Lecture 13 – Introduction to additive manufacturing

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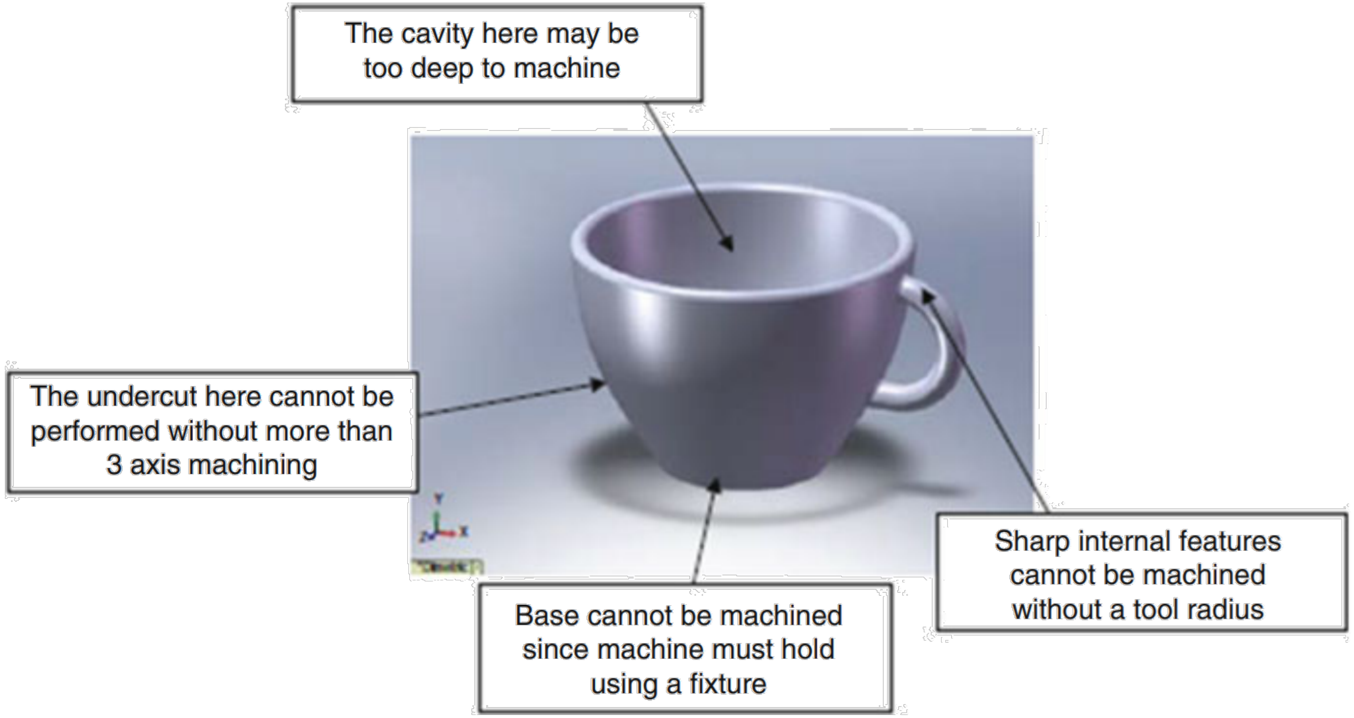
Contents

Discussion in class

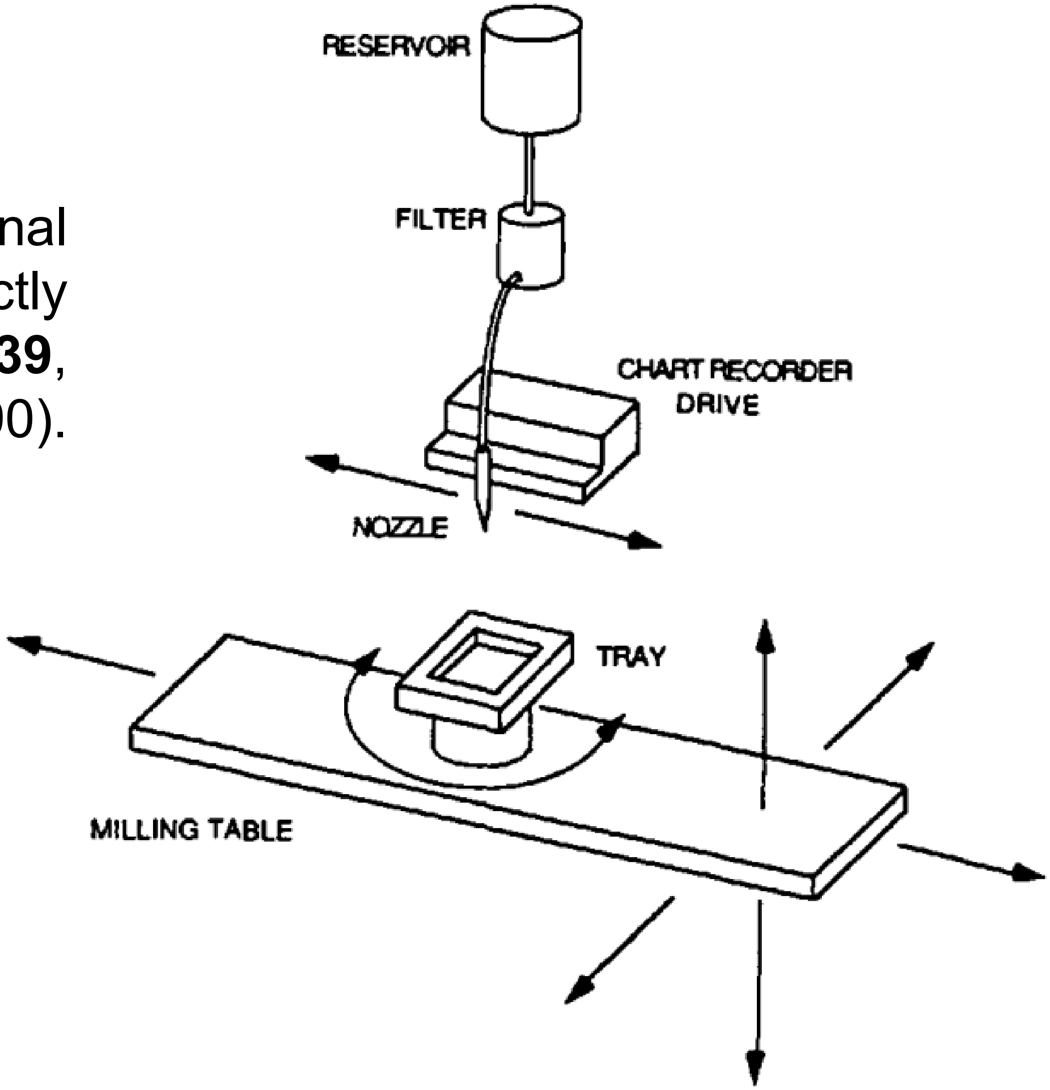
1. How would you manufacture a cup?
2. Suppose you make a metal version. List the possible problems by conventional machining

(Gibson et al, 2015)



Pioneer work

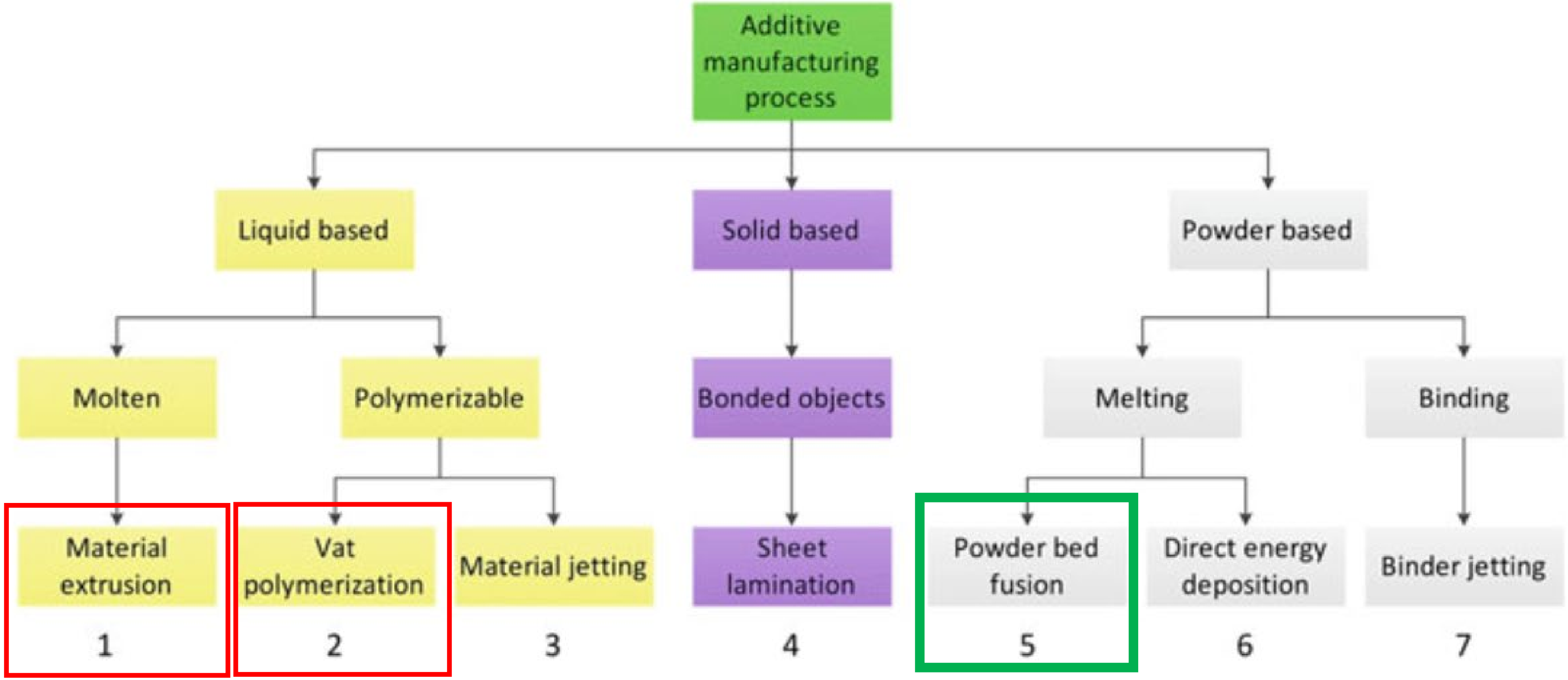
M. Cima and J. Cornie, "Three-Dimensional Printing: Rapid Tooling and Prototypes Directly from a CAD Model," Annals of the CIRP **39**, 201–204 (1990).



Key concepts

- From a ‘CAD’ to a ‘Part’: ‘print a part’!
- **‘Digitizing manufacturing’**
- Discretization of an arbitrary unit volumes into ‘voxels’, ‘layers’ or ‘sheets’ joint together.

The seven additive manufacturing processes

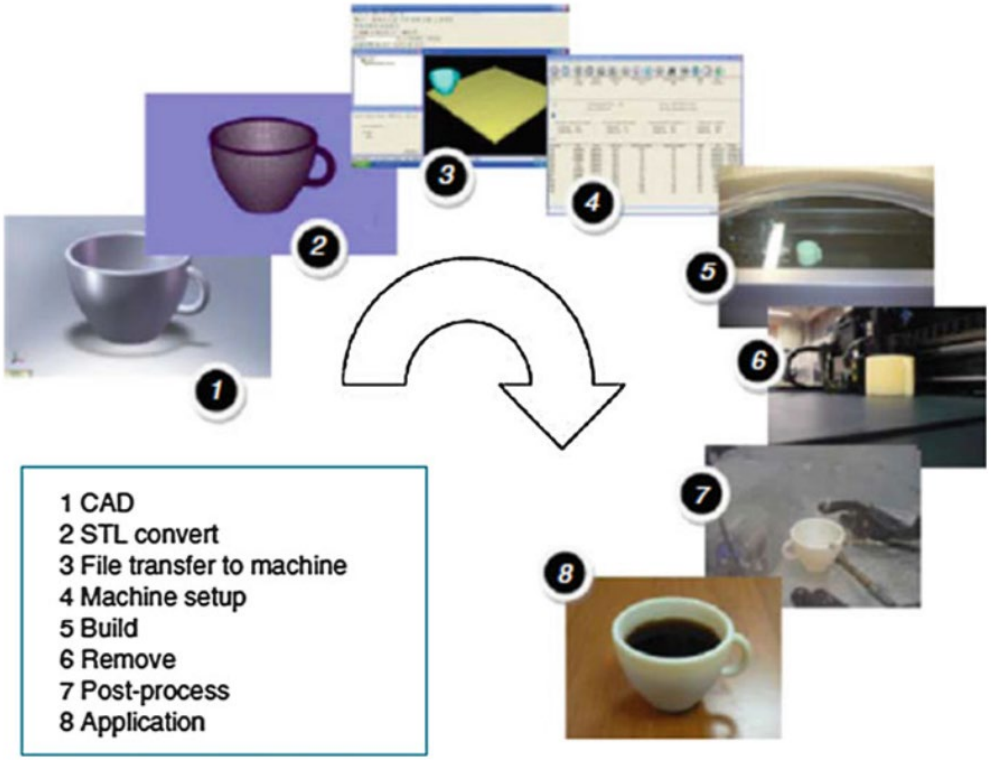


Classification of additive manufacturing according to ISO/ASTM 52,900 (ISO/ASTM)

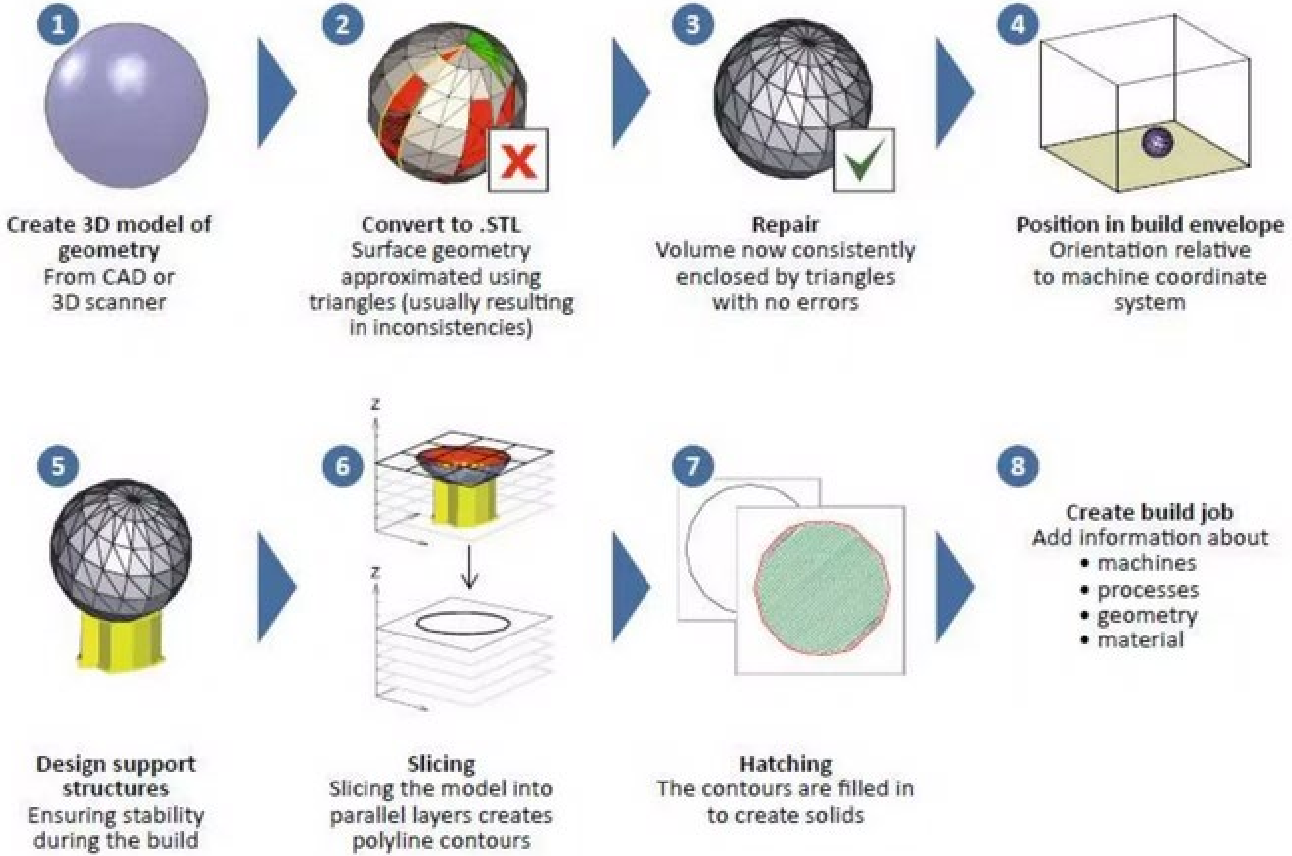
Main additive processes principles

1. **Stereolithography (SLA)** // Material is cured by light-activated polymerization
2. **Material jetting**
3. **Binder jetting** '*Inkjet printing with glue*'
4. **Filament-based extrusion (FDM, FFF, etc.)** // use of material extrusion principles
5. **Sheet lamination**
6. **Selective Laser Sintering** (SLS / SLM) // Powder bed fusion
7. **Directed energy deposition** (laser cladding)

Process flow: from a CAD to a part…'Digitizing manufacturing'



(Gibson et al, 2015)



Filament based extrusion

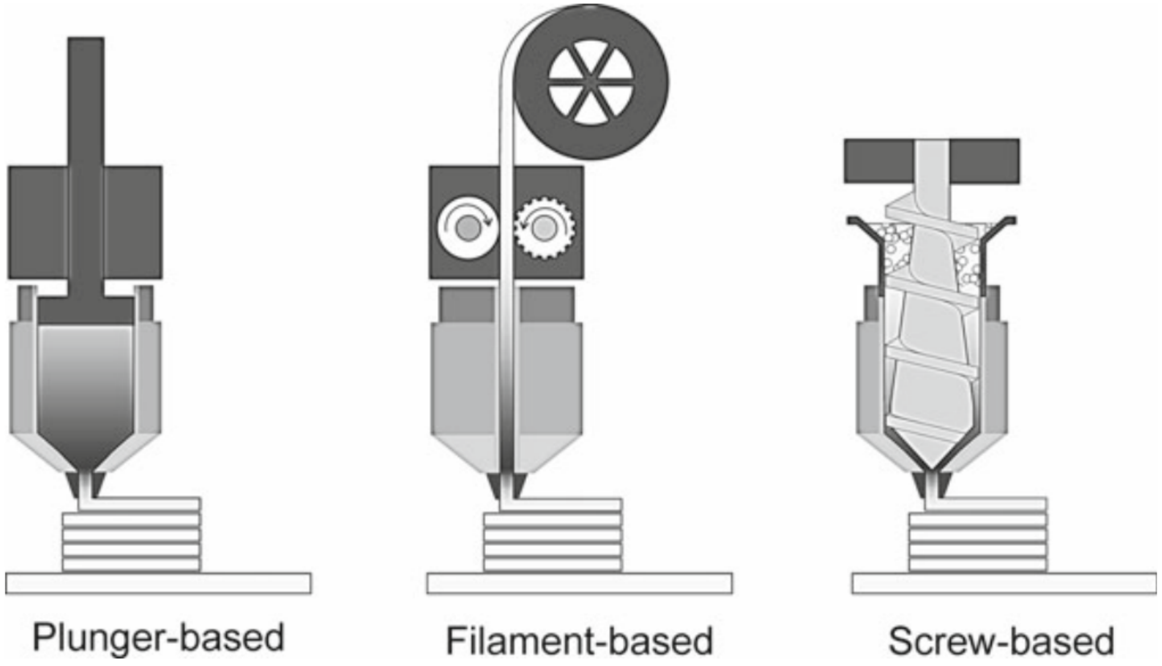


Fig. 1.23 Material extrusion additive manufacturing types (Gonzalez-Gutierrez, J.; Cano, S.; Schuschnigg, S.; Kukla, C.; Sapkota, J.; Holzer, C. Additive Manufacturing of Metallic and Ceramic Components by the Material Extrusion of Highly-Filled Polymers: A Review and Future Perspectives. Materials 2018, 11, 840, licensed under CC BY 4.0)

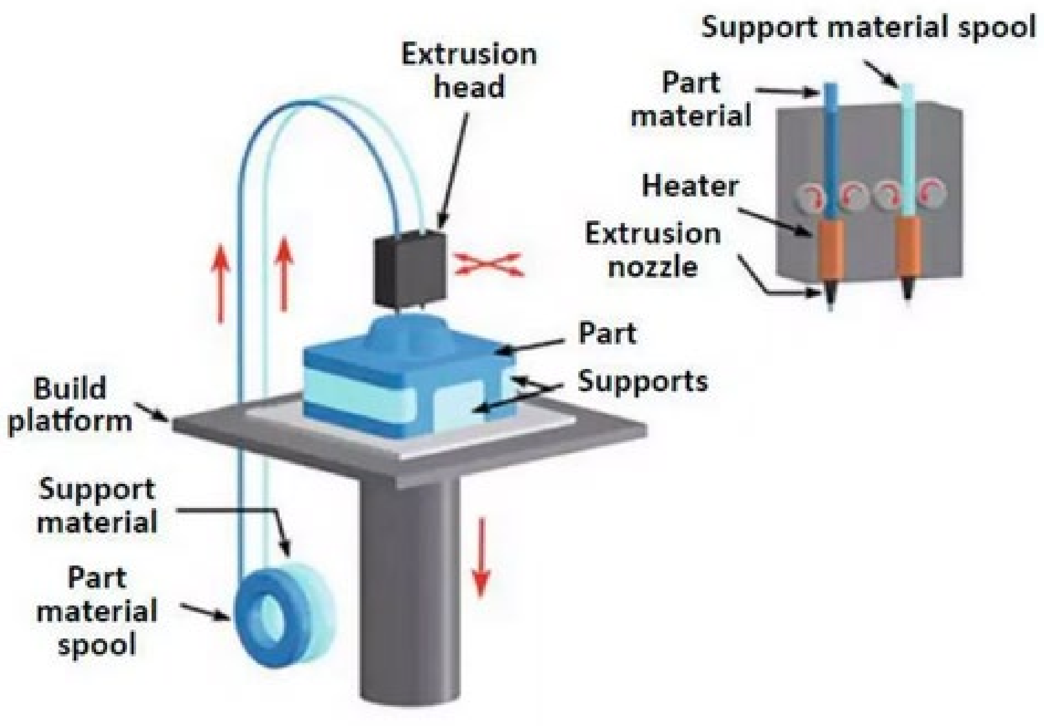


Figure 3-3: Fused Deposition Modelling (FDM™) (Source: CustomPartNet LLC)

From **prototyping** to small **products**

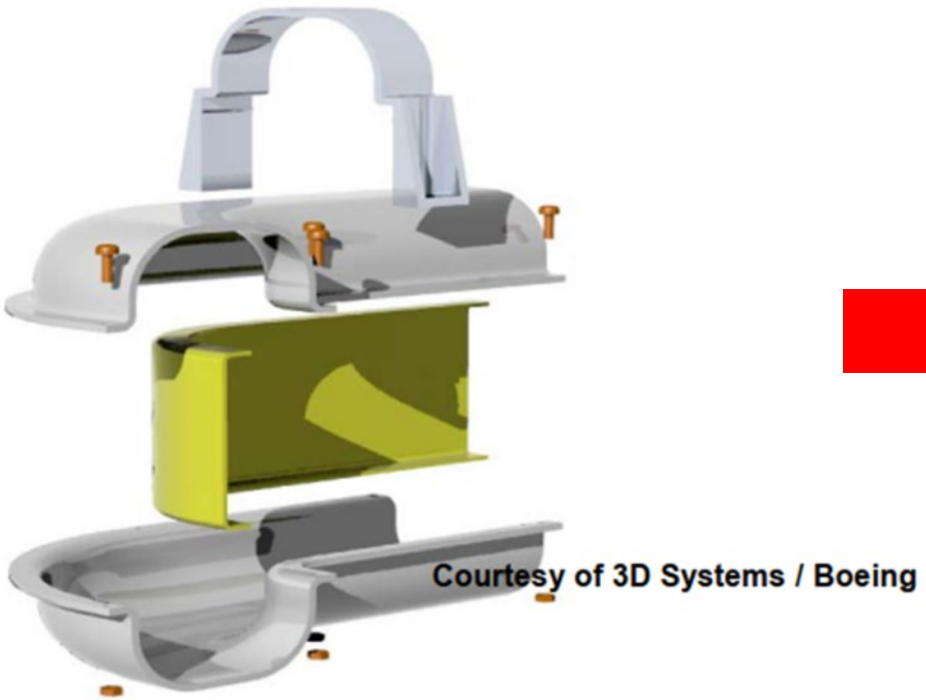
From a few hundred to a few thousand euros…

… to a few hundred of thousands.

https://youtu.be/WHO6G67GJbM

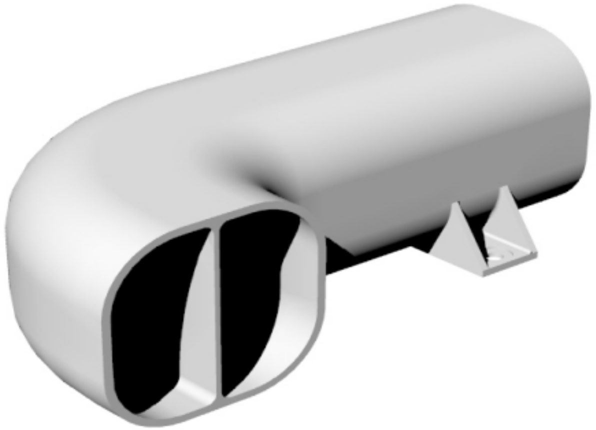
Illustration: ‘Design for manufacturing’

(A) Conventional Duct Fabricated from Vacuum formed plastic



(Part count = 16)

(B) Component modified and consolidated for fabrication via Additive Rapid Direct Manufacture

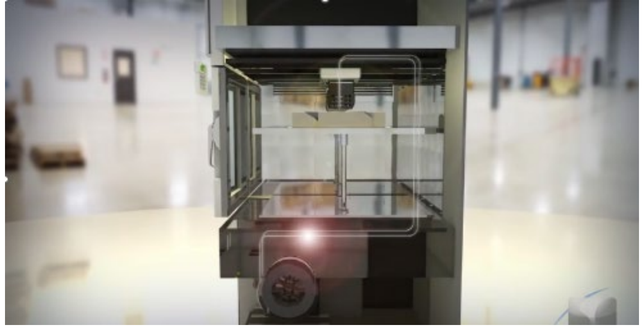


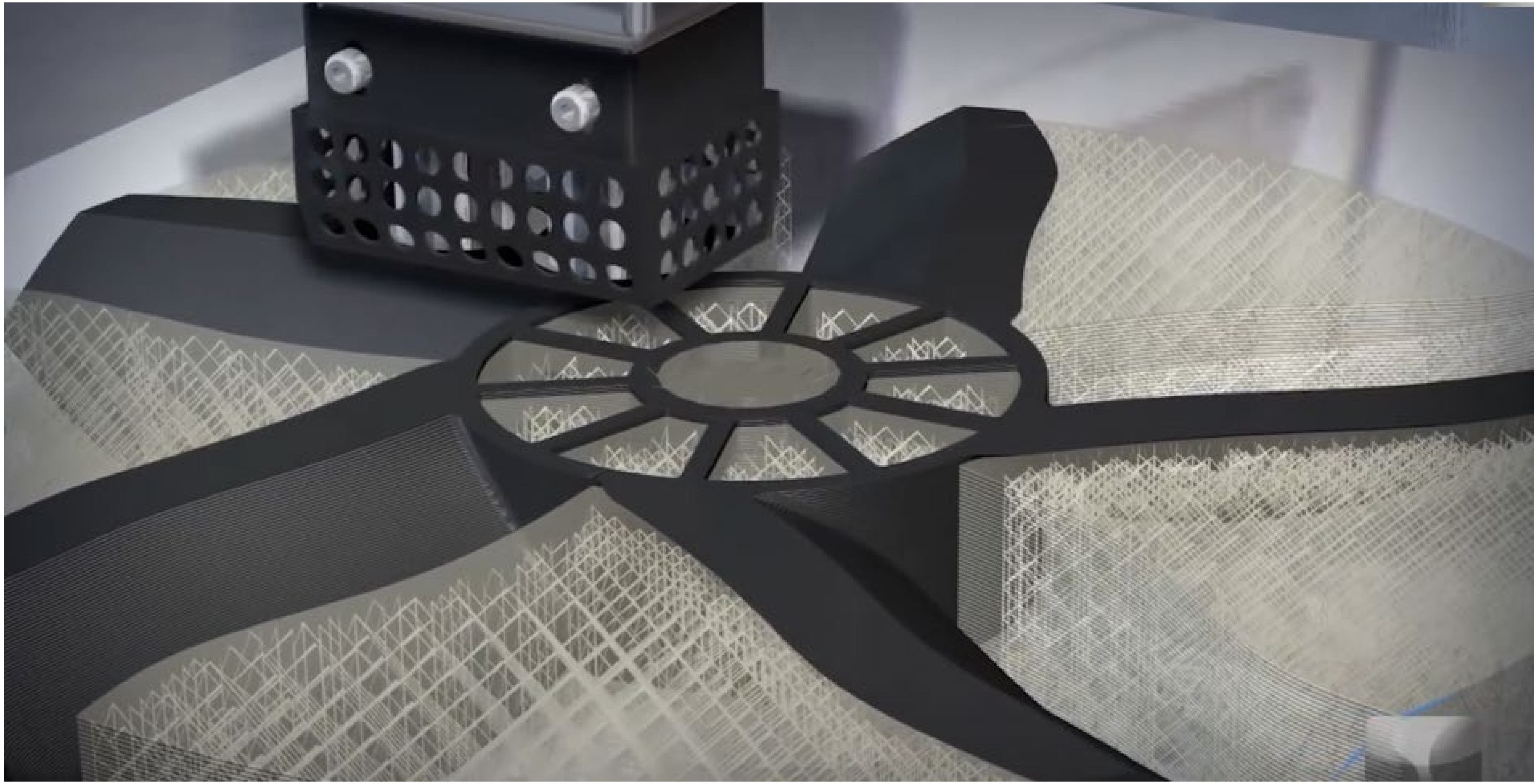
(Part count = 1)

Which materials?

- Thermoplastics
  - ABS
  - Nylon
  - PC (polycarbonate)
  - High-temp plastic (ULTEM)
  - Etc.

