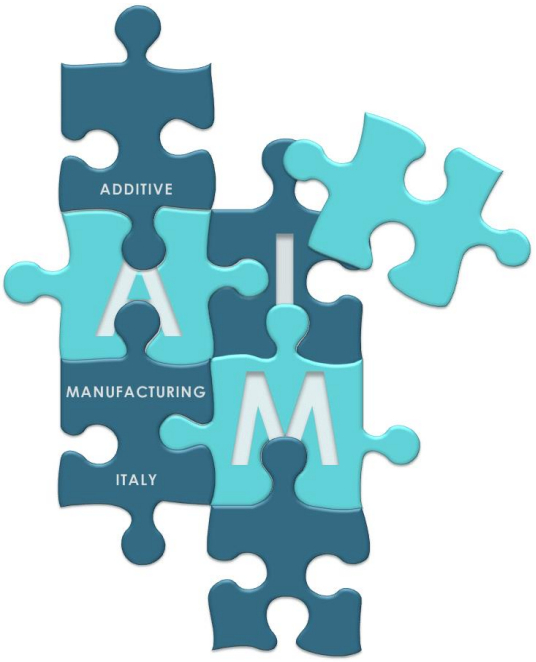
Selection of production process: The case of Additive Manufacturing

Michele Lanzetta Andrea Rossi University of Pisa
Department of Civil and Industrial engineering

AITeM

Associazione Italiana di Tecnologia Meccanica

www.additivemanufacturing.work



Intrest Group
Additive Manufacturing

Coordinator: prof. Michele Lanzetta, University of Pisa

UNIVERSITÀ DI PISA

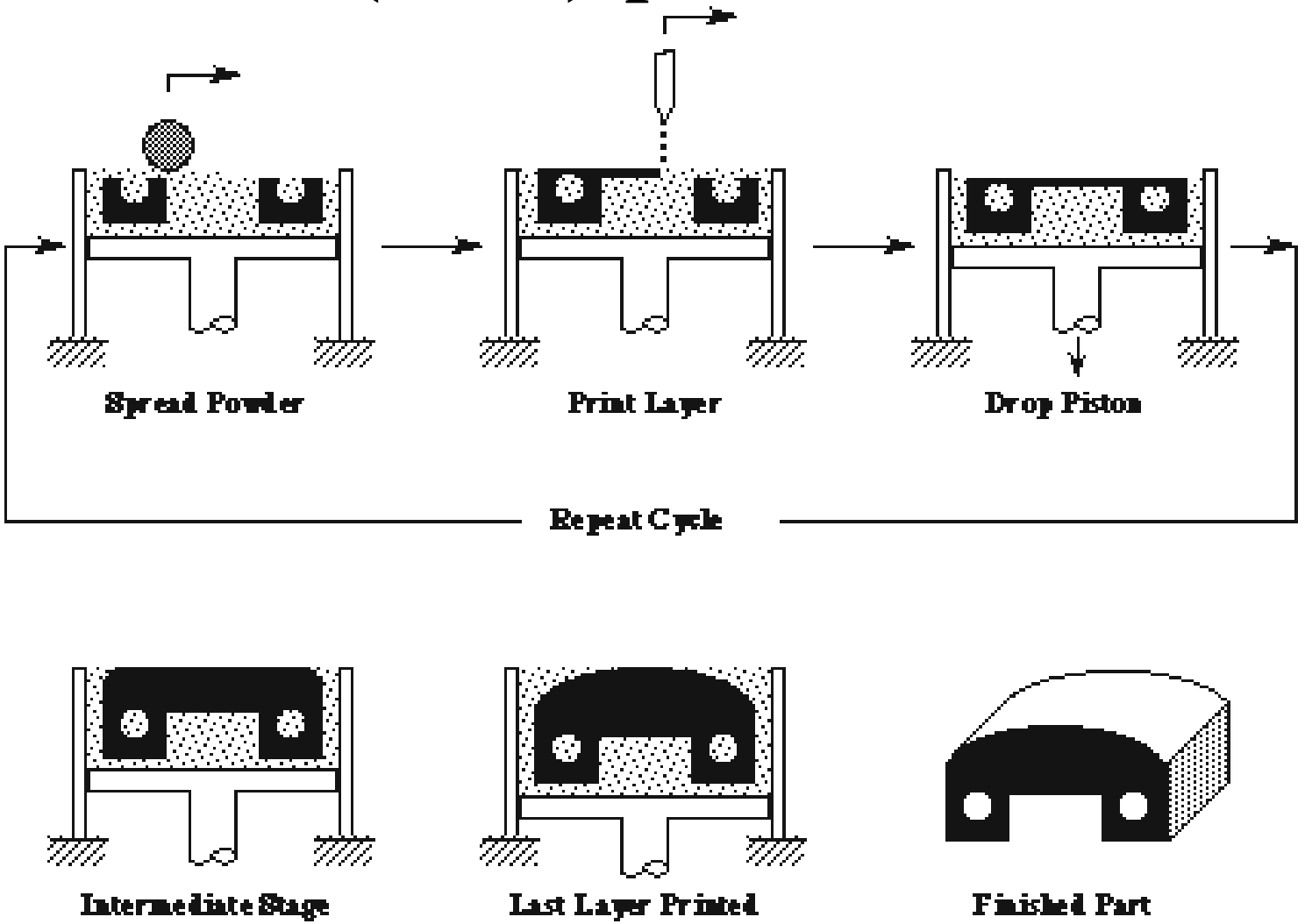
INGEGNERIA

DICI
DIPARTIMENTO DI INGEGNERIA CIVILE E INDUSTRIALE

Keywords

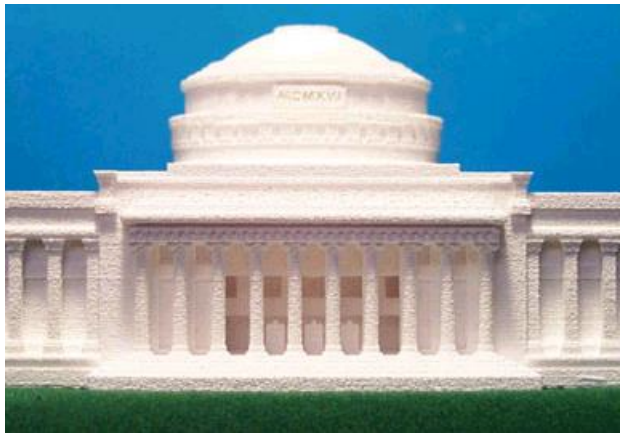
- Stereolitography **SLA**
- Layered manufacturing
- Rapid prototyping
- Rapid tooling
- Additive manufacturing
- 3DPrinting **3DP**
- Fused deposition manufacturing **FDM**
- Fused Filament Fab **FFF**

The Three Dimensional Printing (3DP) process



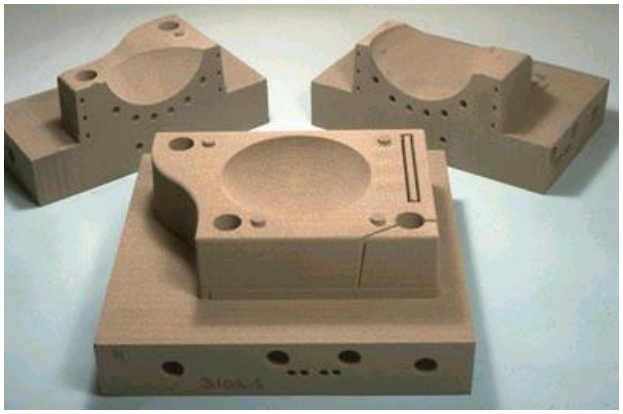
Examples of 3D Printed parts (1/3)

*source:*web.mit.edu/tdp/www

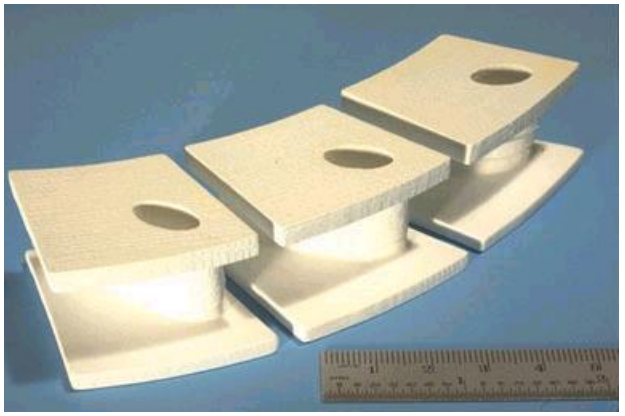


Architectural models (in ceramic)

Alumina slipcasting mold



Metal tools for injection molding



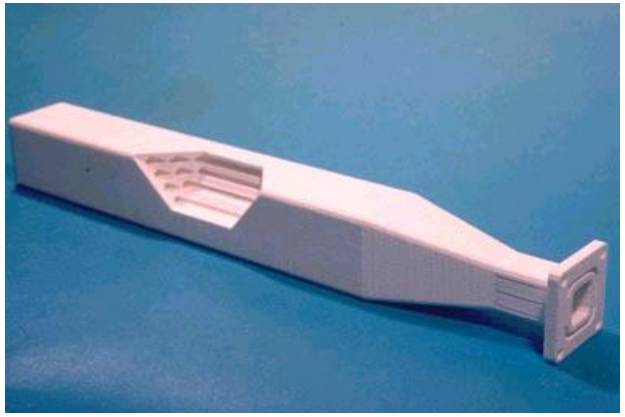
Alumina airfoils (green)

Examples of 3D Printed parts (2/3)

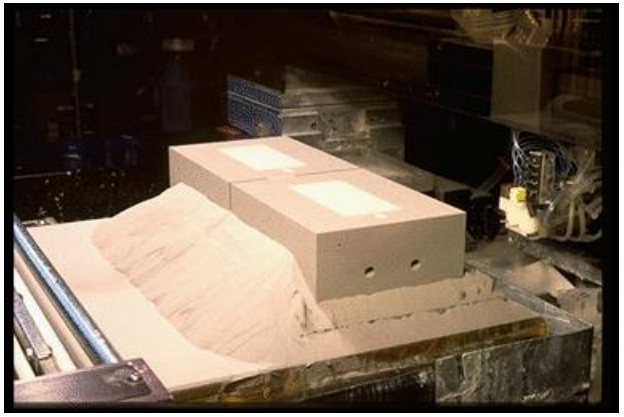
*source:*web.mit.edu/tdp/www

Ceramic appearance model

Ceramic casting (shell & casting)



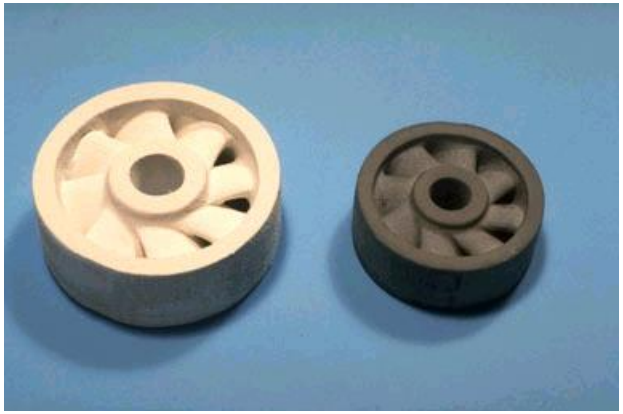
Porous ceramic filter



Printed part emerging from powder

Examples of 3D Printed parts (3/3)

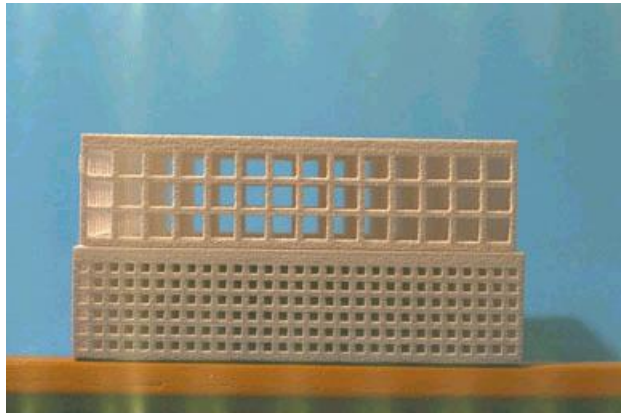
***source:*web.mit.edu/tdp/www**



Silicon nitride rotor

Complex surface texture

Metal injection molds



Ceramic lattice structure

The Experimental Set-up

The control

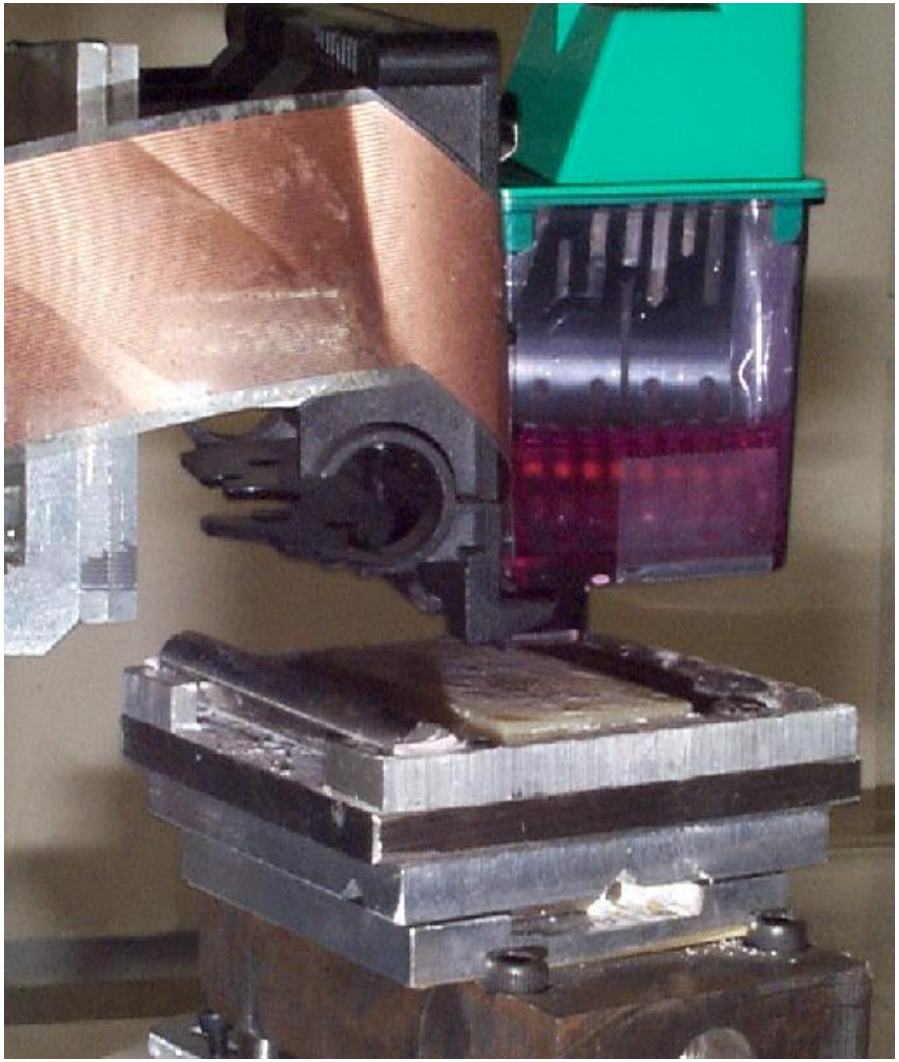
A PC driving an external electronic circuit generates a series of pulses to print drops at a given frequency.

Stackable shims

allow spreading beds of different thickness.

The rotating platform

with a switch connected to the PC to measure the actual speed and all the consequent process parameters.



The printhead

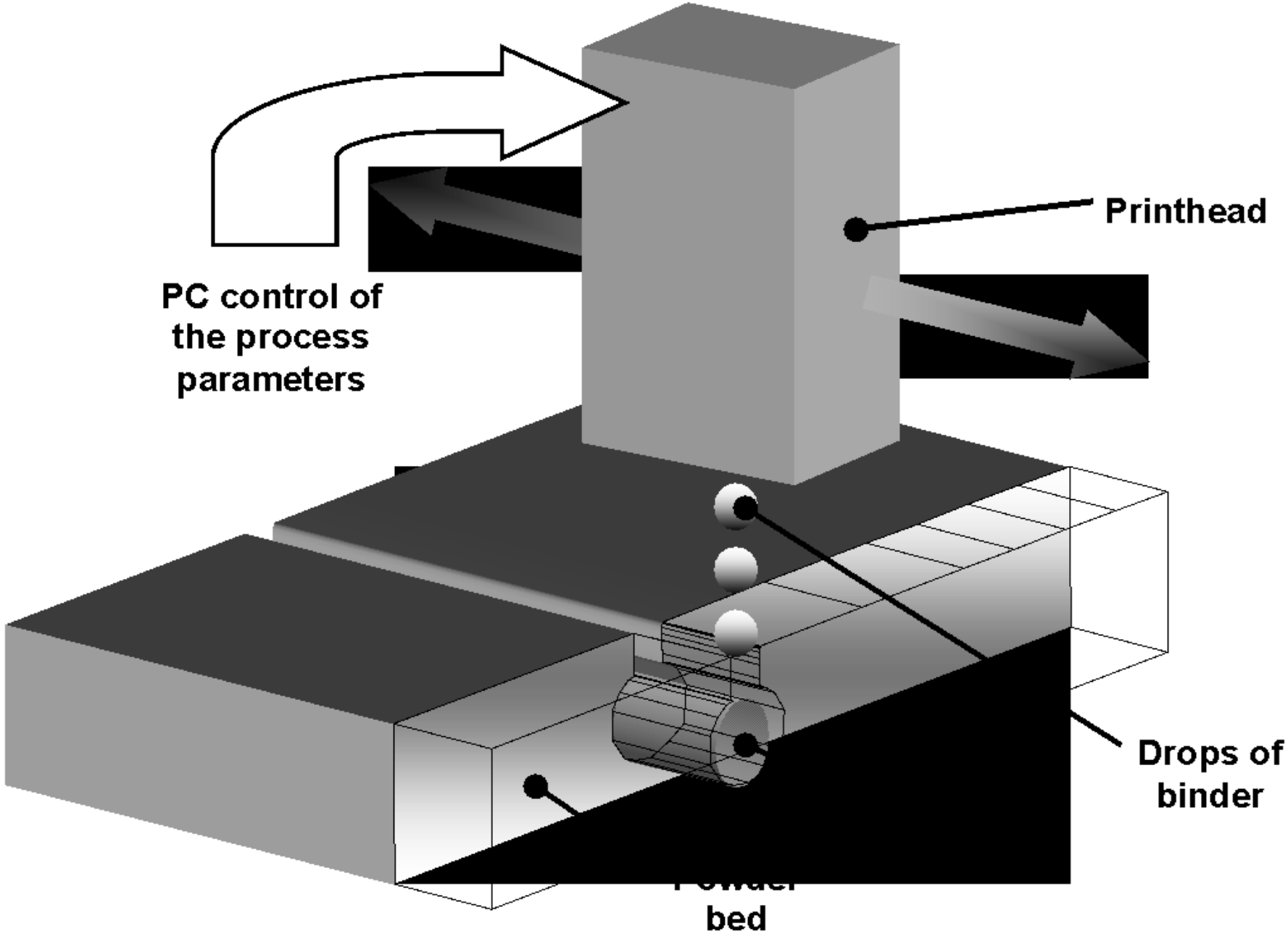
A Drop on Demand, bubble-jet commercial printhead.

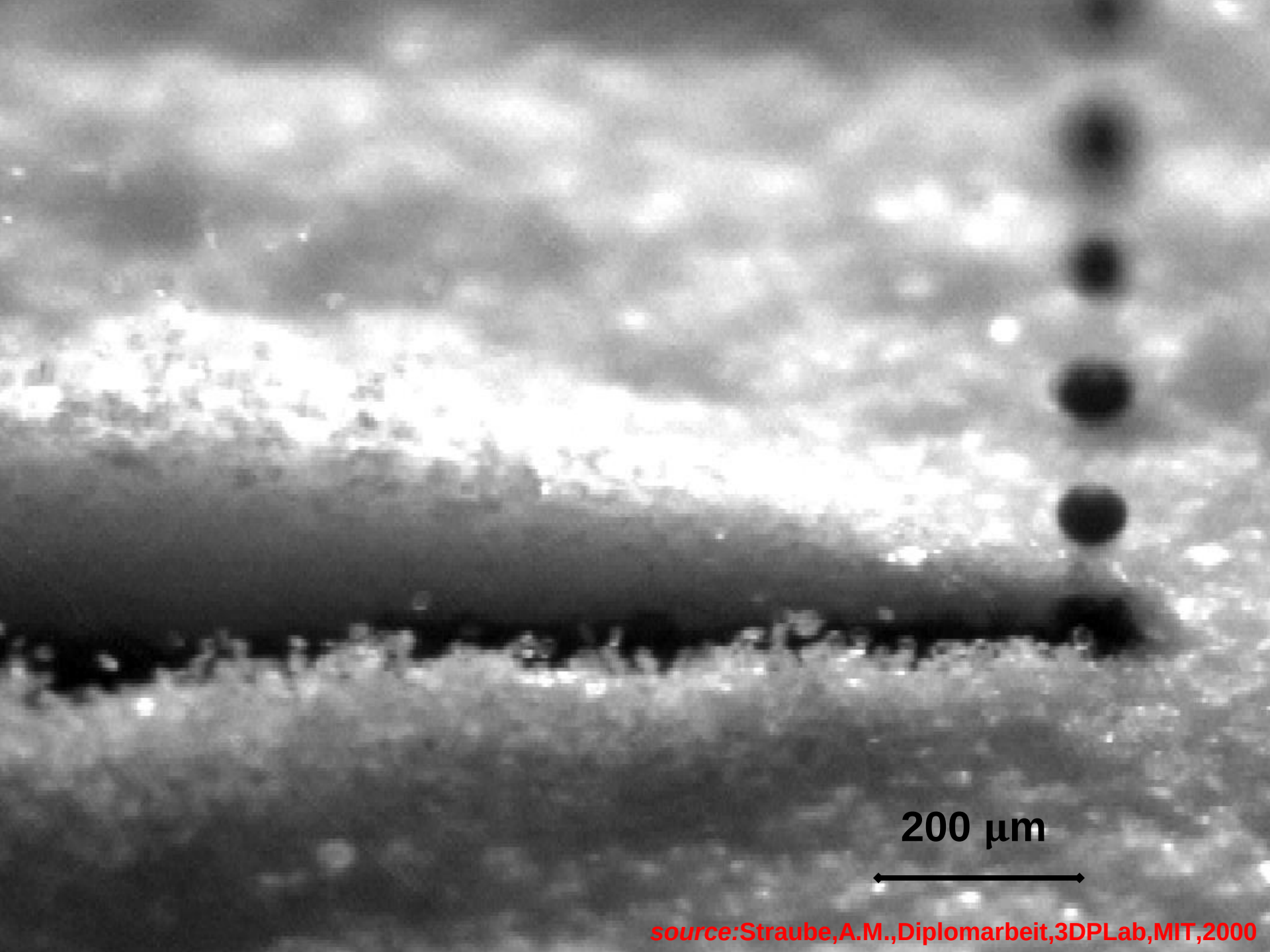
The binder

Colloidal Silica in Ethylene Glycol in water, with food colour to enhance the contrast of lines within the white Alumina powder bed.

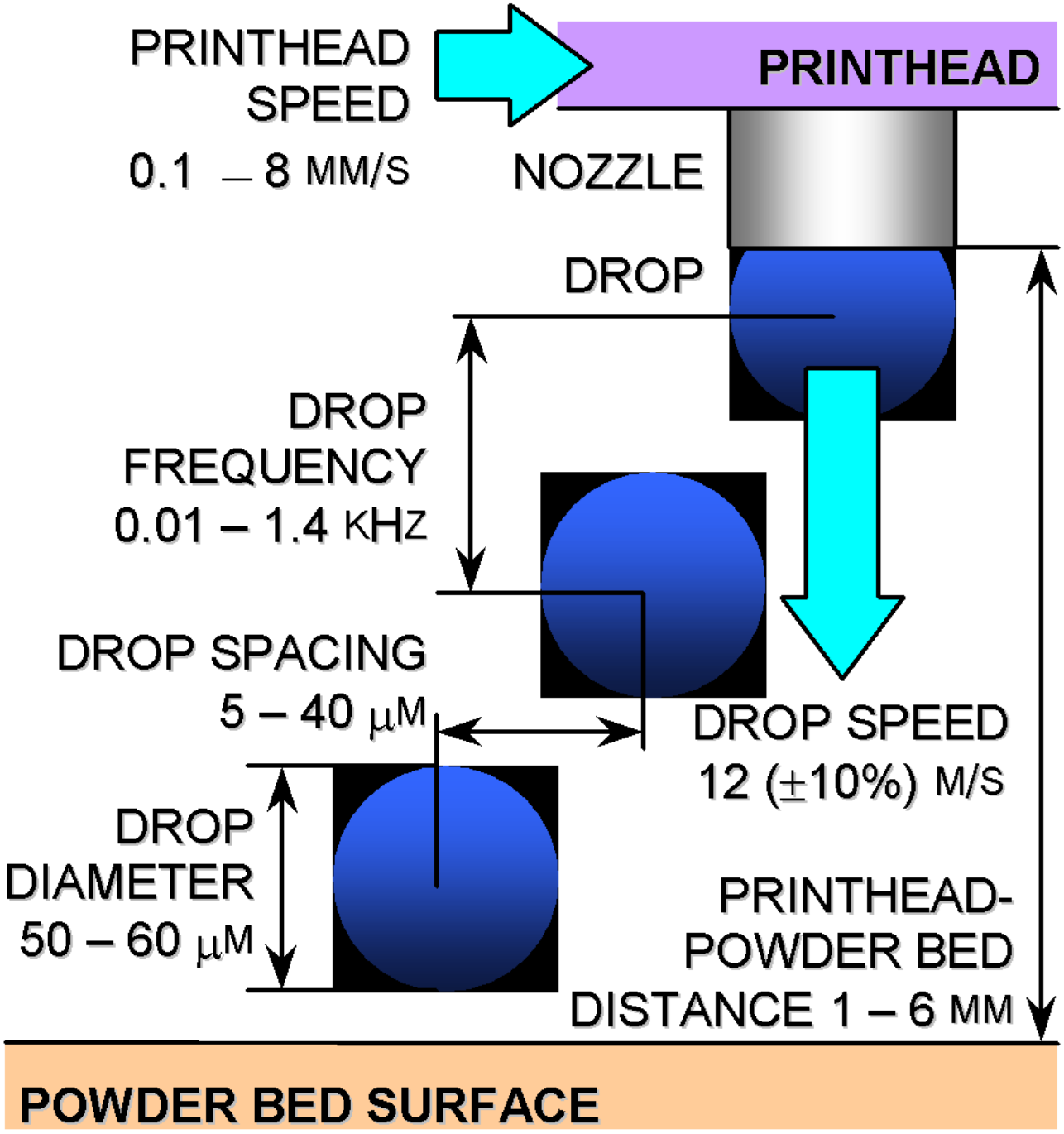
The power bed

Laying on a detachable support, which allows an accurate repositioning.

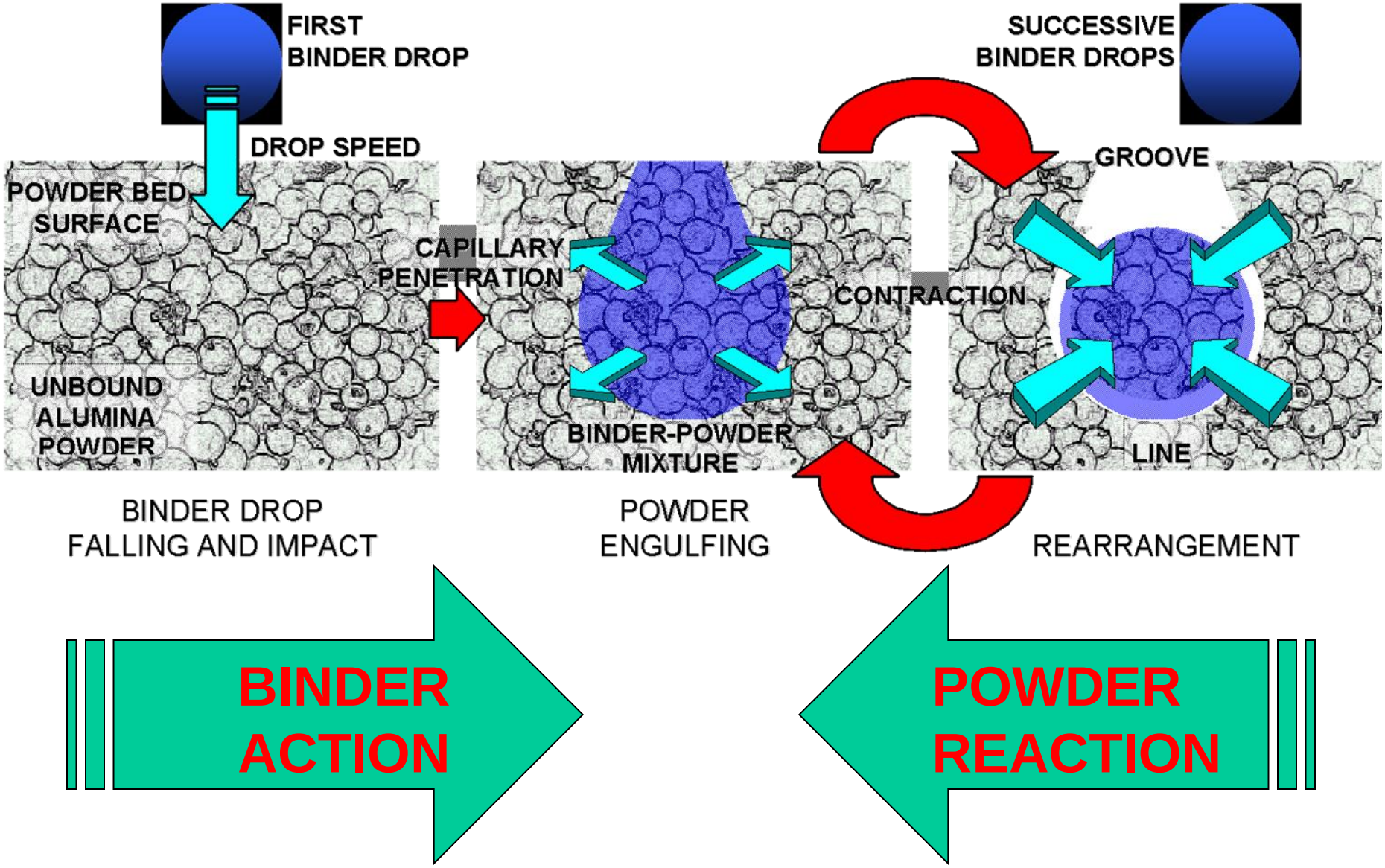

Printhead
PC control of the process parameters
Drops of binder
bed

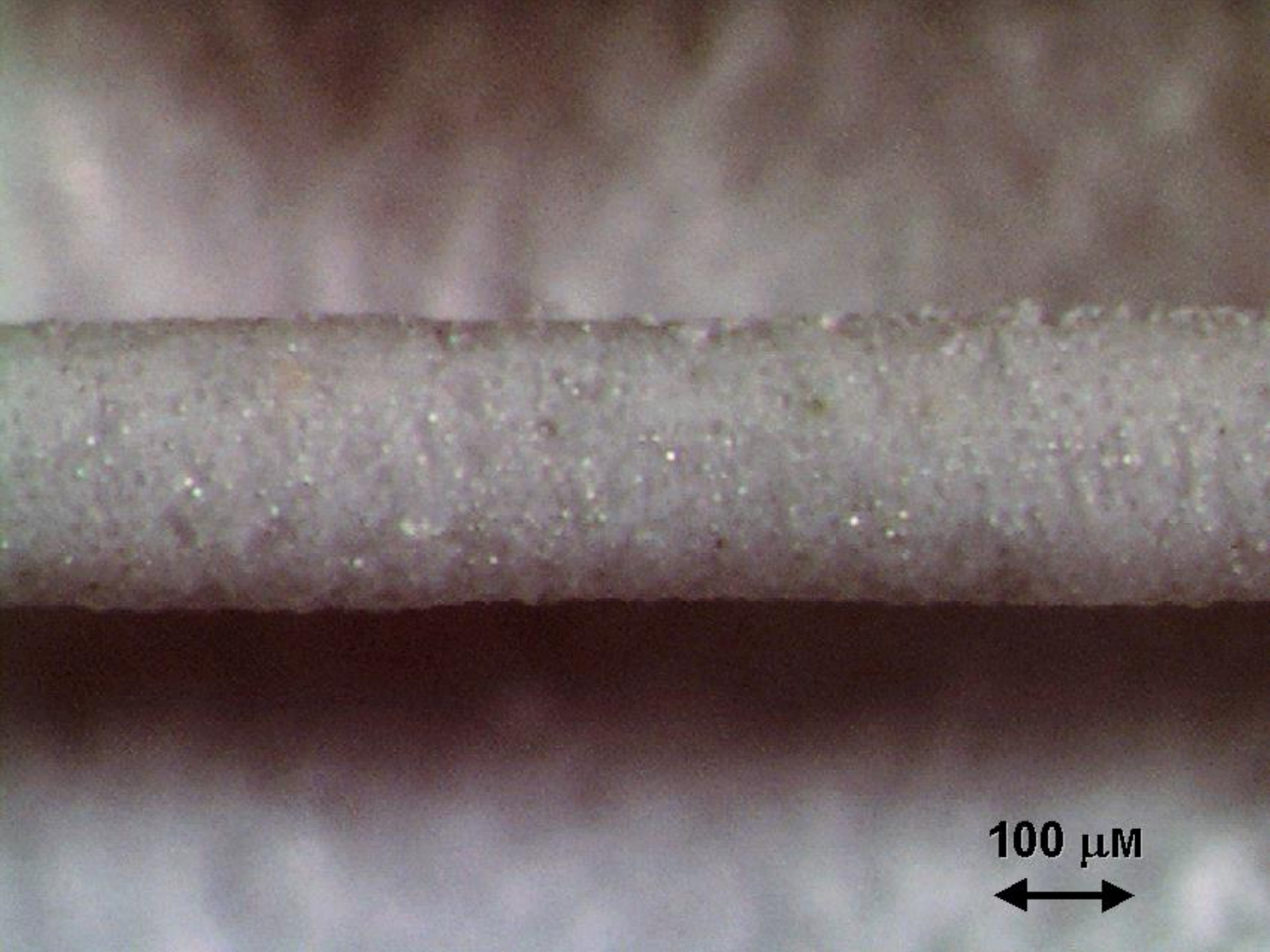


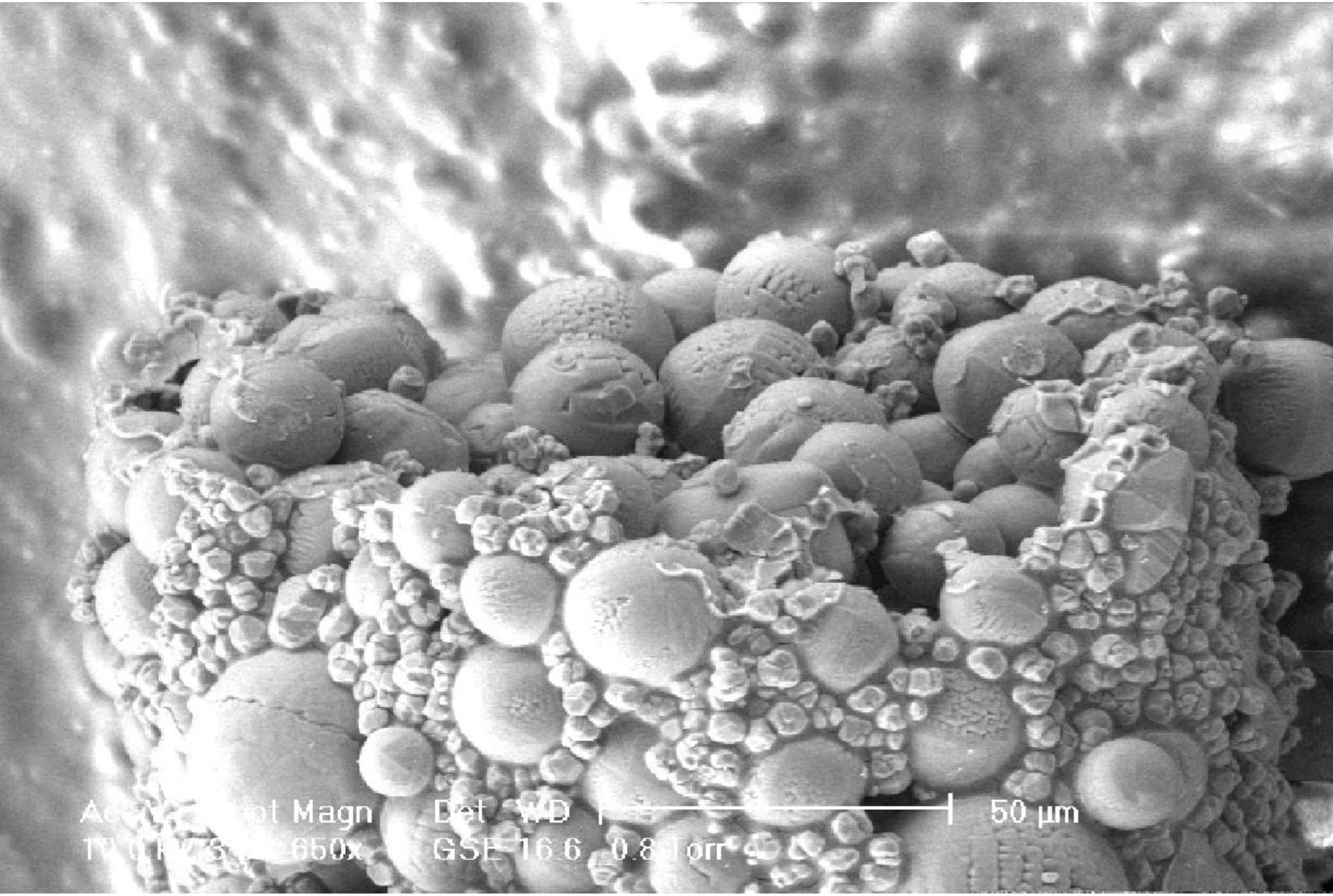
*source:*Straube,A.M.,Diplomarbeit,3DPLab,MIT,2000


