Additive manufacturing

Overview of the most common technologies using input material in solid form

Ing. Petr Keller, Ph.D.

Additive manufacturing - summary

Classification by initial material:

Liquid:
- Stereolithography Apparatus (SLA)
- Digital Light Processing (DLP)
- Polyjet printing

Powder:
- Selective Laser Sintering (SLS)
- Selective Laser Melting (SLM, DMLS)
- Three Dimensional Printing (3DP)
- Multi Jet Fusion (MJF)
- Directed Energy Deposition (DED, Laser Cladding, MPA,…)

Solid:
- Fused Deposition Modelling (FDM)
- Laminated Object Manufacturing (LOM)
- Thermoplastic Ink Jet (TIJ)
- ARBURG Plastic Freeforming (APF)
- Directed Energy Deposition (DED, MIG/MAG welding)

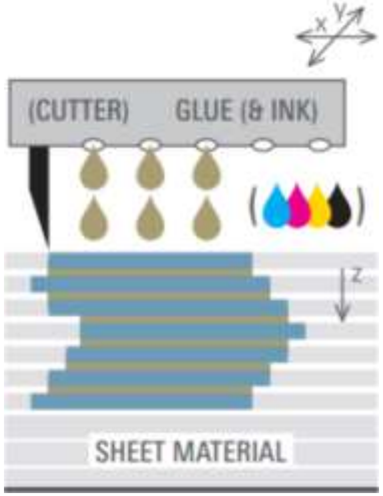
Additive manufacturing

The approved process categories according the standard ISO/ASTM 52900 are presented in the following list:

- material extrusion – an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice
- material jetting – an additive manufacturing process in which droplets of build material are selectively deposited
- binder jetting – an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder material
- sheet lamination – an additive manufacturing process in which sheets of material are bonded to form a part
- vat photo-polymerization – an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization
- powder bed fusion – an additive manufacturing process in which thermal energy selectively fuses regions of powder bed
- directed energy deposition – an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited

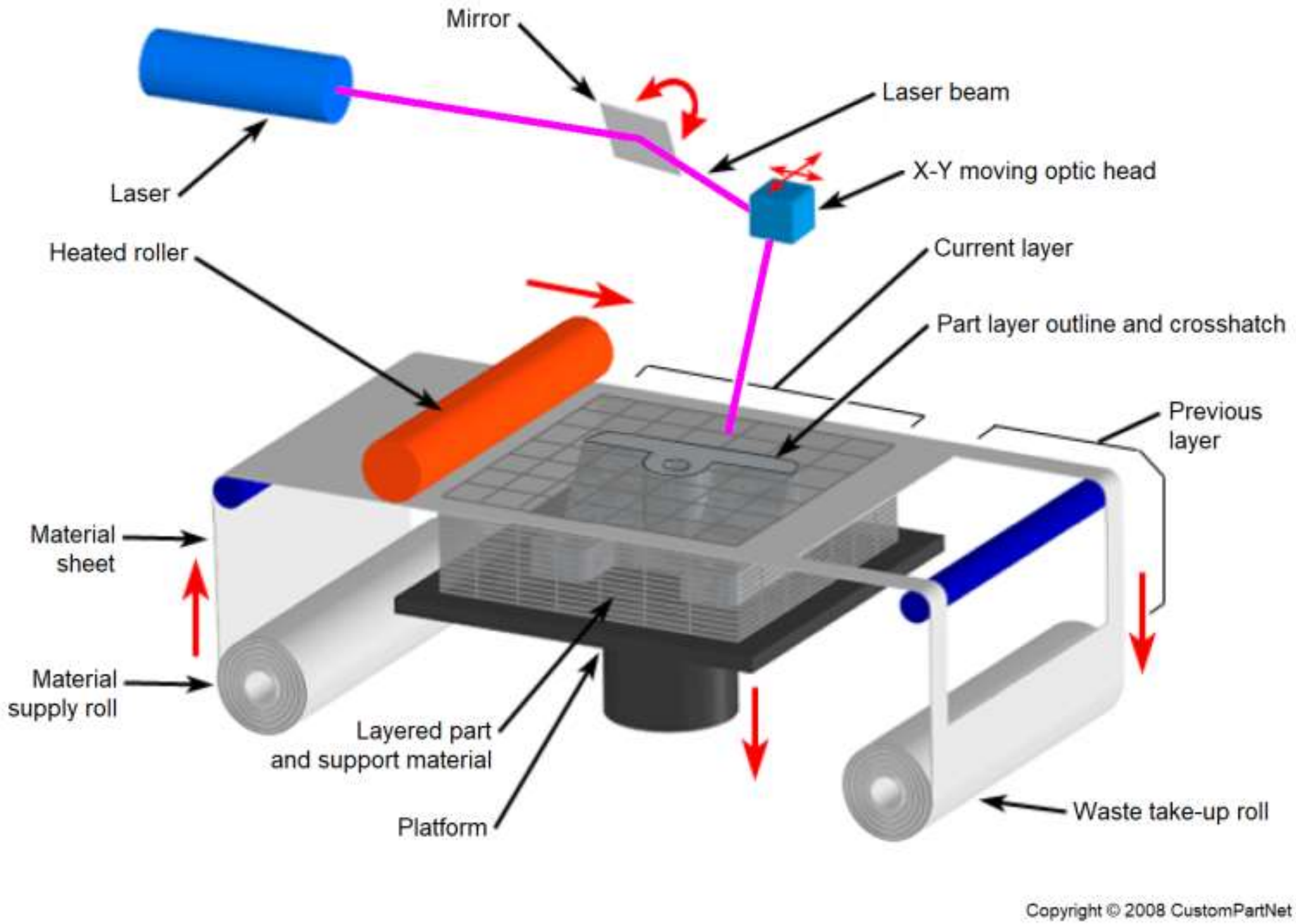
Additive manufacturing – sheet lamination

- sheet lamination – an additive manufacturing process in which sheets of material are bonded to form a part



Source: matca.cz/technologie/aditivni-technologie/

Sheet Lamination
- technology Laminated Object Manufacturing (LOM)



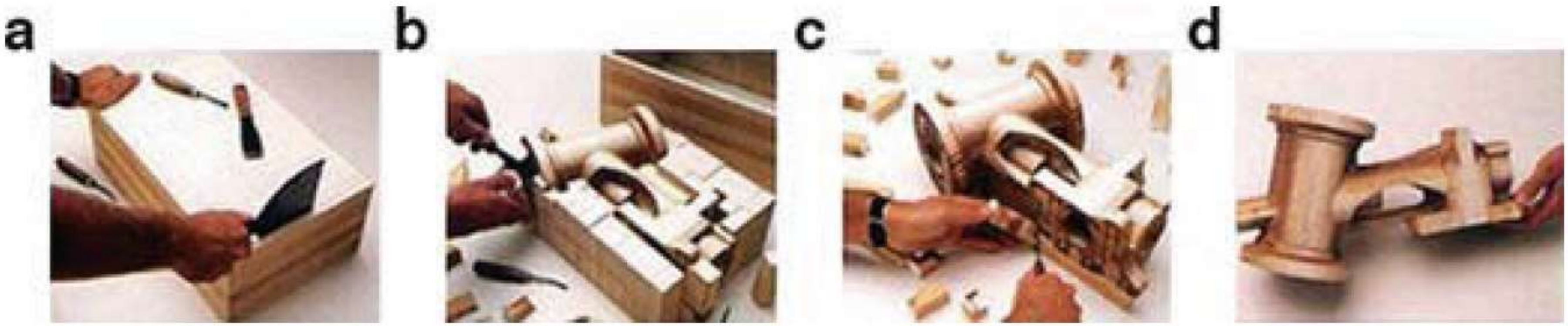
Sheet Lamination

- Creating parts by cutting cross-sections from sheets and gluing, welding, melting or clamping them together
- Possible materials include paper, plastics, ceramics, and metals
- Divided into Bond-then-Form and Form-then-Bond

Existing technologies:

- Laminated Object Manufacturing (Paper)
- Selective Deposition Lamination (Paper)
- Solido Technology (PVC)
- Ultrasonic Consolidation (Metals)

Postprocessing – „decubing“



Helisys

- started 1990
- out of business – 2000

- material: special paper with thermoplastic foil for heat bonding of layers
- laser cutting

Mcor Technologies

- started 2007
- now CleanGreen3D
- patented as Selective Deposition Lamination (SDL)

- material: A4 office paper
- cutting with a knife
- full colour printing

Solido

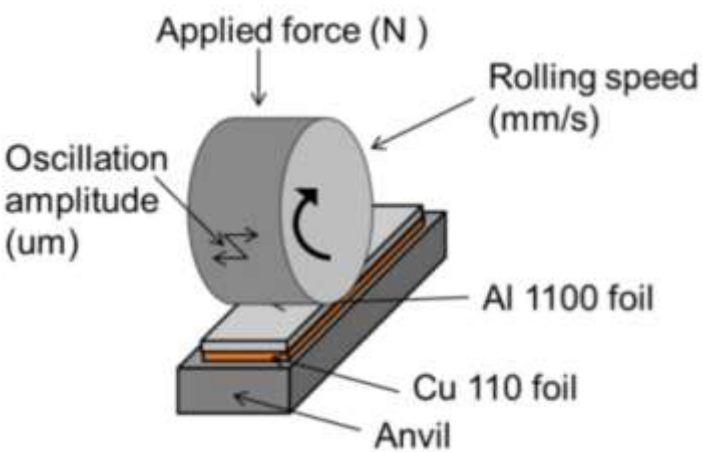
- the cheapest 3D print around 2010
- out of business – 2011

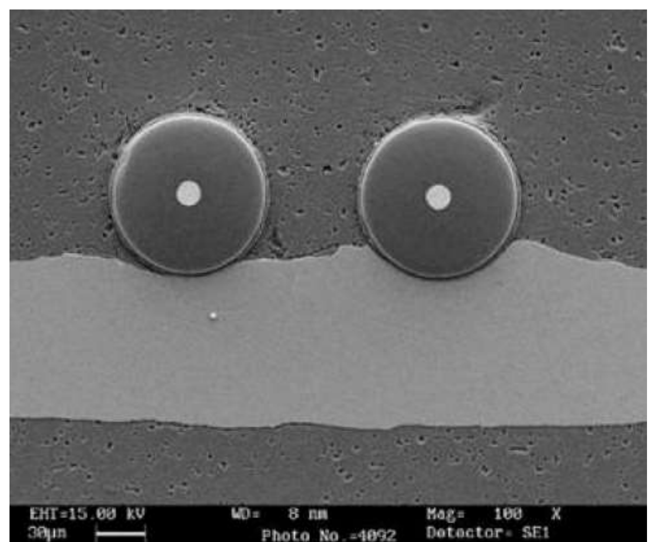
- office use
- material: PVC foil
- cutting with a knife
- gluing the layers with glue

Sheet Lamination – Solido

Fabrisonic

- Ultrasonic Additive Manufacturing (UAM) - 3D printing technology from metals without melting
- combination of ultrasonic welding of metal foils and CNC milling of the shape in a layer





How It Works...Fabrisonic's 3D Printing Technology

The Science (...in a nutshell)

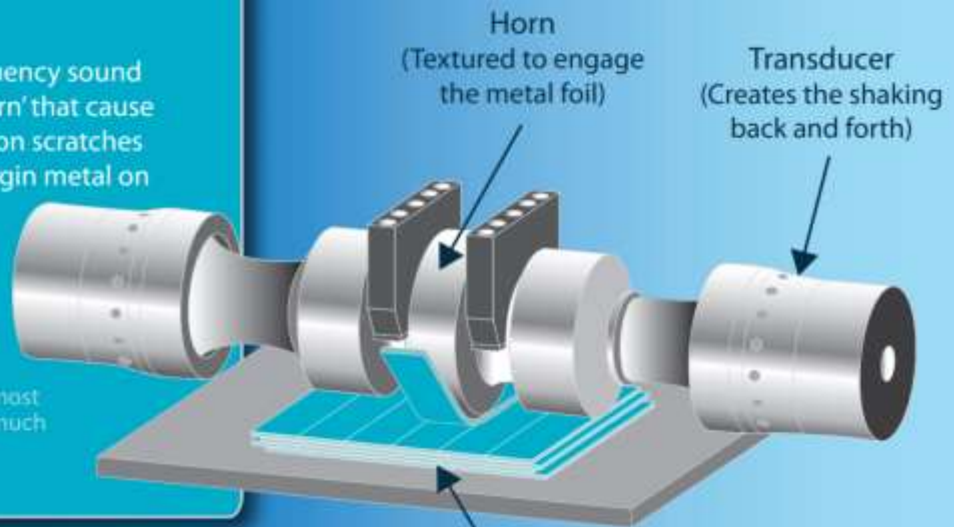
Metals like to fuse to other metals. In the absence of atmosphere, like in outer space, pushing two metal plates together will cause them to bond.

For metals on earth, there is a layer of oxide that interferes with electrons being shared and metals no longer want to naturally bond.

The Technology

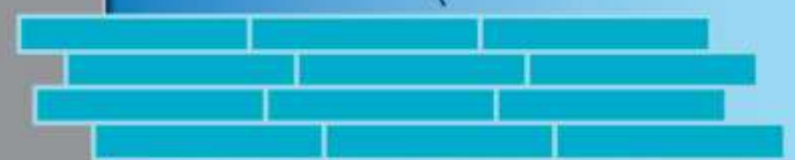
Fabrisonic's process utilizes high frequency sound waves transmitted through a steel 'horn' that cause thin metal foils to vibrate. This vibration scratches off the thin layer of oxide exposing virgin metal on each foil face allowing a bond. Creating this kind of bond is known as *solid-state welding.

