EPFL

Additive Manufacturing in Architecture

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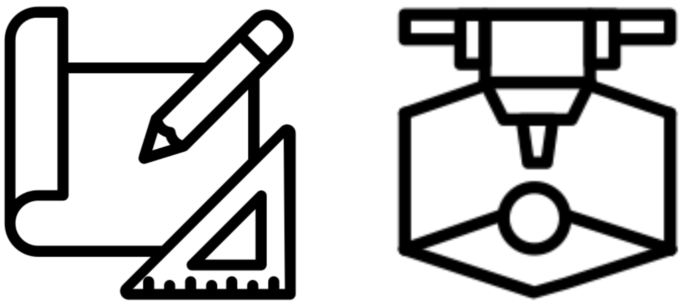
Vincent Vos



ME-413: Introduction to additive manufacturing

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Contents:

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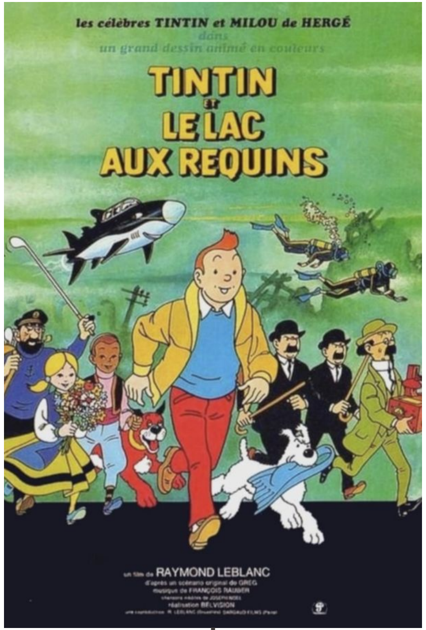
1. Introduction [Jules]

- What is Additive Manufacturing ?

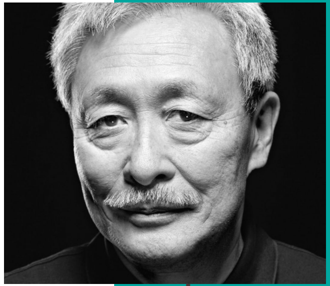
1. Introduction

- How and when did it appeared ?