PRINTHEAD SPEED
0.1 – 8 MM/S
PRINTHEAD
NOZZLE
DROP
DROP FREQUENCY
0.01 – 1.4 KHZ
DROP SPACING
5 – 40 μM
DROP SPEED
12 (±10%) M/S
DROP DIAMETER
50 – 60 μM
PRINTHEAD-POWDER BED DISTANCE 1 – 6 MM
POWDER BED SURFACE

The line formation

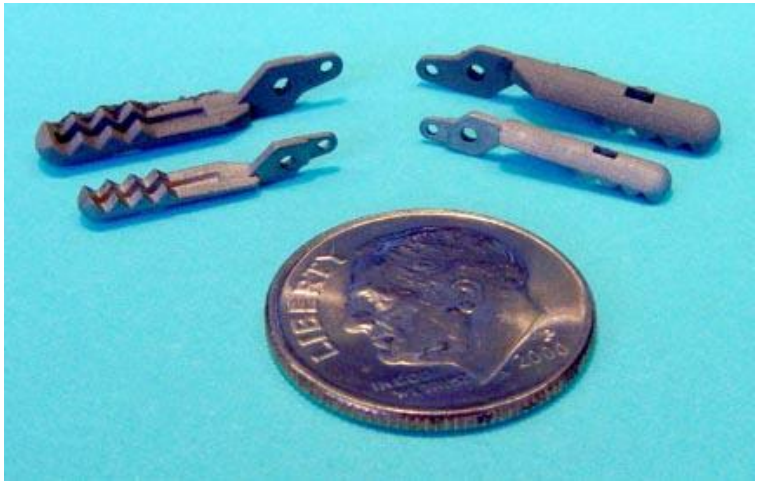


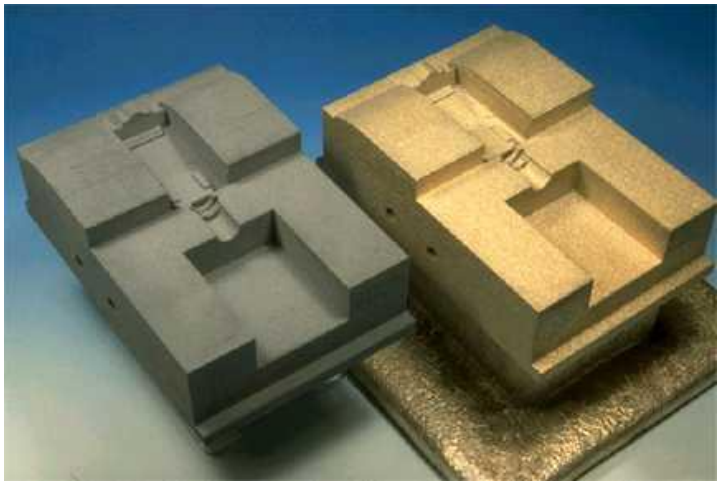

100 µM

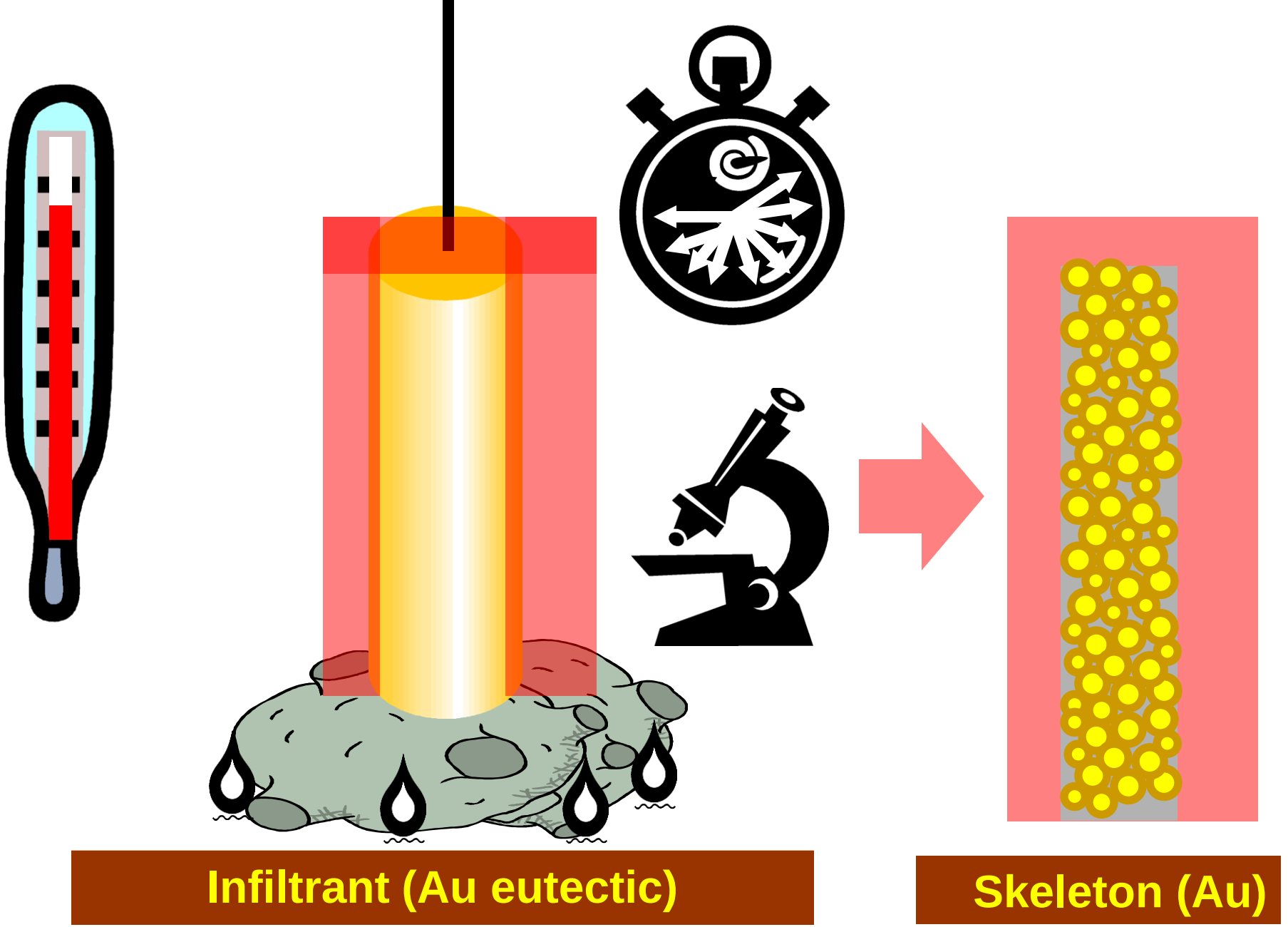

Magn
Det WD
50 µm
650x
GSE 16.6 0.8 Torr

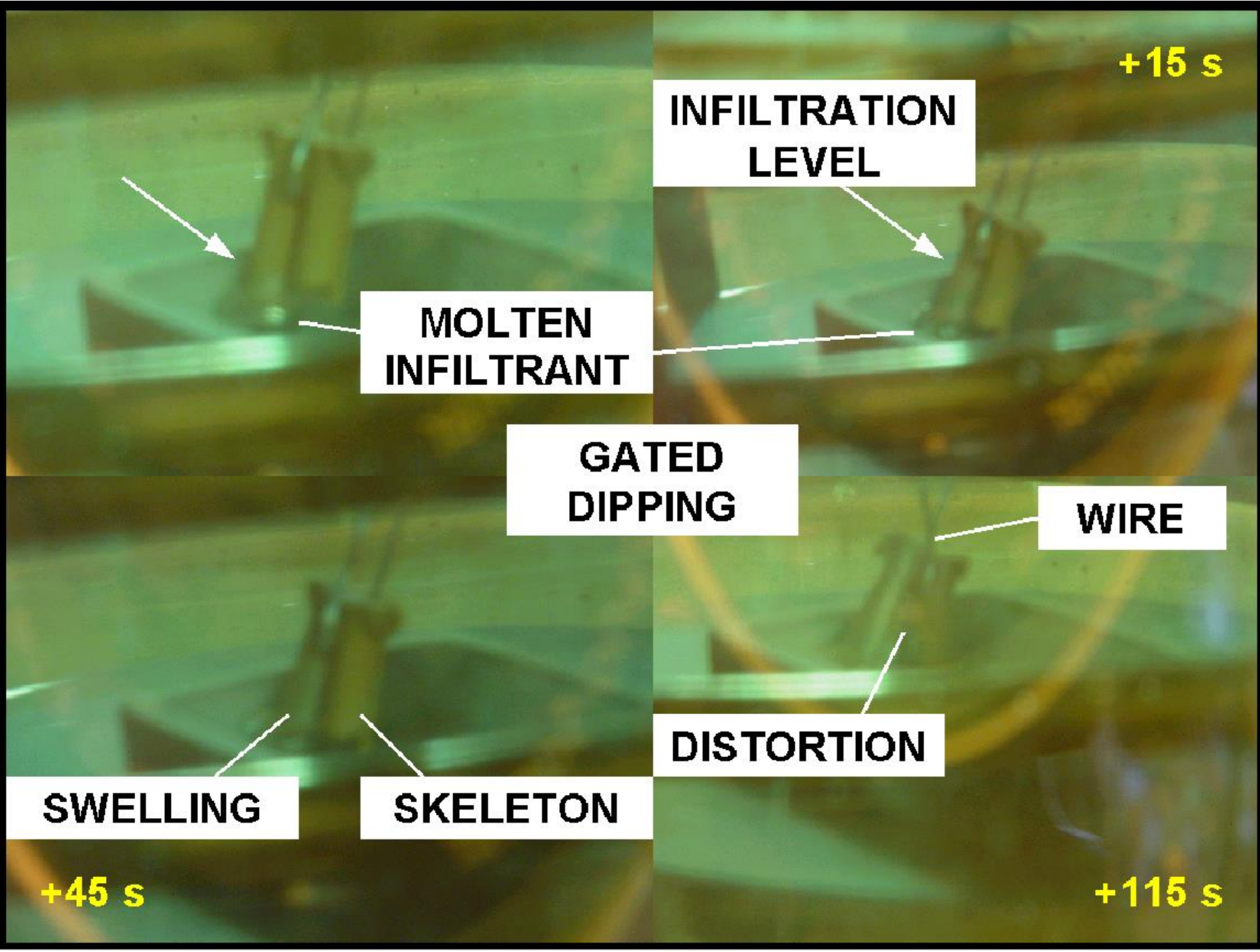
Metal parts made by SFF

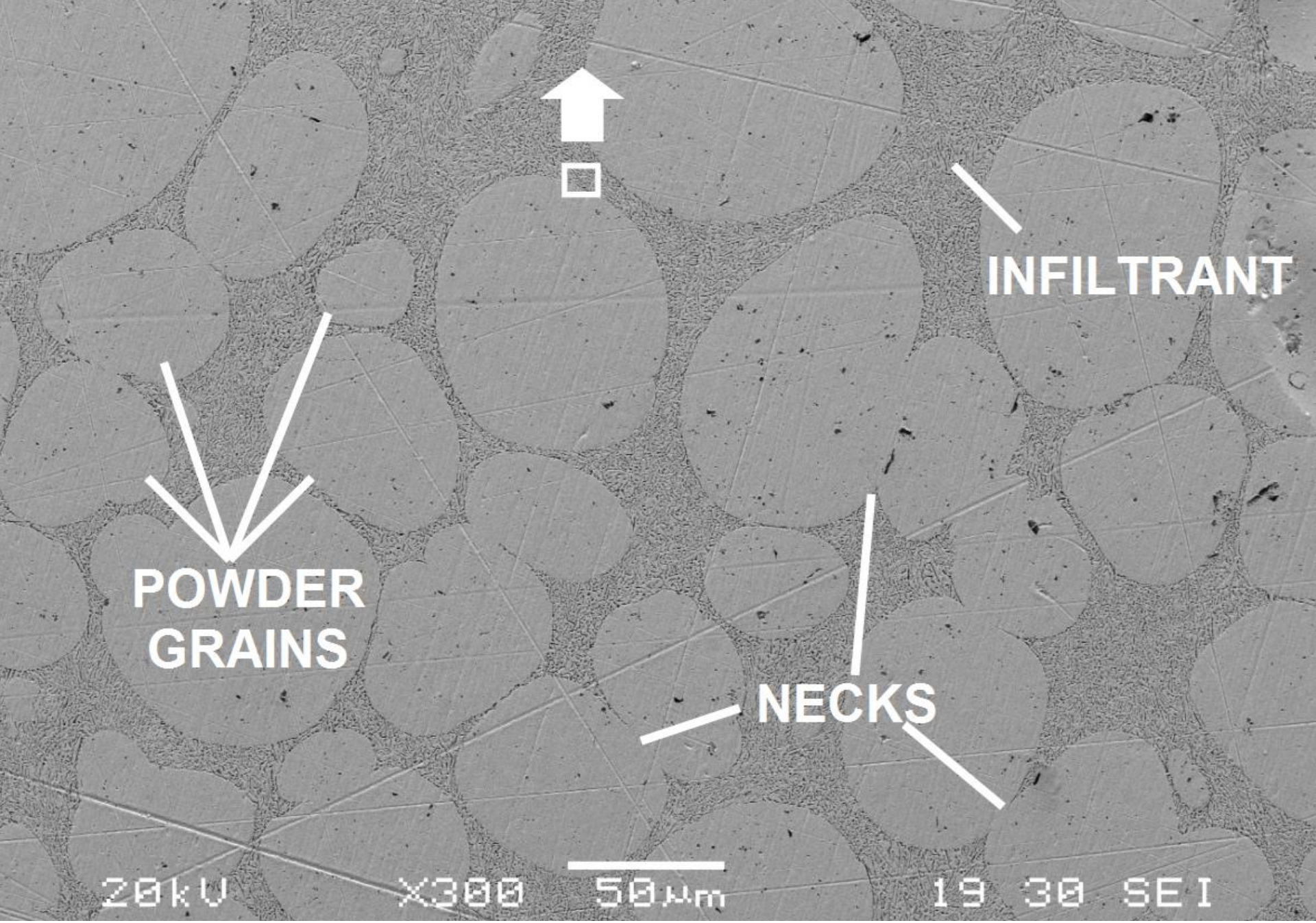
- Sinter to full density
  - choice of materials is very good
  - homogeneous final composition
  - shrinkage of ~15%
- Infiltration to fill voids
  - negligible shrinkage, good for large parts
  - limited material choice
  - heterogeneous final composition



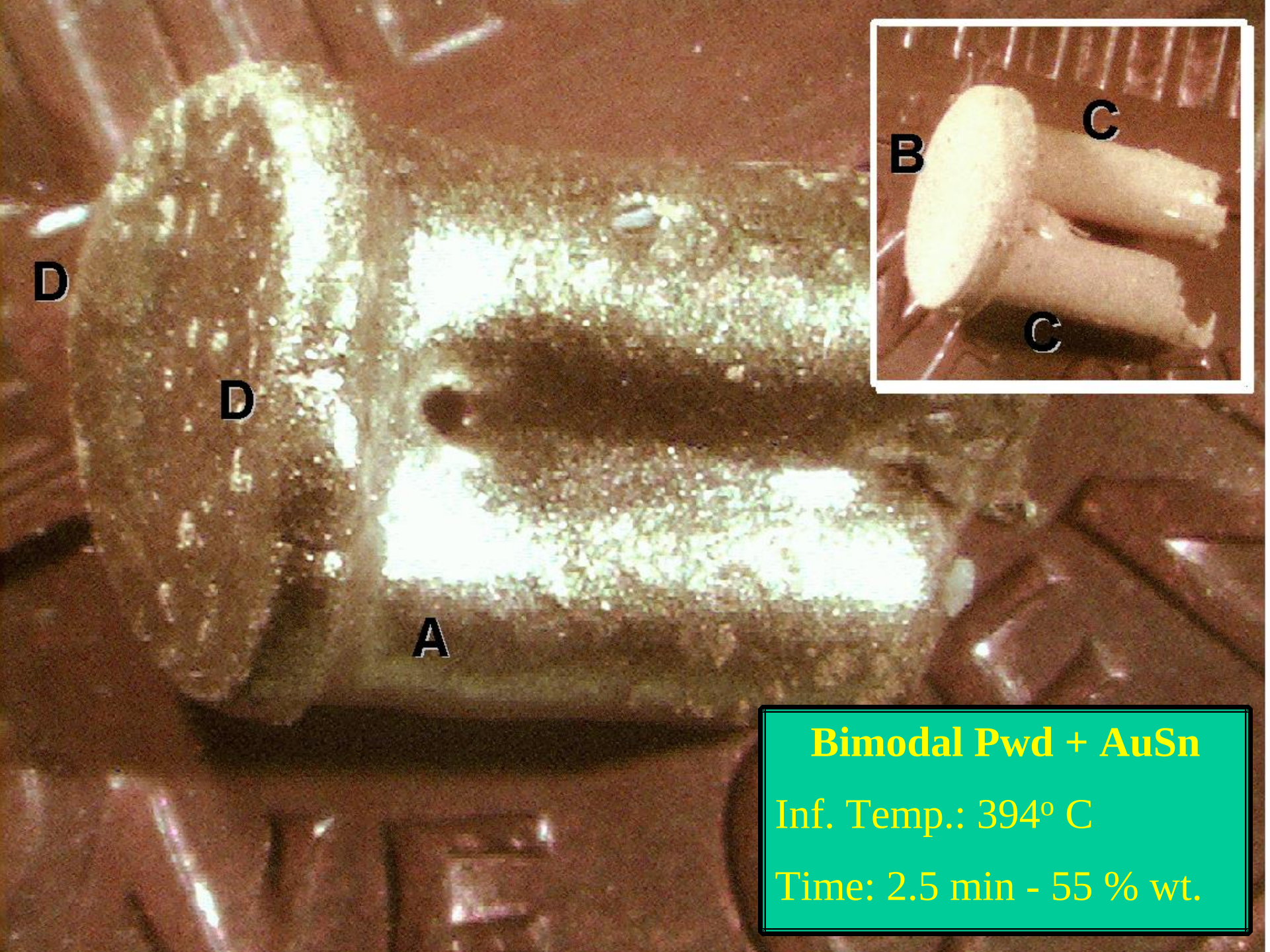



Infiltrant (Au eutectic)
Skeleton (Au)


+15 s
INFILTRATION LEVEL
MOLTEN INFILTRANT
GATED DIPPING
WIRE
DISTORTION
SWELLING
SKELETON
+45 s
+115 s



Sample Section. SEM image. Bimodal Pwd+AuSi



Bimodal Pwd + AuSn

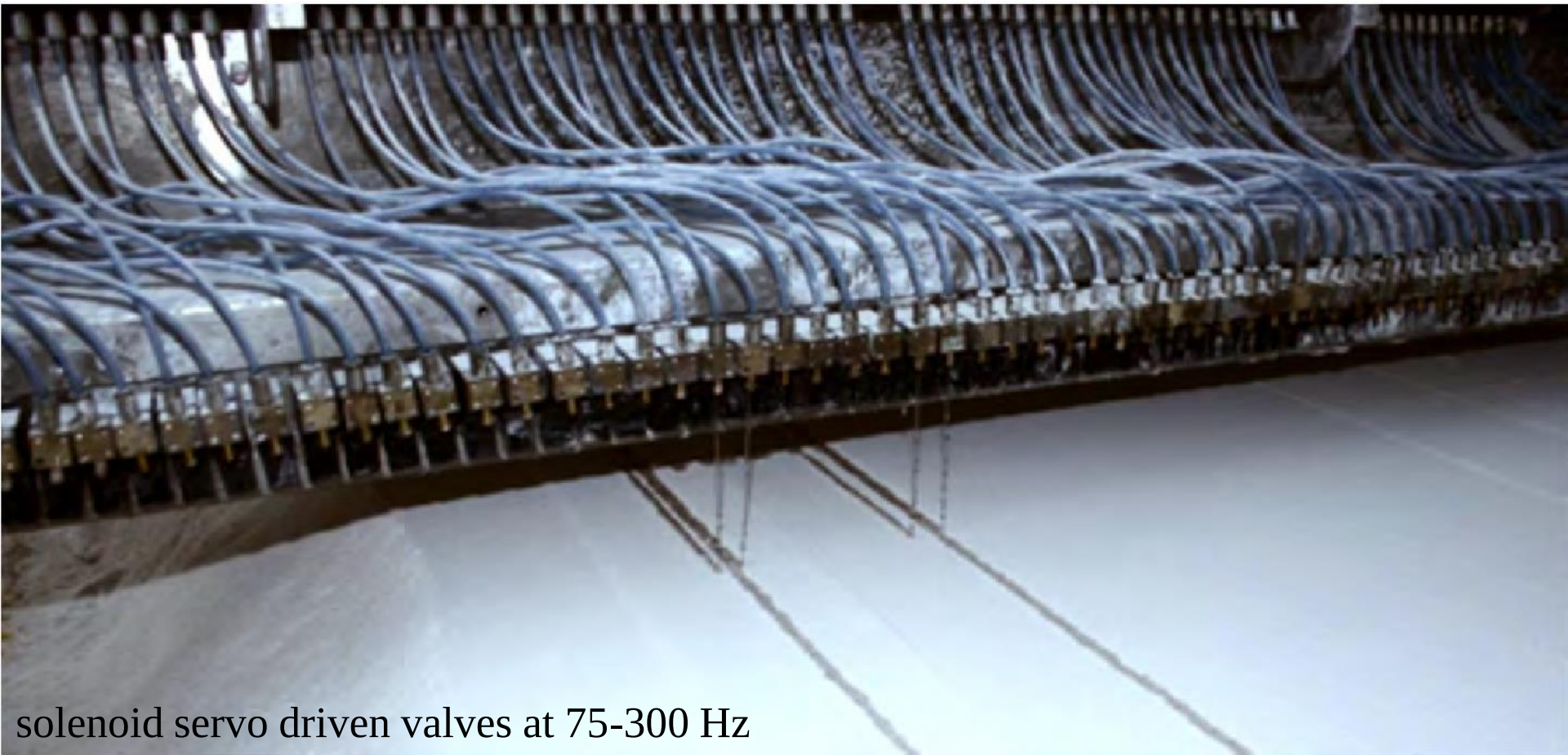
Inf. Temp.: 394º C

Time: 2.5 min - 55 % wt.

Sample Section. High porosity. Bimodal Pwd+AuSn. Inf. Temp.: 394^{o}C

powder compaction rolls

The nozzle system of the D-Shape machine

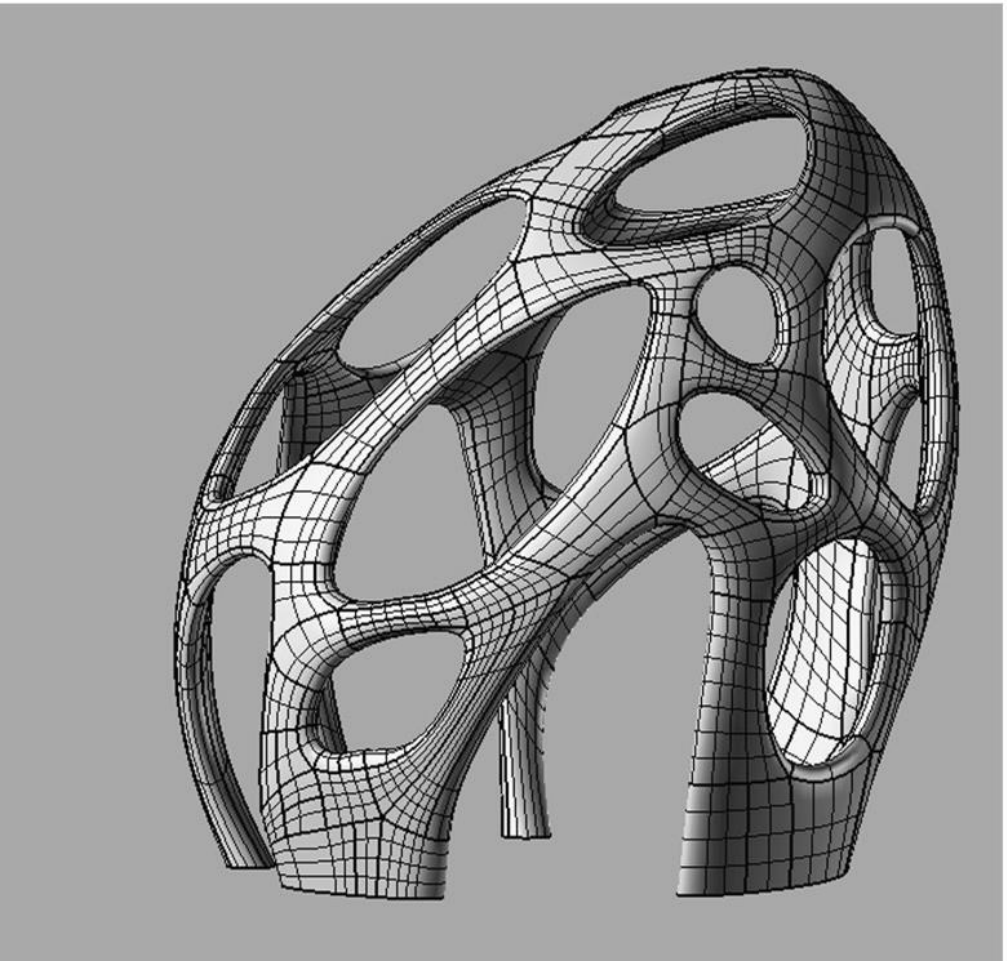


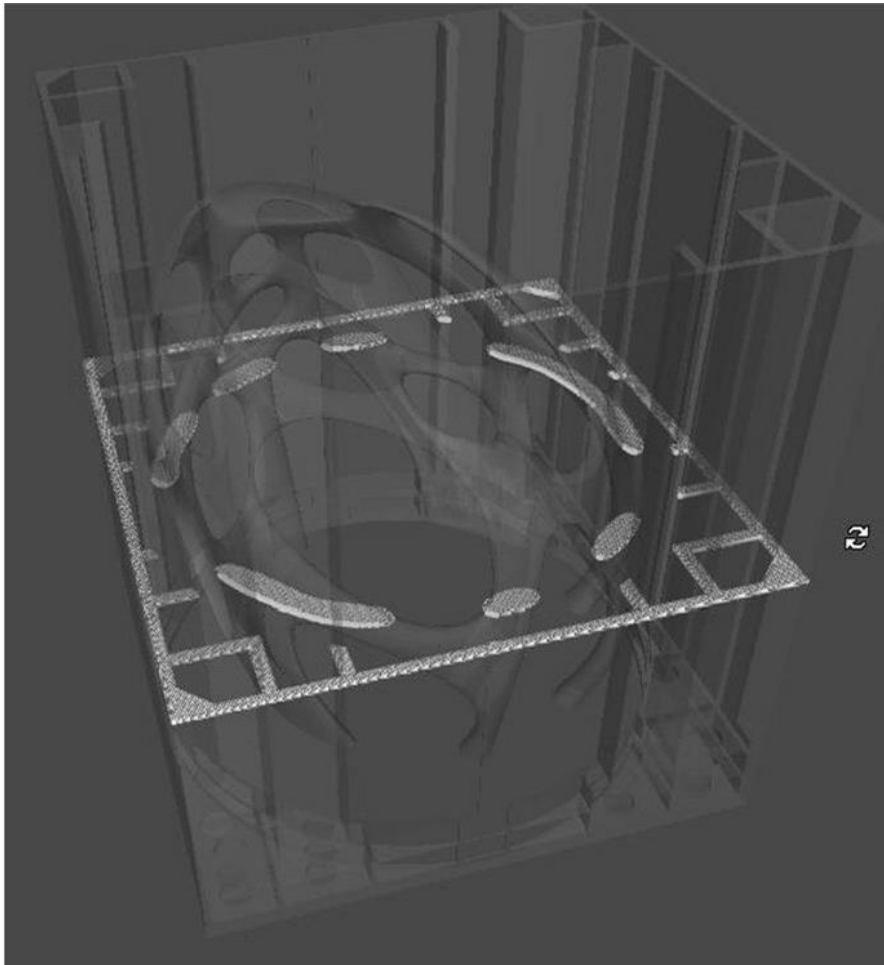
solenoid servo driven valves at 75-300 Hz

3 tons full scale house www.d-shape.com

entangled concrete rings, impossible to make by traditional methods of construction

Conceptual design 1/3

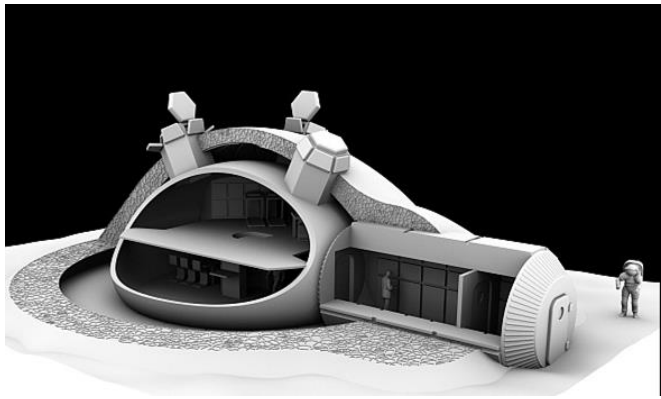


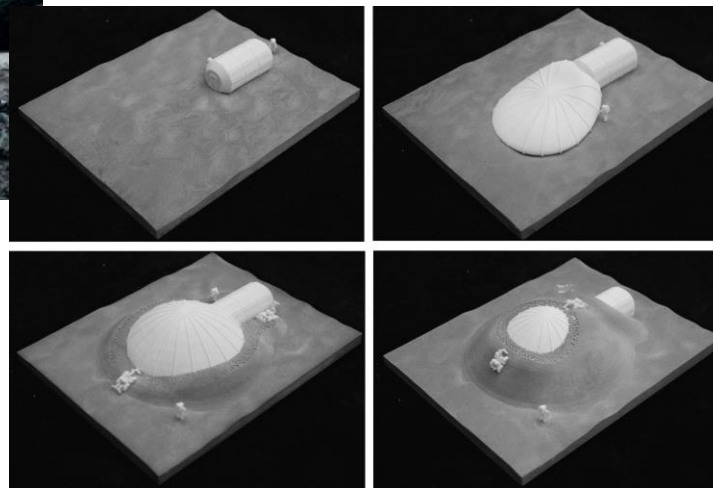


Radiolaria, 3 m^3 gazebo designed by London Architect Andrea Morgante

Conceptual design 2/3

Conceptual design 3/3





http://www.esa.int/Our_Activities/Space_Engineering_Technology/Building_a_lunar_base_with_3D_printing

Shape Deposition Manufacturing of biologically inspired hierarchical microstructures

Michele Lanzetta

University of Pisa, Italy
Department of Mechanical, Nuclear and Production Engineering