*Solid-state welding means that the process does NOT MELT the metals. For our most common metals, Fabrisonic does not reach much more than 200° F. **AGAIN, NO MELTING.**



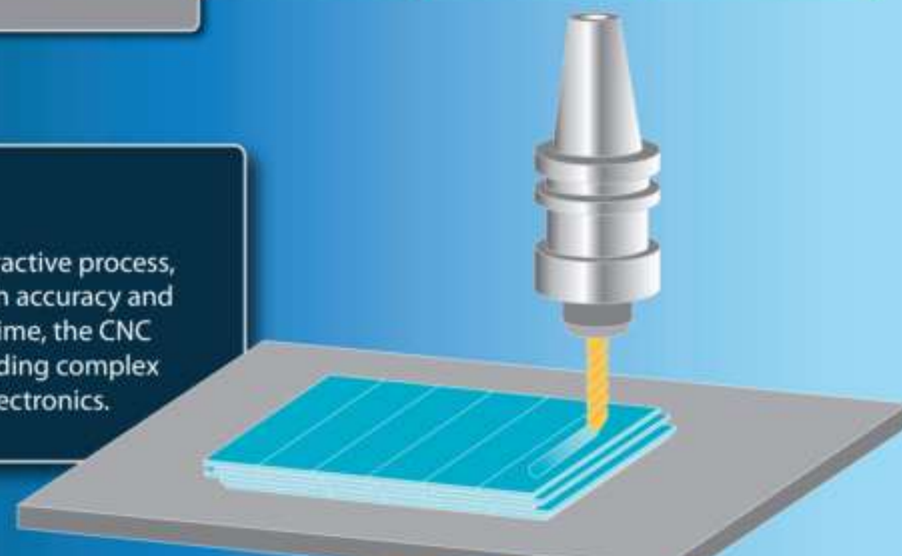
The Layering

3D Shapes are built up to near net shape using a staggering thin metal strips, layer by layer, much like laying brick .



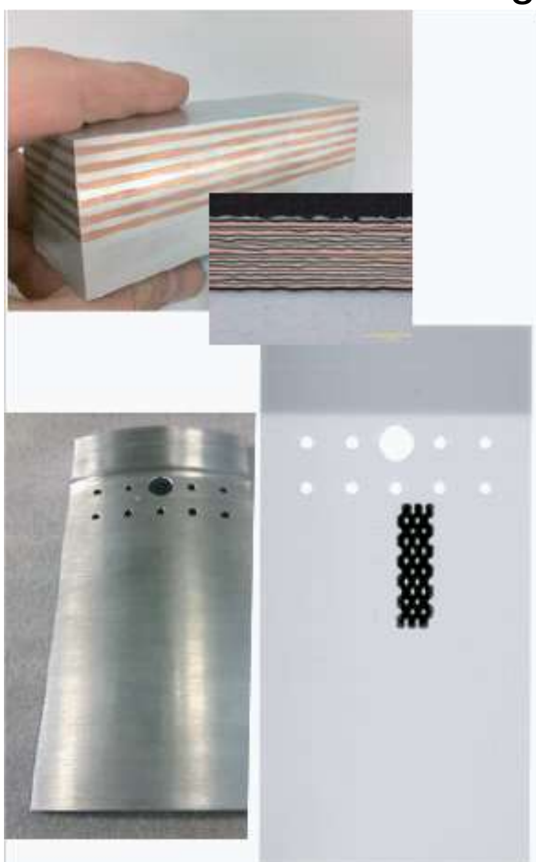
The Machining

With the unique hybrid additive/subtractive process, final shape can be machined with high accuracy and excellent surface finish. At the same time, the CNC milling capability can be used for building complex internal shapes and for embedding electronics.



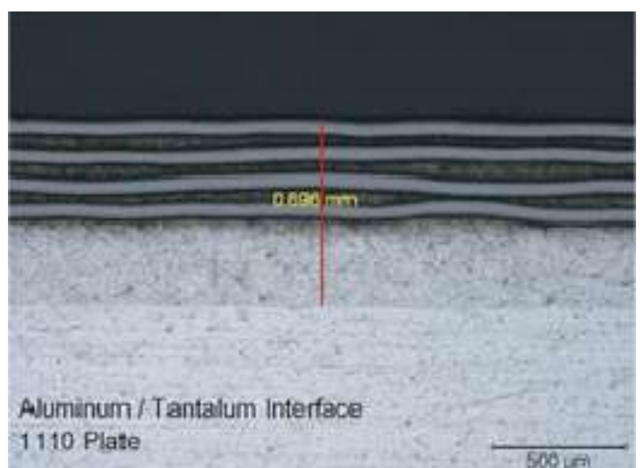
Fabrisonic

- Ultrasonic Additive Manufacturing (UAM) – 3D printing technology from metals without melting



	Al	Be	Cu	Ge	Au	Fe	Mg	Mo	Ni	Pd	Pt	Si	Ag	Ta	Sn	Ti	W	Zr
Al Alloys	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Be Alloys		●	●			●										●		
Cu Alloys			●		●	●	●	●	●	●	●		●	●		●	●	●
Ge					●						●							
Au					●	●			●	●	●	●	●			●	●	●
Fe Alloys						●			●	●	●		●	●		●	●	●
Mg Alloys							●						●			●		
Mo Alloys								●	●		●			●		●	●	●
Ni Alloys									●	●	●			●		●	●	
Pd										●			●	●				
Pt Alloys											●	●		●		●	●	
Si													●	●				
Ag Alloys													●	●				●
Ta Alloys														●		●	●	
Sn															●			
Ti Alloys																●	●	
W Alloys																	●	
Zr Alloys																		●

● Material pair proven for ultrasonic welding



Sheet Lamination – Fabrisonic

Sheet Lamination – Fabrisonic

Advantages of lamination technology

- fast, cheap and relatively accurate printing
- in the original intended mainly for large objects (car body models, aircraft parts, etc.) - special paper
- today as an office equipment - **cheap printing** and **full colour printing**

out of the business

- metal parts without heat - i.e. without internal stress in the part, suitable for special technologies - mixing of different metals in layers (e.g. nuclear energy, special parts for chemical and electrical industry, etc.)

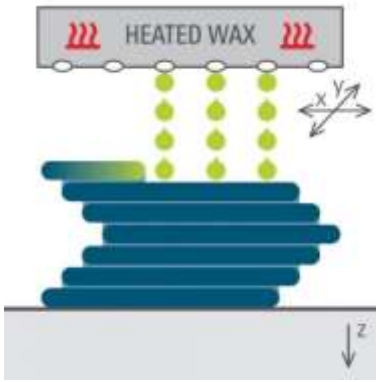
Disadvantages of lamination technology

- in the original the need to use special paper
- really difficult postprocessing
- few materials

- large volume of waste (the smaller the used working volume, the more waste)
- for metal parts, the shape in the layer is limited by the milling technology

Additive manufacturing – material jetting

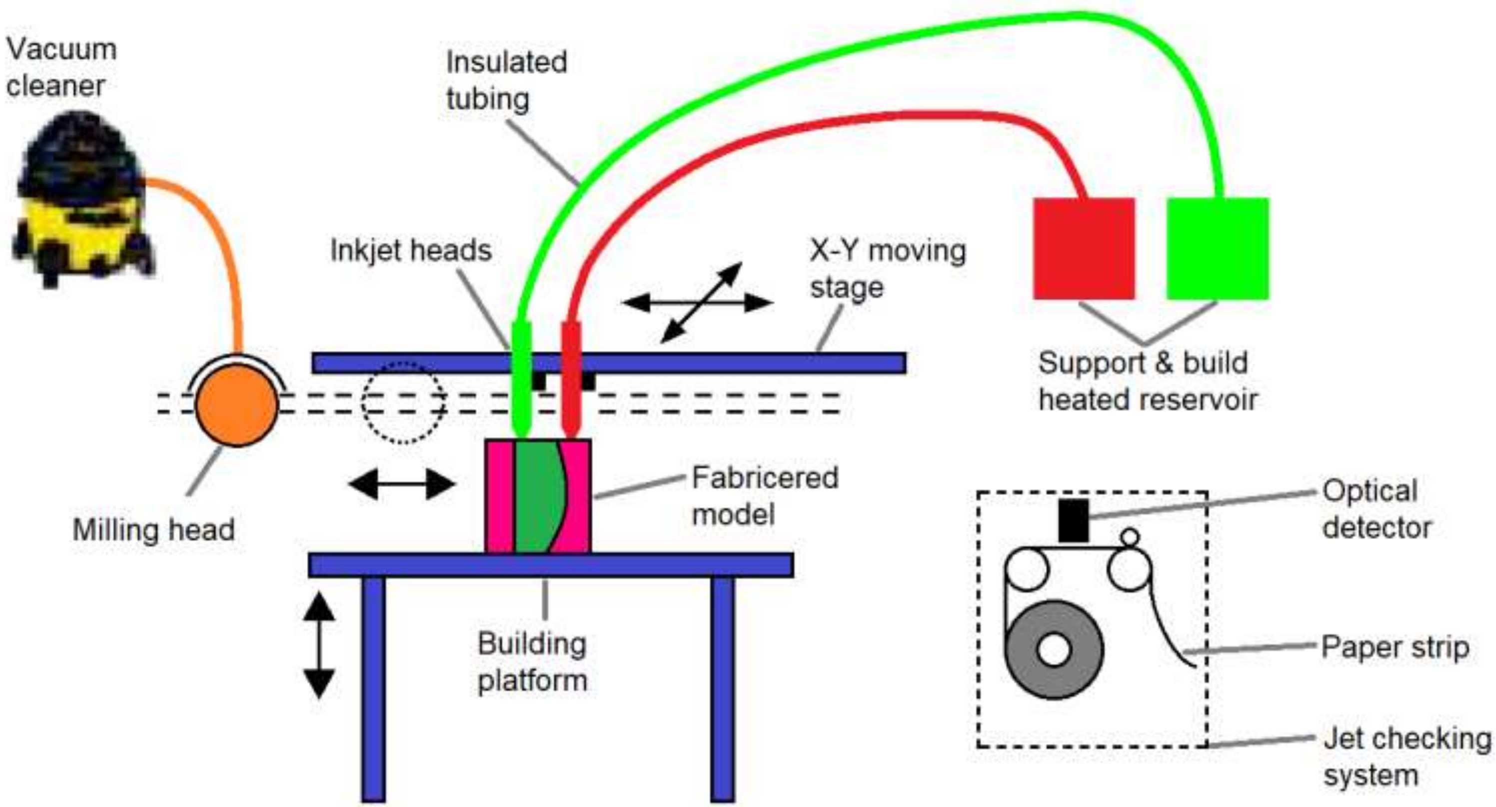
- material jetting – an additive manufacturing process in which droplets of build material are selectively deposited



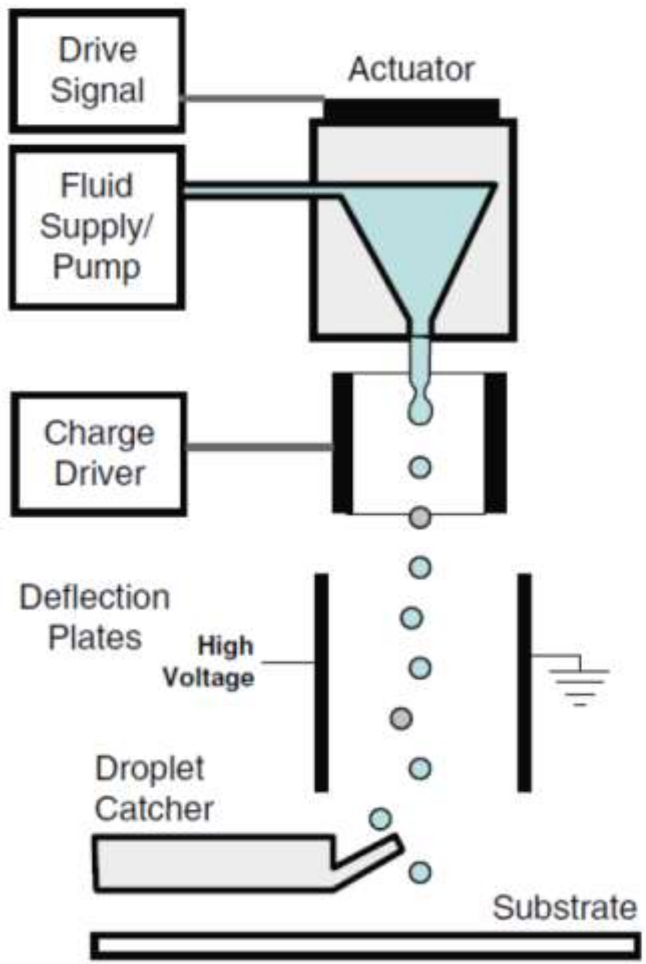
Source: matca.cz/technologie/aditivni-technologie/

Material jetting
- technology Thermoplastic Ink Jet (TIJ)

