New Ideas. New Materials.

TECHNOLOGIE POLYMERE & KOMPOSITE

MC07, UdS WS 2019/2020

Chapter 8: Additive Manufacturing

Evolution of Manufacturing Technology

- Analog subtractive

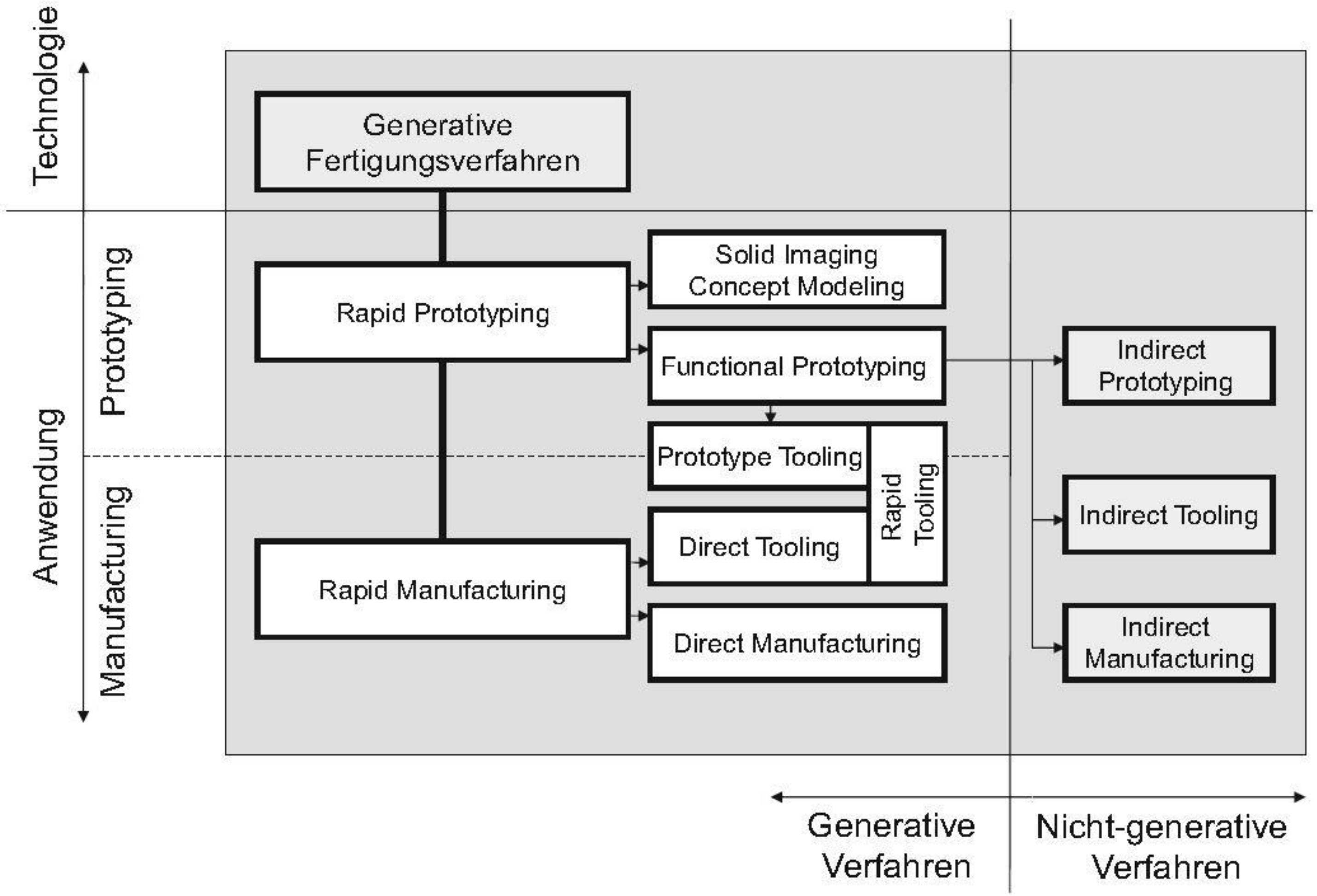
- Analog formative

- Digital additive

- Manufacturing technology has evolved over time
- New technology doesn‘t always replace old one
- Rather:
  - Improves existing ones
  - Increases tool sets for manufacturing

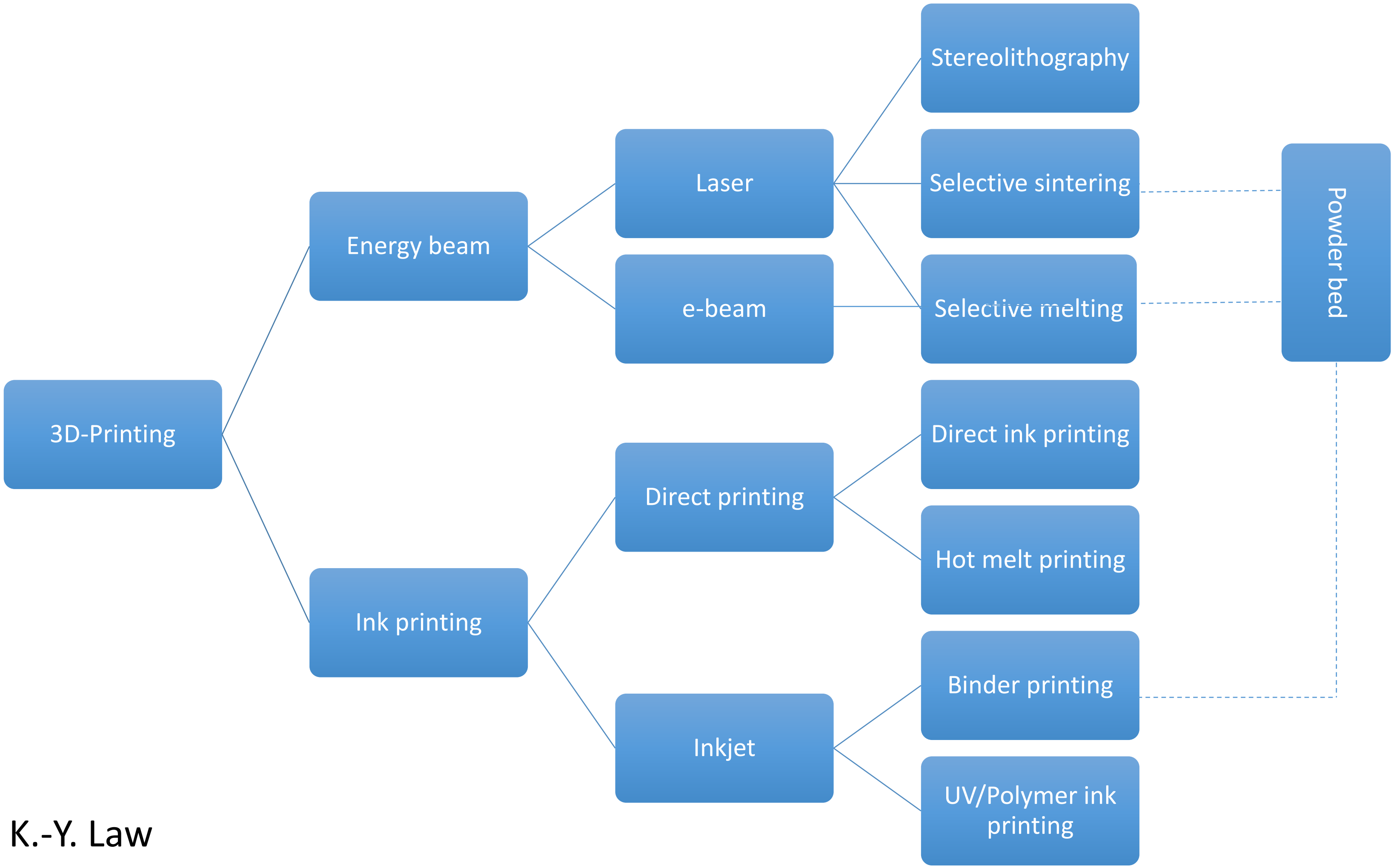
K.-Y. Law

Classification Additive Manufacturing



A. Gebhardt, 3D-Drucken

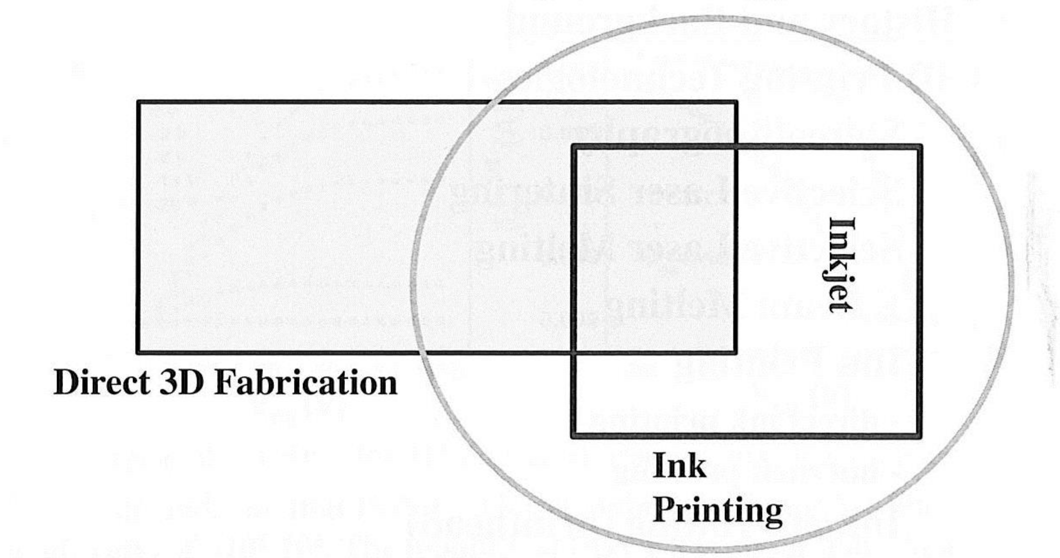
A snapshot at 3D printing technologies



K.-Y. Law

3D Additive Manufacturing landscape

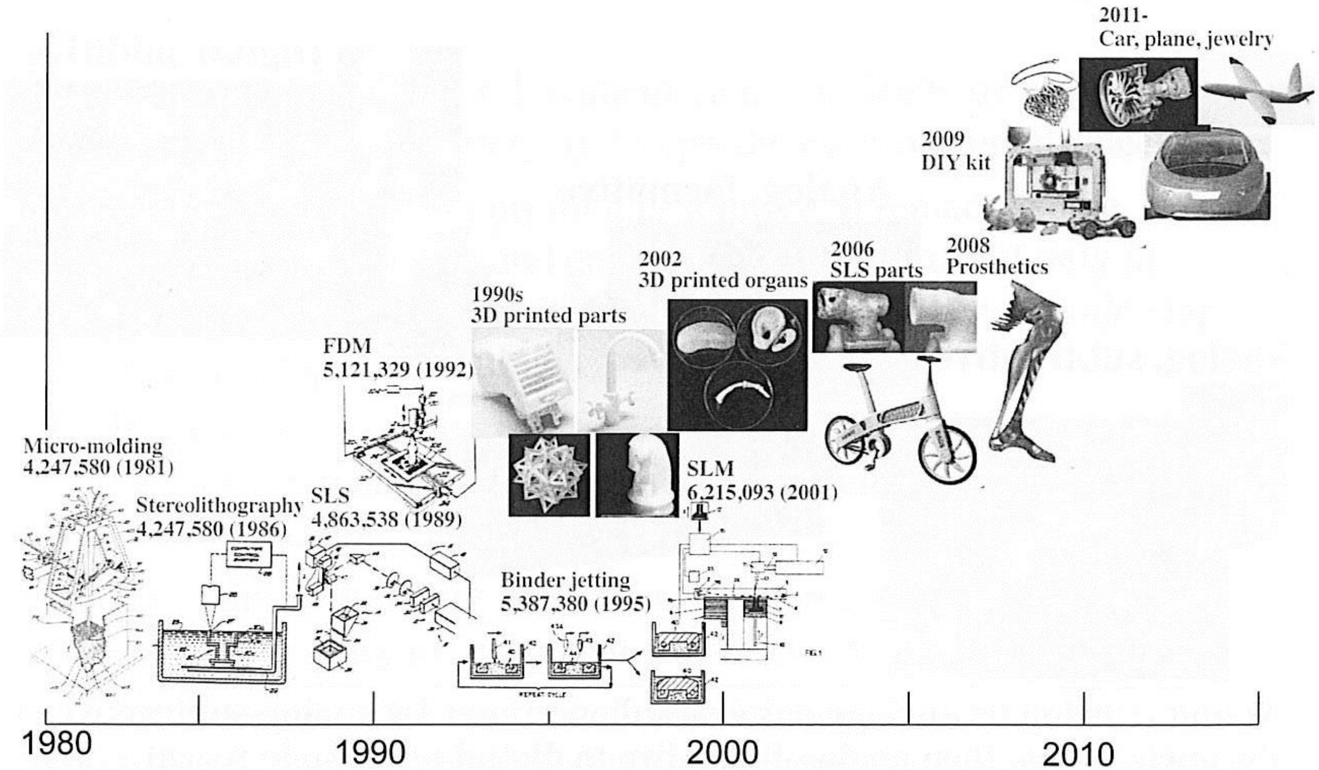
- Concept drawing, not in scale



- Additive manufacturing is the growing trend
- Ink-jet printing is projected to play a significant role in the future (both 2D and 3D)