Arthur C. Clarke



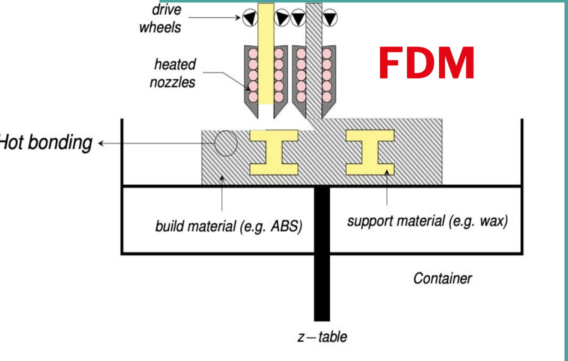
Hideo Kodama

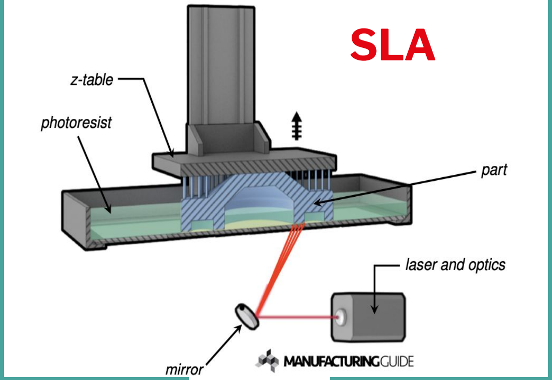


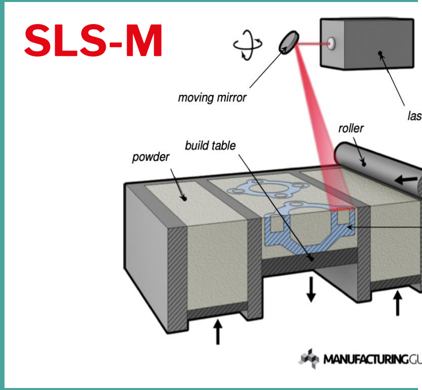
Charles Hull

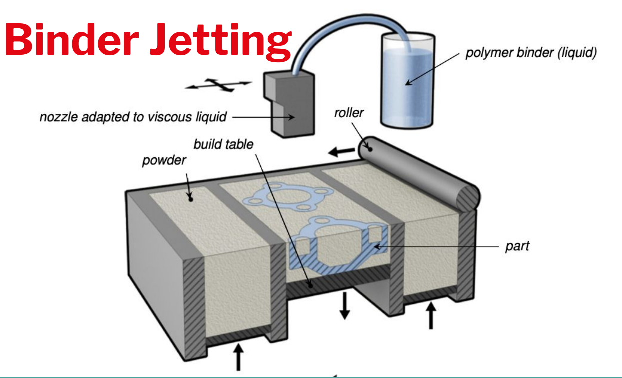
1960 1972 1980 1986

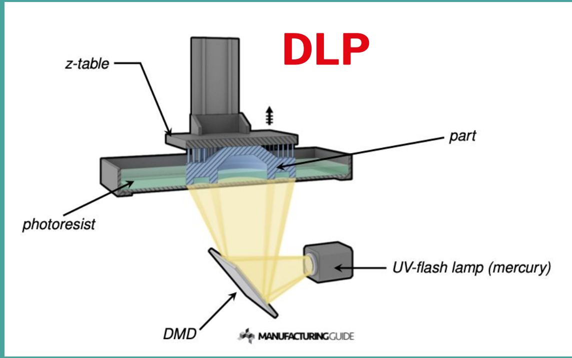
2. Additive Manufacturing processes









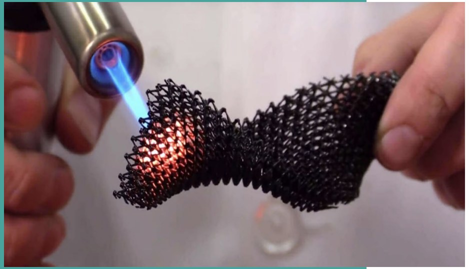


3. Additive Manufacturing Materials

Plastics

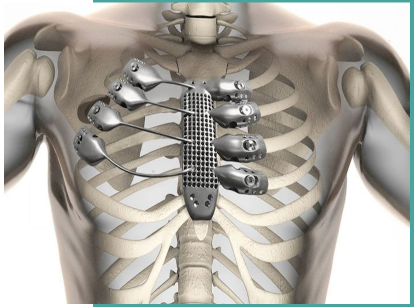
Composits

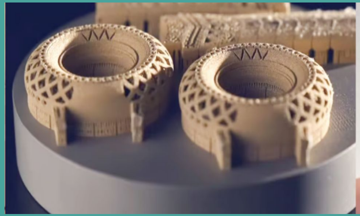
Ceramics

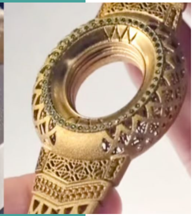


Bio-Materials

Metals

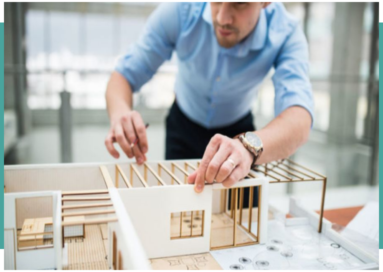


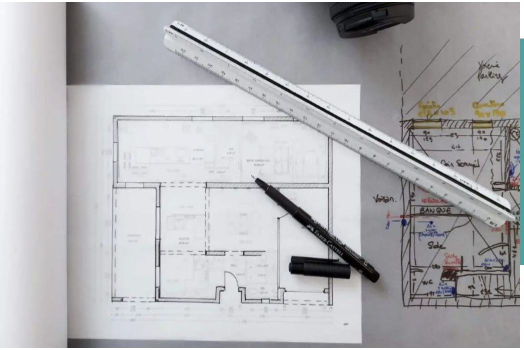




4. Scale Modeling and Prototyping

1) First era





2) Transition

3) 3D printing

5. Extrusion-based concrete 3D printing

- Introduction to extrusion-based concrete 3D printing
- How it works
- Factors affecting Concrete 3D Printing performance
- Wolf Ranch 3D-Printed Homes by Icon

5. Introduction to extrusion-based concrete 3D printing [Clara]

- Main AM technique applied in construction
- No formwork needed:
  - 35–60% reduction of the total cost
  - more environmentally-friendly
- Faster process, less on-site skilled labour
- Why concrete?
  - strength
  - durability
  - versatility
  - availability
- Concrete = cement + aggregate + water

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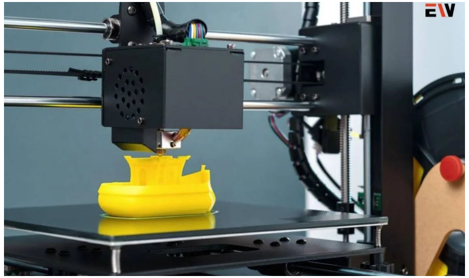
5. How Extrusion-Based concrete 3D printing Works [Clara]

- Method based on fused deposition modeling (FDM)
- Same principle, but significant differences:

	FDM	C3DP
Material	Thermoplastic filaments such as ABS (Acrylonitrile Butadiene Styrene)	Concrete
Scale	Small to medium-scale prototyping or parts Layer height: 0.125mm - 0.3mm	Architectural or construction scale, fabricating walls, houses or large components Layer height: 9mm - 30mm
Operating Principle	Molten thermoplastic filament is extruded through a heated nozzle Consolidation mechanism: liquid phase bonding	Pump system to extrude the concrete mixture through a large nozzle Consolidation mechanism: Concrete hardens as a result of hydration



5. Factors affecting concrete 3D printing performance [Clara]

- Quality and efficiency of C3DP are influenced by two critical factors:

Printer's characteristics:
size, flexibility, and speed to adapt to the material and specific project requirements

Material properties:
particle size, rheological behaviour, and the hardening rate of the concrete mixture

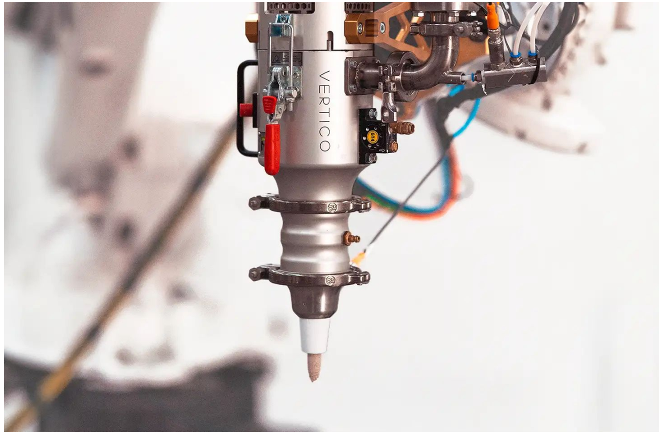
Stability during extrusion (extrudability)

Structural integrity after deposition (buildability)

- To balance these competing needs: material formulation and additives

5. Printer's characteristics [Clara]

- The printing speed and the properties of the raw materials: interconnected for quality printing
- Material extrusion speed should match the printing speed
- The adequate printing speed depends on several factors:
  - Rheological properties of concrete
  - The shape and size of the nozzle
  - The distance between the nozzle and the previously deposited layer
- Optimal extrusion rate → right balance must be achieved
- What happens if extrusion rate is too low or too high?
  - Defective structures
  - Uneven layers
- The printing speed ranges between 39 and 60mm/sec depending on all the mentioned factors.



5. Material properties: concrete content modifications, use of additives [Clara]

- Performance of extrusion-based C3DP can be significantly enhanced through various material modifications → adjusting the aggregate content

- Various studies reveal that
  - amount of aggregate ∝ viscosity (linearly) and ∝ yield stress (non-linearly)
  - balance between amount of binder and aggregate → optimise extrudability and buildability

- Traditional concrete is not compatible with the extrusion-based C3DP method → use of additives

	Modification of Rheological Properties (Extrudability)	**Enhancement of Printed and Hardened C3DP (Buildability)**
Focus	Improve flowability, yield stress, and printability during extrusion	Enhance mechanical properties and long-term durability
Key Additives	Superplasticizer (SP), Expanded Thermoplastic Microsphere (ETM), PEG capsules, nanoclay	Glass fibres, basalt fibres, PVA fibres, PP fibres, nanosilica