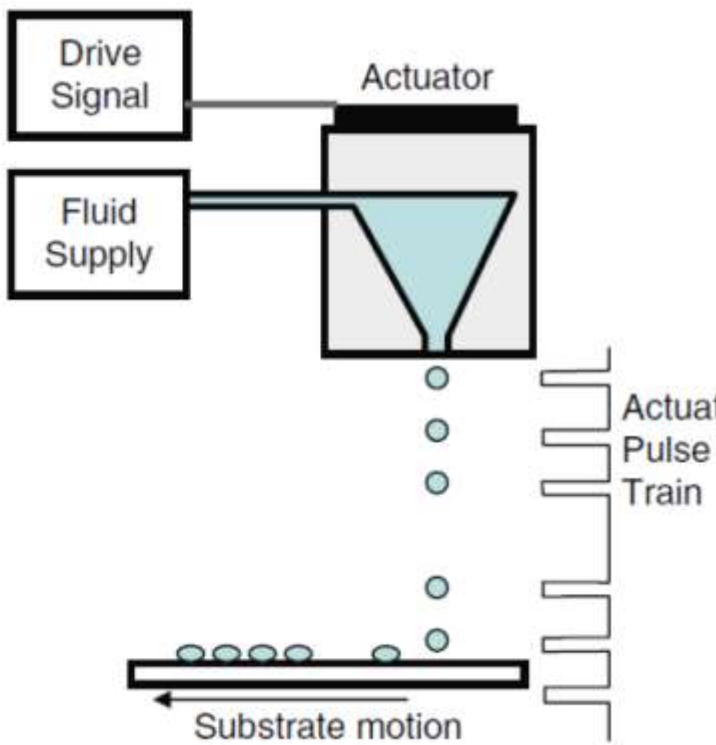
- input material in the form of granules of thermoplastics or waxes
- it is necessary to build support under its own part



Print Head Technologies



Continuous drops and deflection

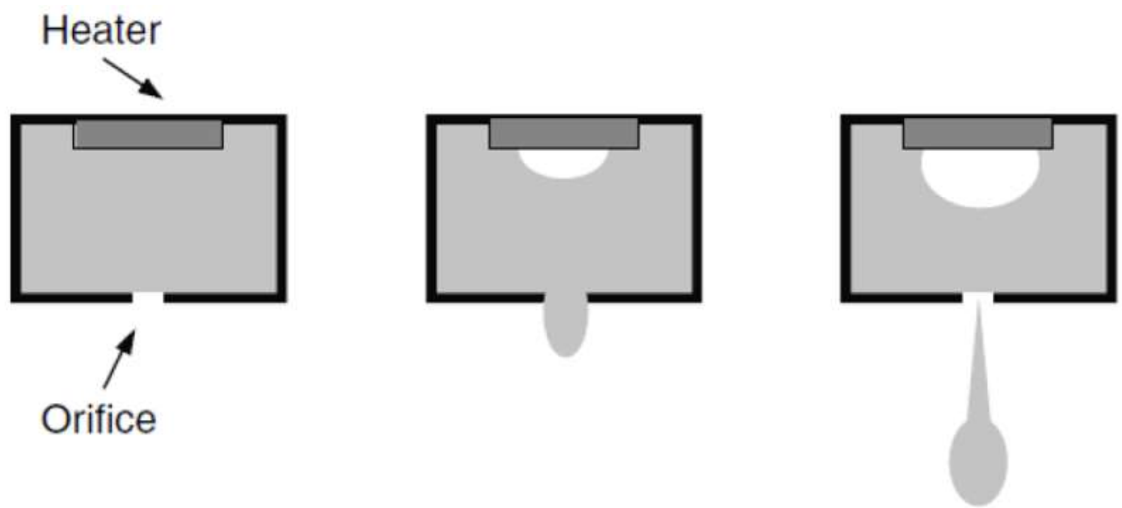


Drop on demand

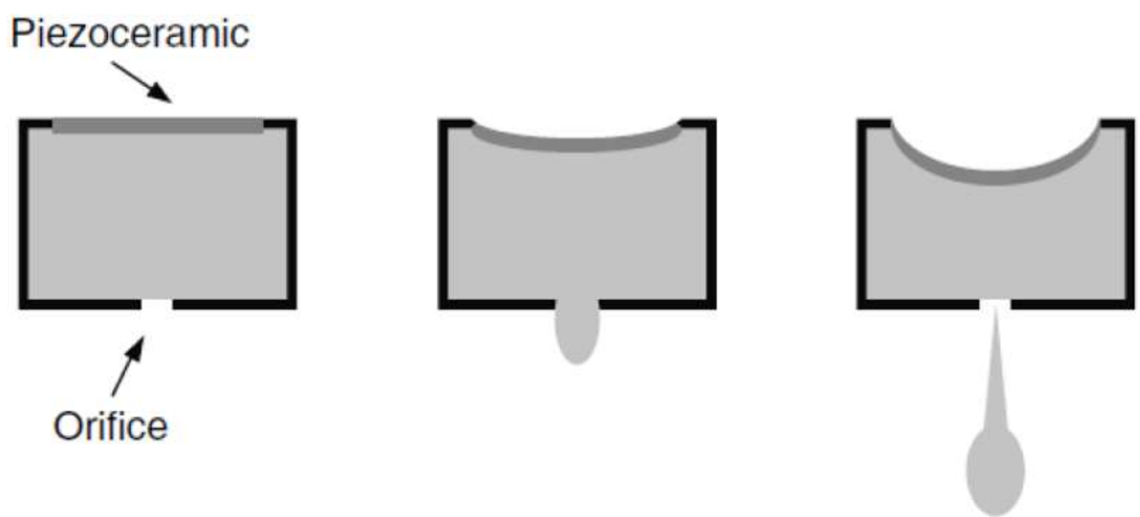
Print Head Technologies

Drop on demand

Thermal ejection



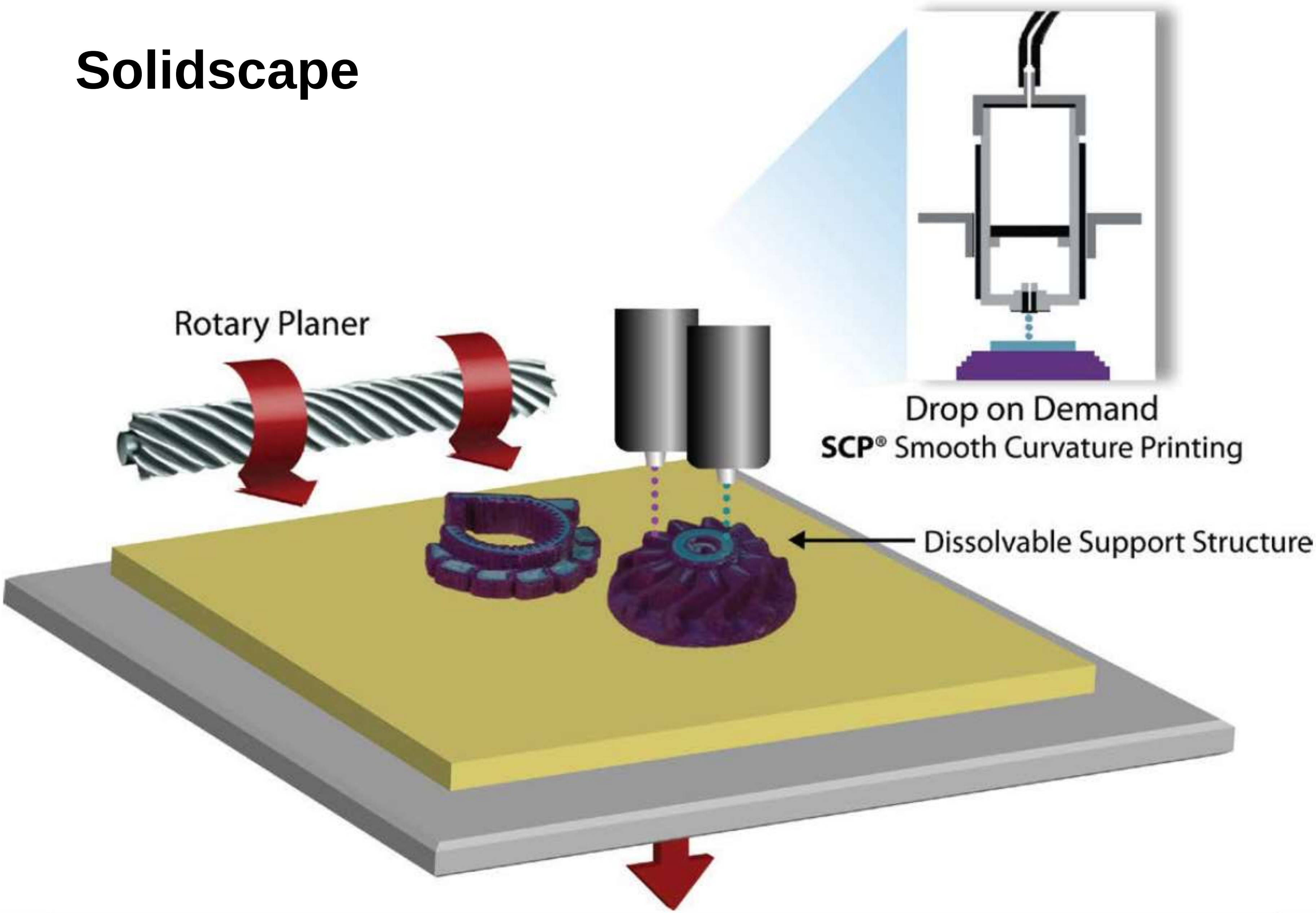
Piezoelectric ejection



Solidscape

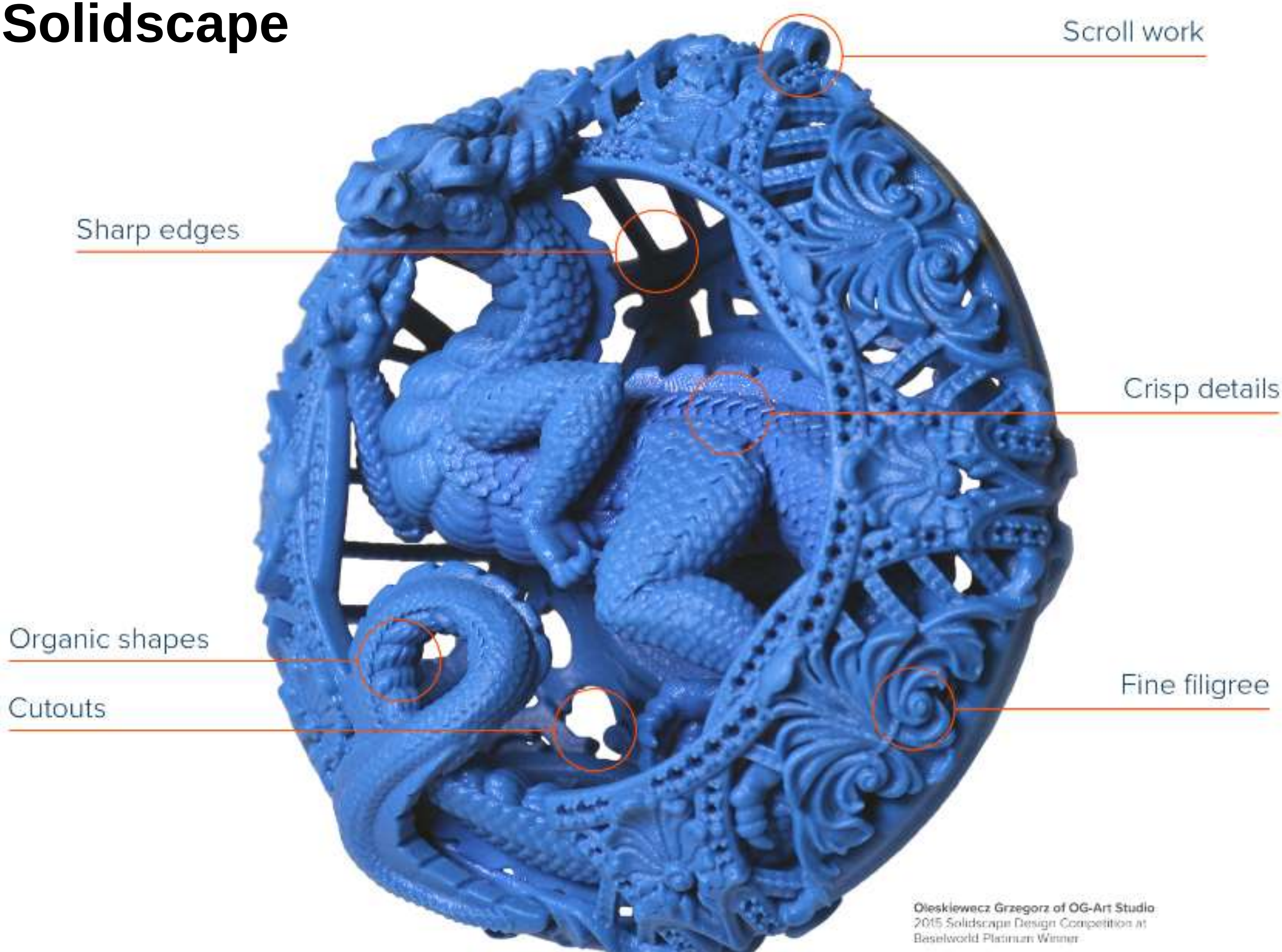
- launched in 1994 under the name Sanders
- today part of Stratasys

Solidscape


Rotary Planer
Drop on Demand
SCP® Smooth Curvature Printing
Dissolvable Support Structure