K.-Y. Law

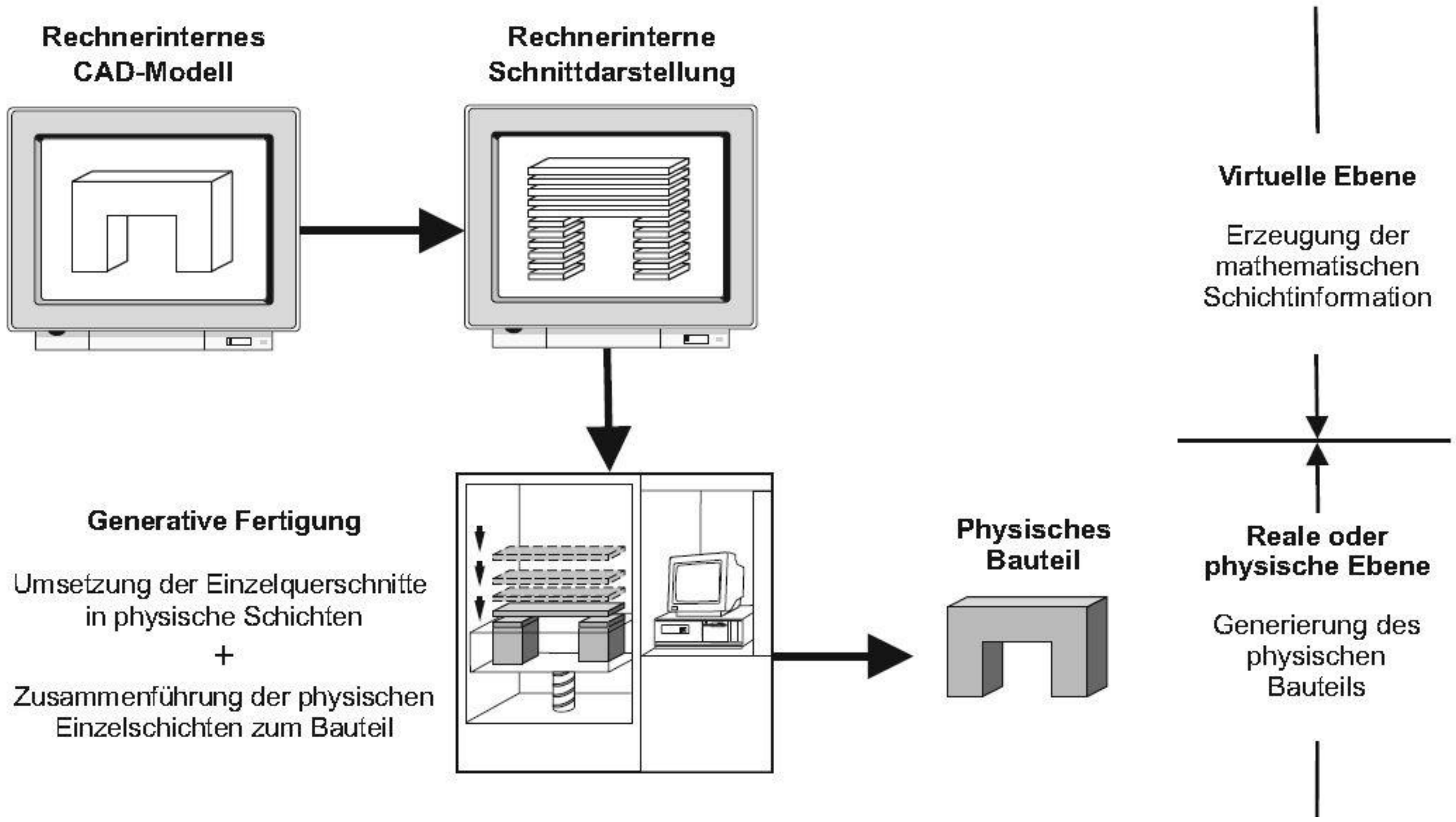
Brief history of 3D printing technologies



- While 3D printing technology took more than a decade to incubate, it took off rapidly at the turn of this century and 3D objects have been built from a variety of technologies.

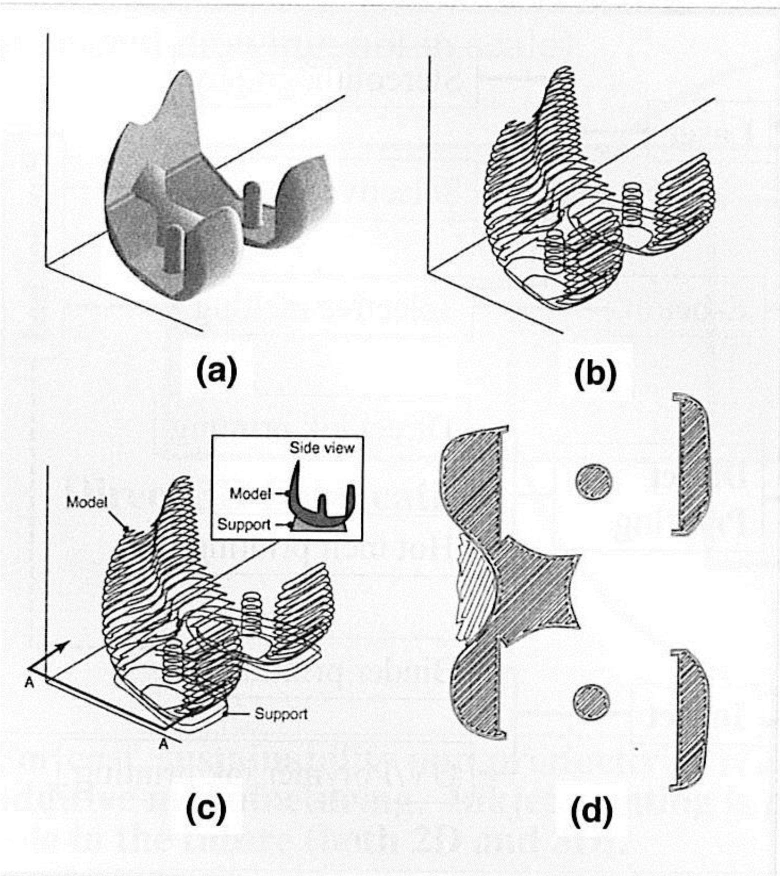
K.-Y. Law

Additive manufacturing process chain

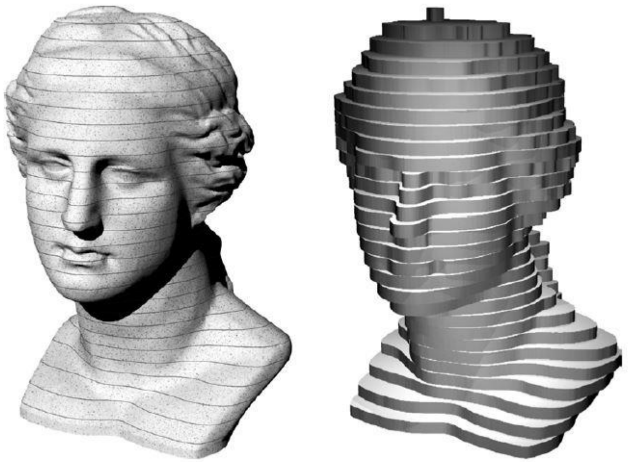


A. Gebhardt, 3D-Drucken

Stereolithography – Creation of CAD-STL file



(a) Three dimensional description of the part (CAD file), (b) divide parts into slices, (c) add support material, and (d) determine tool direction of each slice



A. Gebhardt, 3D-Drucken

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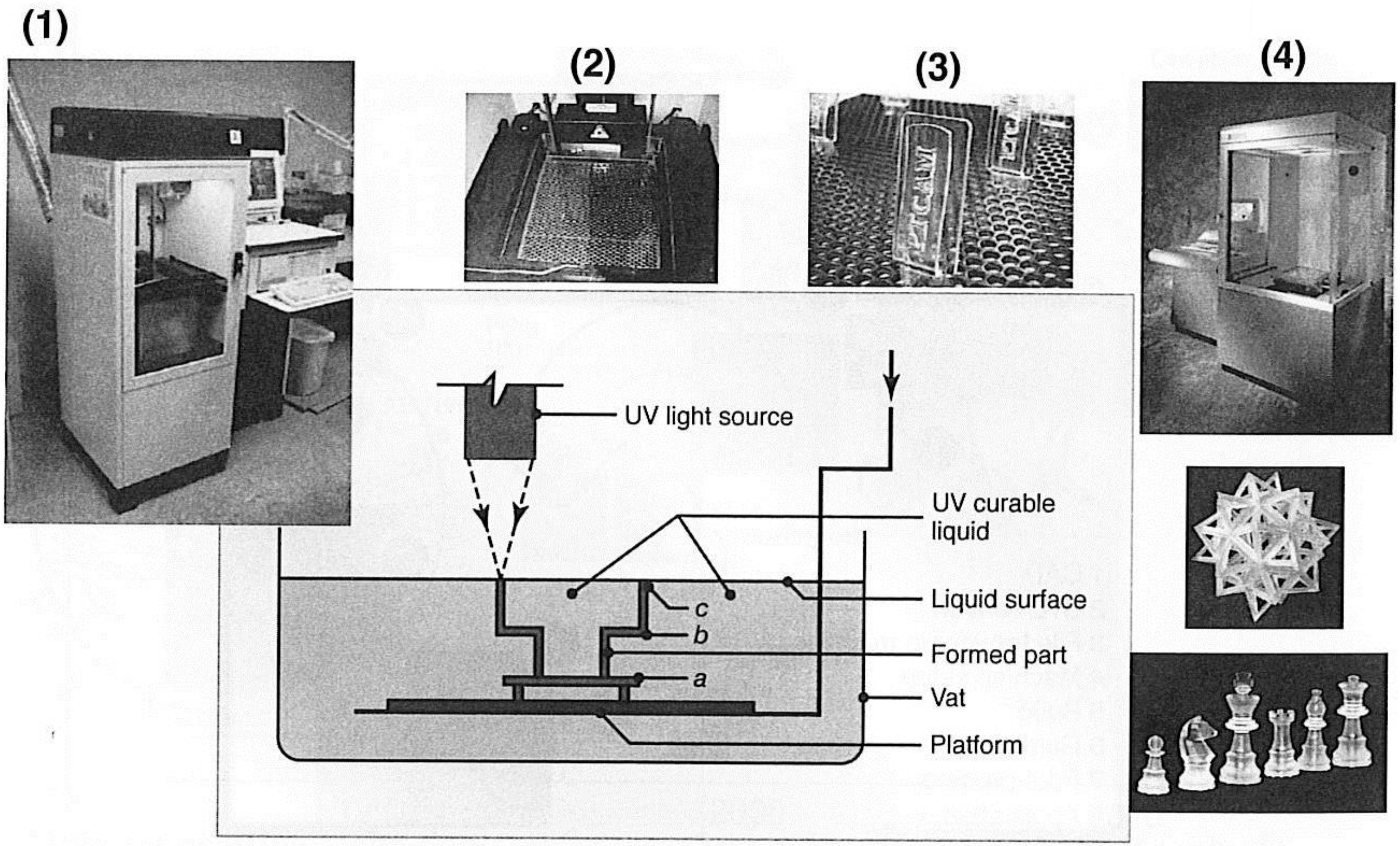
Stereolithography – schematic and basic steps



(1) 3D printer, (2) platform at t=0, (3) printed products, and (4) UV curing.

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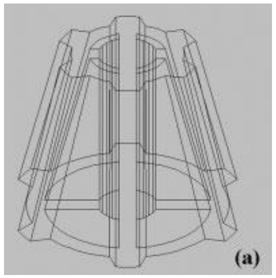
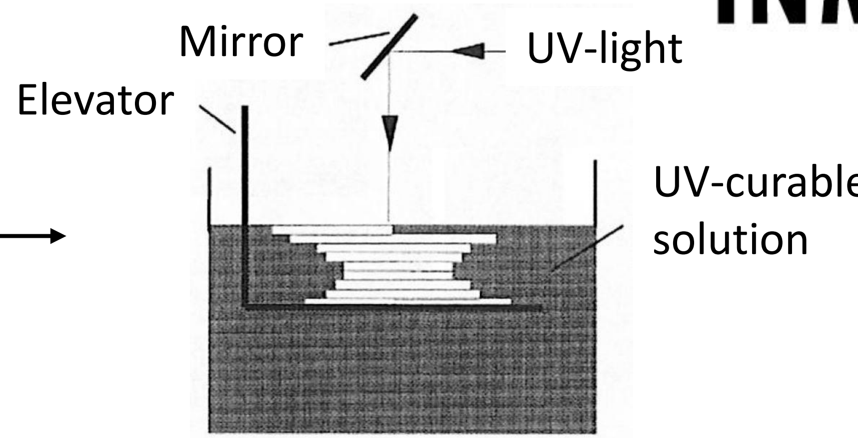
Process for fabricating 3D ceramic part