5. Wolf Ranch 3D-Printed Homes by Icon [Clara]

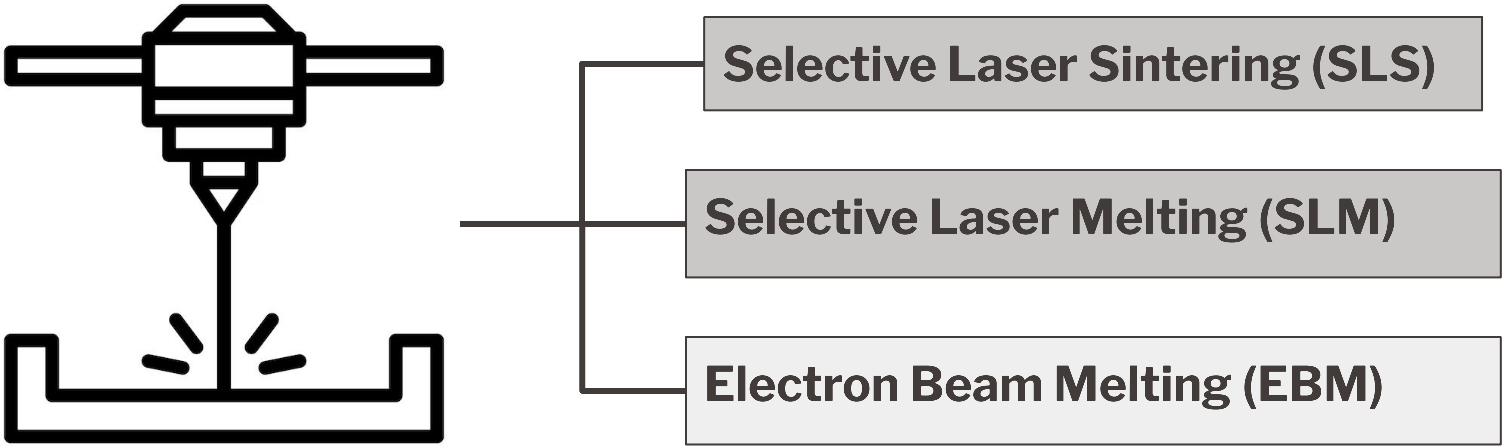
- Wolf Ranch project: 100 3D-printed homes of varying sizes in Texas
- Remarkable technical features:
  - The 3D printer: The Vulcan Printer
    4.9 m x 14 m frame
  - The material adaptation: system dynamically adjusts the concrete mix based on the weather conditions
- Example of a faster, cost-effective and innovative solution for housing needs

6. Powder bed fusion [Vincent]

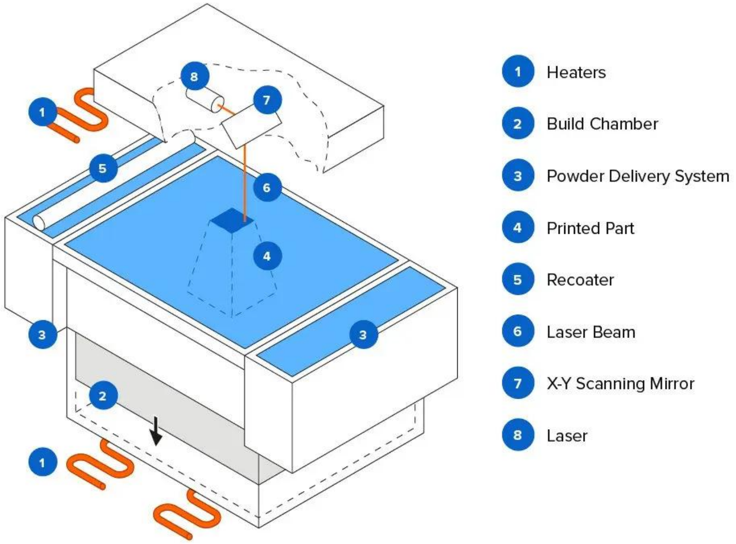
- What is powder bed fusion?
- Selective laser sintering (SLS)
- Selective laser melting (SLM)

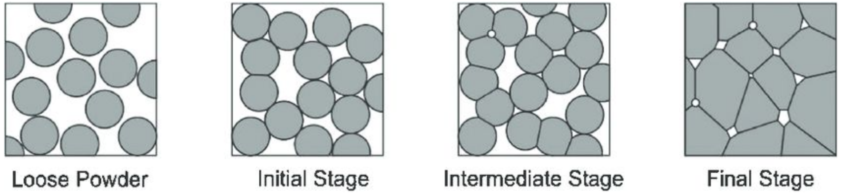
6. What is powder bed fusion?

Powder Bed Fusion (PBF) is an additive manufacturing technique that uses a high-energy source, such as a laser or electron beam, to selectively melt and fuse layers of powdered material to create complex 3D structures.



6. Selective Laser Sintering (SLS)





- **Definition:** SLS uses a high-powered laser to sinter powdered material layer by layer, bonding them to create a 3D object.
- **Materials:** Primarily polymers, such as nylon (PA12) or polyamide, and sometimes composite powders with fillers like glass or carbon fibers.
- **Key Features:** The unsintered powder acts as a natural support for the object during printing, eliminating the need for additional support structures.

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6. Selective Laser Sintering (SLS)

Advantages

- **Design Freedom:** lattice structures or organic forms
- **Rapid Prototyping**
- **Cost-Effective**: unused powder can be recycled
- **Surface finish:** no need for post processing

Limitations

- **Maximum construction size:** 70x50x50cm
- **Build Strength:** due to materials and sintering process

6. Selective Laser Sintering (SLS)

Uses in architecture

Rapid, precise models

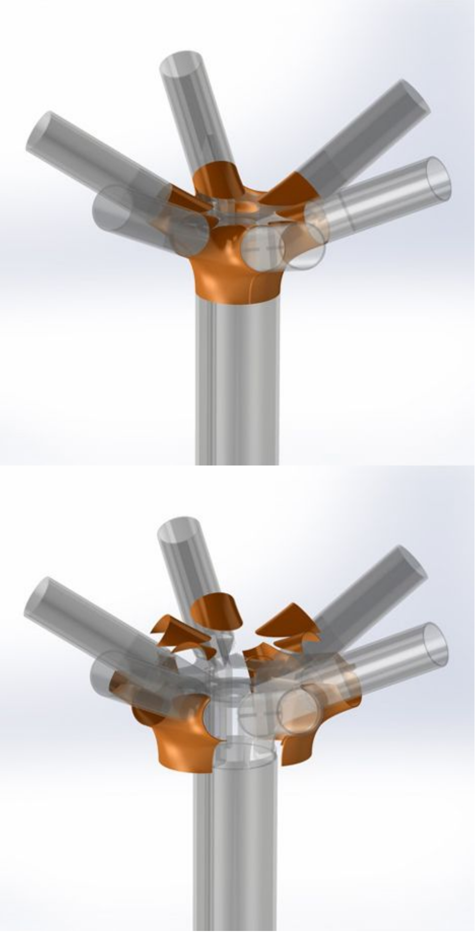
6. Selective Laser Sintering (SLS)