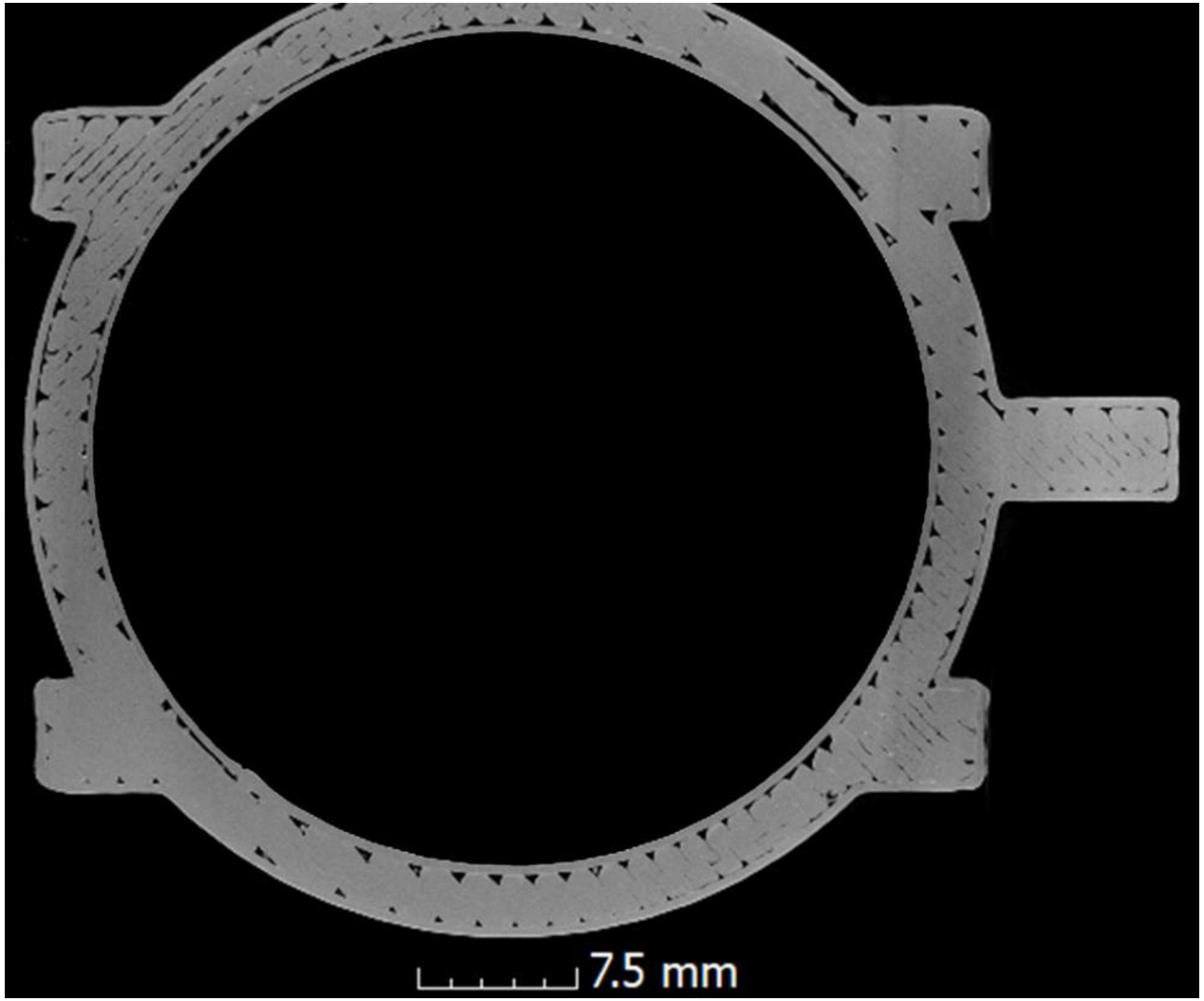
Illustration





(Source: Solid concepts)

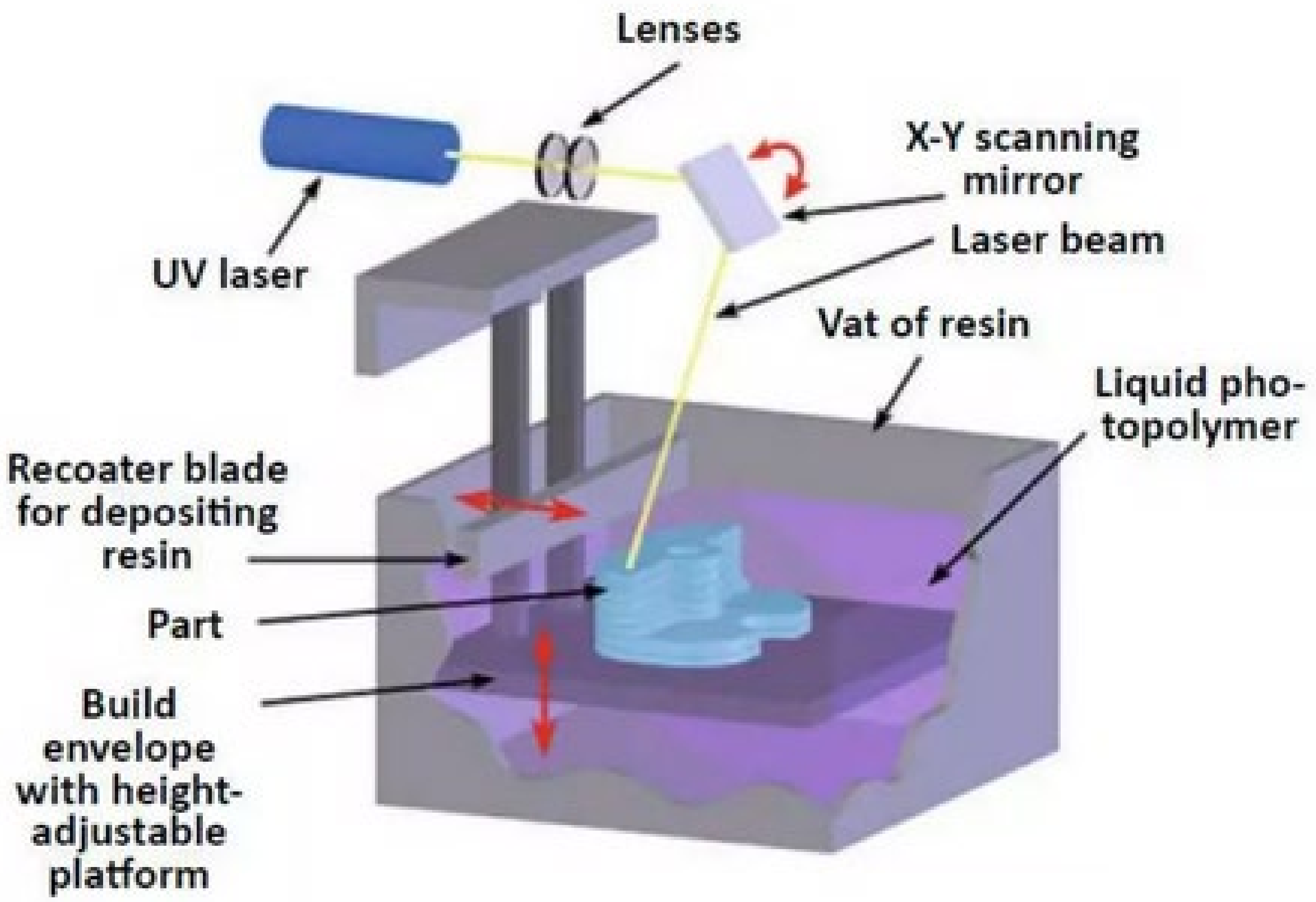
Typical issues



- Porosity
- Anisotropy due to layer-by-layer fabrication

A computed tomography (CT) scan of the inside of a part made via material extrusion shows how deposition strategy (e.g., toolpath, contour, road width) affects the infill and density.
Photo Credit: Timothy W. Simpson

Stereolithography (SLA)



Note: Two-photon lithography uses a similar concept but using ultrafast laser

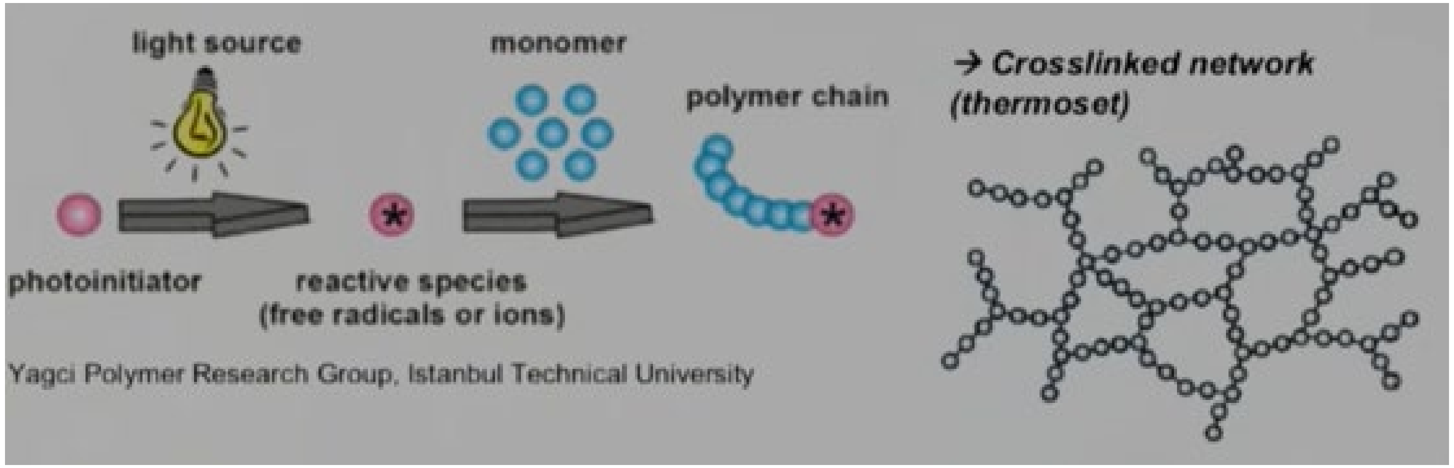
Stereolithography

- Based on photopolymerization (or ‘photocuring’)
- Higher level of details than filament-based extrusion
- Layers (SLA) are smaller than for a FDM part
- Requires post-processing to remove support material
- SLA is usually slower (thinner layer, more details to print)

https://www.youtube.com/watch?v=98xG86GKj7A

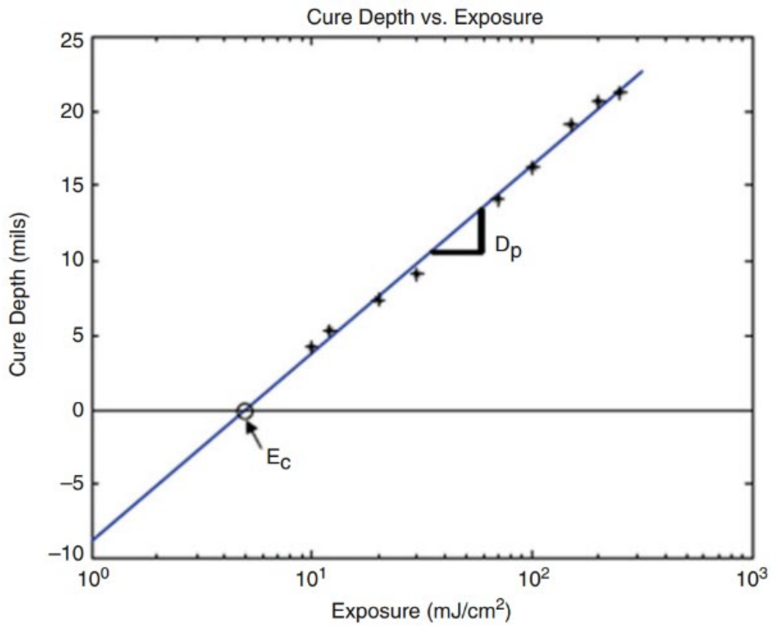
Stereolithography

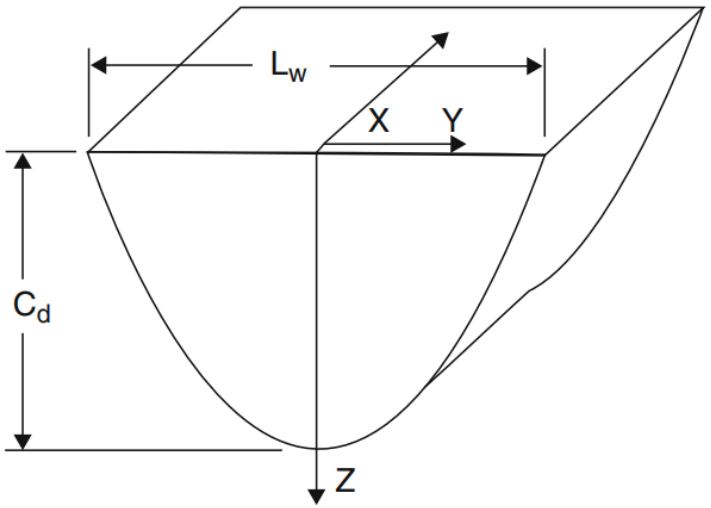
- Based on photopolymerization (or ‘photocuring’)
- Chain reaction:
  - Photon excitation induced the formation of a photo-initiator: a primary radical (R*) though photon excitation.
  - A chain grows by the addition of monomer units (M) to a polymeric radical of length n (Pn)
  - Formation of a stable polymer units of length n (Mn)



Stereolithography resolution

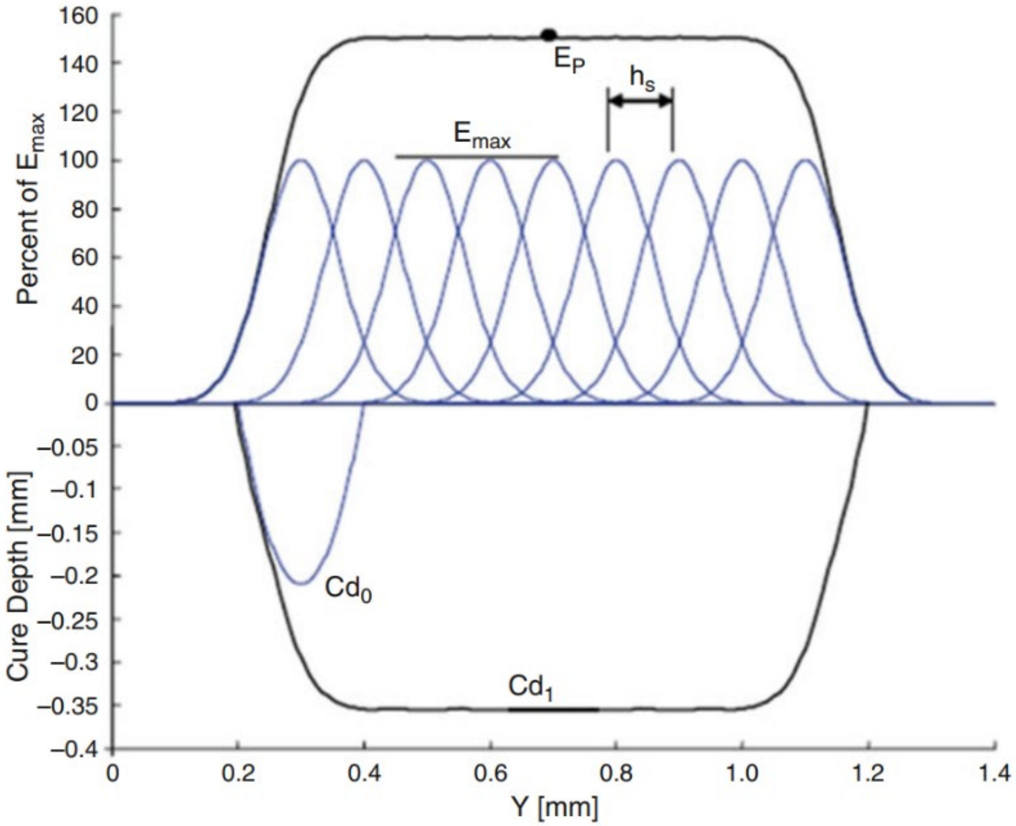
- Governed by shrinkage
- Laser distribution of energy (Gaussian)
- Exposure dose
- Typical features sizes ~ 300 um (axial) / z resolution ~ 25 um
- Patterns density

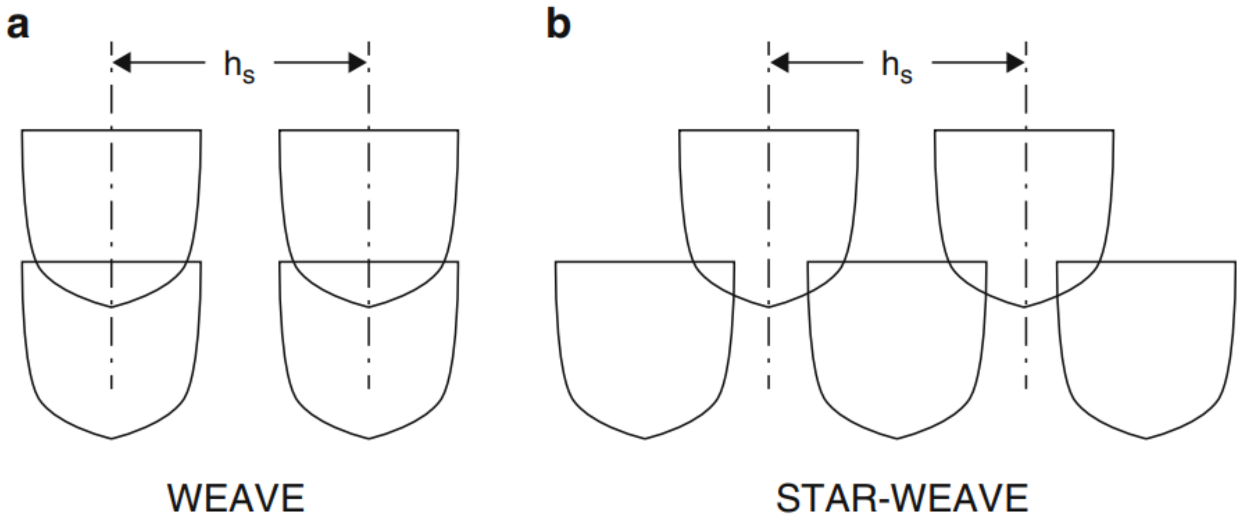




(note: 1 mils = 25.4 microns)

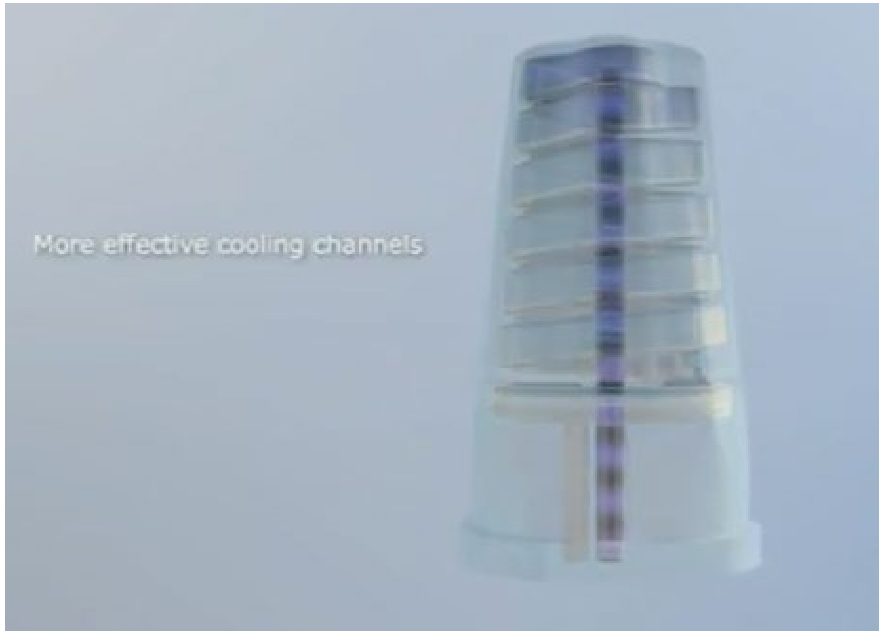
Weave and resolution

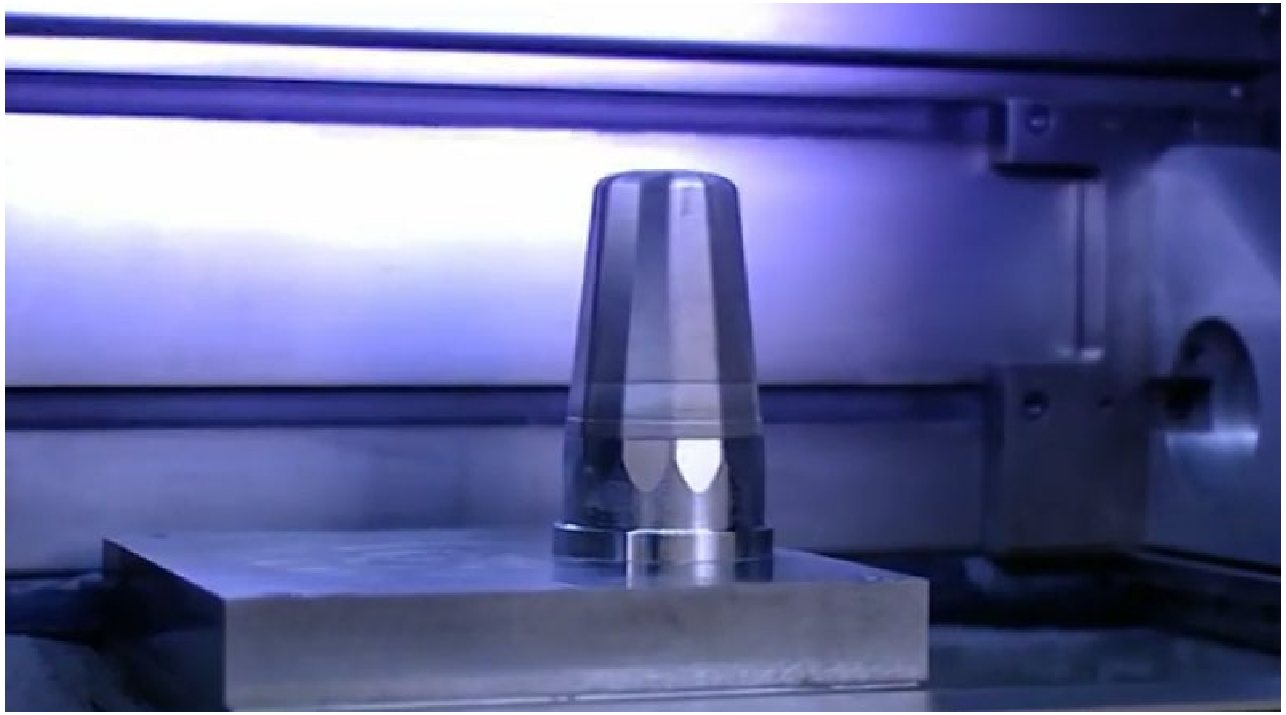




Laser powder-bed fusion (‘Selective Laser Sintering / Selective Laser Melting

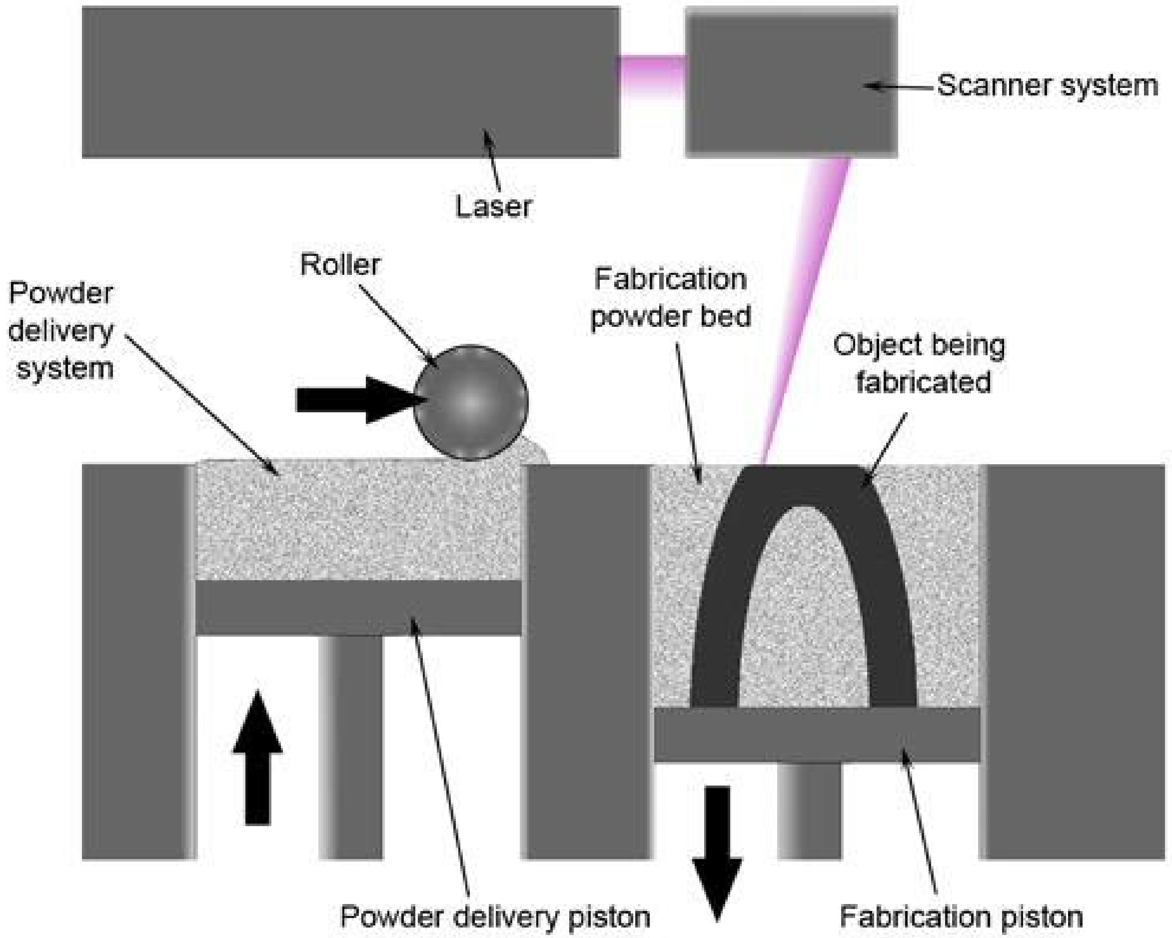
- Introduction and use case

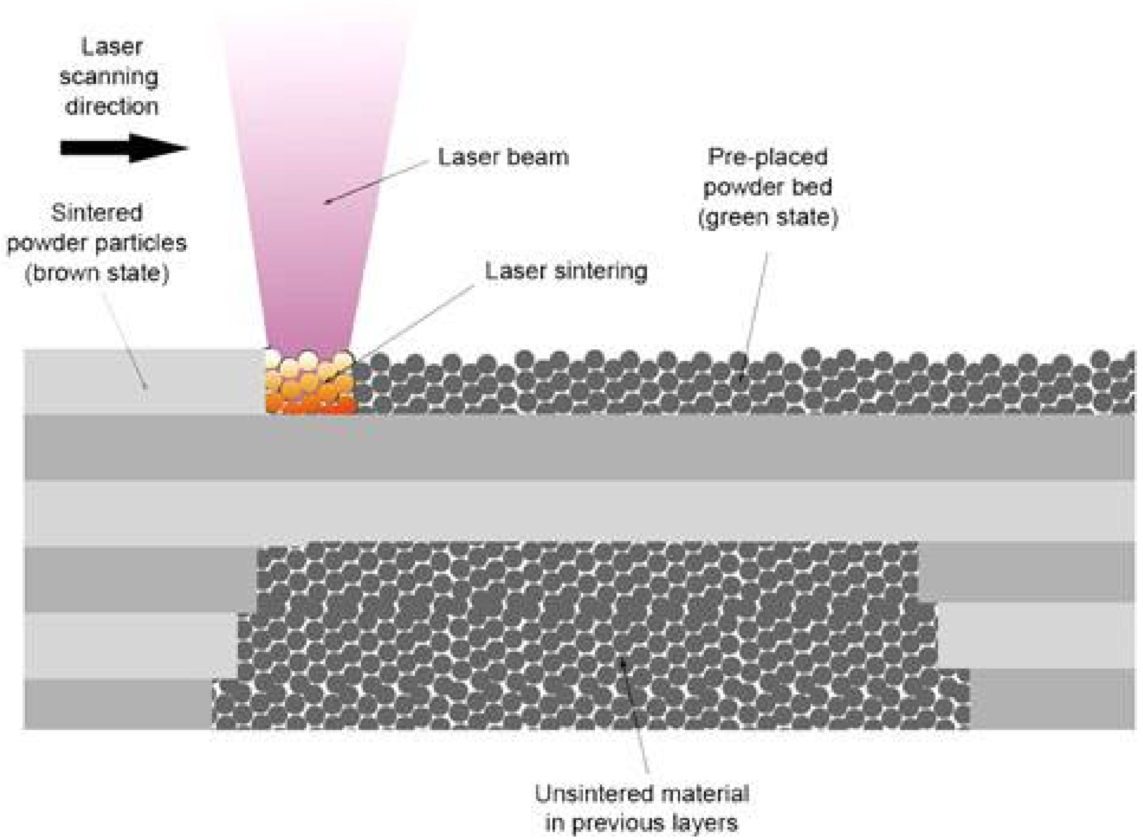




https://www.youtube.com/watch?v=zqWOrwBzOjU

Selective Laser Sintering: working principle

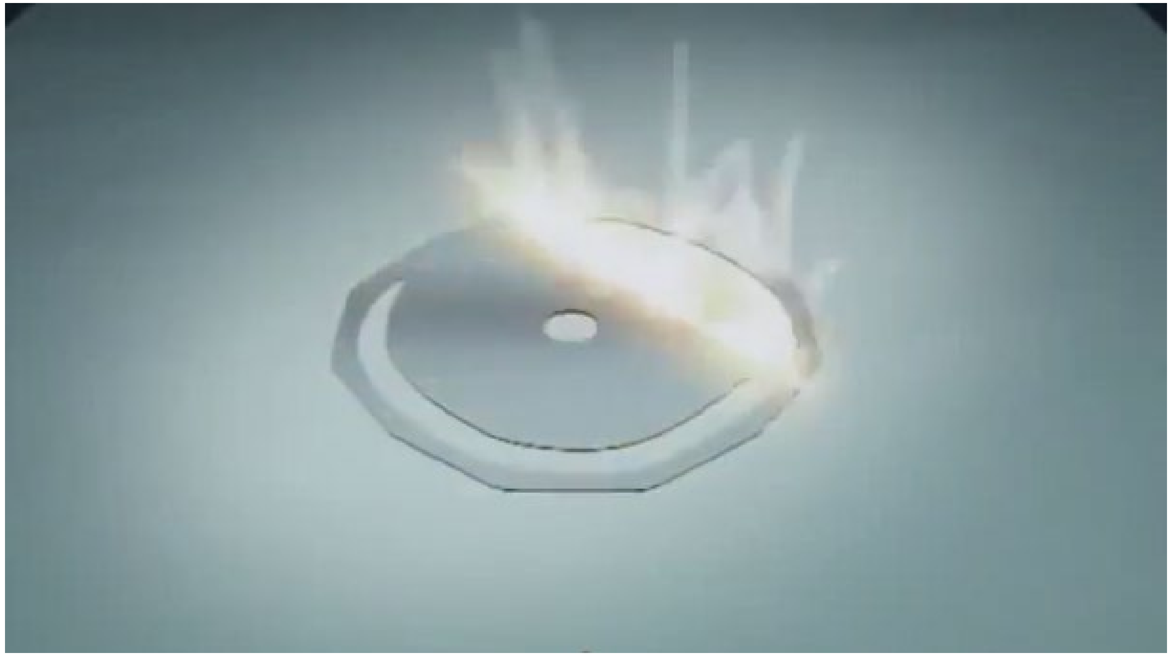




Discussion

- List of process characteristics
- Anticipate possible issues
- Predict possible outcomes