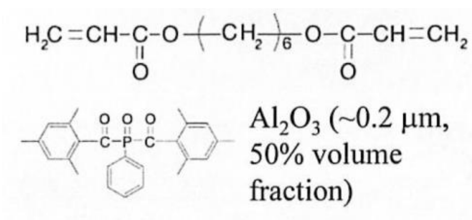


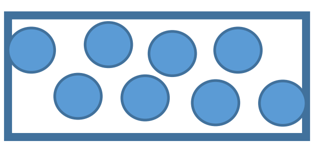
CAD file

2D slice



Stereolithographic process

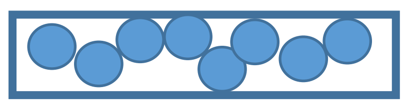




green body with binder

debinding

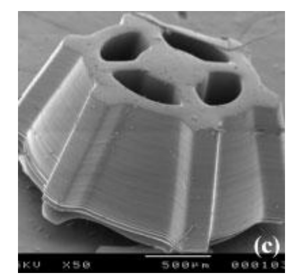
120 °C / 500 °C



green body w/o binder

sintering

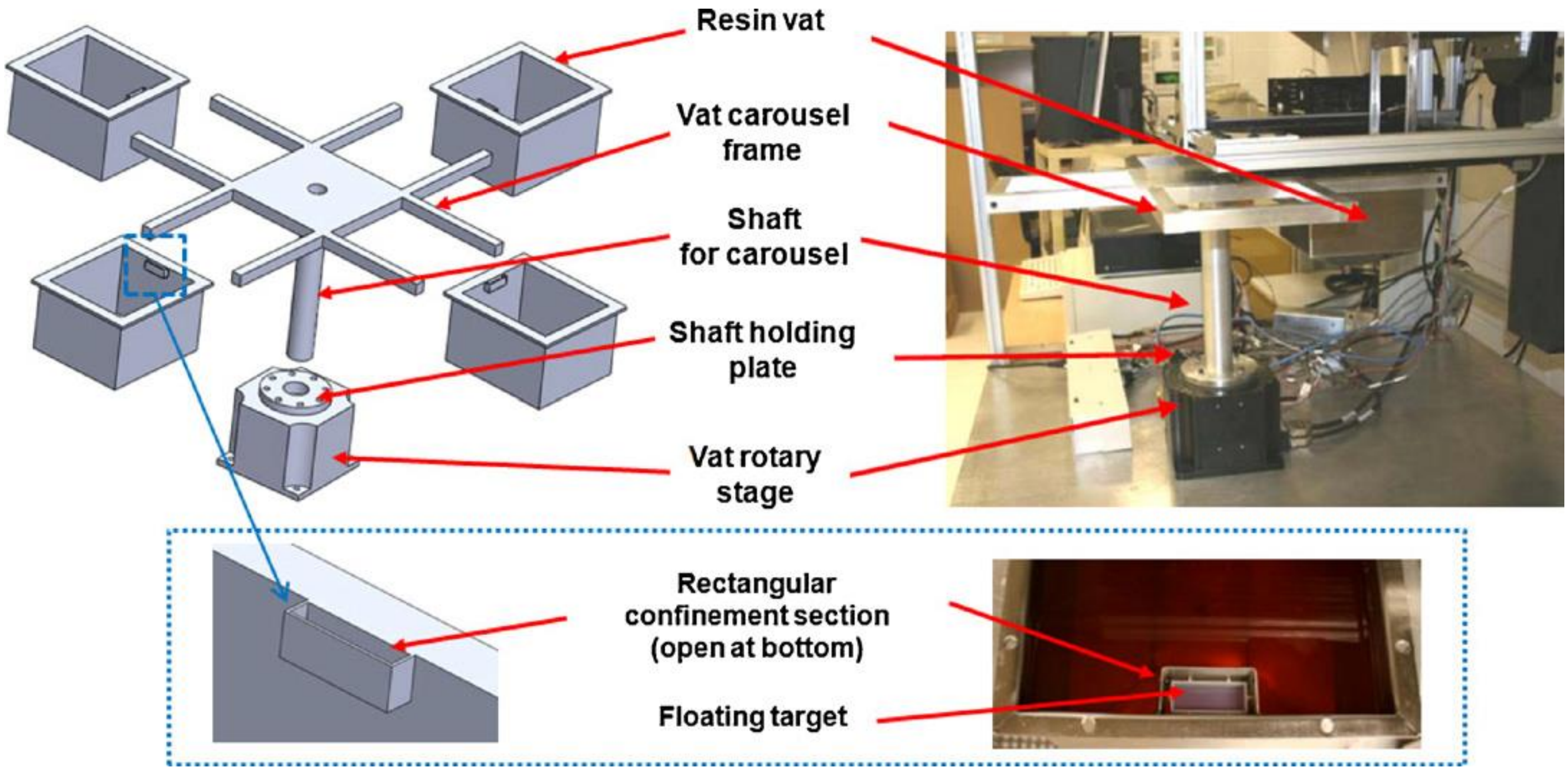
1550 °C



3D ceramic part

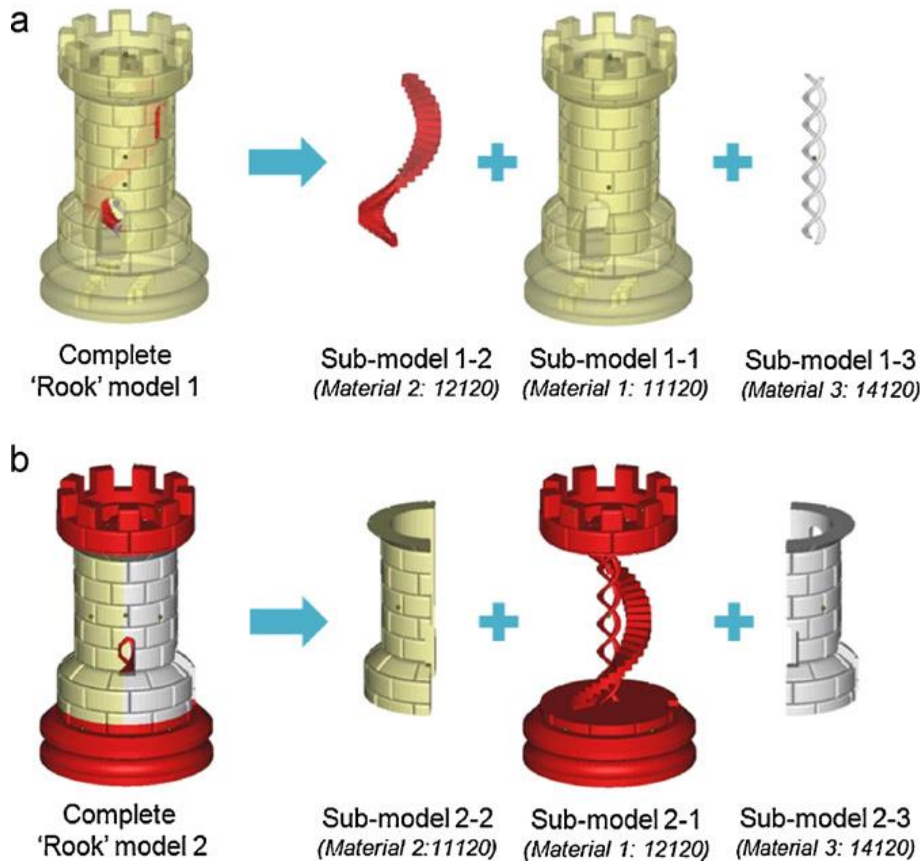
C. Provin, et al. *Adv. Mater.* **2003**, *15*, 994-997

Multi-materials stereolithography



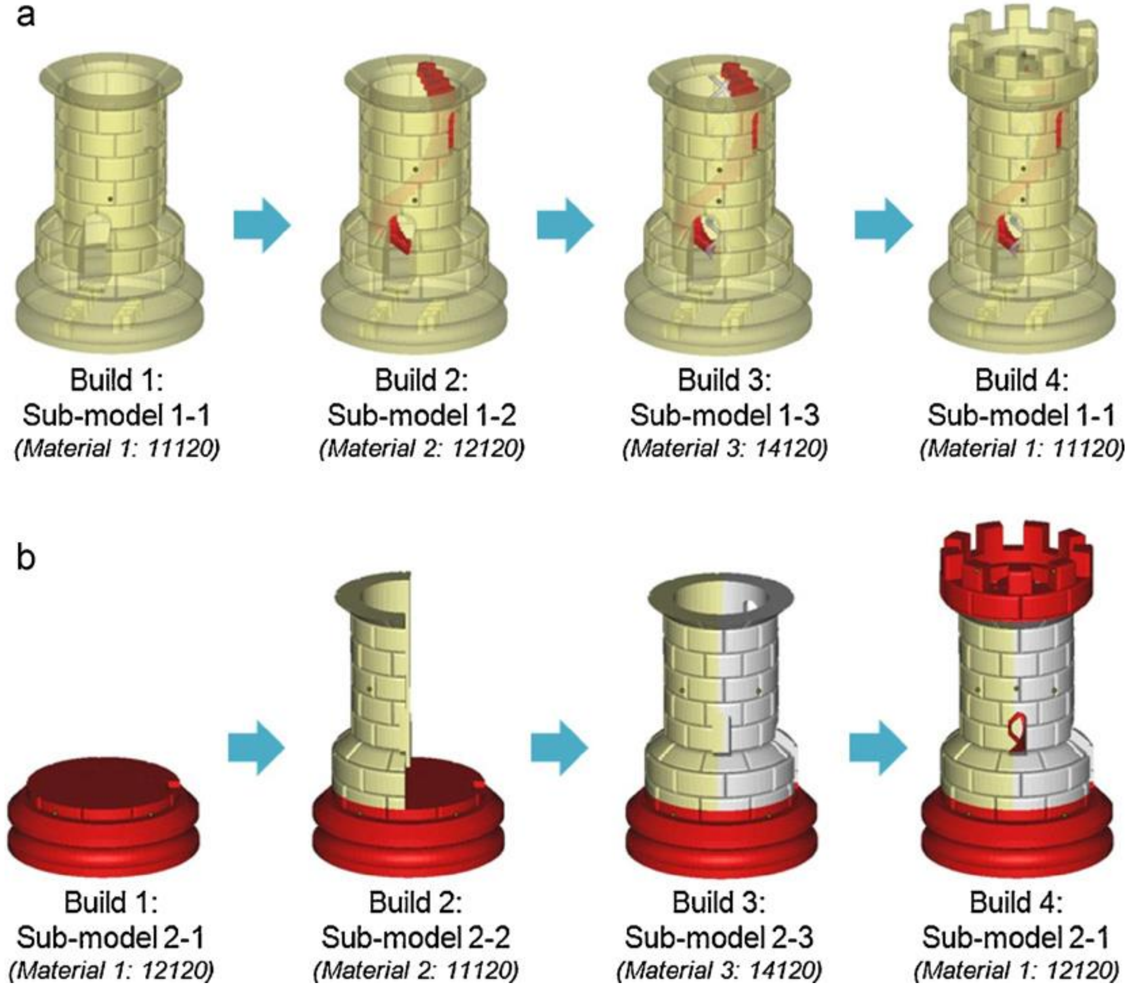
J.W. Choi, et al. *J. Mater. Process. Technol.* **2011**, *211*, 318-328

Multi-materials stereolithography



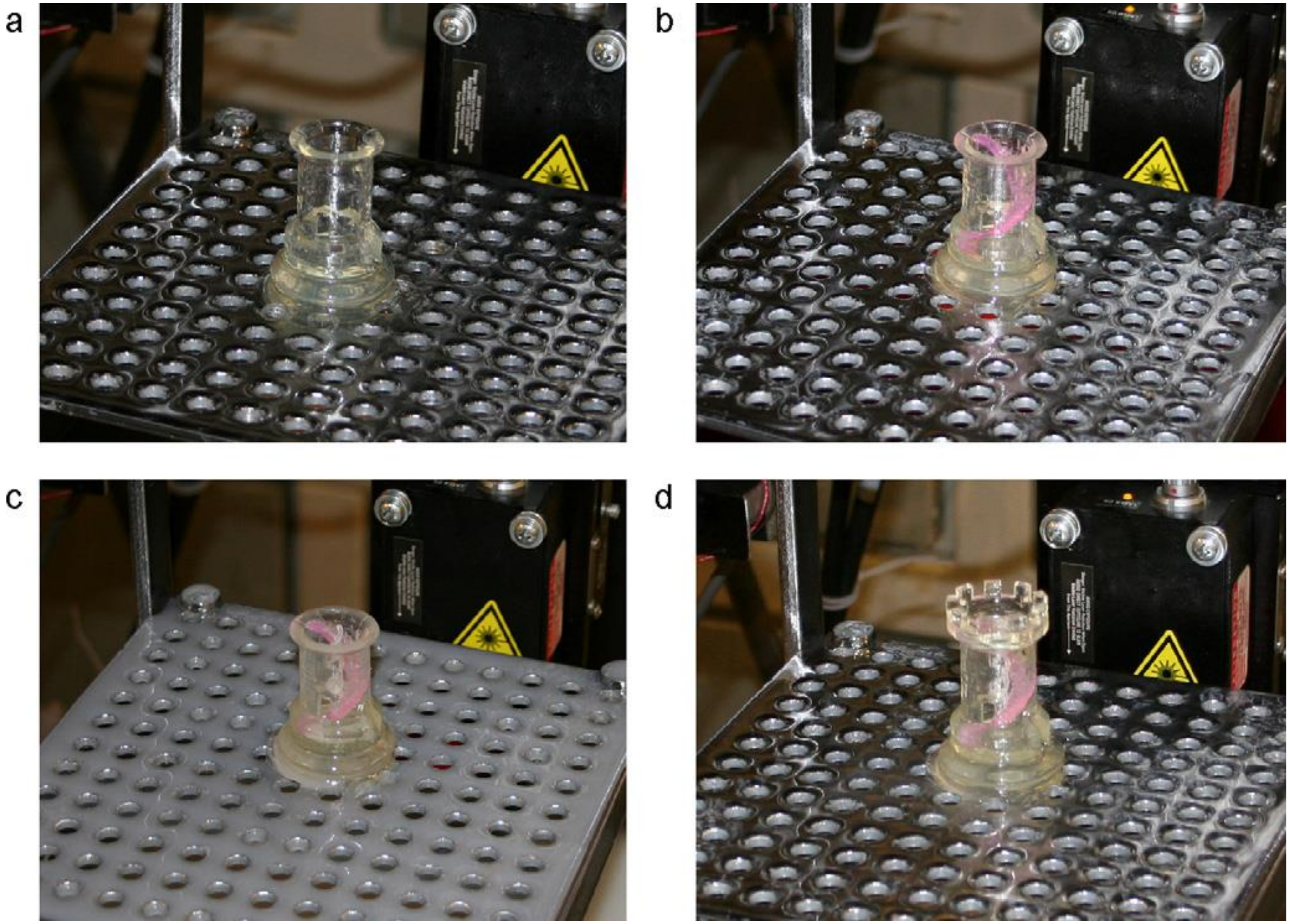
J.W. Choi, et al. *J. Mater. Process. Technol.* **2011**, *211*, 318-328

Multi-materials stereolithography: Process planning



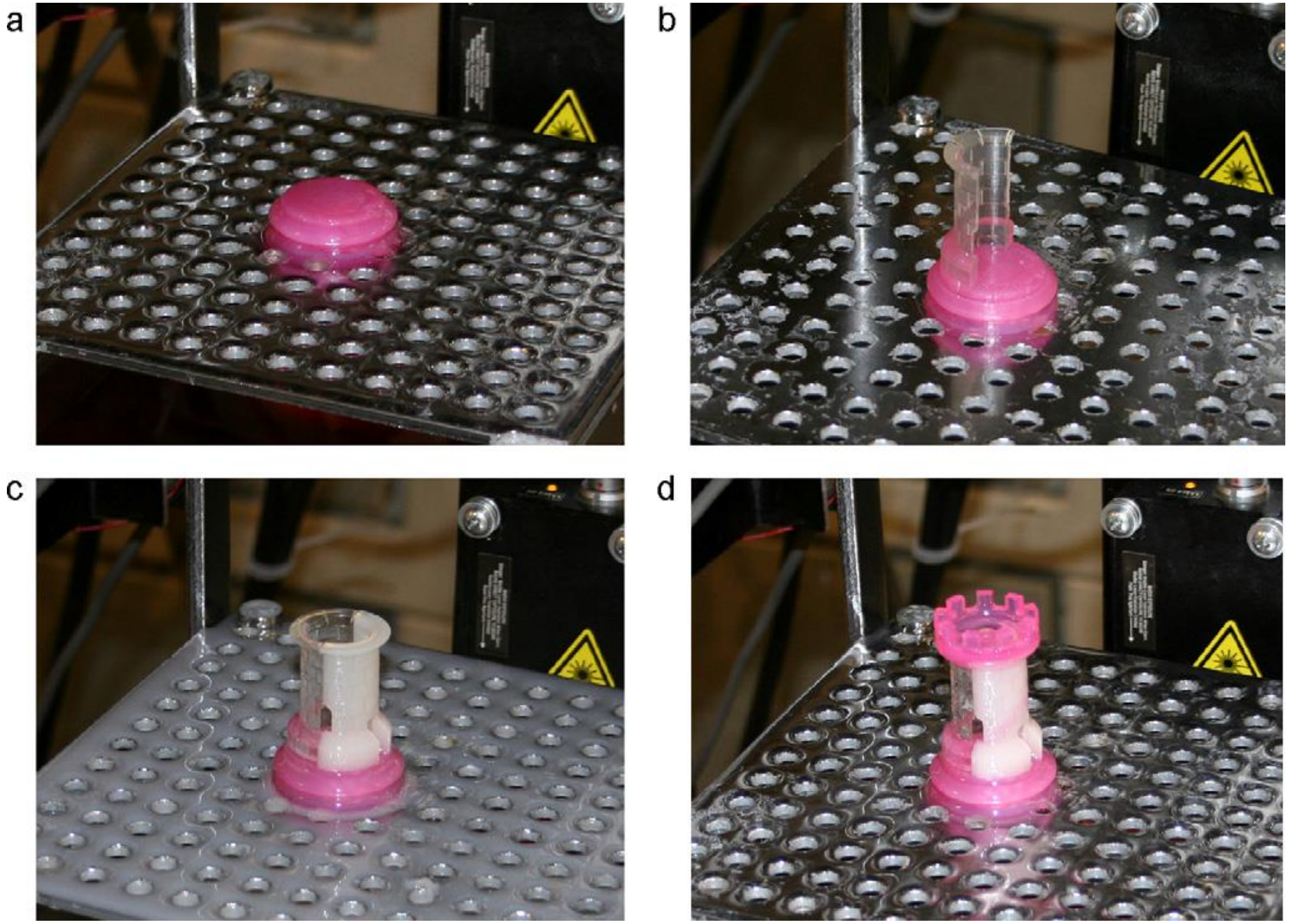
J.W. Choi, et al. *J. Mater. Process. Technol.* **2011**, *211*, 318-328