Uses in architecture

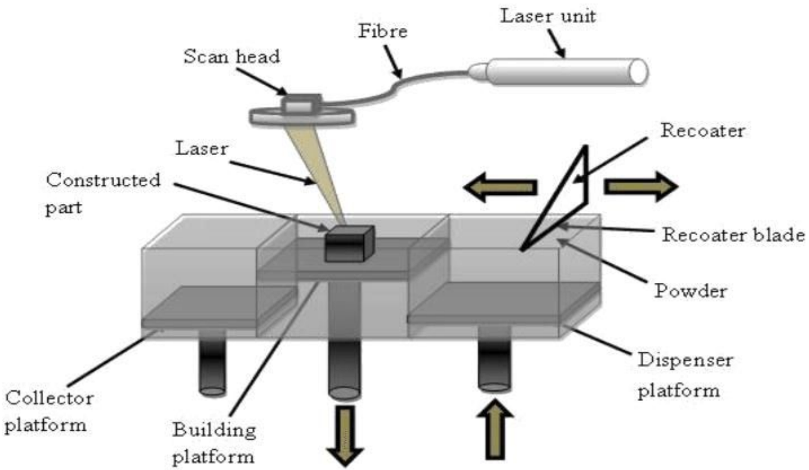
Real life applications

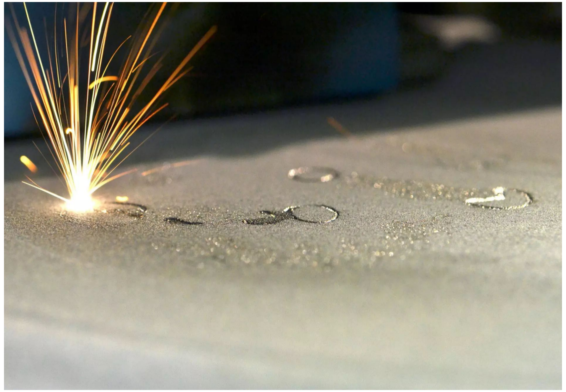
- **Complex**
- **Lightweight**
- **Creative**

3D printed sheaths by Adrian Priestman



6. Selective Laser Melting (SLM)





- **Definition:** SLM uses a high-power laser to completely melt metal powder particles, layer by layer, to produce dense and strong 3D objects.

- **Materials:** Primarily metals, such as stainless steel, titanium, aluminum, and cobalt-chrome alloys.

- **Key Features:** SLM creates fully dense metal parts with mechanical properties comparable to traditionally manufactured components.

6. Selective Laser Melting (SLM)

Advantages

- **Material Strength:** ideal for load bearing components like metal joints or structural brackets
- **Precision and Detail**
- **Customization**
- **Durability**

Limitations

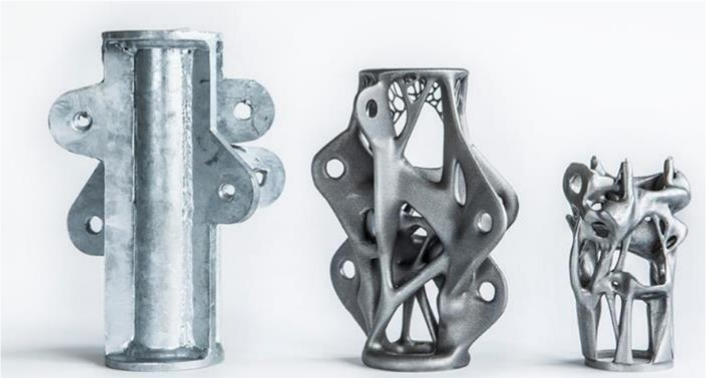
- **Cost:** expensive machines and powders
- **Post-Processing Needs:** rough surface finishes
- **Build Size Limitations:** similar to SLS

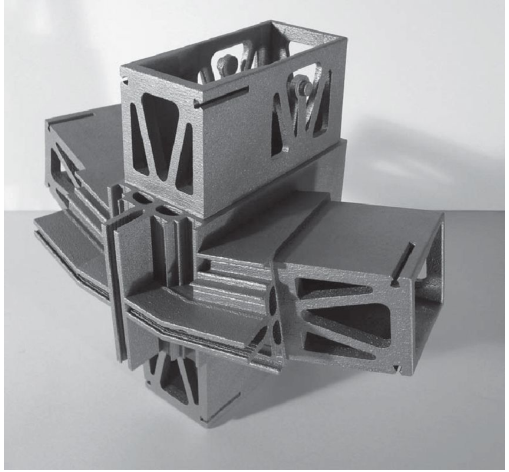
6. Selective Laser Melting (SLM)

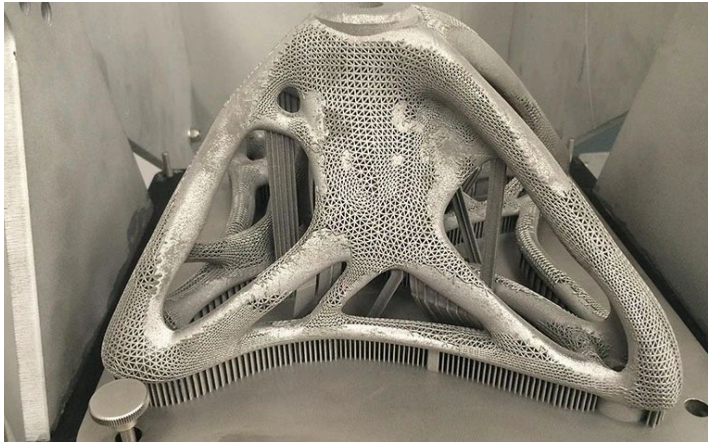
Uses in architecture

Structural elements

Topology optimization: a computational design process that optimizes material distribution within a part to achieve maximum performance with minimal weight