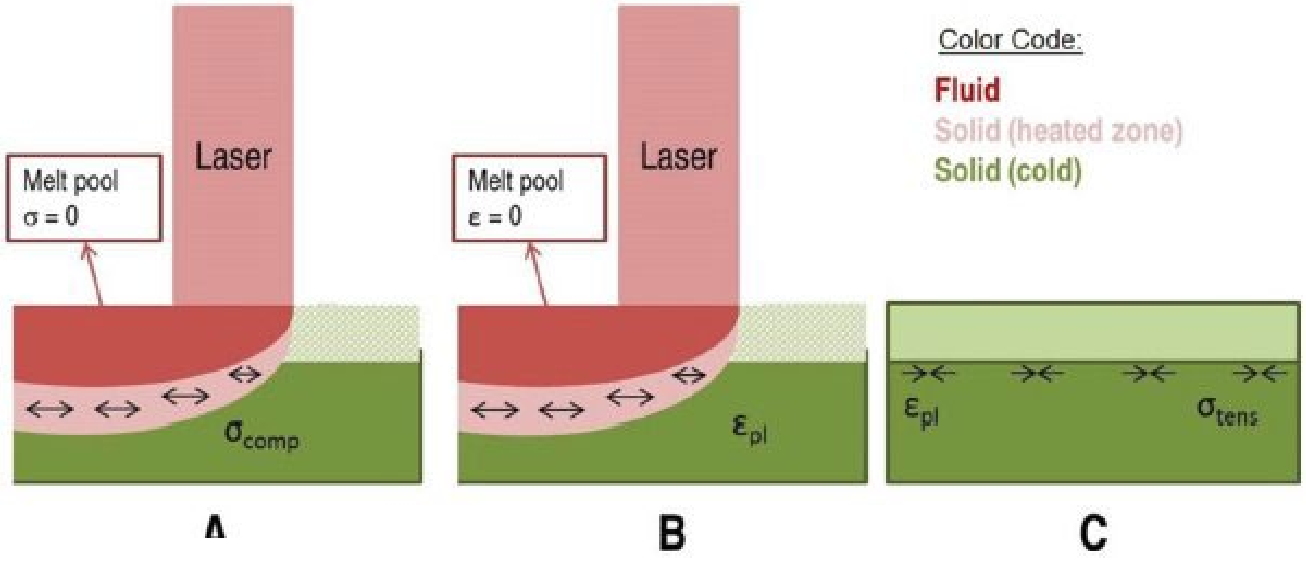
Laser powder bed-fusion (LPBF)



- Very high heating and cooling rates
  - Influence on grain structures, precipitation, phase transformations
  - Residual stresses, size effects
  - Porosities
  - Anisotropic properties
- Complete re-thinking of the usual fabrication rules, and metallurgy
  - Alloy development
  - Modelling and simulation
  - Thermomechanical treatments
  - Microstructure & Characterization

(adapted from Prof. R. Logé, EPFL)

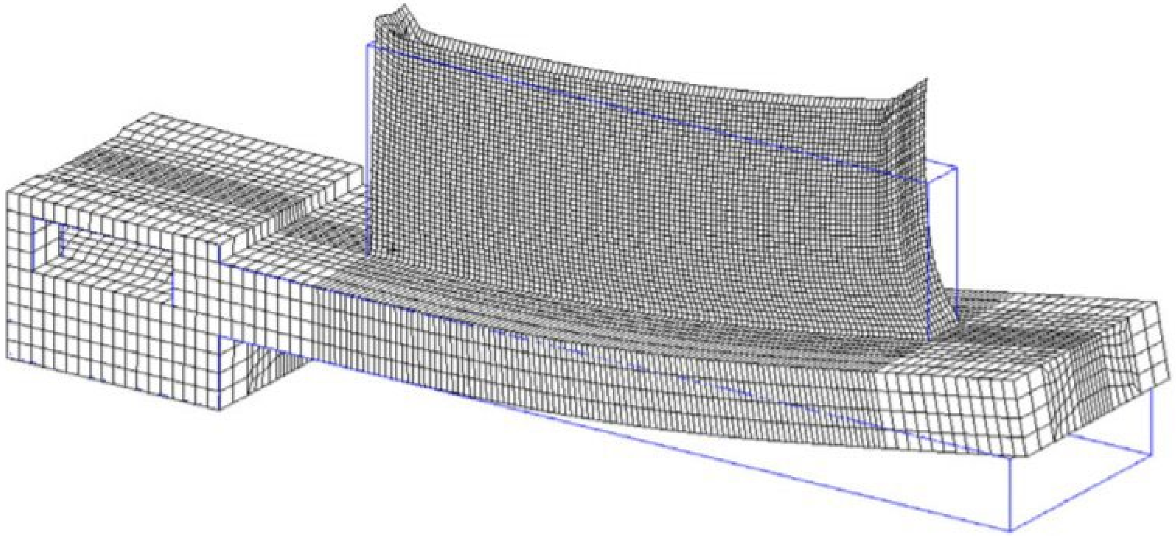
Stress inherently build-up upon cooling…



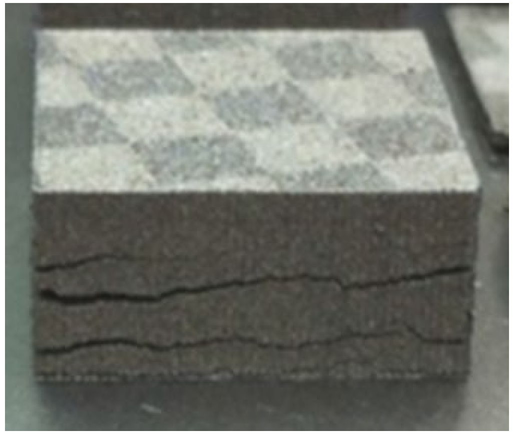
[Kempen et al., 2014]

→ **tensile**

→ **compressive**



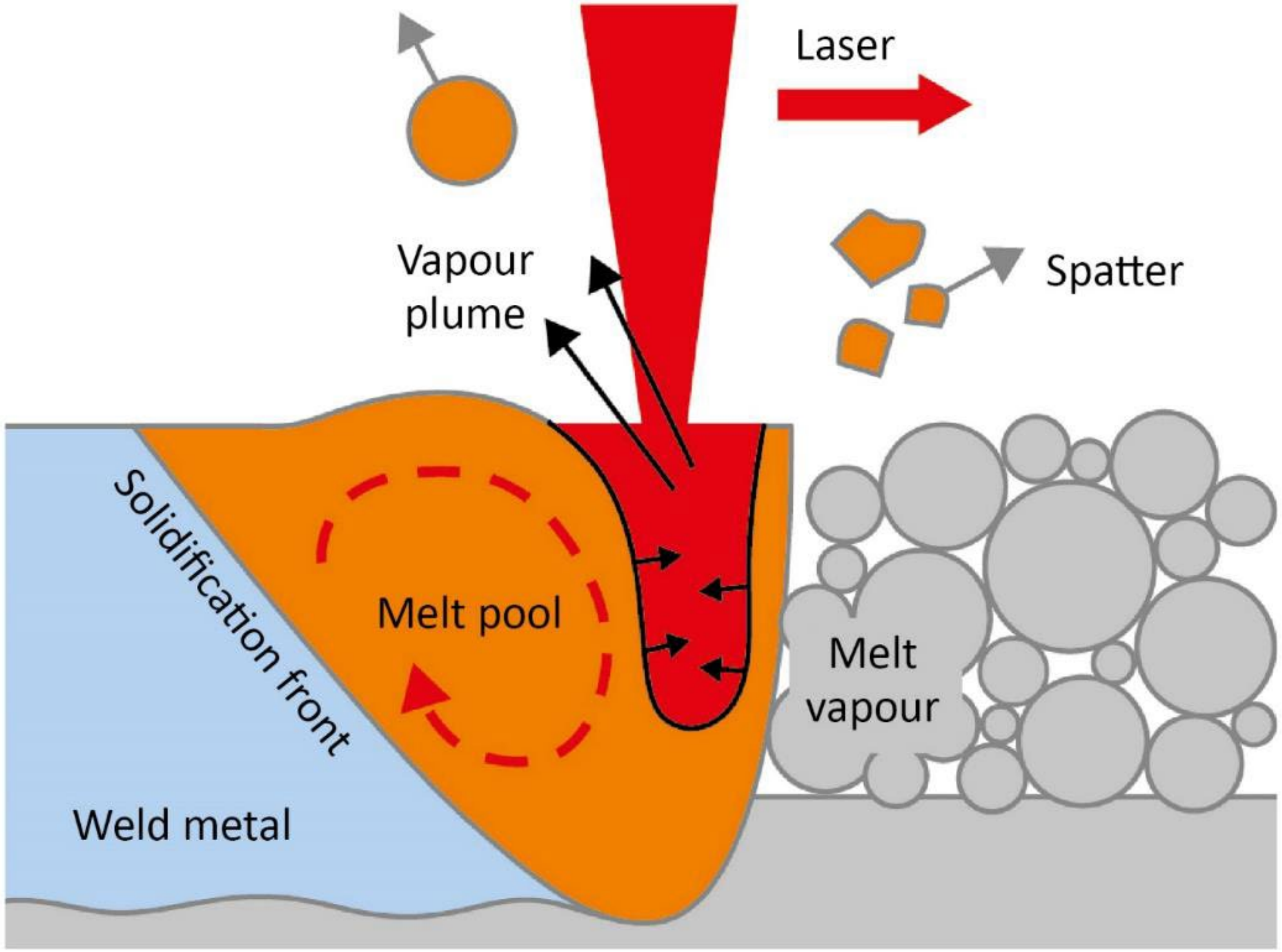
Geometrical distortion



cracking

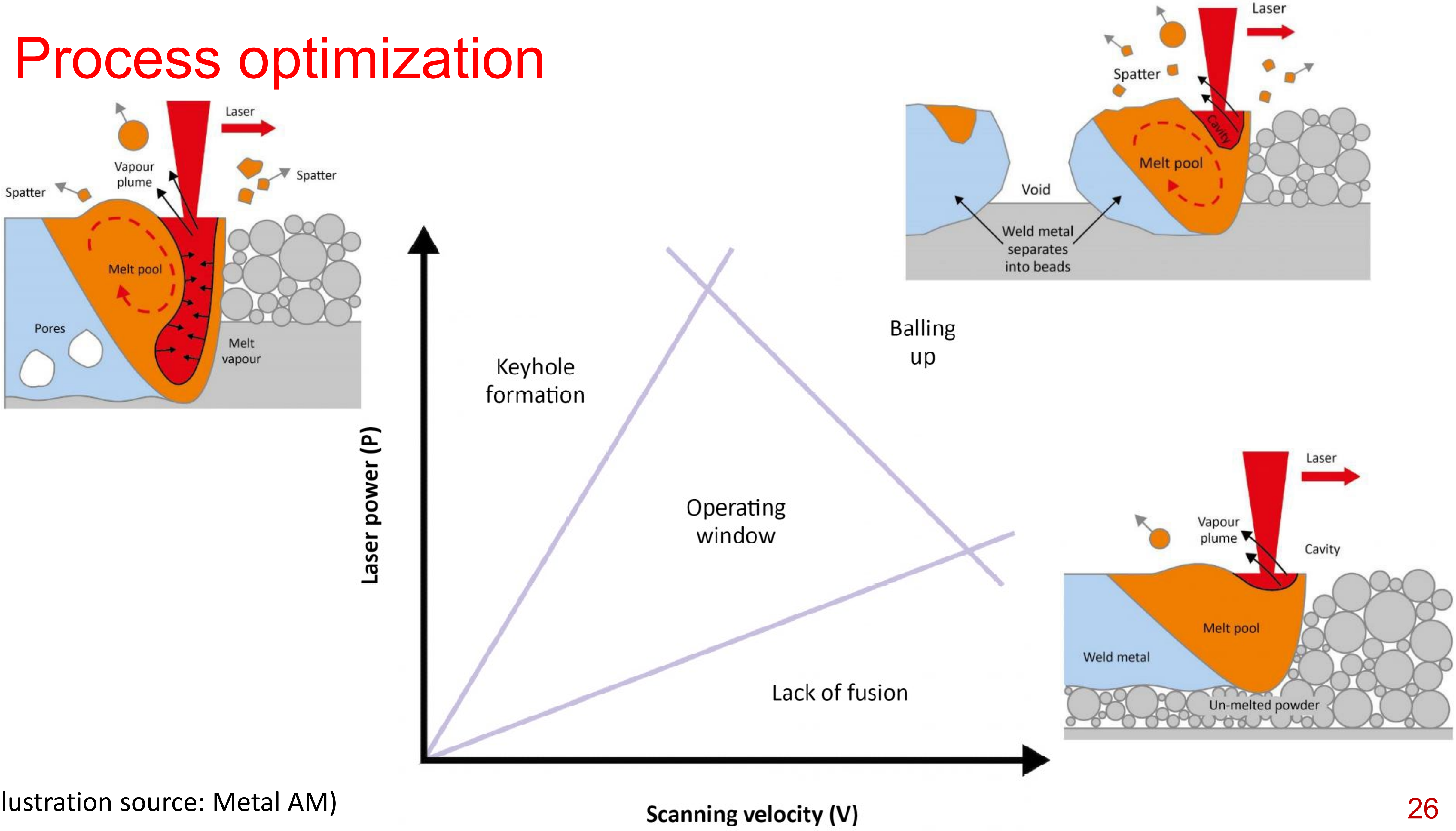
[Kempen et al., 2014]

Working principle



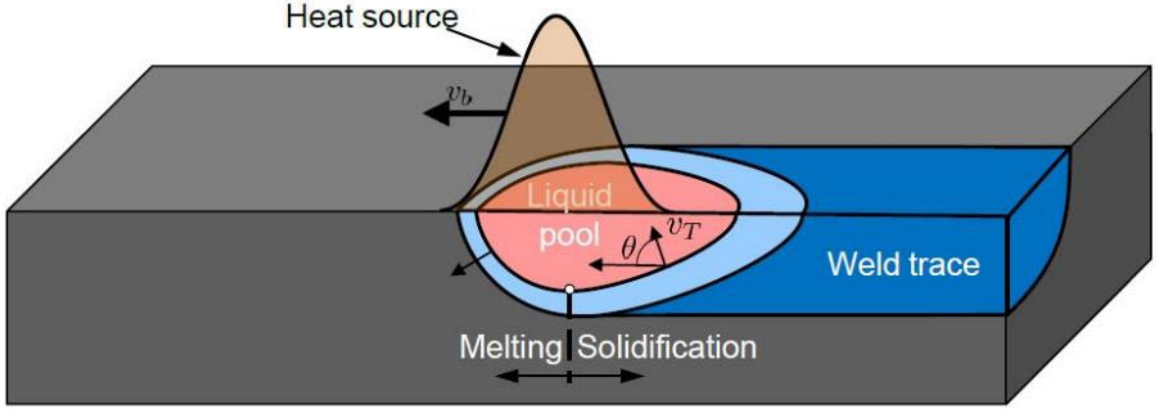
(illustration source: Metal AM)

Process optimization



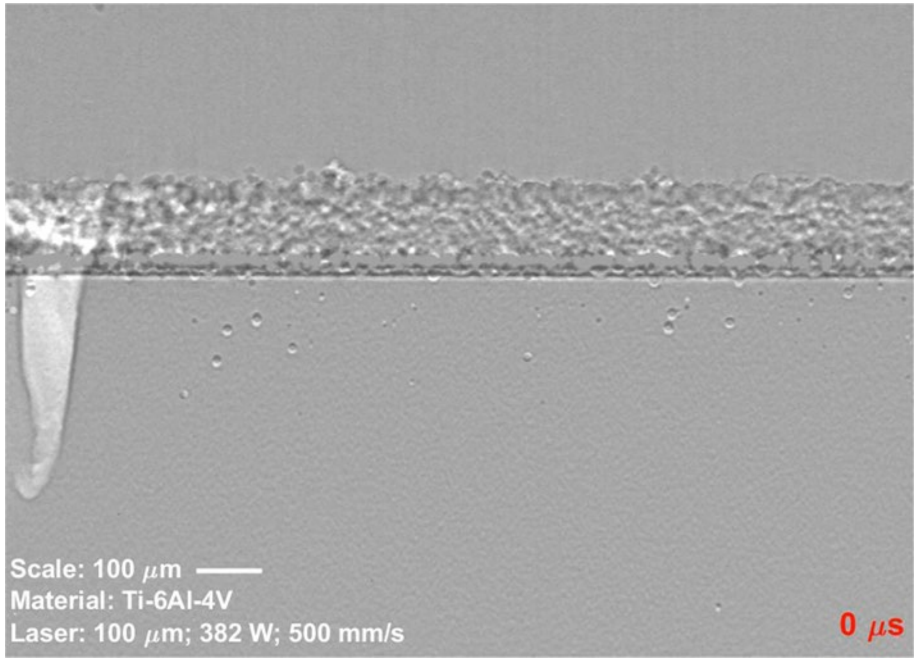
(illustration source: Metal AM)

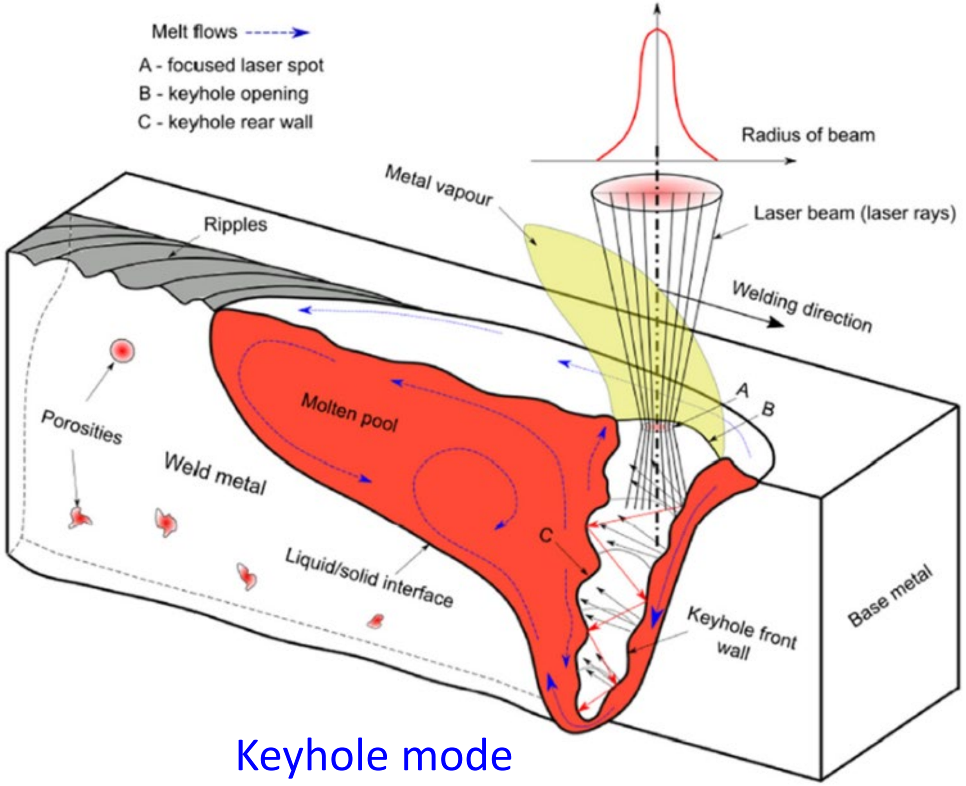
Melting regimes and defects in Laser Powder Bed Fusion



$$v_T = v_b \cos\theta$$

Standard conduction mode



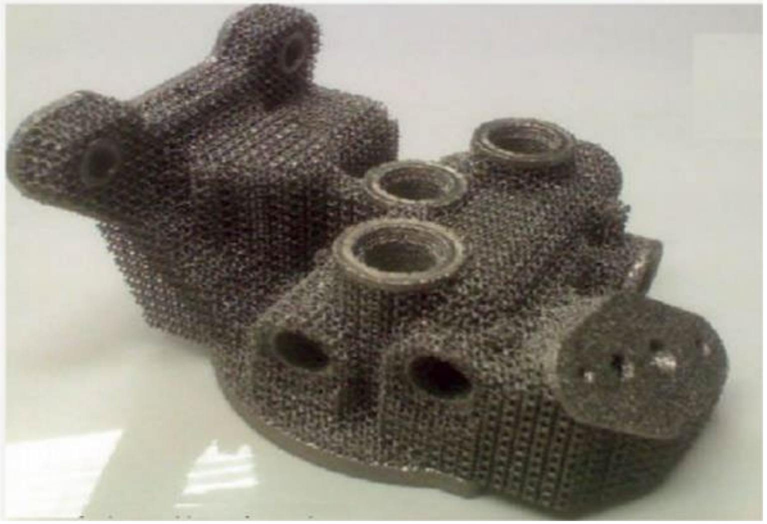


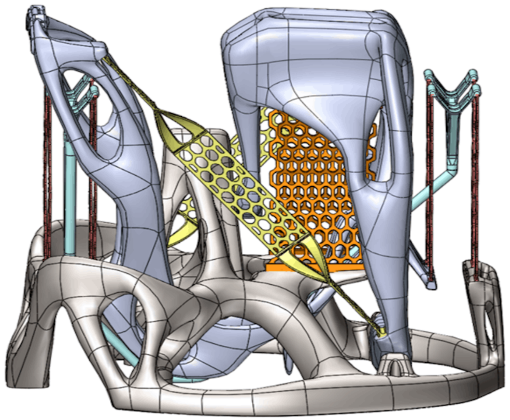
Keyhole mode

Instabilities : porosity formation

Key advantages

Light weight structures with complex geometry (material/weight reduction)

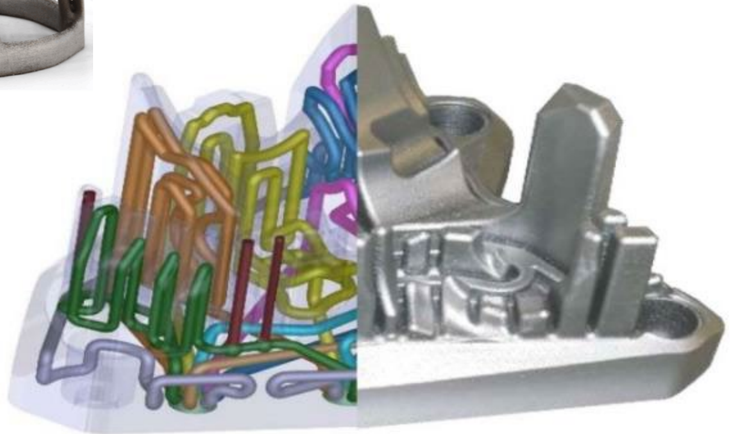




Lighweight mechanism (picture CSEM)

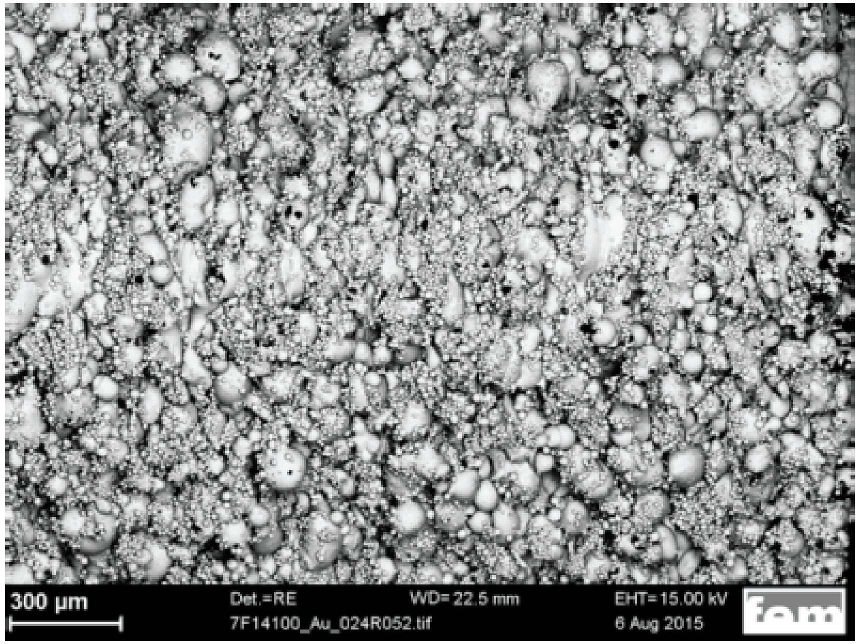
- **Geometrical freedom**, complex 3D shapes
- Near net shape & powder recycling (**low waste**)
- Low lead time
- **Process flexibility**

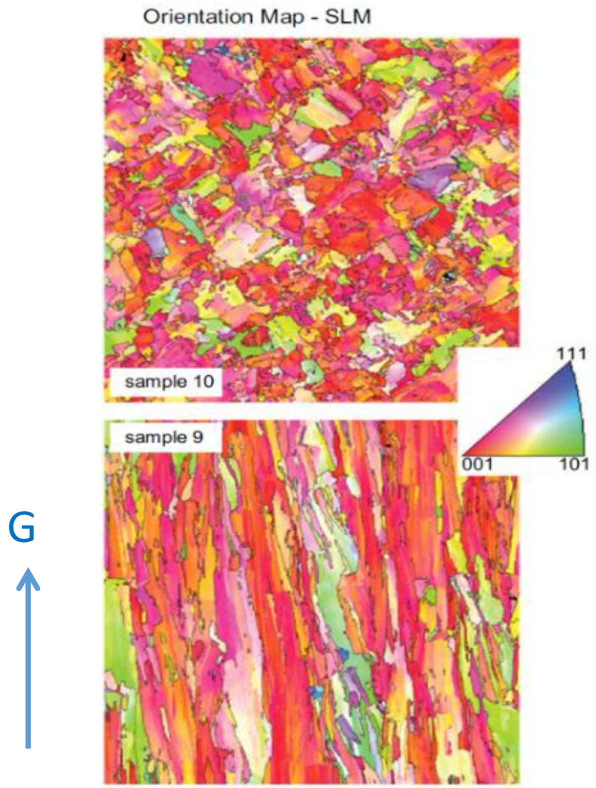
Conformal cooling (embedded channels)



Key issues

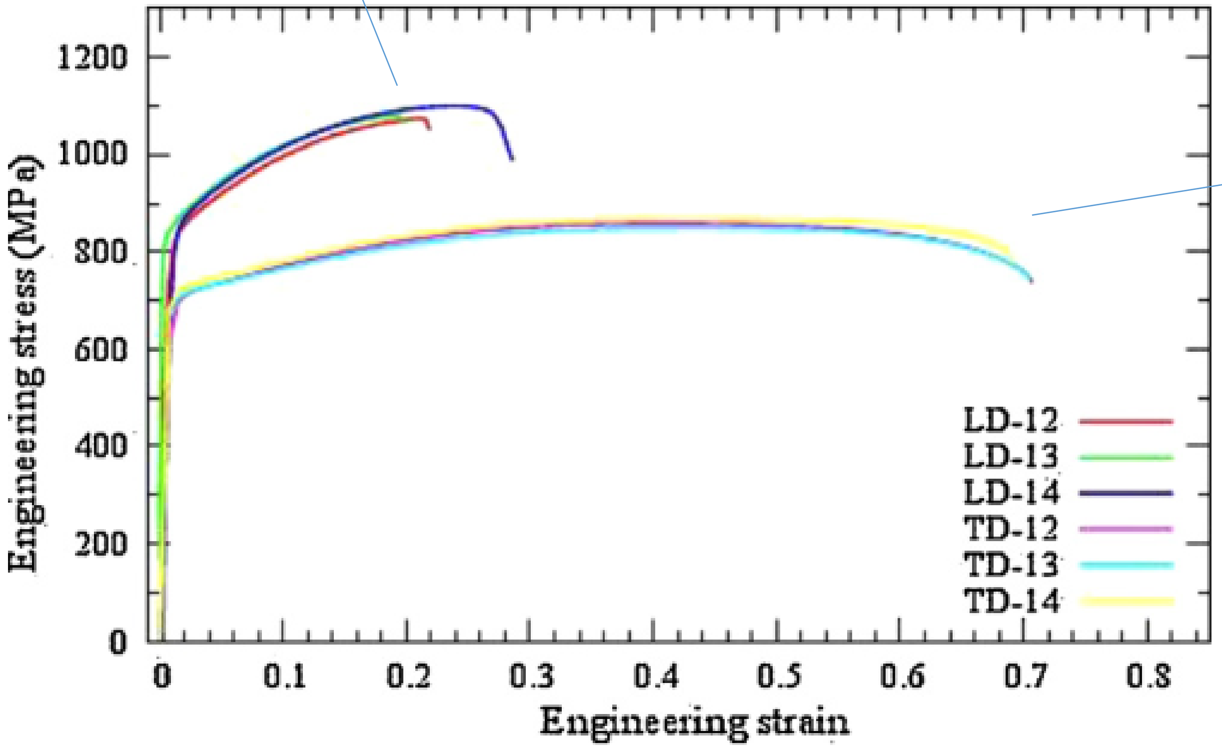
- Porosities
- Surface rougness
- Uncontrolled grain structures, crystallographic and morphological textures:
  - Non optimal mechanical properties
  - Anisotropy



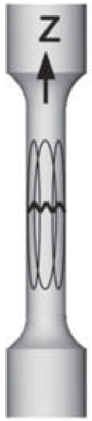


(Illustrations: courtesy of prof. Roland Logé)

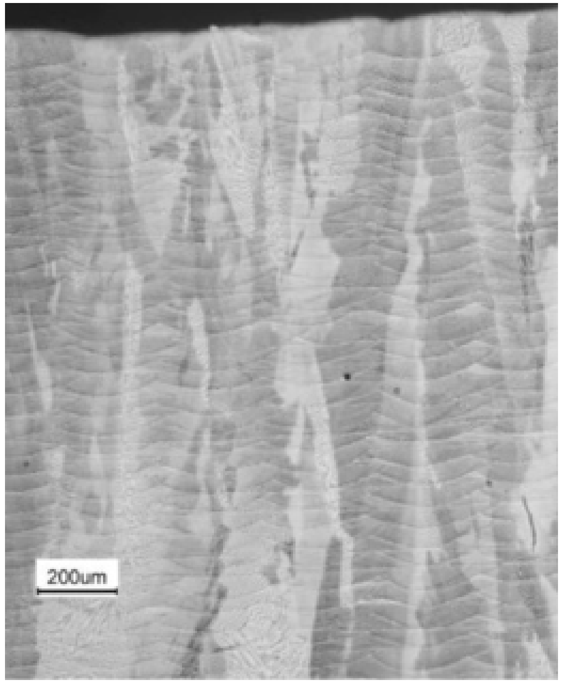
Effect of grain textures on mechanical properties



