
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small pore:	2.00
wide channel:	1.60
narrow channel:	1.00
Cell size:	5.00

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Example: 3D printed adaptable sound absorber

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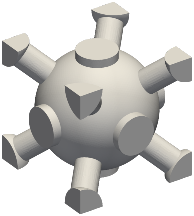

Void diameter [mm]	
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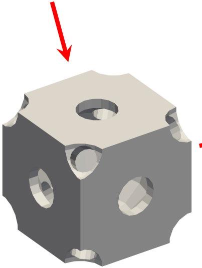
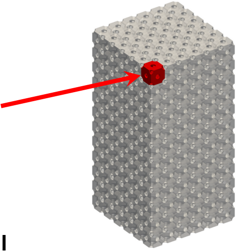


Periodic skeleton cell
(edge length: 5 mm)

(6×6×12 cells)



CAD model

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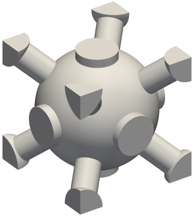
Example: 3D printed adaptable sound absorber

Pore network



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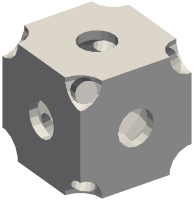
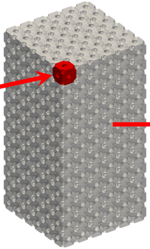


Periodic skeleton cell
(edge length: 5 mm)

(6×6×12 cells)

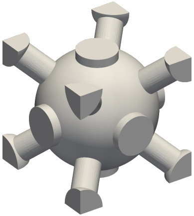


CAD model

Sample

Example: 3D printed adaptable sound absorber

Pore network



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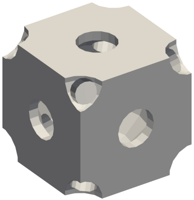
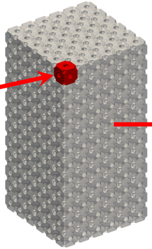


Periodic skeleton cell
(edge length: 5 mm)

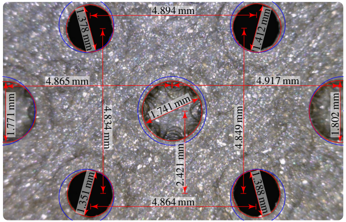
(6×6×12 cells)



CAD model

Sample

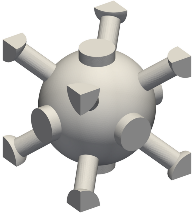
Microscope survey



Impedance tube

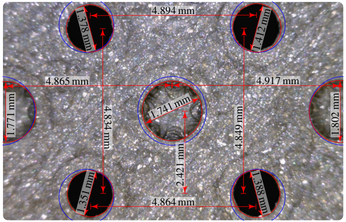
Example: 3D printed adaptable sound absorber

Pore network



Void diameter [mm]	
large pore:	**4.36**
small pore:	**1.76**
wide channel:	**1.36**
narrow channel:	**0.76**
Cell size:	5.00

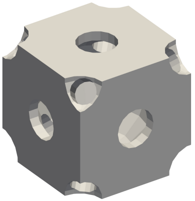
Microscope survey



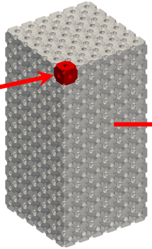
Impedance tube

"actual" geometry
(update predictions)

(6×6×12 cells)



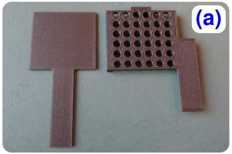
Periodic skeleton cell
(edge length: 5 mm)

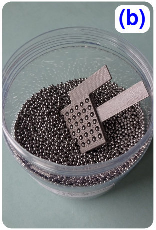


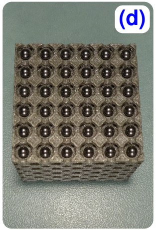
CAD model

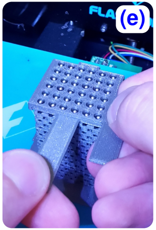
Sample

Example: 3D printed adaptable sound absorber





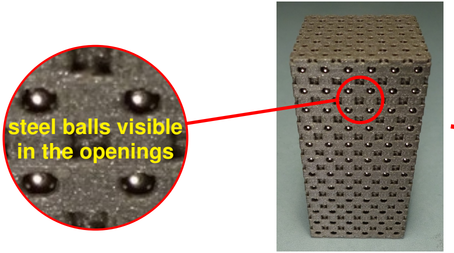




Description:

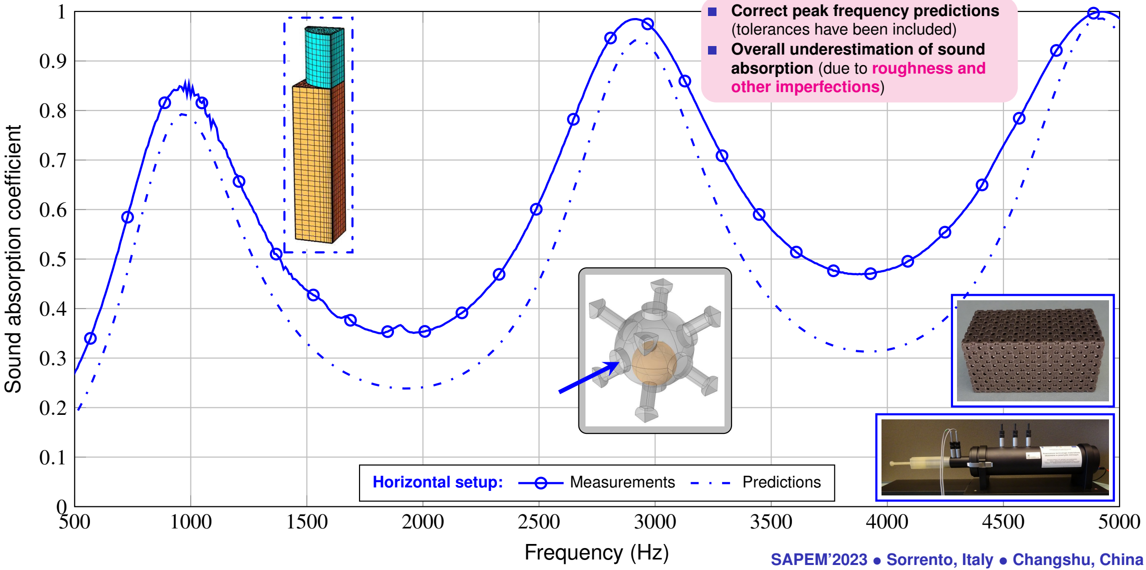
- **(a)** a dismantled ball-insertion tool
- **(b)** scooping 36 balls from a container
- **(c)** inserting 36 balls into 36 pores
- **(d)** 36 balls set in their places inside pores
- **(e)** insertion during the 3D-printing process

Sample with valve balls



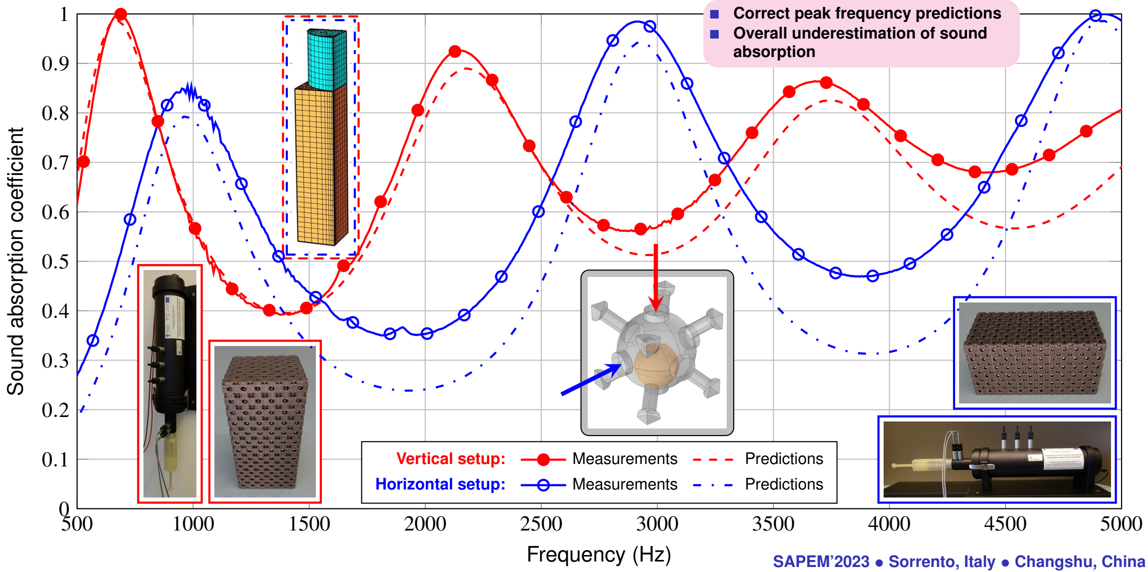
Impedance tube

Example: 3D printed adaptable sound absorber



- **Correct peak frequency predictions** (tolerances have been included)
- **Overall underestimation of sound absorption** (due to **roughness and other imperfections**)