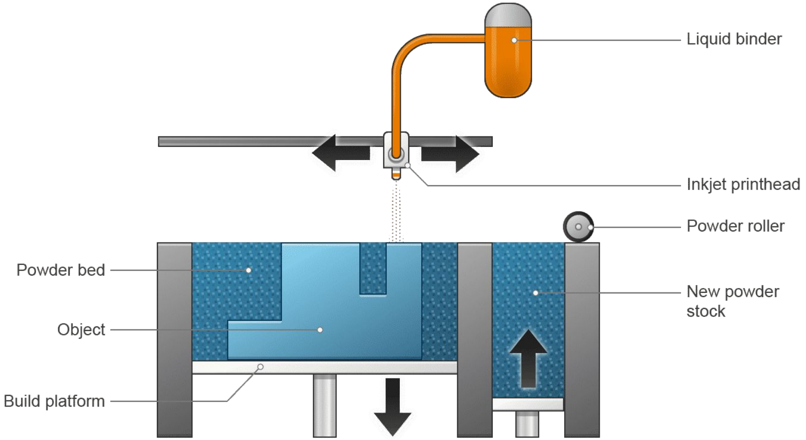


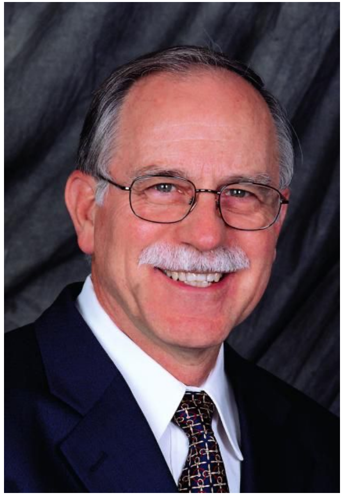
7. Powder Binder Jetting [Lino]

- What is Binder Jetting?
- Materials & Post Processing
- Advantages & Limitations
- Architectural Examples

7. What is Binder Jetting

- **Definition:** Powder-Binder Jetting is an advanced 3D printing process that bonds powdered materials layer by layer using a liquid binder. It works with diverse materials, including polymers, ceramics, metals, sand, and even food products.



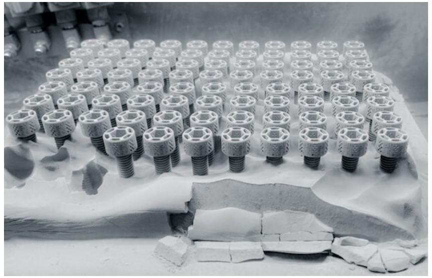


CHUCK HULL, *3D Printing inventor*

7. Materials & Post-Processing

MATERIALS

- SAND
- CERAMICS
- PLASTICS
- METAL



7. Advantages & Limitations

Advantages

- ❑ **Room temperature process:** no thermal effects
- ❑ **Fast construction**
- ❑ **Cost-Effective**: cheap machines and materials
- ❑ **Large build volumes**
- ❑ **No supports needed:** powder acts as support

Disadvantages

- ❑ **Poor Accuracy**
- ❑ **Shrinkage:** due to post processing
- ❑ **Mechanical Properties**
- ❑ **Post-Processing:** added time and costs

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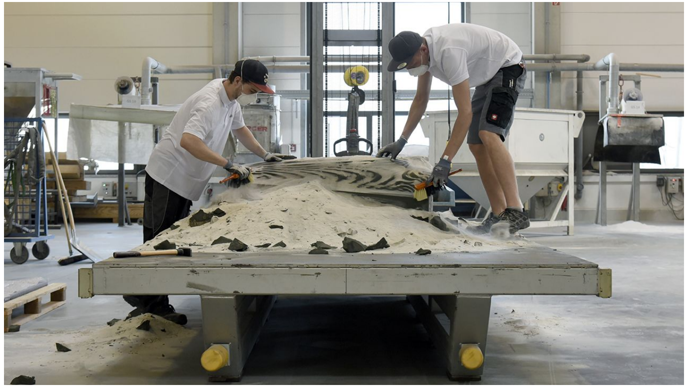
7. *Smart Slab* of DFAB House

OBJECTIVE: demonstrate the potential of computational design and Binder Jetting technology in creating highly optimized, sustainable structures.

- Complex geometries unachievable through conventional methods
- Eleven 7.4 m long prefabricated segments
- Sand moulds for casting process printed through binder jetting
- 70% less weight compared to conventional slabs



7. *Saltygloo* by Emerging Objects

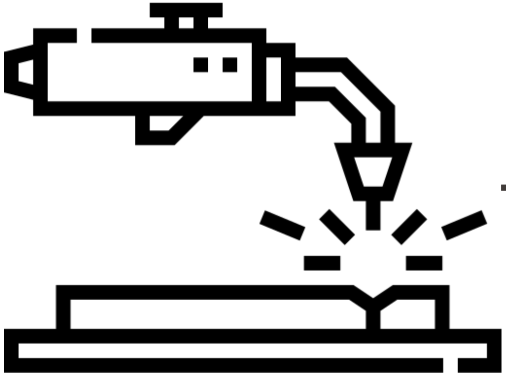
- **Material:** locally harvested salt from the San Francisco Bay through evaporation ponds
- **Composition:** 336 unique translucent panels rotated randomly
- **Binder:** customized “salty glue”
- **Cost-effective, sustainable**

8. Directed Energy Deposition (DED) [Vincent]

- What is DED?
- Laser Metal Deposition (LMD)
- Wire-Arc Additive Manufacturing (WAAM)

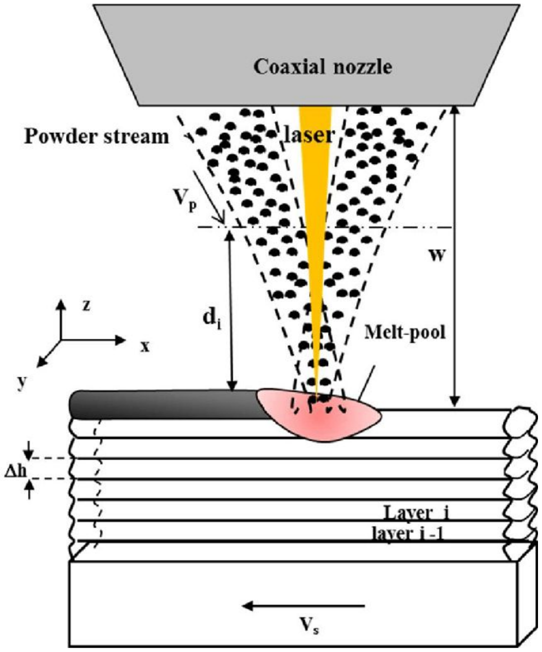
8. What is directed energy deposition?

