Co-funded by the Erasmus+ Programme of the European Union

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

Metal Binder Jetting process
CU 75

December 2022

POLITECNICO MILANO 1863

Manufacturing Technology Centre

skills4am.eu

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AM Focus **Trends 2023**

Home / Additive Manufacturing / Metal Additive Manufacturing / The year of the binder

3D Printer Hardware | 3D Printing Processes | Additive Manufacturing | Formnext 2022 | Metal Additive Manufacturing | Trends 2023

The year of the binder

HP 3D Printing, GE Additive, Desktop Metal/Exone, Markforged/Digital Metal, Ricoh (and others) are going all out in the exciting next phase of the metal AM market

Davide Sher · November 2, 2022 6 minutes read

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MILANO 1863

mtc
Manufacturing
Technology Centre

Politecnico di Milano

Founded in 1863

	FACULTY	STUDENTS
Engineering	925	30430
Architecture	297	8260
Design	94	4054
	1316	*42744*

QS World University rankings

Engineering & Technology (2022)

- 1st in Italy
- 7th in Europe
- **13 th worldwide**

11	EPFL, Lausanne, Switzerland	90.9
12	Harvard University, Cambridge, United States	90.7
13	Politecnico di Milano, Milan, Italy	89.6
14	Tsinghua University, Beijing, China (Mainland)	88.9
15	California Institute of Technology (Caltech), Pasadena, United States	88.5
16	Georgia Institute of Technology, Atlanta, United States	88.2

Manufacturing, Mech and Aerospace Eng (2022)

- 1st in Italy
- 7th in Europe
- **13th worldwide**

11	University of Michigan-Ann Arbor, Ann Arbor, United States	90
12	University of Oxford, Oxford, United Kingdom	89.4
13	Politecnico di Milano, Milan, Italy	88.9
14	Georgia Institute of Technology, Atlanta, United States	88.6
15	California Institute of Technology (Caltech), Pasadena, United States	87.9
16	EPFL, Lausanne, Switzerland	87.3

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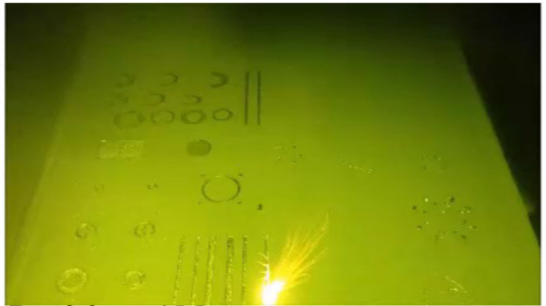
AddMe Lab@Polimi

SAM
SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

AddMe.Lab

Laser Powder Bed Fusion



Renishaw AM250
3DNT LPBF system
3 LPBF prototypes
New system to be installled in 2023

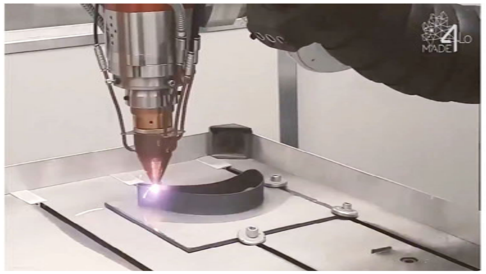
Electron Beam Powder Bed Fusion

Arcam A2

Bound Metal Deposition – Binder jetting

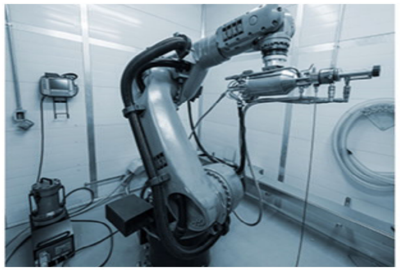
Desktop Metal Studio System+
ExOne Innovent
New BJ module to be installed in 2023