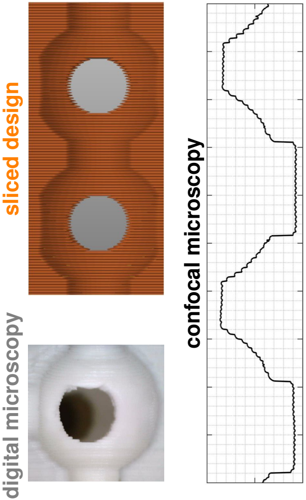
Example: 3D printed adaptable sound absorber



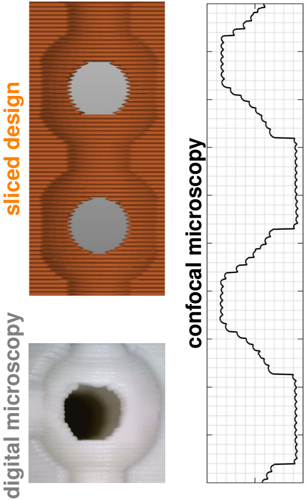
- Correct peak frequency predictions
- Overall underestimation of sound absorption

Staircase-type roughness due to FDM layer height

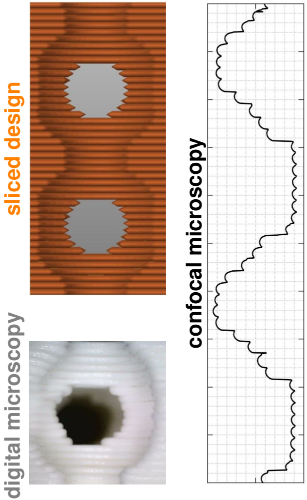
layer height = 0.010 mm



layer height = 0.015 mm



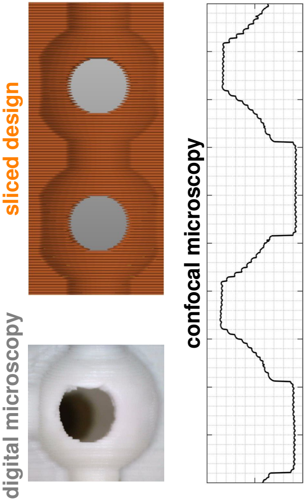
layer height = 0.025 mm



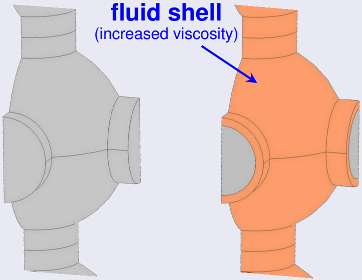
A. CICHON et al. “The impact of surface roughness . . . ”. *J. Sound Vib.* 546 (2023) 117434

Staircase-type roughness due to FDM layer height

layer height = 0.010 mm

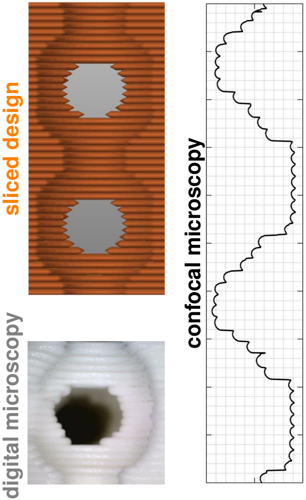


Versatile “fluid shell” approach to model surface roughness



- surface roughness increases the viscous effects
- this can be modelled by increasing the viscosity in the fluid shell

layer height = 0.025 mm

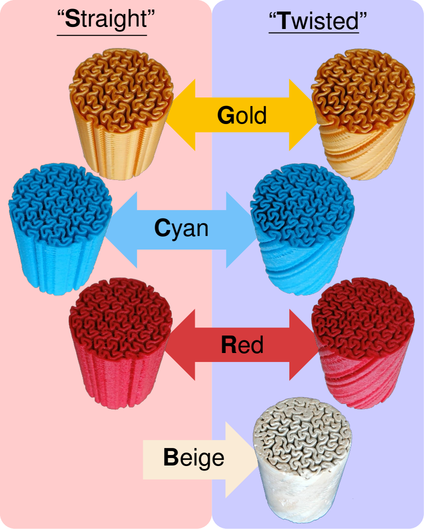


A. CICHON’s PhD thesis (2023, Trinity College Dublin)

Example: 3D printed materials based on the Gosper curve

Sample	*Weight* (g)	*Comments*
S-Gold	17.79	FDM (PLA)
T-Gold	17.81	FDM (PLA)
S-Cyan	10.18	FDM (ABS)
T-Cyan	12.03	FDM (ABS)
S-Red	11.70	FDM (ABS)
T-Red	13.87	FDM (ABS)
T-Beige	30.83	Geopolymer (plastered)

S = “**S**traight” **T** = “**T**wisted”

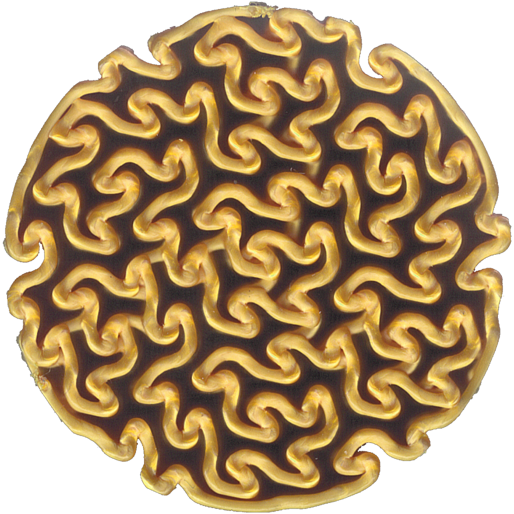


T. G. ZIELIŃSKI (IPPT PAN)
M. D’AGOSTINI, P. COLOMBO (University of Padova)

Example: 3D printed materials based on the Gosper curve

Procedure:

- scan the face of the sample



Example: 3D printed materials based on the Gosper curve

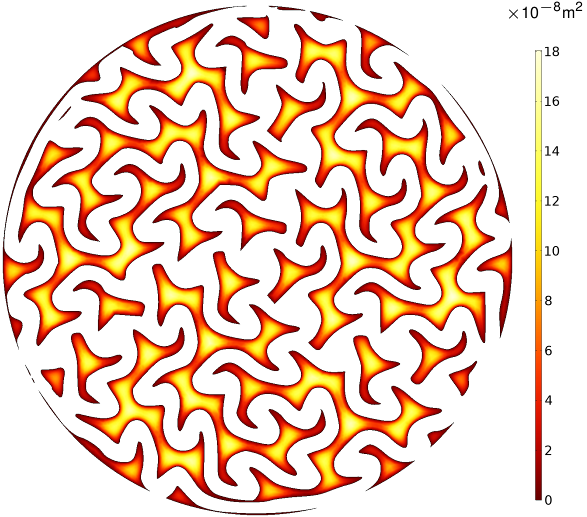
Procedure:

- scan the face of the sample
- extract the fluid domain for the sample inside the circular tube
- mesh the fluid domain
- determine ϕ (the porosity) and Λ_t (the thermal characteristic length)

Example: 3D printed materials based on the Gosper curve

Procedure:

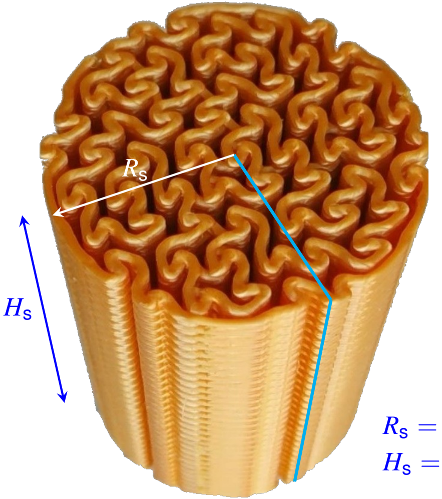
- scan the face of the sample
- extract the fluid domain for the sample inside the circular tube
- mesh the fluid domain
- determine ϕ (the porosity) and Λ_t (the thermal characteristic length)
- solve Poisson's problem for thermal diffusion
- determine Θ_0 (the static thermal permeability) and $\alpha_{0\mathrm{t}}$ (the static thermal tortuosity)