Multi-materials stereolithography: Process



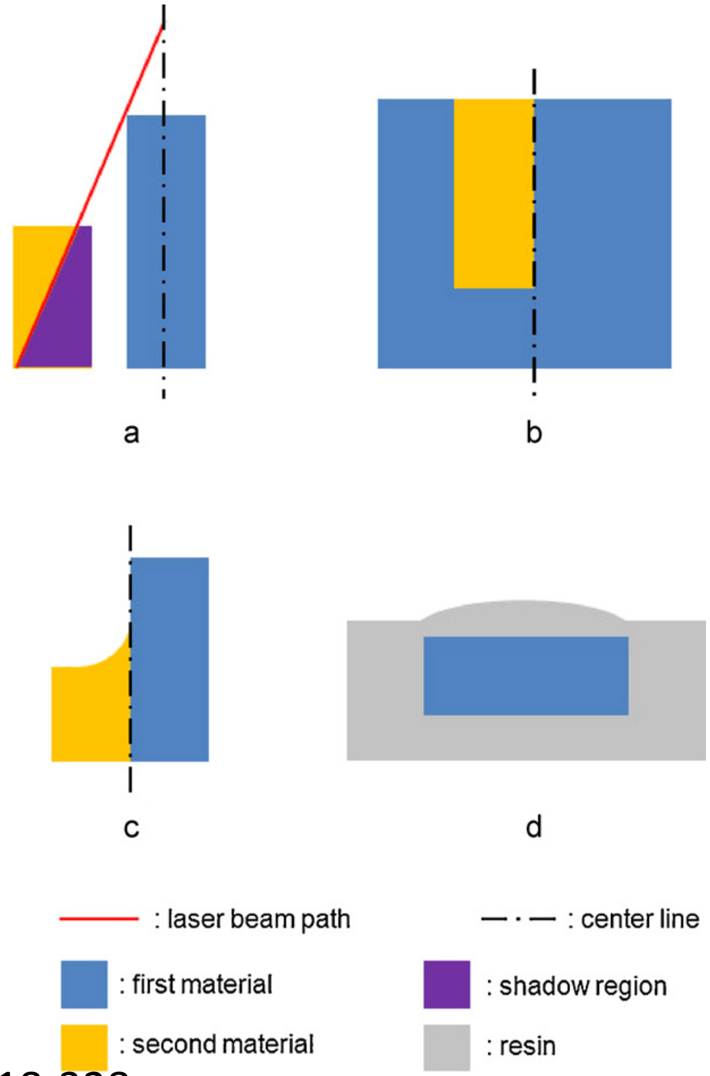
J.W. Choi, et al. *J. Mater. Process. Technol.* **2011**, *211*, 318-328

Multi-materials stereolithography: Process



J.W. Choi, et al. *J. Mater. Process. Technol.* **2011**, *211*, 318-328

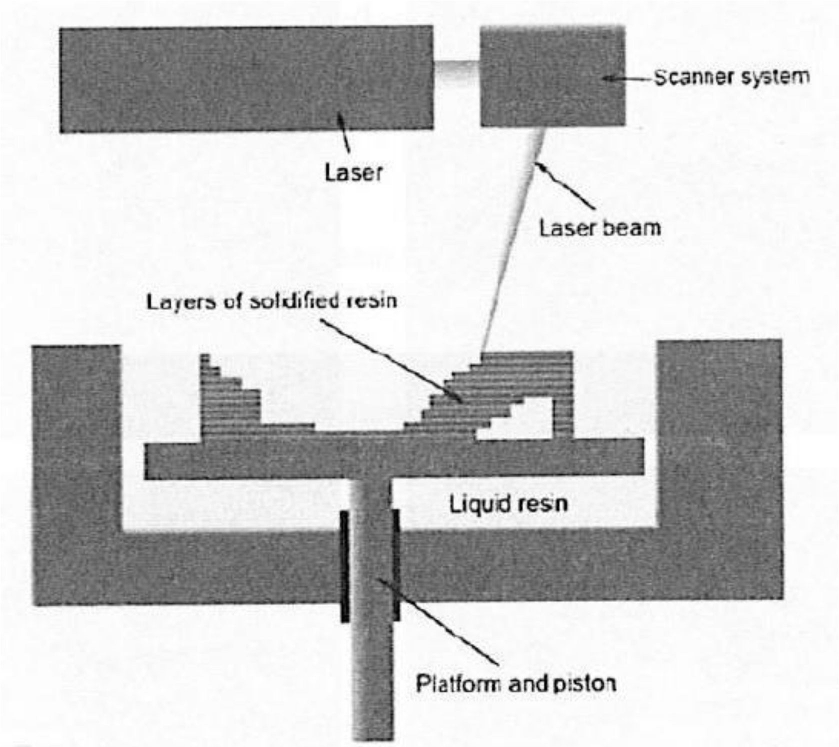
Results and issues specific to multi-materials build

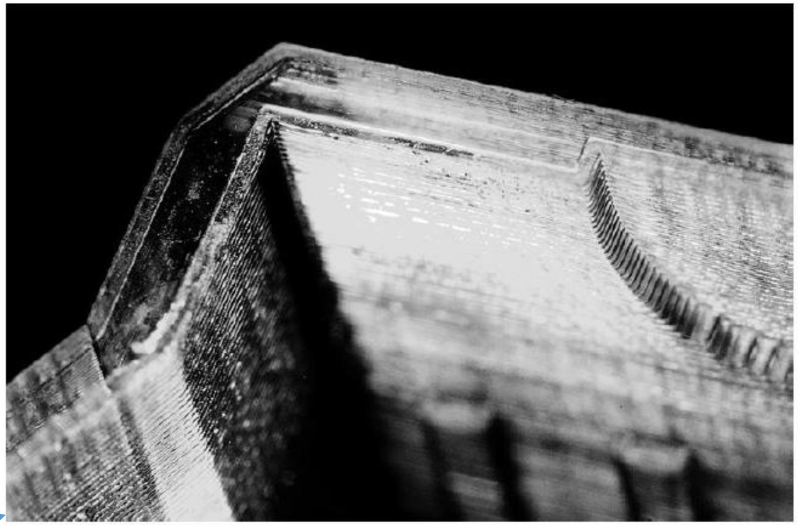


- In addition to cleaning and drying, major technical issues associated with multi materials build include
  - a) laser light path blocking
  - b) trapped volume
  - c), d) surface tension of dissimilar materials

J.W. Choi, et al. *J. Mater. Process. Technol.* **2011**, *211*, 318-328

Major limitations of stereolithography





- process speed low (each layer 25-50µm)
- only 1material set per vat
- limited materials choice
- surface roughness

Fused Deposition Modelling (FDM): TMStratasys (1992)

US005121329A

United States Patent [19] **Crump**

[11] **Patent Number:** **5,121,329**
[45] **Date of Patent:** **Jun. 9, 1992**

[54] **APPARATUS AND METHOD FOR CREATING THREE-DIMENSIONAL OBJECTS**

[75] Inventor: **S. Scott Crump**, Minnetonka, Minn.

[73] Assignee: **Stratasys, Inc.**, Minneapolis, Minn.

[21] Appl. No.: **429,012**

[22] Filed: **Oct. 30, 1989**

[51] **Int. Cl.**[5] **G06F 15/46**
[52] **U.S. Cl.** **364/468**; 364/474.24; 364/477; 264/239; 264/25; 425/174.4
[58] **Field of Search** 364/472, 473, 477; 264/308, 113; 425/174.4; 427/8, 52; 164/94; 239/75, 82, 83, 84, 132

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Asymtek Brochure, "Benchtop Automation" May 1988.

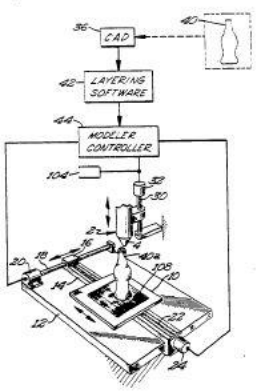
Primary Examiner—Joseph Ruggiero
Assistant Examiner—Patrick D. Muir
Attorney, Agent, or Firm—Moore & Hansen

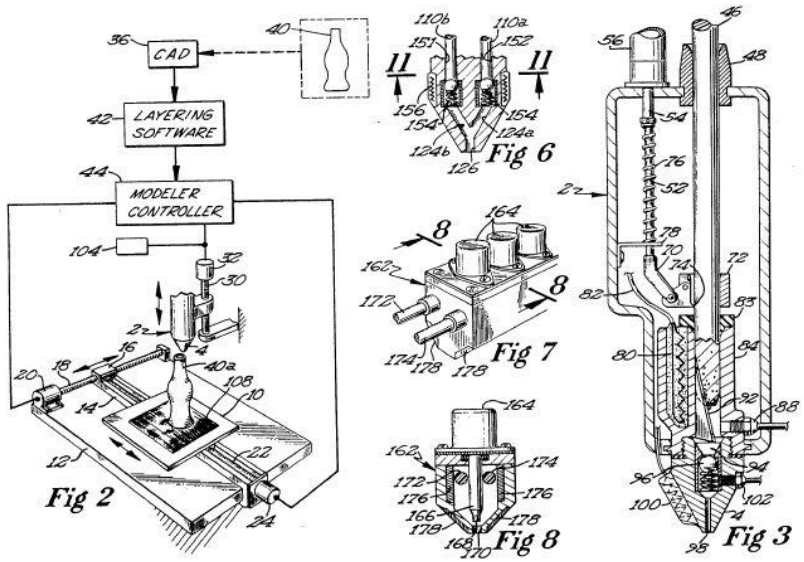
[57] **ABSTRACT**

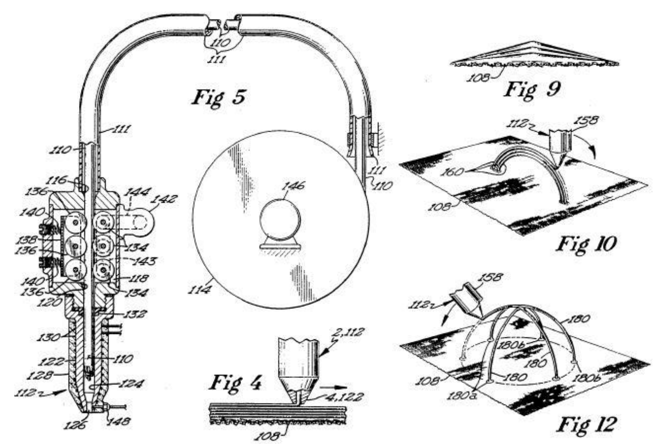
Apparatus incorporating a movable dispensing head provided with a supply of material which solidifies at a predetermined temperature, and a base member, which are moved relative to each other along "X," "Y," and "Z" axes in a predetermined pattern to create three-dimensional objects by building up material discharged from the dispensing head onto the base member at a controlled rate. The apparatus is preferably computer driven in a process utilizing computer aided design (CAD) and computer-aided (CAM) software to generate drive signals for controlled movement of the dispensing head and base member as material is being dispensed.

Three-dimensional objects may be produced by depositing repeated layers of solidifying material until the shape is formed. Any material, such as self-hardening waxes, thermoplastic resins, molten metals, two-part epoxies, foaming plastics, and glass, which adheres to the previous layer with an adequate bond upon solidification, may be utilized. Each layer base is defined by the previous layer, and each layer thickness is defined and closely controlled by the height at which the tip of the dispensing head is positioned above the preceding layer.