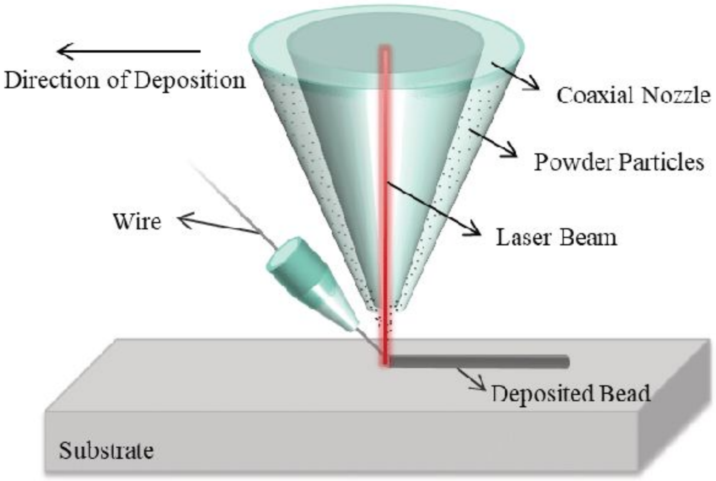
Definition: DED is an additive manufacturing process where material (powder or wire) is deposited and simultaneously fused using a heat source (laser, electron beam, or arc).



- **Laser Metal Deposition (LMD)**
- **Wire-Arc Additive Manufacturing (WAAM)**

8. Laser Metal Deposition (LMD)





Definition: a process that uses a focused laser beam to create a melt pool, where metal powder or wire feedstock is deposited and fused layer by layer to build or repair components.

8. Laser Metal Deposition (LMD)

Advantages

- **High precision and detail:** intricate geometries with fine resolution
- **Material efficiency:** direct deposition
- **Repair and retrofit capabilities**
- **Minimal post processing:** smooth finished surface

Limitations

- **Cost:** expensive machines and powder
- **Production speeds:** slow deposition rate
- **Residual stresses:** rapid warming and cooling

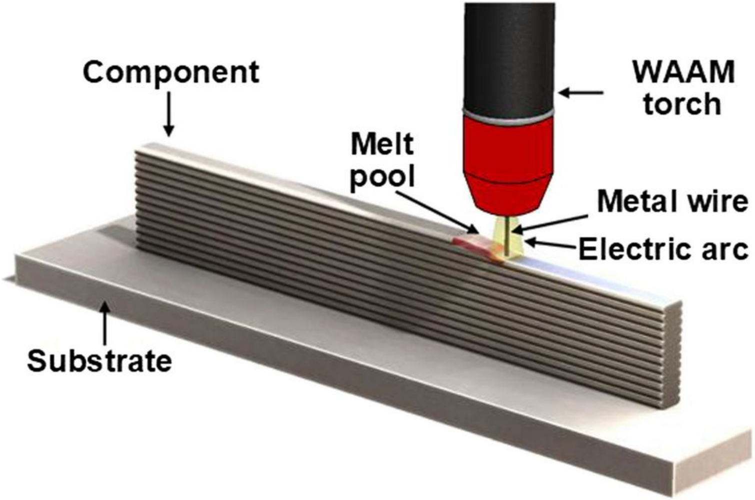
8. Laser Metal Deposition (LMD)

Mostly used in aerospace and automotive industries

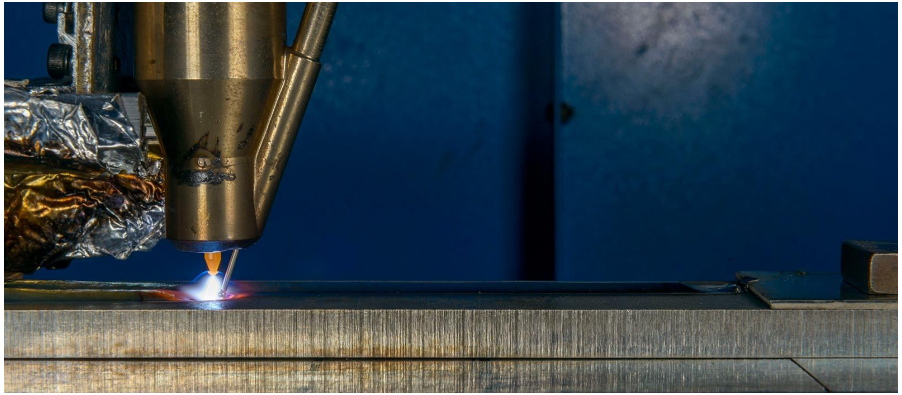
Potential use in reparation of support structures

8. Wire-Arc Additive Manufacturing (WAAM)

Definition: process that uses an electric arc to melt a metal wire feedstock, which is then deposited onto a substrate layer by layer to build a 3D part. The arc serves as the heat source, and the wire is fed into the molten pool created by the arc, fusing the material to the substrate.



A **wire arc** is an electrical discharge



8. Wire-Arc Additive Manufacturing (WAAM)

Advantages

- ❑ **Cost effective:** material and equipment is the same as for welding
- ❑ **High deposition rate**
- ❑ **Large parts and structural components:** use of robot arms
- ❑ **High strength and durability**

Limitations

- ❑ **Lower precision:** due to high deposition rate
- ❑ **Weld residual stresses**
- ❑ **Geometric complexity constraints**