Example: 3D printed materials based on the Gosper curve

"Straight" pore network

- $\phi = 39.3\%$
  (sample weight $= 17.79\,\mathrm{g}$)
- $\Lambda_{\mathrm{v}} \approx \Lambda_{\mathrm{t}} = 0.623\,\mathrm{mm}$
- $\alpha_\infty = 1.08$
- $\alpha_{0\mathrm{t}} = 1.52$
  $\alpha_{0\mathrm{v}} \approx \alpha_\infty \alpha_{0\mathrm{t}} = 1.64$
- $\Theta_0 = 2.40 \cdot 10^{-8}\mathrm{m}^2$
  $\mathcal{K}_0 \approx \Theta_0/\alpha_\infty = 2.22 \cdot 10^{-8}\mathrm{m}^2$



$R_\mathrm{s} = 14.5\,\mathrm{mm}$
$H_\mathrm{s} = 40.5\,\mathrm{mm}$

Example: 3D printed materials based on the Gosper curve

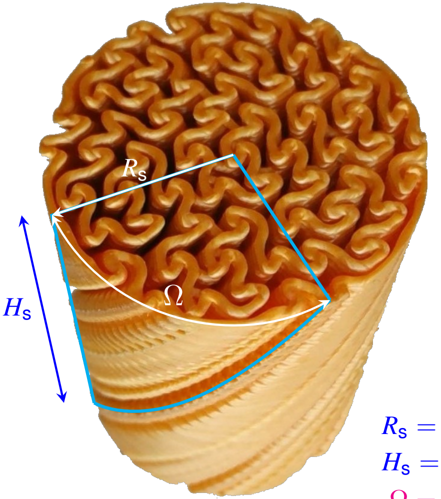
"Twisted" pore network ($\Omega = 90°$)

- $\phi \approx 39.3\%$
  (sample weight $= 17.81\,\mathrm{g}$)
- $\Lambda_\mathrm{v} \approx \Lambda_\mathrm{t} = 0.623\,\mathrm{mm}$
- $\alpha_\infty = 1.25$
- $\alpha_{0\mathrm{t}} = 1.52$
  $\alpha_{0\mathrm{v}} \approx \alpha_\infty \alpha_{0\mathrm{t}} = 1.90$
- $\Theta_0 = 2.40 \cdot 10^{-8}\mathrm{m}^2$
  $\mathcal{K}_0 \approx \Theta_0/\alpha_\infty = 1.92 \cdot 10^{-8}\mathrm{m}^2$

"Twisted" network tortuosity

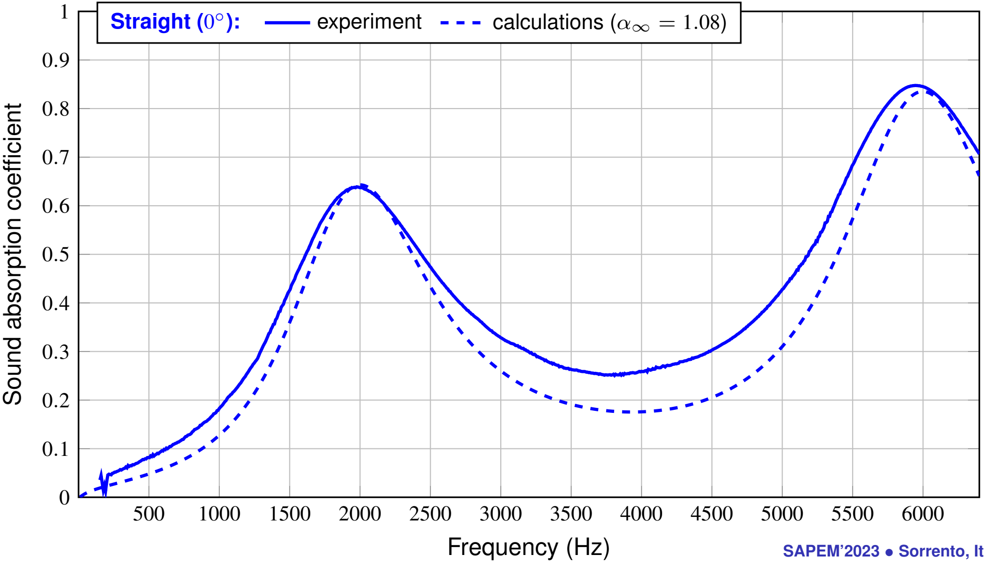
$$\alpha_\infty/(1 + c_\alpha) = 1 + \left(2\pi R_\mathrm{h}/H_\mathrm{h}\right)^2$$

where $R_\mathrm{h} = R_\mathrm{s}/\sqrt{2}, \quad H_\mathrm{h} = 2\pi H_\mathrm{s}/\Omega$

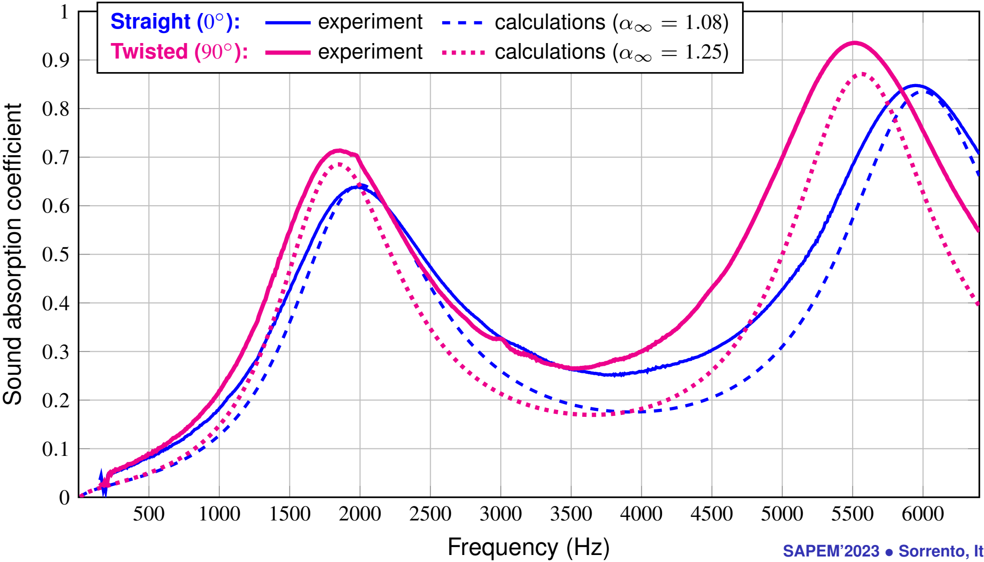


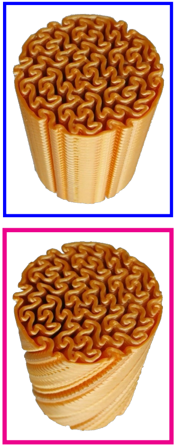
$R_\mathrm{s} = 14.5\,\mathrm{mm}$
$H_\mathrm{s} = 40.5\,\mathrm{mm}$
$\Omega = 90°$

Example: 3D printed materials based on the Gosper curve



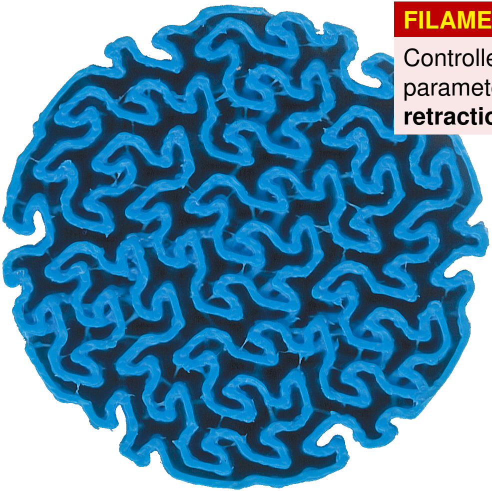
Example: 3D printed materials based on the Gosper curve





Example: 3D printed materials based on the Gosper curve

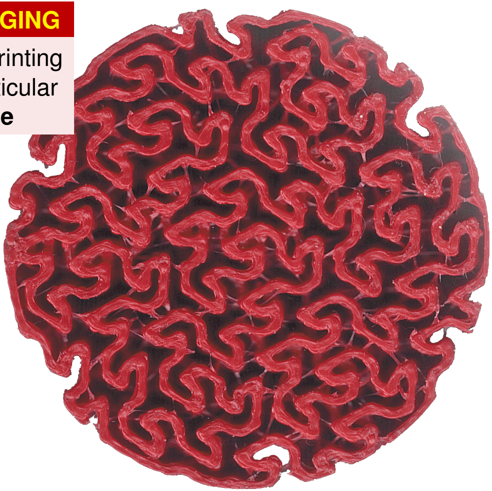
FIBRES in the slits!