Pulling along Z



Tensile properties of Nimonic 263 SLM samples



Z

G

[T. Vilaro et al., Materials Science & Engineering A, 2012]

Successful application

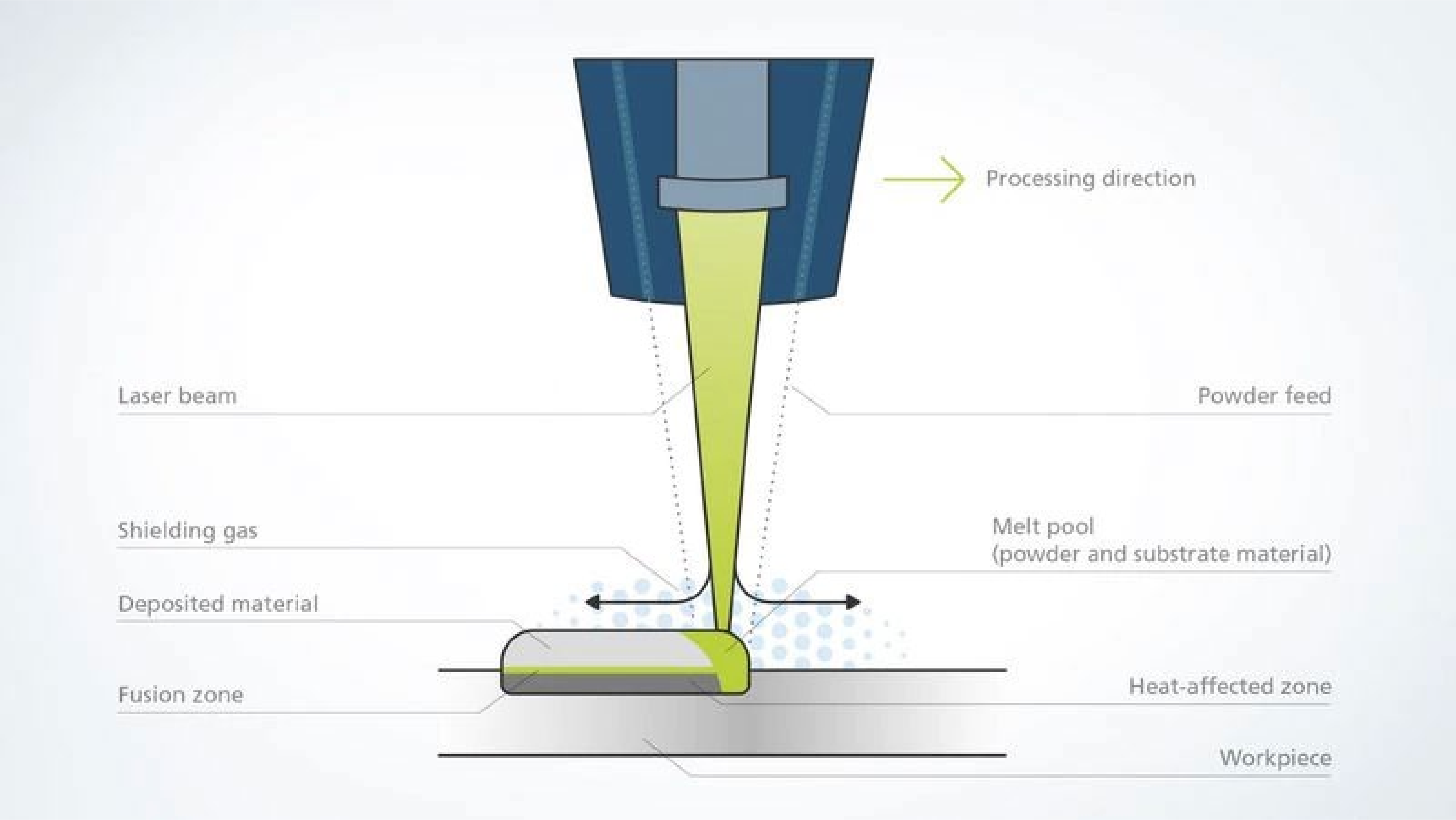
- Medical implants

FDA approved hip titanium implant

(source Azom)

(source Trumpf)

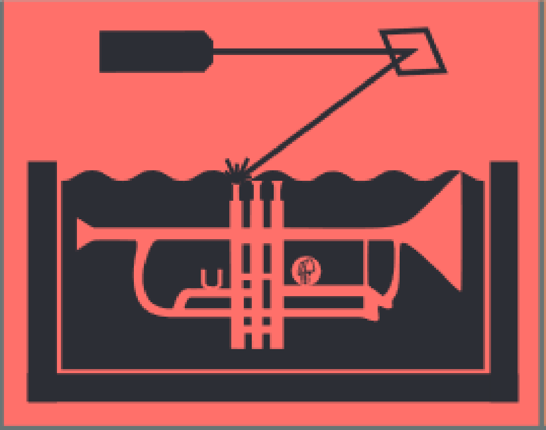
Laser Metal Deposition (LMD)

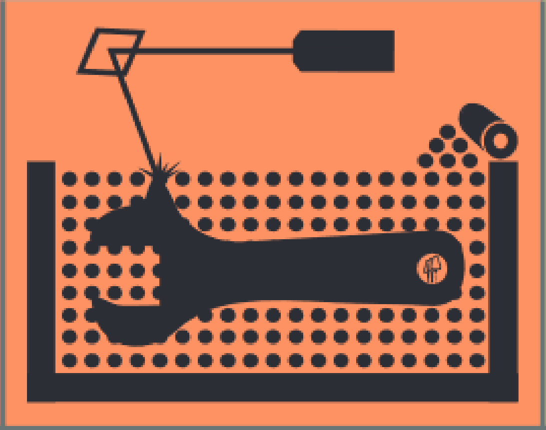


(source: Trumpf)

Laser cladding

Summary of the seven main families of Additive manufacturing processes

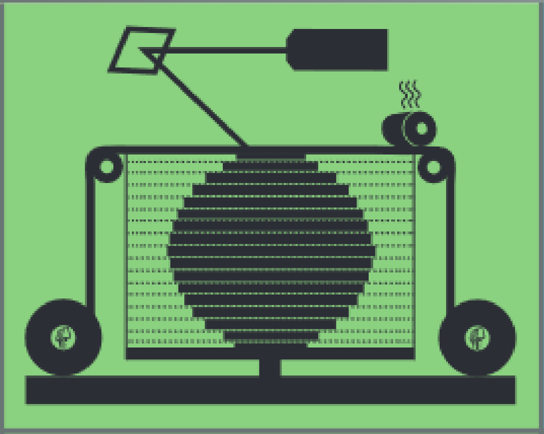
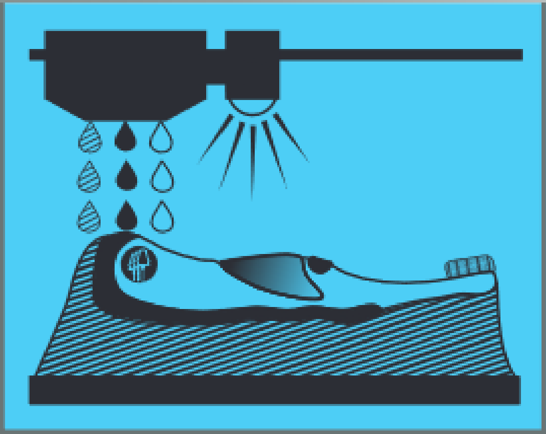
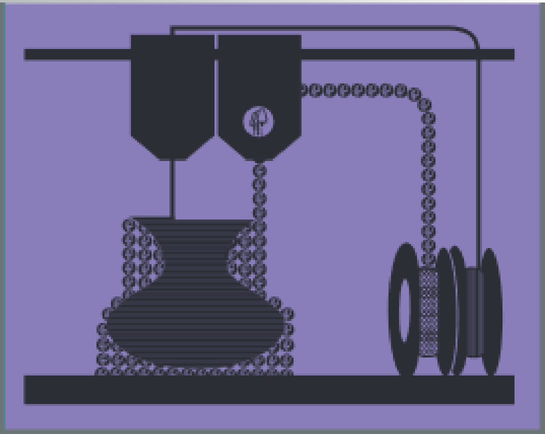




VAT PHOTO-POLYMERIZATION	POWDER BED FUSION (PBF)	BINDER JETTING
Alternative Names: SLA™ - Stereolithography Apparatus DLP™ - Digital Light Processing 3SP™ - Scan, Spin, and Selectively Photocure CLIP™ - Continuous Liquid Interface Production	**Alternative Names:** SLM™ - Selective Laser Melting: (a.k.a. SLS™ - Selective Laser Sintering); DMLS™ - Direct Metal Laser Solidification (f.k.a. Sintering); EBM™ - Electron Beam Melting; MJF™ - Multi Jet Fusion; SHS™ - Selective Heat Sintering	**Alternative Names:** 3DP™ - 3D Printing (Binder Jetting* is available from ExOne, Voxeljet, Desktop Metal's Production System™, and others) *metal & ceramic require post-print sintering
Description: A vat of liquid photopolymer resin is cured through selective exposure to light (via a laser or projector) which then initiates polymerization and converts the exposed areas to a solid part.	**Description:** Powdered materials is selectively consolidated by melting it together using a heat source such as a laser or electron beam. The powder surrounding the consolidated part acts assupport material for overhanging features.	**Description:** Liquid bonding agents are selectively applied onto thin layers of powdered material to build up parts layer by layer. The binders include organic and inorganic materials. Metal or ceramic powdered parts are typically fired in a furnace after they are printed.
Strengths: • High level of accuracy and complexity • Smooth surface finish • Accommodates large build areas	**Strengths:** • High level of complexity • Powder acts as support material • Wide range of materials	**Strengths:** • Allows for full color printing • High productivity • Uses a wide range of materials
Typical Materials UV-Curable Photopolymer Resins	**Typical Materials** Plastics, Metal and Ceramic Powders, and Sand	**Typical Materials** Powdered Plastic, Metal, Ceramics, Glass, and Sand.

(source: Hybrid Manufacturing Technologies)

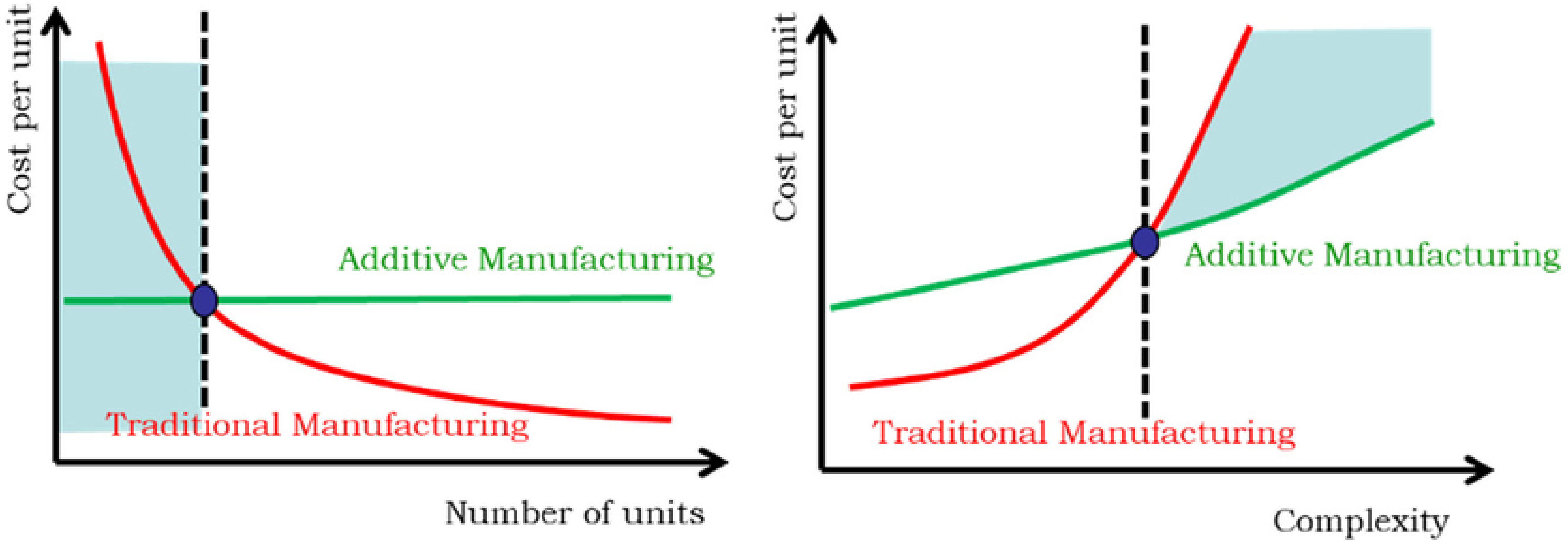
Summary of the seven main families of Additive manufacturing processes (part II)


	Sheet Lamination	Material Jetting	Material Extrusion	Directed Energy Deposition (DED)
Alternative Names:	LOM - Laminated Object Manufacture SDL - Selective Deposition Lamination UAM - Ultrasonic Additive Manufacturing	Polyjet™ SCP™ - Smooth Curvatures Printing MJM - Multi-Jet Modeling Projet™	FFF - Fused Filament Fabrication FDM™ - Fused Deposition Modeling APD™ - Augmented Polymer Deposition ADAM™ - Atomic Diffusion Additive Mfg* BMD™ - Bound Metal Deposition*	LMD - Laser Metal Deposition LENS™ - Laser Engineered Net Shaping DMD - Direct Metal Deposition Laser cladding WAAM - Wire-arc Additive Manufacturing
Description:	Sheets of material are stacked and laminated together to form an object. The lamination method can be adhesives or chemical (paper/ plastics), ultrasonic welding, or brazing (metals). Unneeded regions are cut out layer by layer and removed after the object is built.	Droplets of material are deposited layer by layer to make parts. Common varieties include jetting a photocurable resin and curing it with UV light, as well as jetting thermally molten materials that then solidify in ambient temperatures.	Material is extruded through a nozzle or orifice in tracks or beads, which are then combined into multi-layer models. Common varieties include heated thermoplastic extrusion (similar to a hot glue gun) and syringe dispensing.	Powder or wire is fed into a melt pool which has been generated on the surface of the part where it adheres to the underlying part or layers by using an energy source such as a laser or electron beam.This is essentially a form of automated build-up welding.
Strengths:	• High volumetric build rates • Relatively low cost (non-metals) • Allows for combinations of metal foils, including embedding components.	• High level of accuracy • Allows for full color parts • Enables multiple materials in a single part	• Inexpensive and economical • Allows for multiple colors • Can be used in an office environment • Parts have good structural properties	• Not limited by direction or axis • Effective for repairs and adding features • Multiple materials in a single part • Highest single-point deposition rates
Typical Materials	Paper, Plastic Sheets, and Metal Foils/Tapes	Photopolymers, Polymers, Waxes	Thermoplastic Filaments and Pellets (FFF); Liquids, and Slurries (Syringe Types)	Metal Wire and Powder, with Ceramics

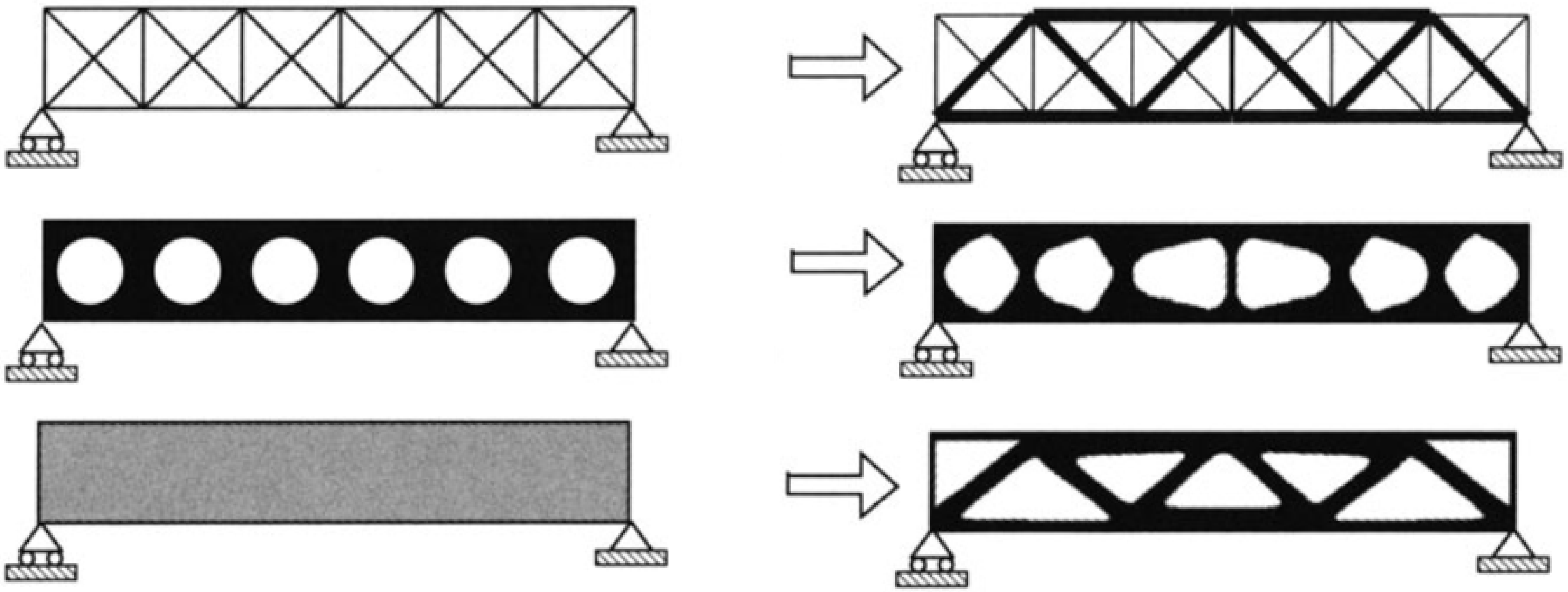
(source: Hybrid Manufacturing Technologies)

Cost vs complexity



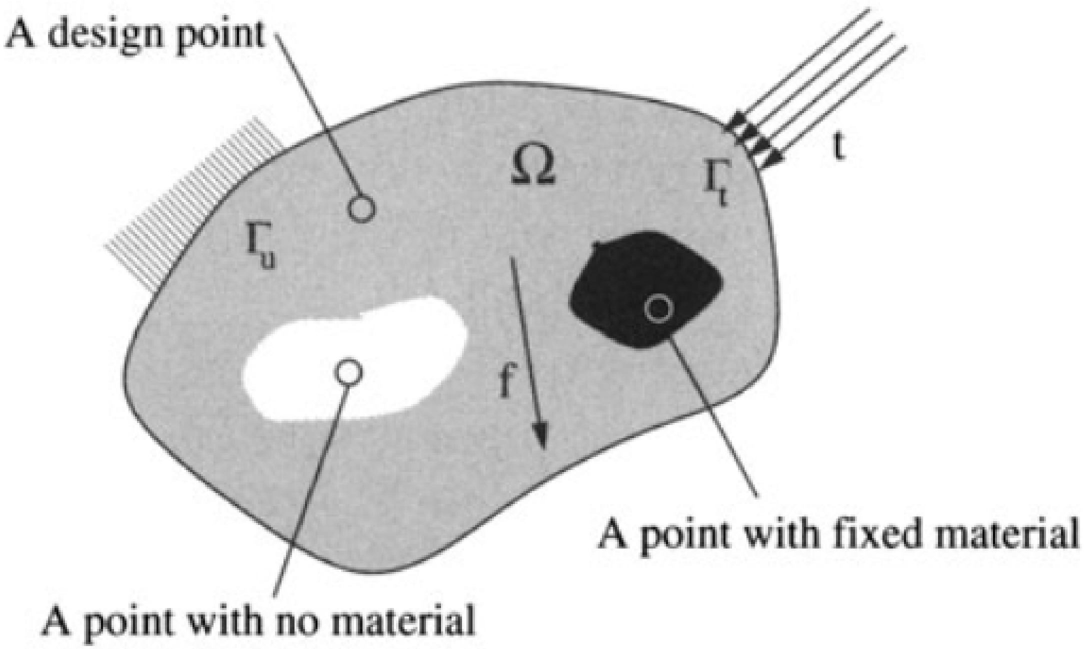
Design opportunities for (additive) manufacturing

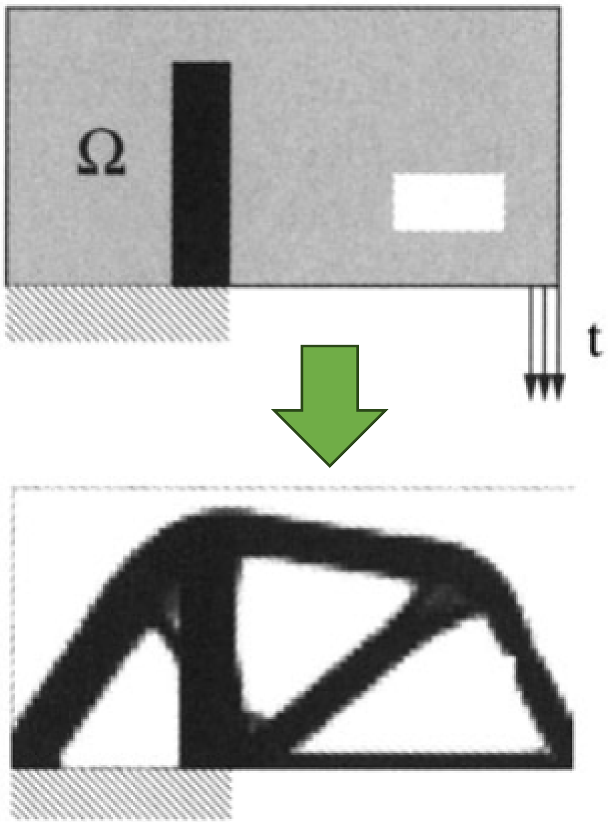
- Topology optimization *(intuitive discussion in class)*



Topology optimization

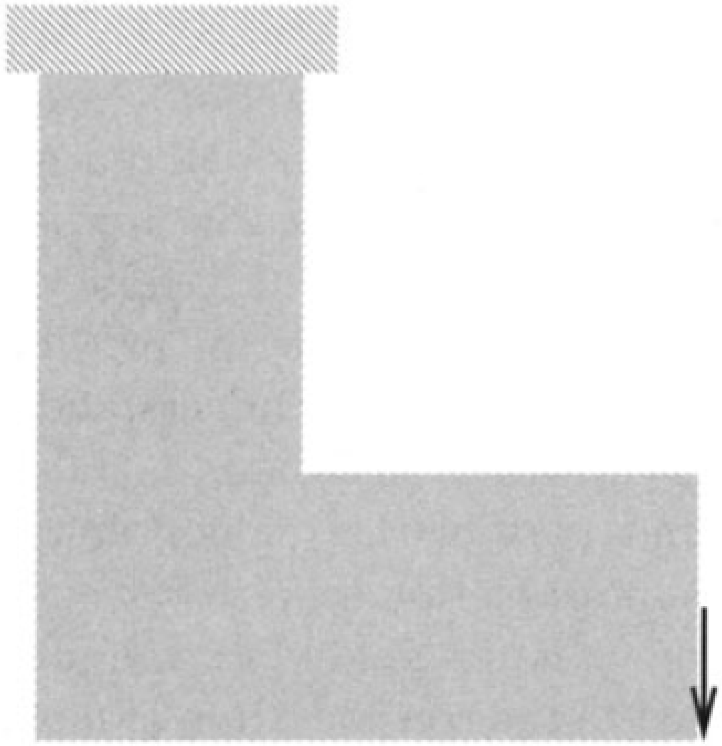
- Problem statement: ‘Find the optimal **material distribution** for a given design problem’



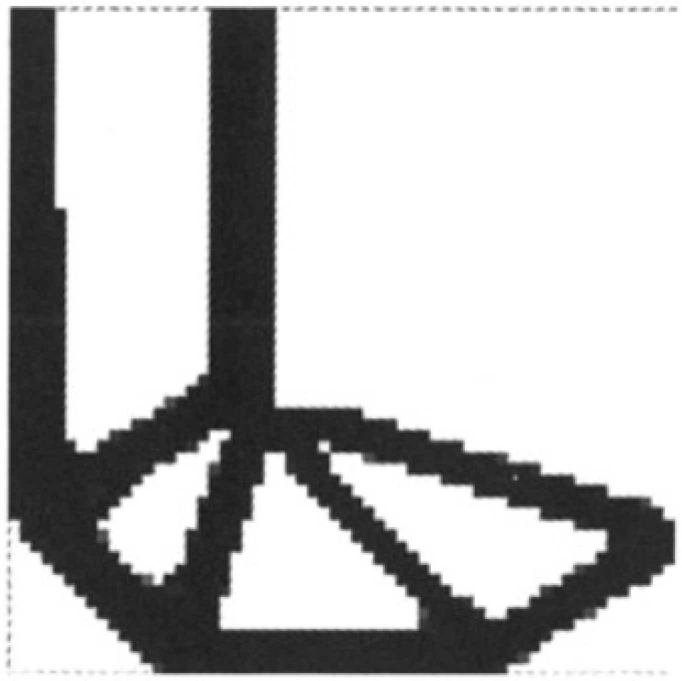


Illustration

Problem statement



Mass distribution optimization



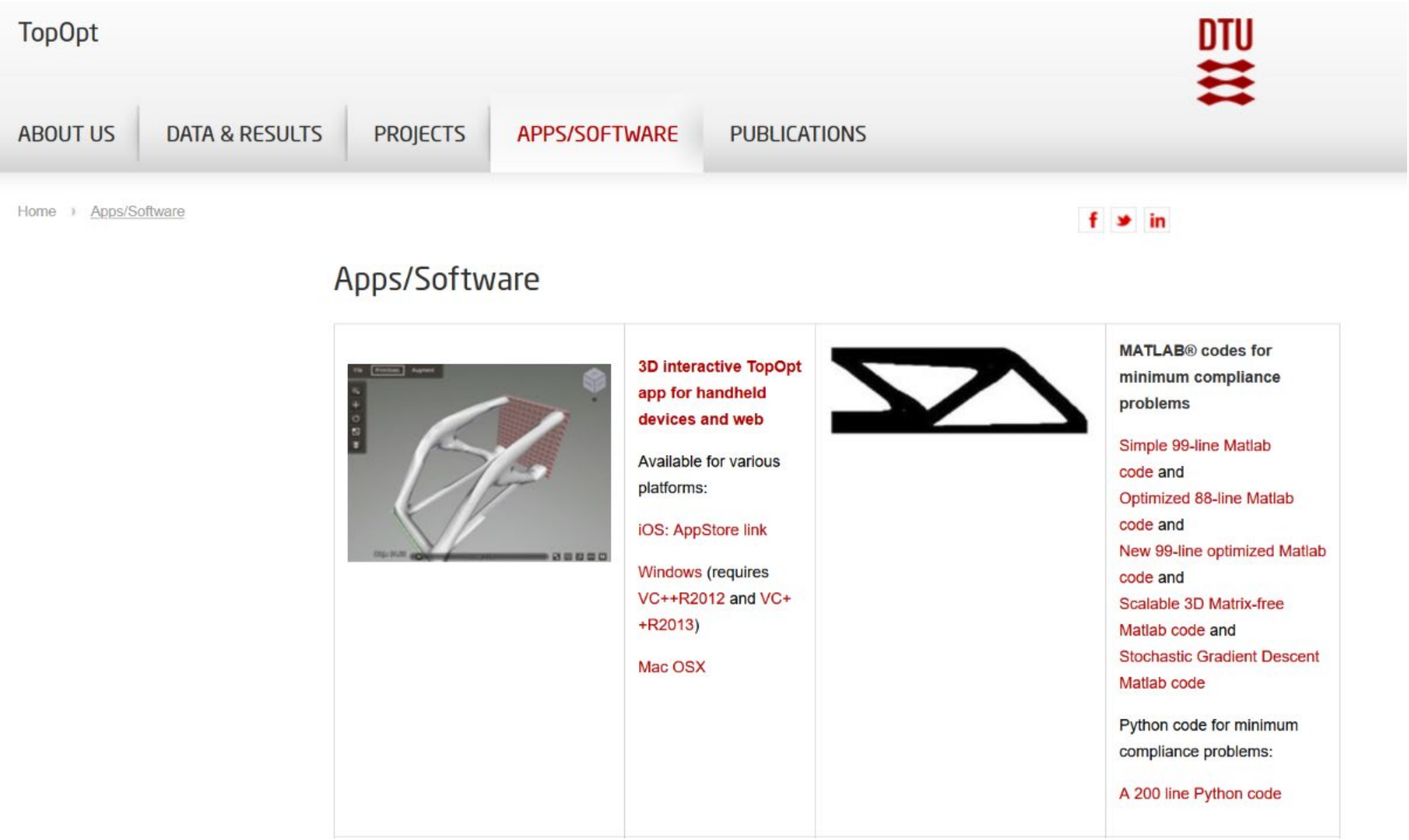
How to manufacture these optimized volumes?