Laser Directed Energy Deposition and WAAM

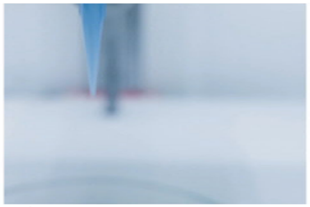


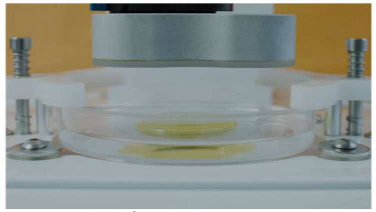
DED wire and powder - WAAM

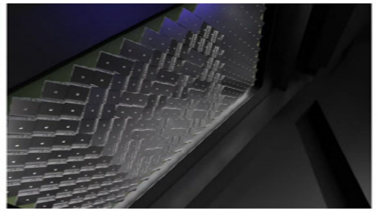
Cold spray



3D Cell Lab – a new lab on bioprinting

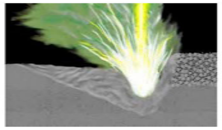
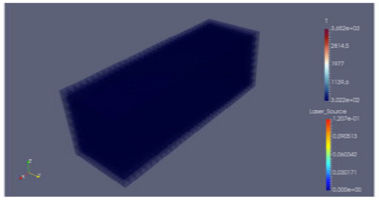






BioX – LumenX- Quantum X Bio

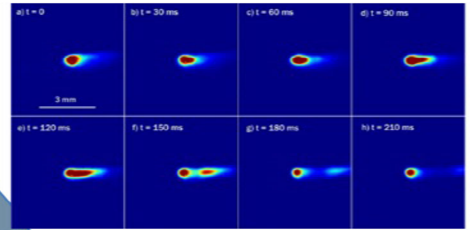
Co-funded by the Erasmus+ Programme of the European Union

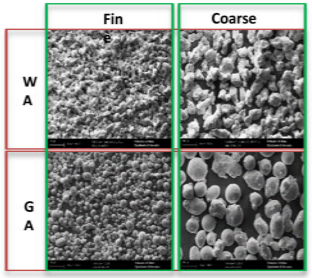



Simulation

Manufacturing

Monitoring



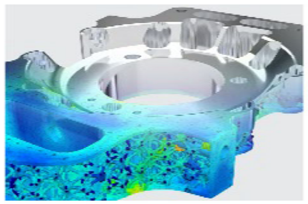


Materials

Challenges

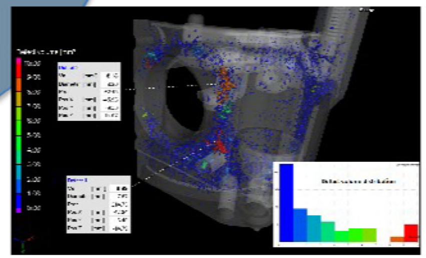
- New challenges
  net shape, lightweight, multimaterials, increase productivity, increase size, increase quality
- New on-board intelligence
  Sensors, big data mining, AI, I4.0
- New processes and new materials
  ceramics, copper, biocompatible, regolith

Post-processing and finishing



Design

Qualification & testing



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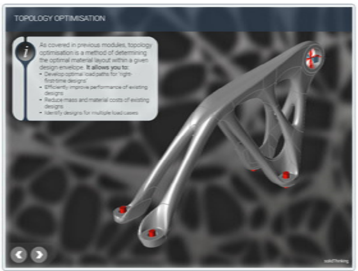
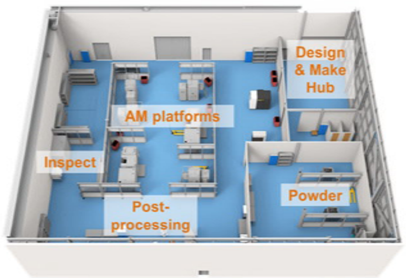
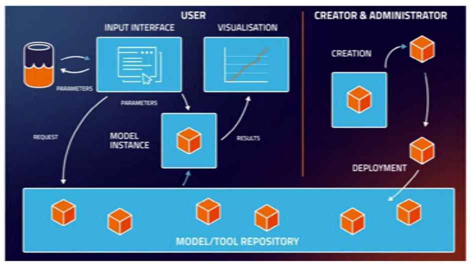
Nation Centre for Additive Manufacturing, Coventry UK