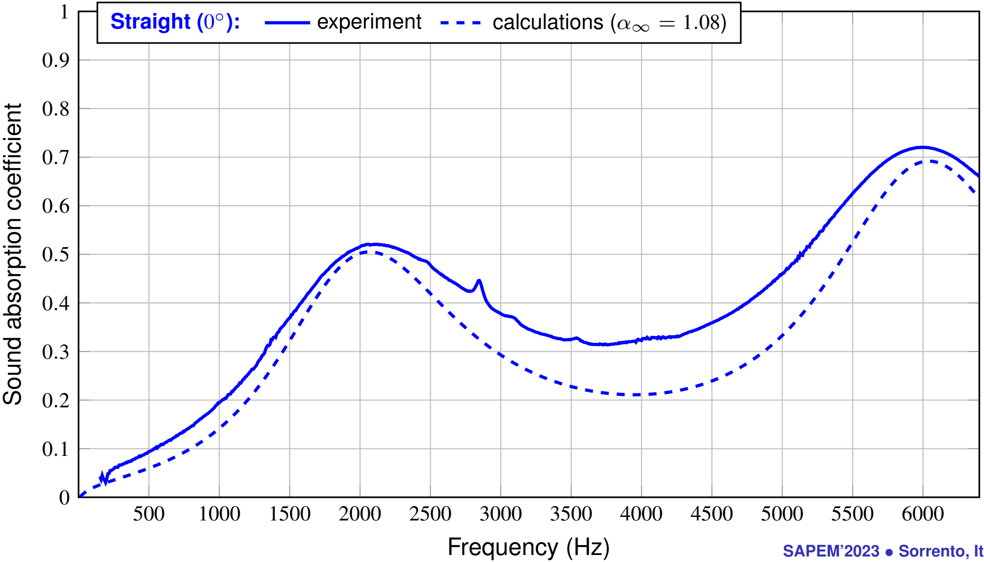
FILAMENT STRINGING

Controlled by 3D printing parameters, in particular **retraction distance**

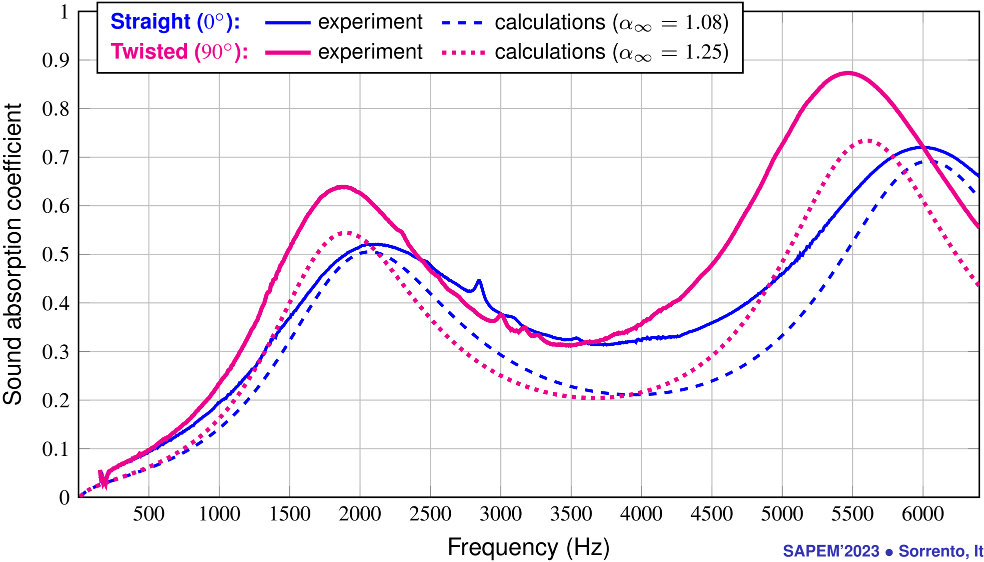
MORE FIBRES in the slits!



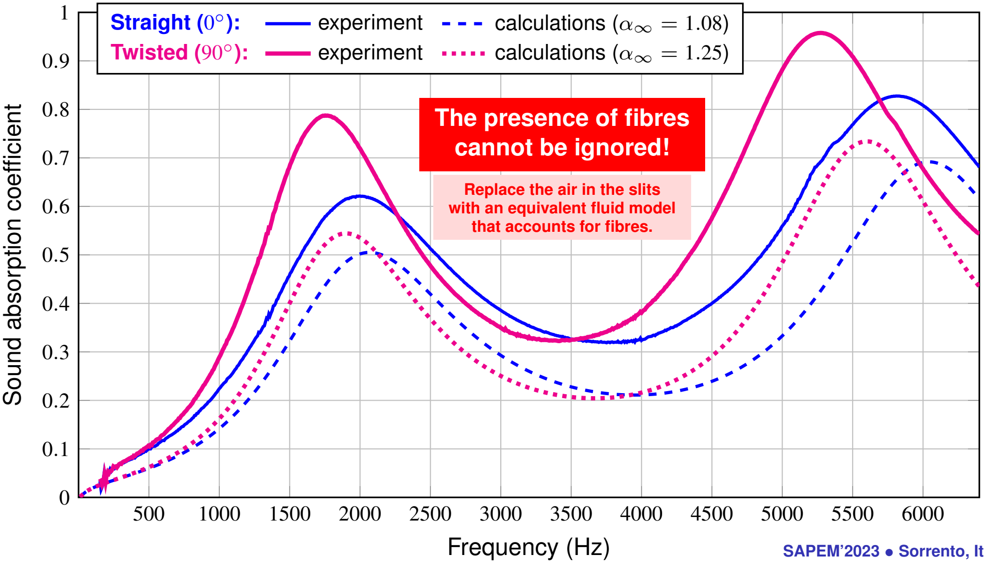
Example: 3D printed materials based on the Gosper curve



Example: 3D printed materials based on the Gosper curve



Example: 3D printed materials based on the Gosper curve



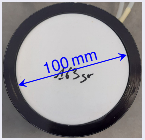
The presence of fibres cannot be ignored!

Replace the air in the slits with an equivalent fluid model that accounts for fibres.

BJP gypsum-based material with open microporosity

Microporous material

- **microporosity**:
  $\phi_\mathrm{m} = 42.6\,\%$
- **permeability**:
  for a disc 3D printed in a **horizontal** position
  $\mathcal{K}_{0\mathrm{m}} = 0.57 \cdot 10^{-12}\,\mathrm{m}^2$
  for a disc 3D printed in a **vertical** position
  $\mathcal{K}_{0\mathrm{m}} = 1.64 \cdot 10^{-12}\,\mathrm{m}^2$
  Anisotropy!

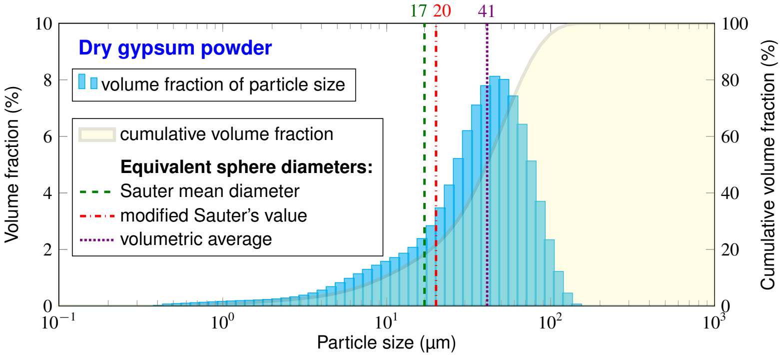


The analytical **estimation of the permeability**

$$\mathcal{K}_{0\mathrm{m}}(d_\mathrm{g}, \phi_\mathrm{m}) \approx \text{measured value}$$

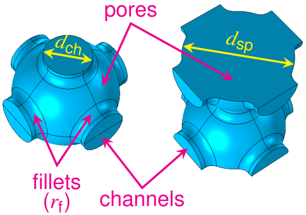
for the **equivalent grain diameter** $d_\mathrm{g} = 20\,\mu\mathrm{m}$.

This is a slightly enlarged value (due to binder and grain agglomeration) of the **Sauter mean diameter** ($17\,\mu\mathrm{m}$) determined for dry gypsum powder.