Mark Cutkosky

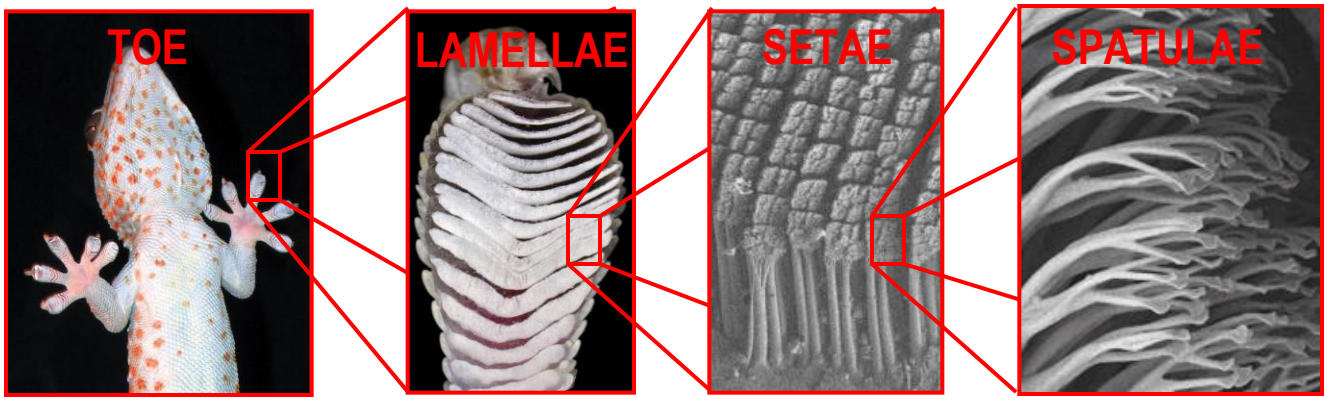
Stanford University, USA
Mechanical Engineering Research Laboratories

CLIMBING

Best Inventions 2006 TIME

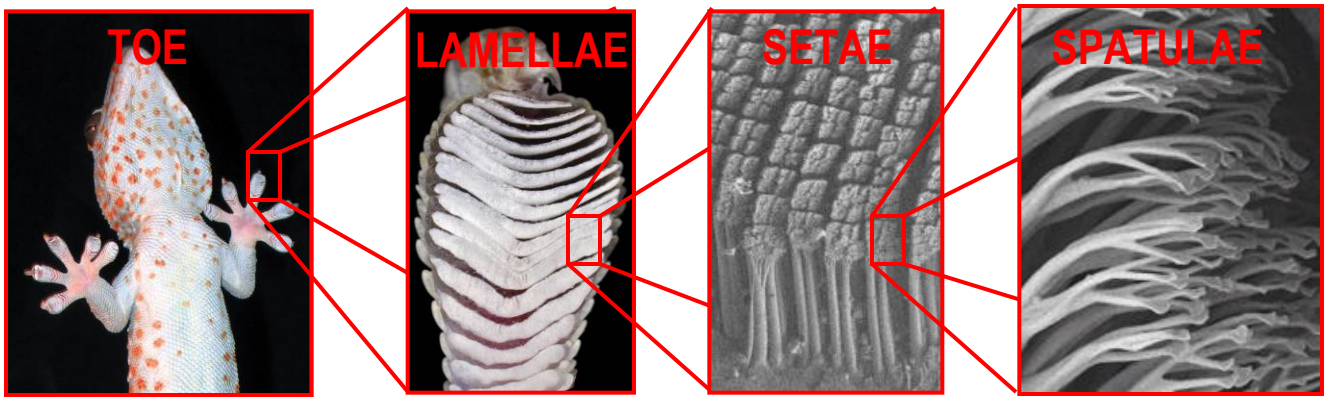
HANDLING

Inspiration: Gecko Adhesion

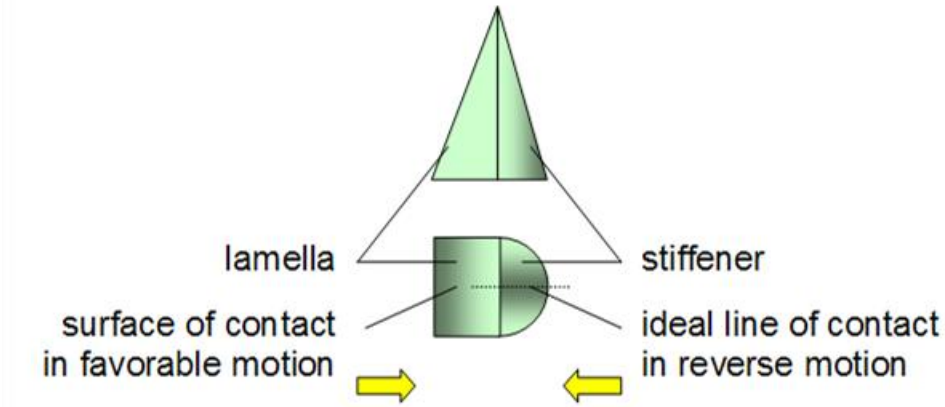


- Main features
  - **Dry** Adhesion
  - **Directional**/Controllable Adhesion
  - Hierarchical **Compliant** Structure

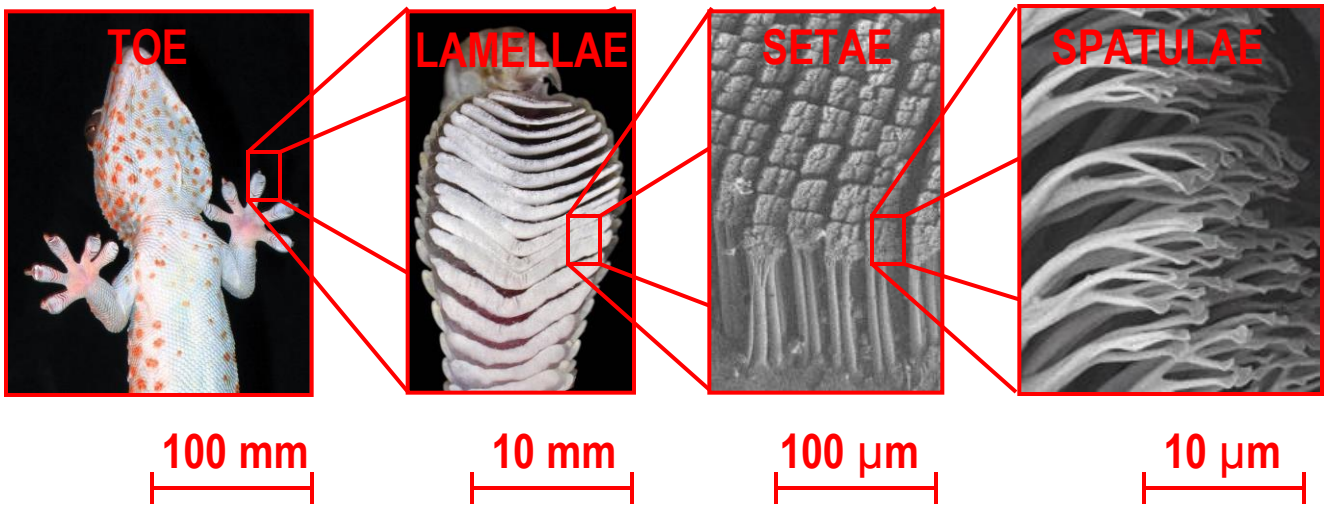
Shape?



- Angles
  - Setae 20^{o}
  - Spatulae 45^{o}

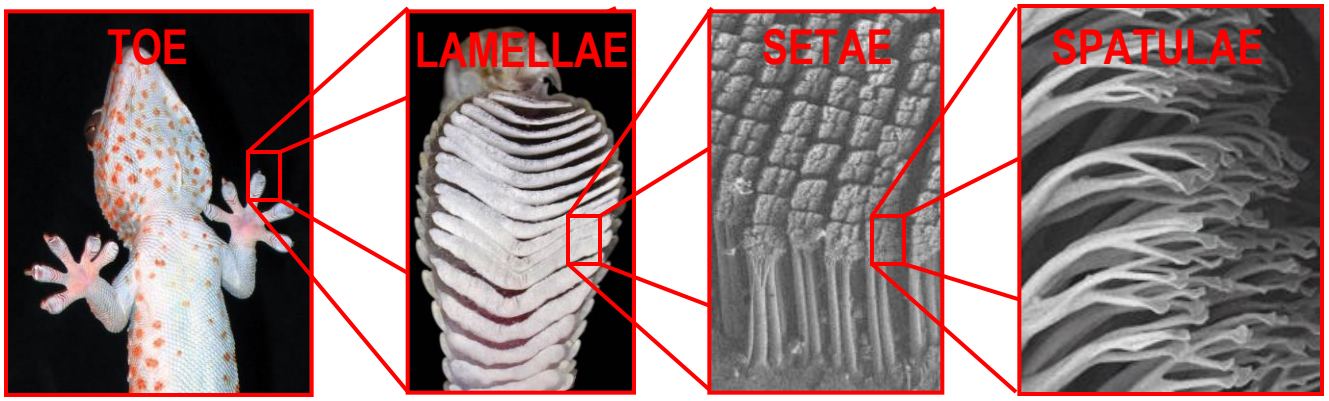


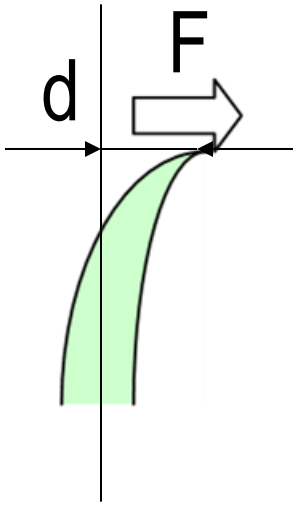
Dimensions?



- size ratio between successive layers
  - Gecko => logarithmic?
  - Theoretical (literature) => constant
  - Our work => 1:4 for three layers

Structural constraints?

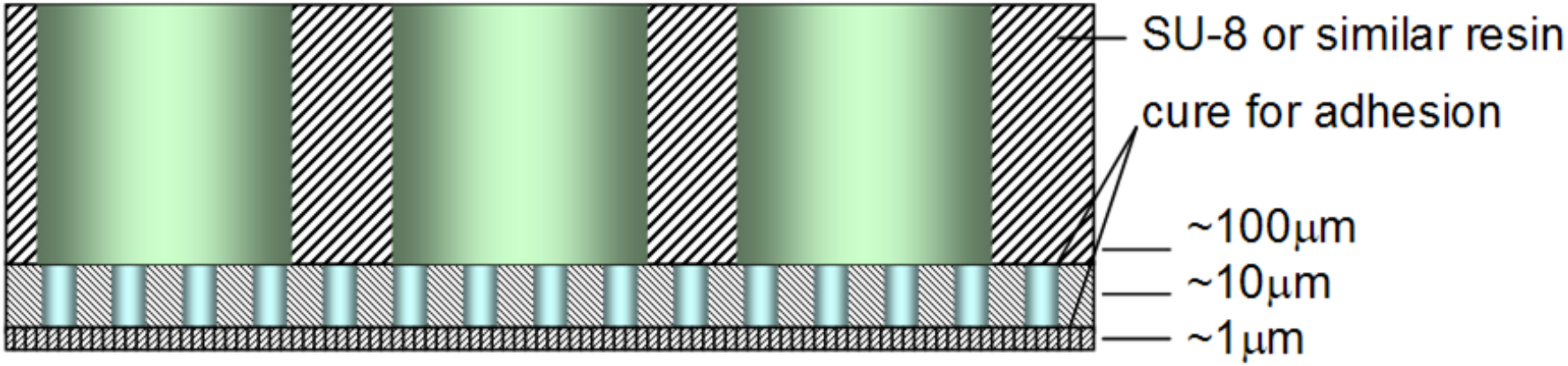




Gecko bending stiffness (defined as F/d)

Hair length/diameter = 2

Layers i-1, i and i+1 displayed



- **Stalk**: the larger structure in the hierarchy (**cylindrical** shape)
- **Lamella**: the larger structures in the hierarchy (triangular or rectangular shape)
- **Hair**: the smallest structure in the hierarchy

- **Layer**: refers to the hierarchy
- **Stack**: refers to the building direction (layered manufacturing)
- **Shim**: a stack of the mold

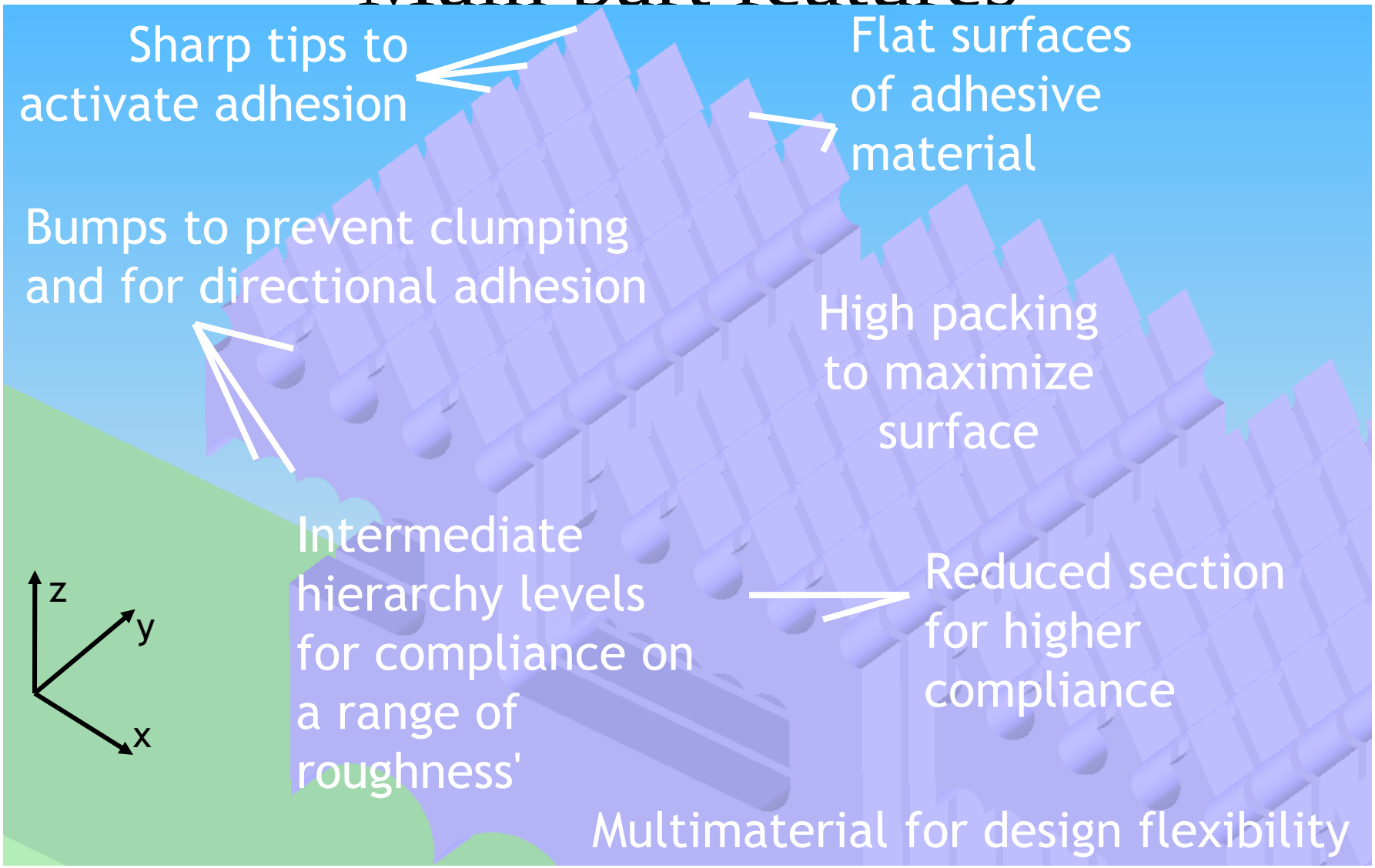
- **Wall**: the climbed surface
- **Toe**: the adhesive surface

Requirements

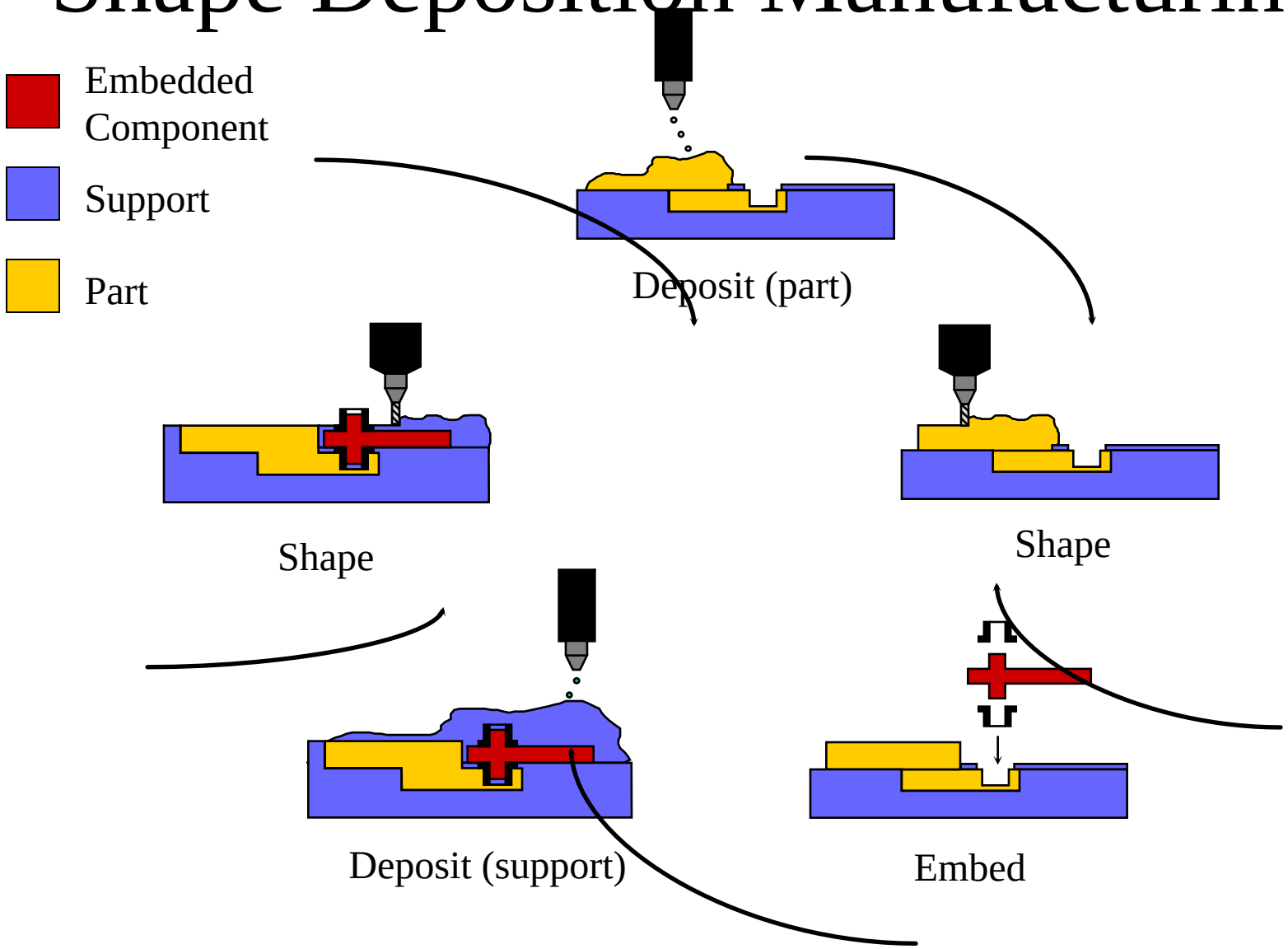
- structure is expandable to lower and higher size
- size steps can be jumped
- resin i-1, i and i+1 can be different but they needs to be compatible (cure to each other)
- layers can be cast from a positive or they can be any very flat plate (e.g. Si or quartz, but also steel, like in a mesh or filter) with holes
- each layer can be extruded and then stacked

...

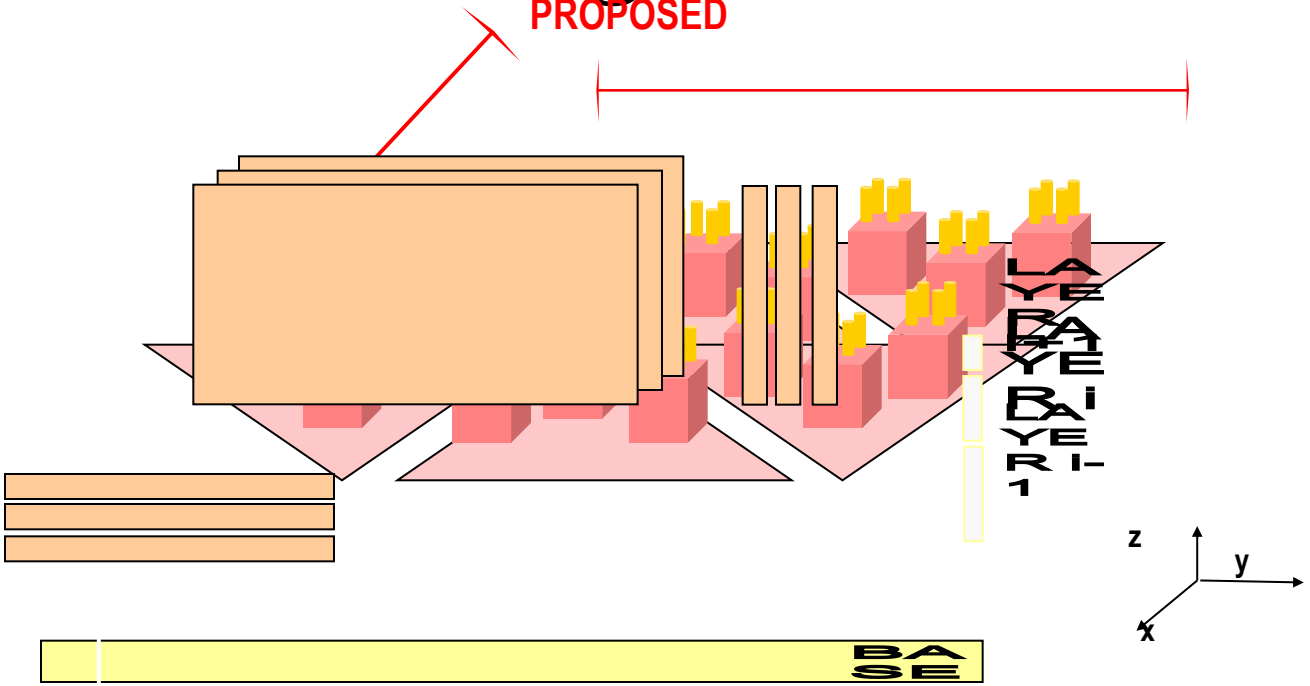
Main part features



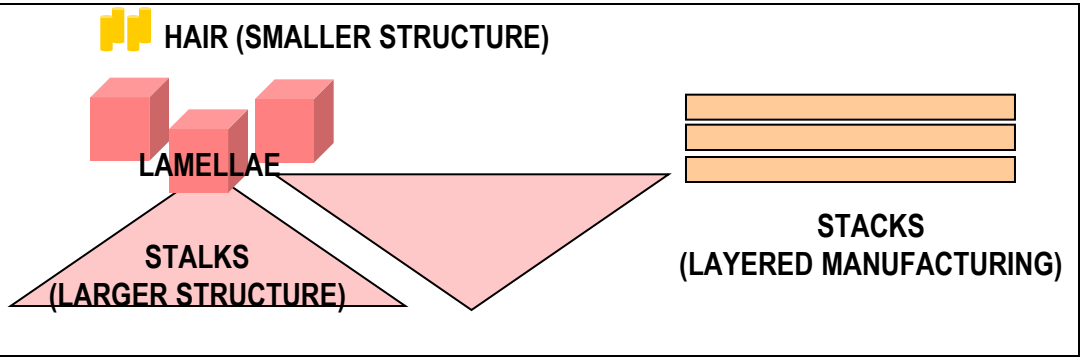
Shape Deposition Manufacturing



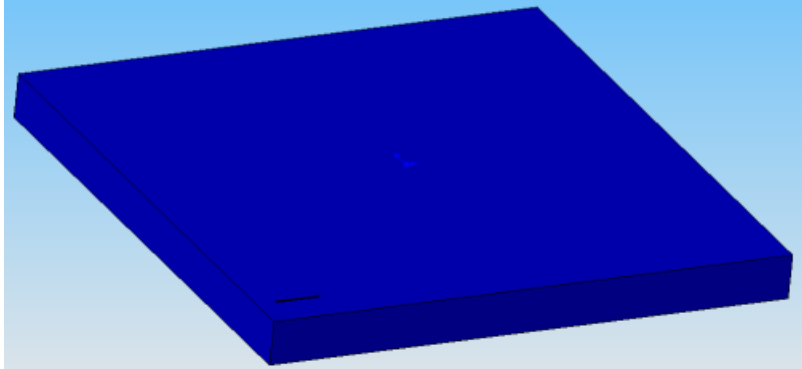
Building direction



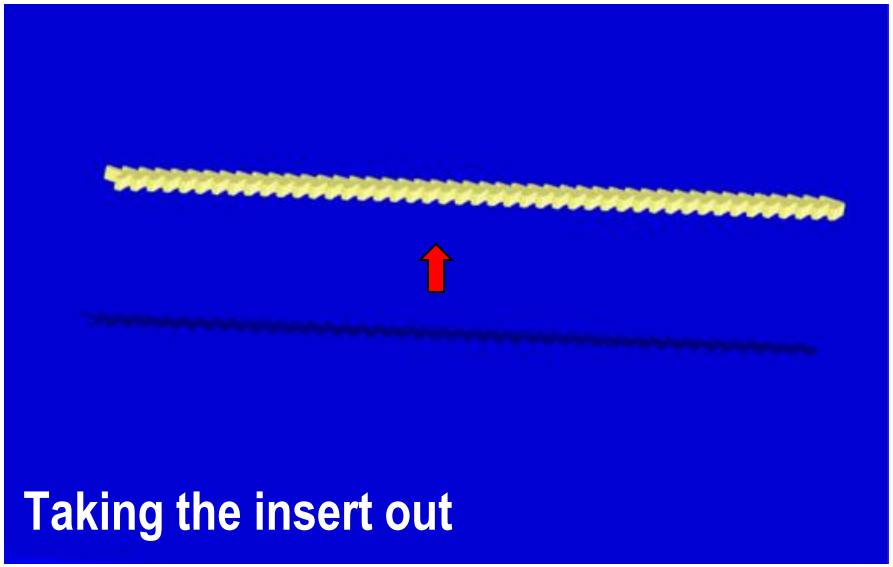
LEGENDA / DEFINITIONS / NOMENCLATURE



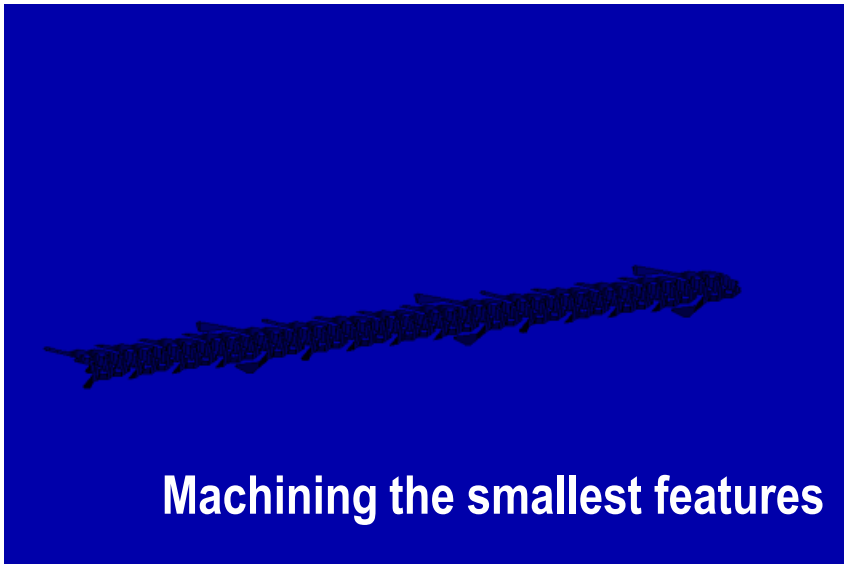
Machining a cavity for the insert



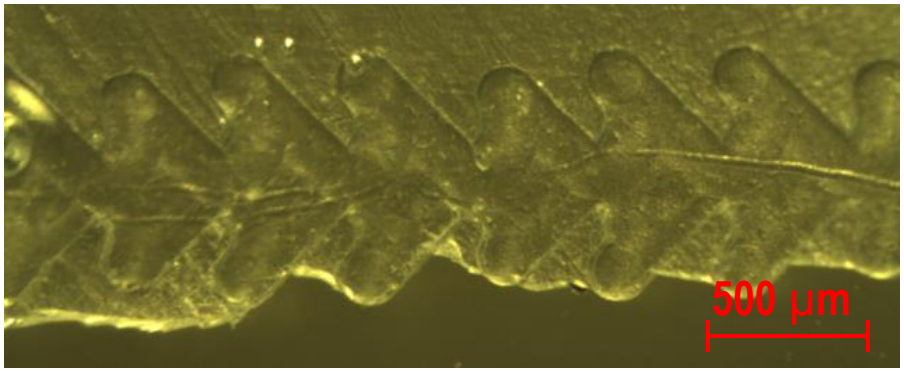
Casting the insert (hard urethane)

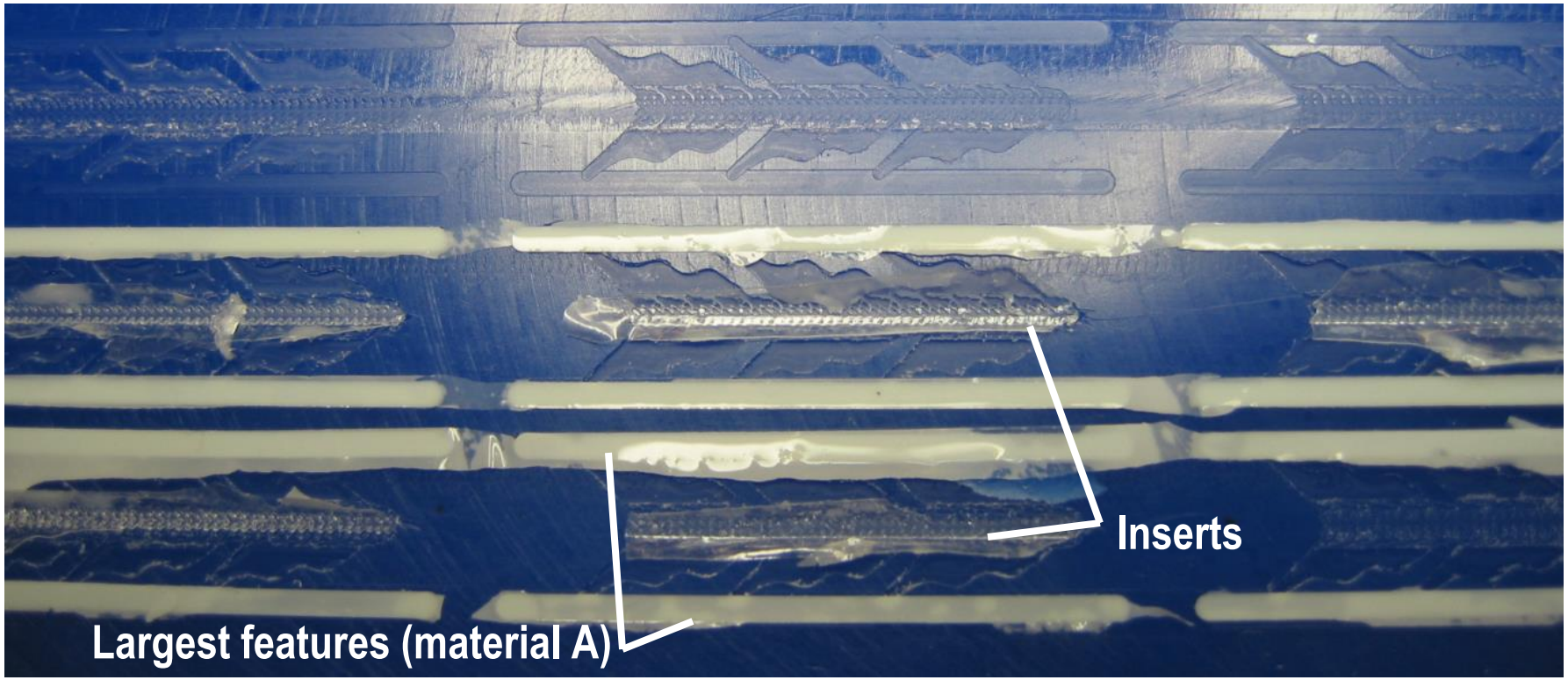


Taking the insert out



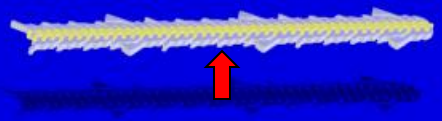
Machining the smallest features

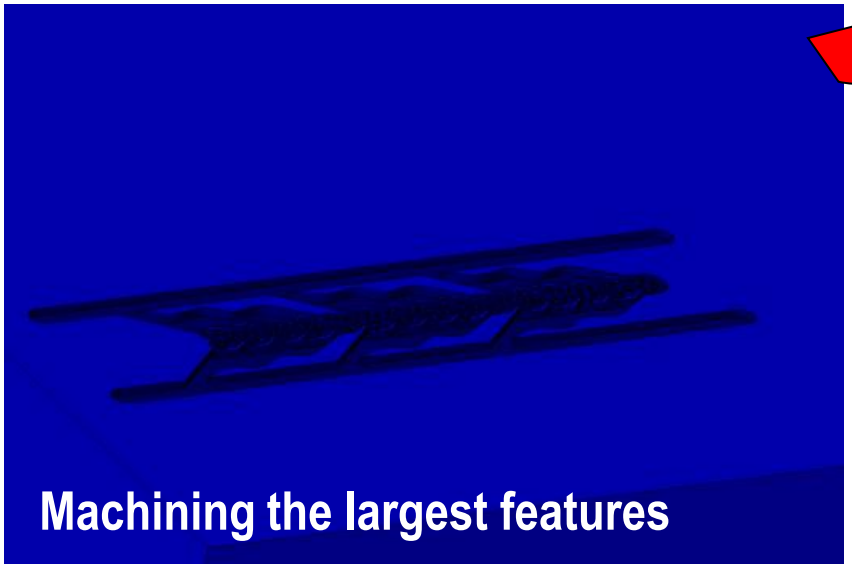

500 µm


Inserts
Largest features (material A)

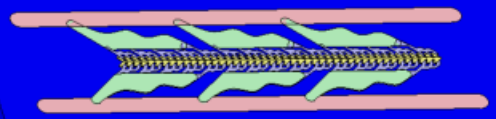
Casting the smallest features (silicone)