Material jetting – Solidscape

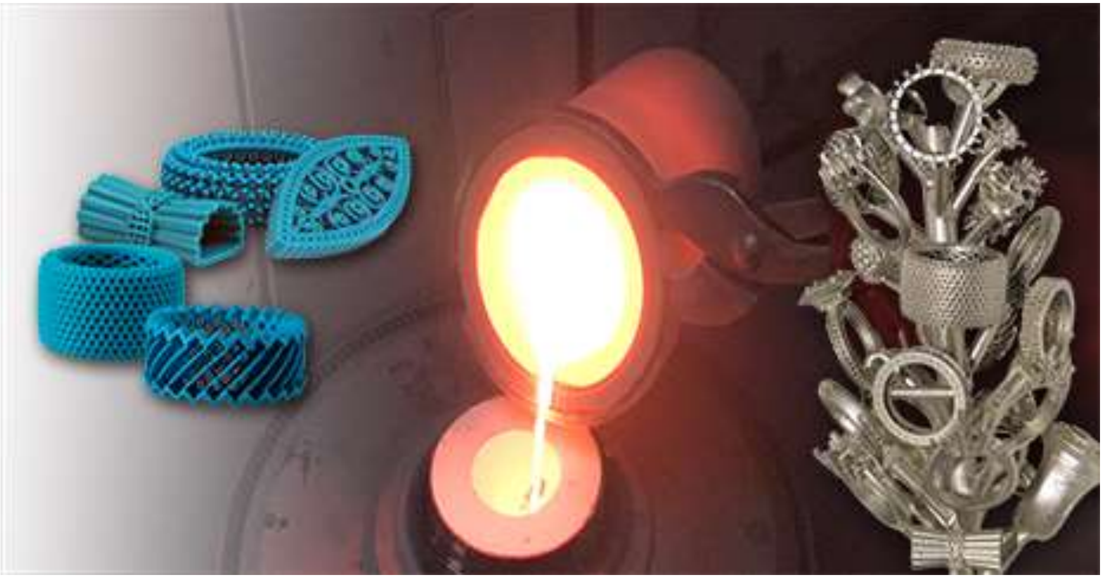
Solidscape



Source: https://www.solidscape.com

Solidscape

- technology suitable for the manufacturing of complex parts with small details, typical use in the production of jewellery
- 3D printing of wax models, followed by investment casting technology



Solidscape – application examples

Material Jetting
- technology MultiJet Printing (MJP)

3D Systems

- ThermoJet machine introduced in 1998
- 3D printers for printing waxes and thermoplastics

ProJet MJP 3600W

Advantages of waxes jetting (or special thermoplastics)

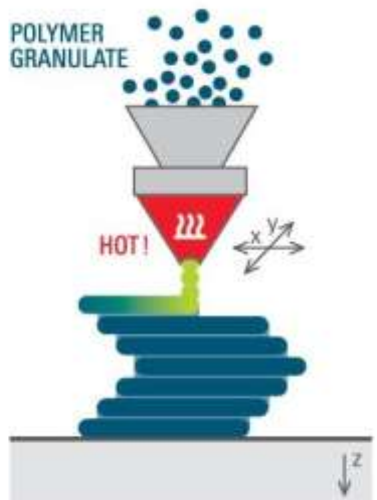
- **detailed and accurate production** (accuracy comparable to SLA)
- ideal for the production of models for investment casting technology (technology of casting metals into a ceramic mold using the lost wax model method)

Disadvantages of waxes jetting

- limited use, relatively small models
- very slow printing
- prints prone to mechanical damage due to the given materials

Additive manufacturing
– material jetting

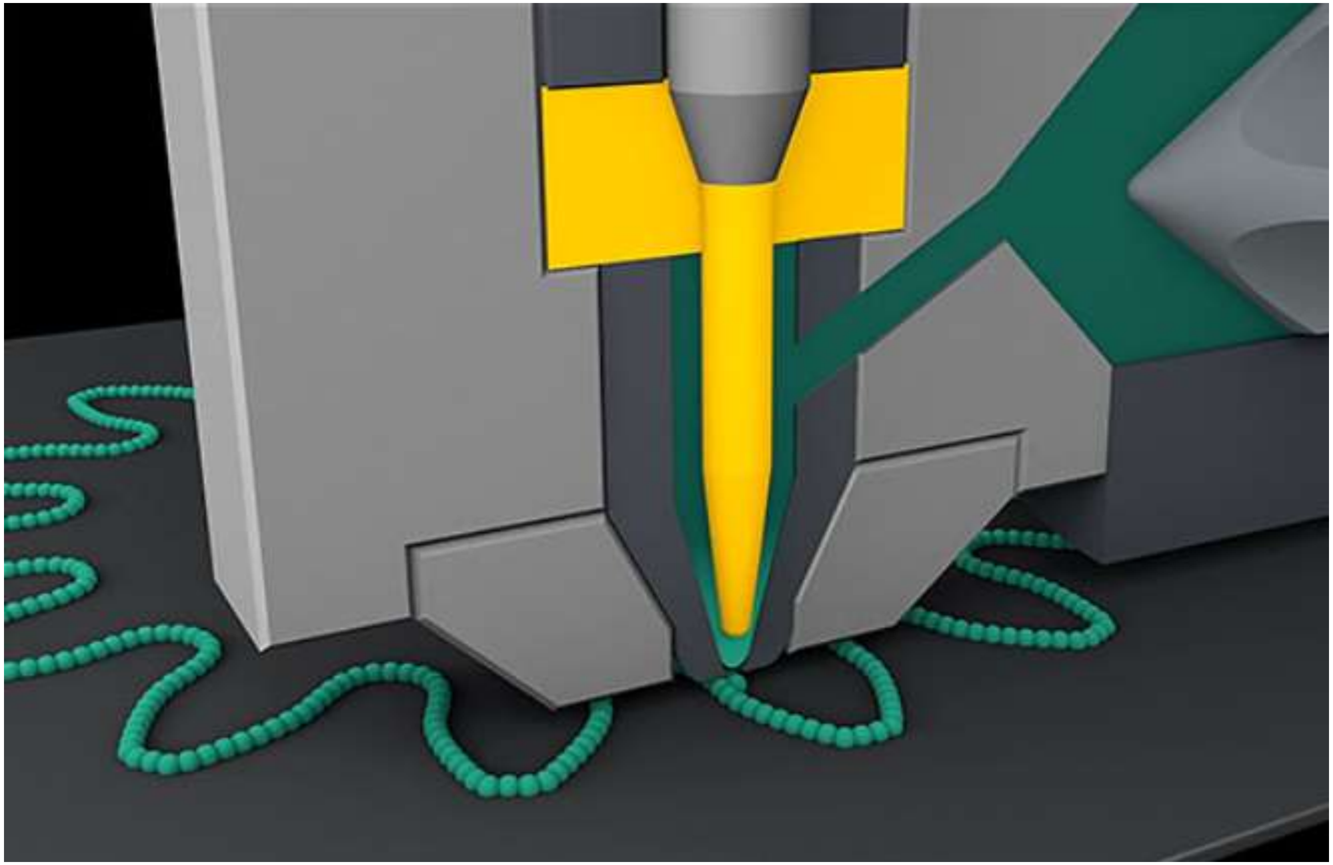
- material jetting – an additive manufacturing process in which droplets of build material are selectively deposited



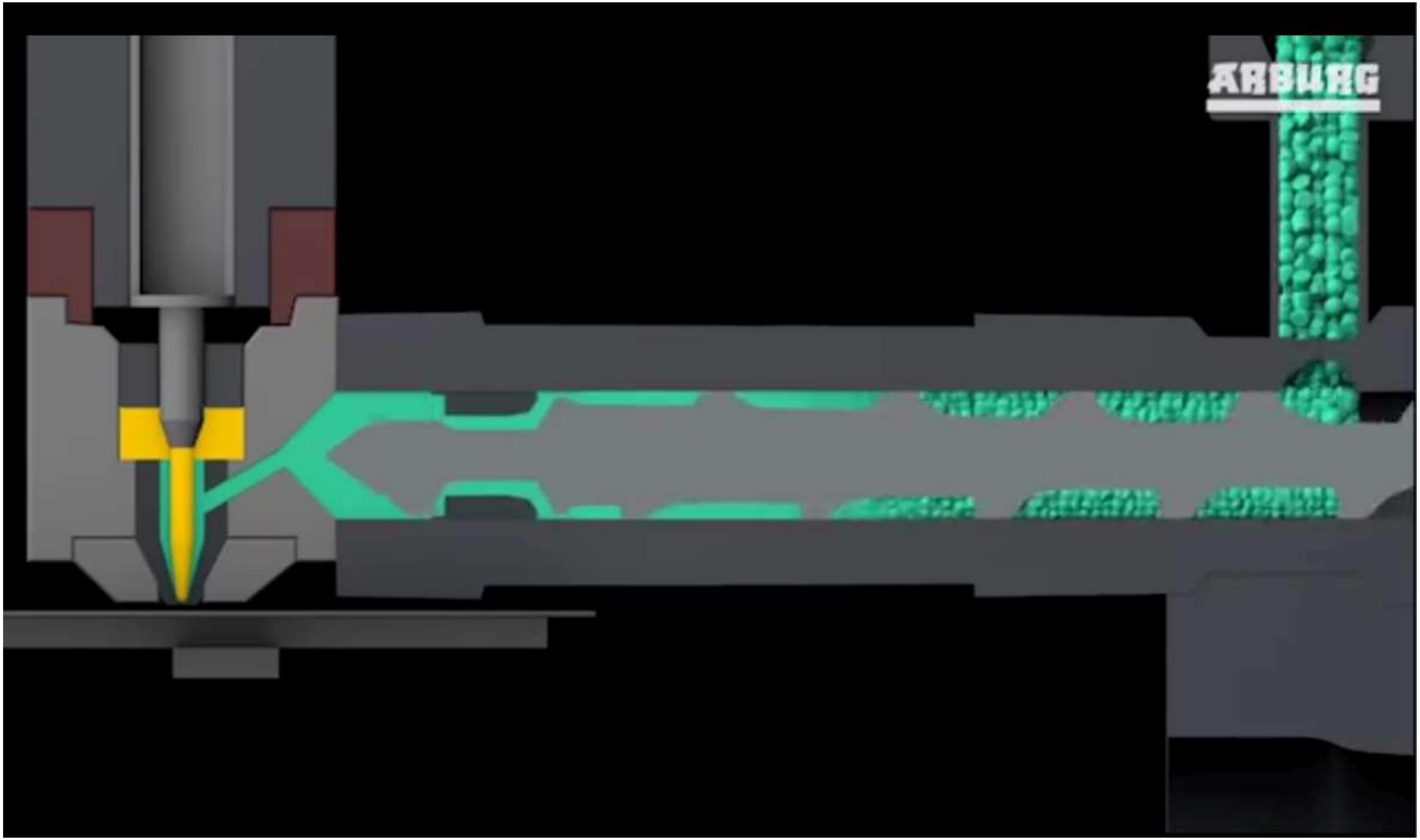
Source: matca.cz/technologie/aditivni-technologie/

Material Jetting

- technology ARBURG Plastic Freeforming (APF)



Material Jetting – ARBURG Plastic Freeforming (APF)



APF possibilities:

combination of materials:
ABS, TPU and armat 21

layer height: 0.2 mm

printing time: approx. 16 hours

printing time: approx. 6 hours

material: SEBS (Cawiton PR13576)

layer height: 0,2 mm

printing time: approx. 4 hours

very soft and tear-resistant material

also suitable as a functional seal

Advantages of APF technology

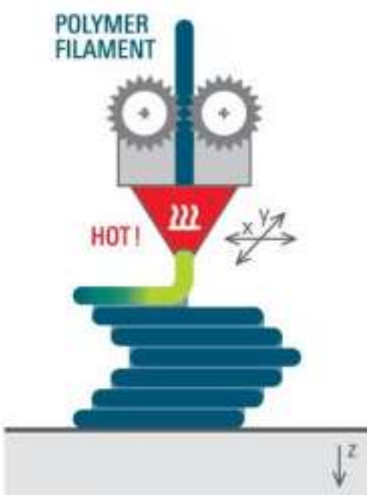
- **very cheap input material** - thermoplastic granulate
- amount of materials the same as plastic injection - initially the same process
- open system - can be equipped with multiple heads for **combining multiple materials** in one print
- special support materials for unusual or complex chemically soluble 3D geometries

Disadvantages of APF technology

- low strength of parts compared to injected parts
- relatively slow printing

Additive manufacturing – material extrusion

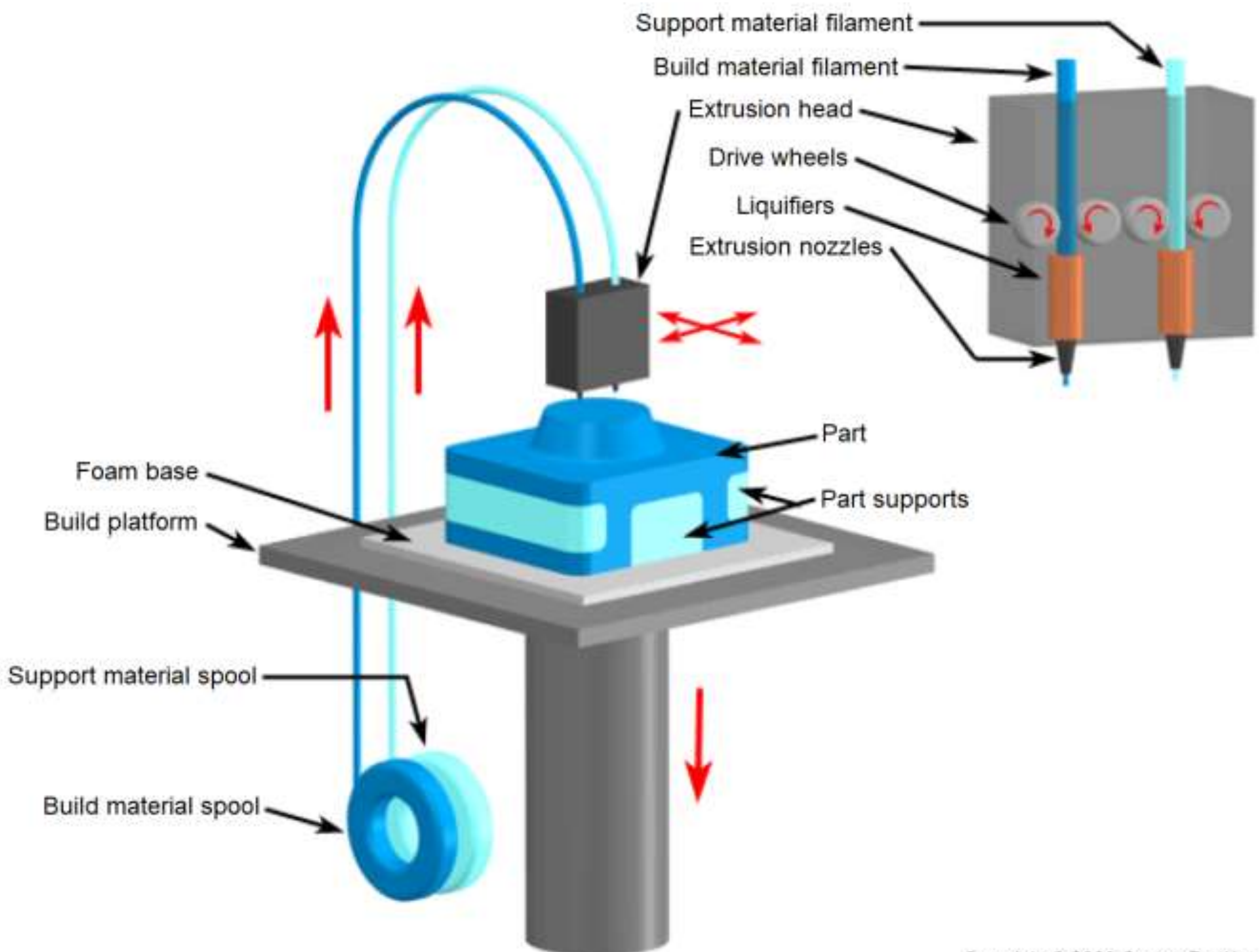
- material extrusion – an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice



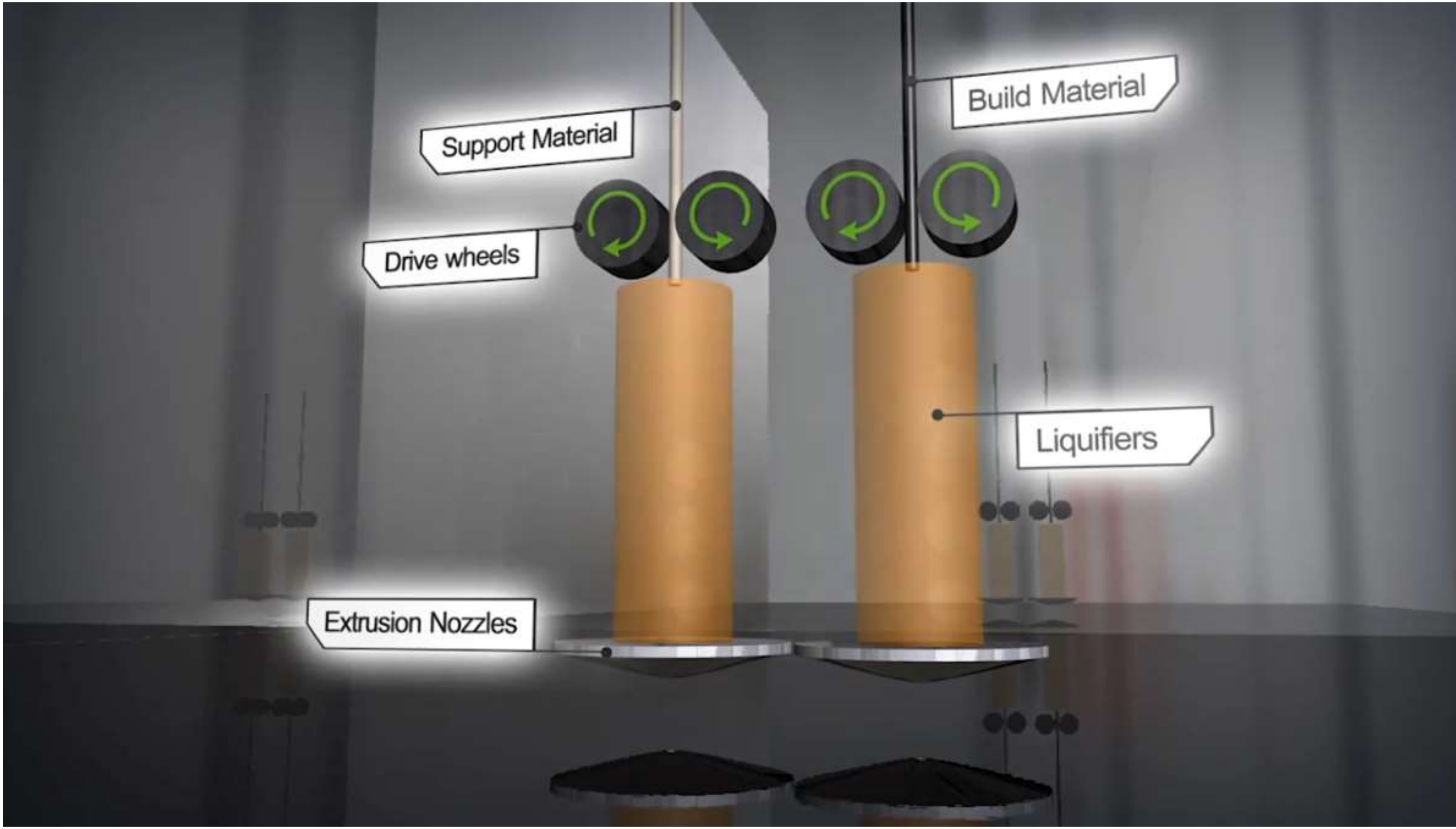
Source: matca.cz/technologie/aditivni-technologie/

Material extrusion – Fused Deposition Modelling (Fused Layer Modelling, Fused Filament Fabrication)

- input material in the form of thermoplastic ‘wire’ - filament
- objects need to be supported from below

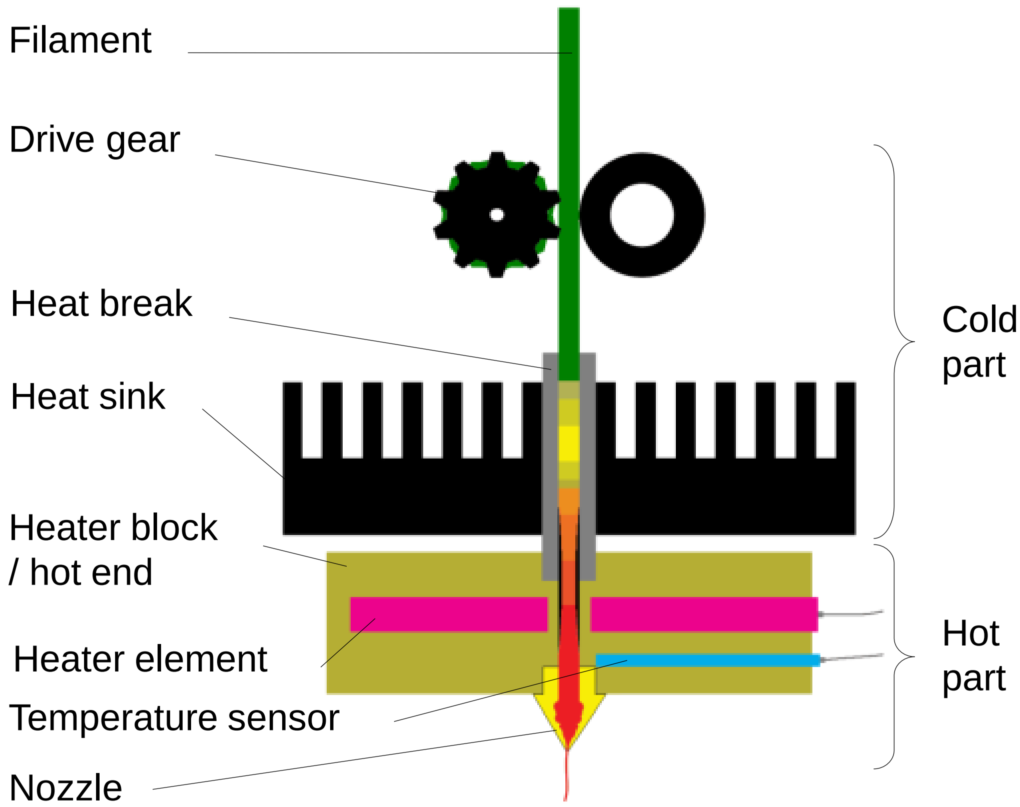


Material extrusion – Fused Deposition Modelling



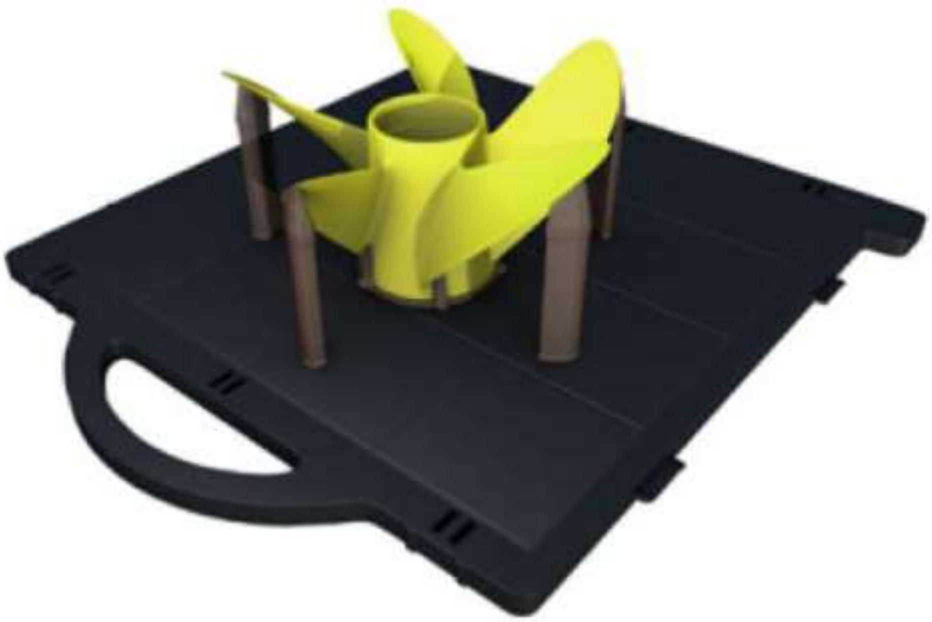
Material extrusion – Fused Deposition Modelling (Fused Layer Modelling, Fused Filament Fabrication)

Principle of the Printing Head:



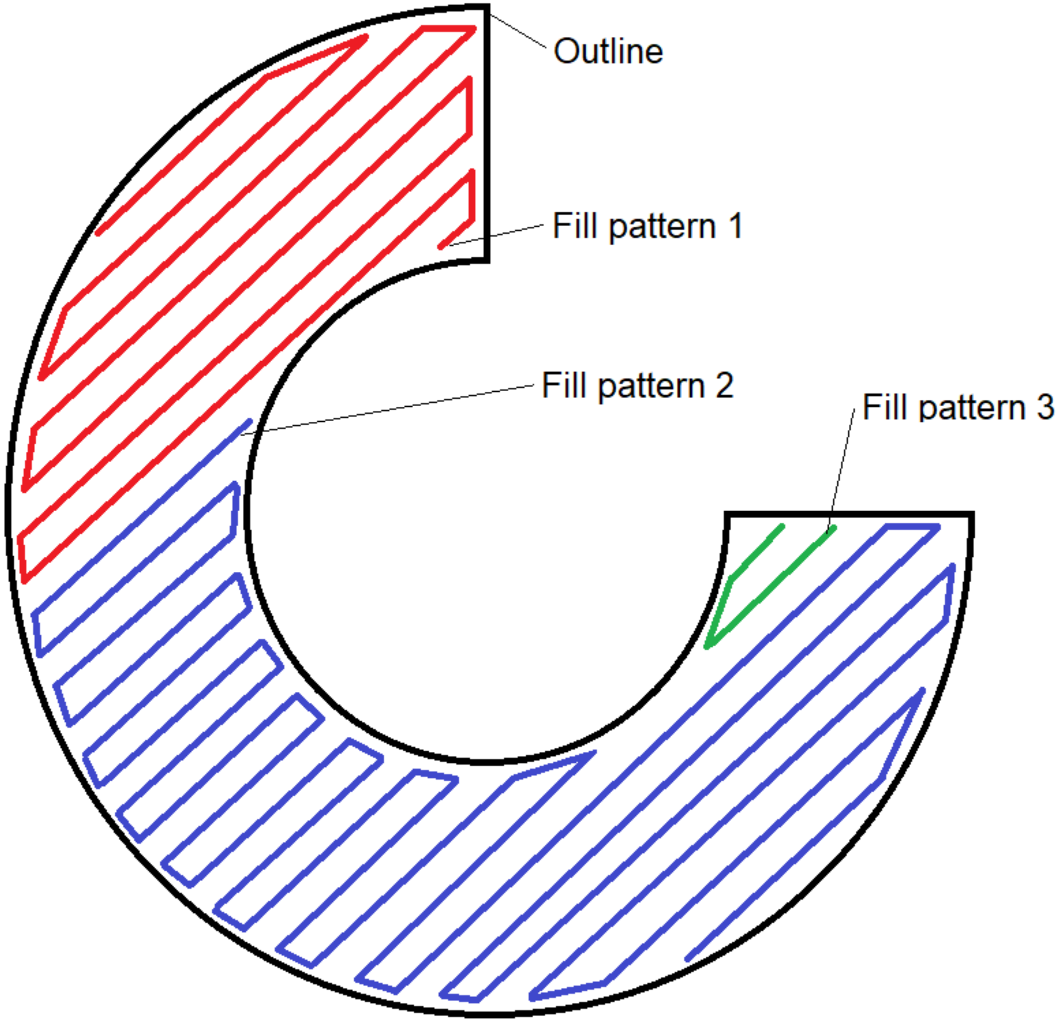
Fused Deposition Modelling

- 3D objects are made by stacking layers from bottom up
- objects need to be supported from below
- easy support removal – soluble support material