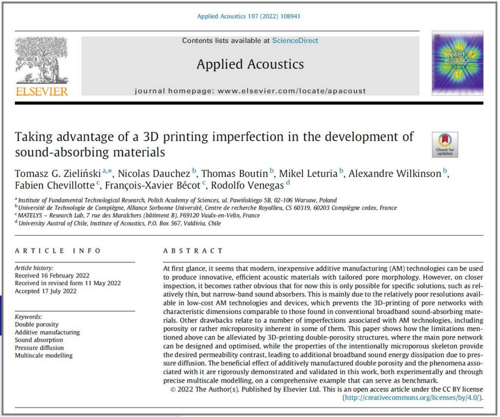
Example: 3D printed acoustic materials with double porosity

Pore network Ω_{pf}



Representative Elementary Volume (REV)

- a cubic cell
- a spherical pore with a diameter d_{sp}
- the pore is connected to six identical pores from adjacent cells (REVs) by four horizontal and two vertical cylindrical channels with the same diameter d_{ch}
- fillets are part of of the design (the fillet radius $r_{\mathrm{f}} = 0.25 d_{\mathrm{ch}}$)



Applied Acoustics 197 (2022) 108941

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Taking advantage of a 3D printing imperfection in the development of sound-absorbing materials

Tomasz G. Zieliński [a,*], Nicolas Dauchez [b], Thomas Boutin [b], Mikel Leturia [b], Alexandre Wilkinson [b], Fabien Chevillotte [c], François-Xavier Bécot [c], Rodolfo Venegas [d]

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[b] Université de Technologie de Compiègne, Alliance Sorbonne Université, Centre de recherche Royallieu, CS 60319, 60203 Compiègne cedex, France
[c] MATELYS – Research Lab, 7 rue des Maraîchers (bâtiment B), F69120 Vaulx-en-Velin, France
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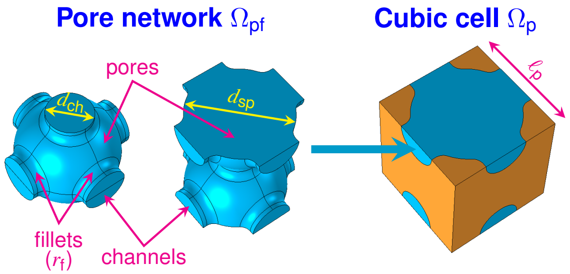
Additive manufacturing
Sound absorption
Pressure diffusion
Multiscale modelling

ABSTRACT

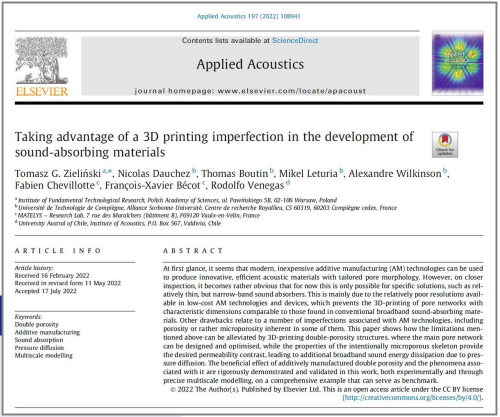
At first glance, it seems that modern, inexpensive additive manufacturing (AM) technologies can be used to produce innovative, efficient acoustic materials with tailored pore morphology. However, on closer inspection, it becomes rather obvious that for now this is only possible for specific solutions, such as relatively thin, but narrow-band sound absorbers. This is mainly due to the relatively poor resolutions available in low-cost AM technologies and devices, which prevents the 3D-printing of pore networks with characteristic dimensions comparable to those found in conventional broadband sound-absorbing materials. Other drawbacks relate to a number of imperfections associated with AM technologies, including porosity or rather microporosity inherent in some of them. This paper shows how the limitations mentioned above can be alleviated by 3D-printing double-porosity structures, where the main pore network can be designed and optimised, while the properties of the intentionally microporous skeleton provide the desired permeability contrast, leading to additional broadband sound energy dissipation due to pressure diffusion. The beneficial effect of additively manufactured double porosity and the phenomena associated with it are rigorously demonstrated and validated in this work, both experimentally and through precise multiscale modelling, on a comprehensive example that can serve as benchmark.

Example: 3D printed acoustic materials with double porosity



Representative Elementary Volume (REV)

- a cubic cell with an edge length $\ell_{p} = 4\,\mathrm{mm}$
- a spherical pore with a diameter $d_{sp} = 3.6\,\mathrm{mm}$
- the pore is connected to six identical pores from adjacent cells (REVs) by four horizontal and two vertical cylindrical channels with the same diameter $d_{ch} = 0.4\ell_{p} = 1.6\,\mathrm{mm}$
- fillets are part of of the design (the fillet radius $r_{f} = 0.25 d_{ch}$)



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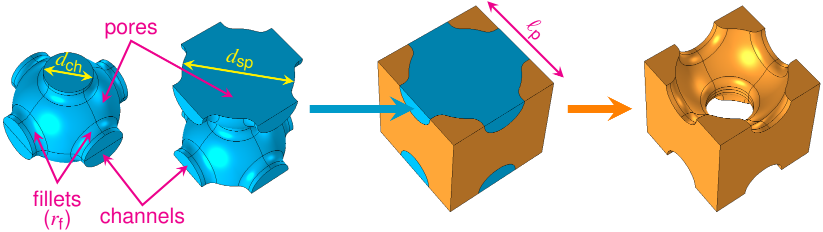
Example: 3D printed acoustic materials with double porosity


Pore network Ω_{pf} **Cubic cell Ω_{p}** **Skeleton Ω_{ps}**

Advice

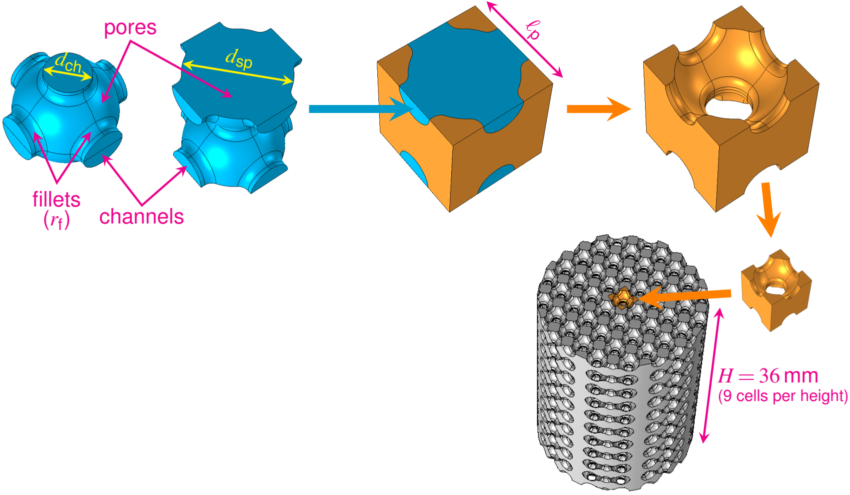
For better geometry control:

- avoid sharp edges by using fillets in the design

Representative Elementary Volume (REV)

- a cubic cell with an edge length $\ell_{\mathrm{p}} = 4\,\mathrm{mm}$
- a spherical pore with a diameter $d_{\mathrm{sp}} = 0.9\ell_{\mathrm{p}} = 3.6\,\mathrm{mm}$
- six cylindrical channels with the diameter $d_{\mathrm{ch}} = 0.4\ell_{\mathrm{p}} = 1.6\,\mathrm{mm}$
- fillets are part of of the design (the fillet radius $r_{\mathrm{f}} = 0.25 d_{\mathrm{ch}}$)
- volume fractions: $\phi_{\mathrm{p}} = 44.1\%$ (**pore network**)
  $\phi_{\mathrm{d}} = 1 - \phi_{\mathrm{p}} = 55.9\%$ (**skeleton**)

Example: 3D printed acoustic materials with **double porosity**



Pore network Ω_{pf}

Cubic cell Ω_{p}

Skeleton Ω_{ps}

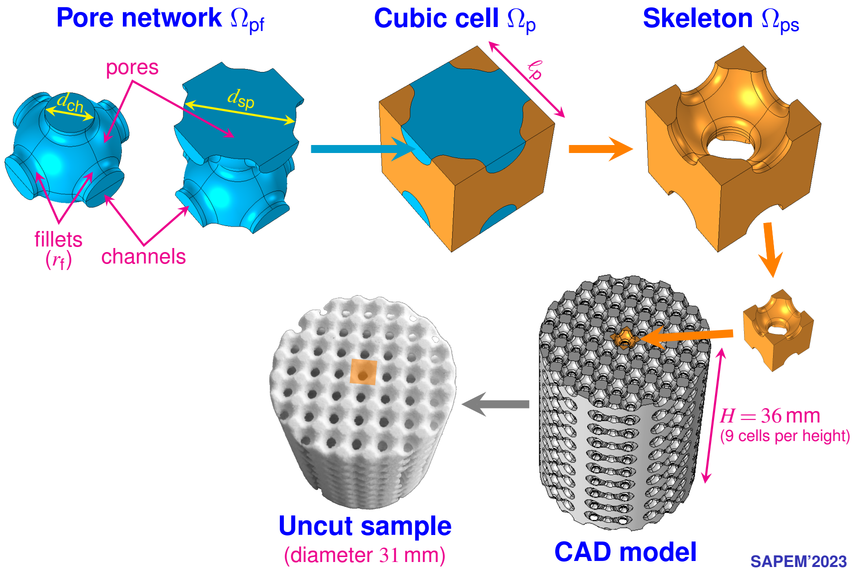
CAD model

Advice

For better geometry control:

- avoid sharp edges by using fillets in the design

Example: 3D printed acoustic materials with double porosity



Advice

For better geometry control:

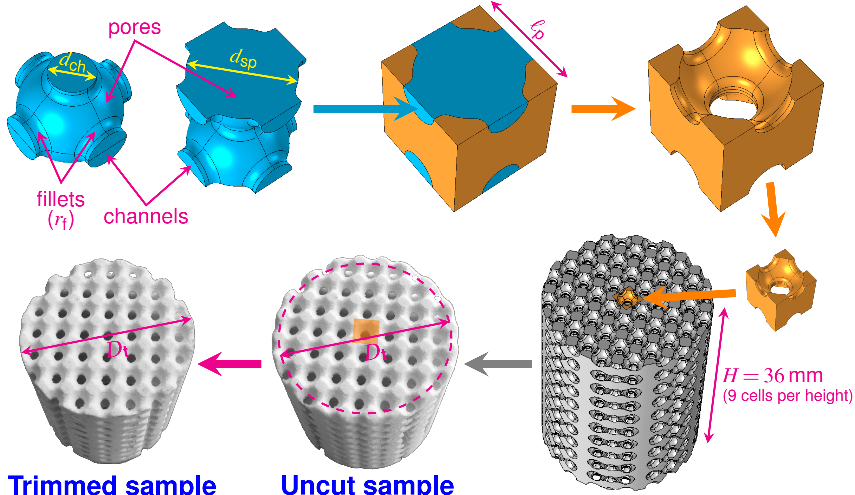
- avoid sharp edges by using fillets in the design

Recommendation!

To avoid leakages around the sample:

- 3D print samples with a diameter larger than the impedance tube

Example: 3D printed acoustic materials with double porosity



Pore network Ω_{pf} **Cubic cell Ω_{p}** **Skeleton Ω_{ps}**

Trimmed sample (diameter $D_{\mathrm{t}} = 29\,\mathrm{mm}$)

Uncut sample (diameter $31\,\mathrm{mm} > D_{\mathrm{t}}$)

CAD model

Advice

For better geometry control:

- avoid sharp edges by using fillets in the design

Recommendation!

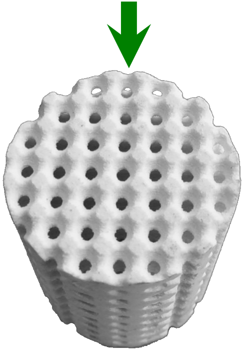
To avoid leakages around the sample:

- 3D print samples with a diameter larger than the impedance tube
- cut them on a lathe for a perfect fit

Example: 3D printed acoustic materials with double porosity

BJP – Binder Jetting 3D Printing

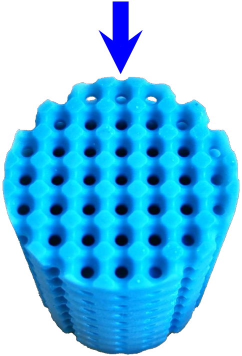
- *3D Systems ProJet 160*
- **gypsum powder**
- + butyrolactam (binder)



gypsum sample

SLA – Stereolithography

- *Formlabs Form 3B*
- **photopolymer resin**
  (of low viscosity)

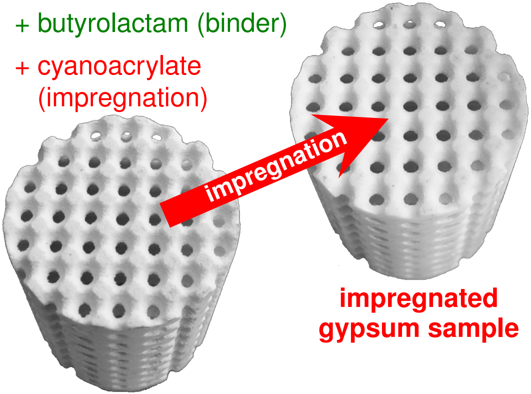


resin sample

Example: 3D printed acoustic materials with double porosity

BJP – Binder Jetting 3D Printing

- *3D Systems ProJet 160*
- **gypsum powder**
- + butyrolactam (binder)
- + cyanoacrylate (impregnation)

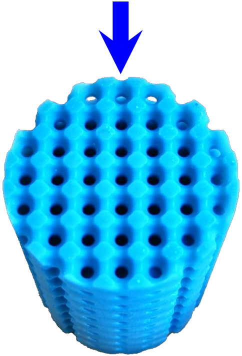


gypsum sample

impregnated gypsum sample

SLA – Stereolithography

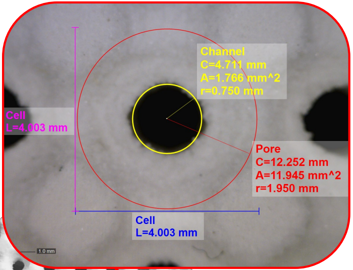
- *Formlabs Form 3B*
- **photopolymer resin** (of low viscosity)

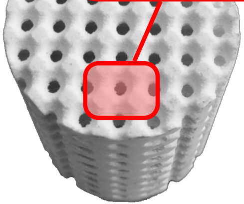


resin sample

Example: 3D printed acoustic materials with double porosity

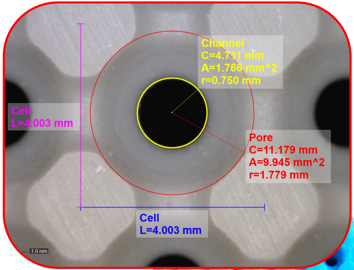
BJP – Binder Jetting 3D Printing

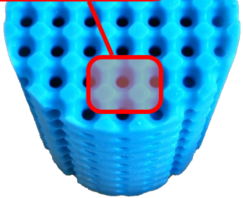




gypsum sample

SLA – Stereolithography



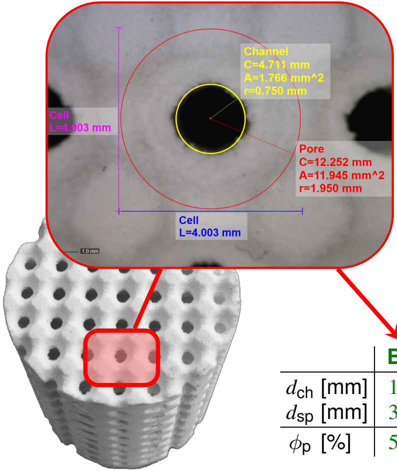


resin sample

CHECK THE ACTUAL DIMENSIONS
of key elements
of the pore network

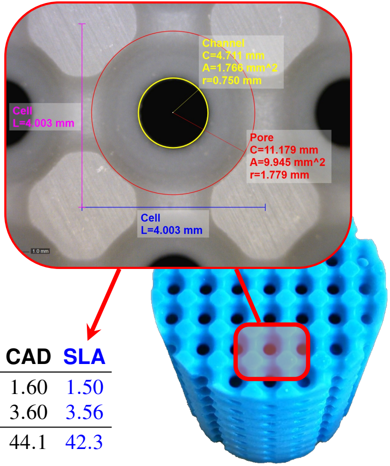
Example: 3D printed acoustic materials with double porosity

BJP – Binder Jetting 3D Printing



gypsum sample

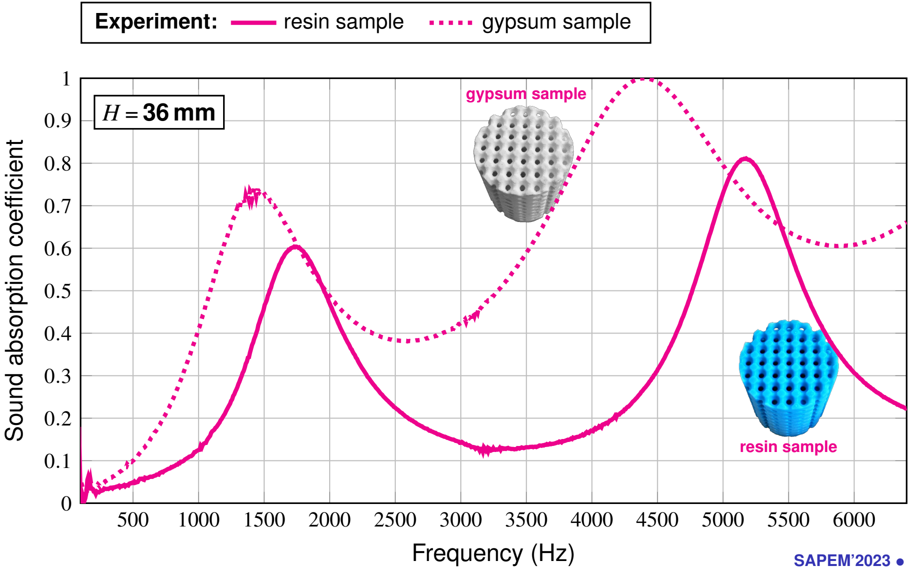
SLA – Stereolithography



resin sample

	BJP	**CAD**	**SLA**
d_{ch} [mm]	1.50	1.60	1.50
d_{sp} [mm]	3.90	3.60	3.56
ϕ_{p} [%]	50.7	44.1	42.3