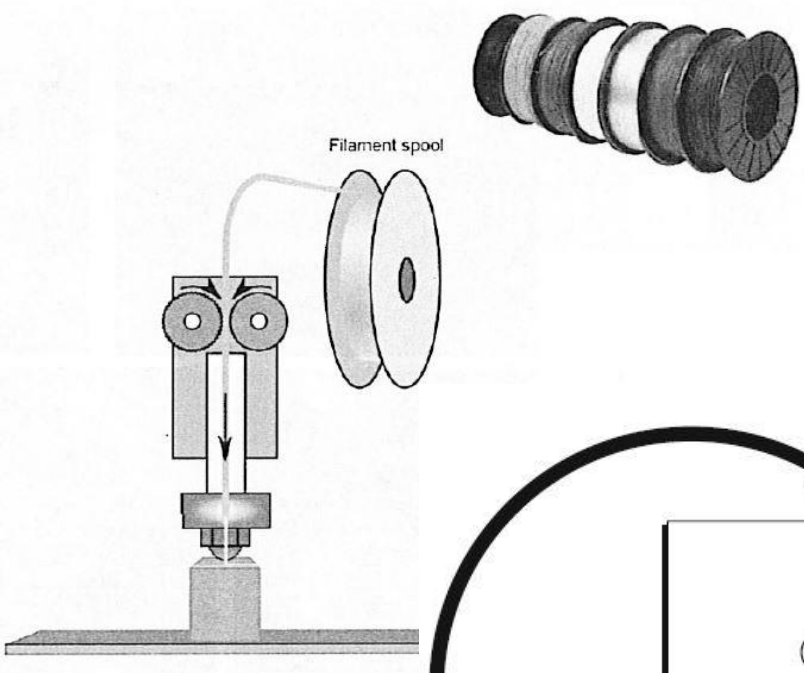
44 Claims, 3 Drawing Sheets

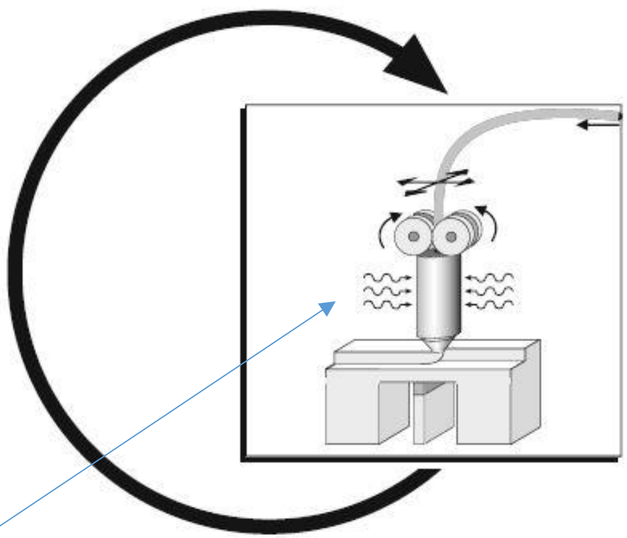






FDM / FFF (Fused Filament Fabrication)-principle





temperature controlled extruder

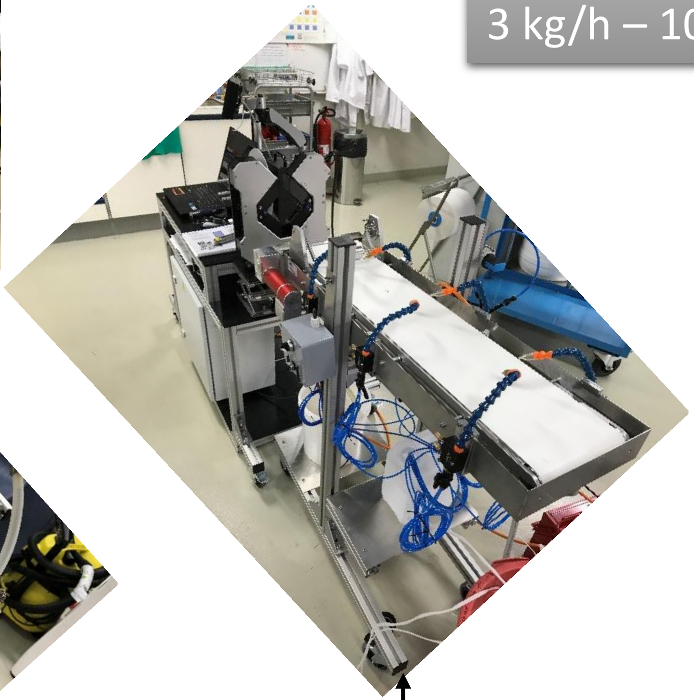
source: Goethe – lab, FH-Aachen

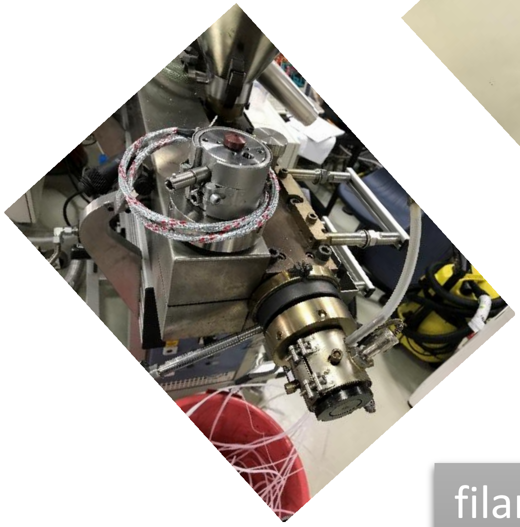
Compounding techniques

Twin-screw extruder: Filaments

Brabender DSE 20

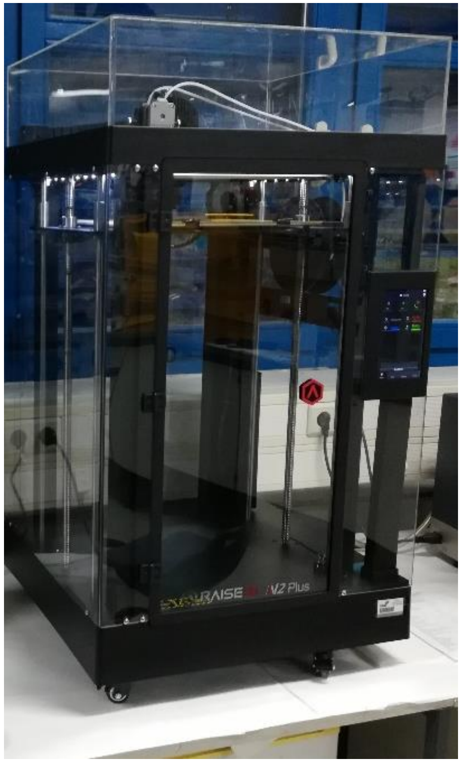
T up to 420 °C
3 kg/h – 10 kg/h

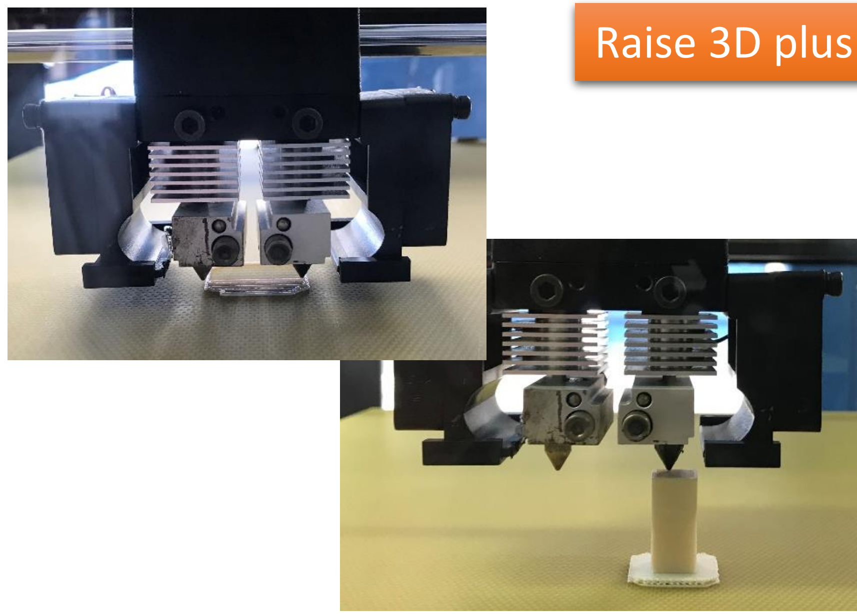




filament drawing unit with
y-/z-online thickness measurement

FFF 3D-printing at INM





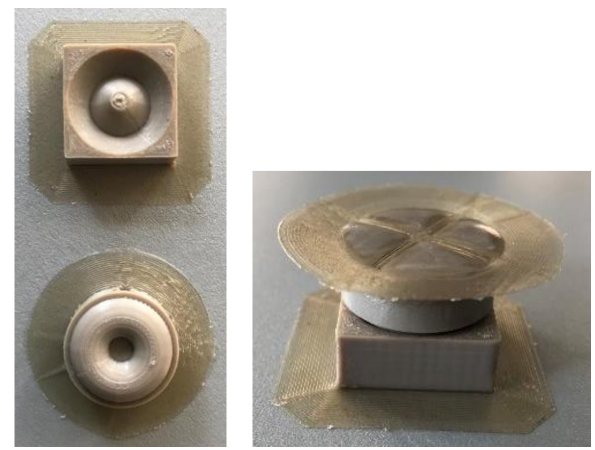
Raise 3D plus

technique	FFF
available space	30 cm x 30 cm x 60 cm
number of extruders	2
heat bed temperature	up to 110 °C
hot end temperature	up to 300 °C

FFF 3D-printing of high performance polymers

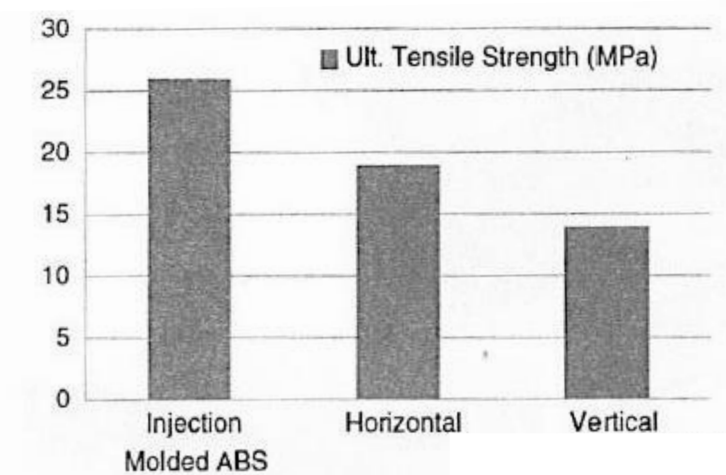
suitable for
- PEEK
- PVDF
- PEI
- PA
- …

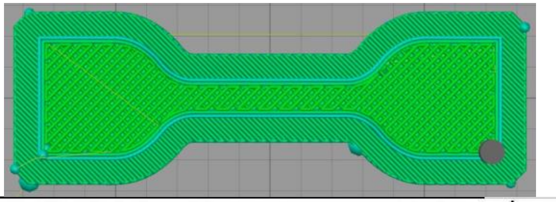
technique	FFF
available space	15 cm x 15 cm x 15 cm
number of extruders	1
heat bed temperature	up to 180 °C
hot end temperature	up to 520 °C

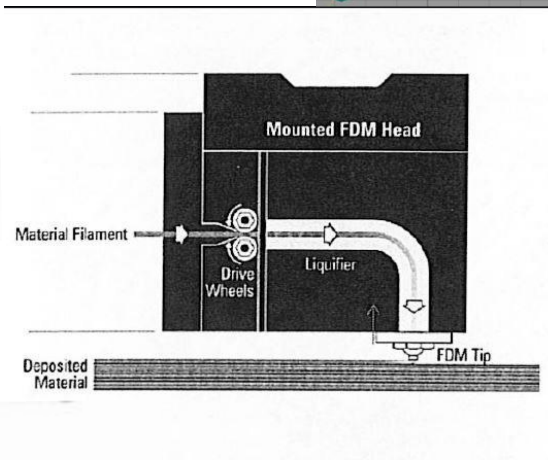


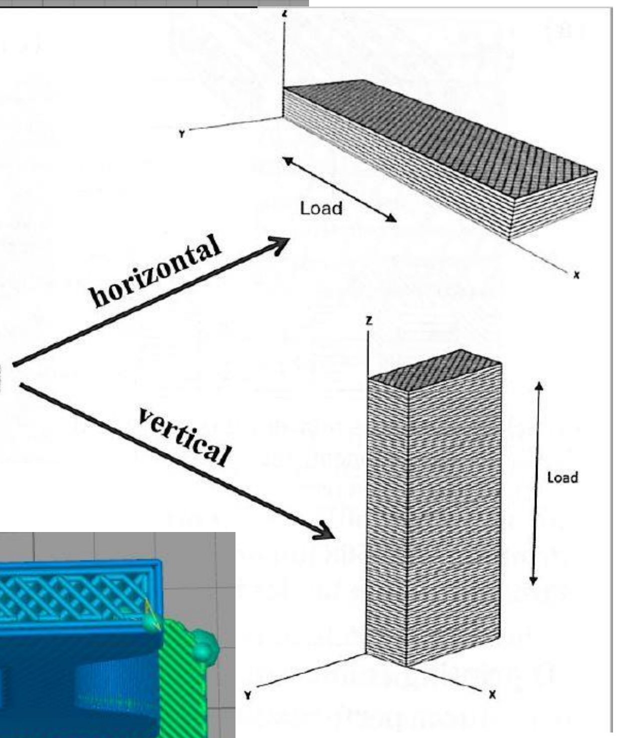
tribometer directly printed from PEEK

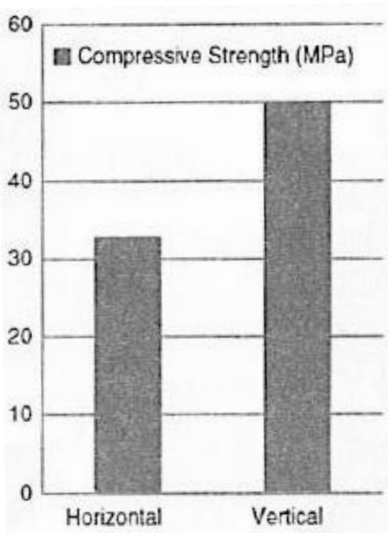
Orientation effects on mechanical properties of ABS

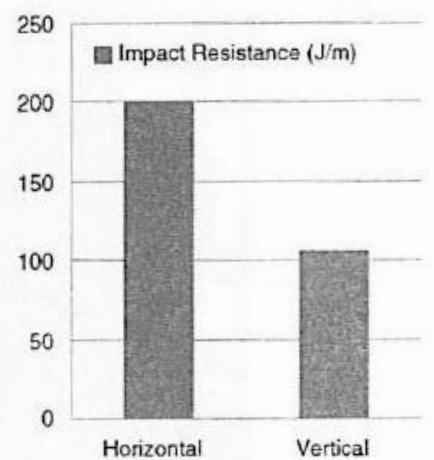


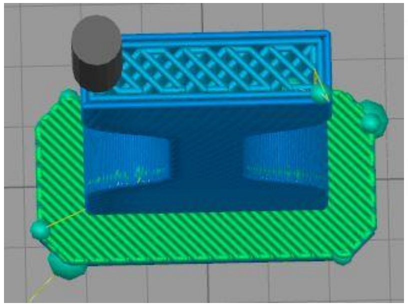












Selective Laser Sintering (SLS) of thermoplastics

R.D. Goodridge et al., *Prog. Mater Sci.* **2012**, *57*, 229

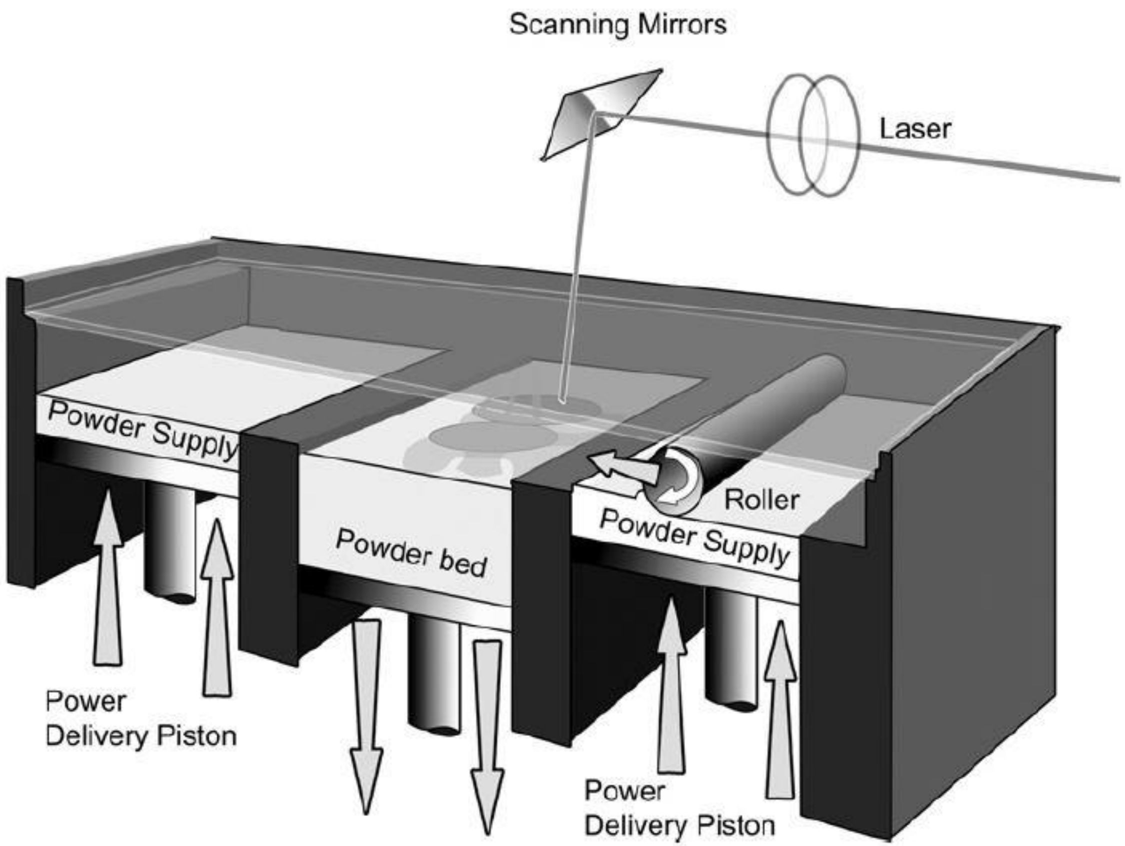


Fig. 1. Schematic of the laser sintering process. (Reproduced with kind permission of Hopkinson et al. [1].)