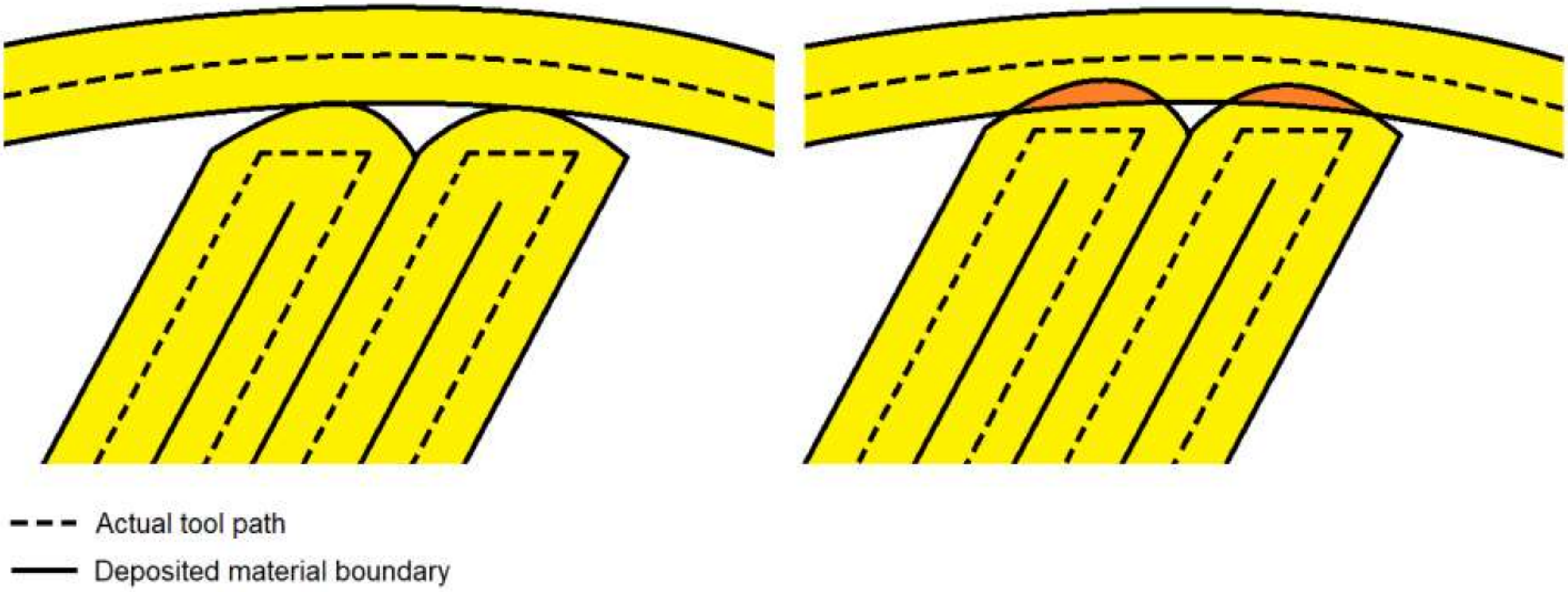
Fused Deposition Modelling

The principle of one layer printing:



Fused Deposition Modelling

Drawing Accuracy:



Fused Deposition Modelling

Stratasys

Dimension

Mojo

Fortus 900

uPrint

Fortus 250


HYDRAULIC PUMP BODY
Material cm³:
Model: 90
Supports: 34
TIME: 9:50´


Scan SFING
ATOS
TRITOP
Mesh 3 mil.


SFING SCULPTURE

2009 – expiration of the first Stratasys patent => expansion of 'hobby' printing

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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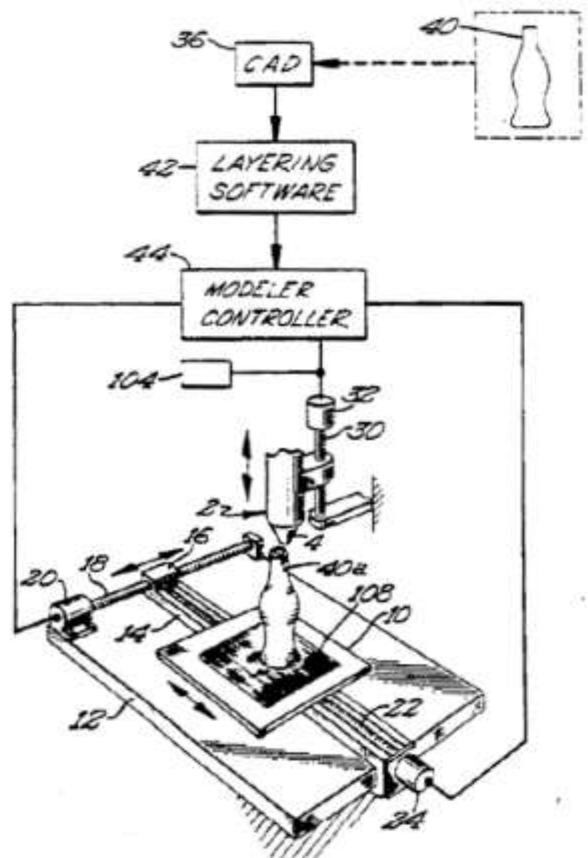
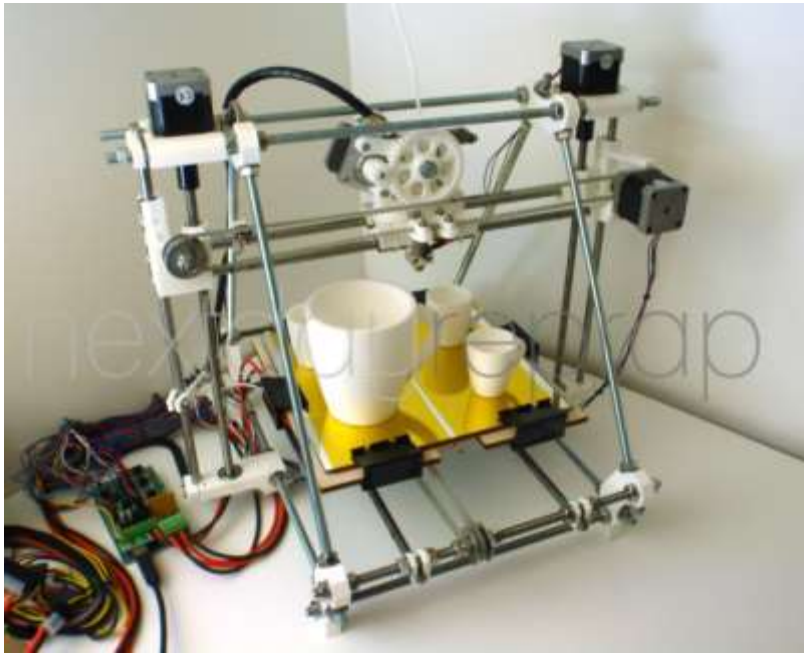
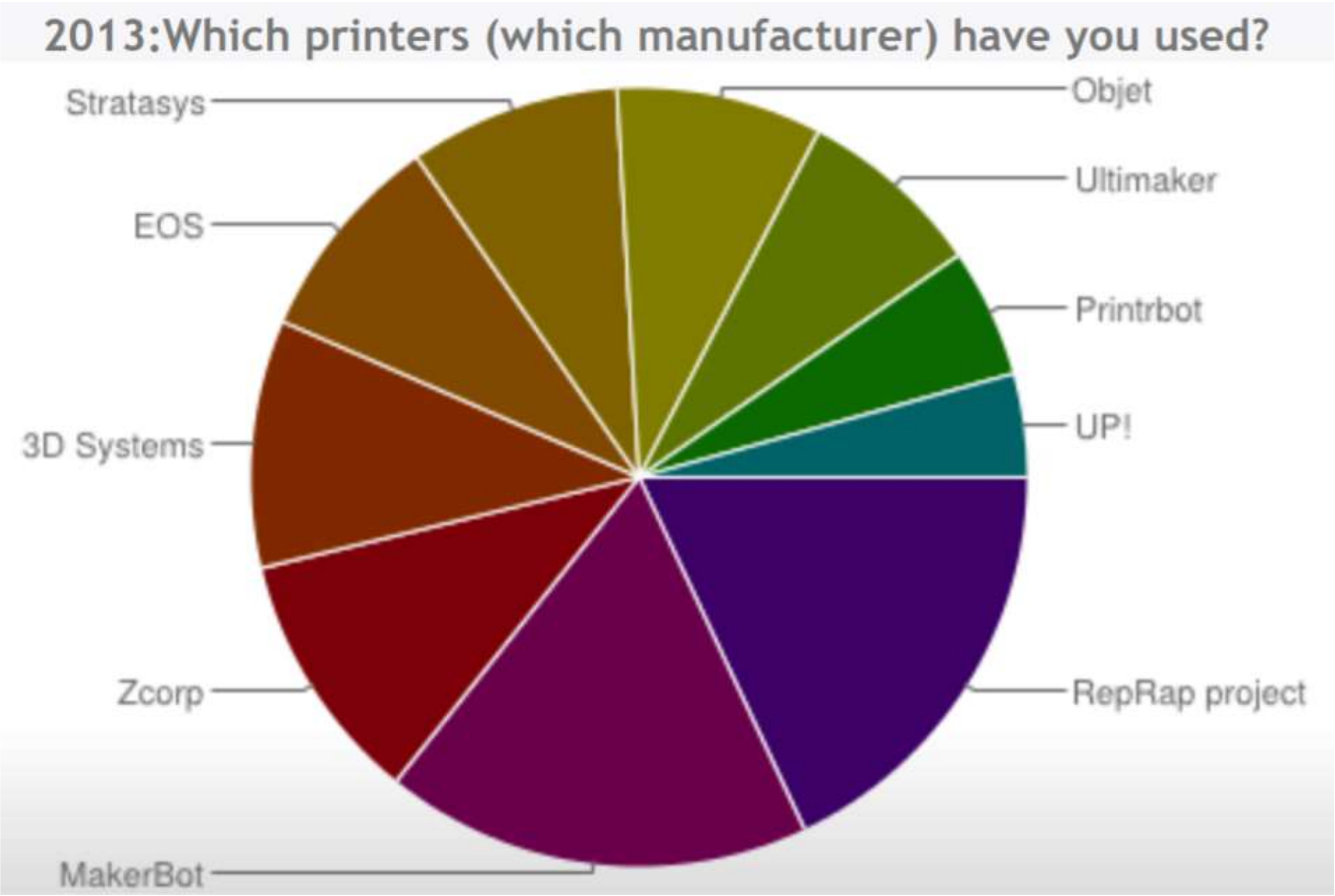


Fused Filament Fabrication (Fused Layer Modelling)

Reprap

- University of Bath
- about 2005
- open source community
- members from all over the world
- some of the device components are made by the device itself (self replicating)
- 499 £ for the kit on the right
- There are many low cost systems (300 - 5000 €) on the market currently
- in CZ Prusa Research company – higher price balanced by the philosophy of ‘*buy, assemble and print*’





Source: Moilanen, J. & Vadén, T.: Manufacturing in motion: first survey on the 3D printing community, *Statistical Studies of Peer Production*

Advantages of material extrusion

- relatively **simple process** - probably the most used technologies (FFF, FLM)
- quite cheap printing
- available a number of thermoplastic materials (PLA, ABS, TPU, PETG, PA, composites PA-C, PA-GF…)

Disadvantages of material extrusion

- significant inhomogeneity of printed parts in different directions
- relatively slow printing
- **toxicity of some materials** when printing in an open work area

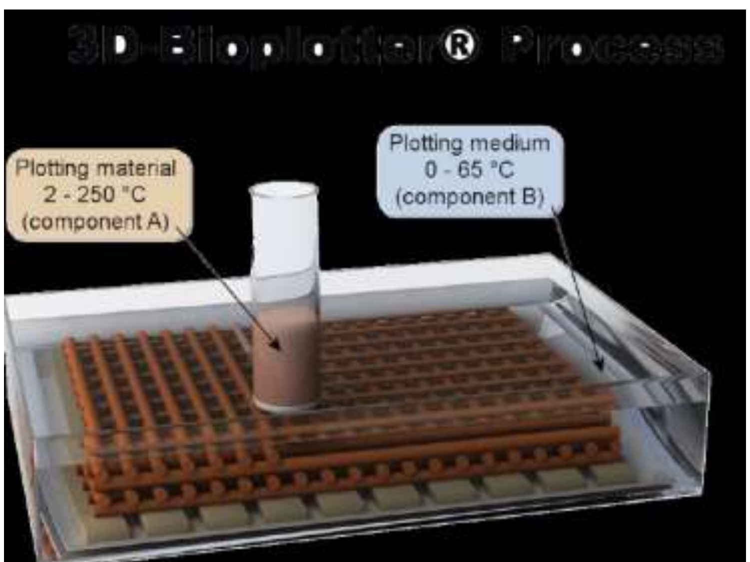
Material extrusion

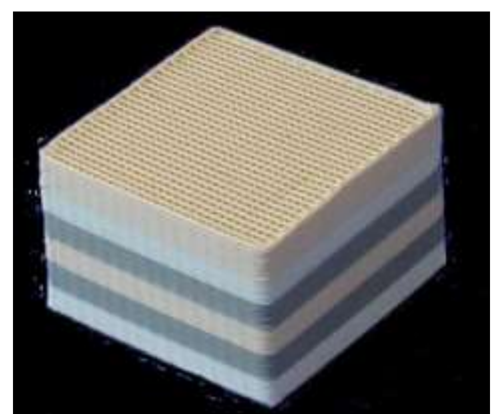
Thanks to the simplicity of the process and the RepRap project (Adrian Bowyer MBE, University of Bath), a number of variations of extrusion technology have been developed for a range of applications:

- medical applications
- civil engineering
- food industry
- indirect 3D printing of metals, ceramics, etc.