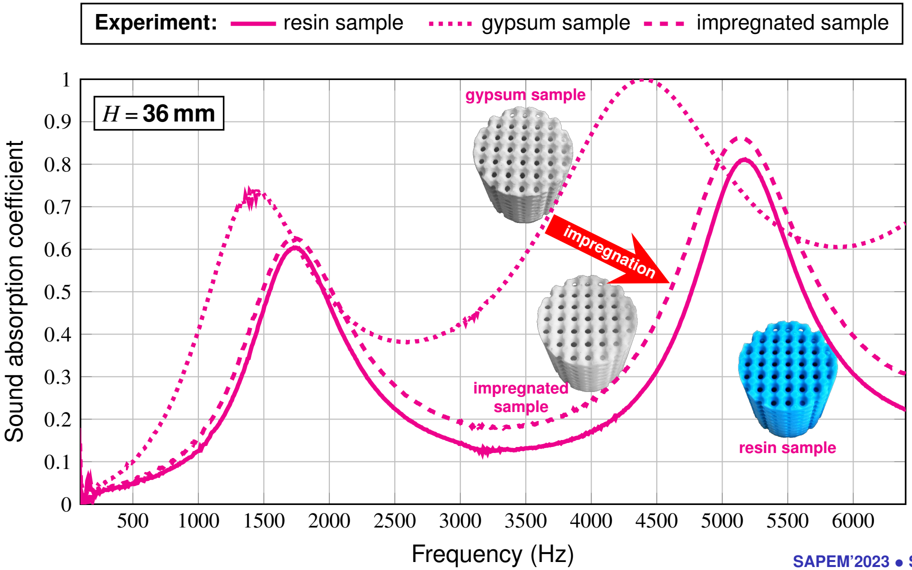
Example: 3D printed acoustic materials with double porosity



Measurements

- **Huge improvement in sound absorption** for the gypsum-based material

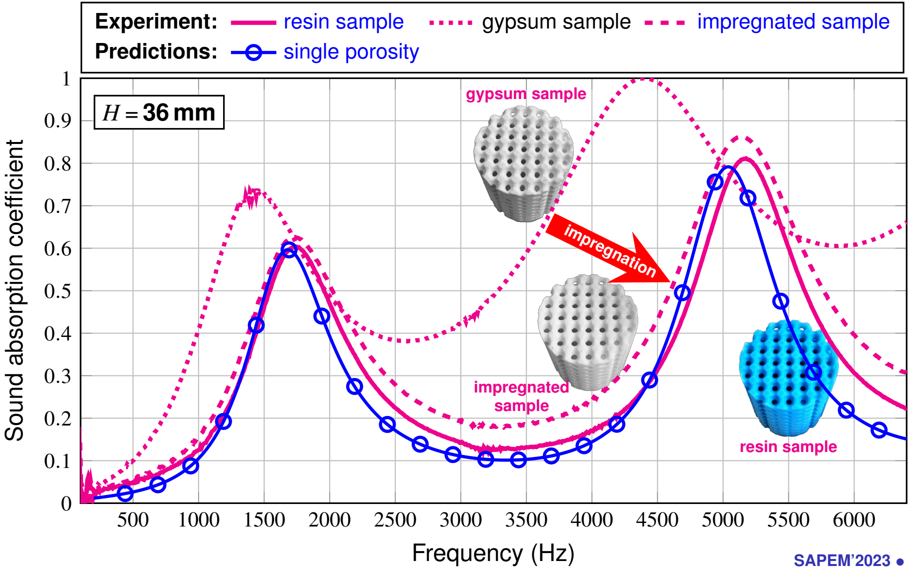
Example: 3D printed acoustic materials with double porosity



Measurements

- **Huge improvement in sound absorption** for the gypsum-based material
- . . . is due to the **microporous skeleton**

Example: 3D printed acoustic materials with double porosity



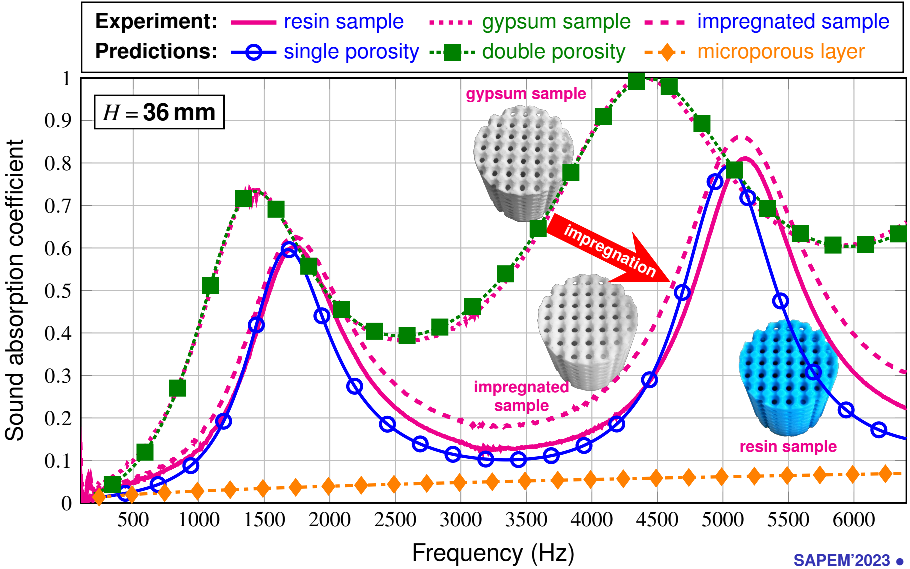
Measurements

- **Huge improvement in sound absorption** for the gypsum-based material
- …is due to the **microporous skeleton**

Modelling

- **Very good agreement** between modelling and measurements

Example: 3D printed acoustic materials with **double porosity**



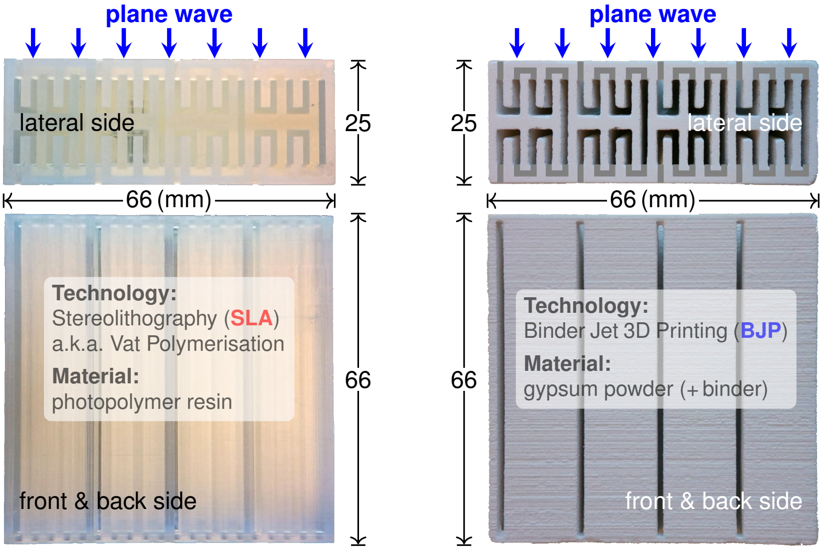
Measurements

- **Huge improvement in sound absorption** for the gypsum-based material
- . . . is due to the **microporous skeleton**

Modelling

- **Very good agreement** between modelling and measurements
- An additional dissipation mechanism in the **double-porosity** material is **pressure diffusion** in the micropores

Example: 3D printed panels with extremely tortuous slits



Technology:
Stereolithography (**SLA**)
a.k.a. Vat Polymerisation
Material:
photopolymer resin

Technology:
Binder Jet 3D Printing (**BJP**)
Material:
gypsum powder (+ binder)

RESIN sample (SINGLE porosity)

GYPSUM sample (DOUBLE porosity)