8. Wire-Arc Additive Manufacturing (WAAM)

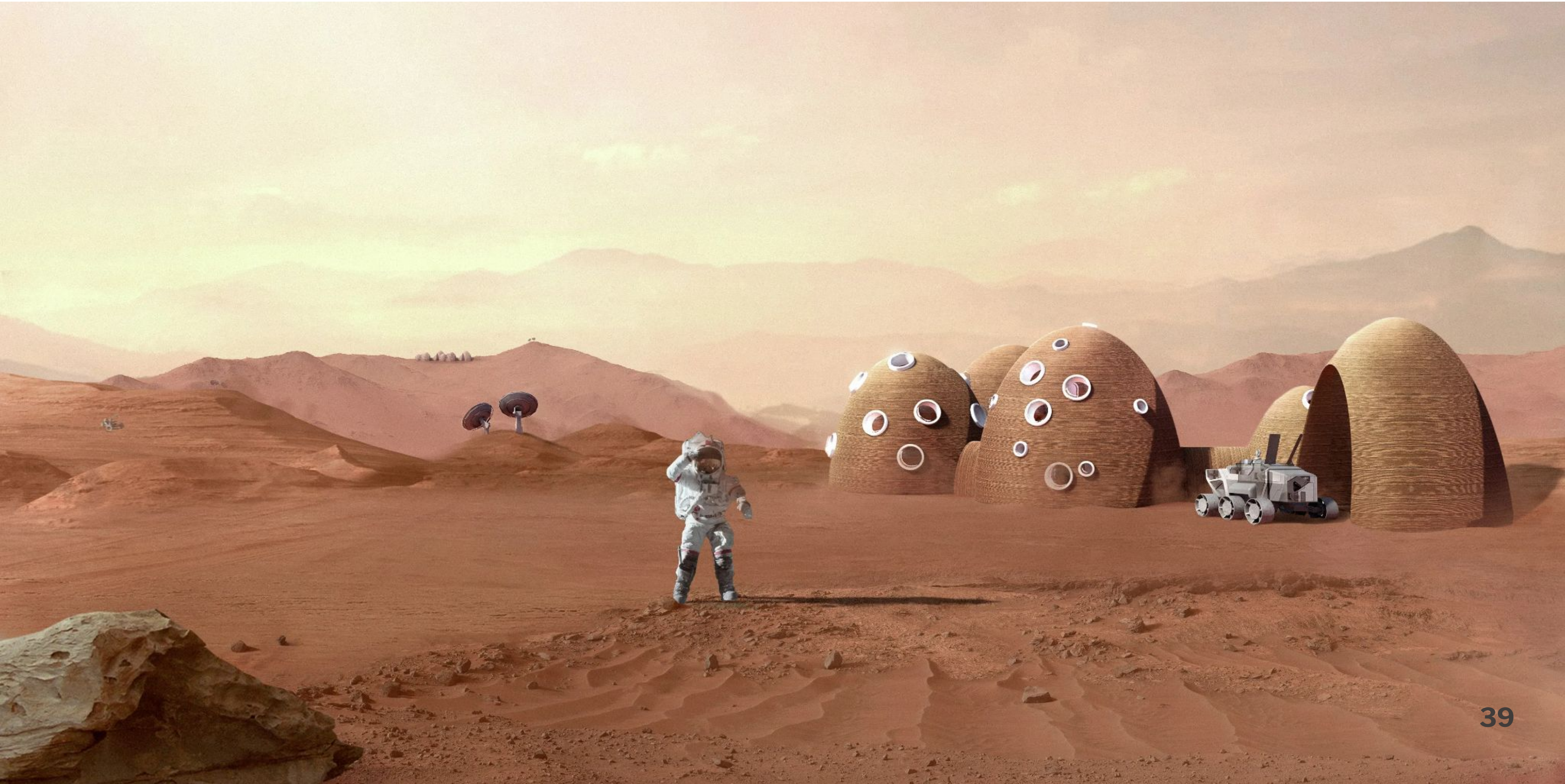
In architecture

MX3D joint for Takenaka

8. Wire-Arc Additive Manufacturing (WAAM)

MX3D bridge
Amsterdam

9. The Future of Sustainable Architecture and Space Exploration [Berta]



9. The Future of Sustainable Architecture and Space Exploration [Berta]

Portland Concrete

Sand & gravel

+

Cement

+

Water

'Lunarcrete'

Lunar Regolith

+

Molten Sulfur

- **Resource Availability**: Sulfur is available in certain volcanic deposits on the Moon and requires minimal energy.
- **Fast Strength Gain**: Sulfur-based concrete sets rapidly as it cools, eliminating the need for a lengthy hydration process (28 days for Portland concrete).
- **Adaptability**: The concrete can be tailored for specific mechanical properties by adjusting the sulfur-to-regolith ratio.

% Sulfur	25	30	35	40	50	60	70
Number of Specimens	3	9	9	10	6	6	6
Avg. Compresive Strength [MPa]	6.07	24.0	**33.8**	25.4	24.7	25.0	15.7
Avg. Tensile Strength [MPa]	0.33	2.9	3.7	2.0	2.7	2.6	1.4

2% of aluminum fibers by weight further improve compressive strength to **45.5 MPa** while reducing brittleness.

9. The Future of Sustainable Architecture and Space Exploration [Berta]

Additive Manufacturing Process

- Material Preparation:
  - Sulfur is heated to approximately 150°C to achieve a molten state.
  - Lunar regolith simulant is mixed with the molten sulfur ensuring uniform coating and optimal bonding.
- Extrusion-Based Layering:
  - The molten sulfur-regolith mix is extruded layer by layer to form structures.
  - Heated nozzles prevent premature solidification during deposition, while precise robotic control ensures structural accuracy.
- Compaction and Cooling:
  - To enhance bonding between layers, each extruded layer undergoes light compaction.
  - The structure is allowed to cool under ambient lunar temperatures, facilitating rapid strength development.