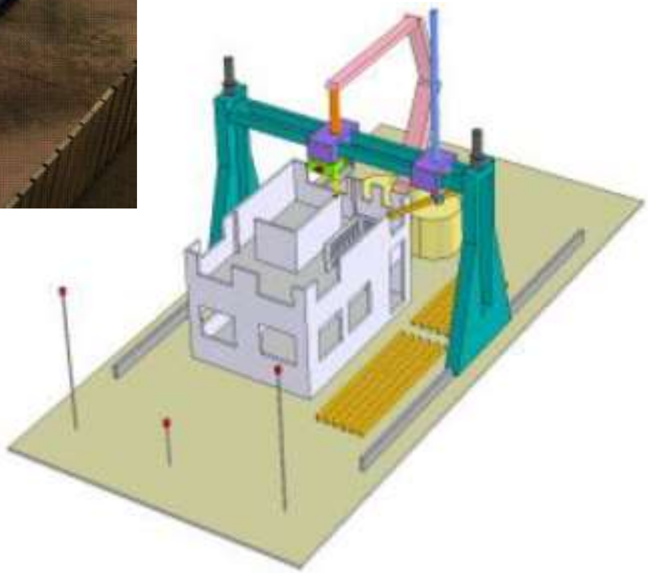
Envisiontec Bioplotter

- 3D-Printing of Biomaterials.
- biocompatible polymers
- scaffold materials
- growth factors
- even living cells





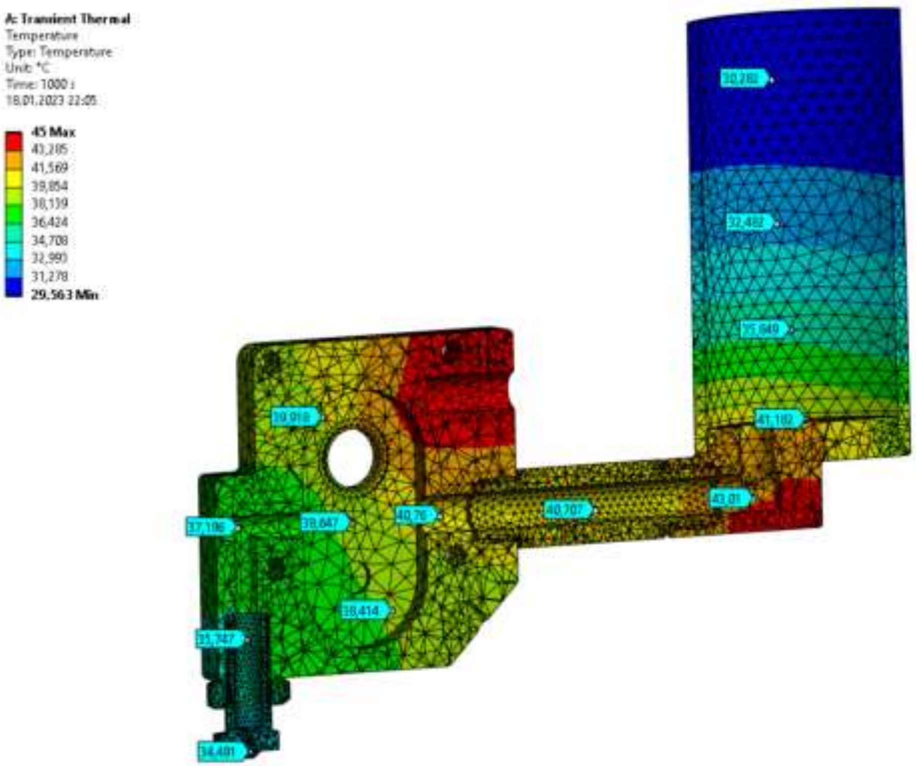
3D-Printing of concrete on a scale needed for building houses



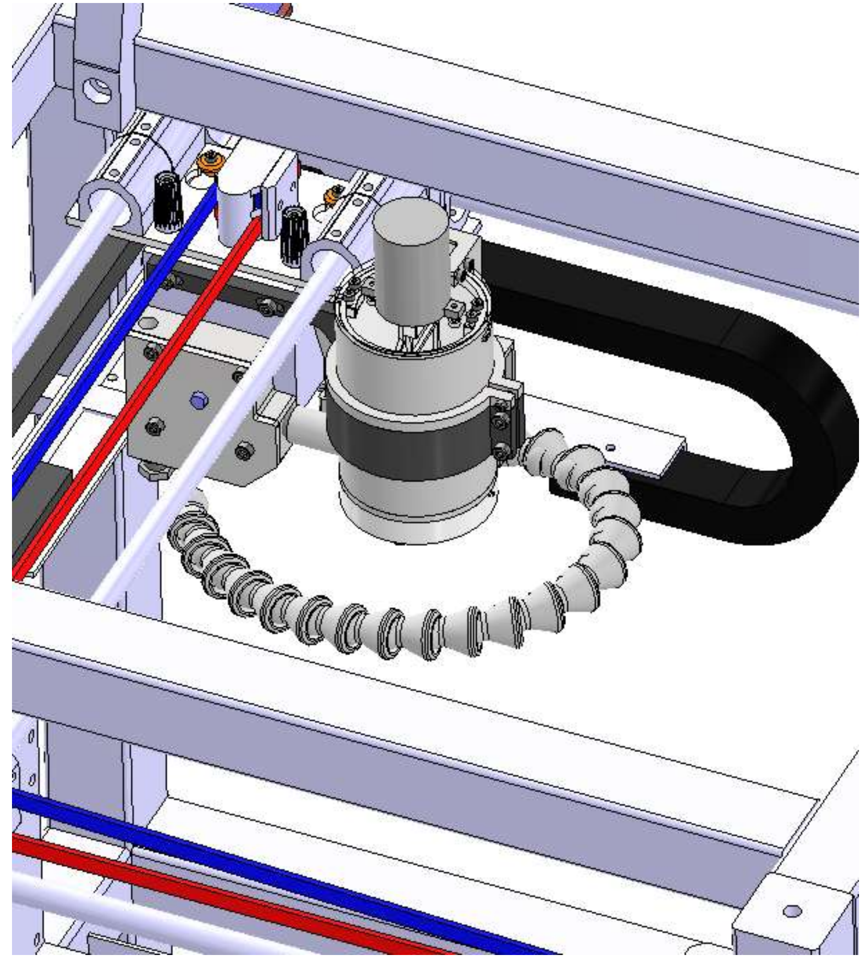
Project TUL – 3D printing in civil engineering and architecture (3D STAR)

Project TUL – 3D printing in civil engineering and architecture (3D STAR)

Research at KSA - 3D printing from chocolate



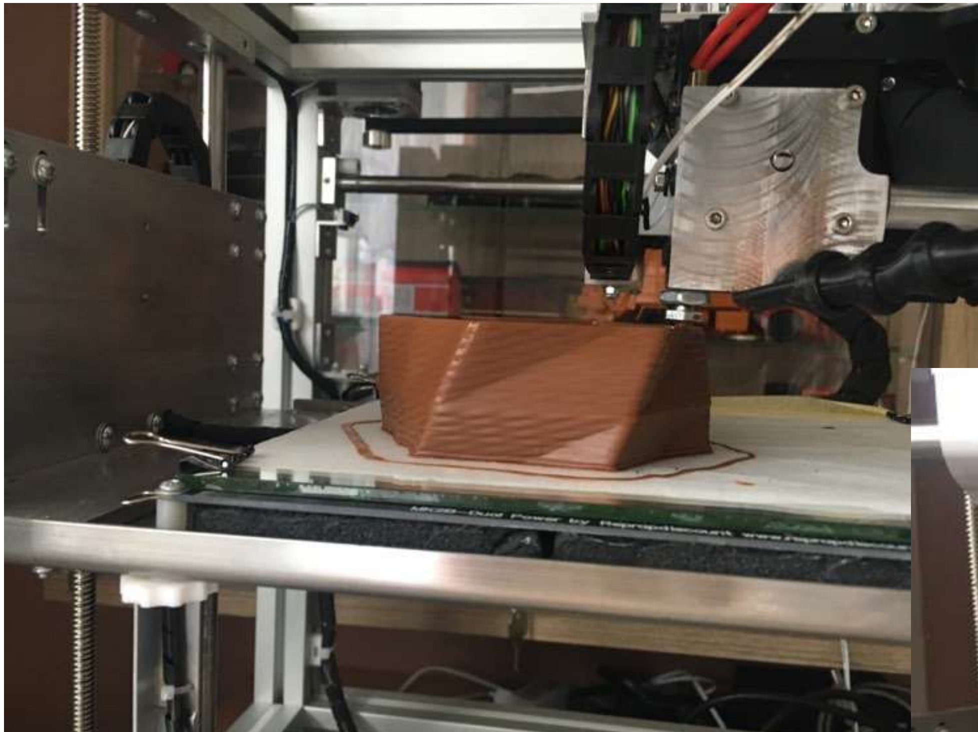
FEM temperature analysis

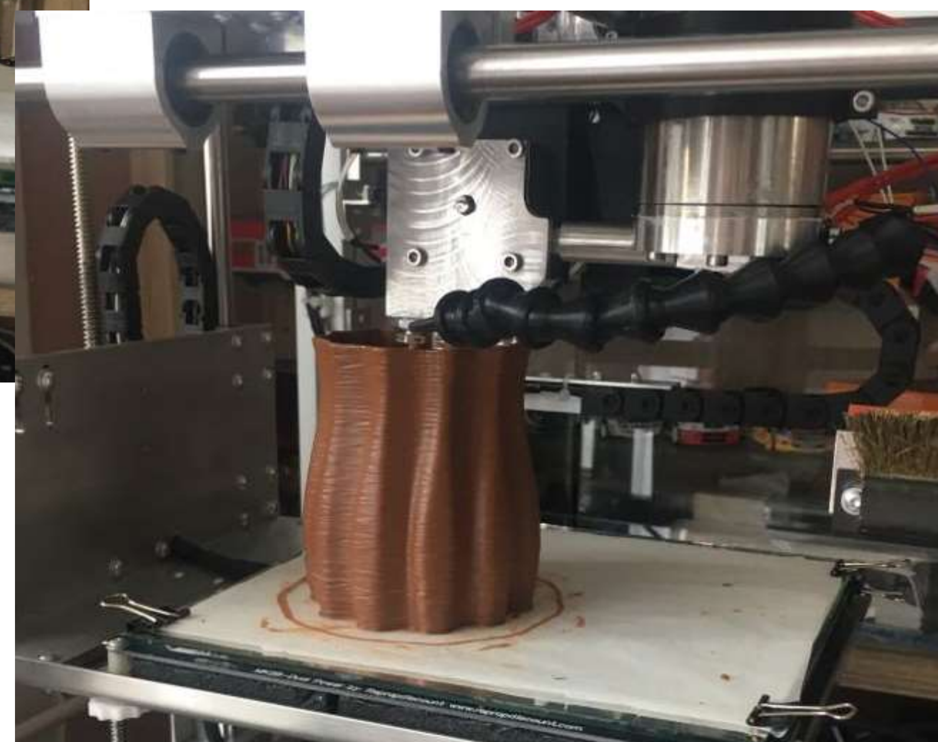


CAD design of the print head

Research at KSA - 3D printing from chocolate

sample of our own printing





Additive manufacturing
– material extrusion for metal parts

- material extrusion – an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice

The printing process is the same as for thermoplastics. The difference is in the filament used and the finishing operations. The manufacturing of metal parts using FDM technology requires a filament that contains metal powder and two types of binder. After printing, finishing operations must be performed on the part to obtain the desired mechanical properties. The printed part is called a 'green part' from which one of the binders must be removed by a catalytic process. This process produces a 'brown part', which is placed in an oven that removes the second binder at high temperatures and sinters the metal particles. The result is a homogeneous metal part.