Illustrations

Same mechanical requirements,
Less materials…

Source: Fabbaloo

Interesting softwares and code for exploring the topic


TopOpt

ABOUT US | DATA & RESULTS | PROJECTS | APPS/SOFTWARE | PUBLICATIONS

Home › Apps/Software

Apps/Software

3D interactive TopOpt app for handheld devices and web

Available for various platforms:

iOS: AppStore link

Windows (requires VC++R2012 and VC++R2013)

Mac OSX

MATLAB® codes for minimum compliance problems

Simple 99-line Matlab code and
Optimized 88-line Matlab code and
New 99-line optimized Matlab code and
Scalable 3D Matrix-free Matlab code and
Stochastic Gradient Descent Matlab code

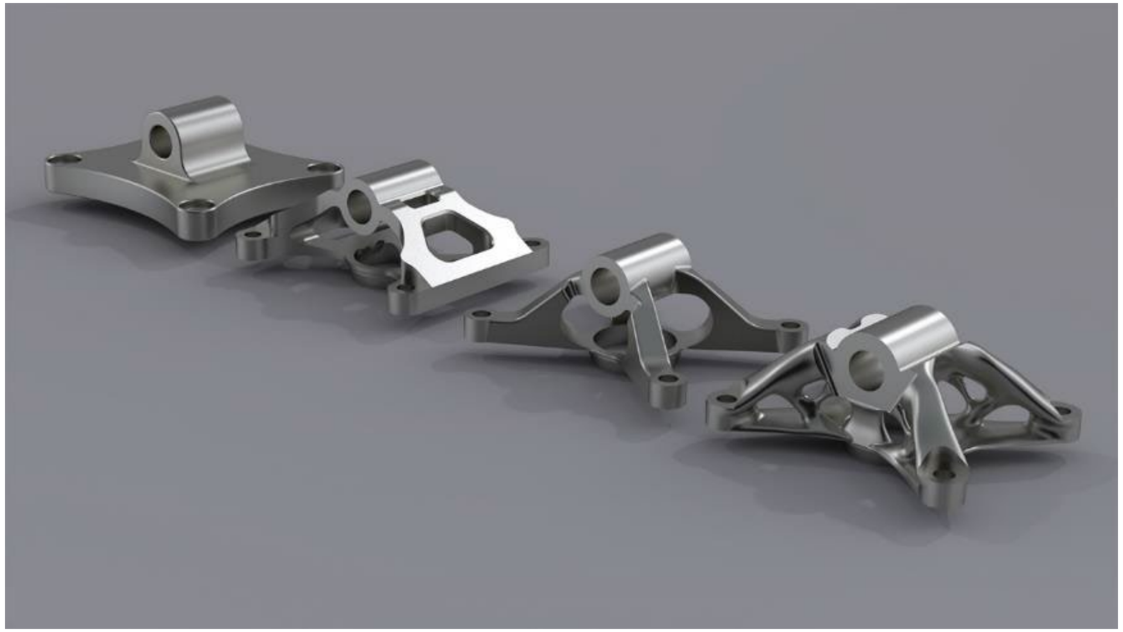
Python code for minimum compliance problems:

A 200 line Python code

https://www.topopt.mek.dtu.dk/apps-and-software

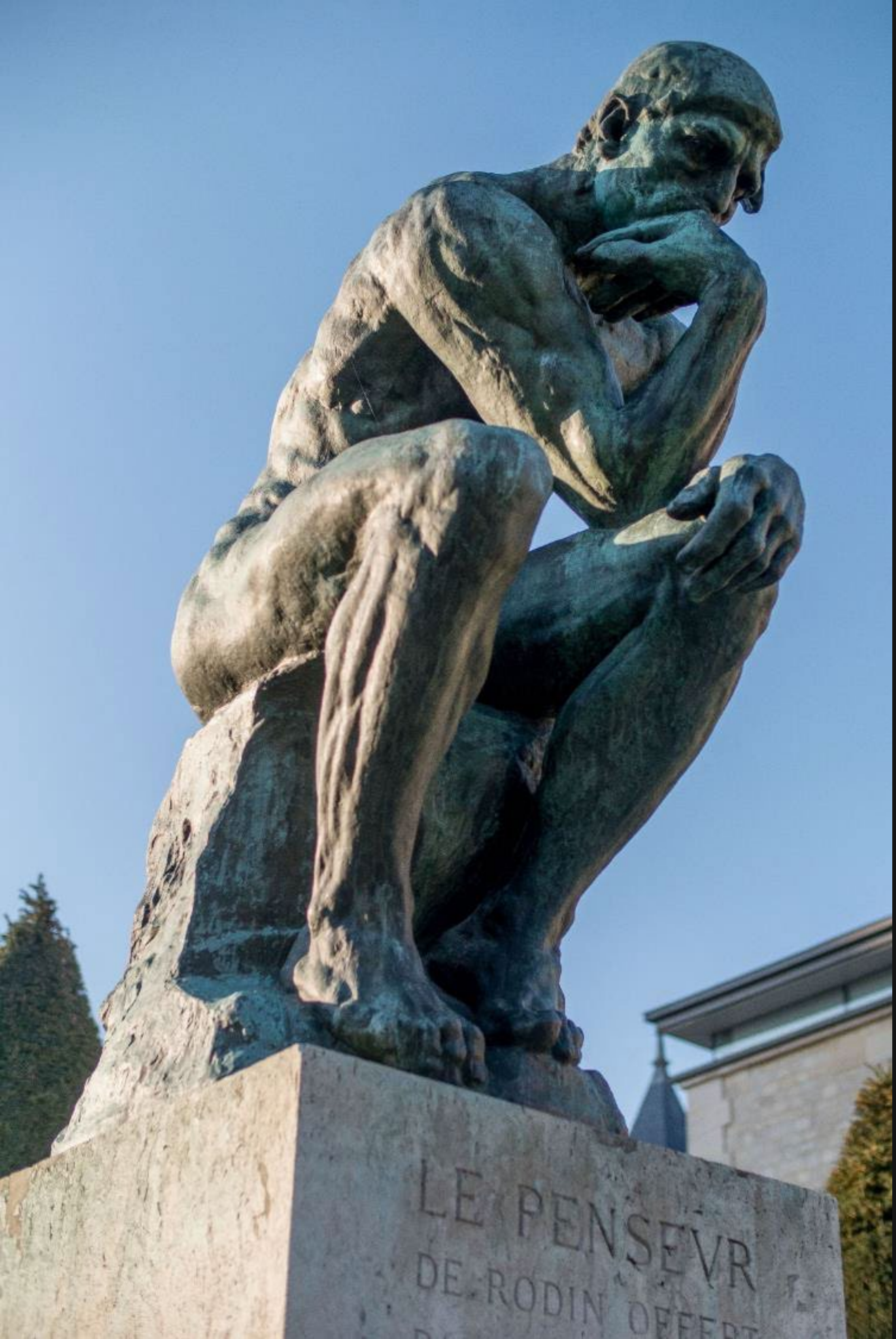
Lightweight-structures: 3D printing offers the solution!

(Source: APWorks)



(Source: 3DS)

Source: Re3DTech



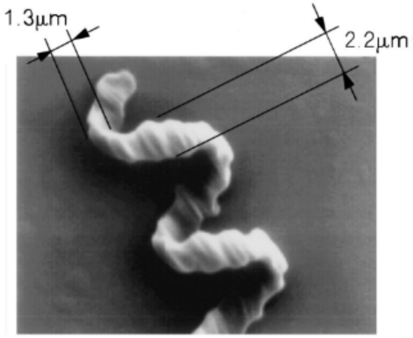
Adding or removing material?

Tuc d'Audoubert
(-14.000 BC)

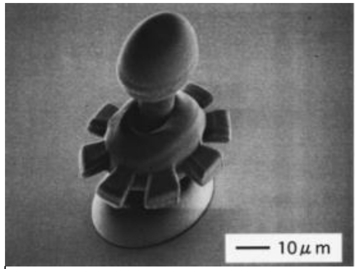
Upper
paleolithic

Angles sur l'Anglin
(-14.000 BC)

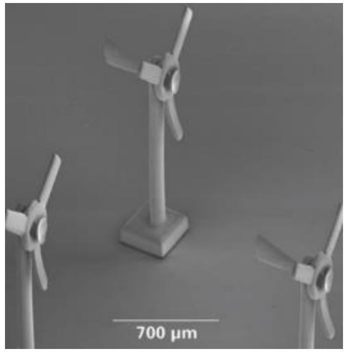
The additive way…



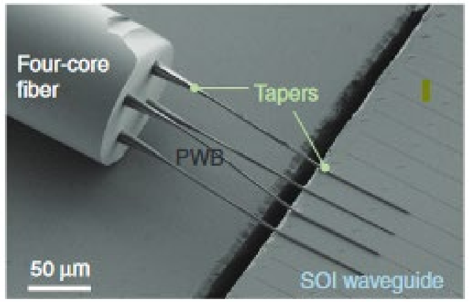
S. Maruo, *et al.* (1997).



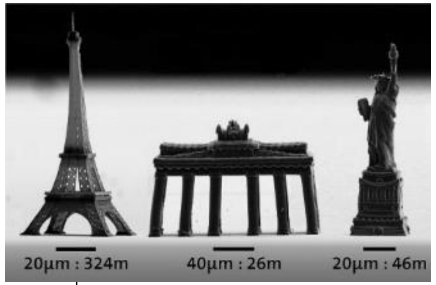
S. Maruo et al. (2000).

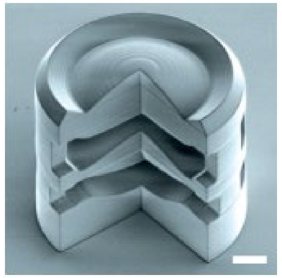


C. Koos et al. (2015)

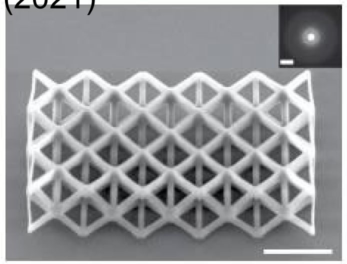


T. Gissibl, *et al.,* Nature Photon (2016)



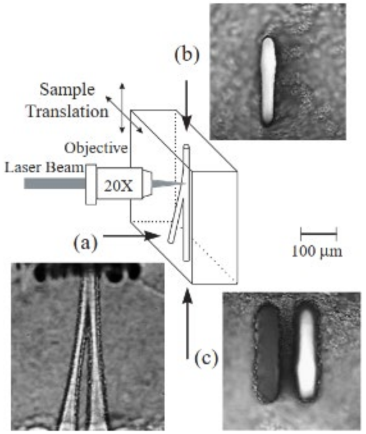


X. Wen, *et al*. Nat. Mater. (2021)

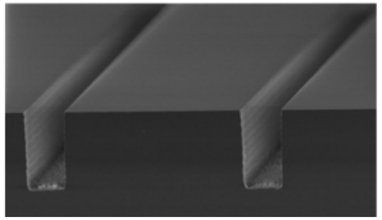


1995 | 2000 | 2005 | 2010 | 2015 | 2020

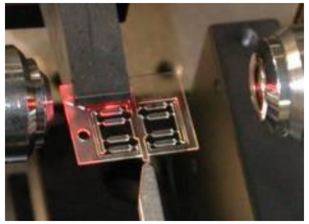
The substrative path…



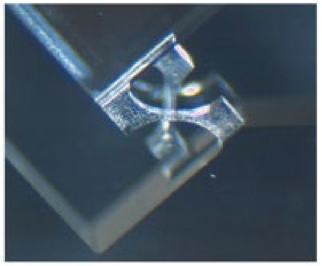
Y. Kondo, et al. (1999).



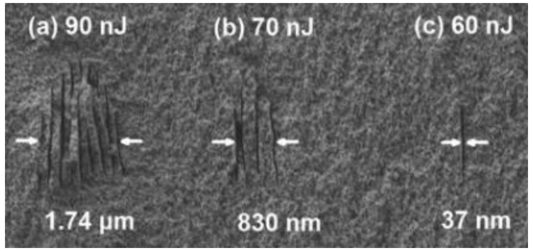
Y. Bellouard *et al.* (2004)

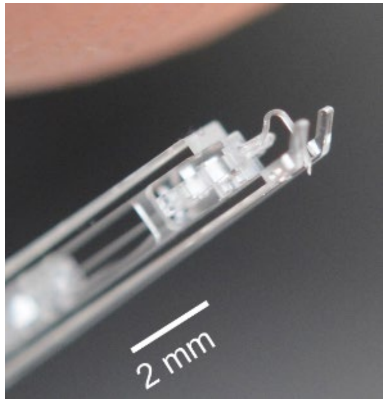


V. Tielen *et al.* (2013)



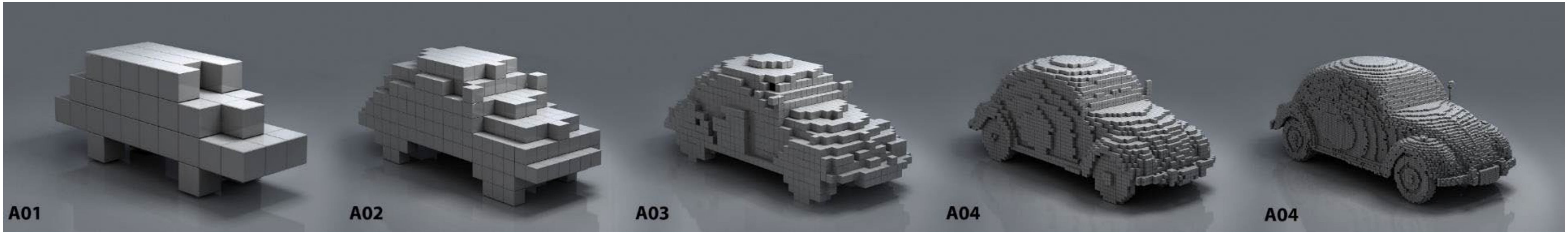
Liao *et al.* (2013)





FEMTOprint
3D printing for glass microdevices

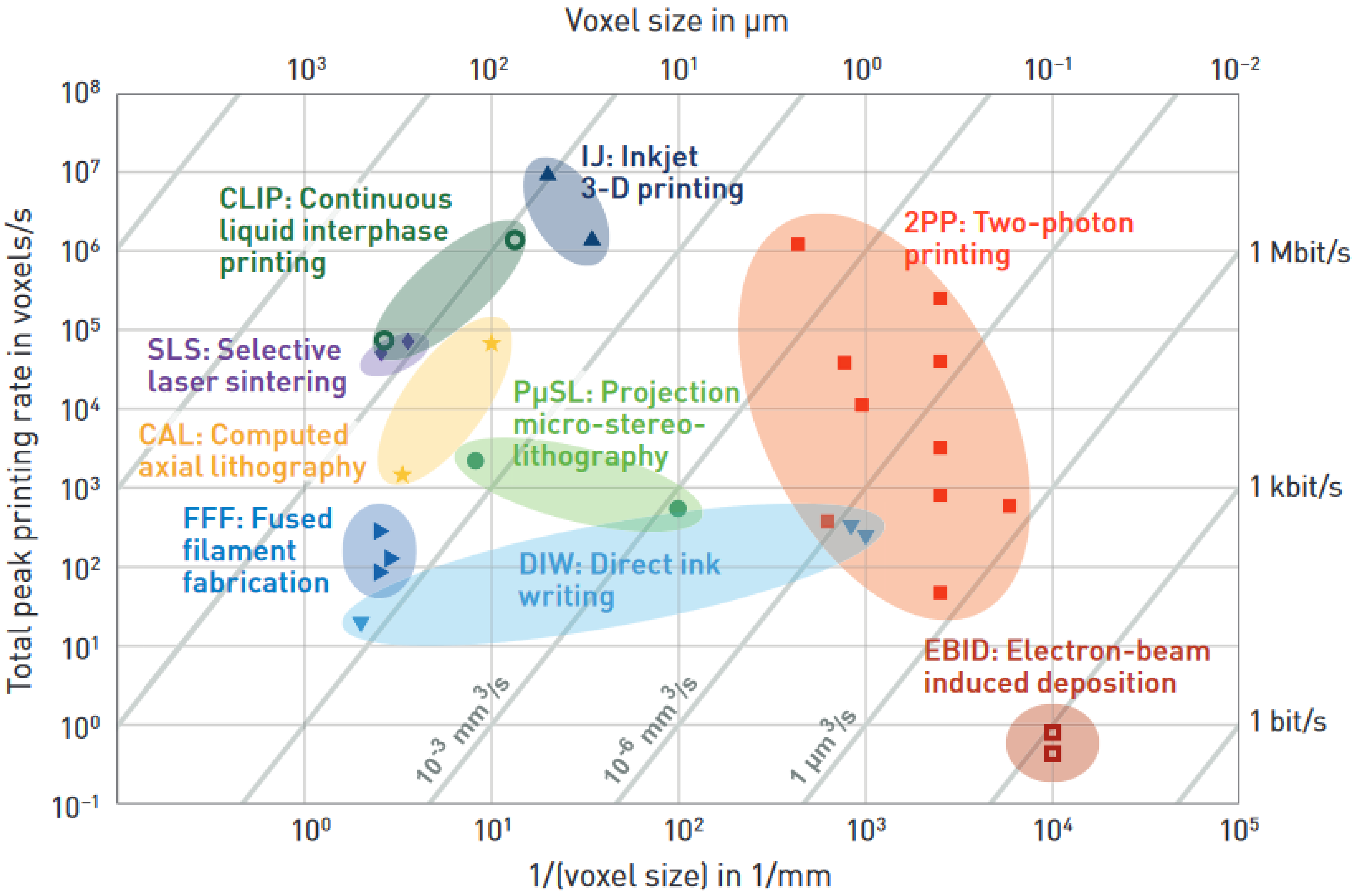
Volume discretization through voxel…



- Consider a 1 cm sample size and 100 nm voxels (2PP lithography)

=> 10^{15} voxels => 1000 TBits of information!

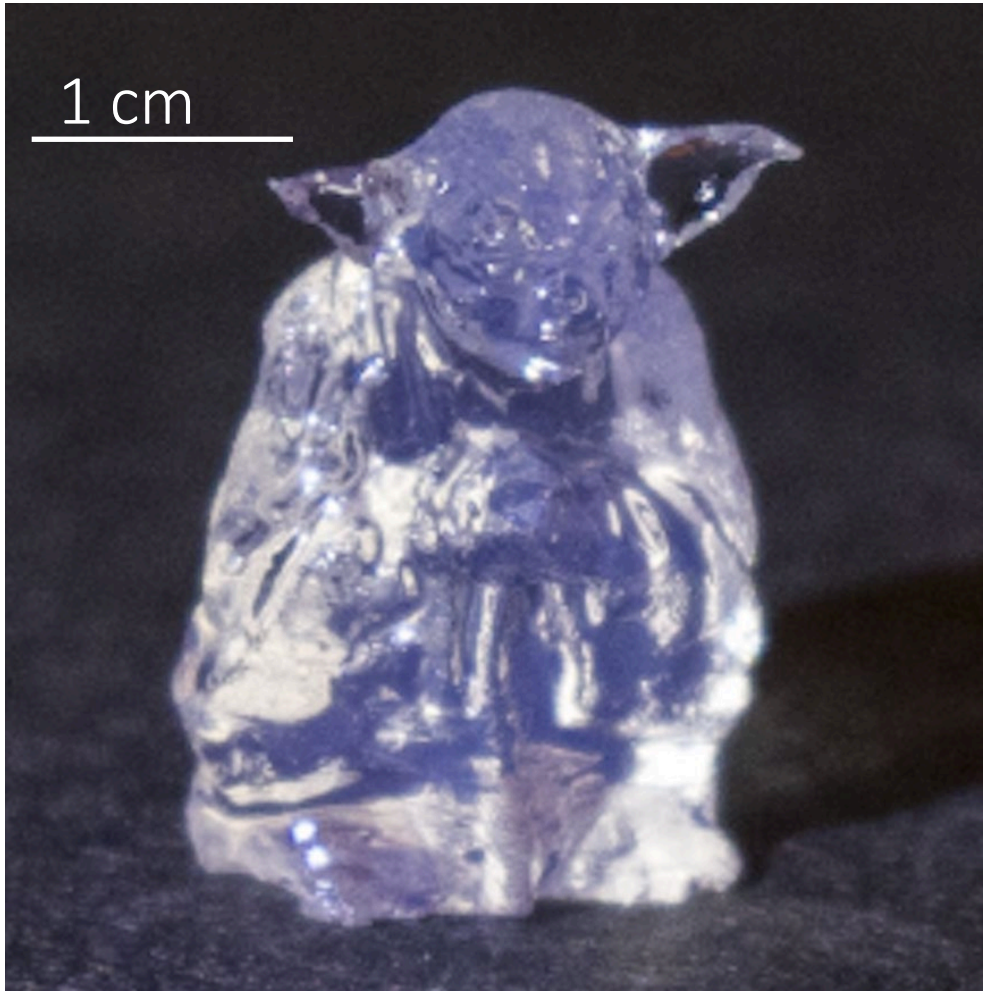
Source: http://www.bilderzucht.de/blog/



Additive manufacturing: Speed versus feature size

Additive-manufacturing technologies compared by inverse voxel size versus printing rate; parallel gray diagonals are lines of constant 3-D-printed volume per second. *Additional details and references are online at www.osa-opn.org/link/3-D-nanoprinting.*

Volumetric printing



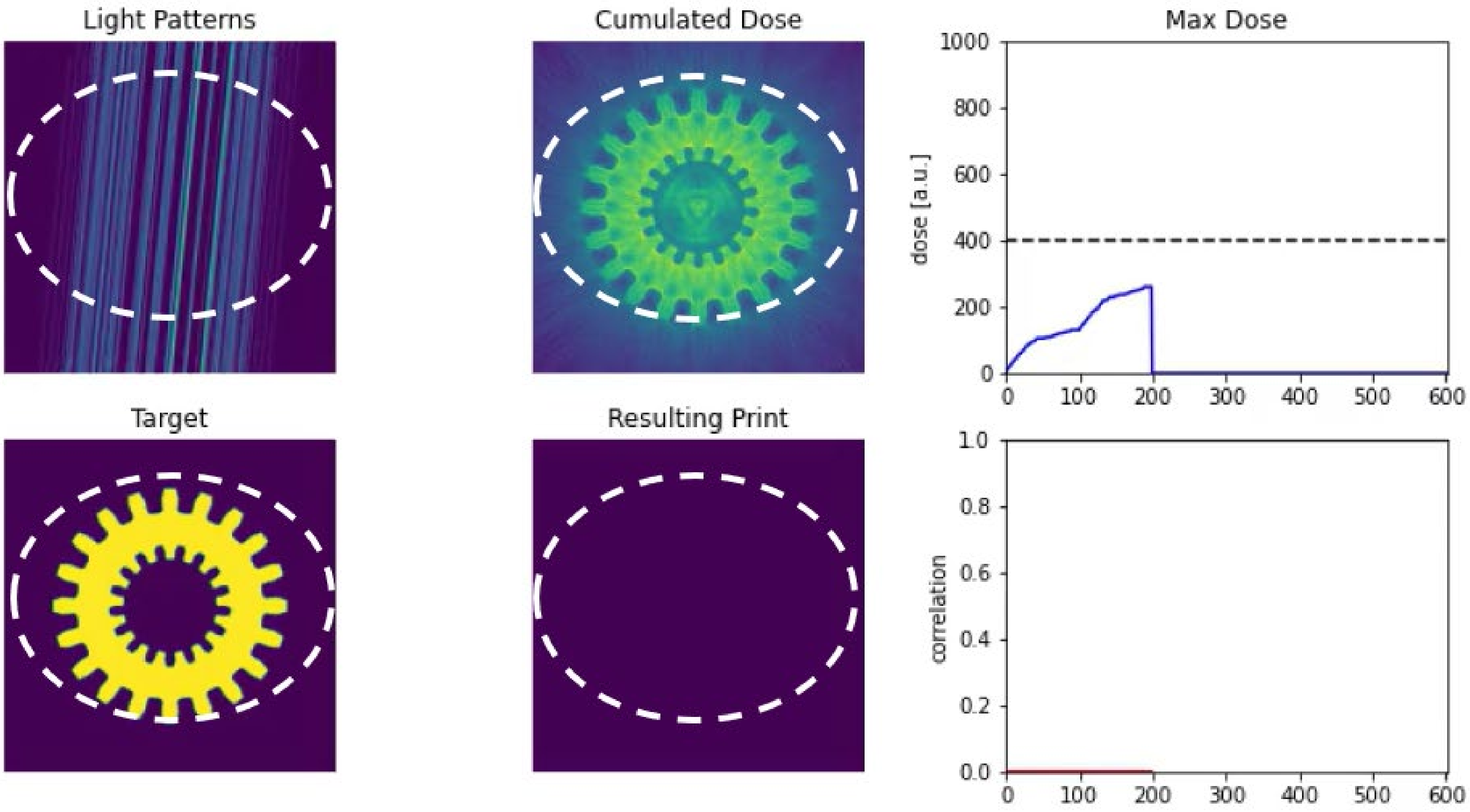
Kelly B.E et al. Volumetric additive manufacturing via tomographic reconstruction, *Science*, 2019

Bernal PN et al. Volumetric BioPrinting of complex living-tissue constructs within seconds, *Adv Mat. 2019*

Delrot P et al. High resolution volumetric additive manufacturing, Nat. Comm.,11,852 , 2020

(Courtesy of Christophe Moser)

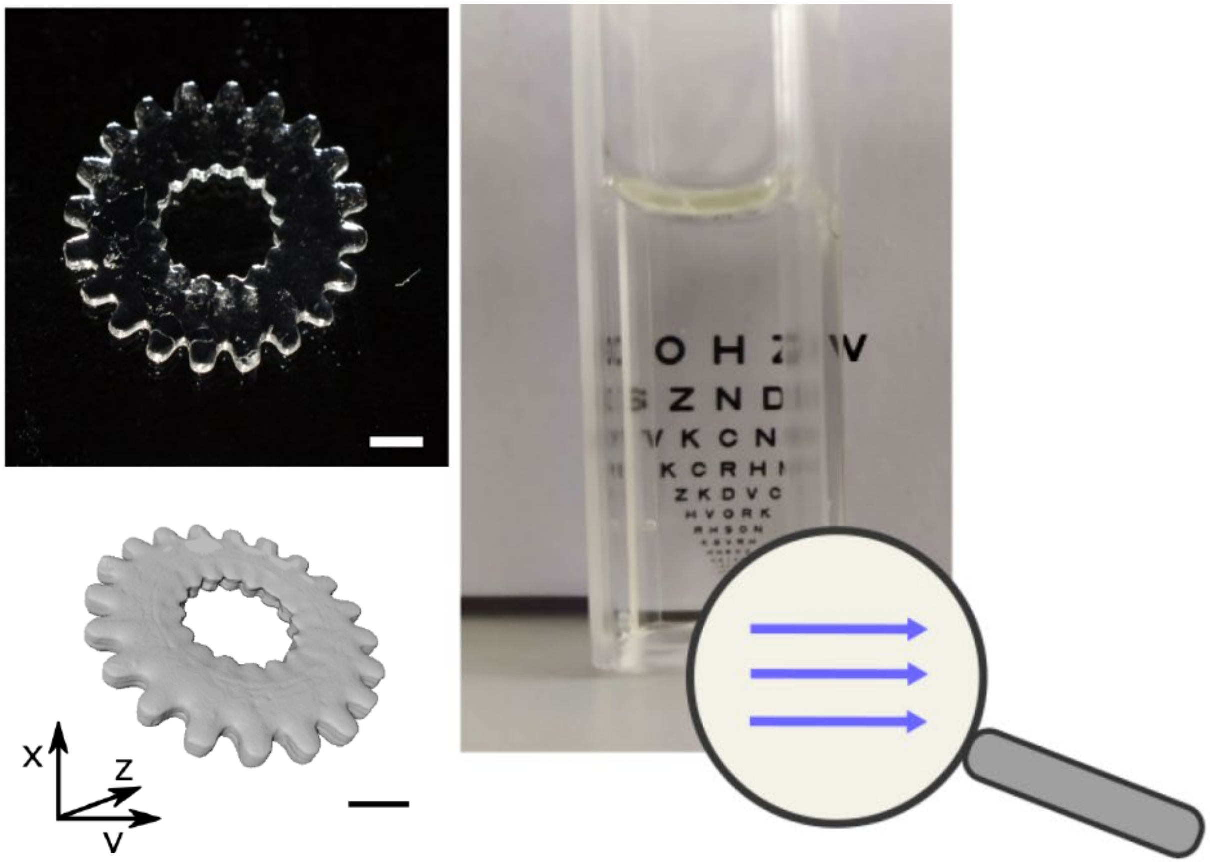
Working principle



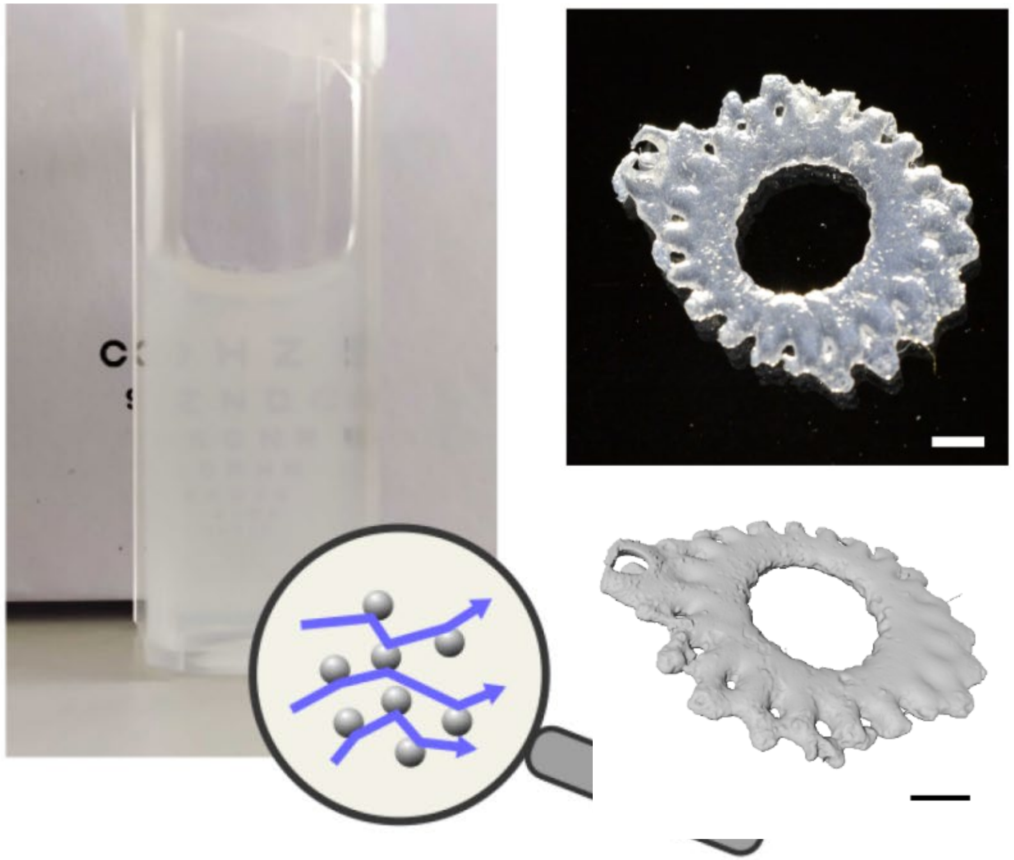
(Courtesy of Prof. Christophe Moser)

Challenges in volumetric printing: scattering

Transparent hydrogel



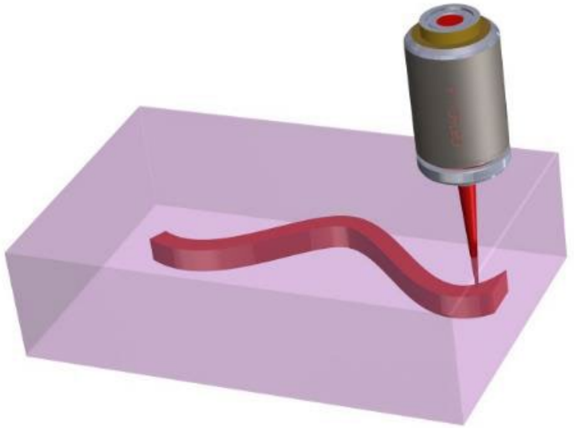
Hydrogel with cells



(Courtesy of Christophe Moser)

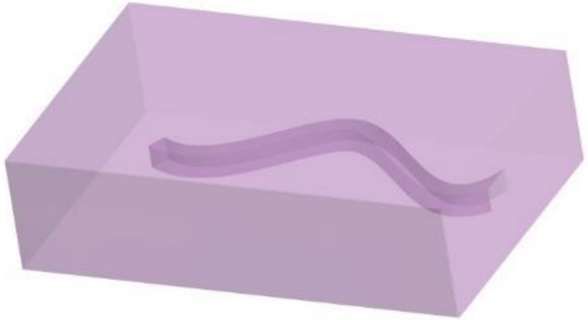
Case study: Non-ablative femtosecond laser processing