Taking the cast (and the insert) out



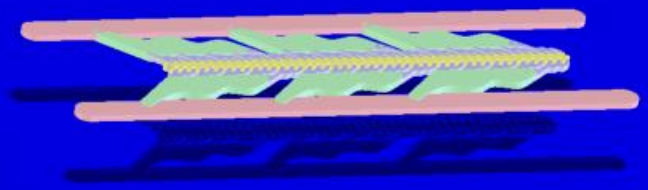


Machining the largest features

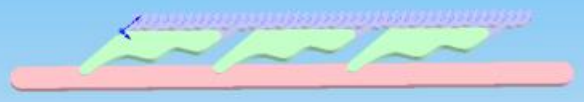


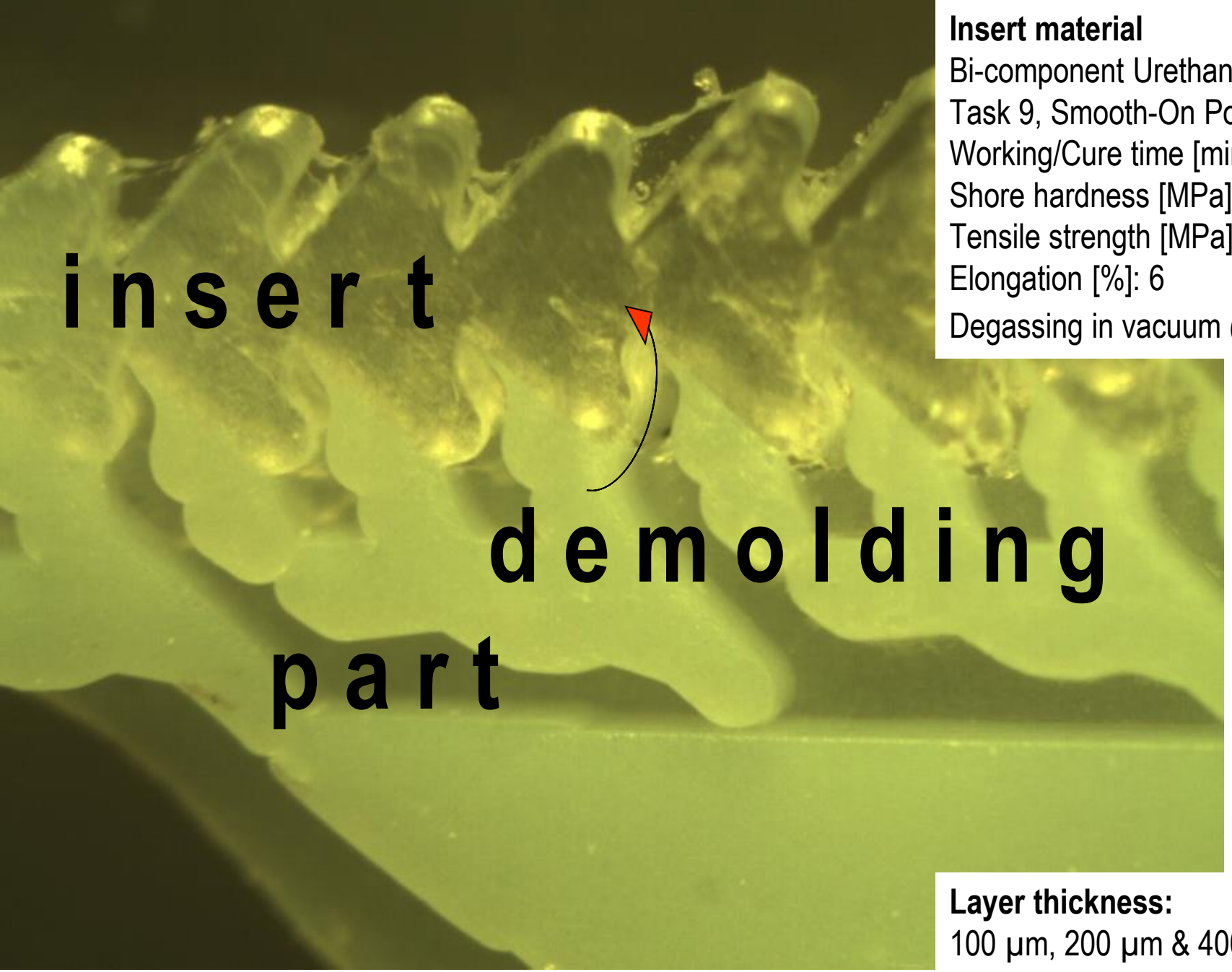
(compatible silicone)
Casting the largest features

Demolding the final part



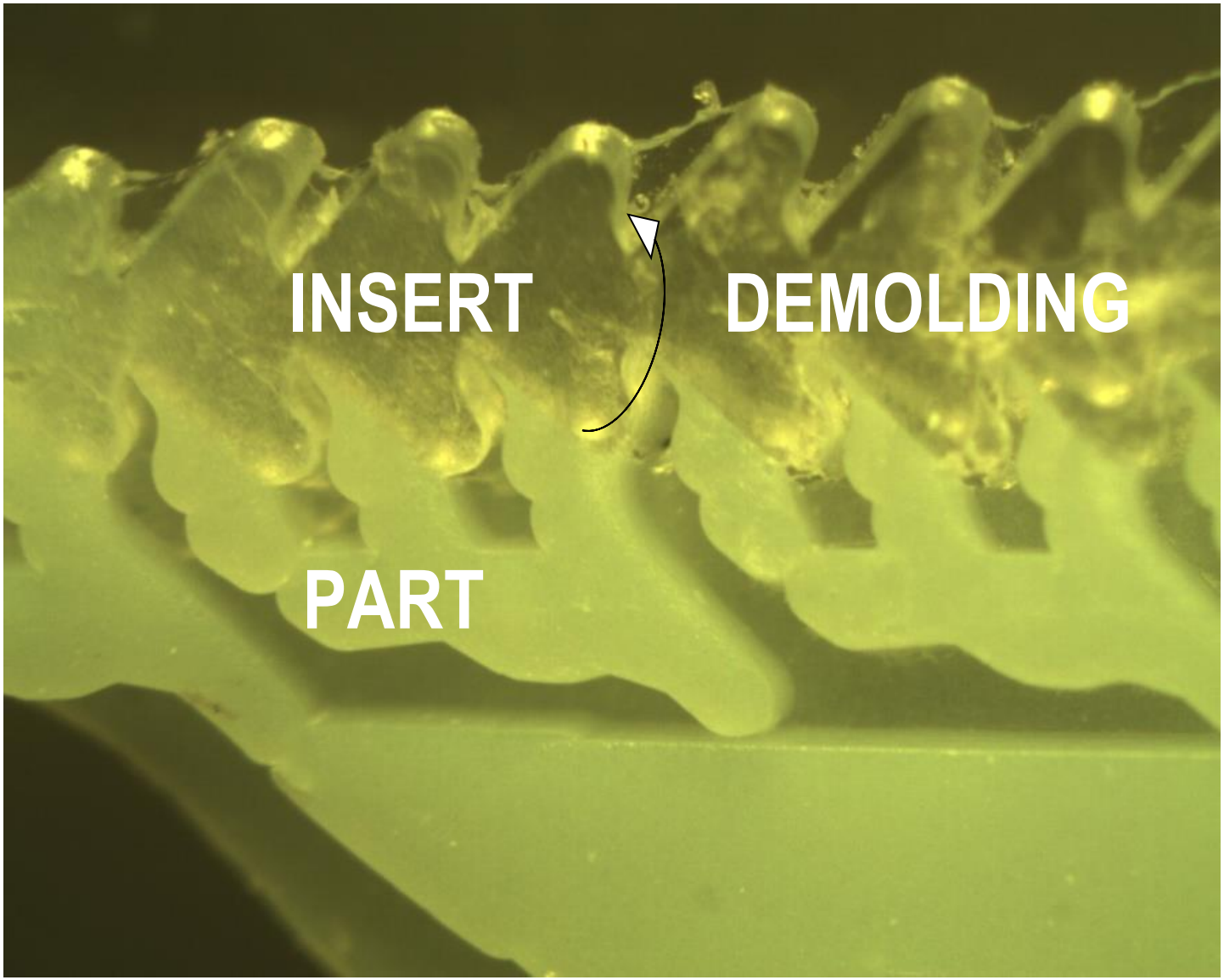
Splitting into two symmetrical parts



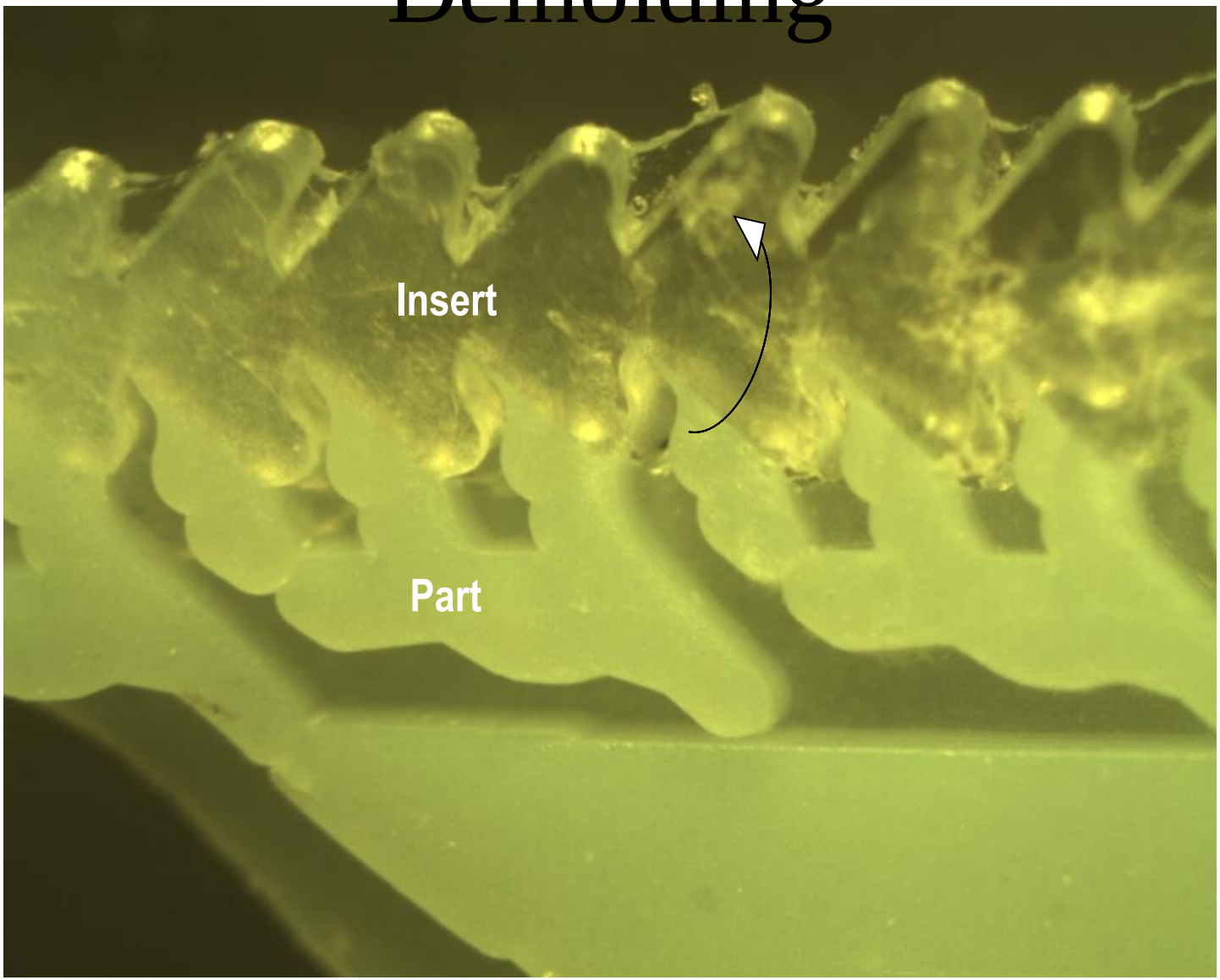


Insert material
Bi-component Urethane:
Task 9, Smooth-On Polymers, Inc.
Working/Cure time [min./h.]: 7/14
Shore hardness [MPa]: 85D
Tensile strength [MPa]: 54
Elongation [%]: 6
Degassing in vacuum @ 26” Hg

Layer thickness:
100 µm, 200 µm & 400 µm


INSERT
DEMOLDING
PART

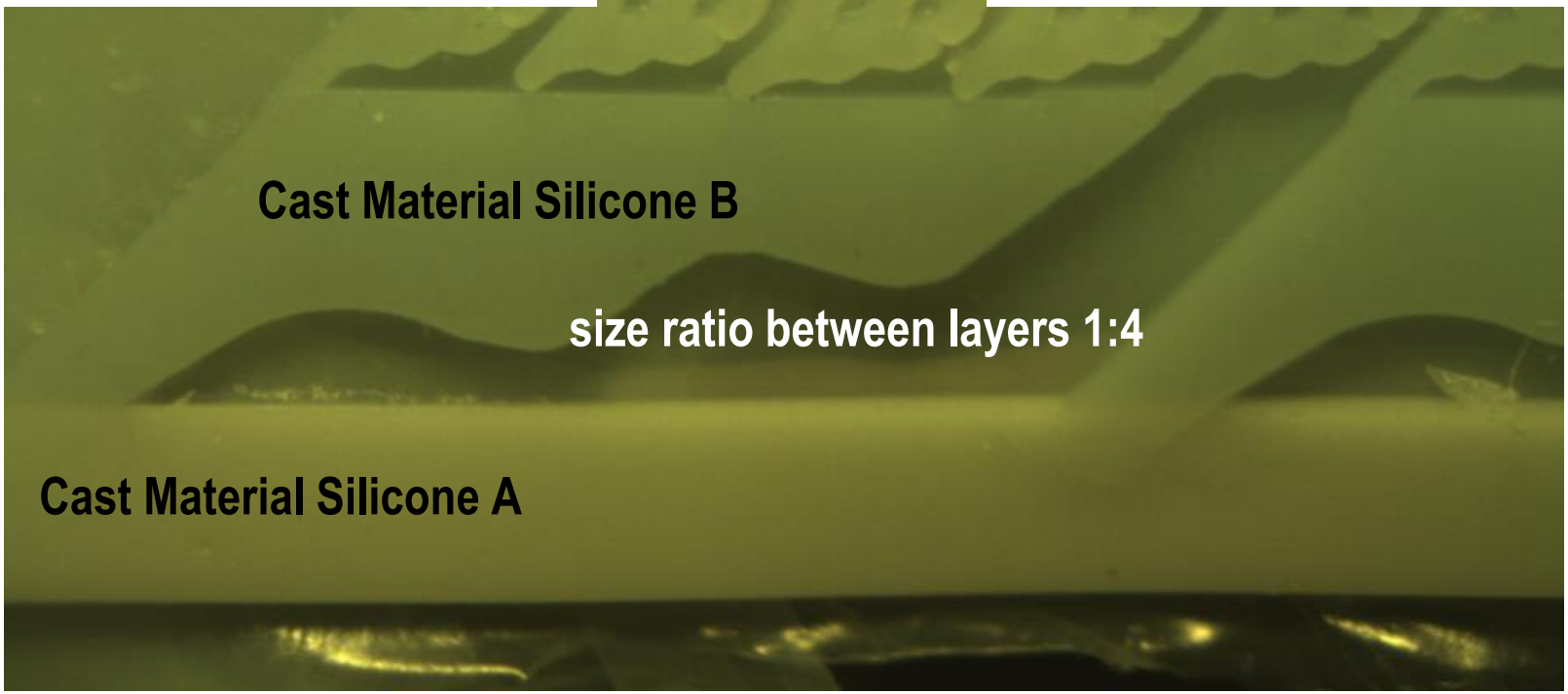
Demolding

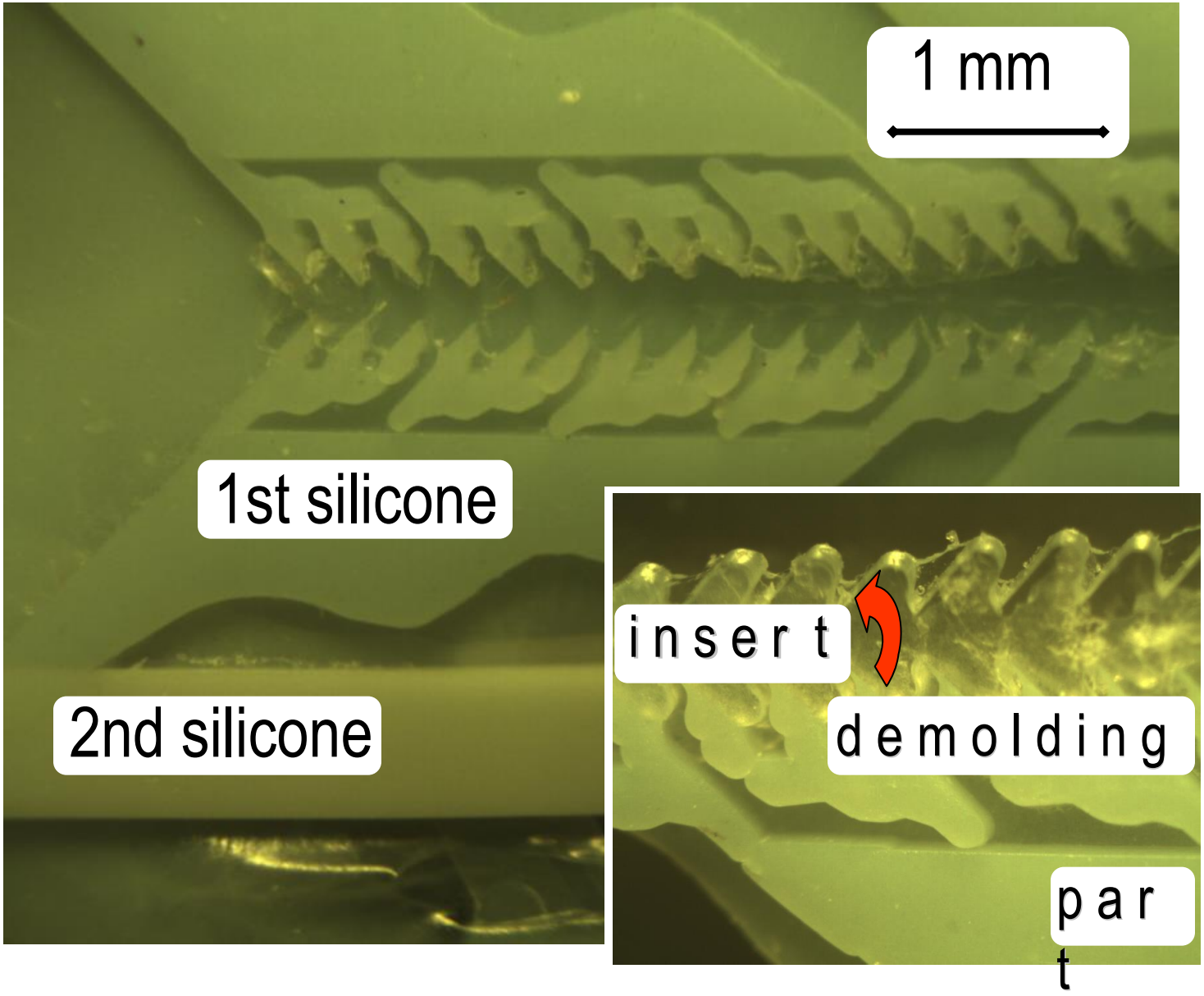


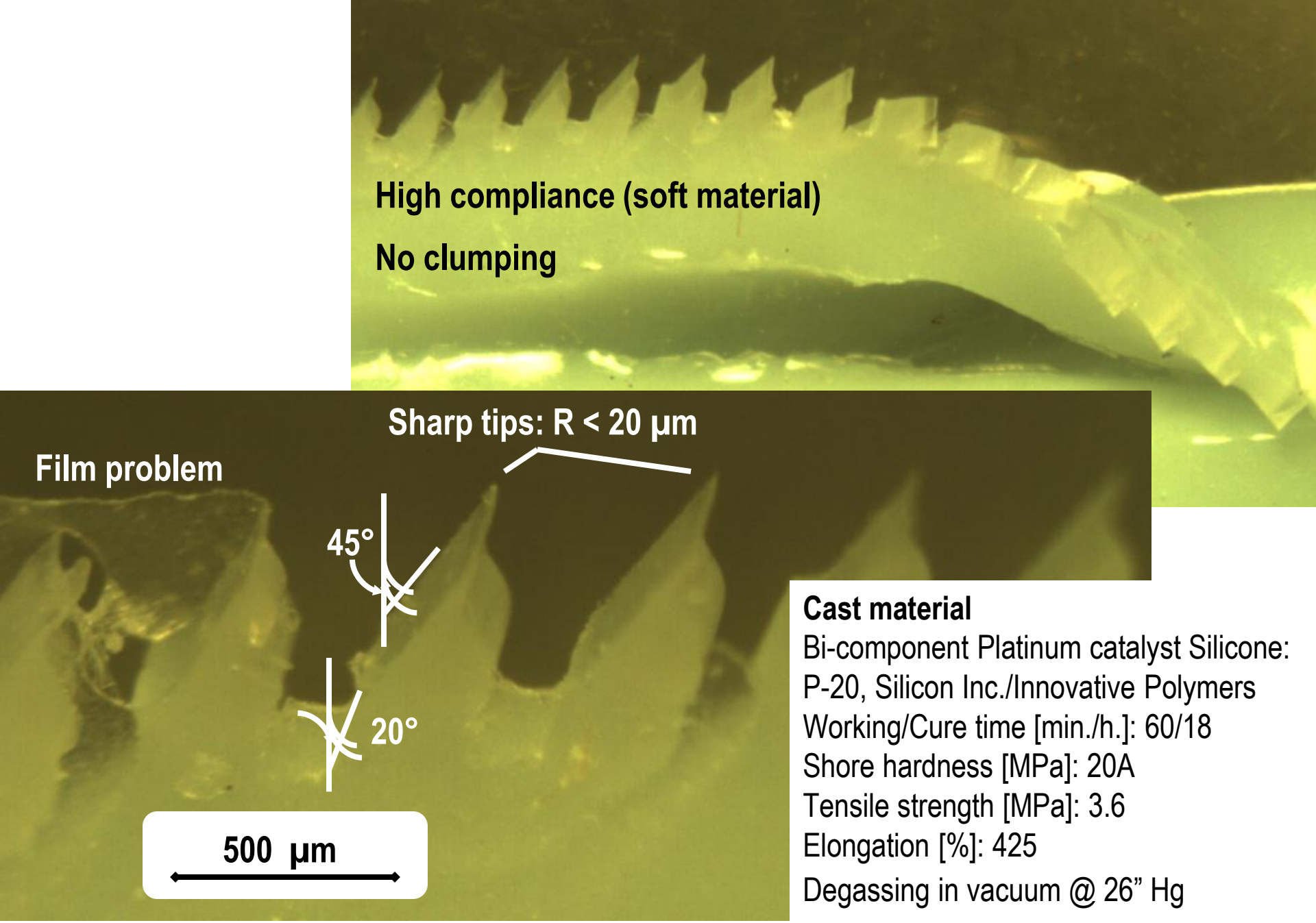
Two symmetrical hierarchical structures

Cast material A
Bi-component Platinum catalyst Silicone:
P-100, Silicon Inc./Innovative Polymers
Working/Cure time [min./h.]: 60/24
Shore hardness [MPa]: 80A
Tensile strength [MPa]: 3.3
Elongation [%]: 345
Degassing in vacuum @ 26” Hg

Cast material B
Bi-component Platinum catalyst Silicone:
P-20, Silicon Inc./Innovative Polymers
Working/Cure time [min./h.]: 60/18
Shore hardness [MPa]: 20A
Tensile strength [MPa]: 3.6
Elongation [%]: 425
Degassing in vacuum @ 26” Hg




1 mm
1st silicone
2nd silicone
insert
demolding
part



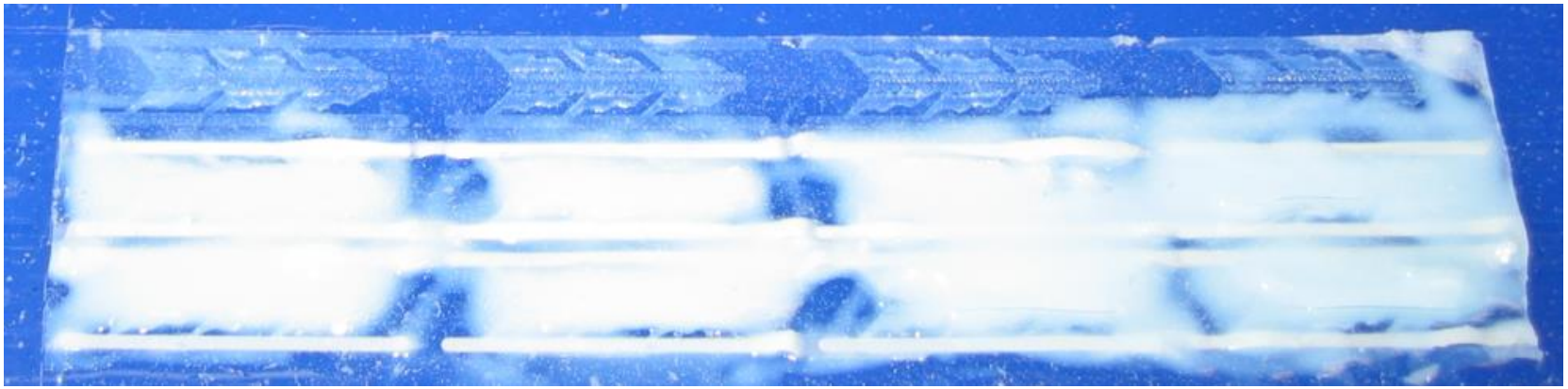
Cast material

Bi-component Platinum catalyst Silicone:
P-20, Silicon Inc./Innovative Polymers
Working/Cure time [min./h.]: 60/18
Shore hardness [MPa]: 20A
Tensile strength [MPa]: 3.6
Elongation [%]: 425
Degassing in vacuum @ 26” Hg

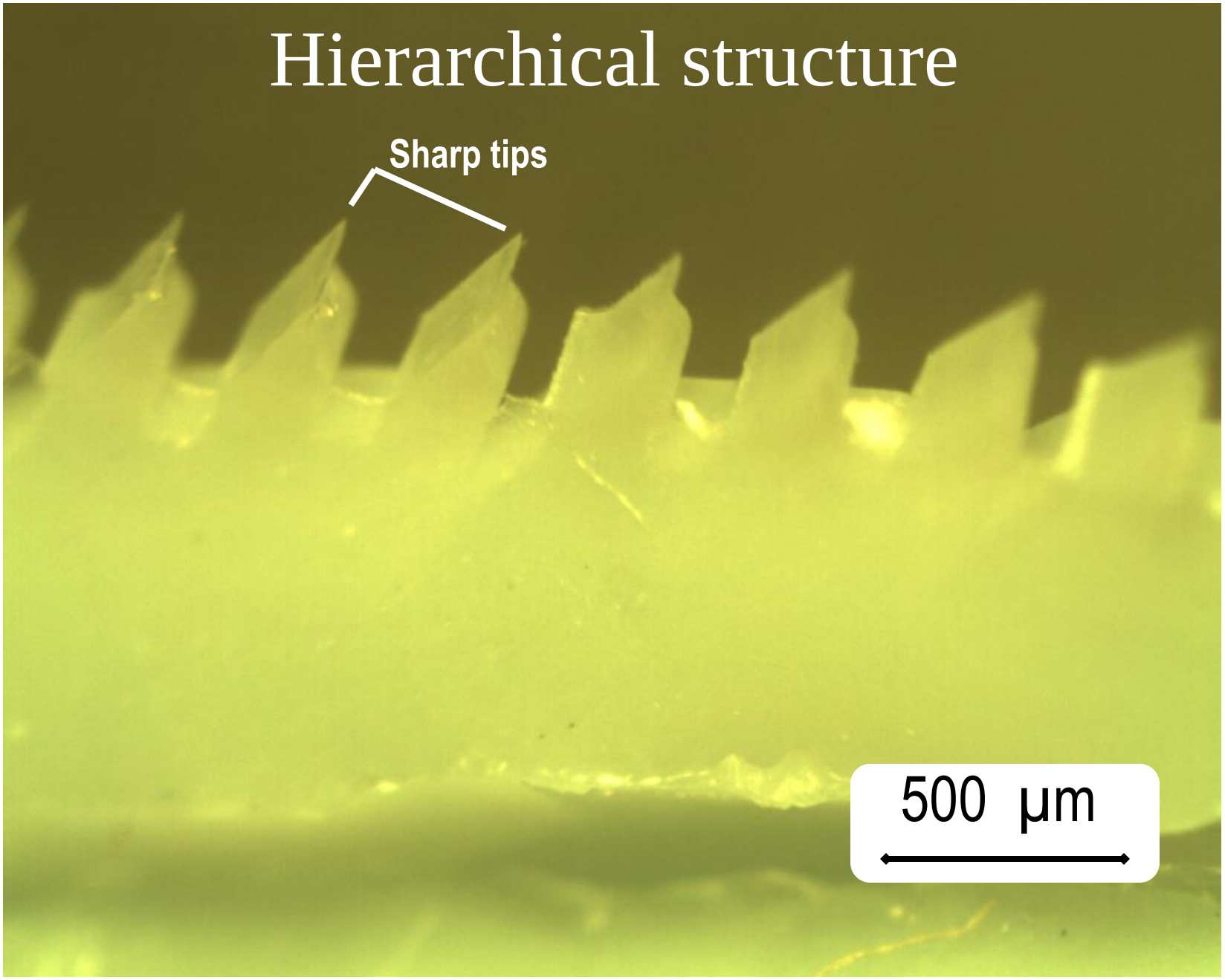
Casting problem

Batch of 42 parts

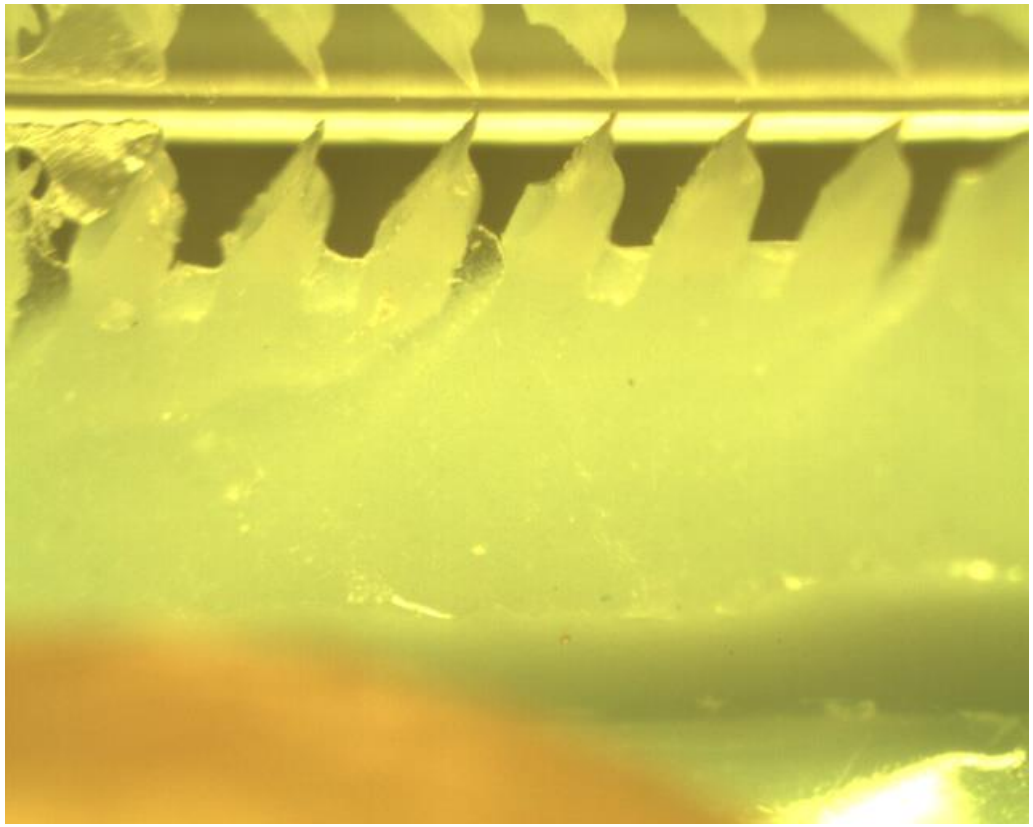
Depth of cavity: 100 µm (top row); 400 µm (middle row); 200 µm (bottom row)



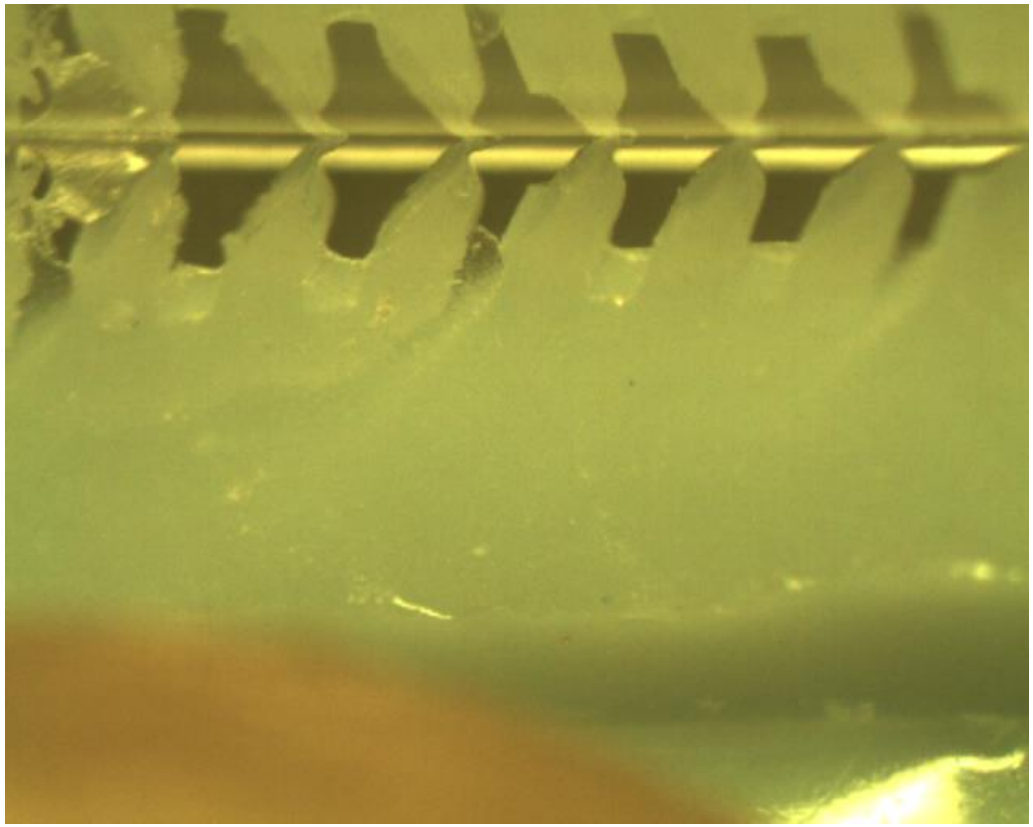
- Excess of cast material
  - it is too thick to spread uniformly
  - is too soft to plane after curing