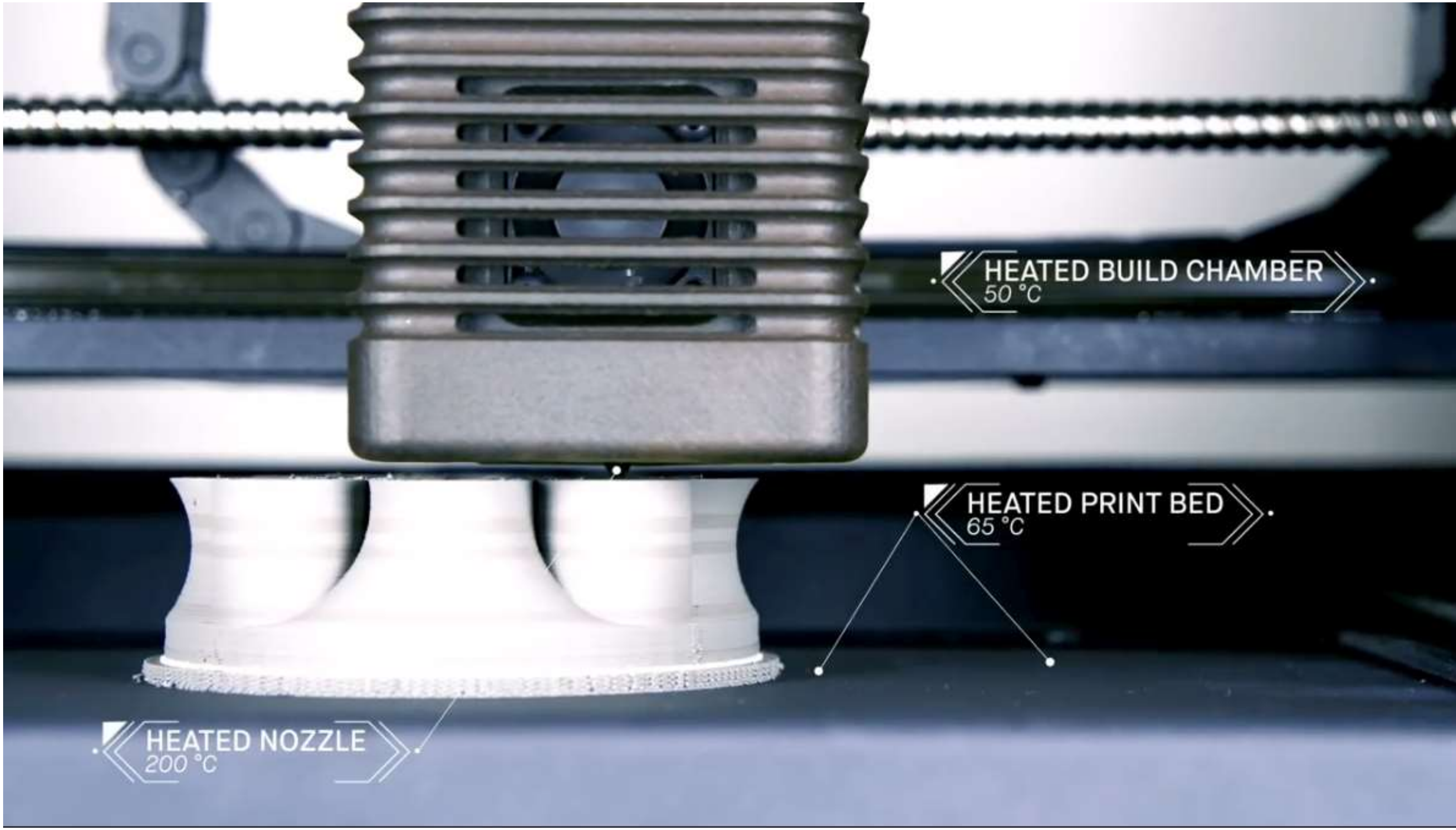
Source: matca.cz/technologie/aditivni-technologie/

Studio System+ – metal 3D printing by extrusion of material

Desktop Metal

- technology launched in 2019 as Studio System+
- 10 times cheaper than laser systems
- designed for the office
- the material are metal powder rods bonded with polymer
- necessary so-called debinding - a process for removing the binder (polymer) and subsequent sintering to obtain a functional metal model

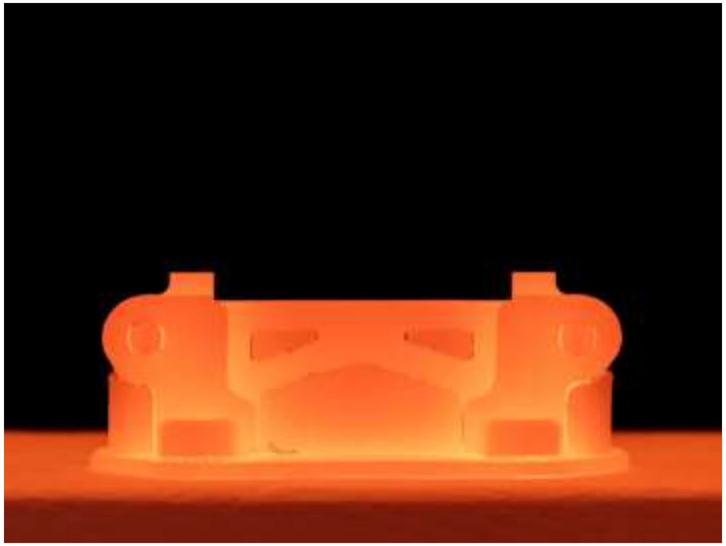
Metal 3D printing by extrusion of material – Studio System+



Desktop Metal

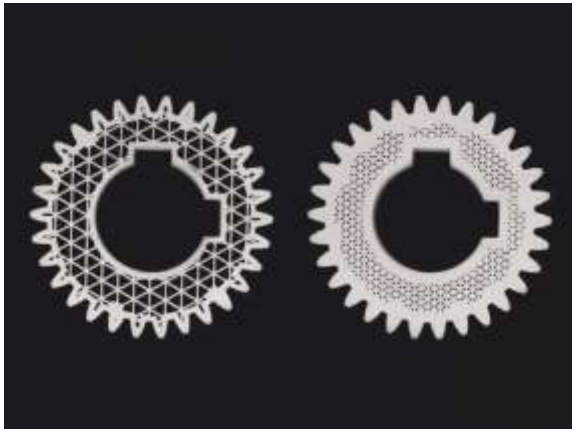
Currently available materials:

- Steel 17-4PH - stainless steel - strong and corrosion resistant
- Steel 4140 - one of the most versatile steels, medium carbon steel with high strength and toughness
- Steel 316 L - stainless steel - corrosion resistance at high temperatures
- Copper - thermal and electrical conductivity
- Inconel 625 - superalloy - strong and resistant to corrosion at high temperatures
- Steel H13 - tool steel - hard and abrasion resistant at elevated temperatures

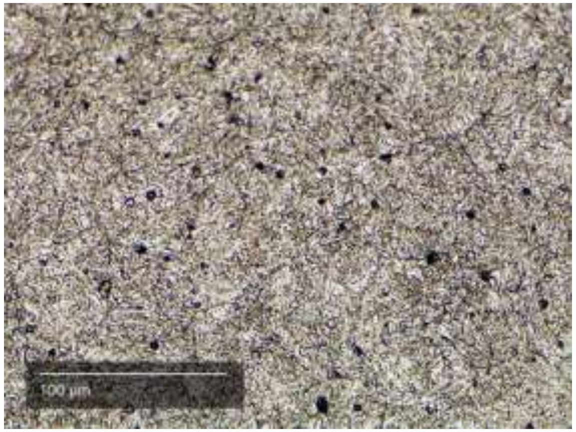


Desktop Metal

- Interchangeable print heads - standard (400μm), high-res (250μm) - and layer height as low as 50μm allow users to optimize prints for build speed or print ultra-fine features.



- adjust shell thickness and infill density to 3D print stronger parts or enable faster post-processing. Create walls up to 4mm thick and fully-dense parts (with no infill) up to 8 mm thick.



- achieve part densities of up to 98 percent - similar to cast parts - through the use of high metal volume fraction media, high-pressure extrusion, and vacuum sintering at temperatures of up to 1400ºC

Advantages of metal 3D printing by extrusion of material

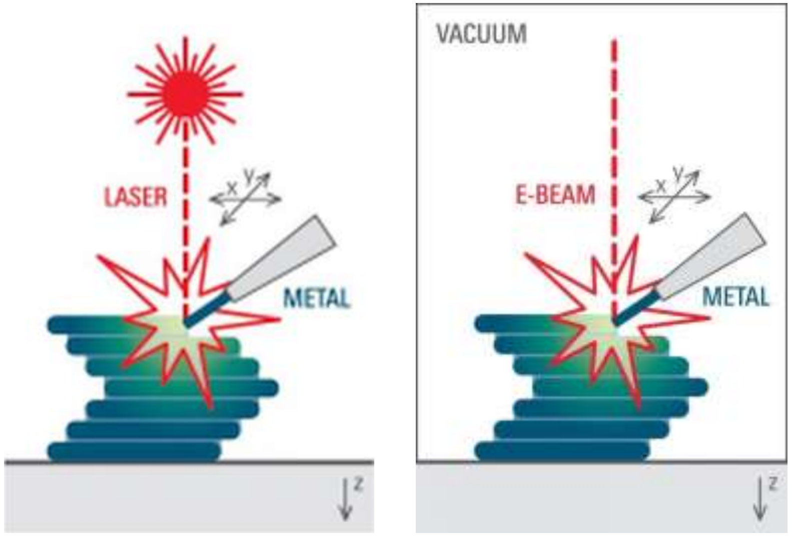
- relatively cheap indirect 3d printing of metal parts
- office system = clean process
- the choice of material microstructure is selectable via the furnace control software (e.g. austenitic / bainitic structure)
- easy removal of supports due to ceramic interlayer

Disadvantages of metal 3D printing by extrusion of material

- postprocessing - necessary debinding and sintering to obtain the final metal part
- thin-walled parts only (wall thickness up to 8 mm)
- relatively small parts, working area is 240 x 150 x 155 mm, recommendation for part max. 150 x 150 x 110 mm

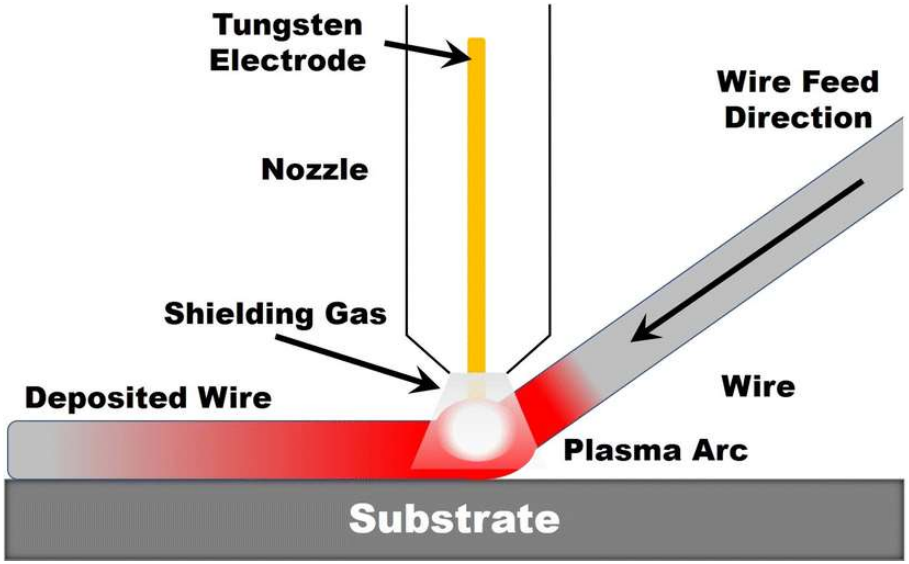
Additive manufacturing
– directed energy deposition

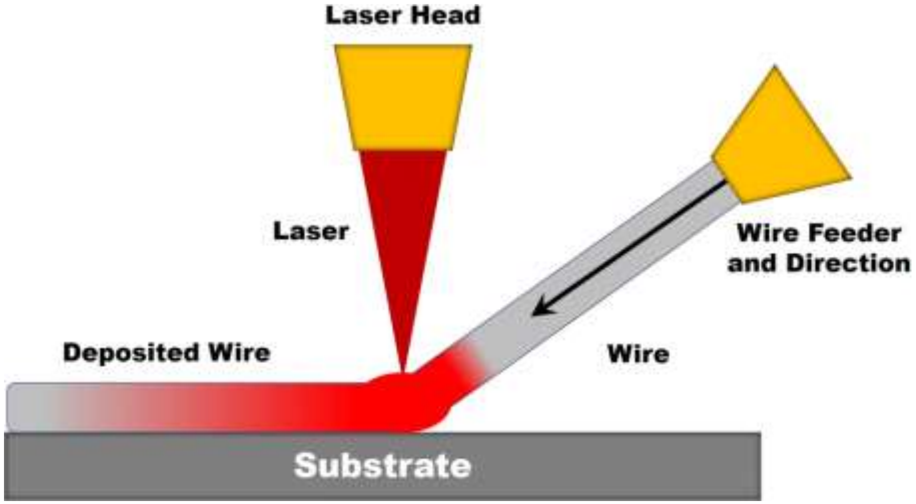
- directed energy deposition – an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited



Source: matca.cz/technologie/aditivni-technologie/

Directed energy deposition





DED processes can use either a pulsed plasma arc, a pulsed laser or an electron beam in vacuum. A material in the form of a wire is fed into the heat source path and locally melted onto the substrate or previous layers. The wire diameters range from 0.2 to 4 mm, the smaller wire diameter being deposited by the laser heat source and the larger by the pulsed plasma arc.

LENS - the input material for this type of printing can be either metal powder or continuous metal wire. The laser creates a bath of molten metal on the build platform into which the metal powder or wire is fed. The high precision of this technology reduces the need for further machining of the print. Due to the lower inerting requirements of the atmosphere and the absence of a powder bed, this method can produce relatively large parts with minimal waste.

Source: https://doi.org/10.1007/s11663-019-01612-1

Directed energy deposition

Typical technologies:

- **DED** – summary abbreviation (Directed Energy Deposition)
- **WAAM** – Wire and arc additive manufacturing (additive method of welding using el. arc and wire additive) – general name for arc welding processes for AM
- **MIG / MAG / TIG** welding / cladding
- **LENS** – laser cladding of powder or wire

Additive manufacturing

categories according the standard ISO/ASTM 52900 :

1. material extrusion:
2. material jetting:
3. binder jetting:
4. sheet lamination:
5. vat photo-polymerization:
6. powder bed fusion:
7. directed energy deposition:

SLA

DLP

PolyJet

SLS

SLM, DMLS

EBM

3DP

MJF

LENS

Laser cladding

LOM

DOD, TIJ

APF

FLM, FDM, FFF

MIG/MAG cladding