1/ Laser exposure **(no ablation)**



- Femtosecond laser exposure (Ti-Sapphire, ~100fs pulses, 250 kHz rep-rate**, low-pulse energy <1 µJ**) – "Exposure" (both fluidic and waveguide) and (Yb) 500fs pulses, 870kHz

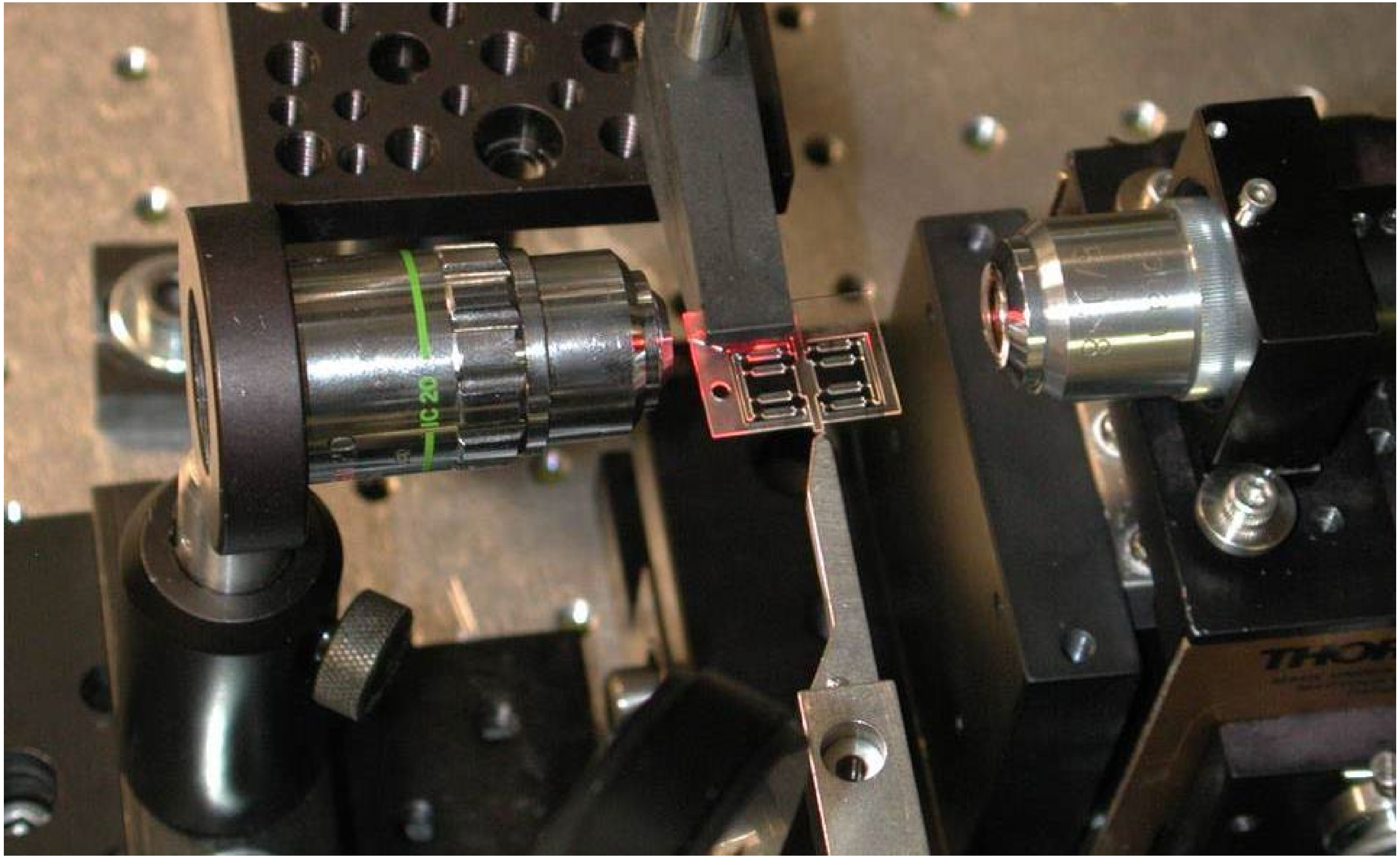
2/ Chemical etching **('development step')**



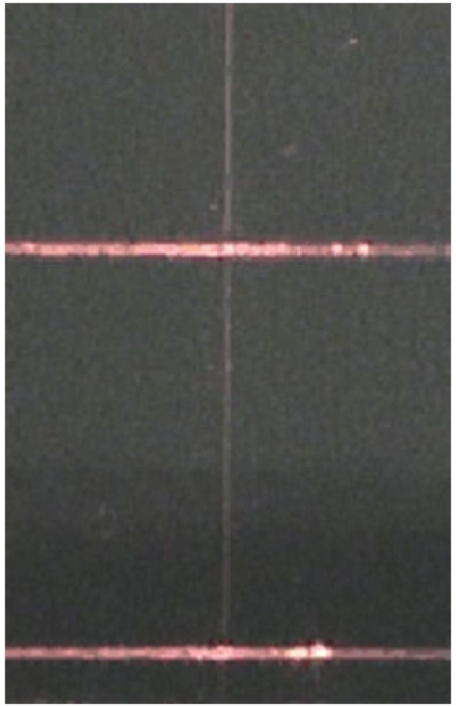
- Etching in a low concentration HF bath (2.5 to 5%) or KOH

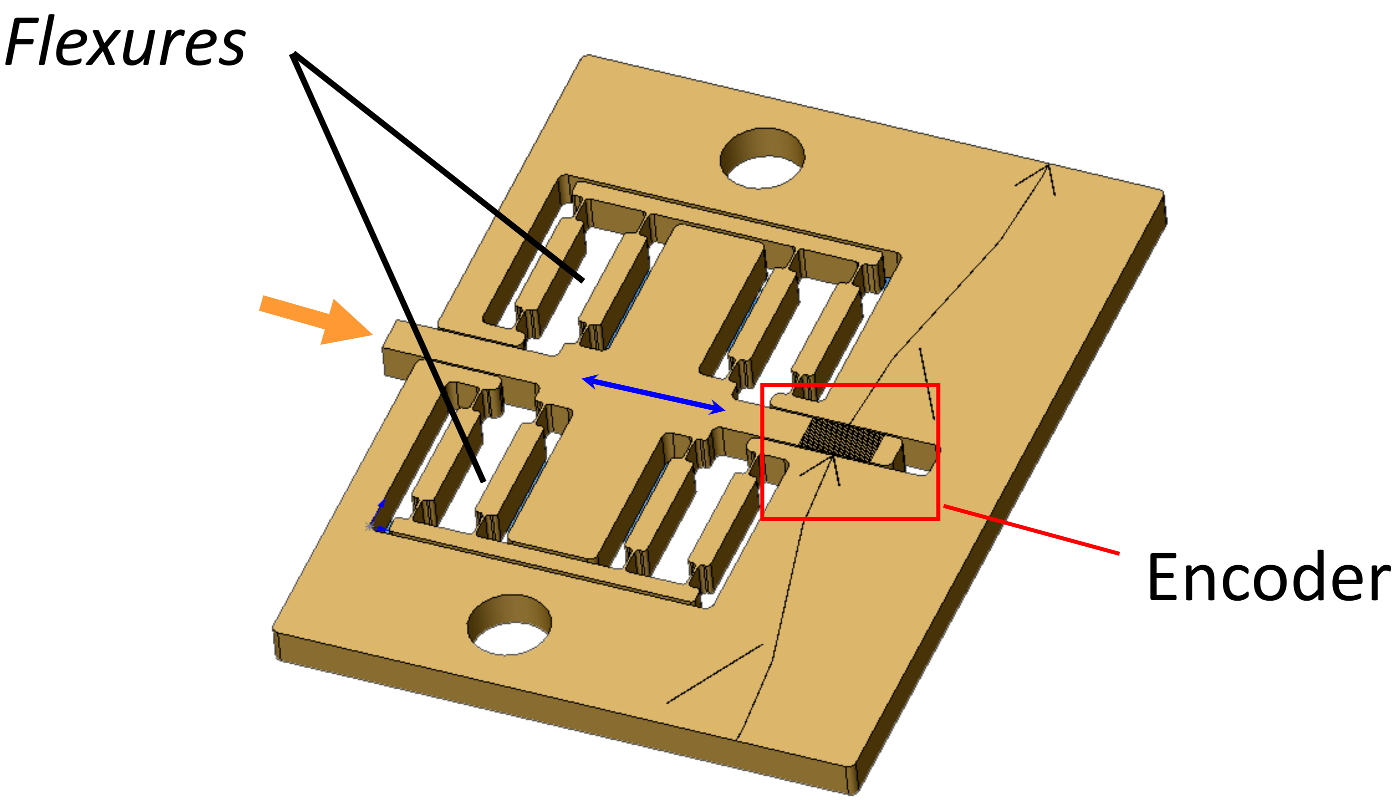
*Y. Bellouard, A. Said, M. Dugan, P. Bado, Optics Express, **12**, 2120-2129 (2004).*

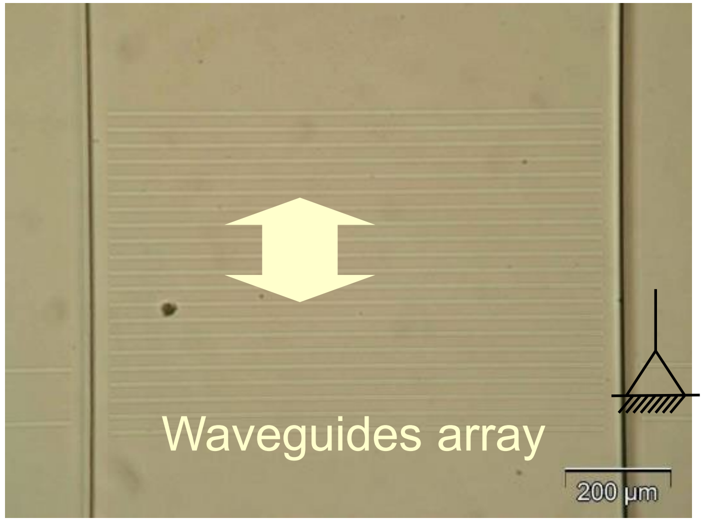
Specificity: ‘multi-modal process’ / Not just structural…

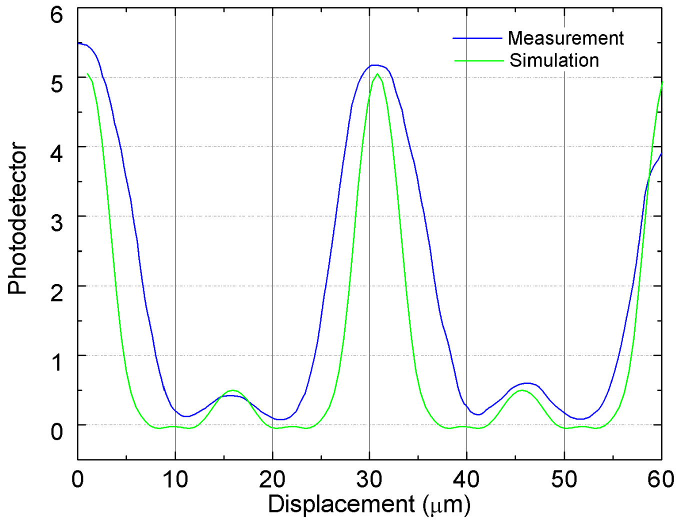


Y. Bellouard, A. Said, P. Bado, Opt. Express **13,** 6635-6644 (2005).

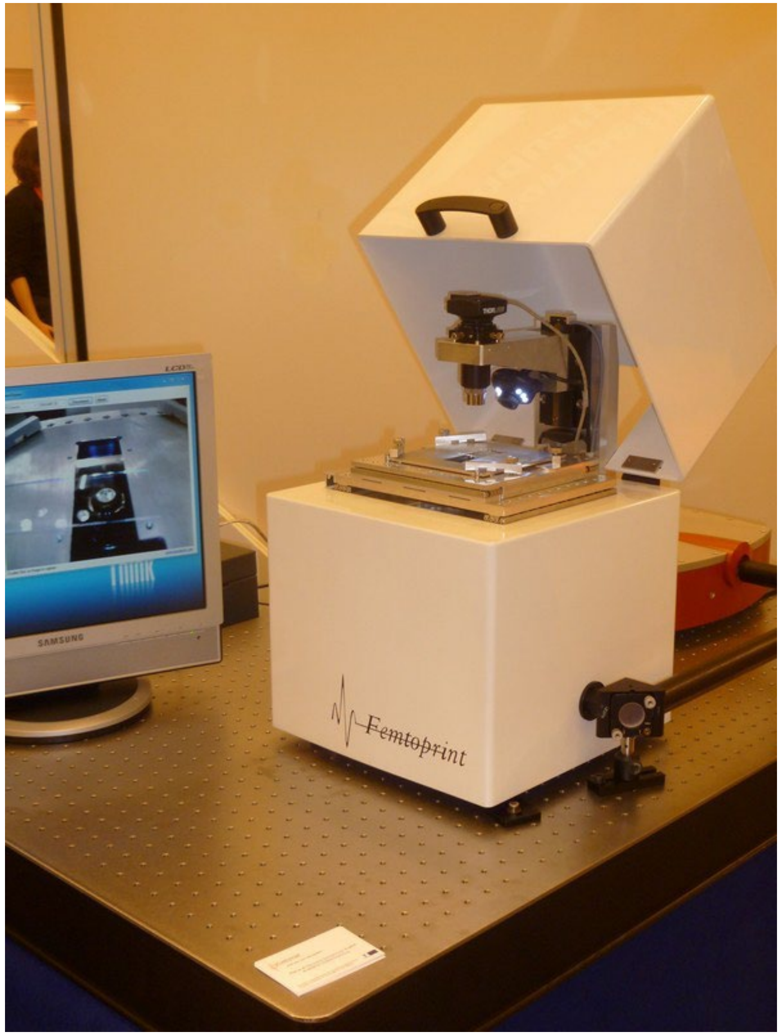



Flexures
Encoder


Waveguides array
200 µm


Measurement
Simulation
Photodetector
Displacement (µm)
0
1
2
3
4
5
6
0
10
20
30
40
50
60

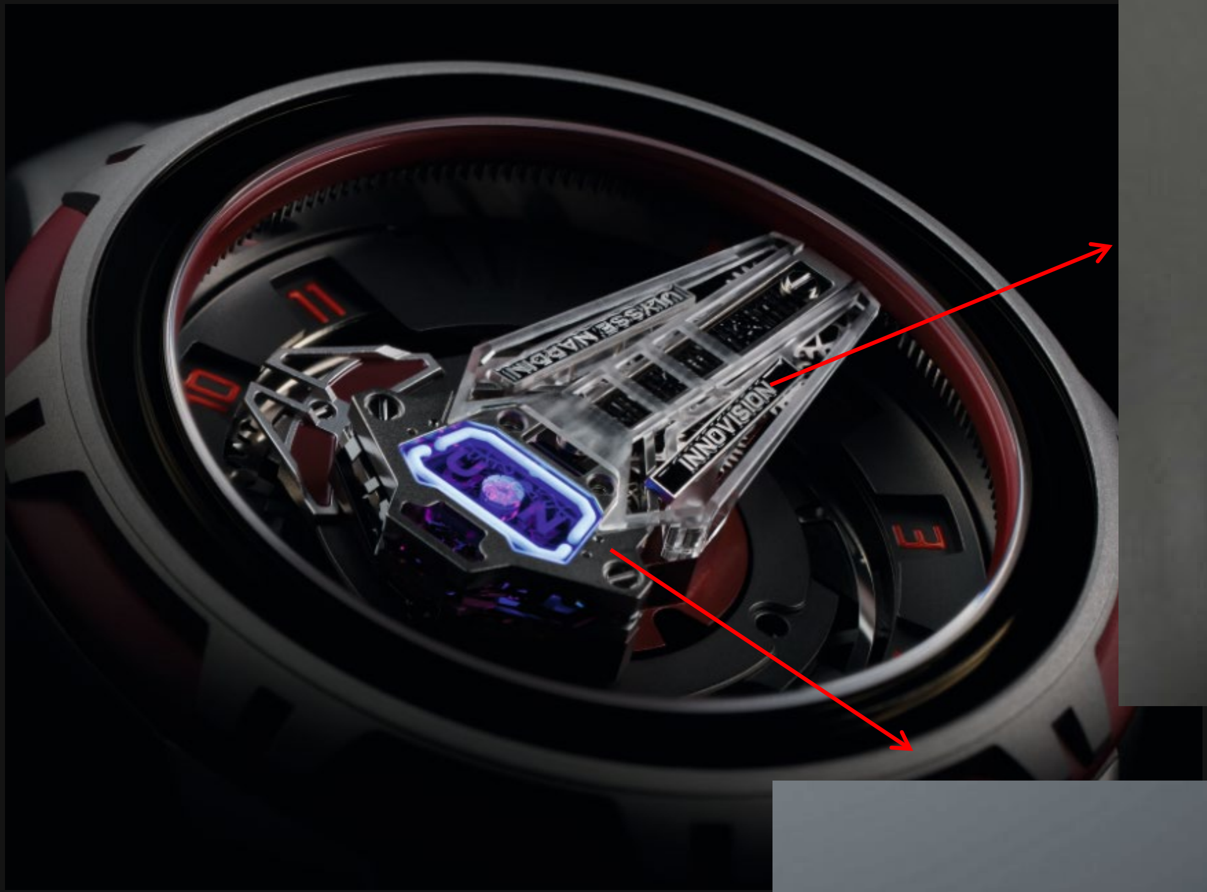
From the lab to industry...

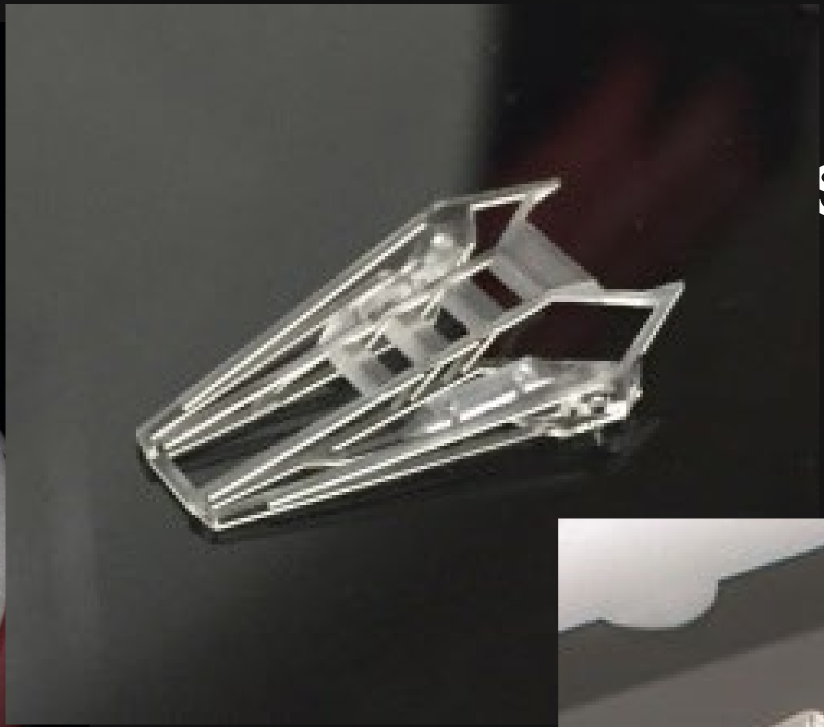


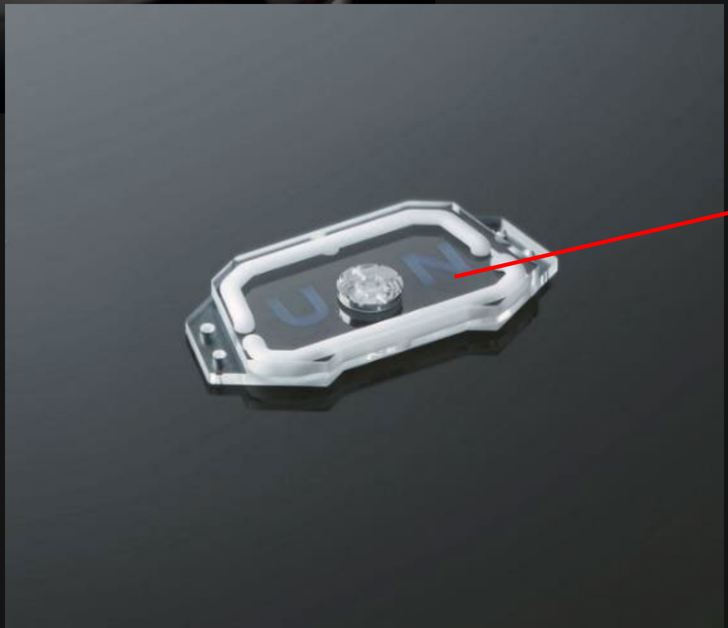
(2013)

(2015)

stration







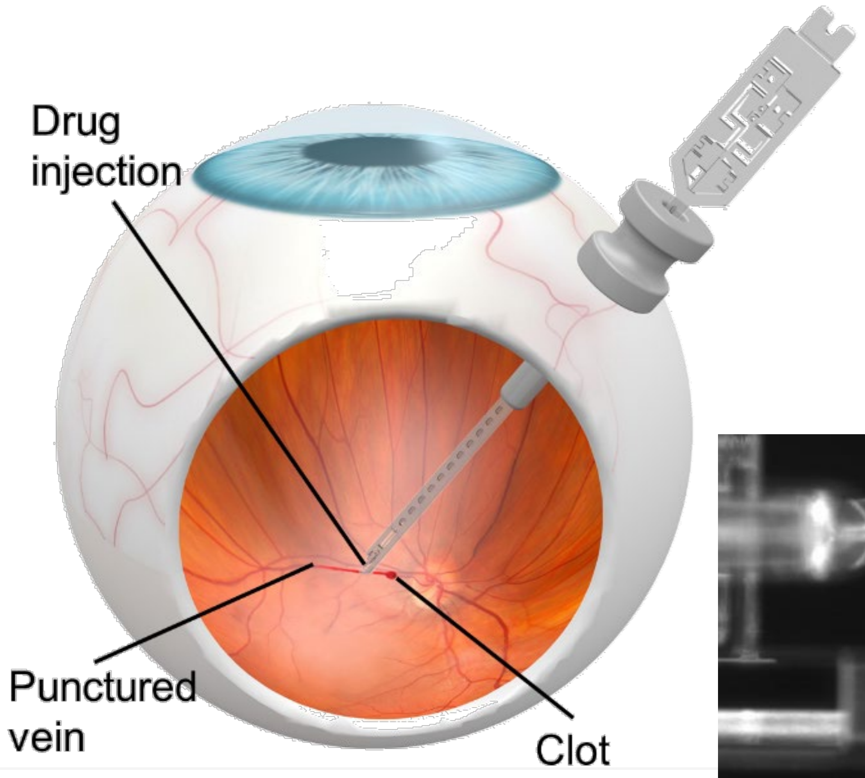
Courtesy of

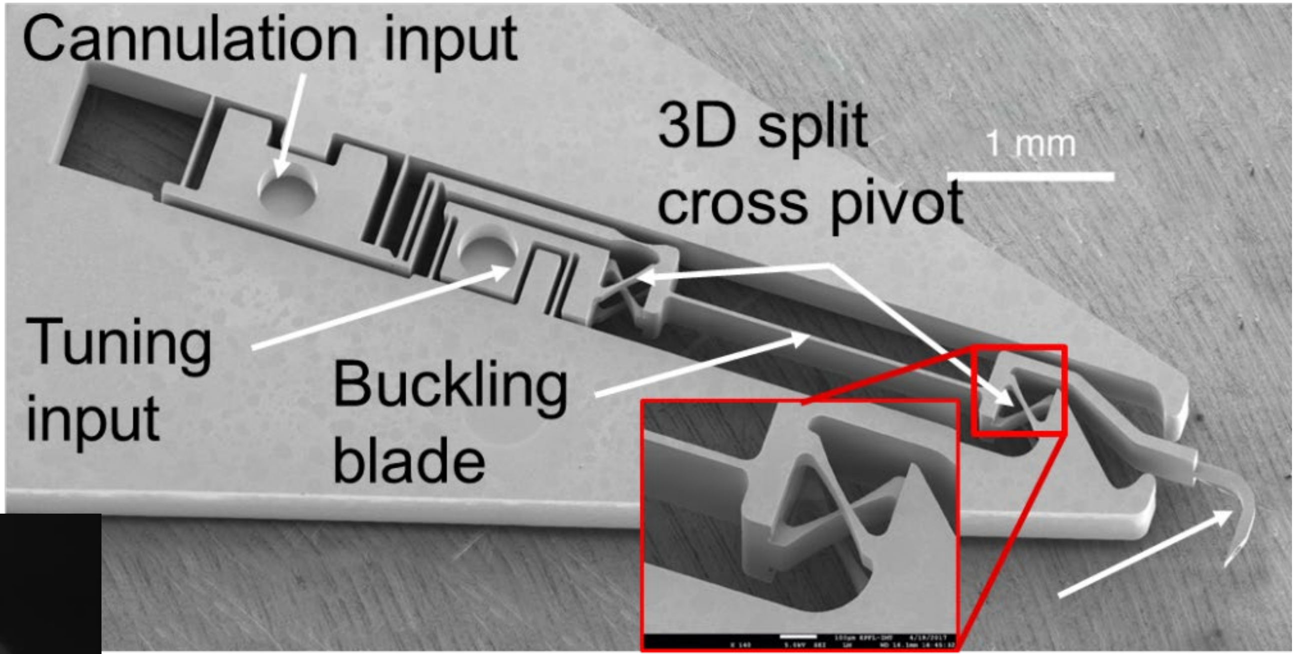
ULYSSE NARDIN

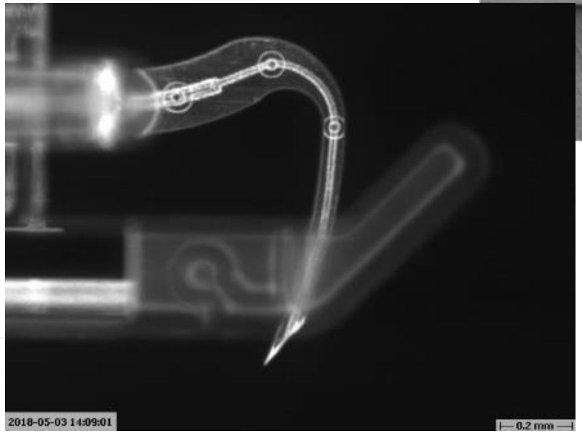
FEMTOprint

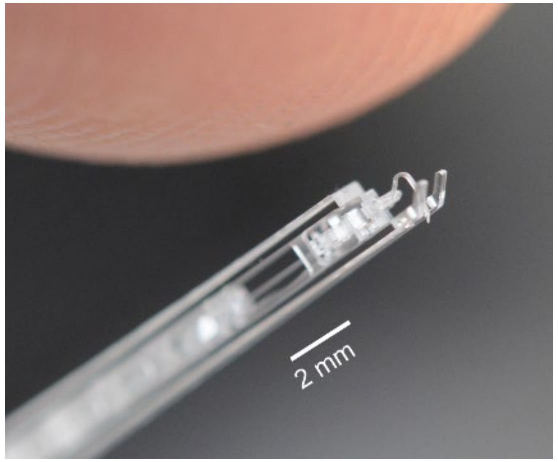
3D printing for glass microdevices

Buckling mechanical device: pushing the frontiers of micro-mechanics...