Hierarchical structure
Sharp tips
500 µm

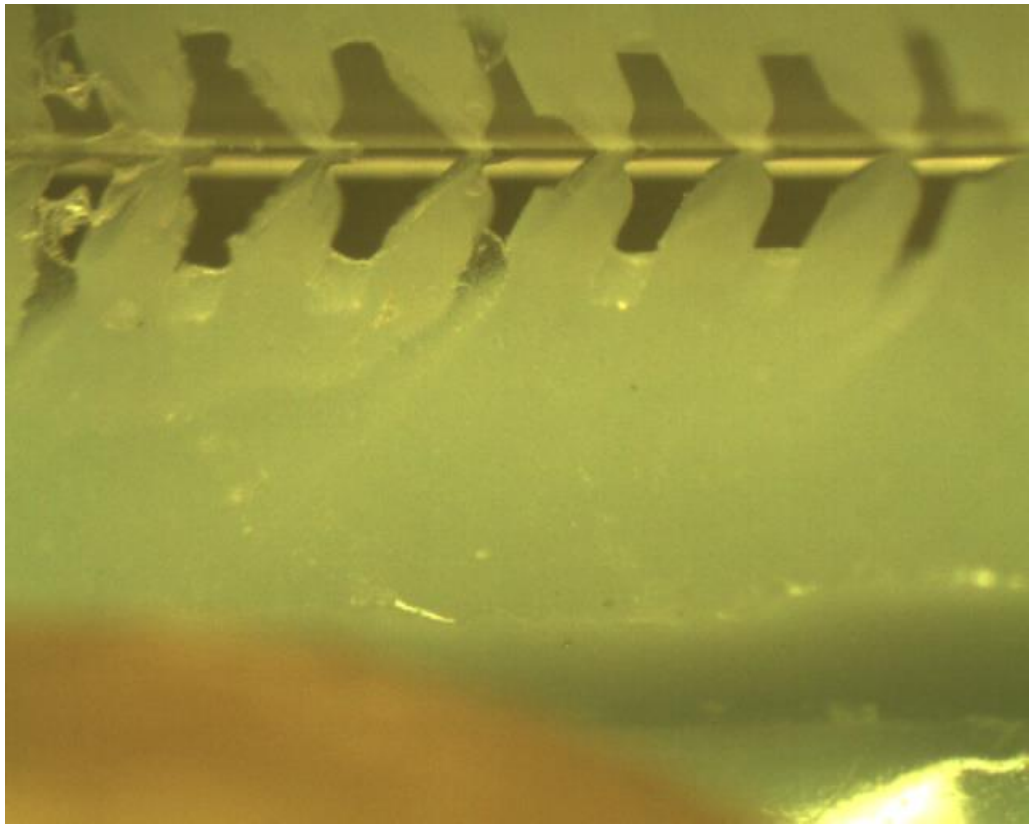
Adhesion activation



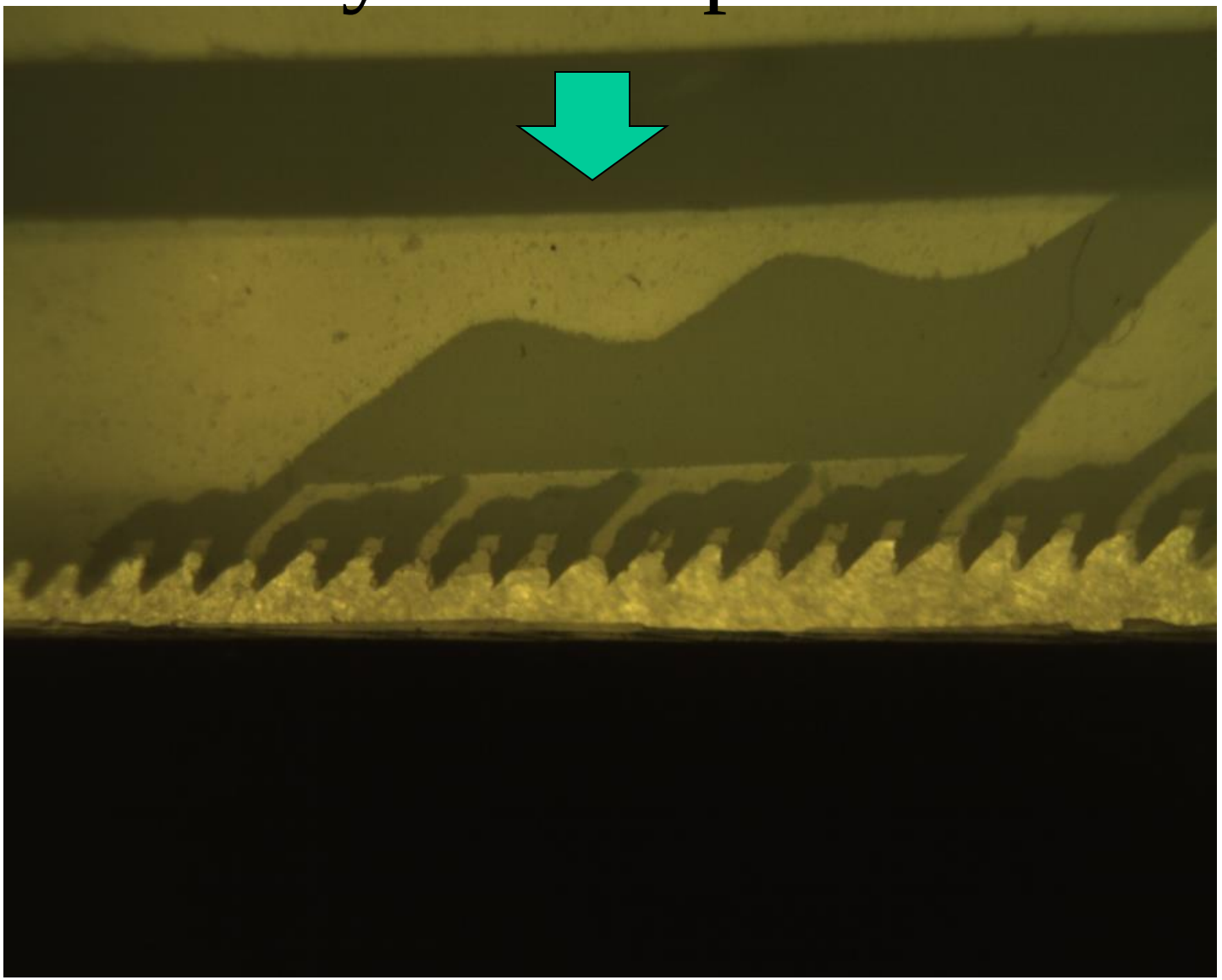
Adhesion activation



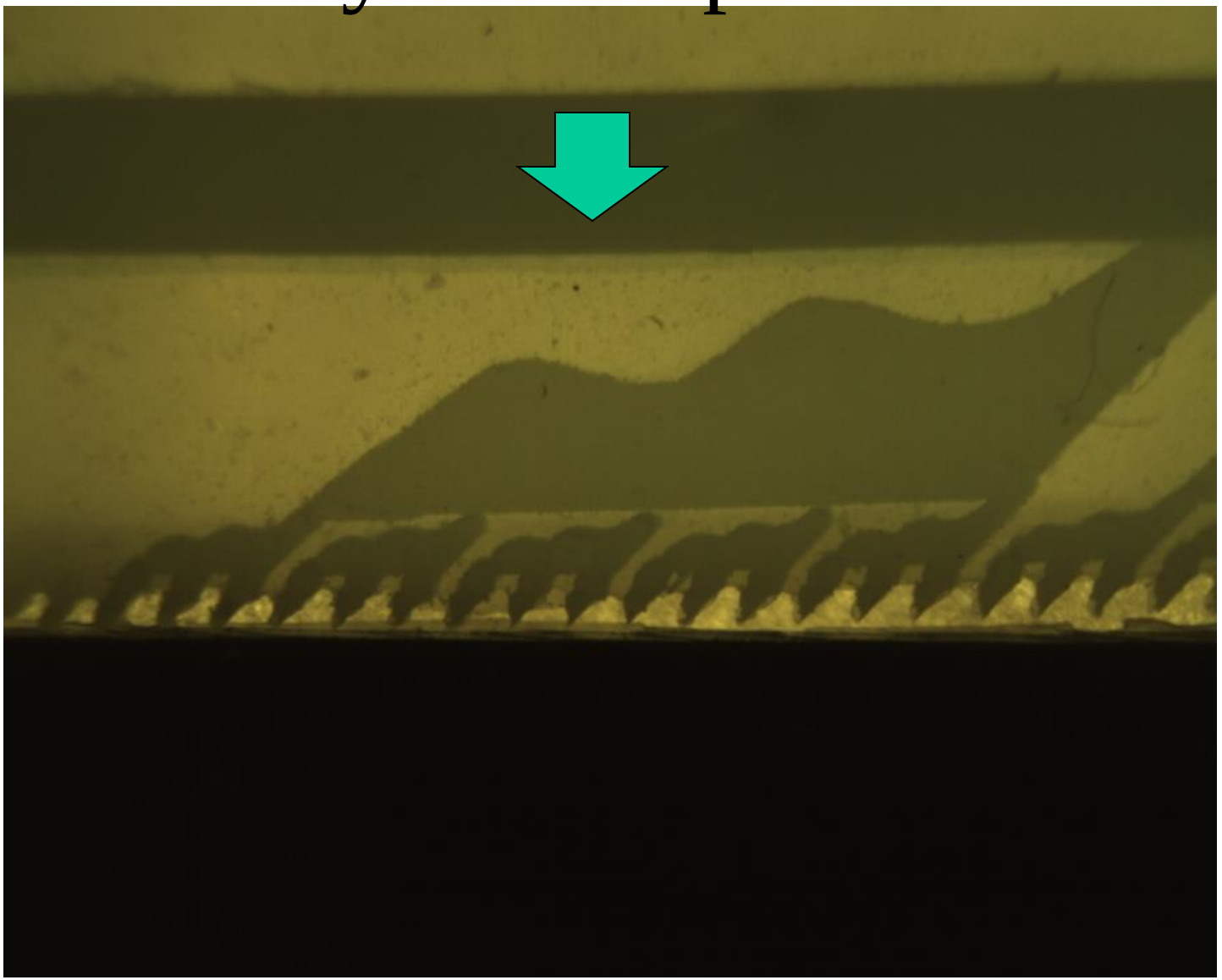
Adhesion activation



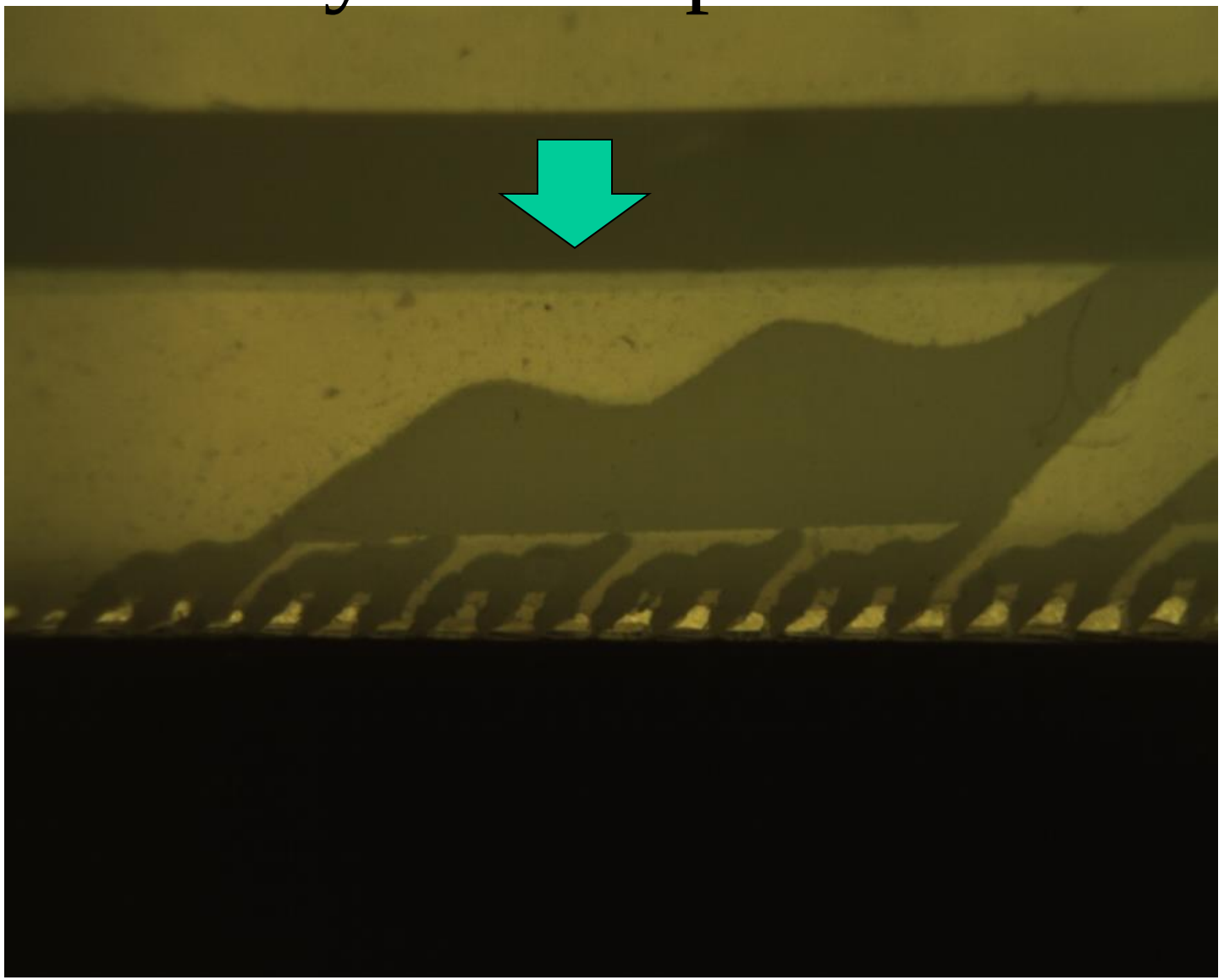
Layers compliance



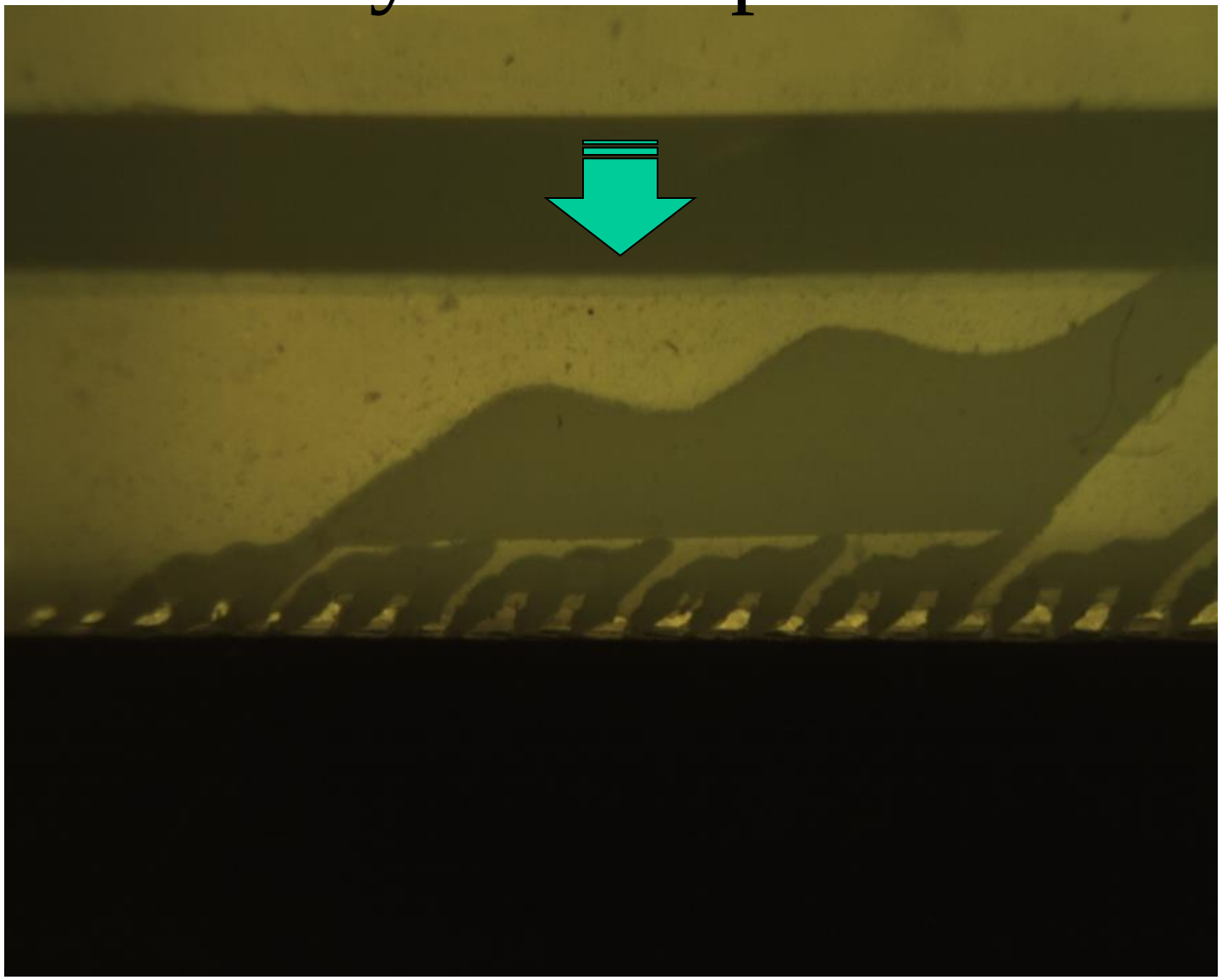
Layers compliance



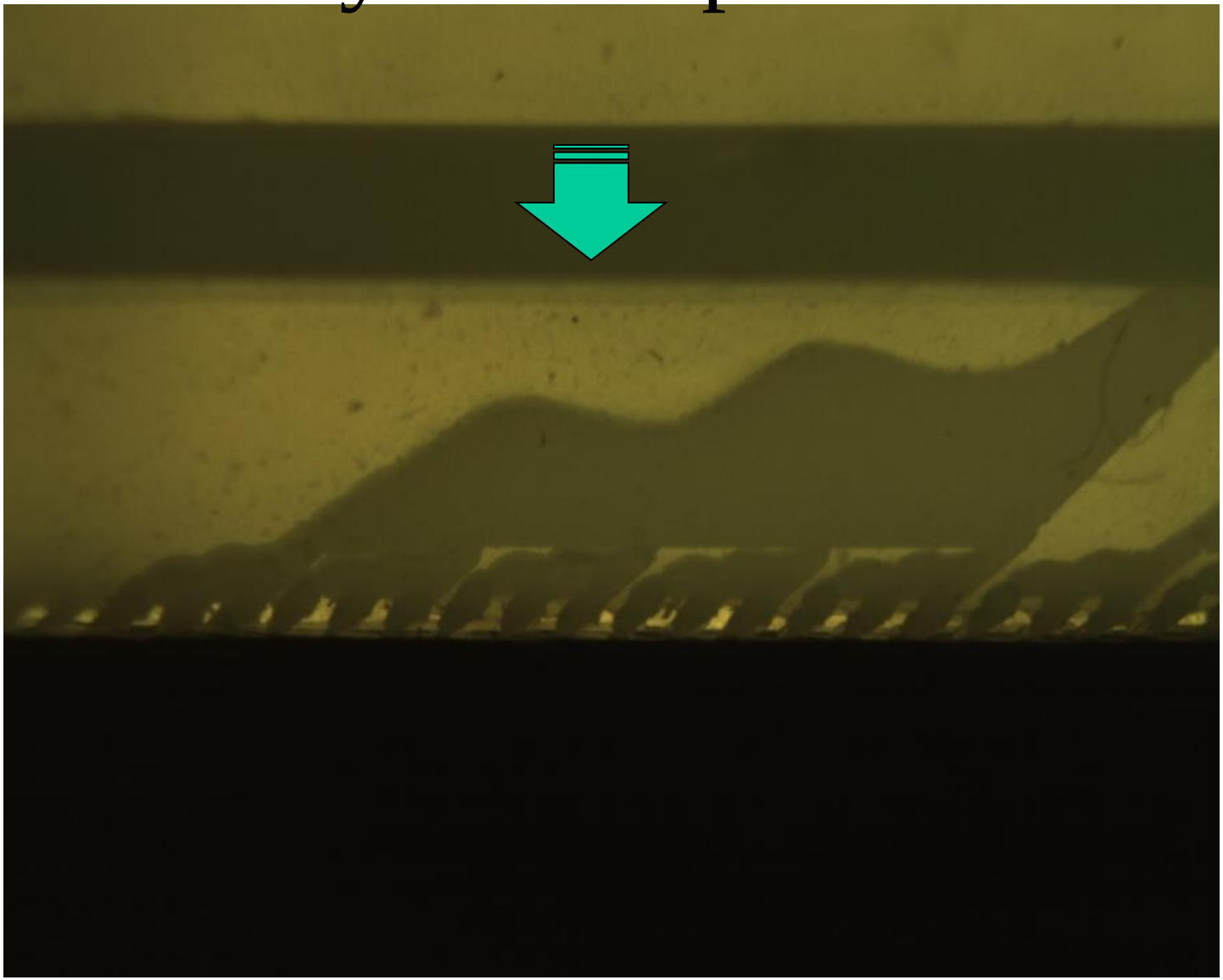
Layers compliance



Layers compliance

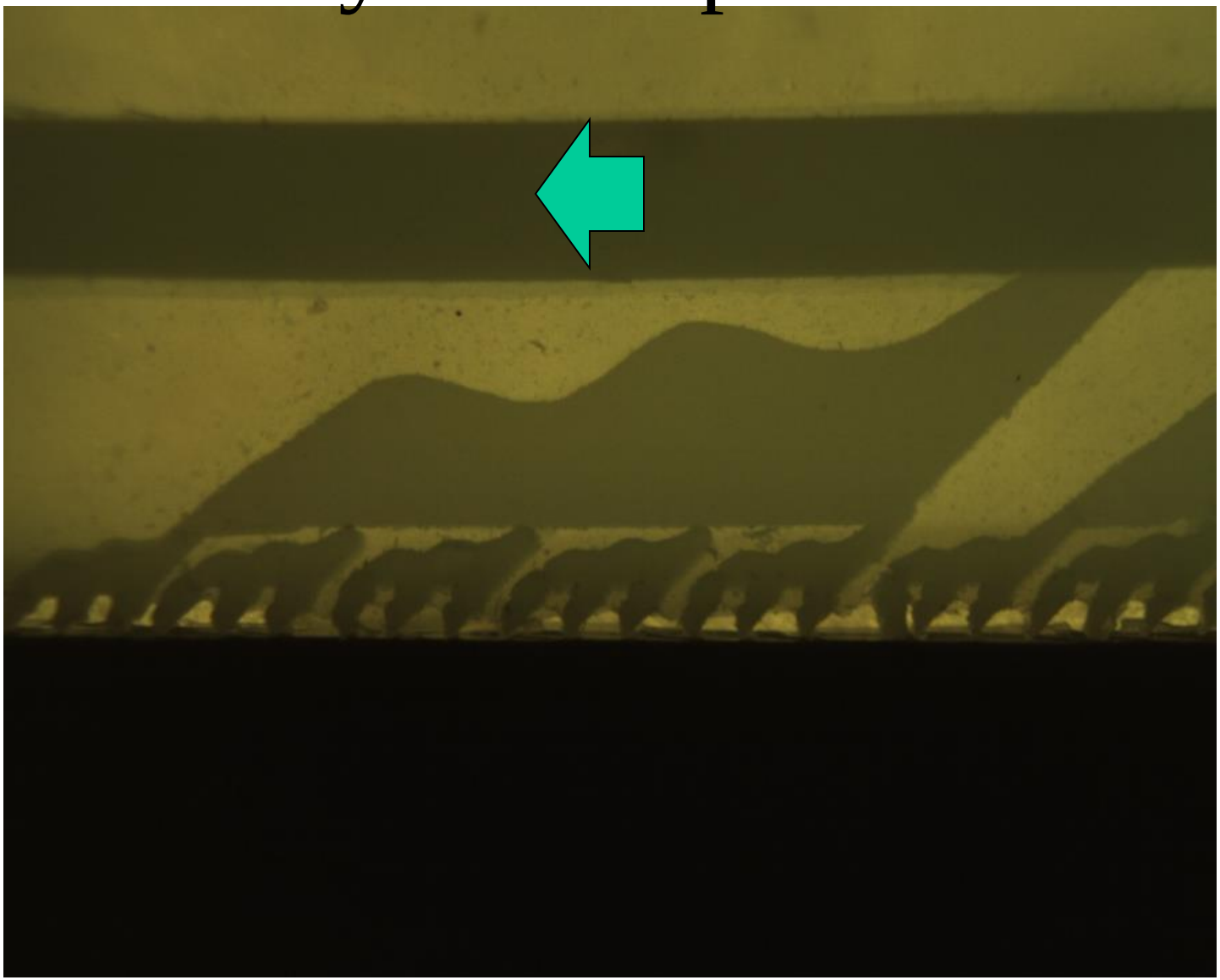


Layers compliance

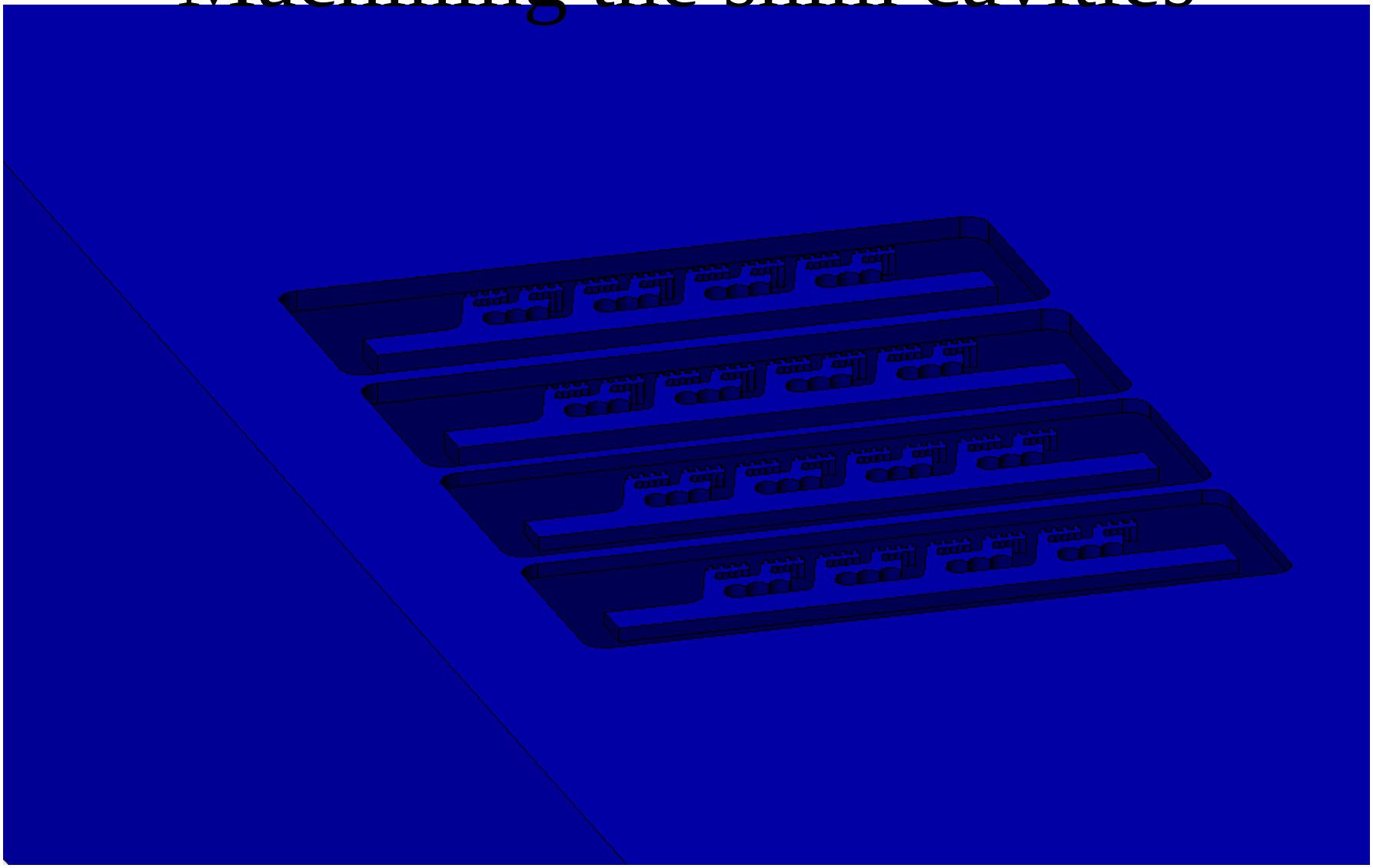


Layers compliance

Layers compliance

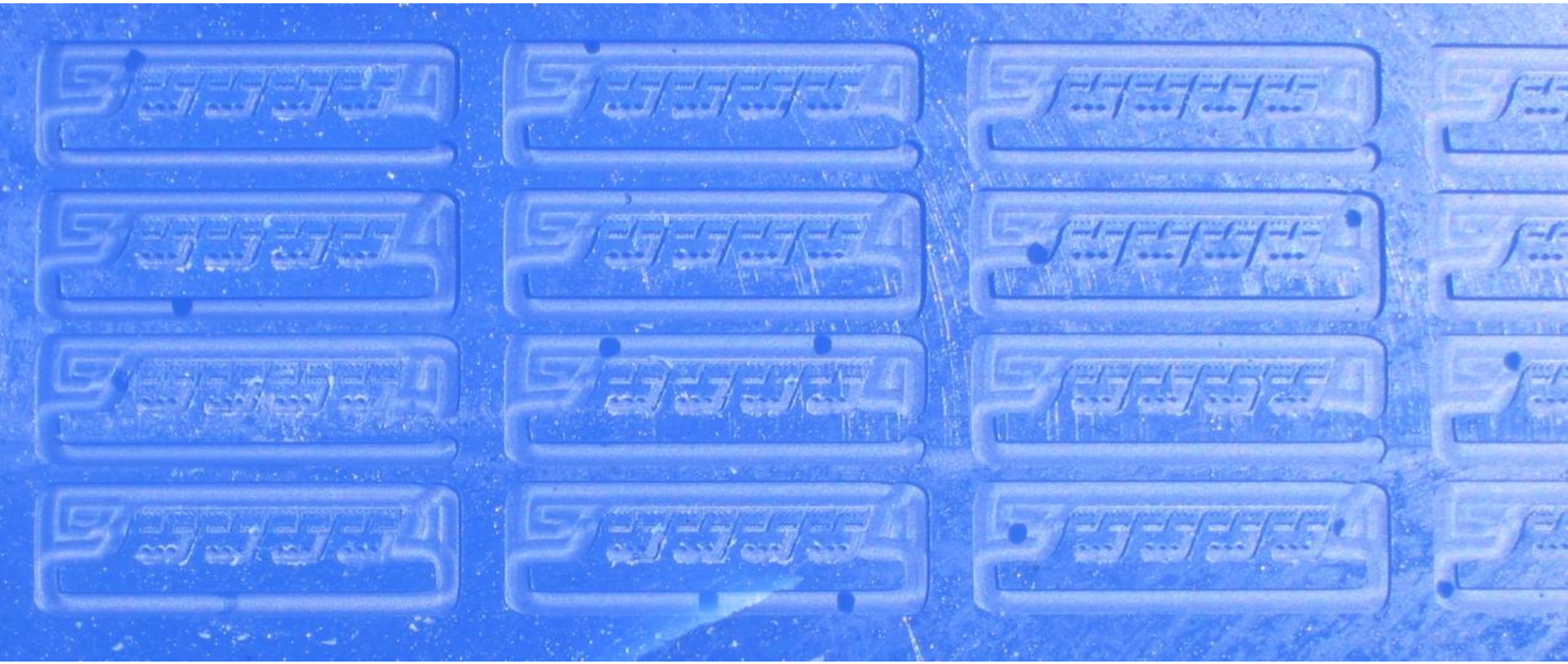


Machining the shim cavities



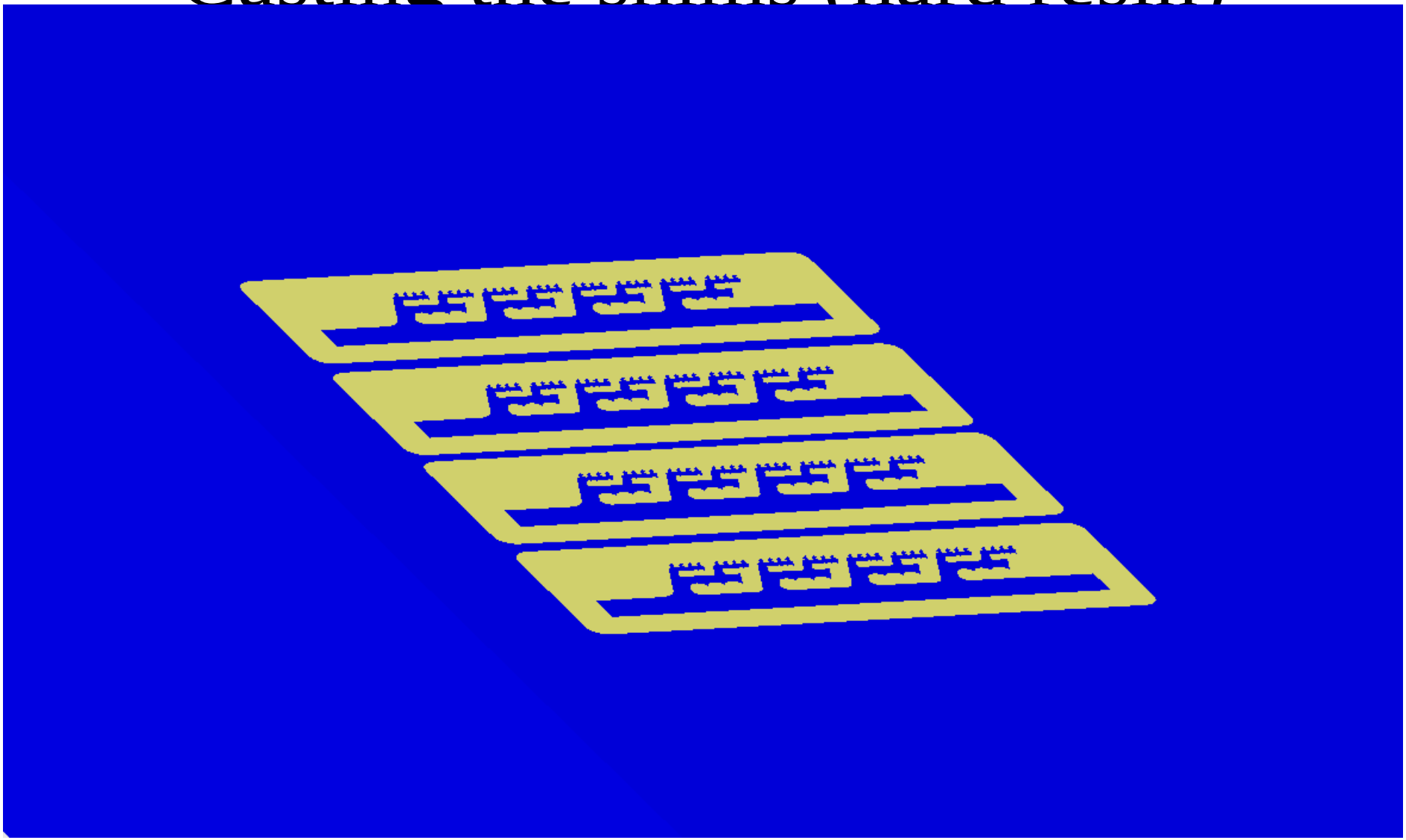
Machining the shim cavities

Batch of 40 parts

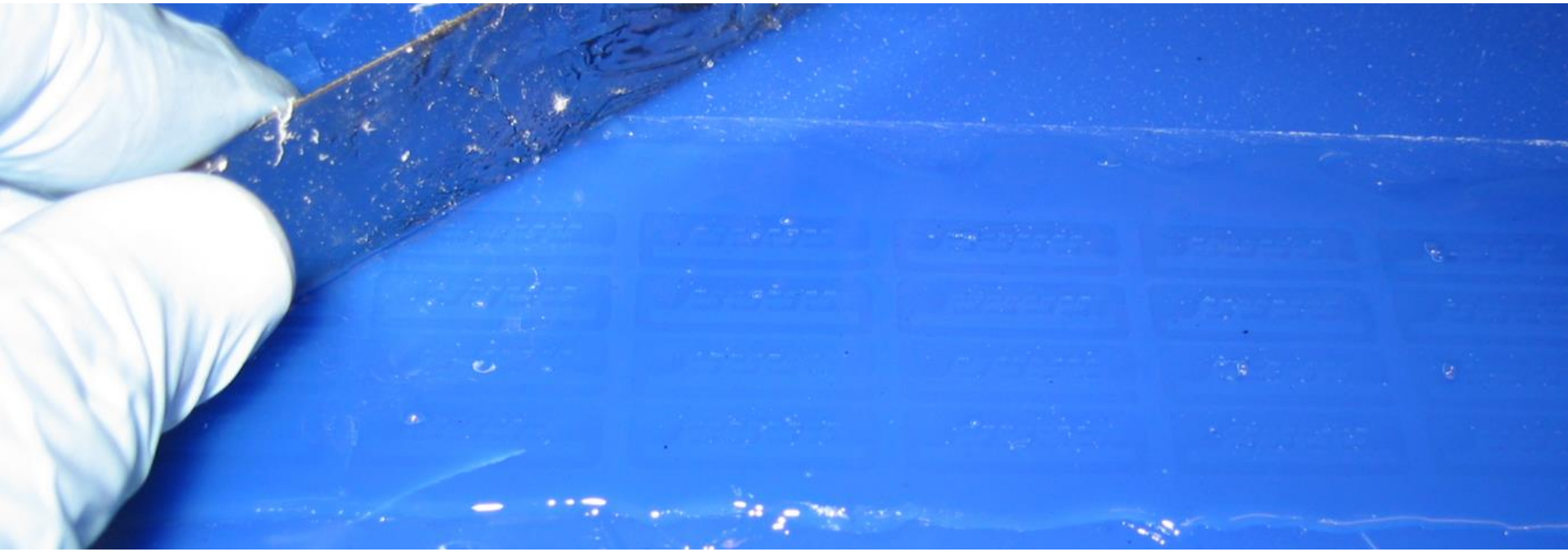


Depth of cavity: 750 µm (top two rows); 500 µm (bottom two rows)