Selective Laser Sintering (SLS) of thermoplastics

R.D. Goodridge et al., *Prog. Mater Sci.* **2012**, *57*, 229

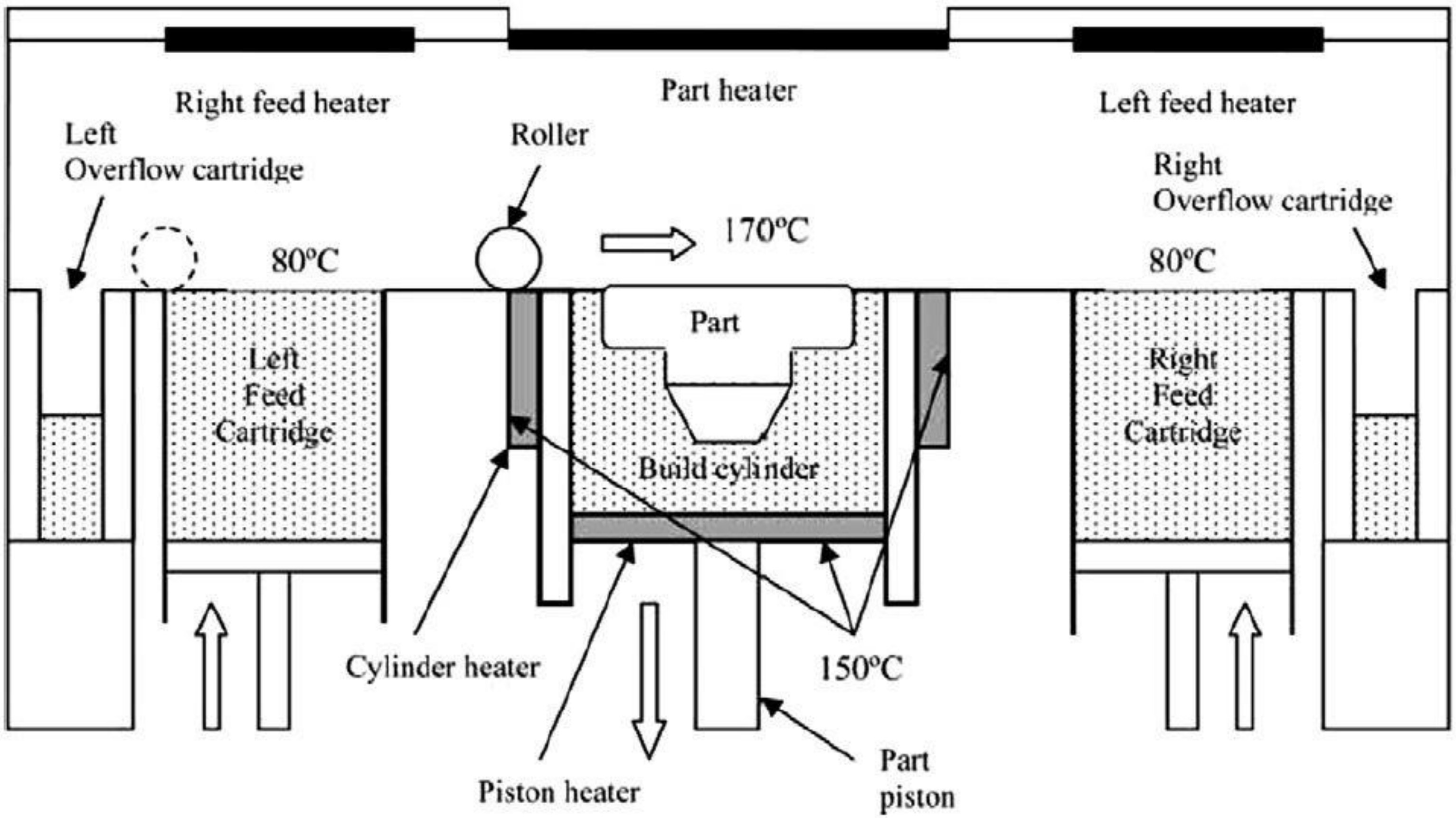
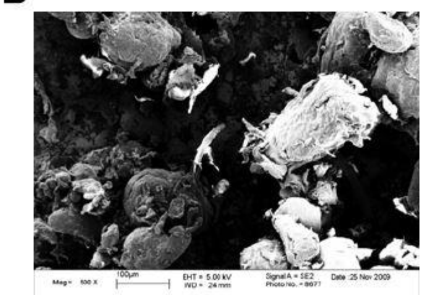
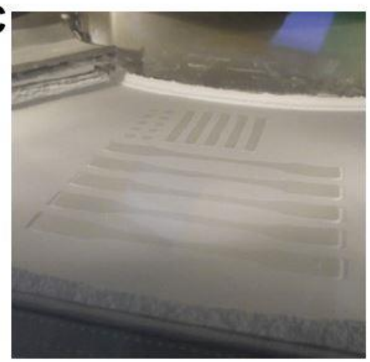


Fig. 2. Schematic of the 3D Systems Sinterstation® HiQ™ System. (Reproduced with kind permission of Pham et al. [109].)

Selective Laser Sintering (SLS): powder characteristics

R.D. Goodridge et al., *Prog. Mater Sci.* **2012**, *57*, 229

Production of Duraform®PA12	Standard commercial process	Cryogenic Fracture
SEM of Powder morphology (x500)	A 	B 
Powder bed during processing	C 	D 
Laser Sintered Part	E 	F 

Selective Laser Sintering (SLS): temperature distribution

R.D. Goodridge et al., *Prog. Mater Sci.* **2012**, *57*, 229

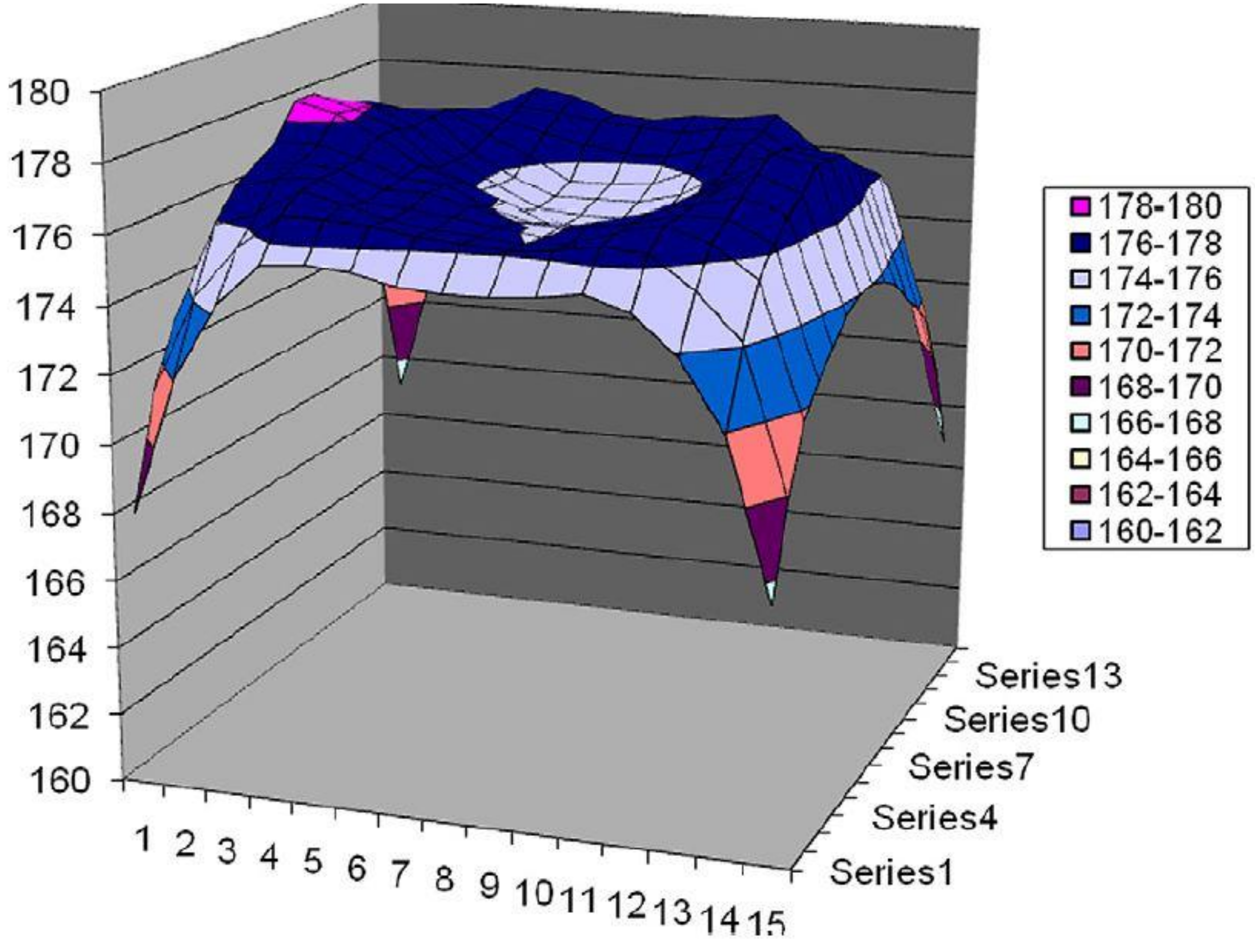


Fig. 10. Temperature distribution on an EOS P390 machine.

Mechanical properties dependent on position in chamber

R.D. Goodridge et al., *Prog. Mater Sci.* **2012**, *57*, 229

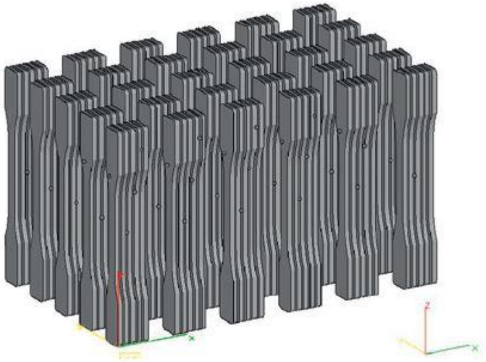


Fig. 11. 3D Systems powder bed divided into 30 zones (left) with five tensile test pieces built in vertical orientation in each temperature zone (right).

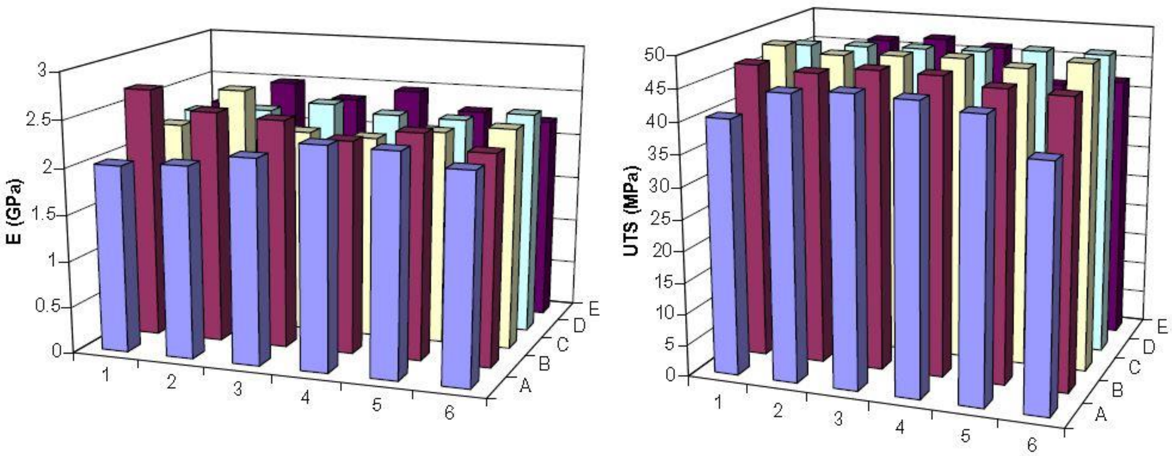


Fig. 12. Distribution of modulus and UTS values on a 3D Systems Vanguard Build Platform for Duraform® Polyamide 12.

Mechanical properties dependent on printing direction

R.D. Goodridge et al., *Prog. Mater Sci.* **2012**, *57*, 229

0° 90°

Table 4
Variation in mechanical properties with build direction. (Reproduced with kind permission of Ajoku et al. [77].)

Mechanical property	X-axis	Y-axis	Z-axis	Maximum difference (%)
Tensile				
UTS (MPa)				
Ave.	*48.7*	*44.7*	*40.9*	*16.0*
Max.	50.4	47.9	42	
Min.	46.9	38.5	39.9	
E_T (MPa)				
Ave.	*2047.1*	*1944.1*	*1817*	*11.2*
Max.	2070.6	2004.8	1830.2	
Min.	2014.3	1803.6	1806.9	
ε (%)				
Ave.	*9.0*	*8.0*	*8.4*	*11.1*
Max.	10.8	8.7	8.6	
Min.	8.0	7.3	8.0	

σ_{max}

-16% @ 90° vs 0°

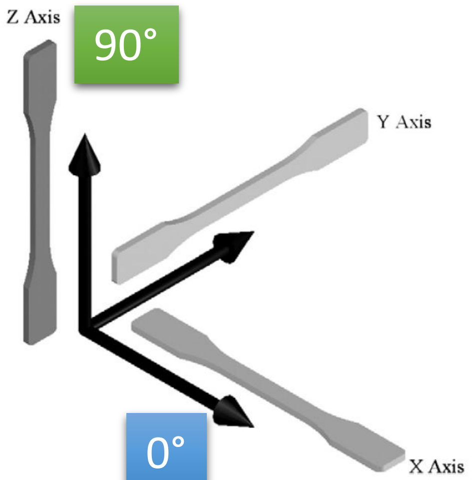


Fig. 18. Build orientation of test parts used by Ajoku et al. [87].