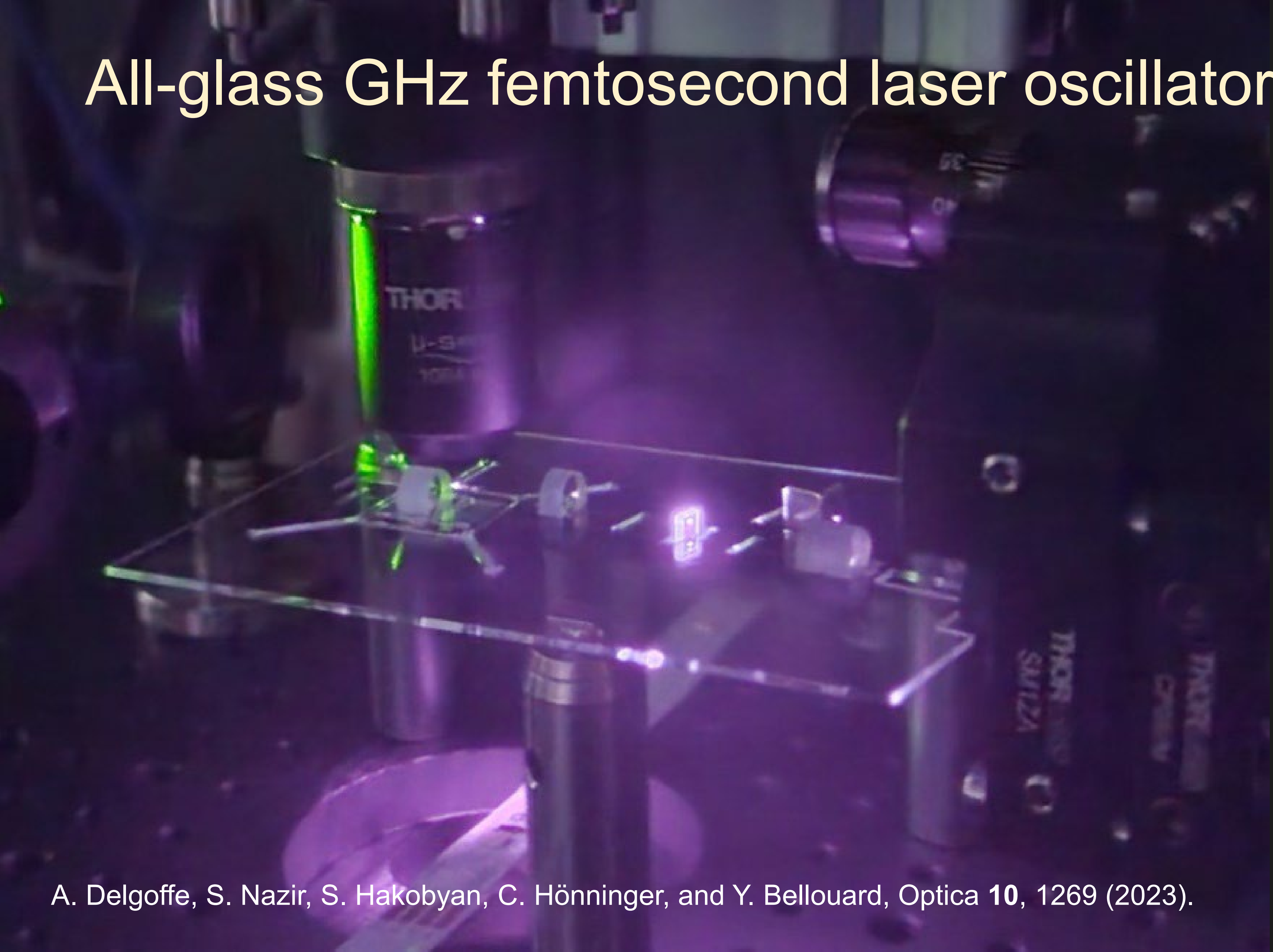
(Collaboration with Instant Lab)

FEMTOprint

EPFL

Hôpital ophtalmique Jules-Gonin
Service universitaire d'ophtalmologie
Fondation Asile des aveugles

All-glass GHz femtosecond laser oscillator



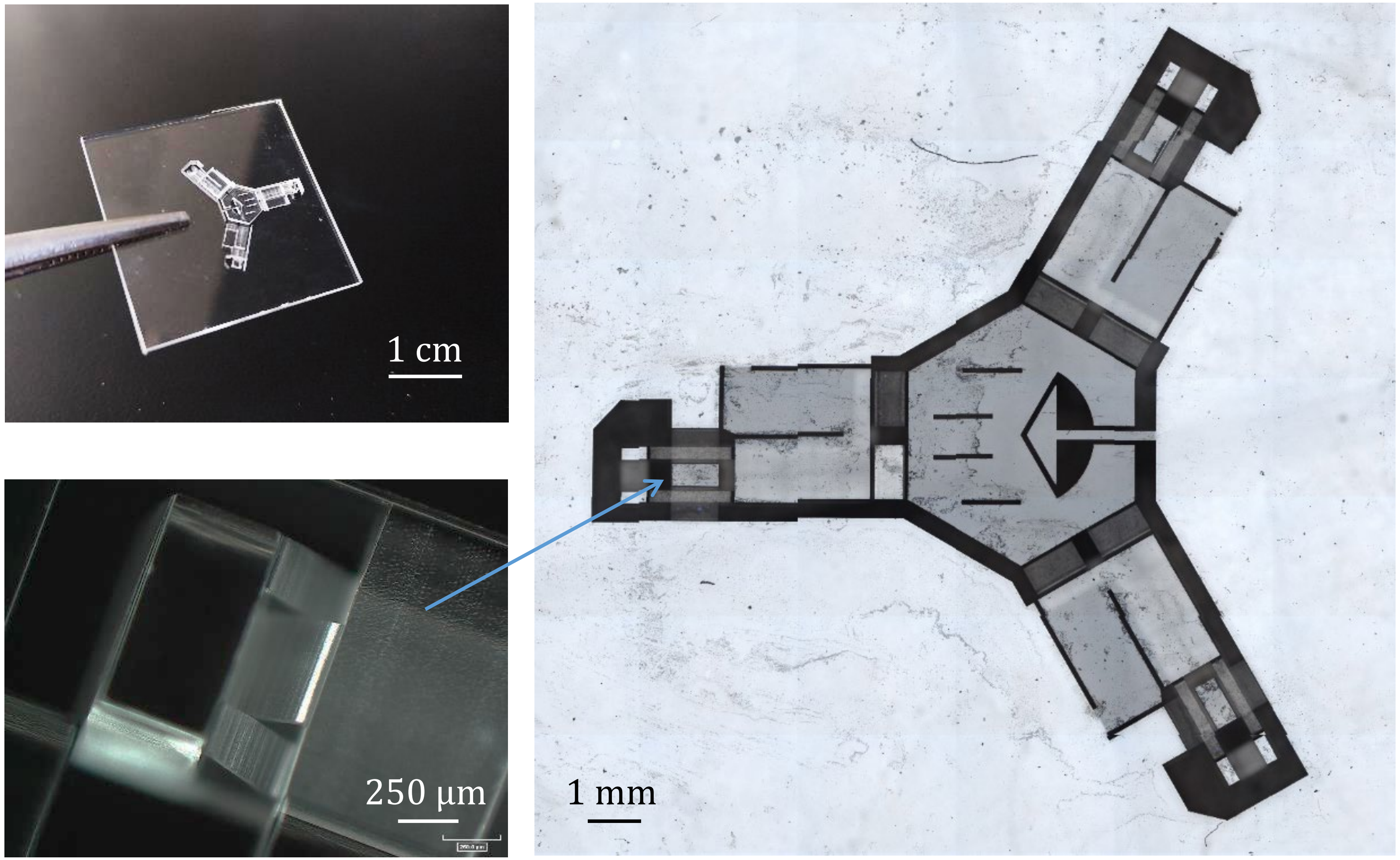
A femtosecond laser making a femtosecond laser!

CASSIO-P
All-Glass Optical Systems

A. Delgoffe, S. Nazir, S. Hakobyan, C. Hönninger, and Y. Bellouard, Optica **10**, 1269 (2023).

Secret ‘Microengineering’ guest 1

An All-Glass 3D-Printed Parallel Micro-robot

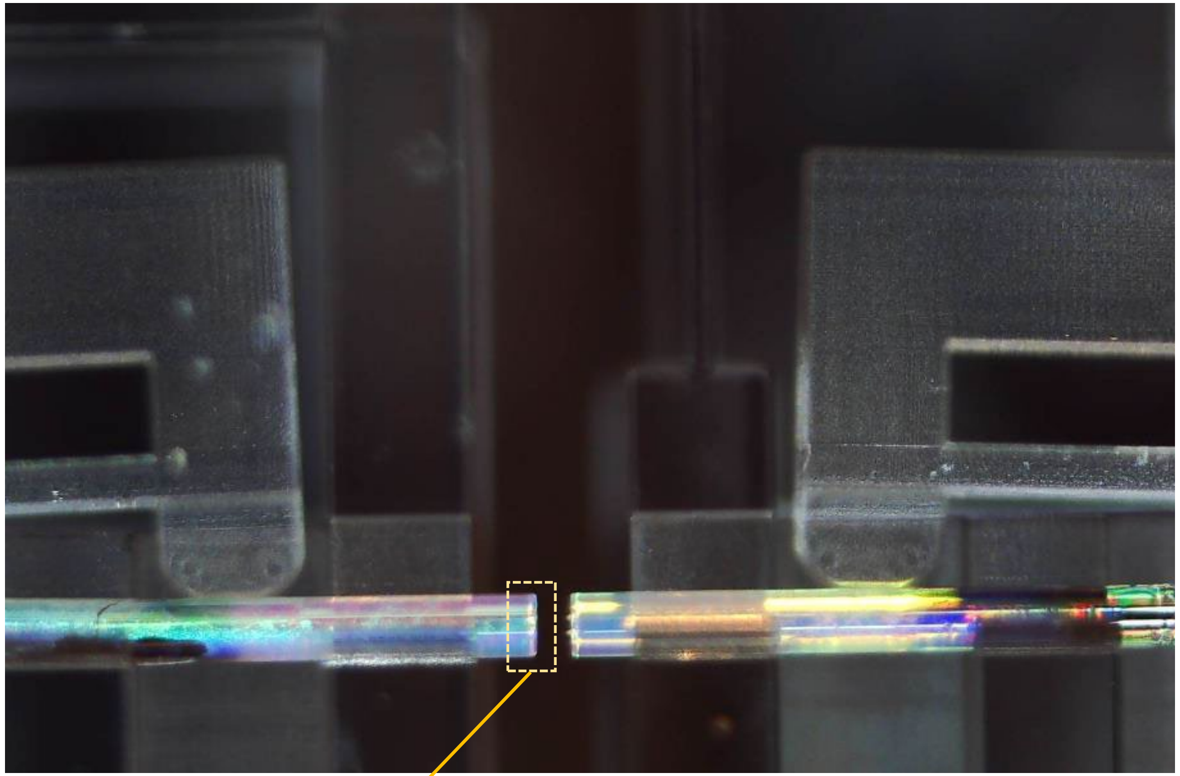


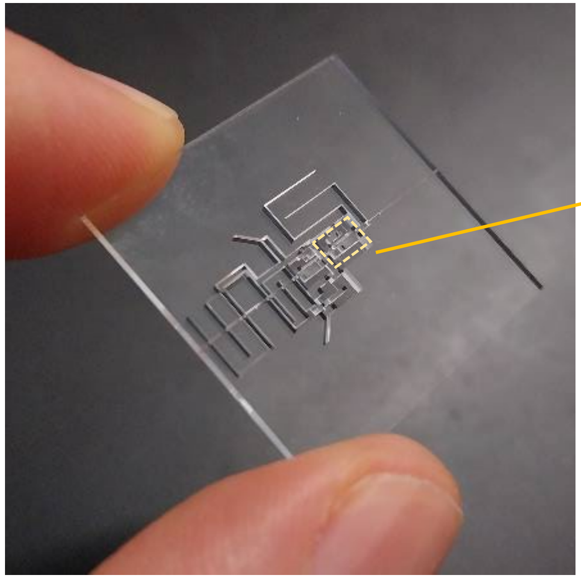
- *Process:* femtosecond laser 3D-printing
- *Writing time:* 32h
- *Chemical etching:* 32h
- *Material:* fused silica

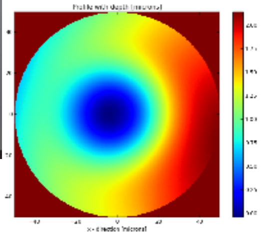
Stitched confocal microscope pictures of the parallel stage

Contact-less **optical integration for quantum system**

- Fiber Fabry-Perot cavity in all-glass chips
- Fine-tuned and aligned using femtosecond laser exposure
- Finesse > 100’000
- Applications: quantum trap, sensors







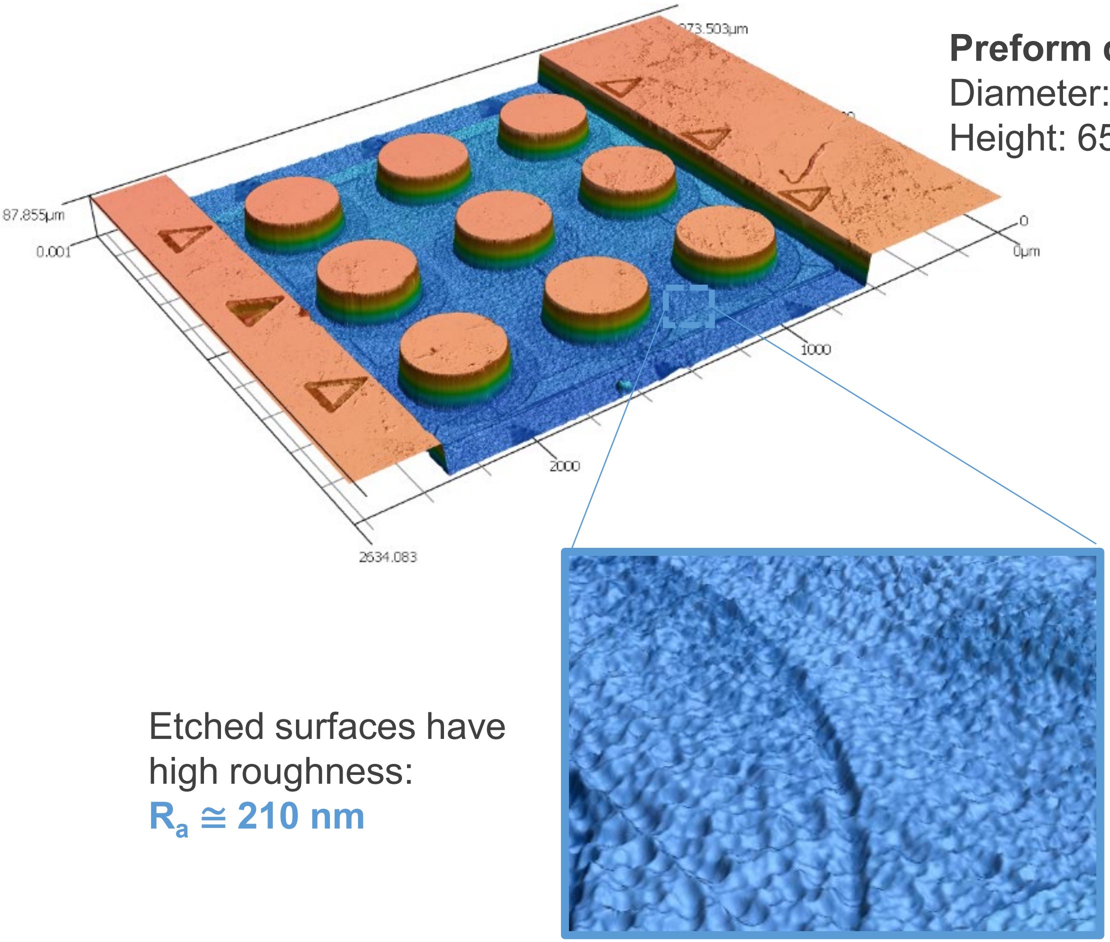
Collaboration with LKB (Paris):

Laboratoire Kastler Brossel
Physique quantique et applications

Secret ‘Microengineering’ guest 2

Manufacturing process: femtosecond laser processing

- Fabrication of preforms using femtosecond laser exposure followed by wet etching



Preform dimensions (all identical):
Diameter: 360 µm
Height: 65 µm

Requirement for surface roughness of optical elements: max. λ/20, preferably λ/100.

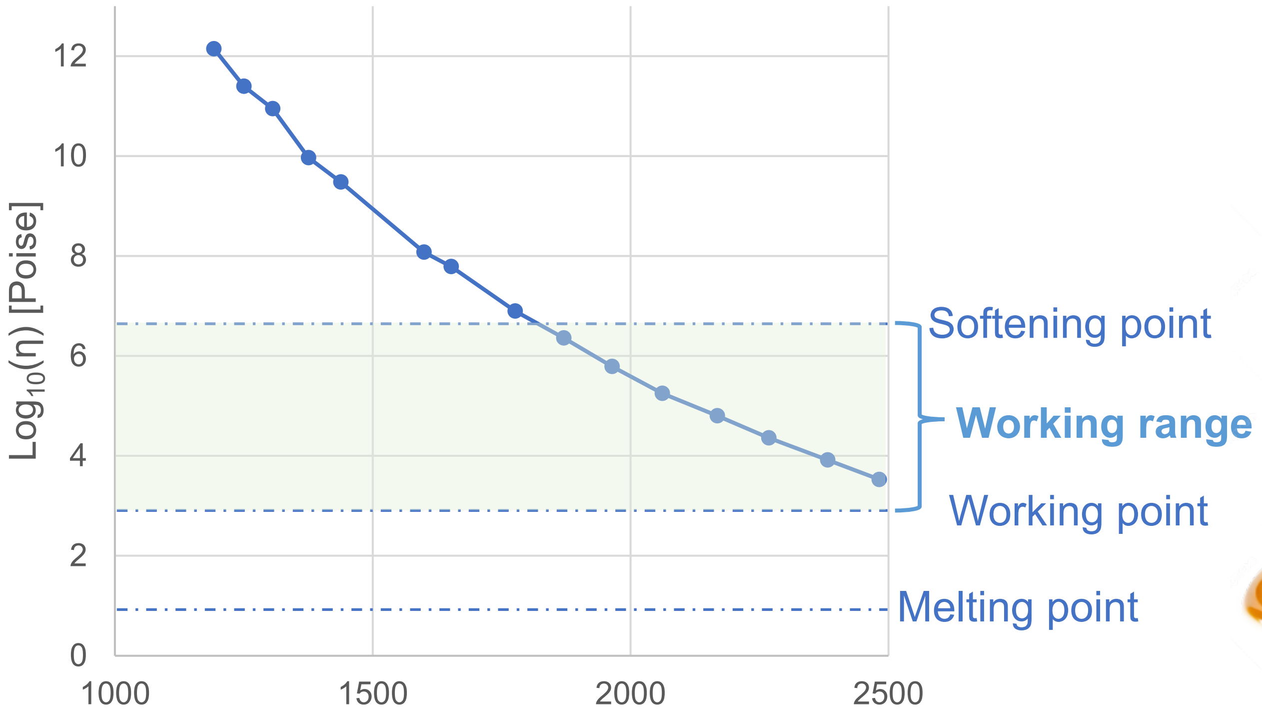
Etched surfaces have high roughness:
$R_a \cong 210$ nm

How to achieve optical quality with large voxels (larger than targeted resolution) ?

Thermal reflow

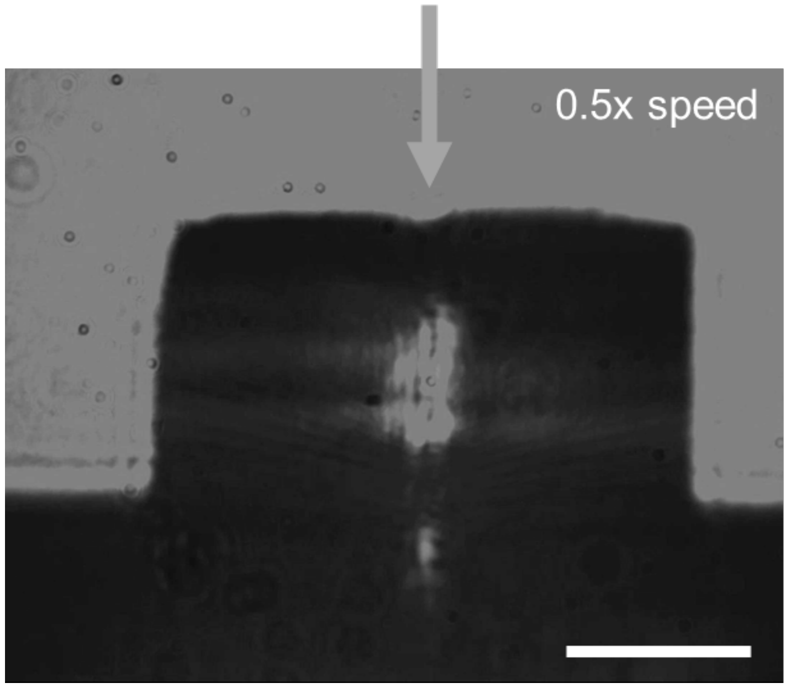
- Fabricated preforms: high roughness and poor surface quality, unusable for optical elements
  - Laser thermal reflow allows for surface tension driven shapes, and improved surface quality