Casting the shims (hard resin)



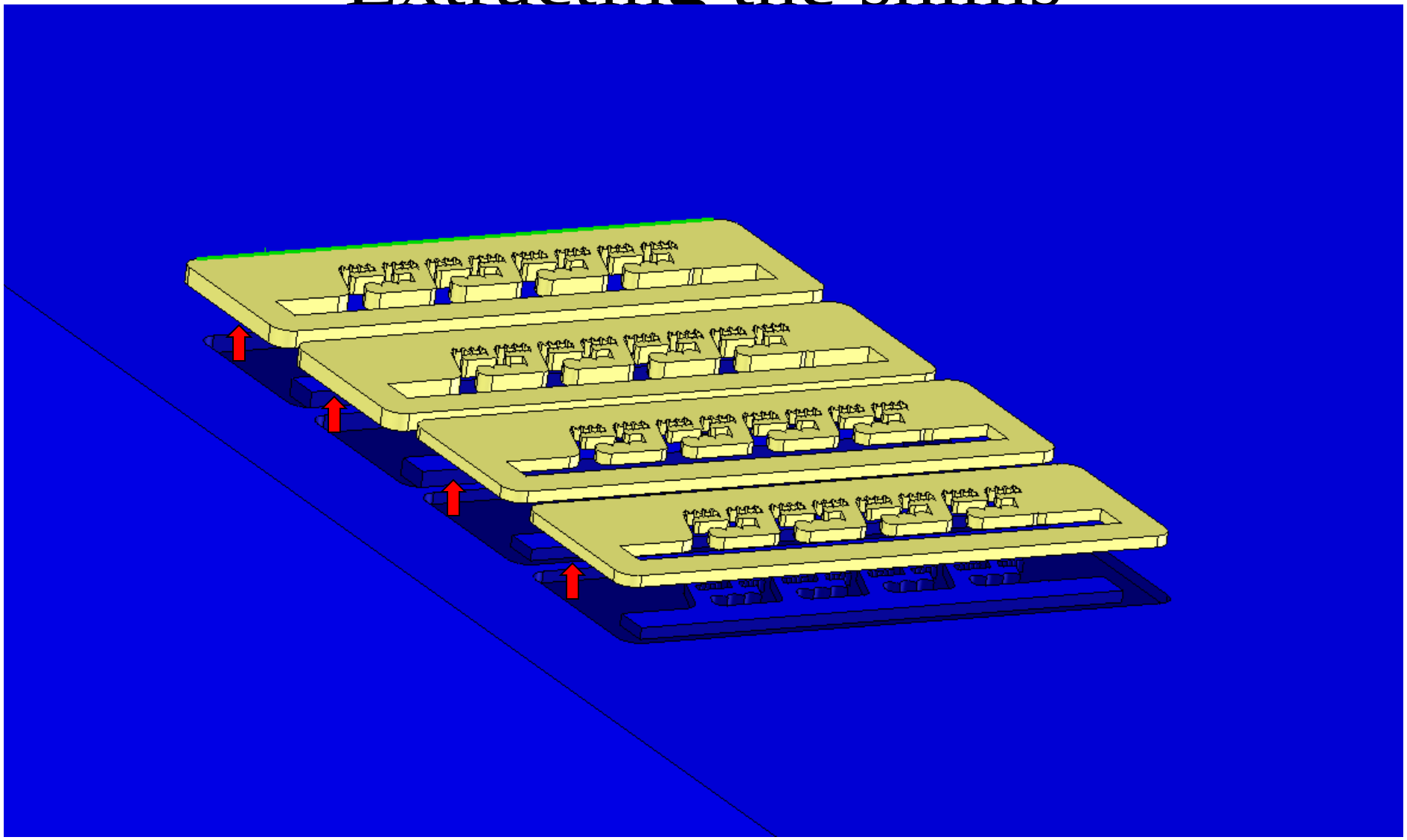
Spreading the resin



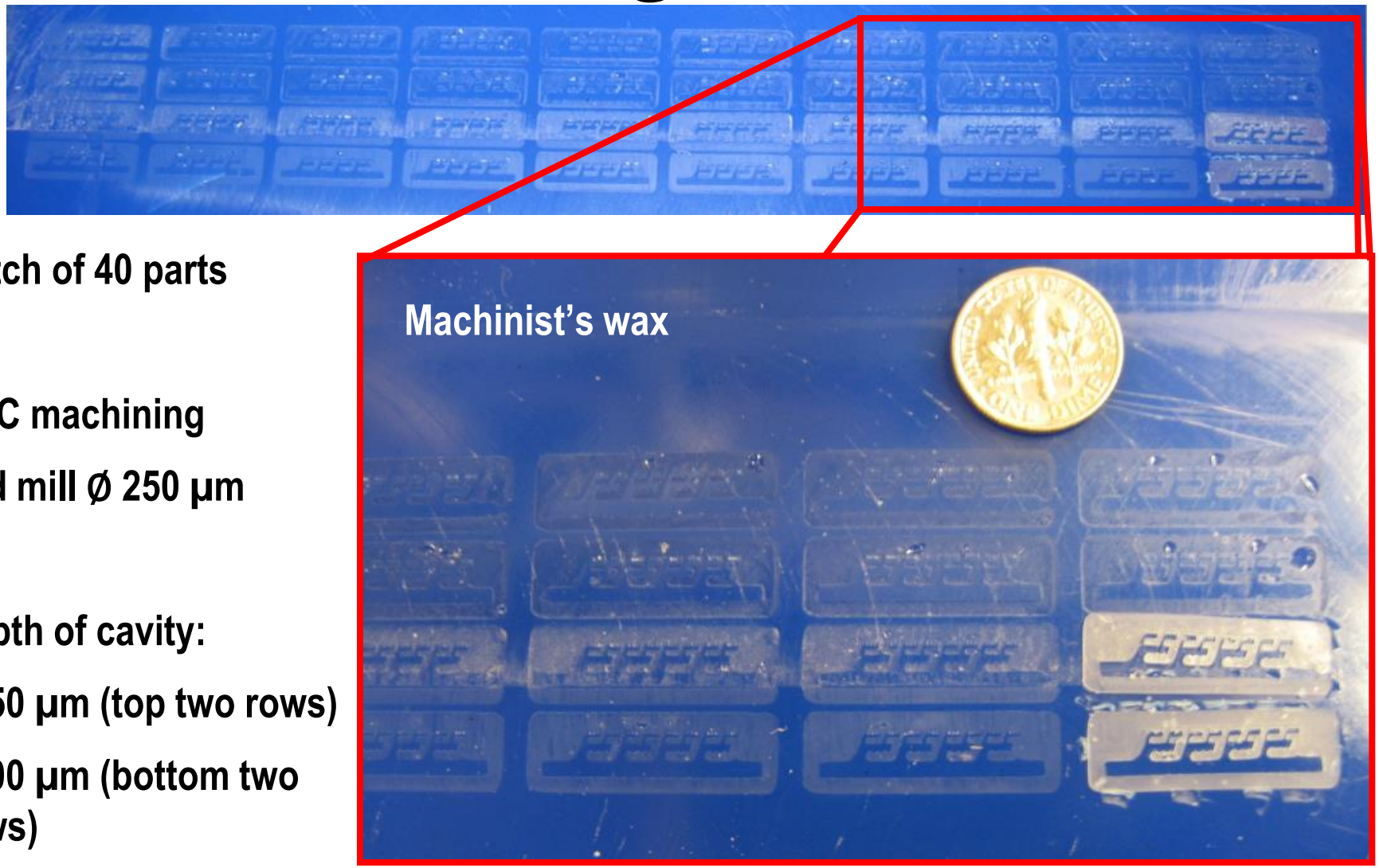
Cast material: Bi-component Urethane from SmoothOn Task 9

Degassing in vacuum @ 26” Hg for 5 minutes (working time)

Extracting the shims



Extracting the shims



Batch of 40 parts

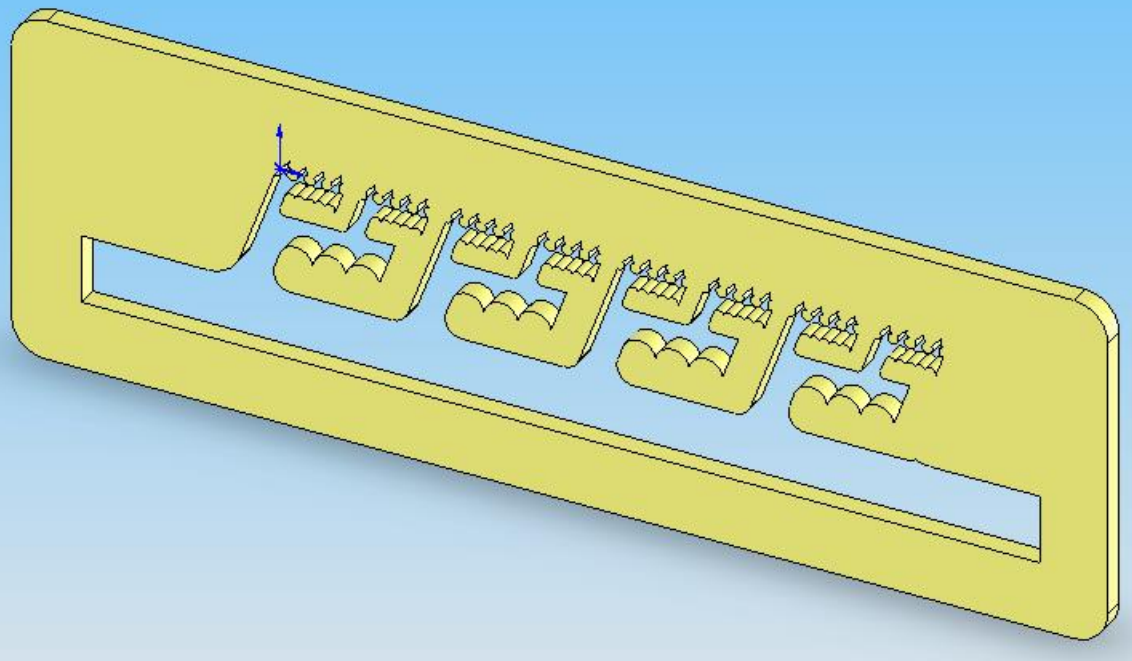
CNC machining

end mill Ø 250 µm

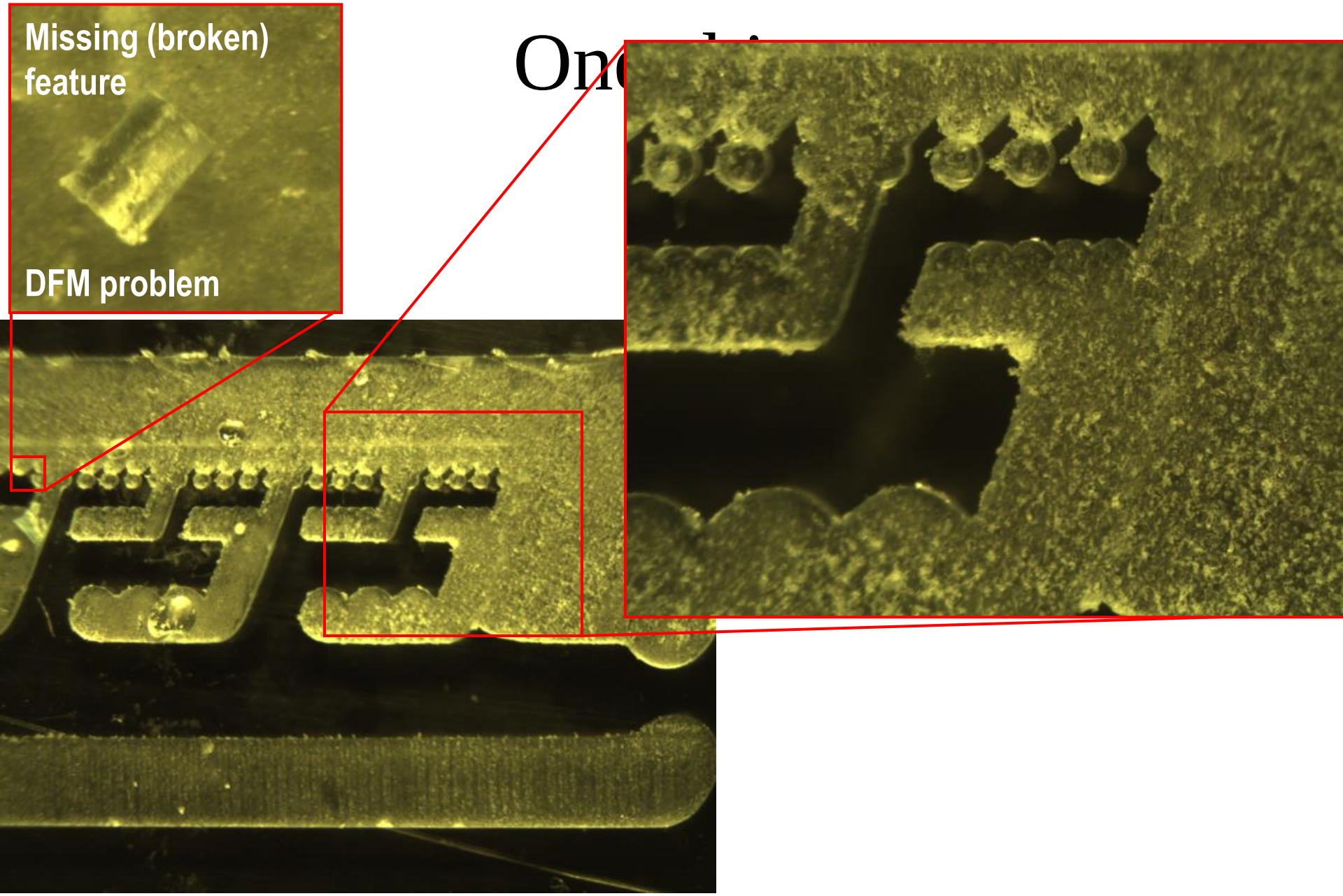
Depth of cavity:

- **750 µm (top two rows)**
- **500 µm (bottom two rows)**

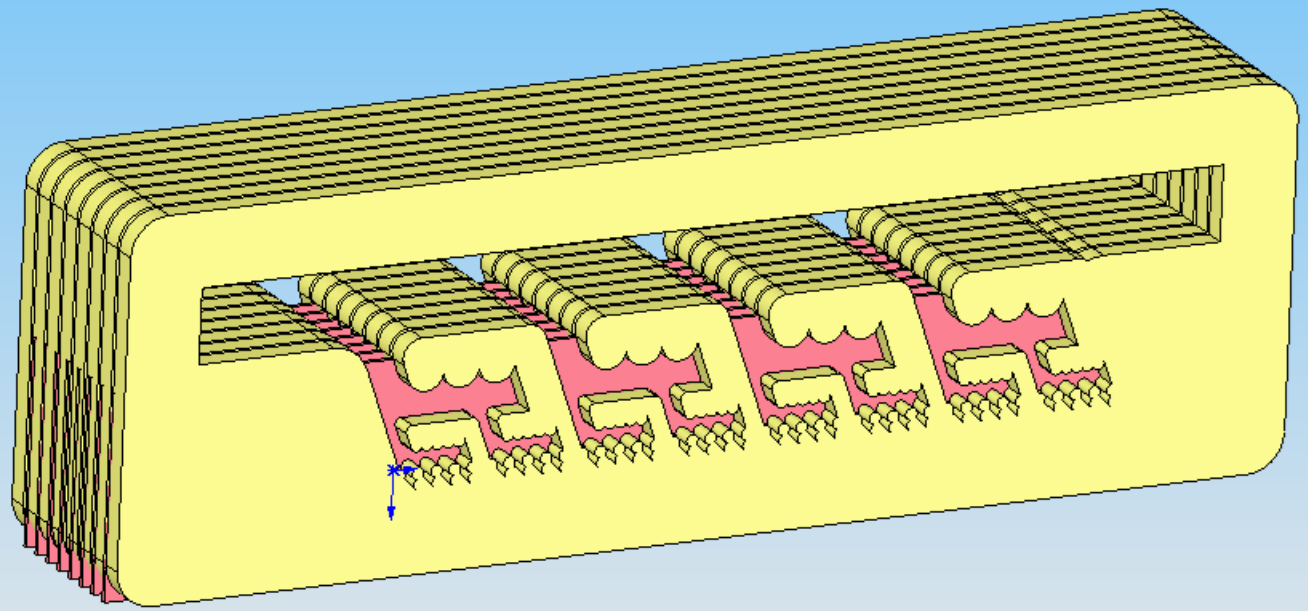
One shim



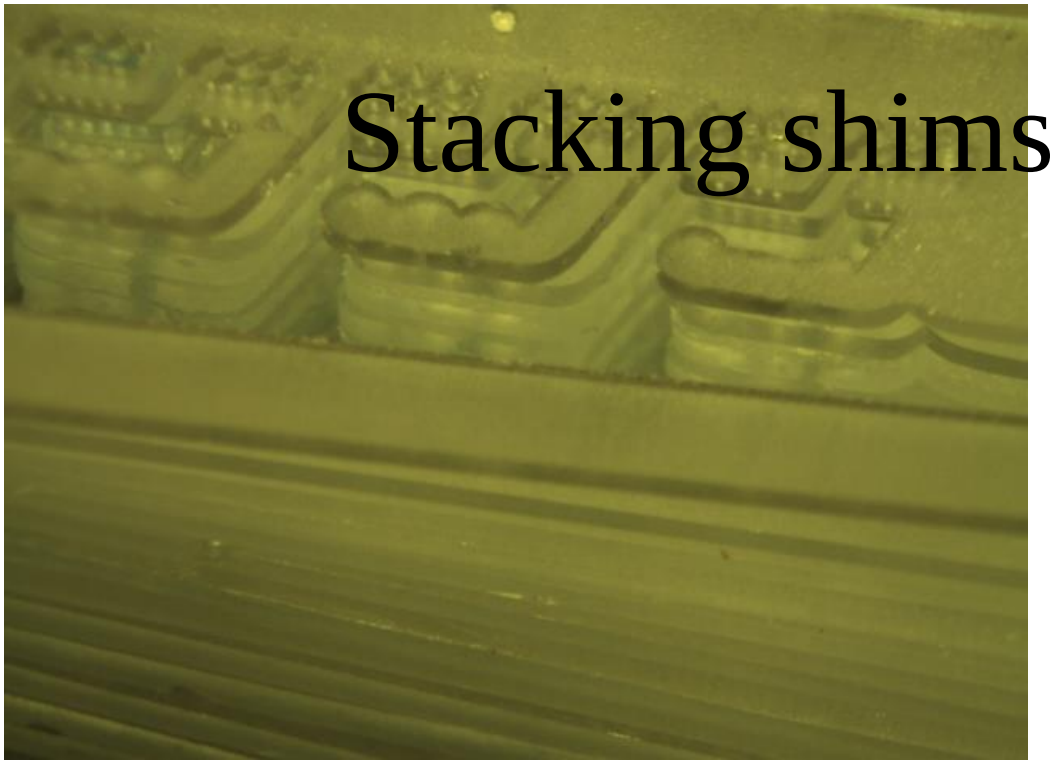
On

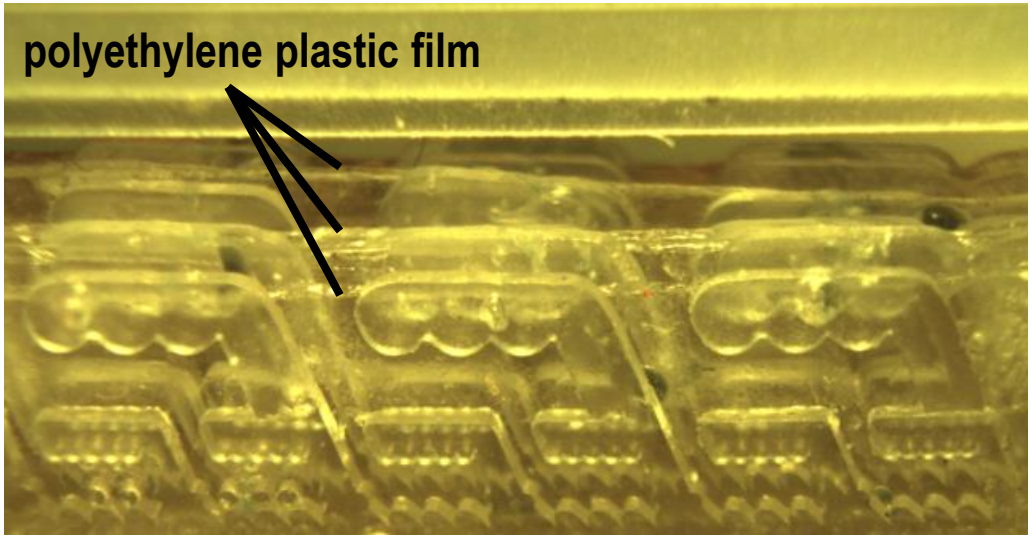


Stacking shims and films



Stacking shims and films



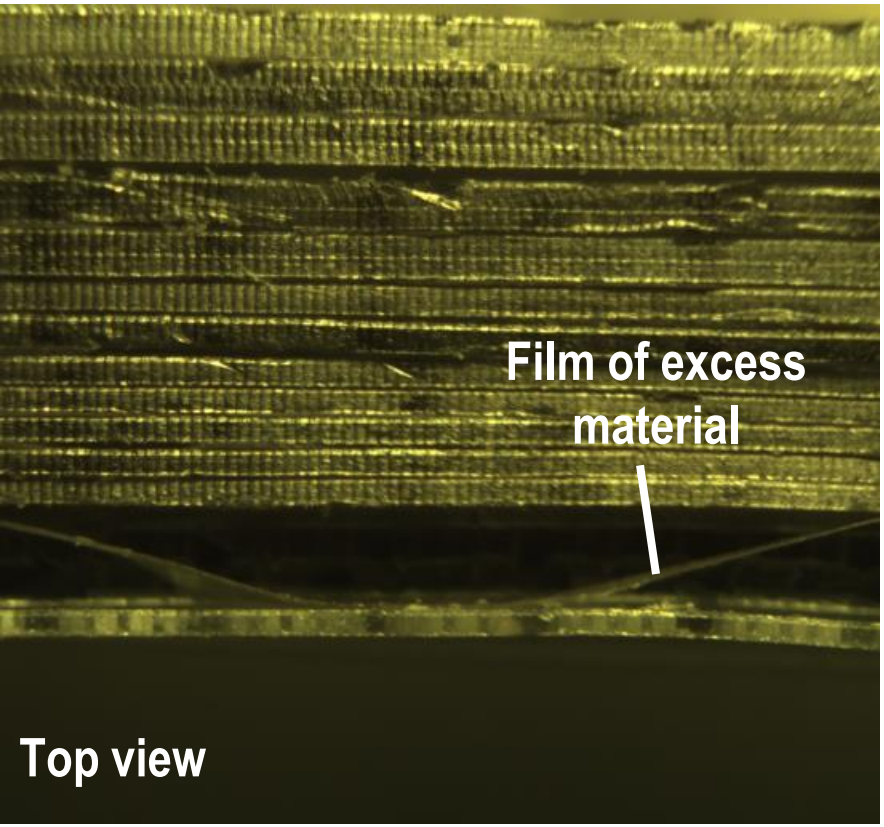


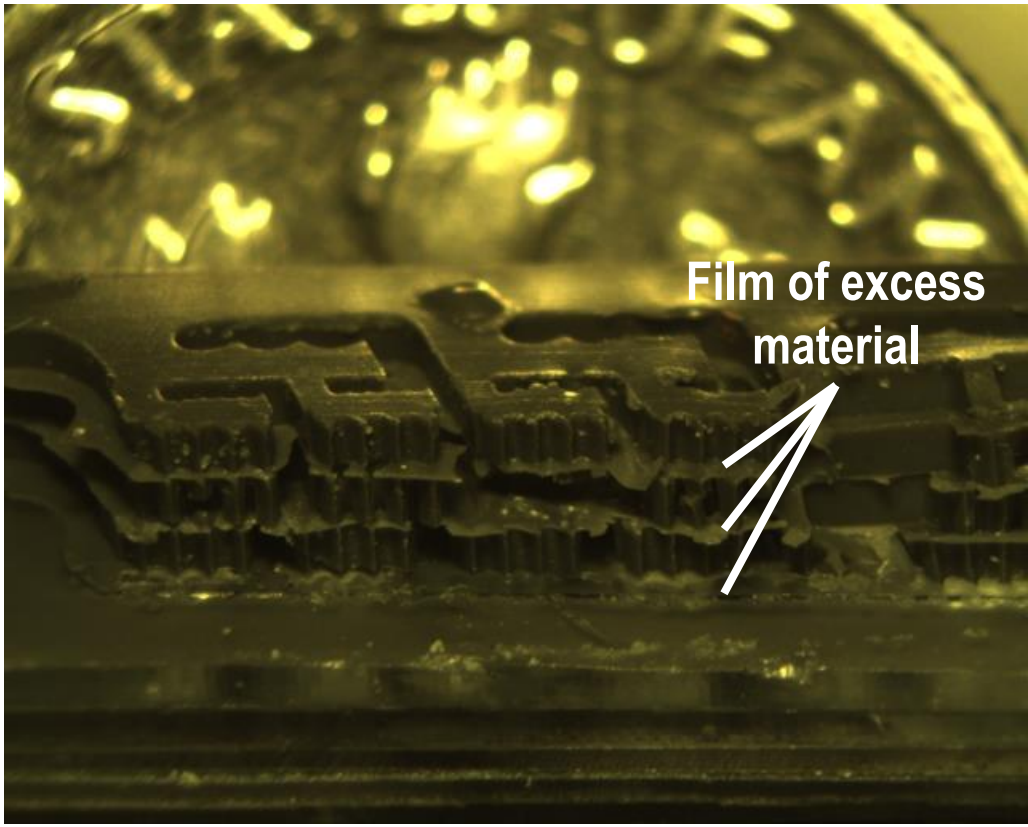
Shim material

Bi-component Urethane:
Task 9, Smooth-On Polymers, Inc.
Working/Cure time [min./h.]: 7/14
Shore hardness [MPa]: 85D
Tensile strength [MPa]: 54
Elongation [%]: 6

Degassing in vacuum @ 26” Hg

Mold without tape: connected stacks





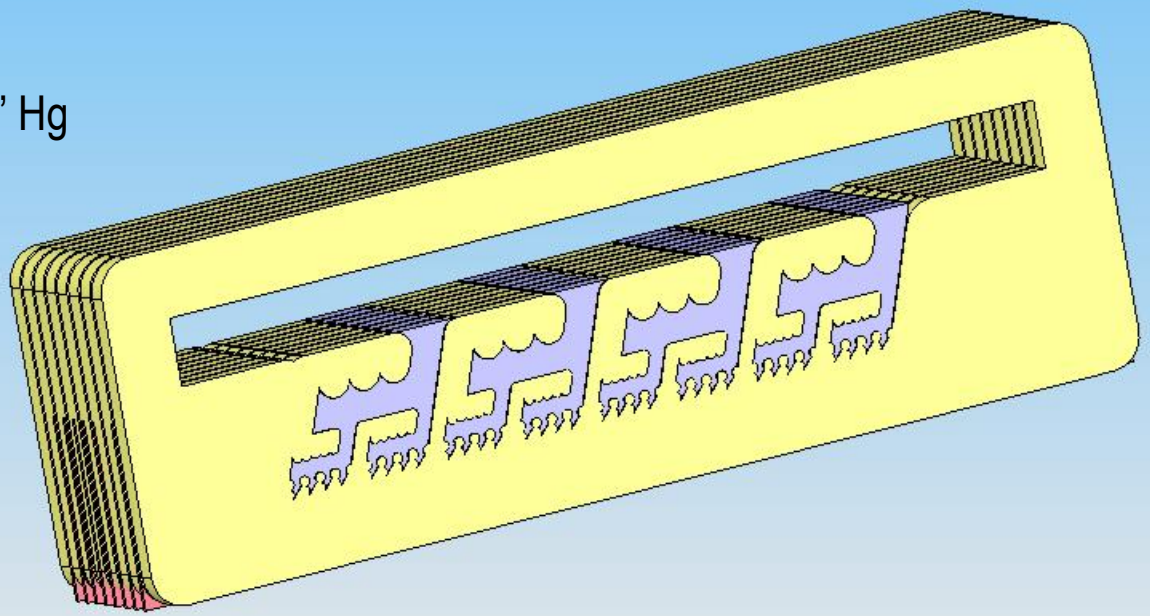
Cast material: Bi-component Platinum catalyst Silicone from Dow Corning Sylgard 170

Degassing in vacuum @ 26” Hg for 30 minutes (working time)