https://ncam.the-mtc.org/

DESIGN FOR AM	AM DEMONSTRATION FACILITIES	DIGITAL TOOLS TO SUPPORT AM ADOPTION	AM TRAINING	KNOWLEDGE HUB
DESIGN AND SIMULATION TOOLS PRODUCT PORTOLIO ASSESSMENT PROCESS SELECTION	STATE OF THE ART FACILITIES COVERING END-END PROCESS CHAIN: • METAL • POLYMER • CERAMIC PRODUCE PARTS 1CM^3 TO 1M^3	• AM COST MODELLING • PHYSICS MODELLING OF AM PROCESS CHAIN • AM FACTORY AND OPERATIONS PLANNING	28 AM COURSES • FACE TO FACE • ONLINE • BLENDED AM APPRENTICESHIP	FREE ACCESS REFERENCE LIBRARY FOR AM INFO







KNOWLEDGEHUB

the-amtc.co.uk/training/engineer-training/additive-manufacturing

knowledgehub.the-mtc.org

AM Equipment

Metal powder bed fusion

ncam.the-mtc.org/who-we-are/am-equipment

Renishaw RenAM 500Q

- 500W quad laser
- Build volume: 250 x 250 x 350 mm [xyz].
- In-process monitoring fitted.
- In-situ powder recovery with integrated sieve.
- Lasers are full field.
- Materials currently available at NCAM: Titanium

Renishaw - AM250 PlusPac

- 200W single laser
- 245 x 245 x 300 mm [xyz].
- Build chamber reduction kit available
- Materials currently available at NCAM: Inconel/ Stainless Steel/ Maraging Steel/ Aluminium

Trumpf TruPrint 3000

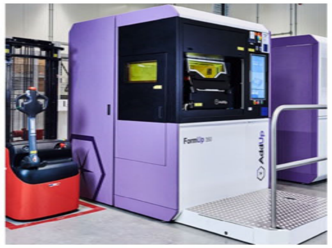
- 500W single laser
- Build volume: Ø300 x 400 mm
- Interchangeable build cylinders
- Materials currently available at NCAM: Aluminium

EOS M280

- 400W single laser
- 250 x 250 x 325 mm
- Equipped with Sigma Labs PrintRite3D in-process monitoring
- Materials currently available at NCAM: Inconel/ Titanium/ Stainless Steel/ Aluminium

EOS M400-4

- 400W quad laser machine
- 400 x 400 x 400 mm
- Lasers are not full field
- Materials currently available at NCAM: Inconel



AddUp FormUp 350

- 500W dual laser machine
- 350 x 350 x 350 mm
- Materials currently available at NCAM: Maraging Steel

Arcam Q20+

- Electron beam [3kW].
- Ø350 x 380mm
- In addition to the two EBM machines owned by MTC, we operate a pilot production facility for a customer containing multiple additional machines.
- Materials currently available at NCAM: Ti6Al4V

Matsuura Lumex hybrid PBF system

GE Arcam Q10 coming soon for processing copper

AM Equipment

Polymer AM

ncam.the-mtc.org/who-we-are/am-equipment

Stratasys Fortus 450mc

- Fused deposition modelling
- 406 x 355 x 406 mm
- Materials currently available at NCAM: ABS, PA, ULTEM 1010, ULTEM 9085, Nylon-12 & carbon fibre, PPSF, Antero (PEKK)

HMT PE-1 large scale deposition head

- Fused granulate fabrication (FGF). Print size dependent on gantry / robot motion limits
- Currently on a DMG DMU 210FD CNC, build area of 2x1.5x1.2 m
- Materials currently available at NCAM: ABS, PLA, PET, PP or Custom materials

HP Jet Fusion 4200

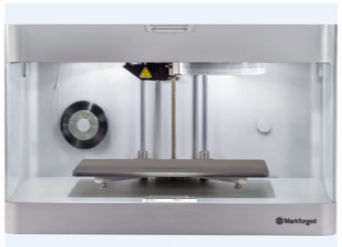
- Polymer powder bed fusion (high speed sintering).
- 380 x 284 x 380 mm
- Materials currently available at NCAM: PA

Stratasys Objet 1000 Plus

- Polymer material jetting. 1000 x 800 x 500 mm
- Materials currently available at NCAM: Multi-material capabilities. Variety of polymer materials including material mixing capability and full colour