Log viscosity of silica (SiO_2) as a function of temperature

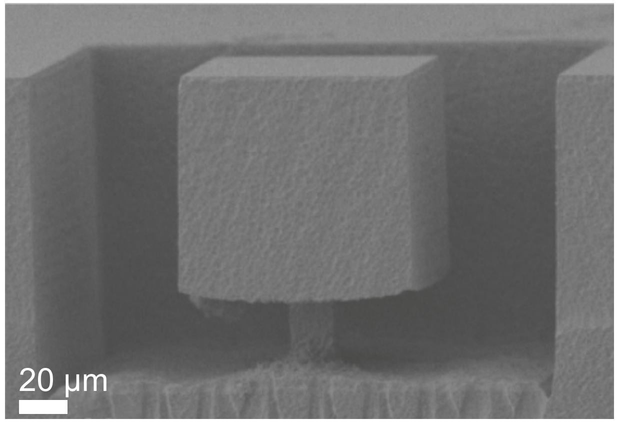


Urbain et al., Geochimica et Cosmochimica Acta – 1982

Heat source:
gaussian IR continuous laser

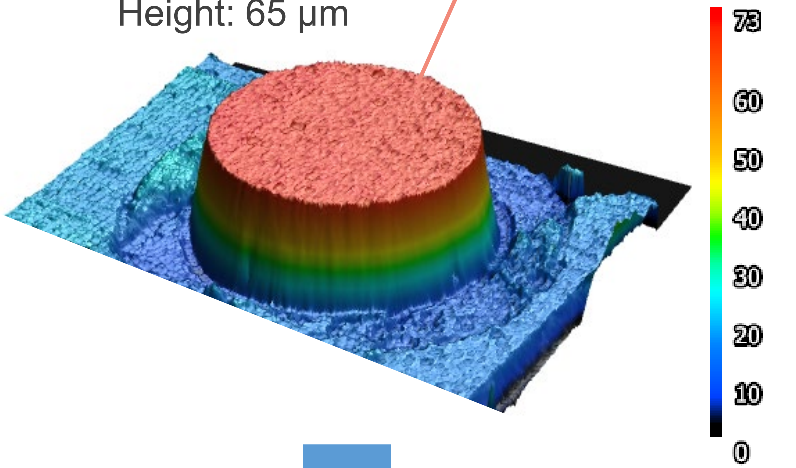


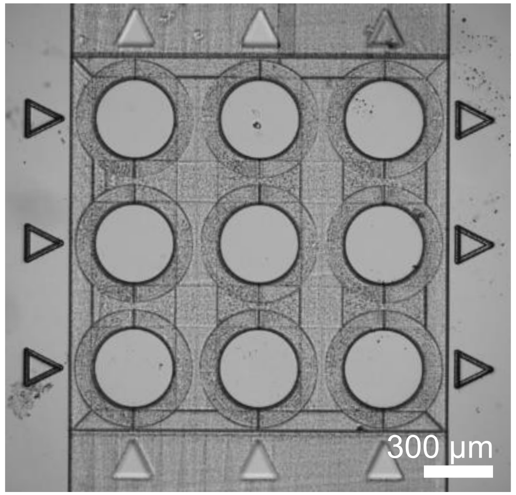
Thermal reflow

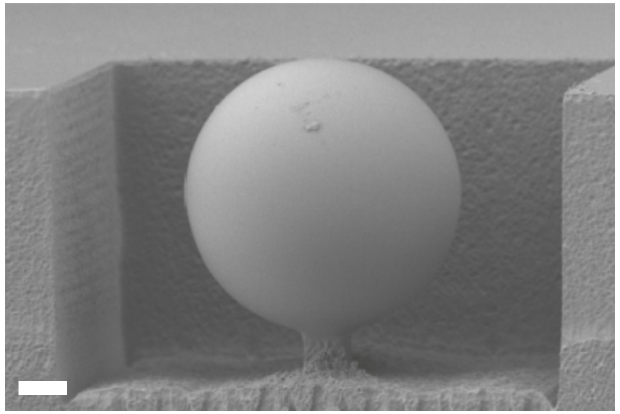


Diameter: 360 µm
Height: 65 µm

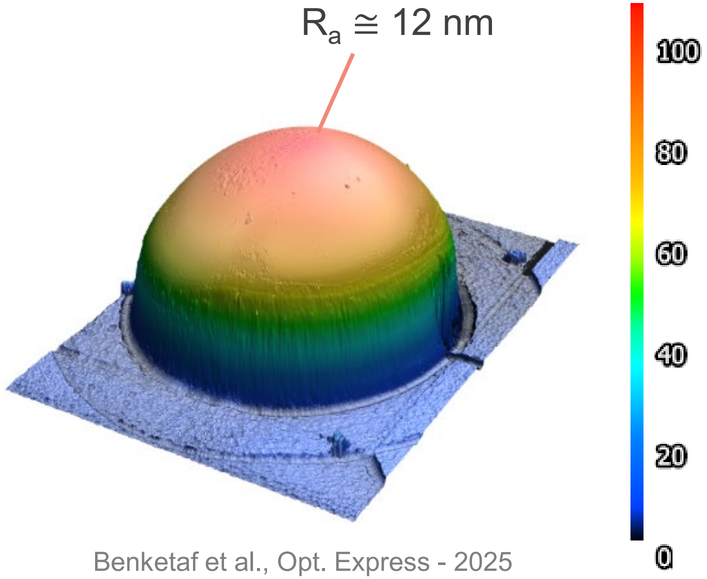
$R_a \cong 210$ nm

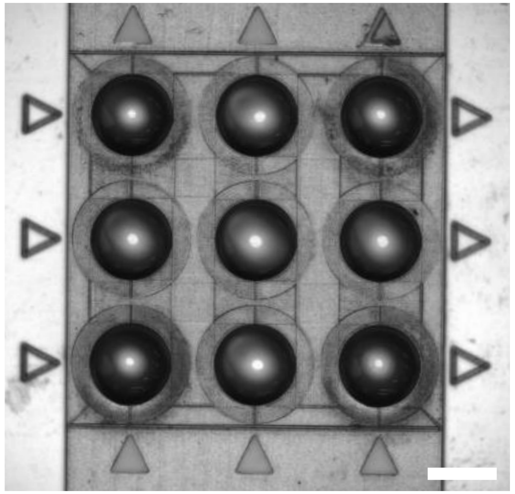






$R_a \cong 12$ nm



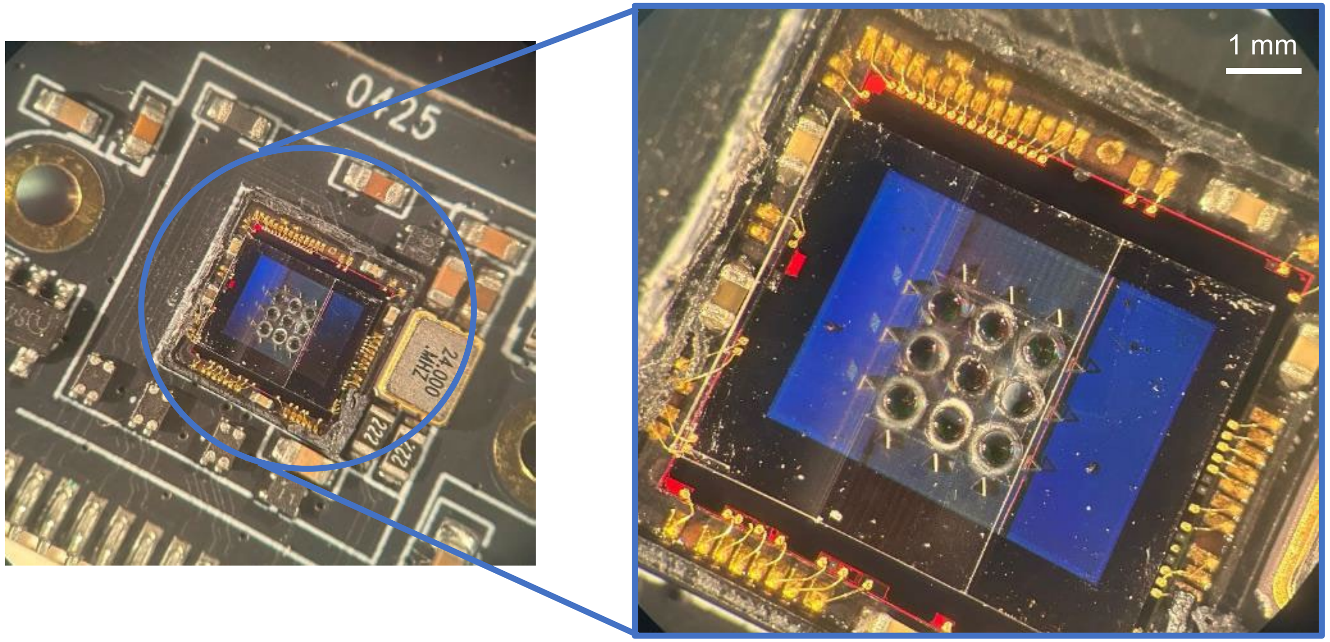


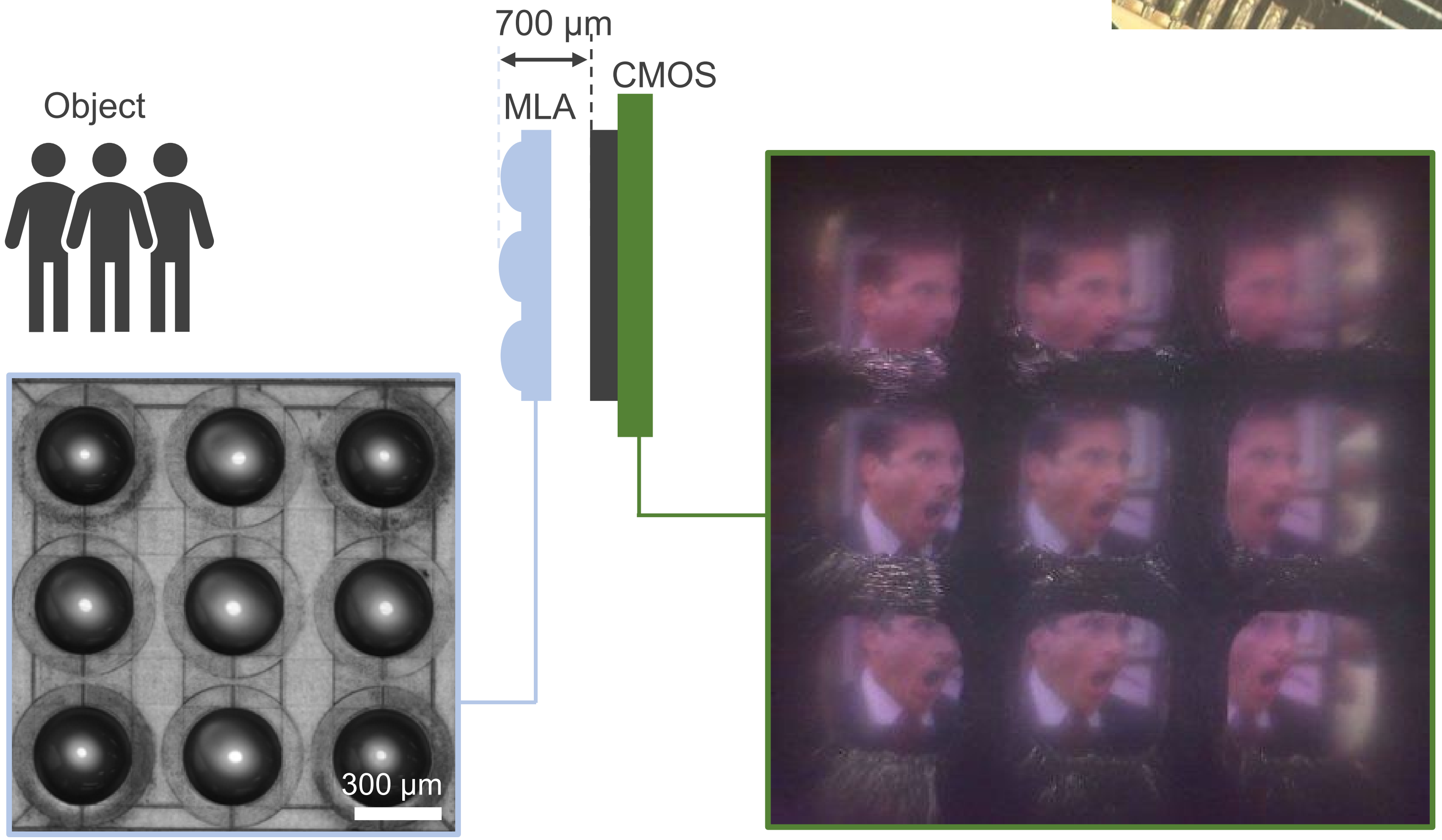
Drs et al., Opt. Express - 2015

Benketaf et al., Opt. Express - 2025

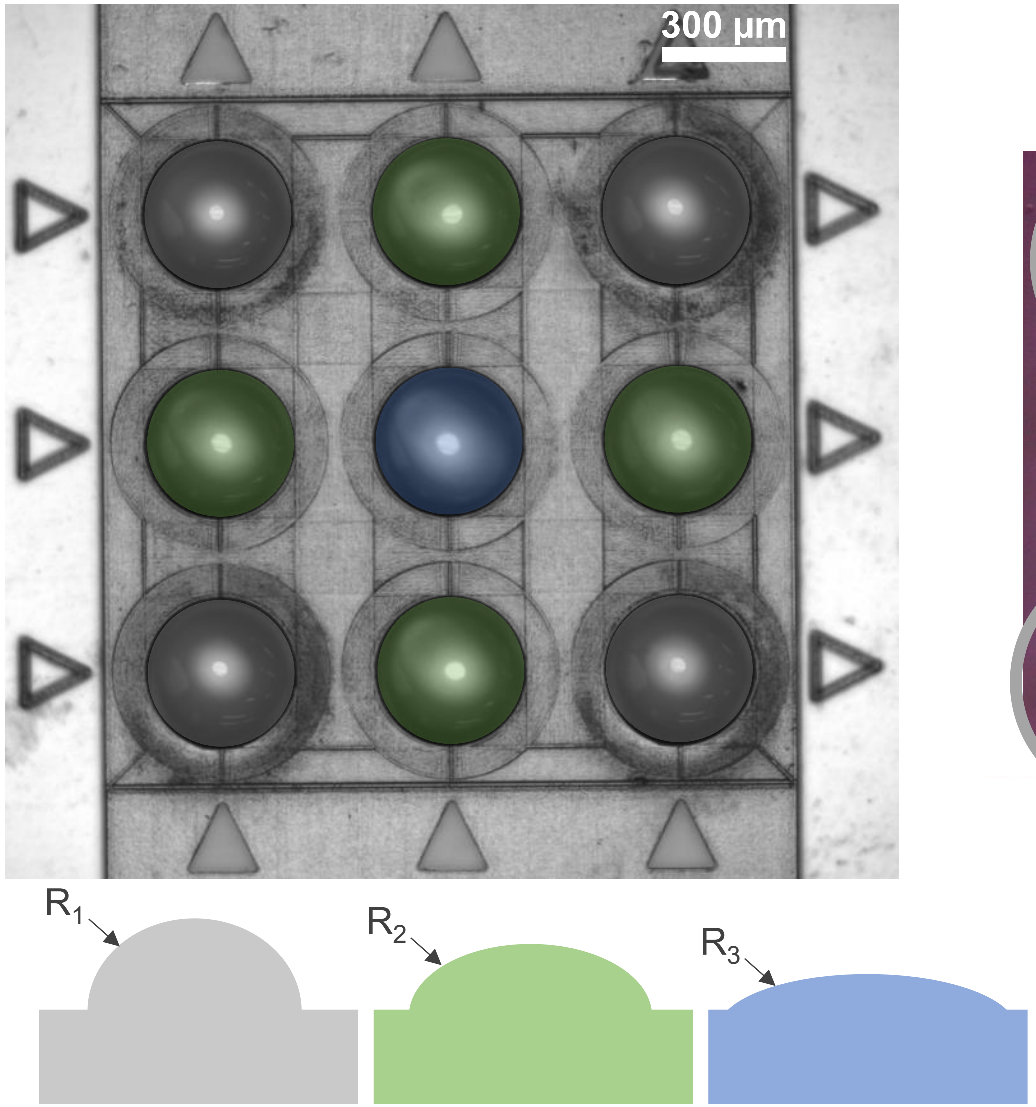
Application

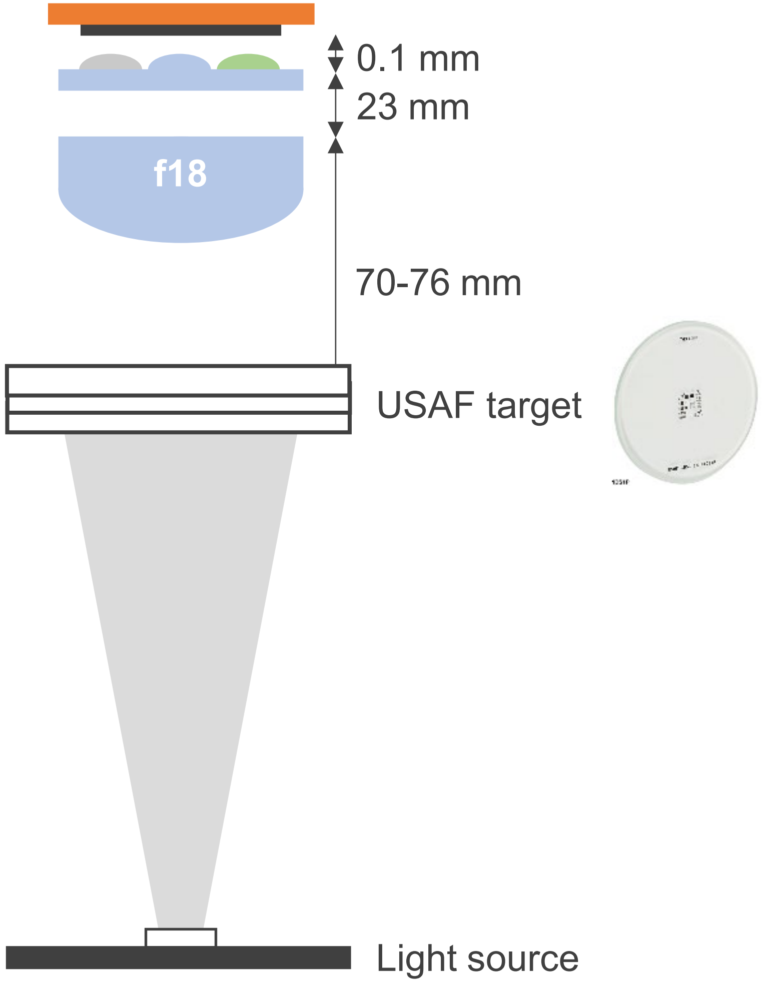
- Array of identical glass microlenses
- Ultra-thin imaging systems
- Image redundancy for further processing





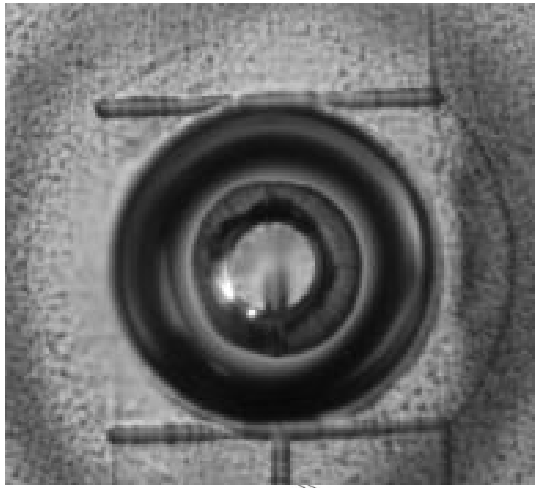
Application to multifocal imaging

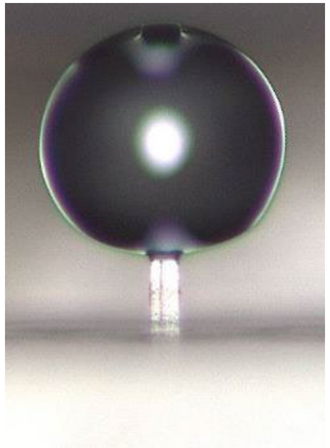


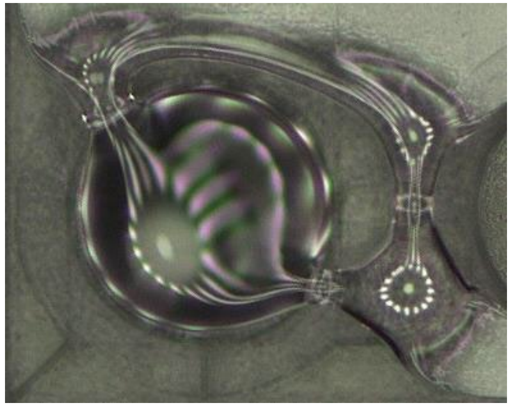


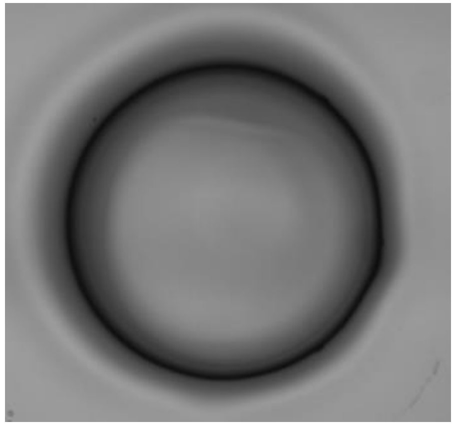
Towards more complex shapes

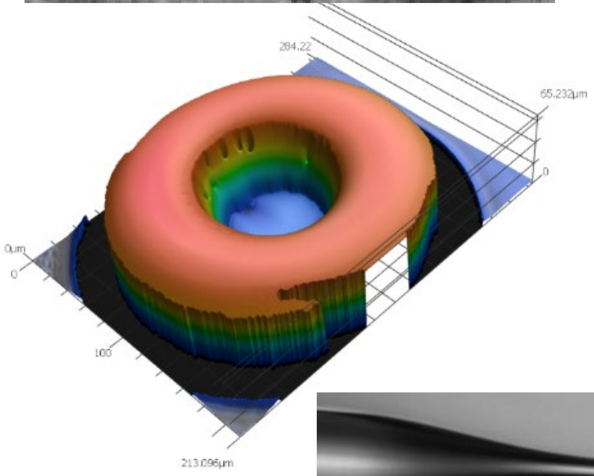
- Concave lenses, aspheric lenses, cylindrical lenses, toroid, …

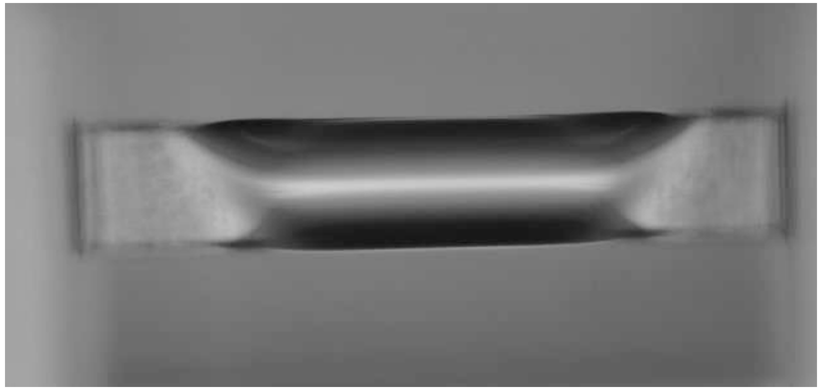


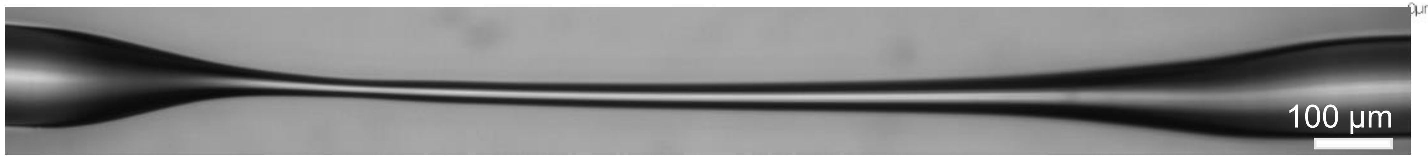


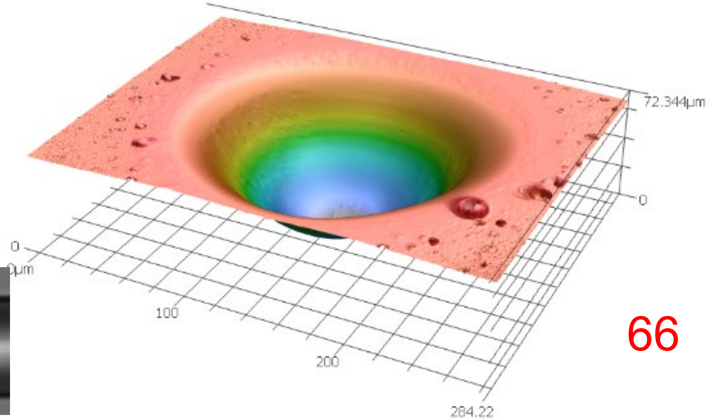












Wrapping up! / Post-scriptum

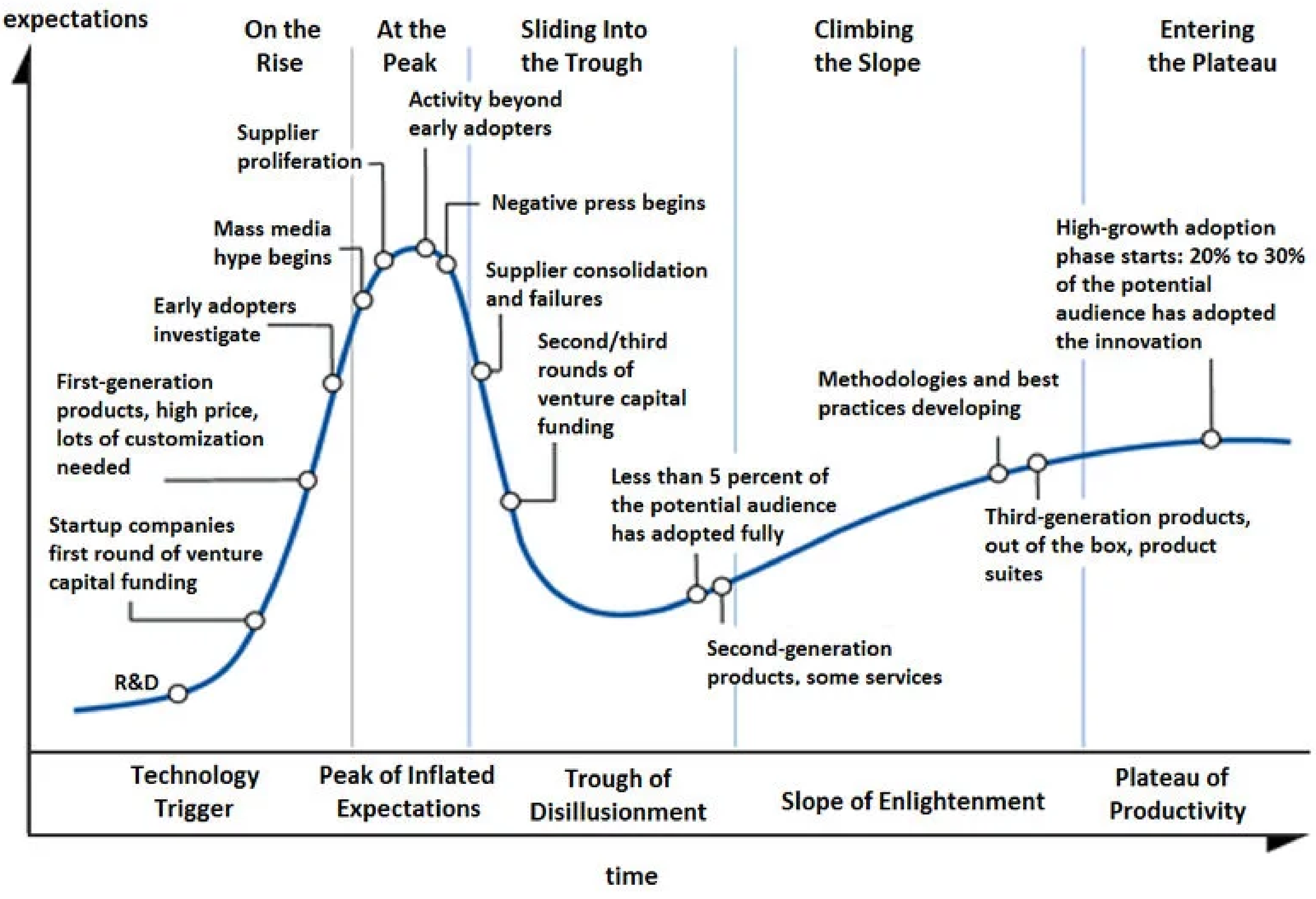
Conclusions

'Oedipe rencontrant l'oracle de Delphes.'

- **A hot topic! Full of promises…**
- Not yet fully developed…
- So far, confined to niche markets, but rapidly evolving
- Will it replace everything? Future?

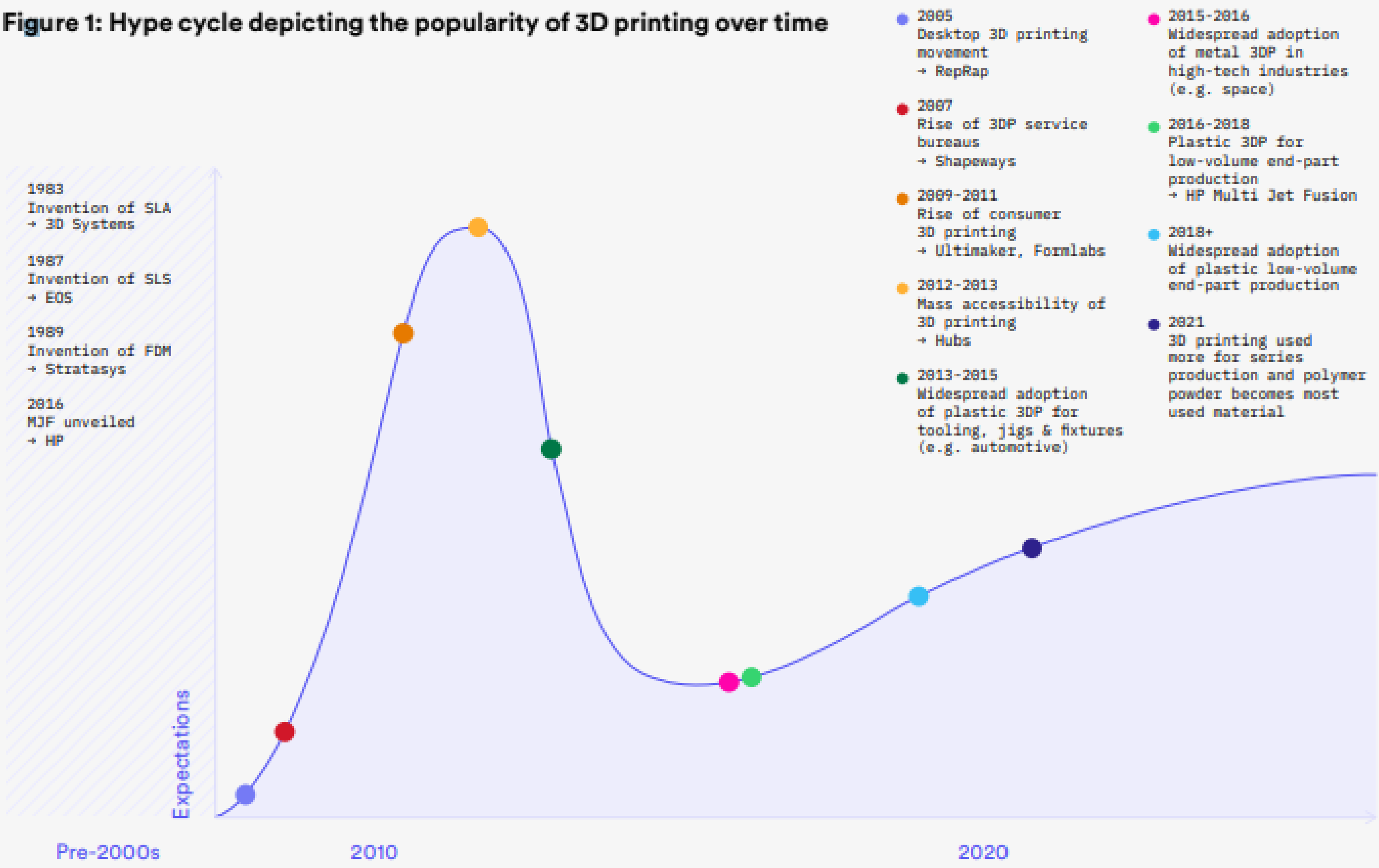
Management of the technology: ‘Gartner Hype Cycle’

- Describes typical cycle of innovations
- Decision-making
- Risk management
- Predictive tool, not science
- Based on tech survey/observations/investment trends, etc.



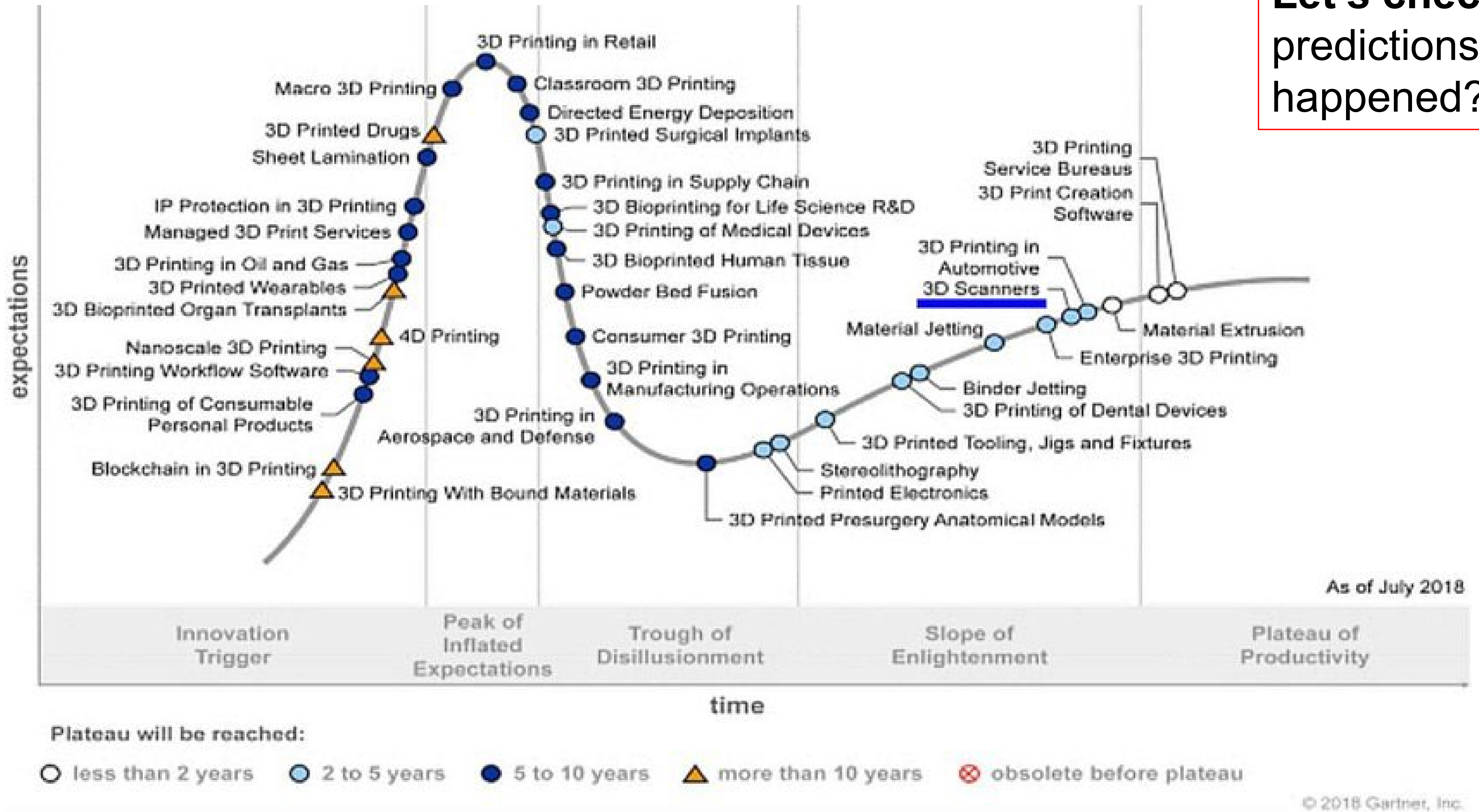
https://youtu.be/jB1RDz9jaj0?feature=shared

Figure 1: Hype cycle depicting the popularity of 3D printing over time



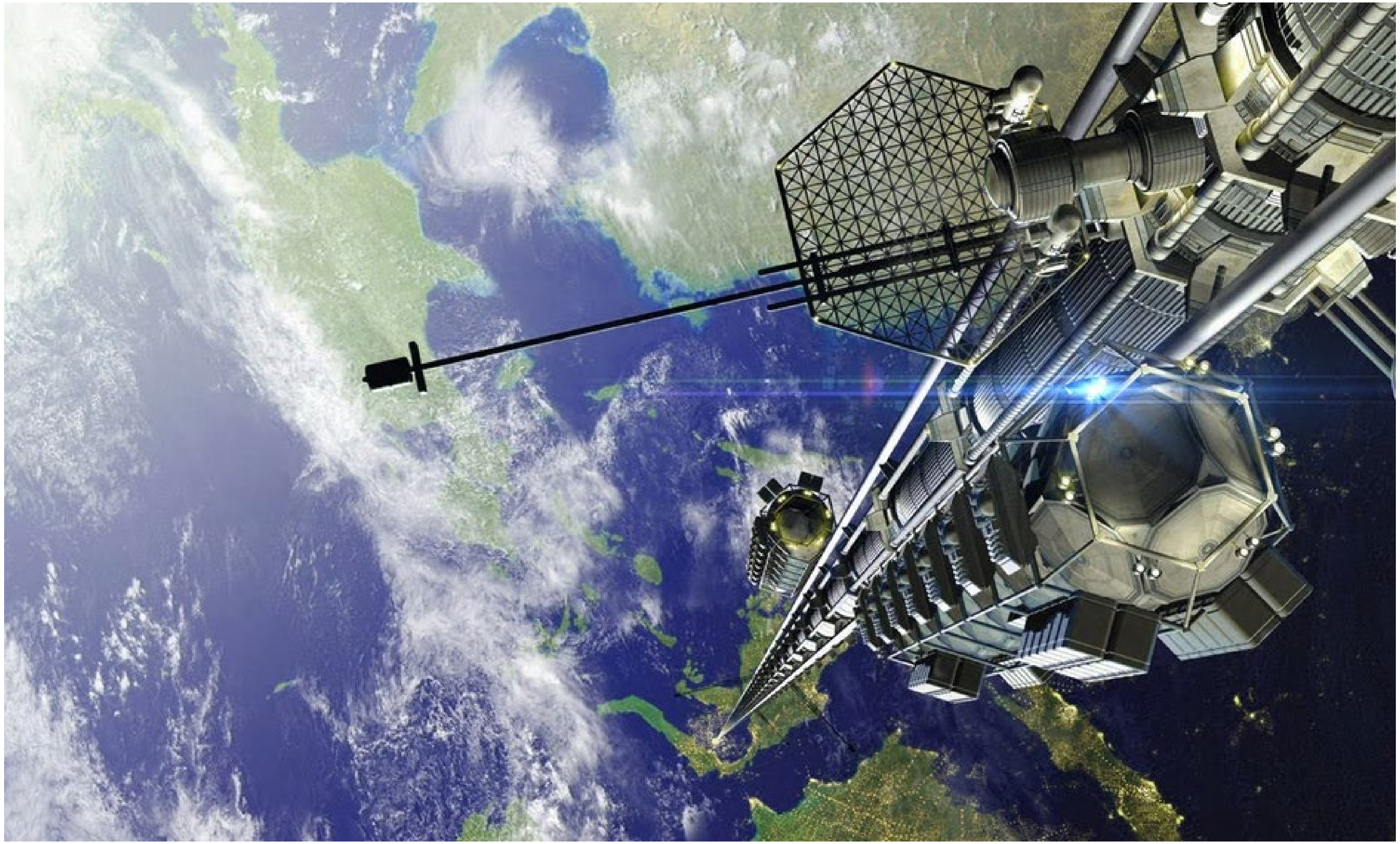
Source: Hubs

Forecast in 2018s



Let's check: did predictions really happened?

The carbon nanotubes space elevator…



Prediction in 2005

~ 25 years later, is it really coming?

Cultivate your critical thinking! ☺

What are things to remember?

- A general overview of the various types of additive processes
- Some understanding of typical issues related to 3D printing processes and alike (pixelization, possible material issues, cost model, …)
- The Gartner hype cycle
- Exciting research!

Projects at EPFL in advanced manufacturing

- Labs in Neuchâtel:
  - Prof. Roland Logé (Selective laser sintering, powder-bed fusion)
  - Prof. Daryl Yee (Chemistry and Advanced manufacturing)
  - Prof. Vivek Subramanian (Printing processes for MEMS, advanced manufacturing processes)
  - Prof. Yves Bellouard (3D laser processing & Applications, direct-write processes)

- Labs in Lausanne:
  - Prof. Christophe Moser (Volumetric printing)

- … and more!

Further courses in microengineering curricula

Advanced additive manufacturing technologies

Download the coursebook (PDF)

MICRO-413 / **3 credits**

Teacher(s): Brugger Jürgen, Moser Christophe

Language: English

Withdrawal: It is not allowed to withdraw from this subject after the registration deadline.

Summary

Advanced 3D forming techniques for high throughput and high resolution (nanometric) for large scale production. Digital manufacturing of functional layers, microsystems and smart systems.

In the programs

Microengineering
2023-2024 Master semester 2

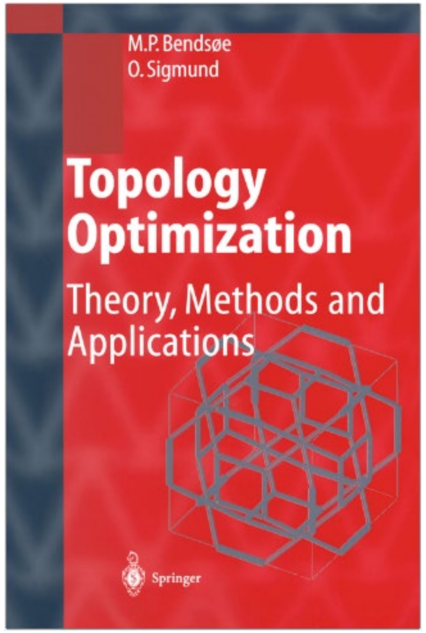
- **Semester:** Spring
- **Number of places:** 40
- **Exam form:** Oral (summer session)
- **Subject examined:** Advanced additive manufacturing technologies
- **Lecture:** 2 Hour(s) per week x 14 weeks
- **Practical work:** 1 Hour(s) per week x 14 weeks

Introductory videos

- Stereolithography (SLA): https://youtu.be/_CISyU3D3WE?si=daohm3SngIEB7ovO
- Material jetting (DoD): https://youtu.be/AYNPhJFfSOA?si=B6ZjRt5PhnT_jFNV
- Fused Deposition Modeling (FDM): https://youtu.be/WHO6G67GJbM?si=r29tKC0VowIMIEvt

Useful offline and online resources

- https://engineeringproductdesign.com/article-categories/additive-manufacturing-processes/



eBook available at the library
https://link.springer.com/content/pdf/10.1007/978-3-662-05086-6.pdf

Interesting codes and softwares:
https://www.topopt.mek.dtu.dk/apps-and-software

Introductory videos:

- Stereolithography (SLA): https://youtu.be/_CISyU3D3WE?si=daohm3SngIEB7ovO
- Material jetting (DoD): https://youtu.be/AYNPhJFfSOA?si=B6ZjRt5PhnT_jFNV
- Fused Deposition Modeling (FDM): https://youtu.be/WHO6G67GJbM?si=r29tKC0VowIMIEvt