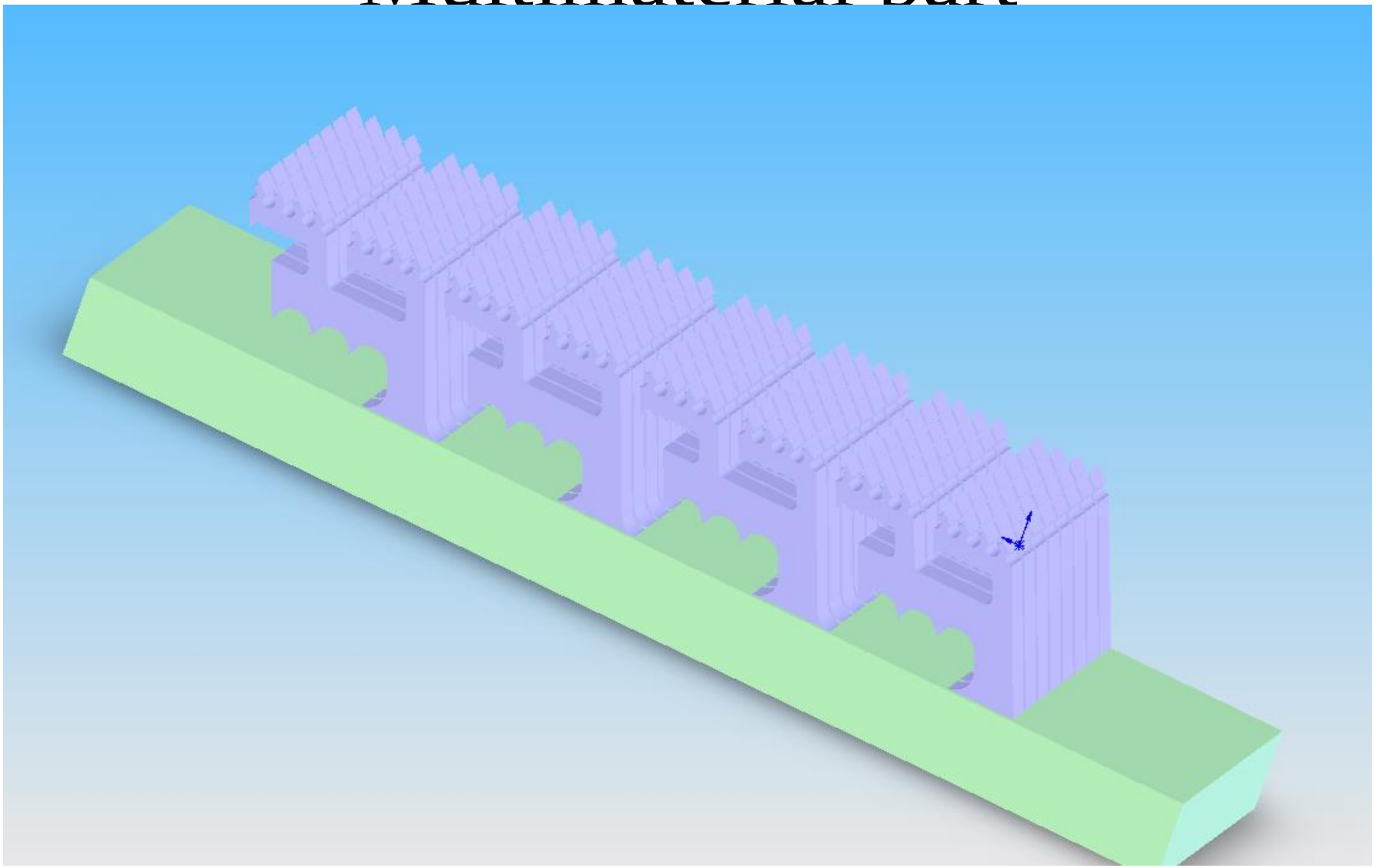
Casting material (clear silicone)

Cast material

Bi-component Platinum catalyst Silicone:
P-20, Silicon Inc./Innovative Polymers
Working/Cure time [min./h.]: 60/18
Shore hardness [MPa]: 20A
Tensile strength [MPa]: 3.6
Elongation [%]: 425
Degassing in vacuum @ 26” Hg



Multimaterial part



Casting material A (clear sili…)

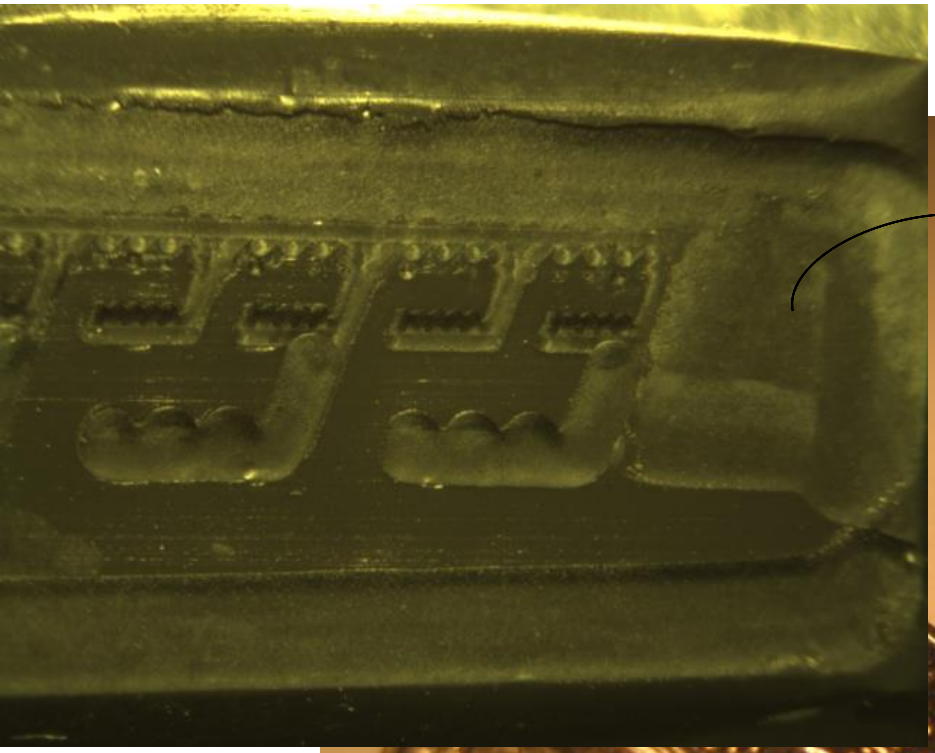
In fact, it filled completely the mold (very good wetting/filling property)

Too low clearance above film

Cast material: Bi-component Platinum catalyst Silicone from Silicon Inc./Innovative Polymers P-20

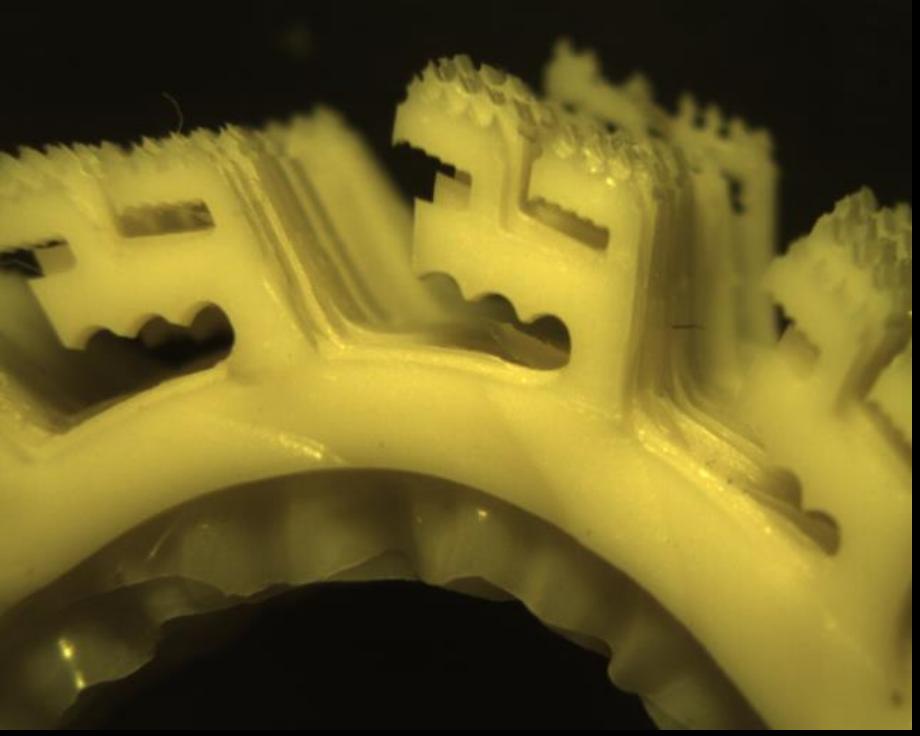
Degassing in vacuum @ 26” Hg for 30 minutes (working time)

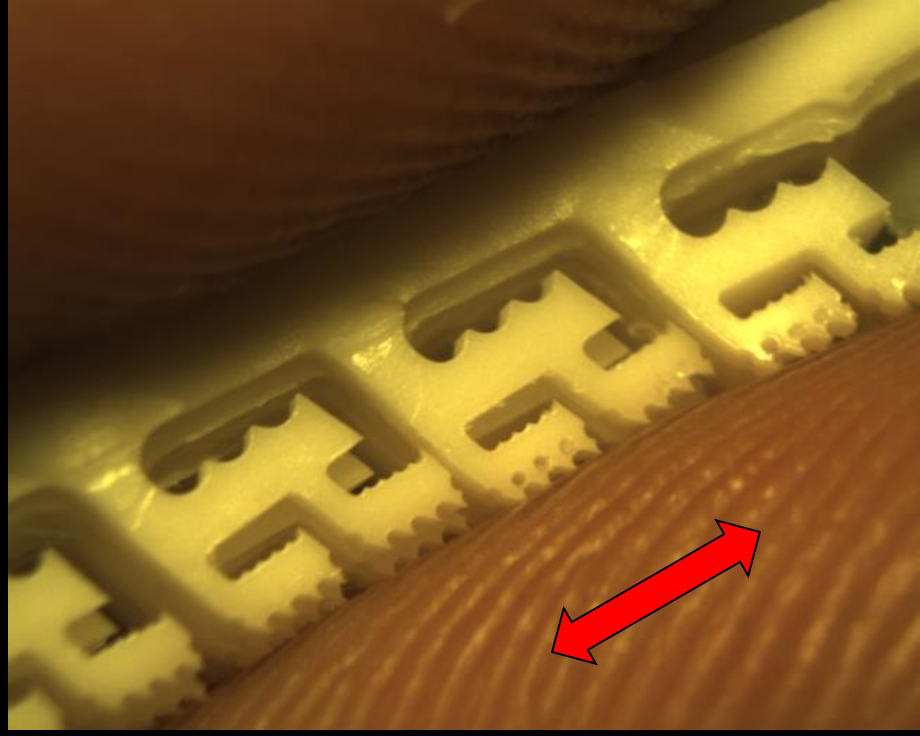
Cast part (black silicone)

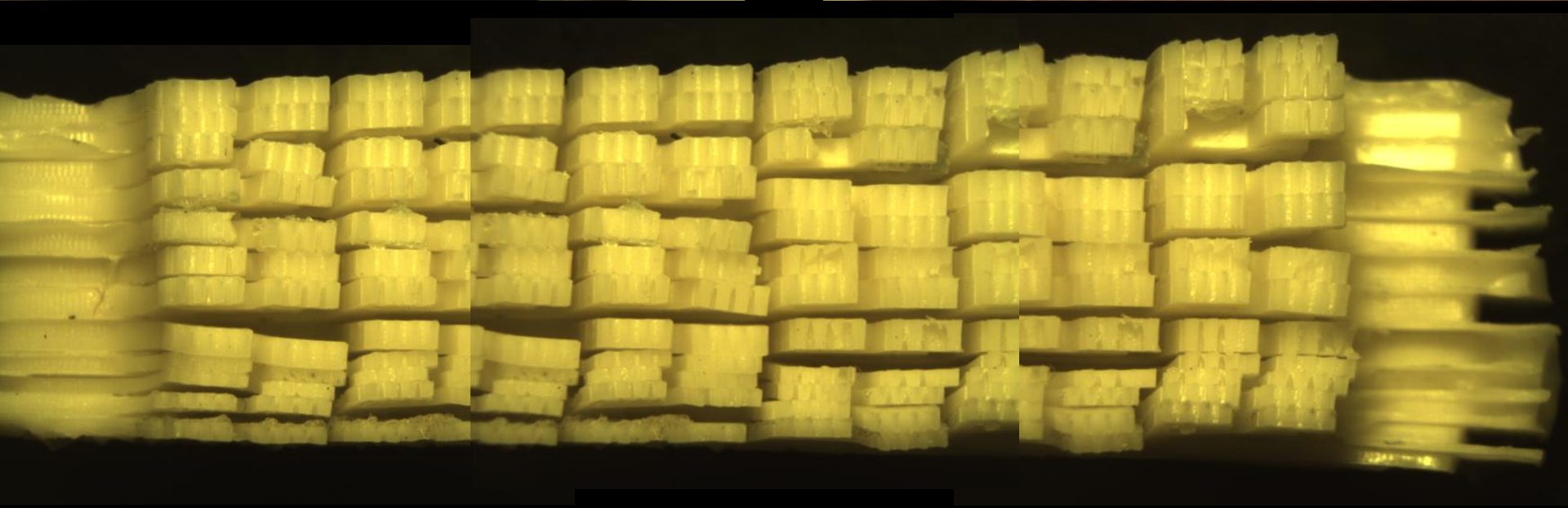


Cast material
Bi-component Platinum catalyst Silicone:
Sylgard 170, Dow Corning
Working/Cure time [min./h.]: 15/24
Shore hardness [MPa]: 40A
Degassing in vacuum @ 26” Hg

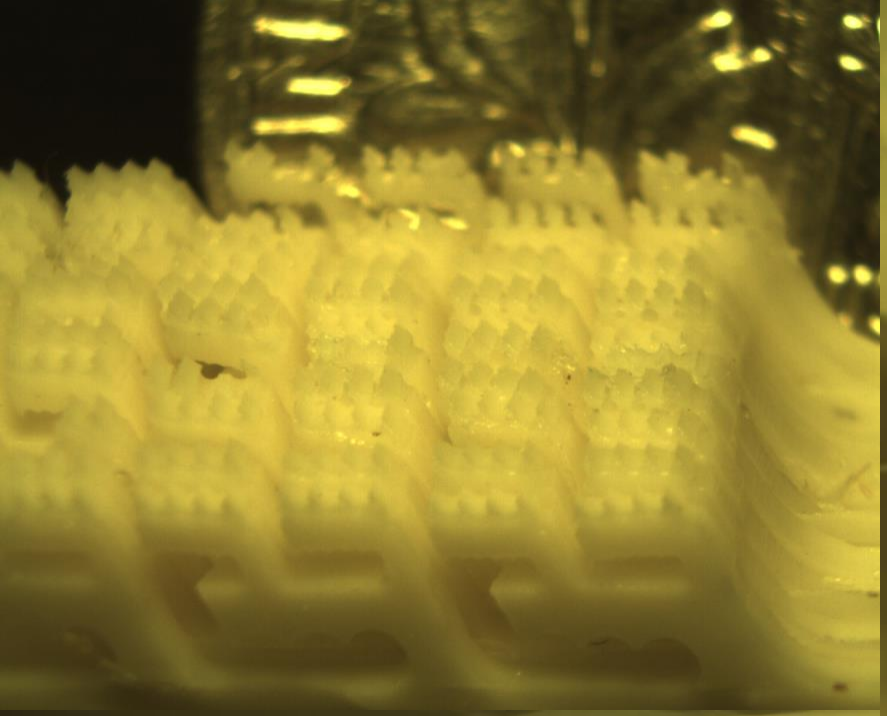
Demolding problems

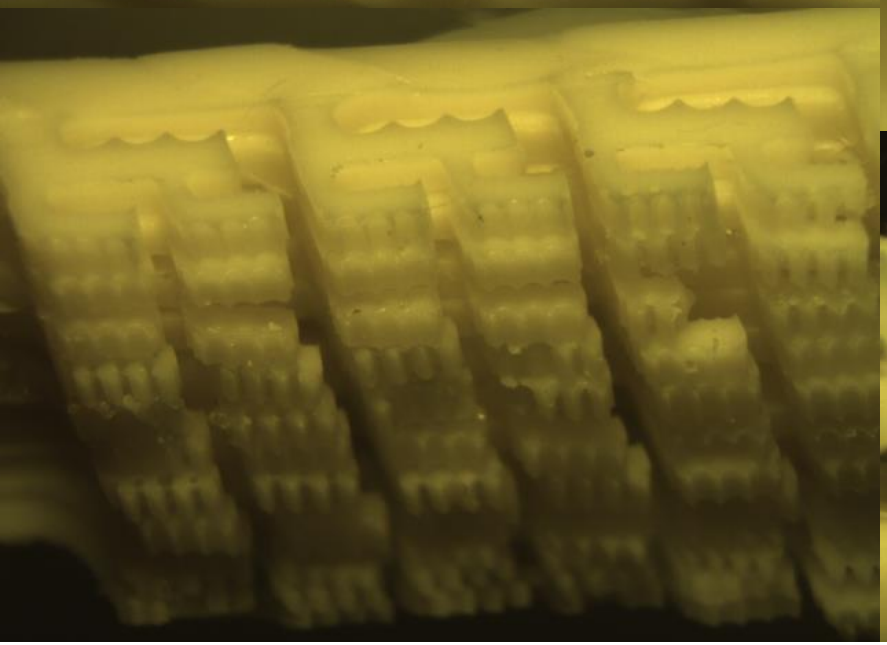


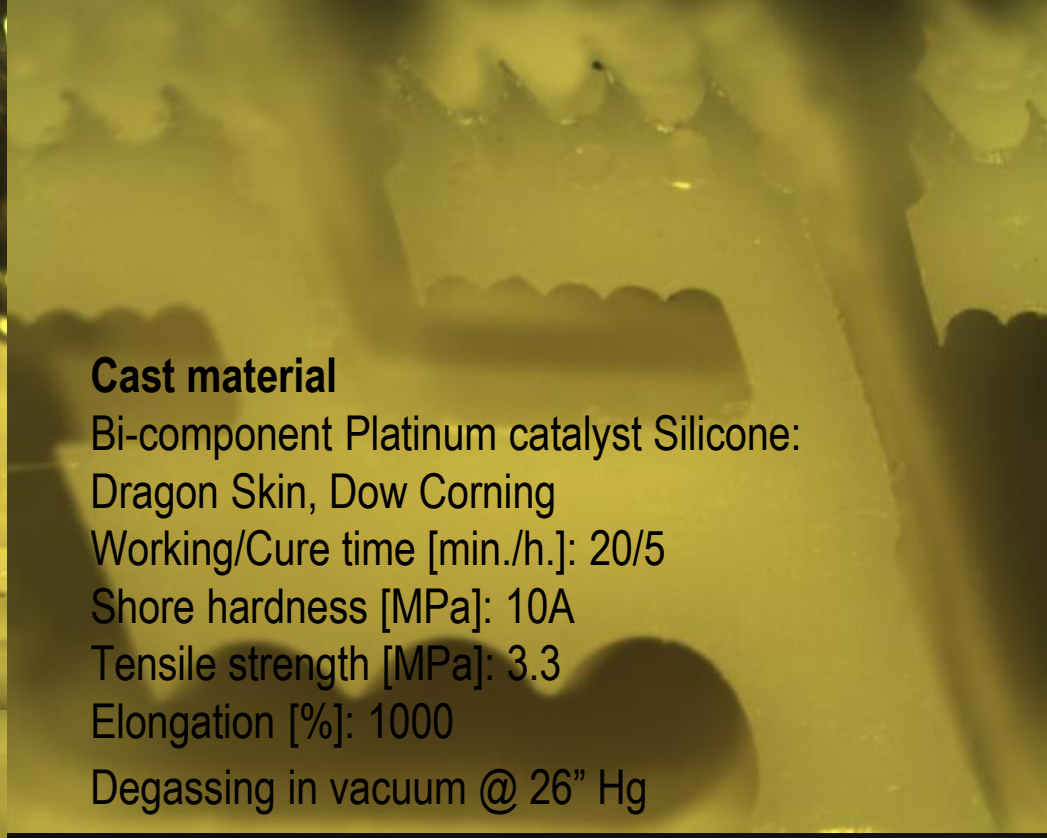




MOLD
SDM

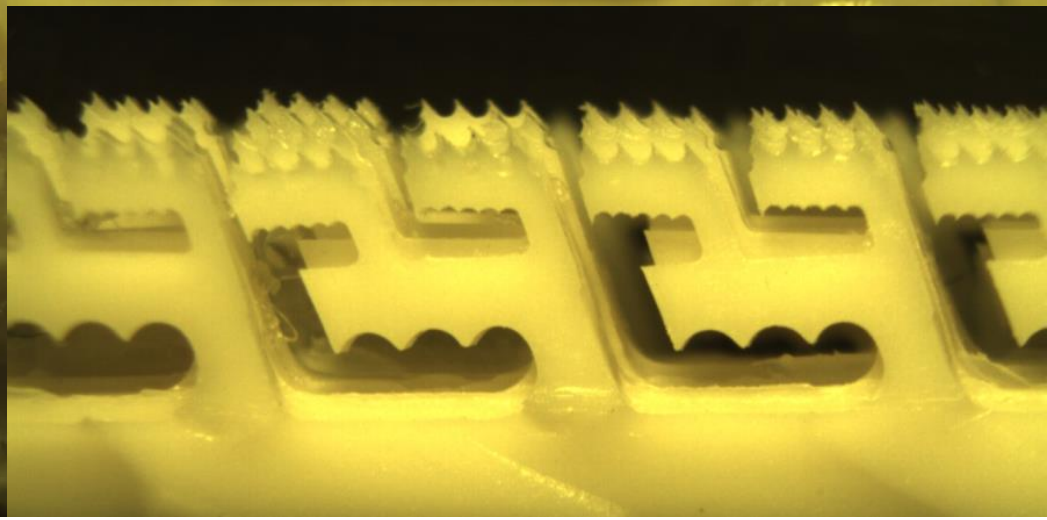


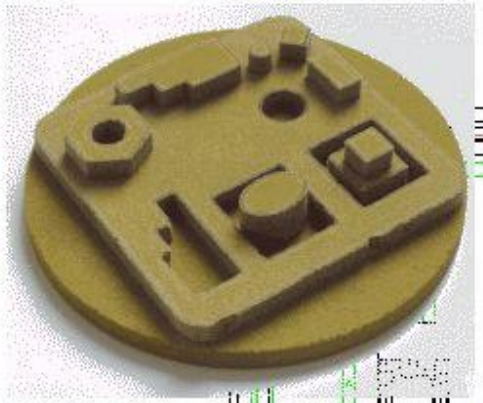


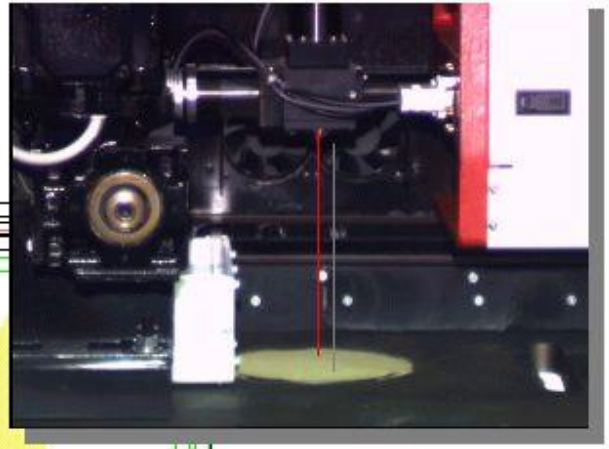


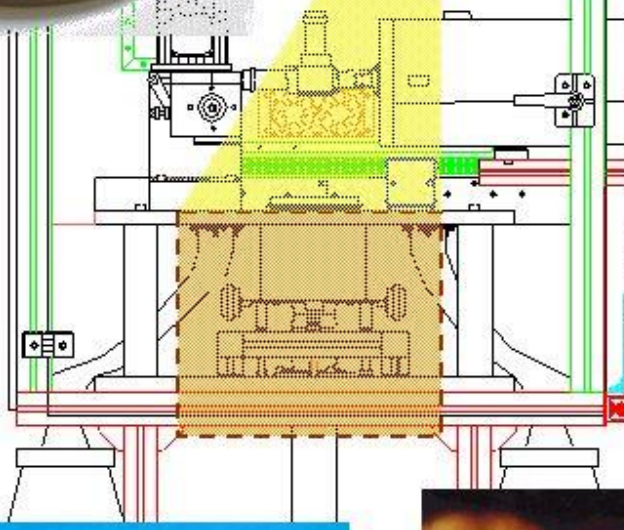
Cast material

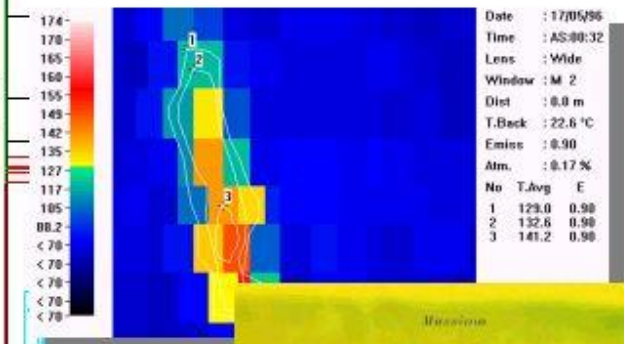
Bi-component Platinum catalyst Silicone:
Dragon Skin, Dow Corning
Working/Cure time [min./h.]: 20/5
Shore hardness [MPa]: 10A
Tensile strength [MPa]: 3.3
Elongation [%]: 1000
Degassing in vacuum @ 26” Hg

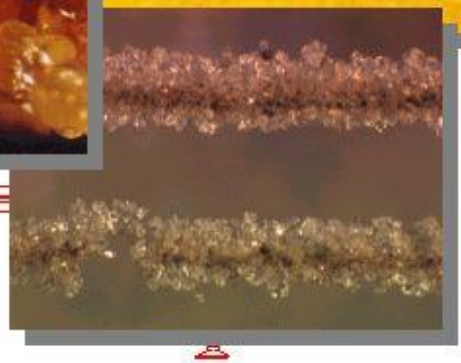






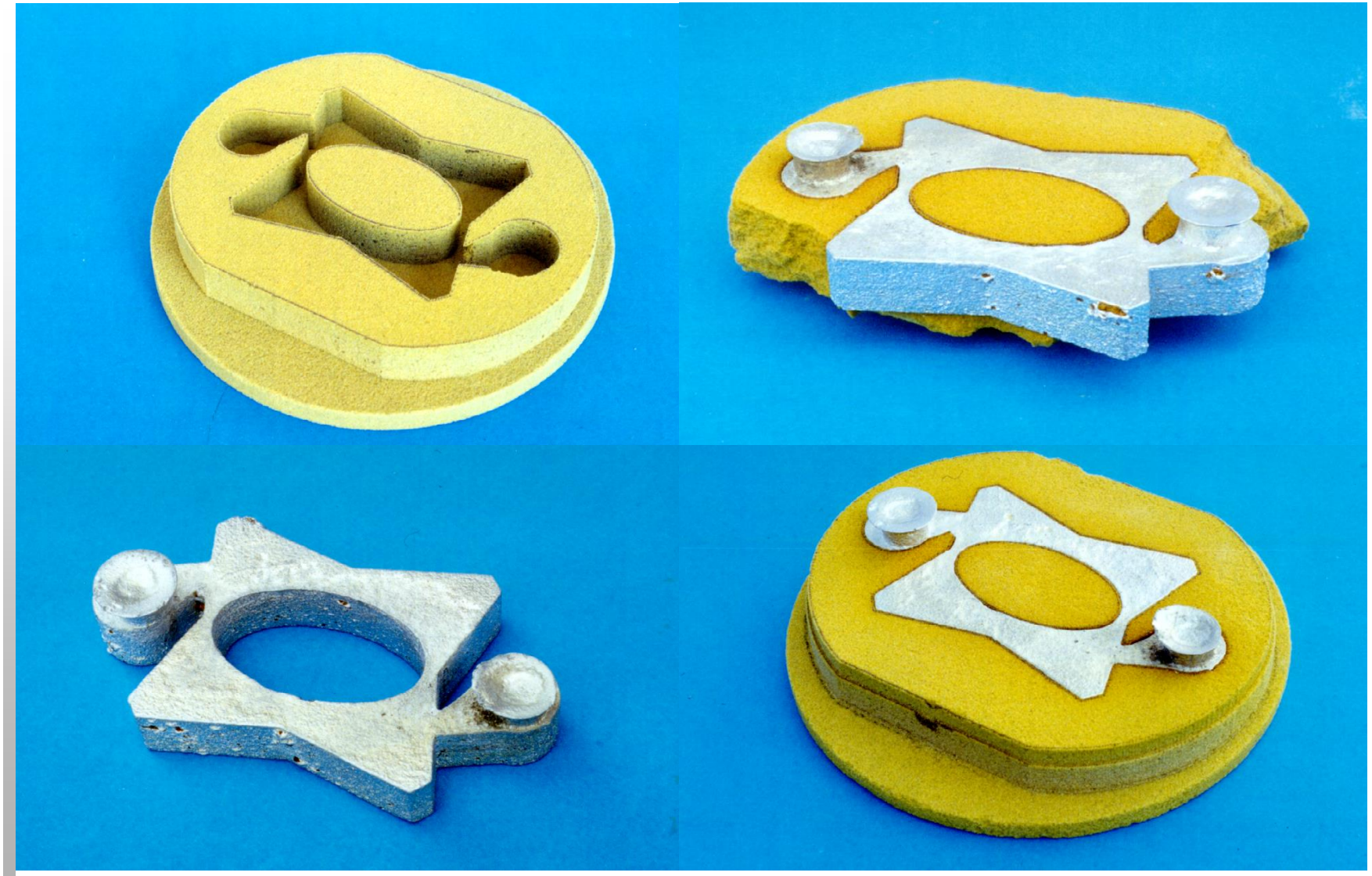



174
170
165
160
155
149
142
135
127
117
105
88.2
< 70
< 70
< 70
< 70
< 70
Date : 17/05/96
Time : AS:00:32
Lens : Wide
Window : M 2
Dist : 0.0 m
T.Back : 22.6 °C
Emiss : 0.90
Atm. : 0.17 %
No T.Avg E
1 129.0 0.90
2 132.6 0.90
3 141.2 0.90



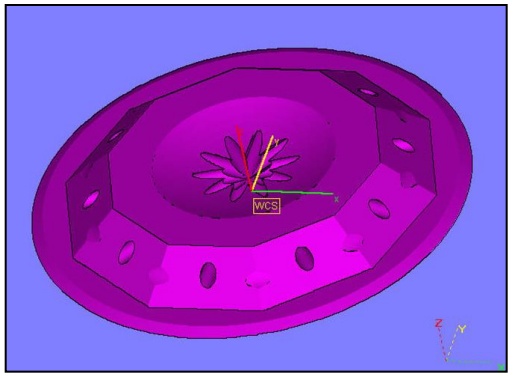
Final phase

Prototype realization

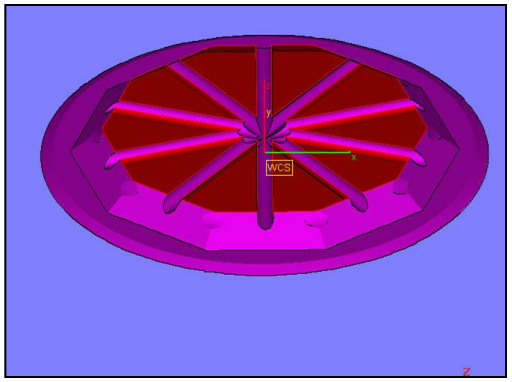


Experimental analysis of SLS process:

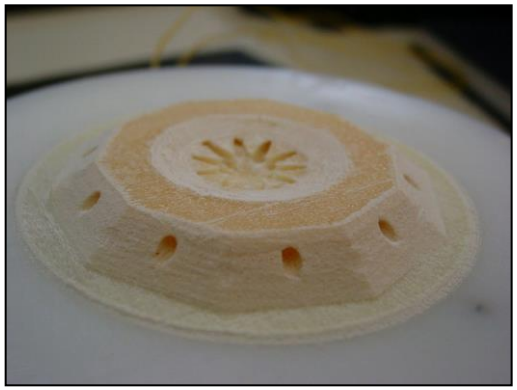
Machine setup phase, the *curling*



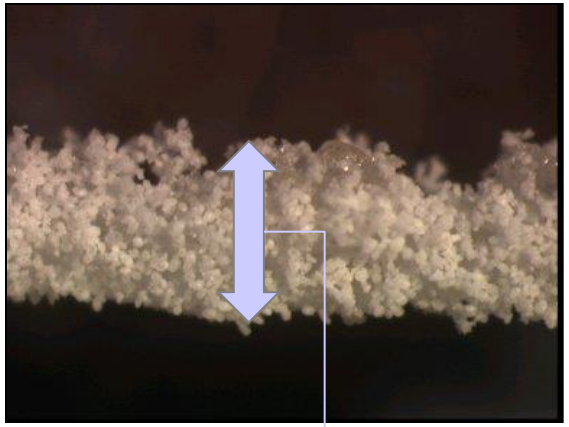
Results with traditional support

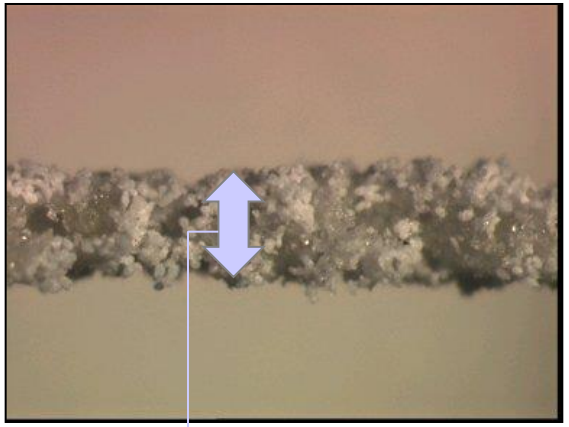


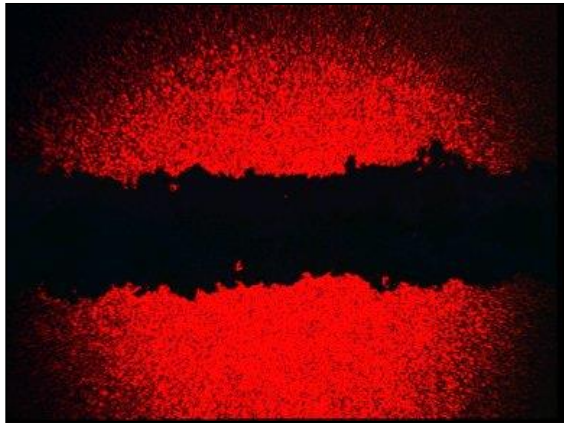
Results with heated support



Simulation model setup





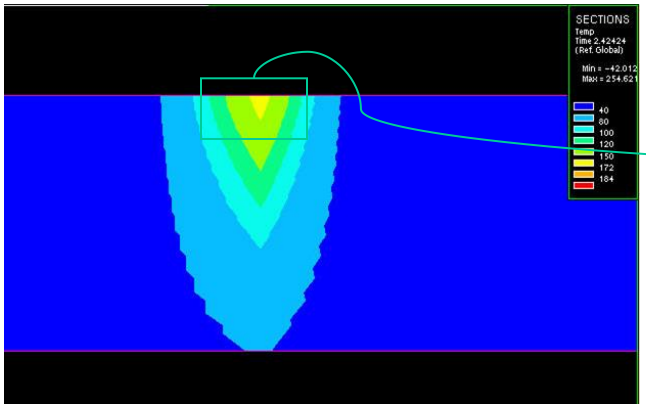


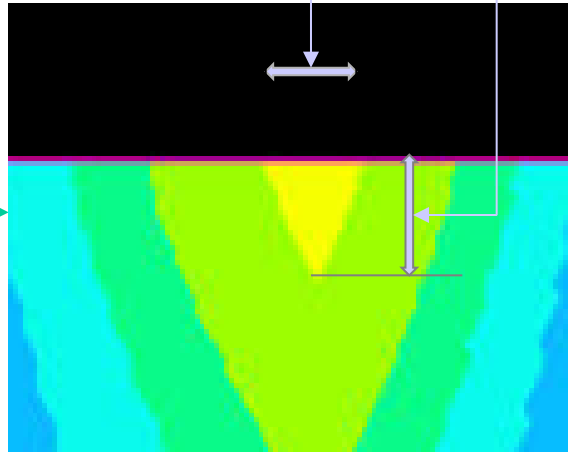
Measured sintering depth

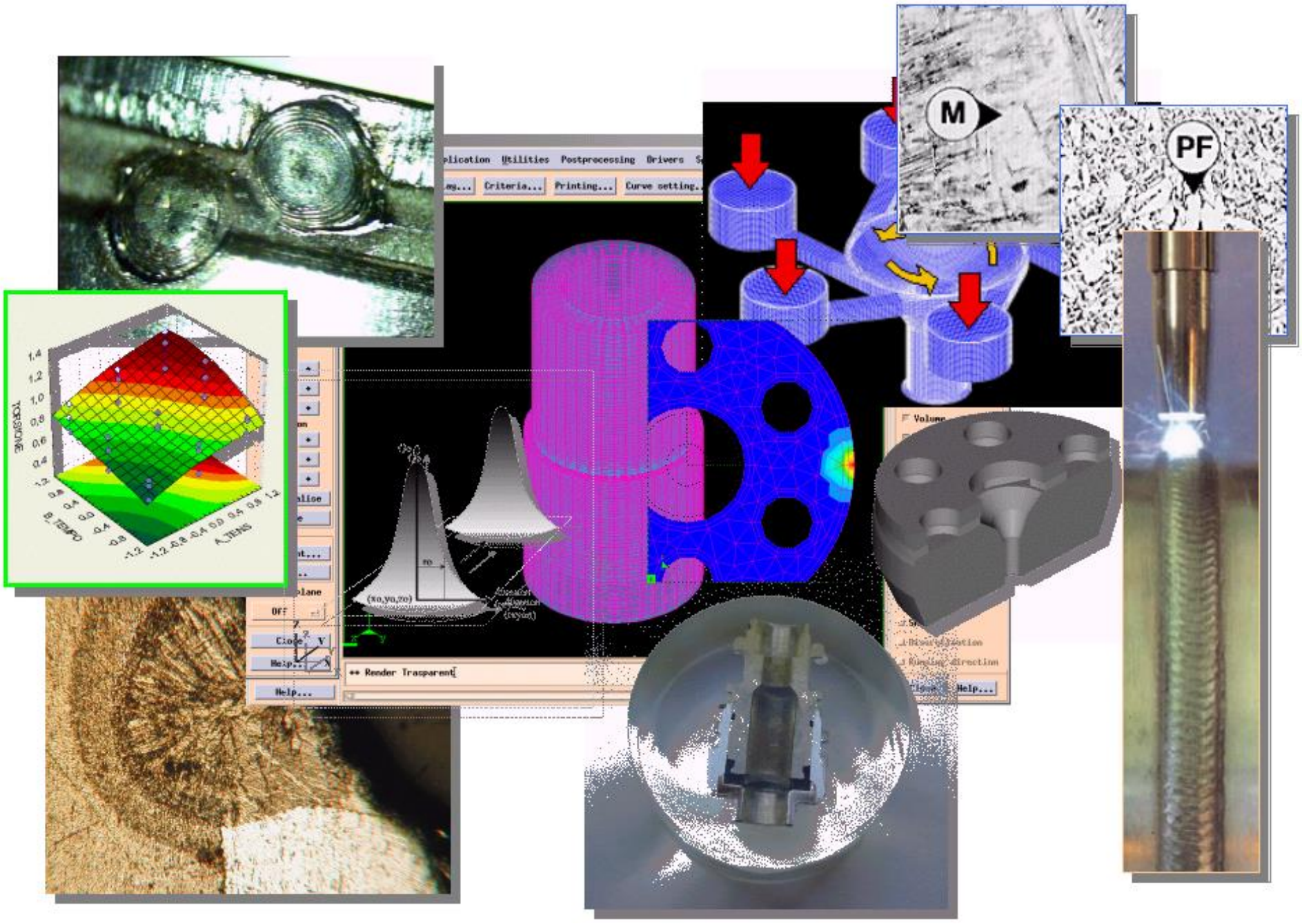
Measured sintering width

Simulated sintering width

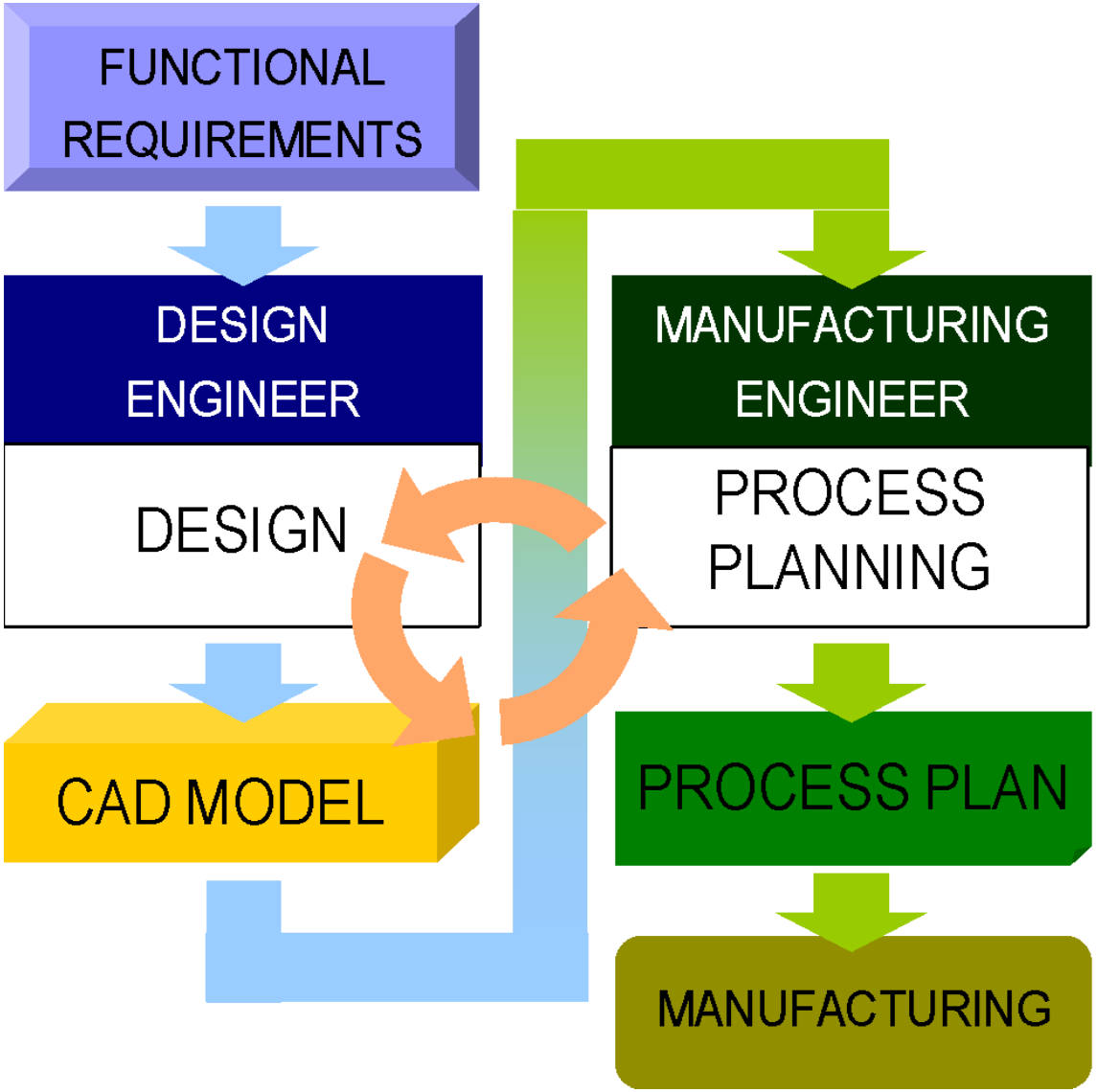
Simulated sintering depth



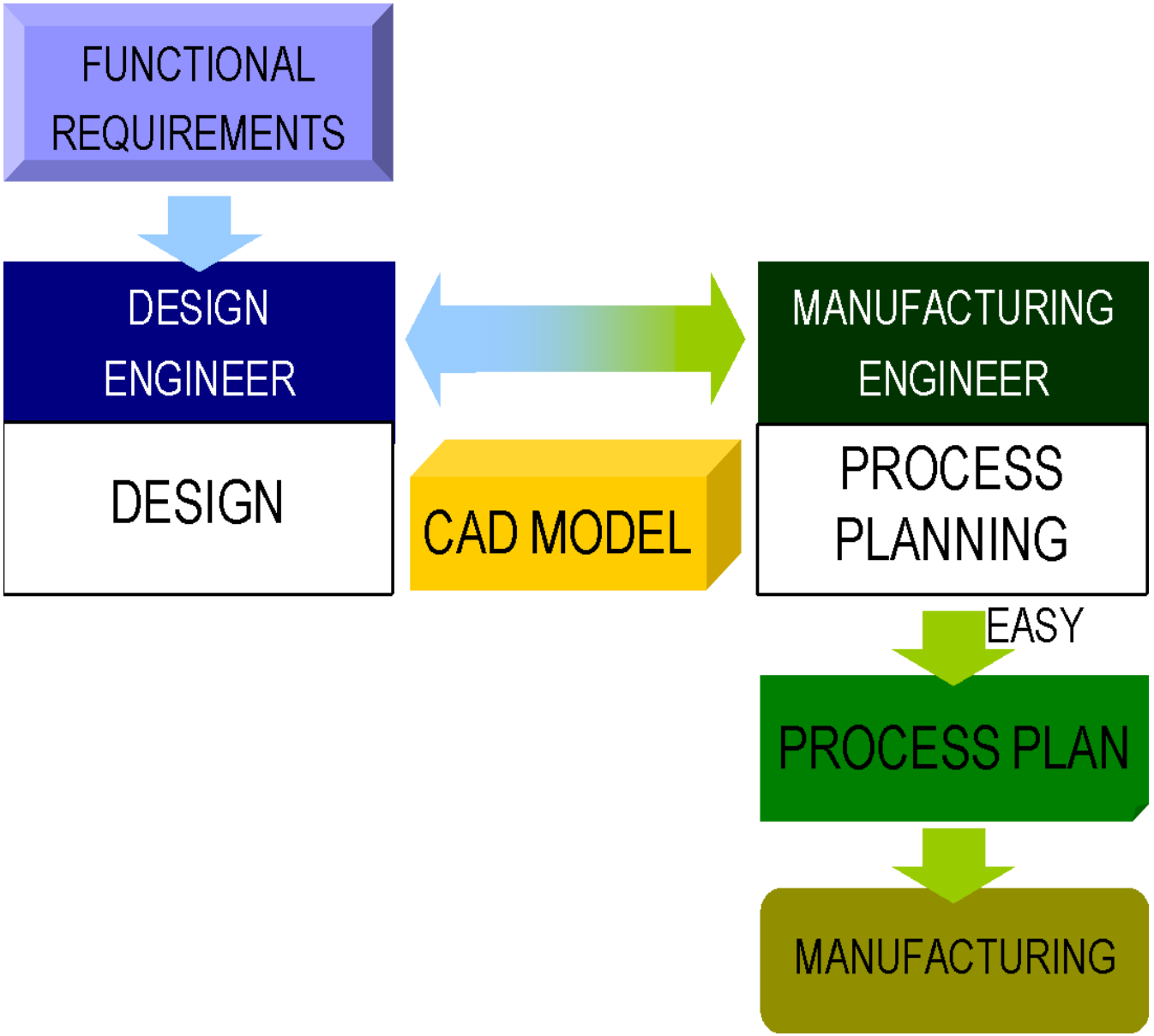



M
PF
Utilities
Postprocessing
Drivers
Criteria...
Printing...
Curve setting...
Off
Help...
** Render Trasparent

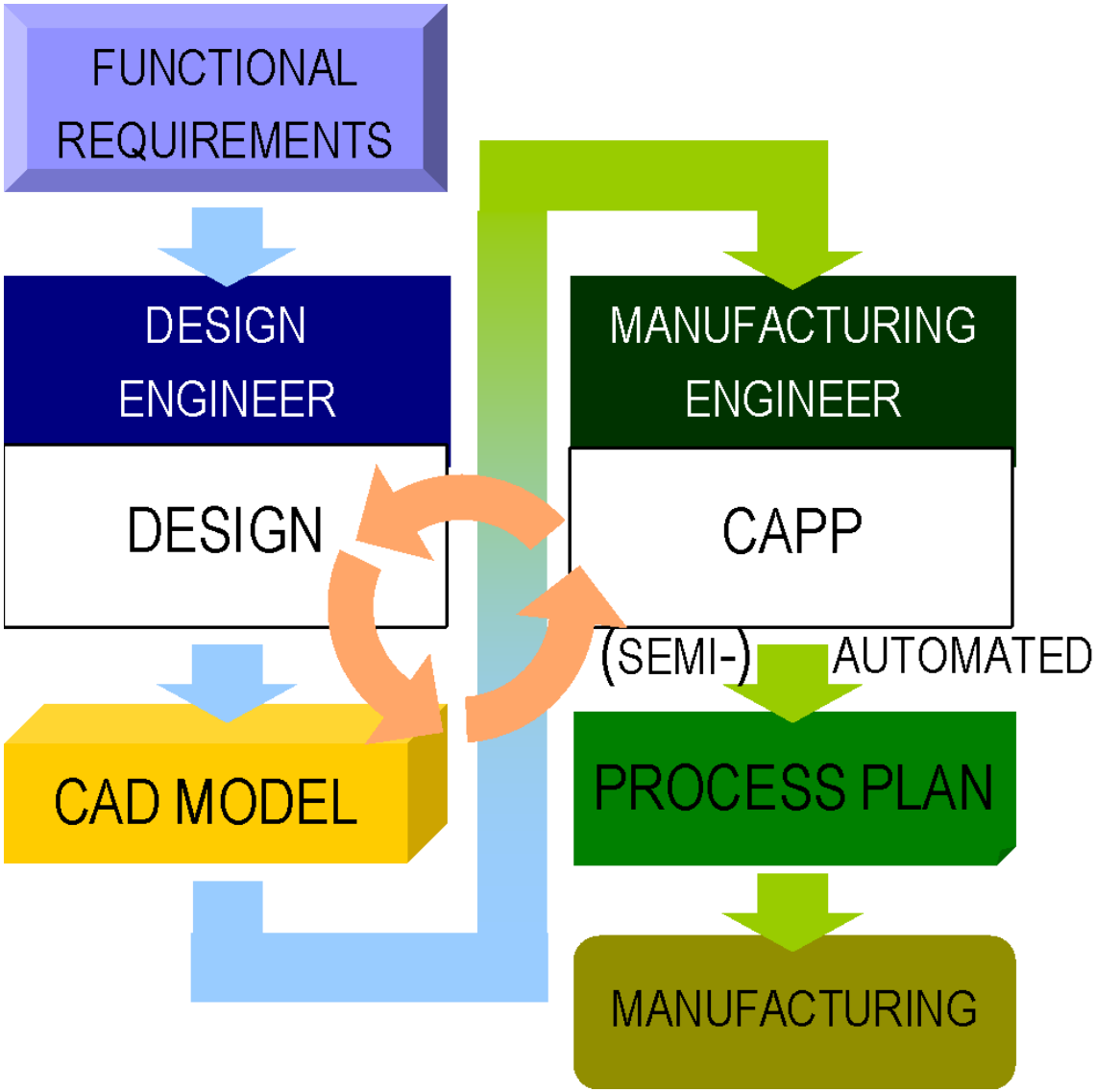
Traditional Process Planning



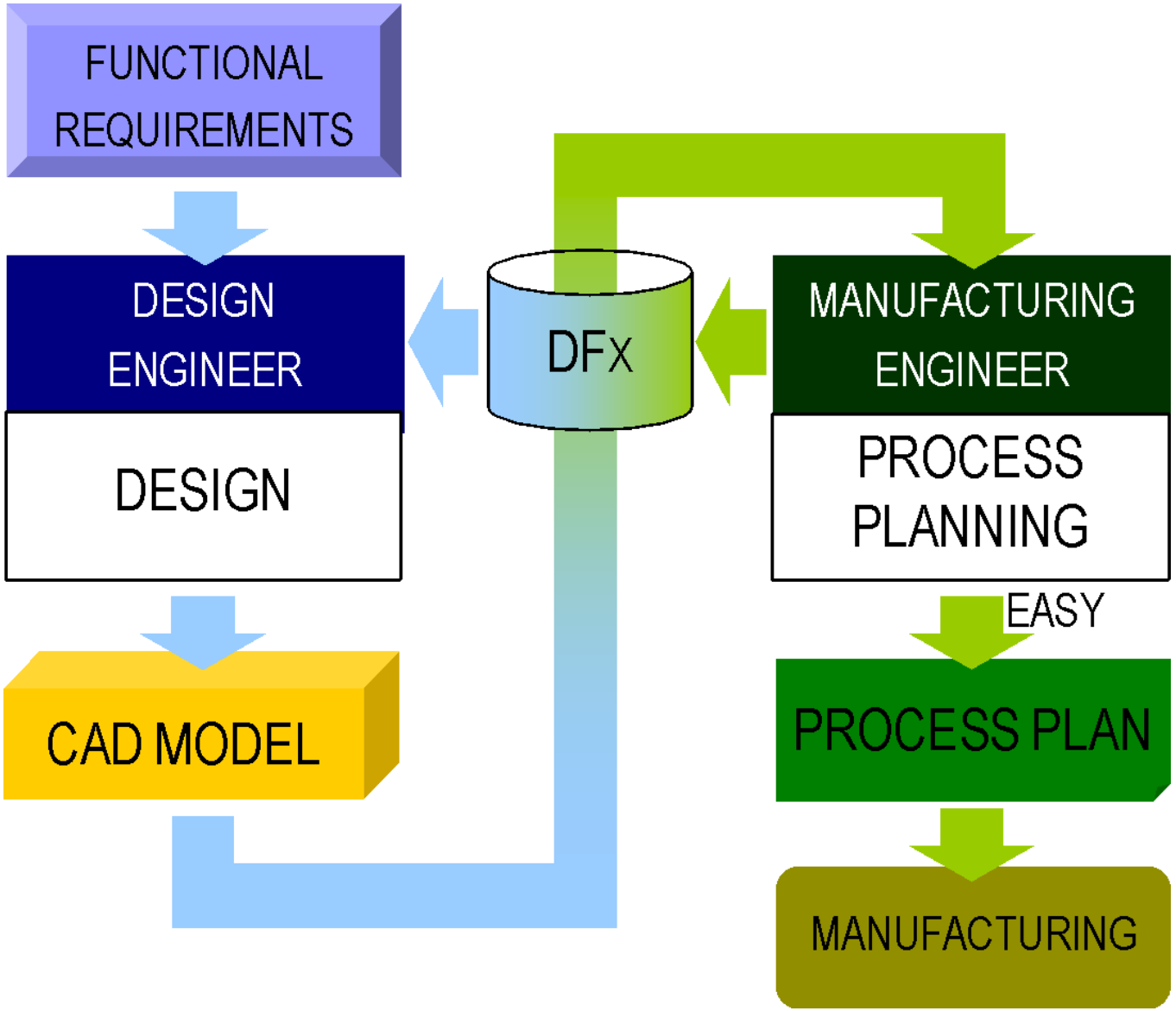
Concurrent Engineering



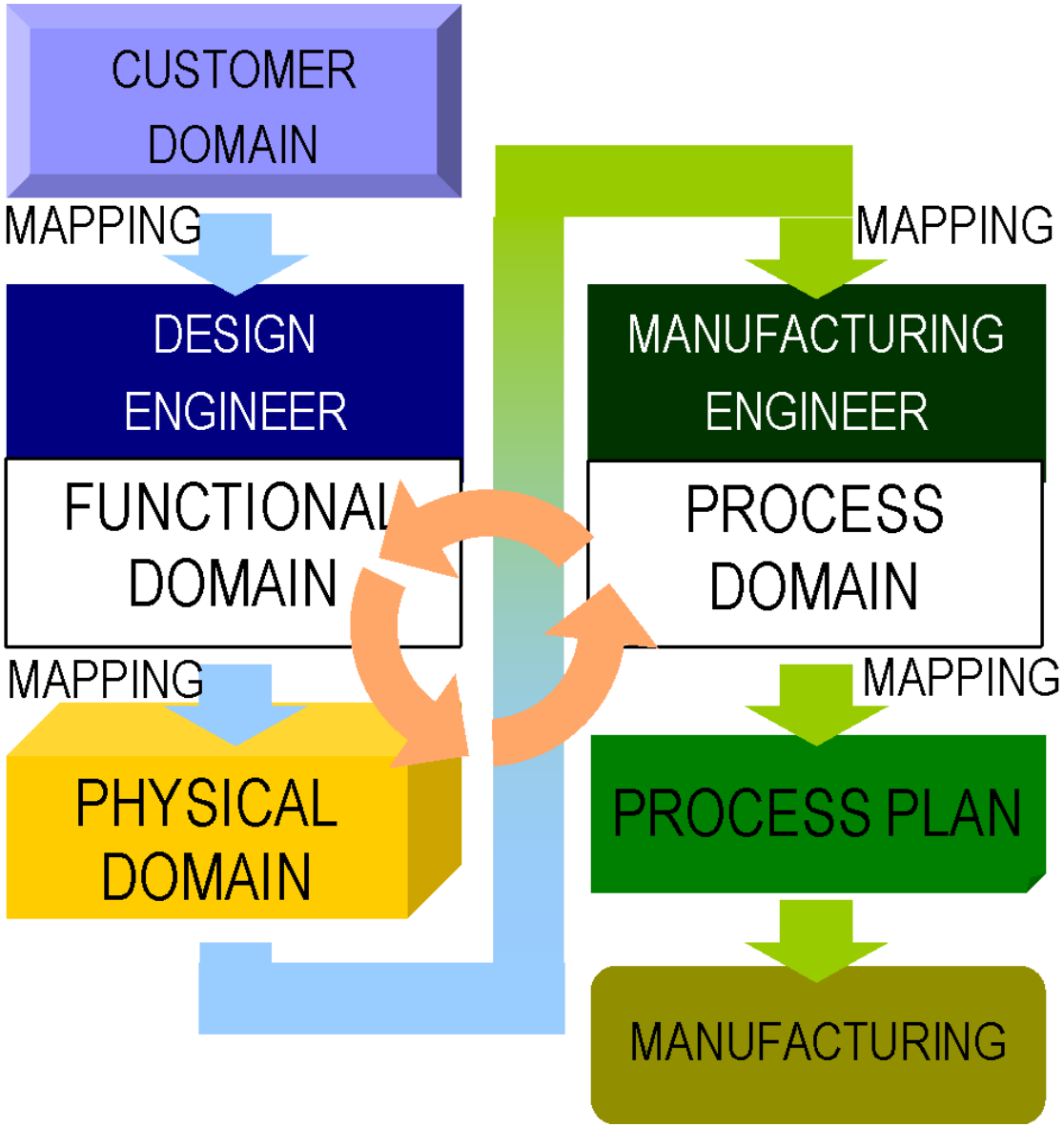
Computer Aided Process Planning



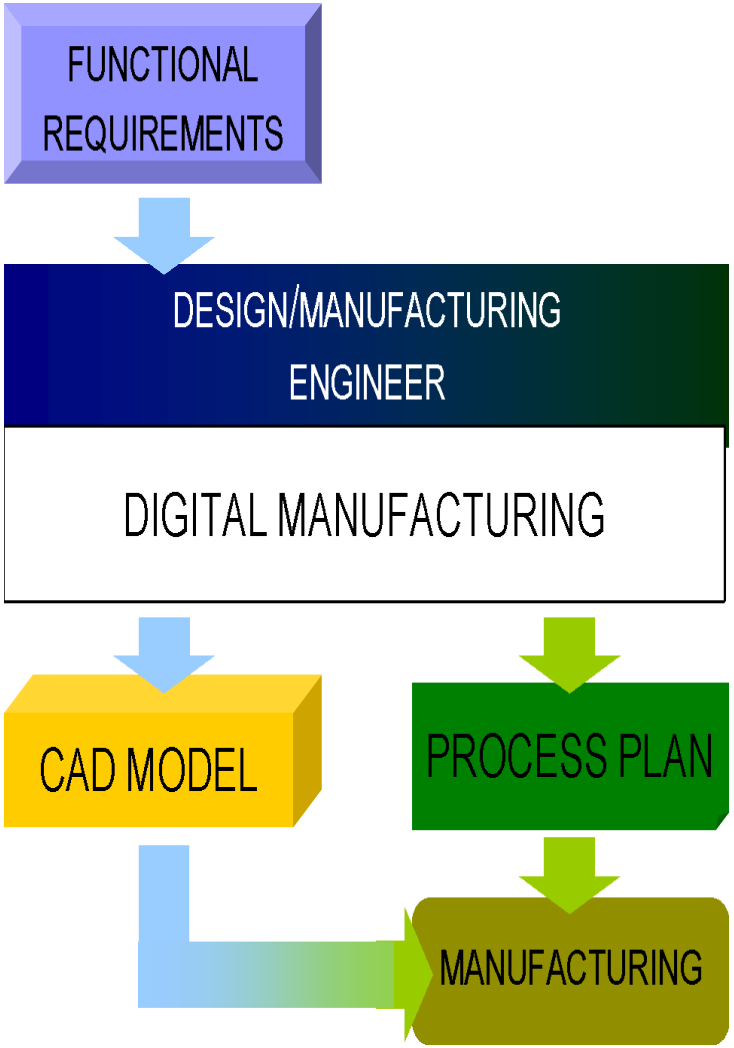
Design for Manufacturing



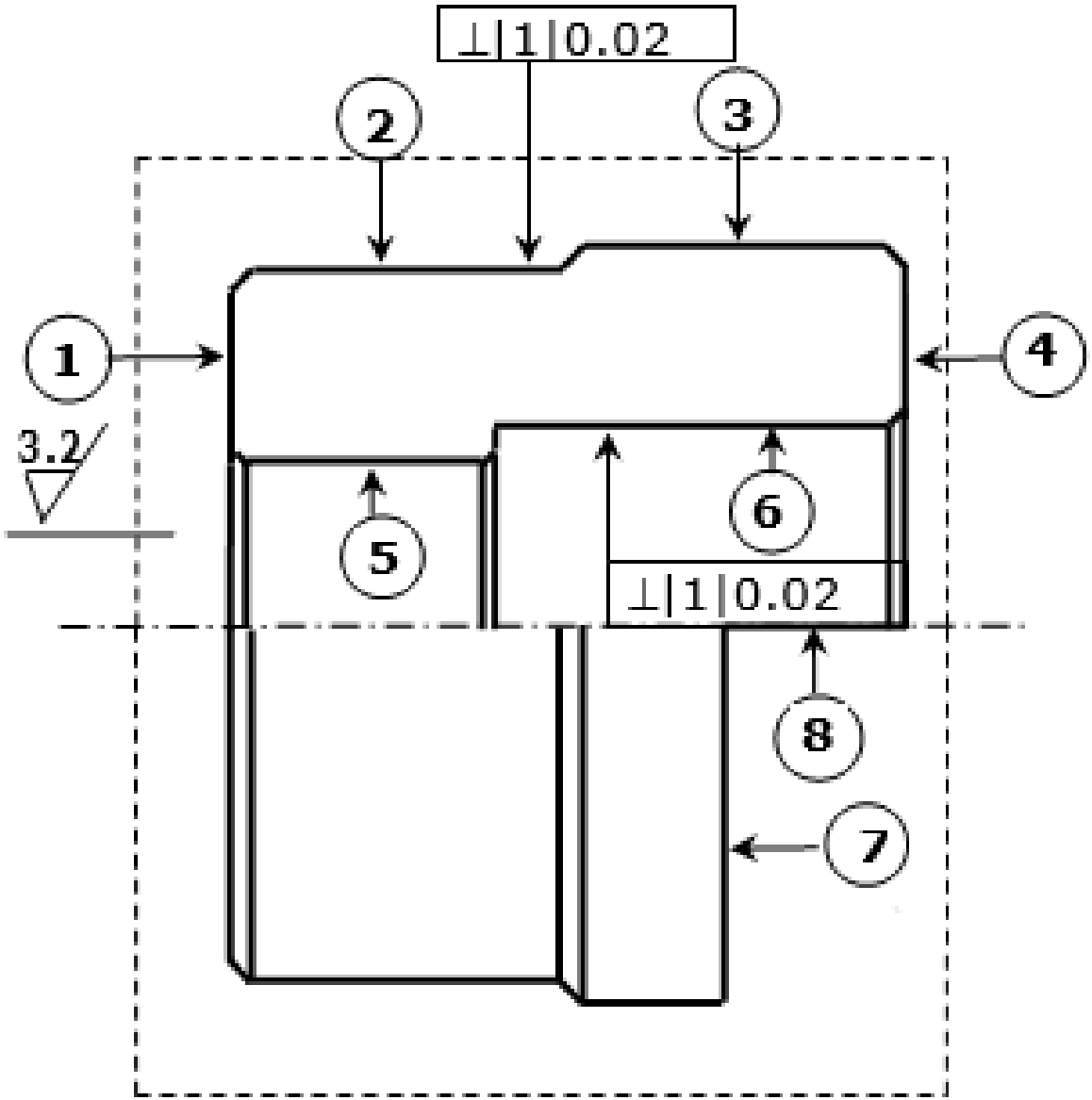
Axiomatic Design



Additive Manufacturing



Mechanical part



Fully developed process plan

#	Operation			Modes Id	Description	Tool	Fixture	Clamping surface
	Id	Surfaces	Quality					
0	O	3	Raw		Starting surface		Chuck1	
1	A	1,2	Roughing	1,2	Face-Extern turning	1,2	Chuck1,2	3
2	B	1,2	Finishing	3,4	Face-Extern turning	3,4	Chuck1,2	3
3	C	3,4	Roughing	5,6	Face-Extern turning	1,2	Chuck1,2	2
4	D	5,6	Centering	7,8	Centering on 1	5,6	Chuck1,2	3
				9,10	Centering on 4	5,6	Chuck1,2	2
5	E	5,6	Roughing	11,12	Drilling by 1	7,8	Chuck2	3
				13,14	Drilling by 4	7,8	Chuck2	2
6	F	6	Finishing	15	Back Boring (TurnCenter)	9	Chuck1	3
				16,17	Boring	10,11	Chuck1	2
7	G	7,8	Roughing	18	Face milling	12	Chuck1	2
				19	Slitting	13	Chuck1,2	2

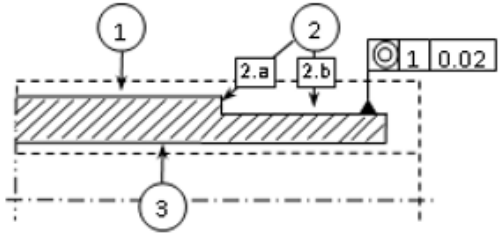
Alternative operations

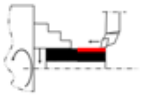
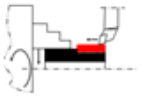
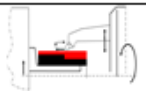
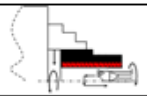
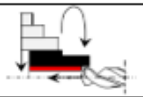
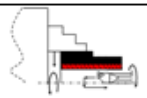
Technology

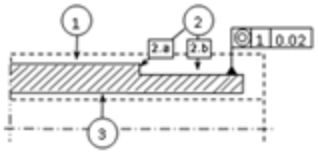
Alternative tools

Alternative fixturing

Deployment

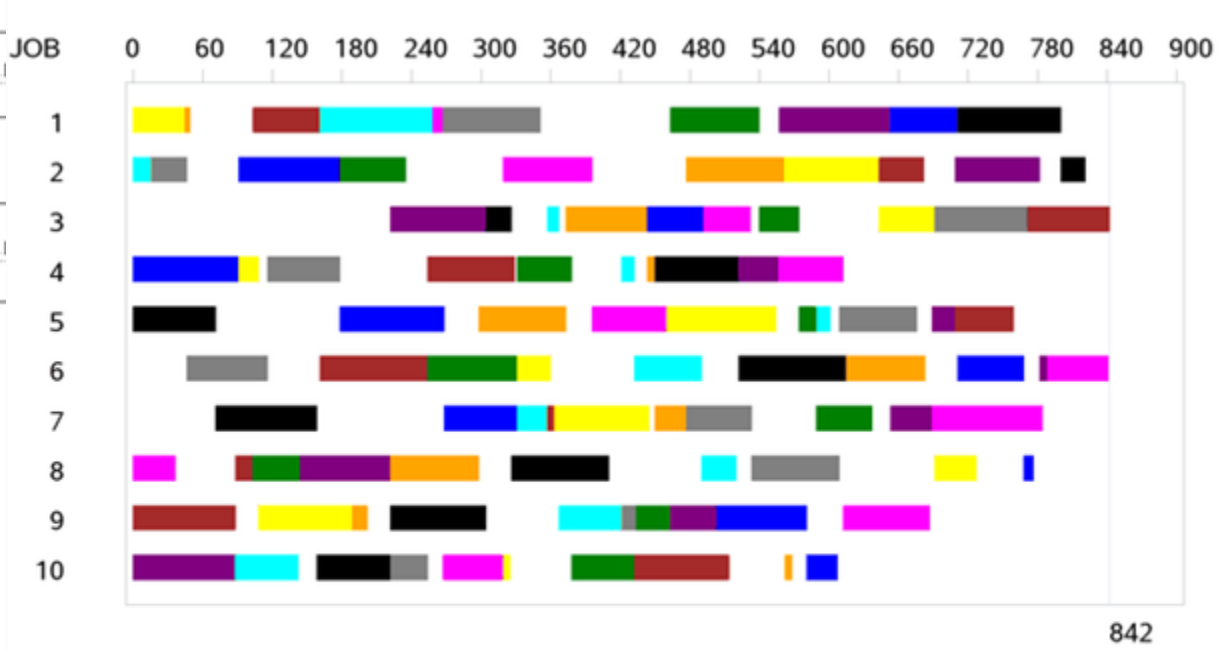


Operation (Surface)	Modes Id	Technology: Turning center / Machining center	Tool	Fixture	Clamping surface
1	A	External turning 		Chuck	2
2	C	External turning 		Chuck	1
1-2	BD	External turning 		InvertedChuck	3
3	E	Spade drilling 		Chuck	1
	F	Internal turning 		Chuck	1
	G	Spade drilling 		Chuck	1
	H	Internal turning 		Chuck	1



Planning

Operation (Surface)	Modes Id	Technology Turning center / Machining center	Tool	Fixture	Clamping surface
1	A	External turning		Chuck	2
2	C	External turning		Chuck	1
1-2	BD	External turning		InvertedChuck	3
3	E	Spade drilling		Chuck	1
	F	Internal turning			
	G	Spade drilling			
	H	Internal turning			



Scheduling

Machine Required

M0 M1 M2 M3 M4
M5 M6 M7 M8 M9