Carbon Digital Light Synthesis M2

- Stereolithography (CLIP process)
- 189 x 118 x 326 mm
- Materials currently available at NCAM: High performance and engineering photopolymers



Markforged Mark 2 Enterprise Composite

- Fused Filament Fabrication (FFF)
- 320 x 132 x 154 mm
- Materials currently available at NCAM: Carbon fibre/ Fiberglass/ Kevlar reinforced nylon

Arburg Freeformer

AM Equipment

Ceramic and Sinter-based AM

ncam.the-mtc.org/who-we-are/am-equipment

Photocentric LC Precision Ceramic

- Ceramic stereolithography with daylight curable resin.
- 121 x 68 x 160 mm [xyz]
- Materials currently available at NCAM: Alumina, other materials are available, please enquire

XJet Carmel 1400

- Ceramic [and metal] nanoparticle loaded jetting
- 500 x 280 x 200 mm [xyz]
- Materials currently available at NCAM: Zircona

Larger Photocentric ceramic system

AIM3D ExAM 255

- Open-materials fused granular fabrication [FGF] AM system using injection moulding feedstock
- Build Volume: 255 x 255 x 255 mm [xyz]
- Layer height: Depends on the desired printing time and component quality [75 – 250 µm]
- Heating of the heating plate: Up to 120 °C
- Currently materials available at NCAM: Stainless Steel 316L [but many others available]

Digital Metal DMP2500

- Scaled build volume of 170 x 150 x 57 mm [xyz]
- Materials currently available at NCAM: 316L Stainless Steel
- Other materials are available for Digital Metal [17-4PH, D2 tool steel, nickel superalloys: DM625, DM247 and Ti64].

Carbolite HTK 8

- Insulation material: Molybdenum
- Functional volume: 250 x 250 x 400mm
- Tmax vacuum [°C]: 1600
- Operational in: Vacuum, H2 or N2 atmospheres

SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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Metal Binder Jetting process
CU 75