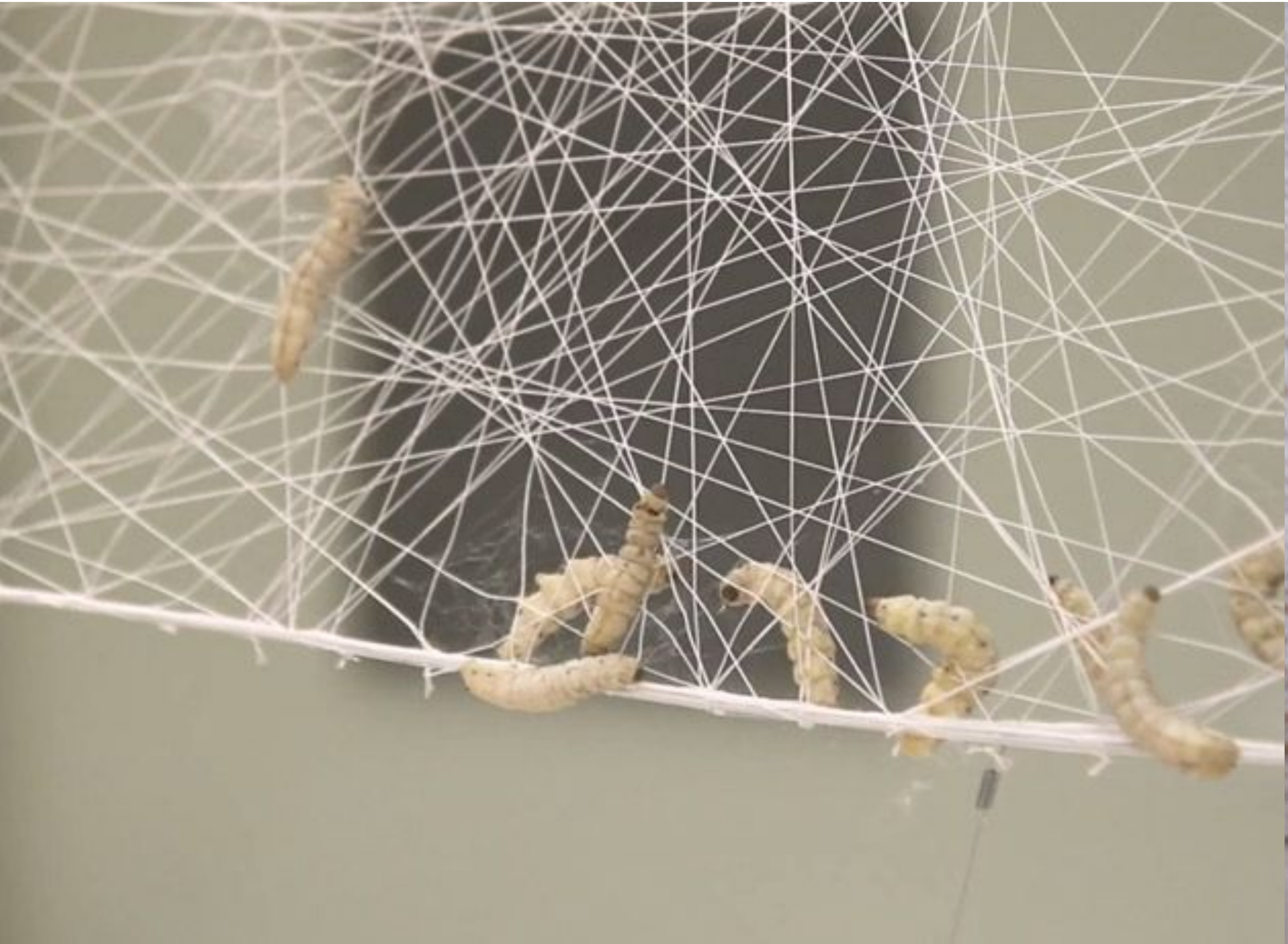
9. The Future of Sustainable Architecture and Space Exploration [Berta]

Challenges

- **Thermal Extremes:** Lunar temperatures swing from 100°C during the day to -150°C at night.
- **Dust Management:** Lunar regolith is highly abrasive and poses operational challenges for machinery.
- **Structural Integrity:** Ensuring homogeneity across layers and avoiding cold joints is vital to maintaining structural performance.

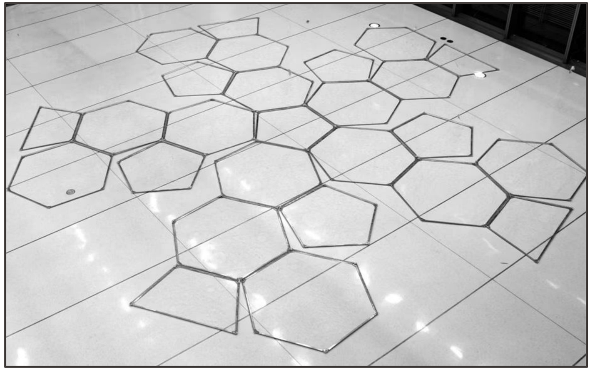
Simulated lunar concrete tested at NASA's *Marshall Space Flight Center* can withstand temperatures exceeding 3400°F (**1870°C**)

9. The Future of Sustainable Architecture and Space Exploration [Berta]



9. The Future of Sustainable Architecture and Space Exploration [Berta]

Neri Oxman's Silk Pavilion: Silkworms as Nature's 3D Printers



6,500 live silkworms spun kilometers of silk threads to complete the dome.

- **Dynamic Material Behavior**: Silkworms respond to **light**, **heat**, and **spatial density**, allowing precise control over silk thickness and distribution. The silkworms were found to migrate to darker and denser areas.
- **Algorithmic Design**: A computational algorithm informed the pavilion's geometry, strategically guiding the placement of apertures to manipulate light and heat. This influenced silkworm activity and the resulting silk density.
- **Biological Efficiency**: Each silkworm spun a thread up to 1 km in length, demonstrating the high efficiency of natural fabrication. Their eggs can be recollected and around **250 new pavilions** can be made.

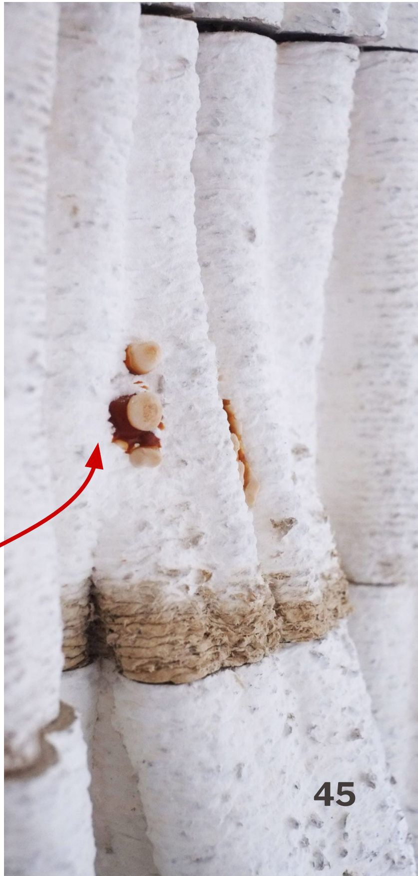
9. The Future of Sustainable Architecture and Space Exploration [Berta]

The Tree Column: Growing Architecture from Waste

- **Material Preparation**: Waste paper cups are sterilized by boiling and pulped into a paste, then combined with mycelium spores and optional pigments for coloration.
- **3D Printing**: The paste is extruded layer by layer with a 3D printer. To build the column, 10 modules were printed and then stacked and fused with additional mycelium to form the final structure.
- **Growth**: Over 3-4 weeks, the mycelium must be kept in a humid environment in order to let the fungus grow.
- **Drying**: The fully-grown column is dried at 80°C to kill the organism, solidify the material, and ensure its structural stability.

Blast Studio aims to create a self-repairing pillar by partially drying the mycelium to halt growth without killing it, enabling it to regrow and fix cracks when exposed to water.

Fungus used is edible.



Thanks for your attention!