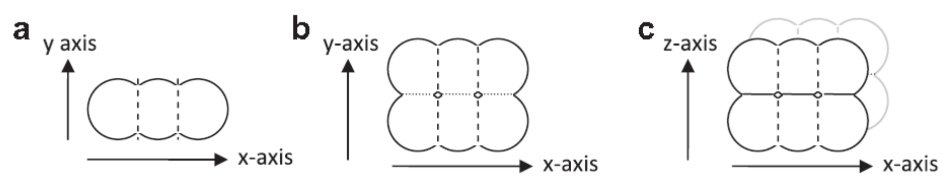
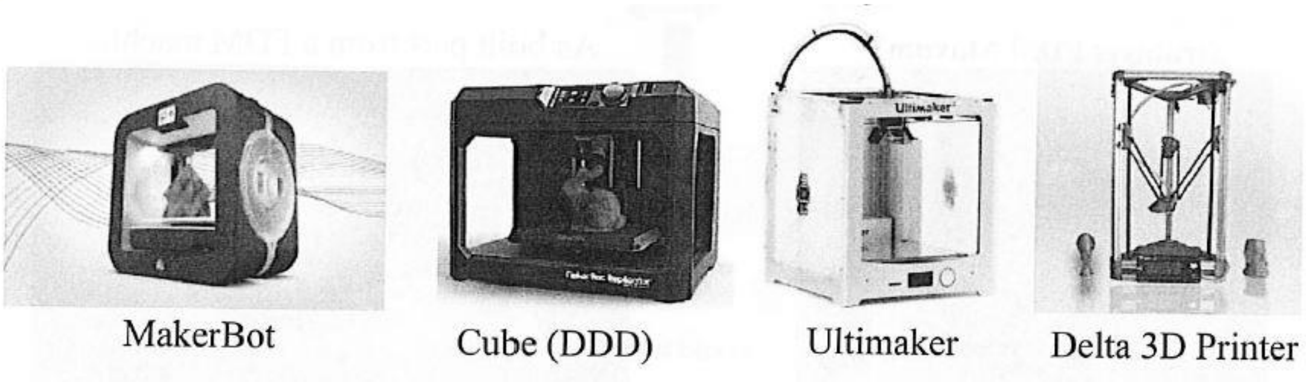


Fig. 19. Schematic illustration of sintering in the laser sintered process, with (A) showing necking between particles in a single vector, (B) necking between two parallel vectors and (C) necking between different layers.

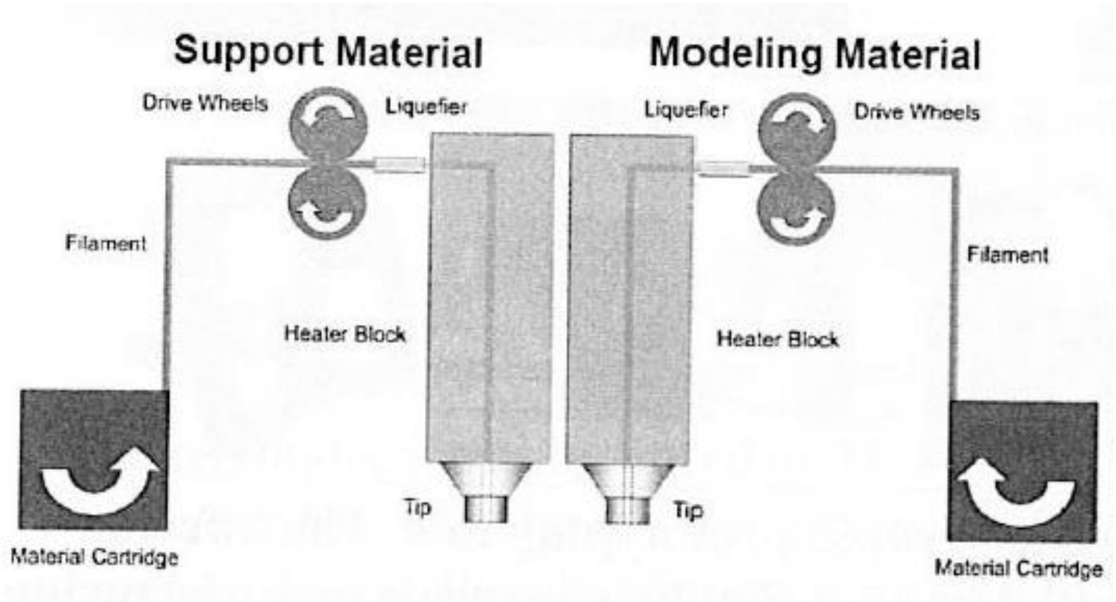
Commercialised FFF systems

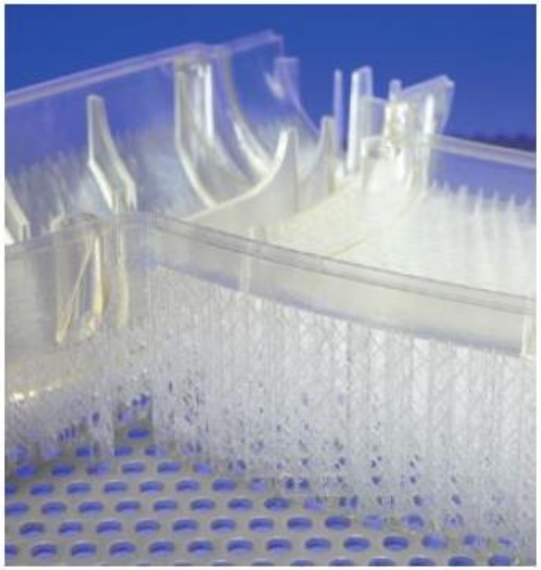


printers with 2 nozzles:

- 1 for build material
- 1 for support material

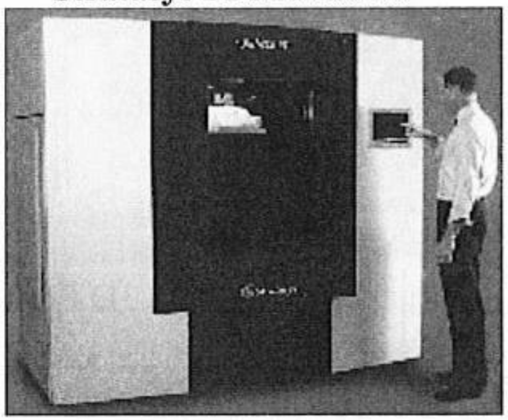
(support = water soluble)



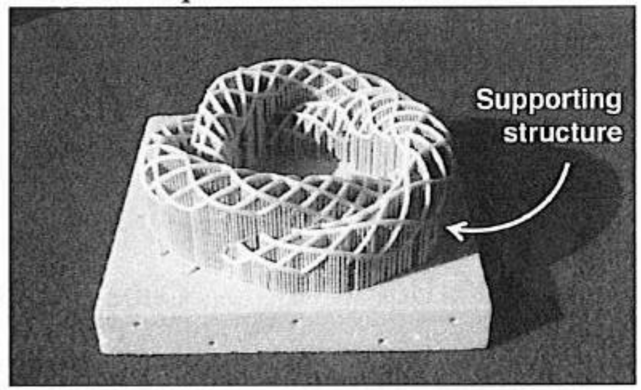


Applications of FFF-system

Stratasys FDM Maxum™



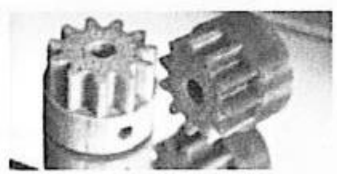
As built part from a FDM machine



Tool

Medical

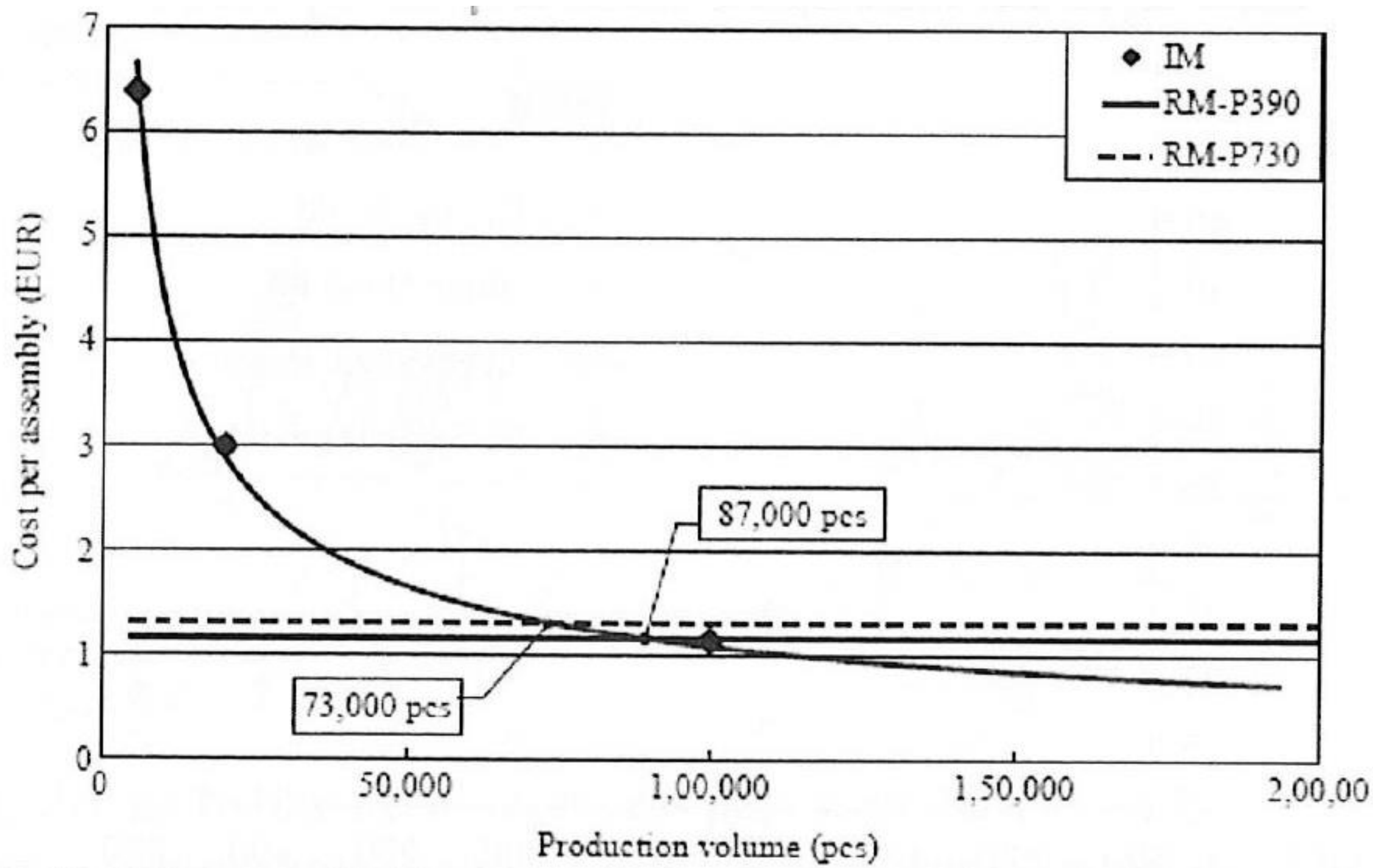
Aeronautic



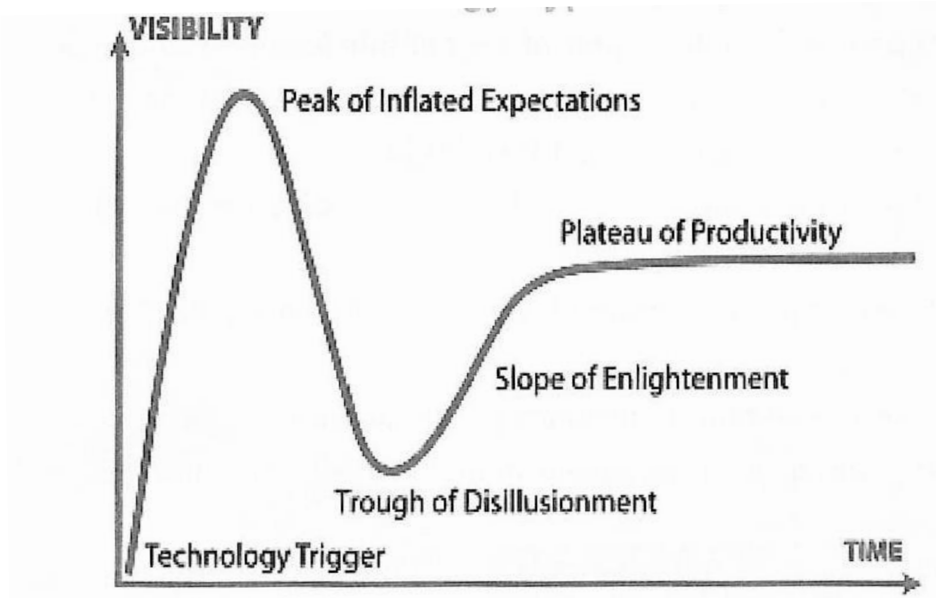
Automotive

FDM has been primarily used as a rapid prototyping tool. The inferior mechanical property has limited its adoption in large scale manufacturing.

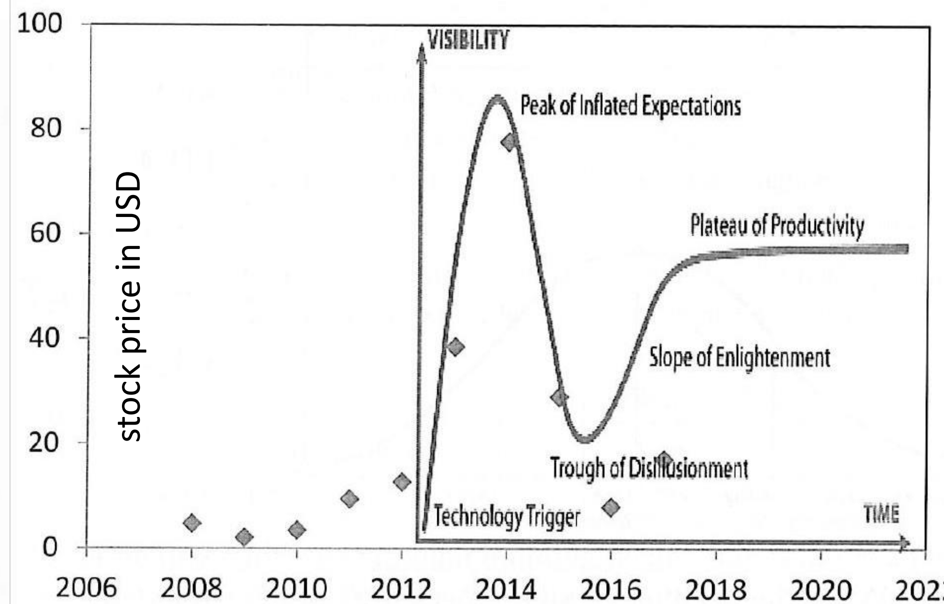
„Cost"-comparison Injection moulding vs SLS



Technology hype of 3D-printing?