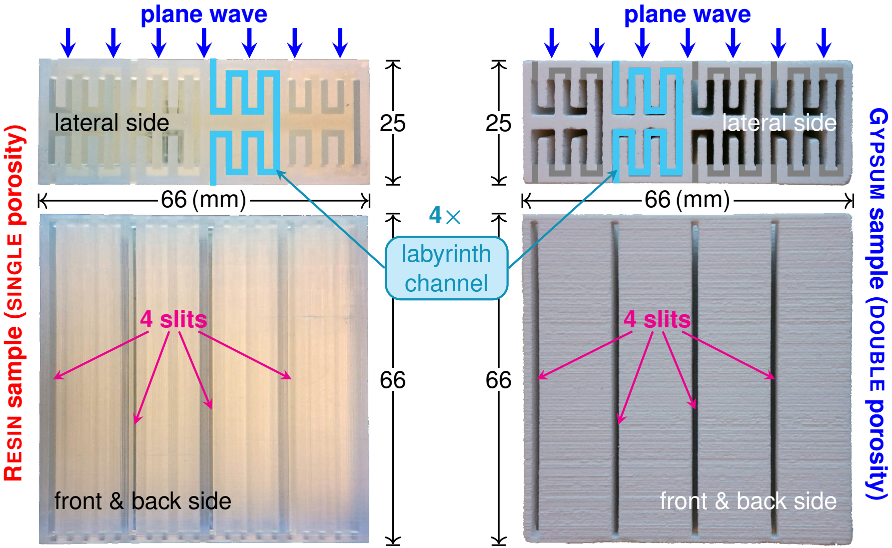
SLA (Formlabs Form 3B)
resin sample:

- **high quality**
- transparent
- low-viscosity resin is easily removed from the slit channels

BJP (3D Systems ProJet 160)
gypsum sample:

- **open microporosity**
- surface and geometric **imperfections**
- **removing powder residue is difficult** and may damage the structure

Example: 3D printed panels with extremely tortuous slits



SLA (Formlabs Form 3B) **resin sample:**

- **high quality**
- transparent
- low-viscosity resin is easily removed from the slit channels

BJP (3D Systems ProJet 160) **gypsum sample:**

- **open microporosity**
- surface and geometric **imperfections**
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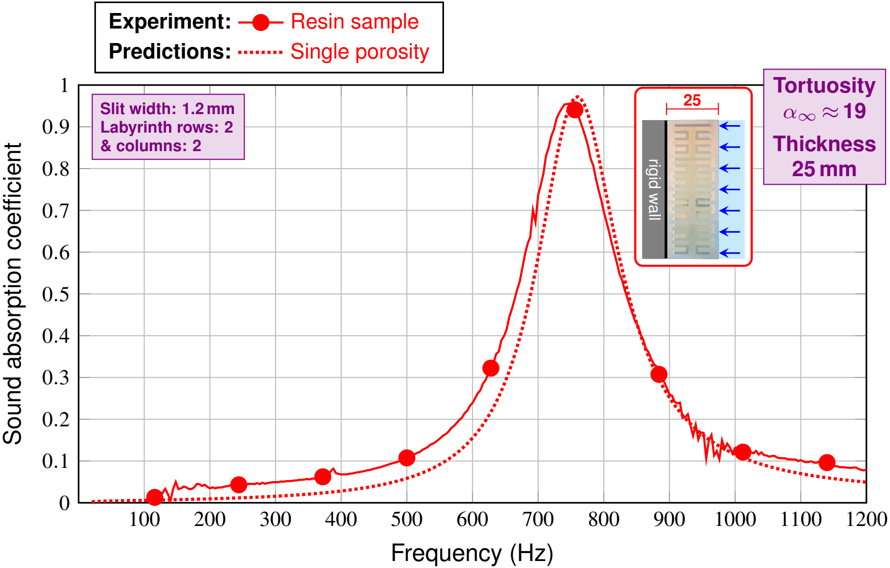
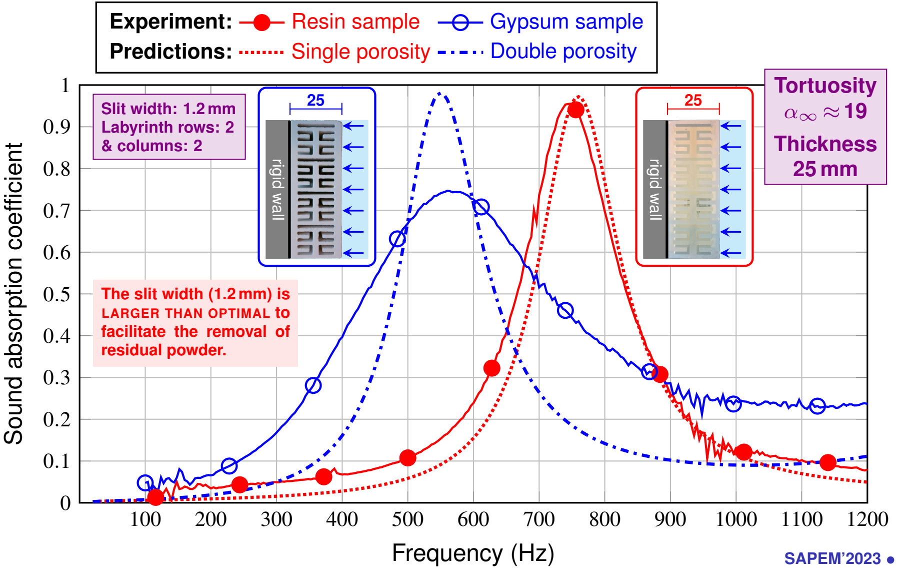
Example: 3D printed panels with extremely tortuous slits



SLA (Formlabs Form 3B) **resin sample:**

- **very good agreement** between **analytical predictions** and **measurements**

Example: 3D printed panels with extremely tortuous slits



Slit width: 1.2 mm
Labyrinth rows: 2
& columns: 2

The slit width (1.2 mm) is LARGER THAN OPTIMAL to facilitate the removal of residual powder.

Tortuosity
$\alpha_\infty \approx$ **19**
Thickness
25 mm

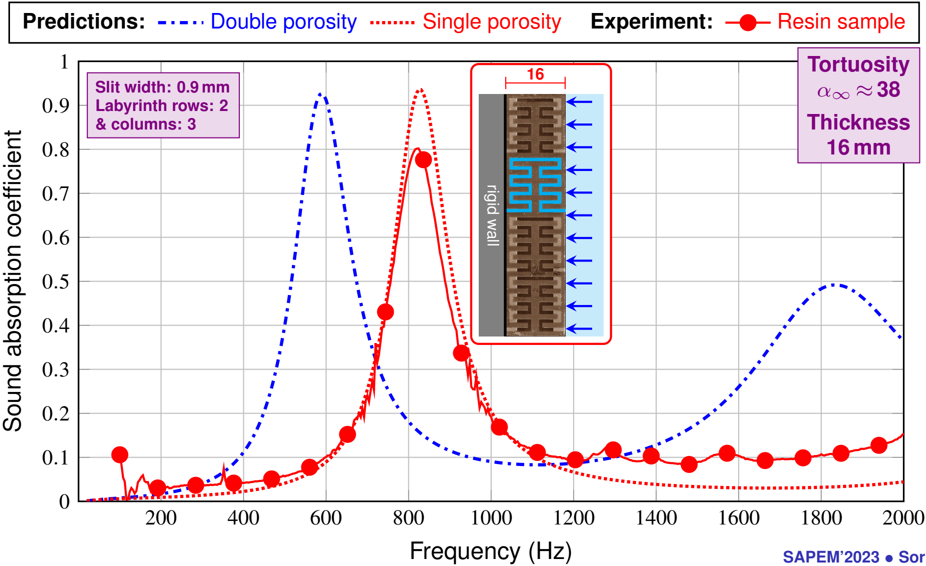
SLA (Formlabs Form 3B) **resin sample:**

- **very good agreement** between **analytical predictions** and **measurements**

BJP (3D Systems ProJet 160) **gypsum sample:**

- **pressure diffusion** caused by **double porosity** is confirmed by experiment
- **large discrepancies** between predictions and measurements due to: **sound leaks**, geometric **imperfections**, surface **roughness**, microporous **anisotropy**

Example: 3D printed panels with extremely tortuous slits



Slit width: 0.9 mm
Labyrinth rows: 2
& columns: 3

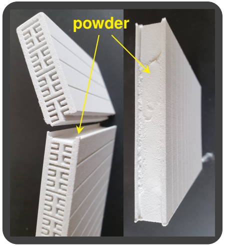
Tortuosity
$\alpha_\infty \approx 38$
Thickness
16 mm

Original design

Thinner panel:

- thickness: **16 mm**
- slit width: **0.9 mm**
- tortuosity: **38**

Problems removing powder residues!



Conclusions

3D printing imperfections

- Typical 3D printing **imperfections**, such as roughness, microporosity, and fibres, usually **increase** effects responsible for the **dissipation** of sound wave energy.
- **Minor** imperfections **can often be ignored** in the modelling and design, and simply explain small (acceptable) discrepancies between the predictions and measurements.
- Major imperfections cannot be ignored, however, **irregular and random** imperfections are **difficult to model**.
- **Imperfections can be controlled and should therefore be included in the modelling to design and optimise more efficient acoustic materials.**

Basic but important recommendations

- **Modelling:** Include 3D printing tolerances in the modelling for final predictions.
- **Testing:** Avoid leakages around the samples tested in an impedance tube (3D print samples with a larger diameter and cut them on a lathe for a perfect fit).