When there is a lot of hype, expectations are high and stock price becomes irrational.

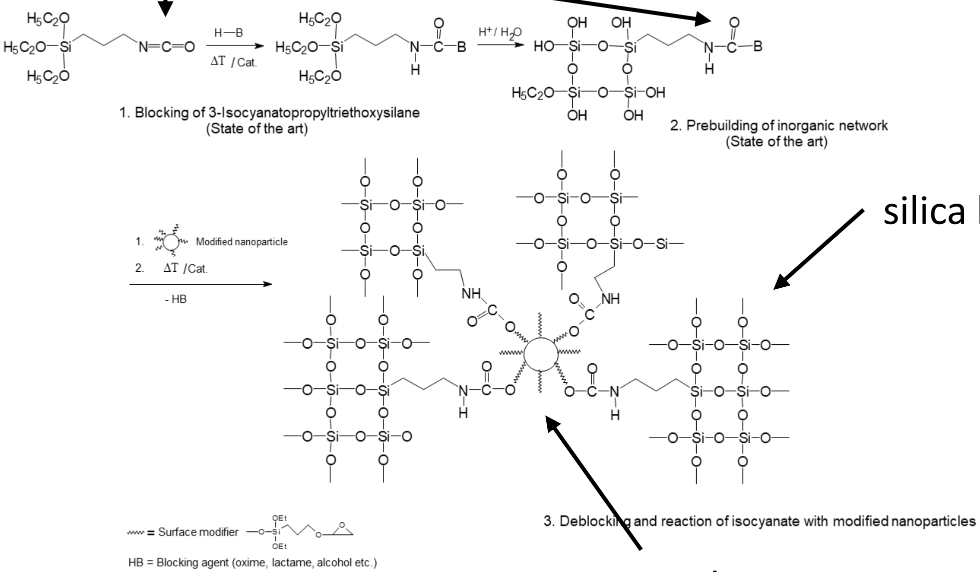


The fate of 3D printing remains to be determined!!!

Nanomer® materials for direct 3D-printing at INM

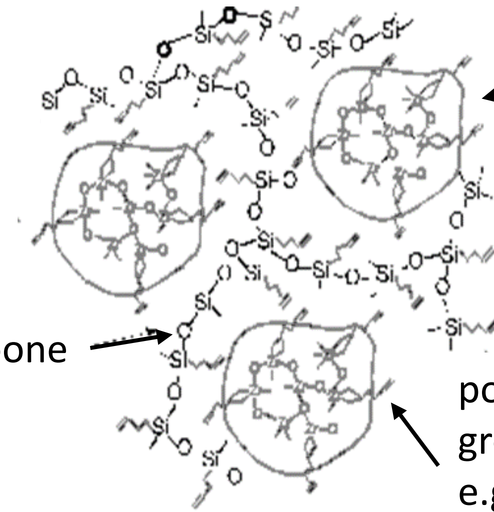
organic-inorganic hybrid nanocomposites

polymerisable groupings
e.g. -NCO, epoxy, …



silica backbone

nanoparticles



nanoparticles

polymerisable groupings
e.g. -C=C, epoxy, …

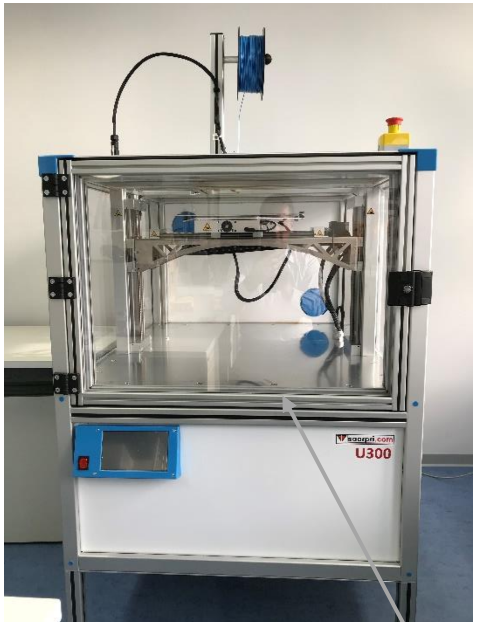
reactive printing: ΔT

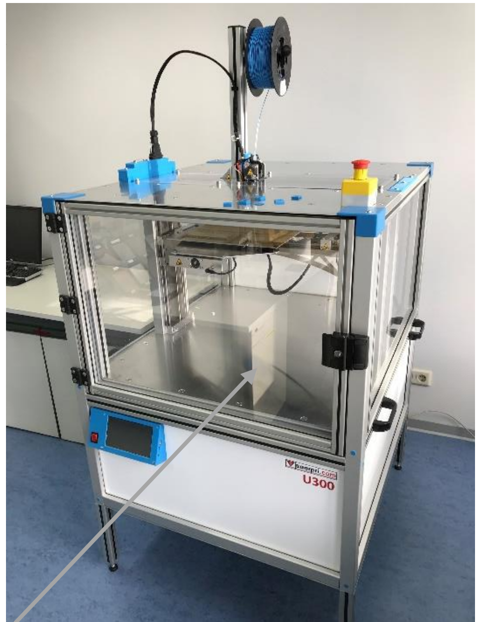
reactive printing: UV

Direct 3D-printer for reactive 2K and UV-systems

INM

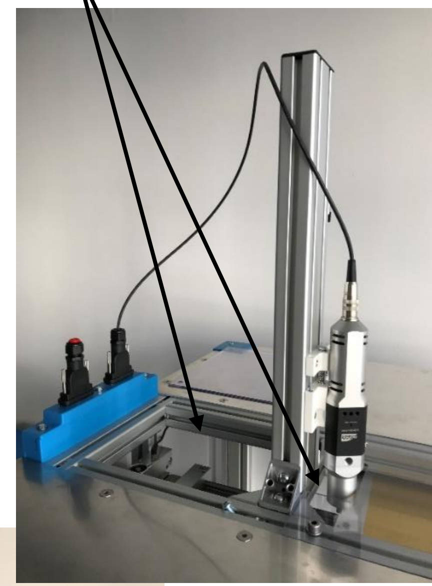
saar.pri

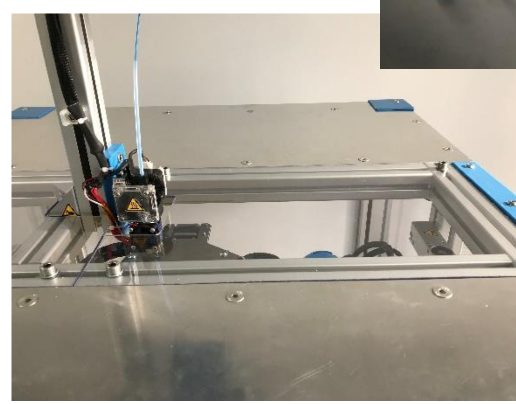




2 positions for exchangeable printing head

- FFF
- 1K UV
- 2K thermal
- …



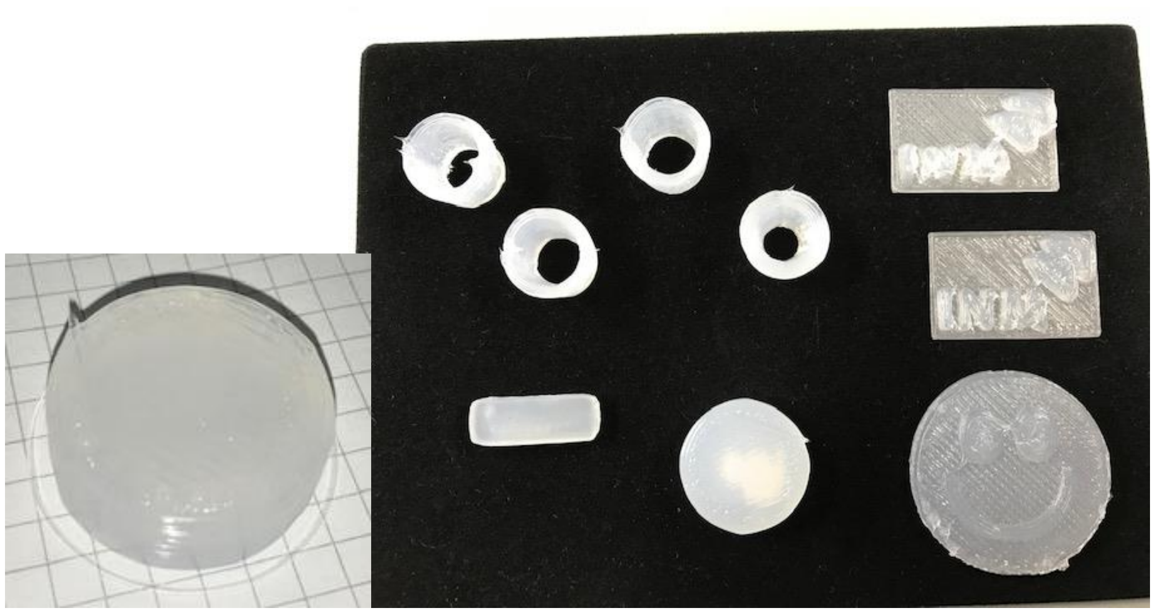


chamber with controllable climate

- protective gas: Ar, N_2
- T: 10 °C -70 °C
- humidity: 10 rel.% - 90 rel.%

Results from Nanomer® reactive direct-3D-printing

parts from room-temperature curable silicone-resin



Direct 3D-printing of organic-inorganic hybrid materials

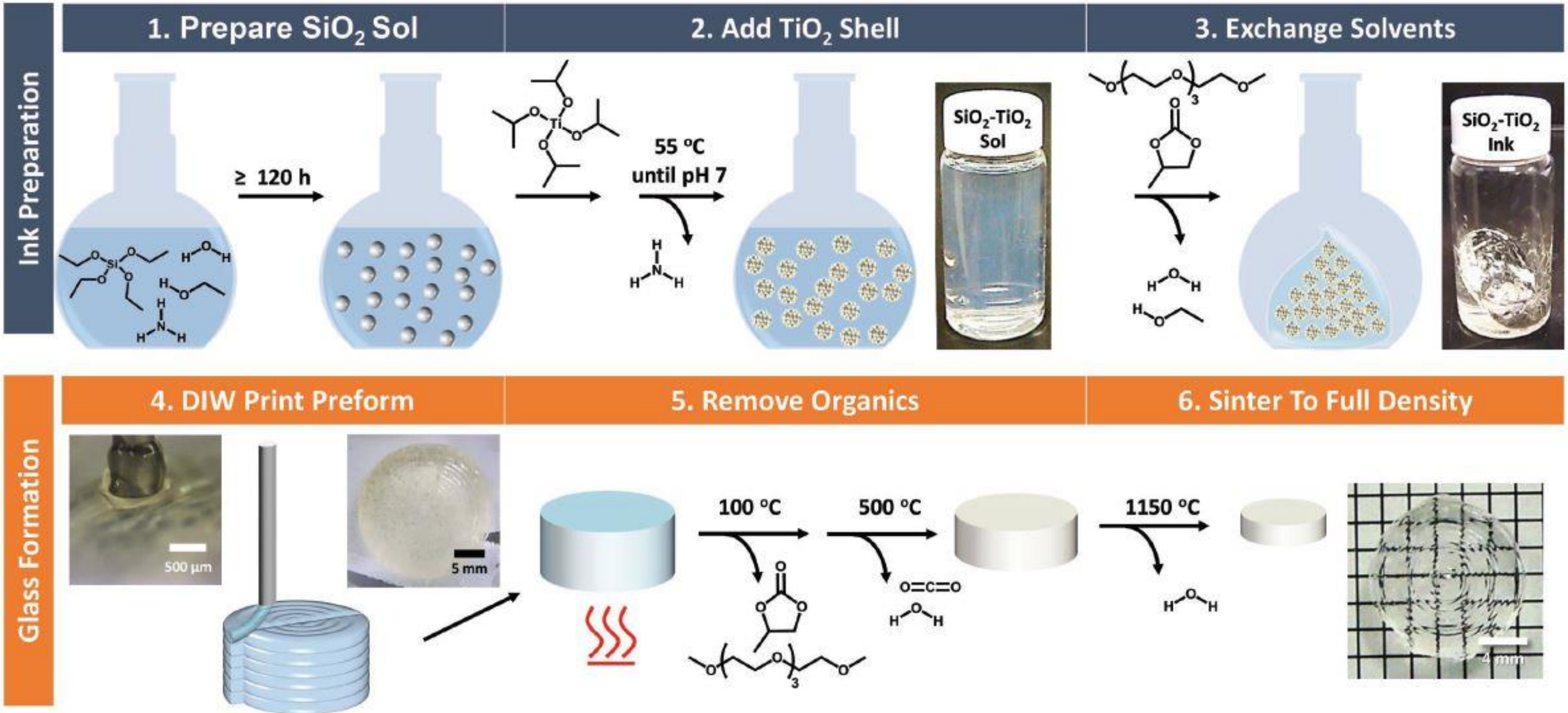


Figure 1. Sol–gel derived DIW $SiO_2/SiO_2–TiO_2$ glass fabrication scheme. (1) SiO_2 particle sol preparation. (2) $TiO_2–SiO_2$ core–shell particle preparation. (3) Ink preparation via solvent exchange from particle sol to DIW printable ink. (4) DIW printing of glass preform. (5) Organic removal to low density inorganic glass preform. (6) Sintering to full density optical quality glass (unpolished).

Joel F. Destino et al., Adv. Mater. Technol. 2018, 3, 1700323, DOI: 10.1002/admt.201700323

Summary for (2D) and 3D printing

- 2D and 3D printing are descriptors for a number of different fabrication technologies
- They are all additive manufacturing technologies, not subtractive or formative
- They are new manufacturing tools for modern society
  - their uses depend their merits in the quality, cost and their delivery schedule, not their newness
- 2D printing has already made tremendous impact on consumable electronics
- 3D printing already paying an important role in healthcare and aviation (metals). It will be one of the manufacturing tools in the future.