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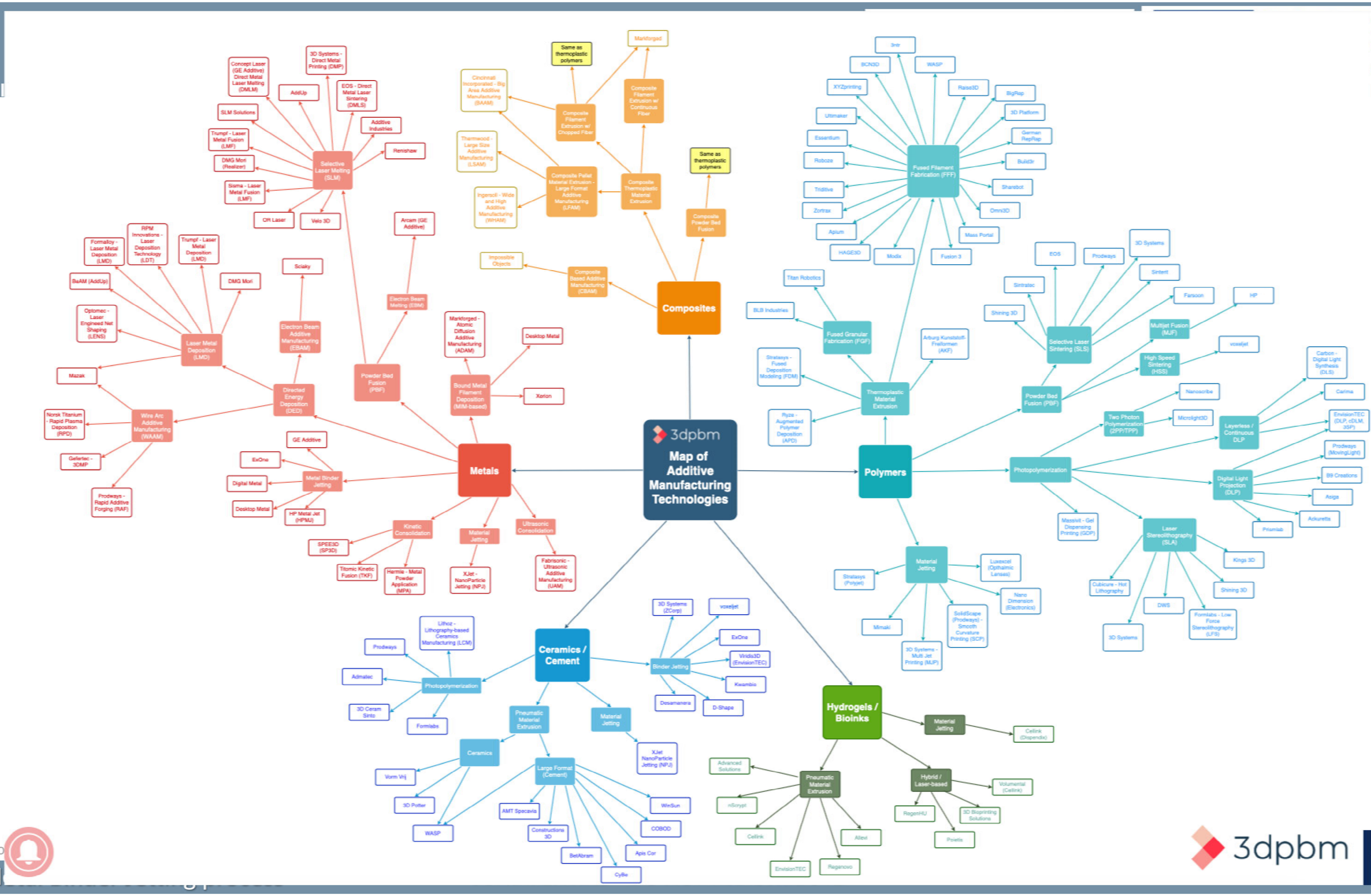
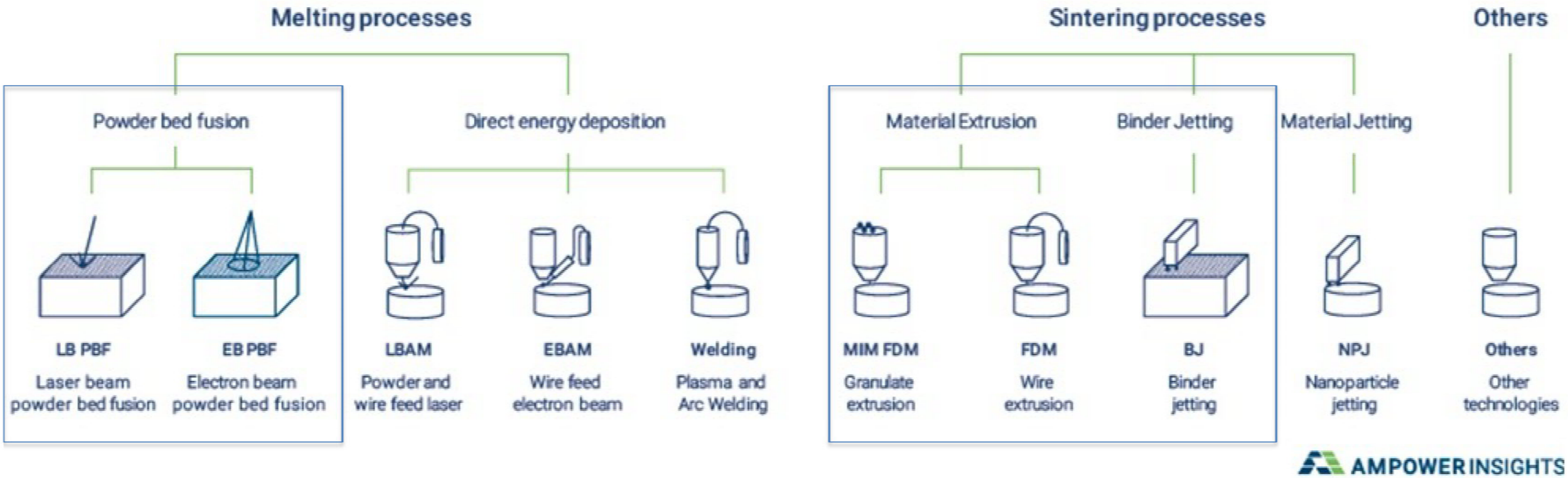


Metal Additive Manufacturing Technologies



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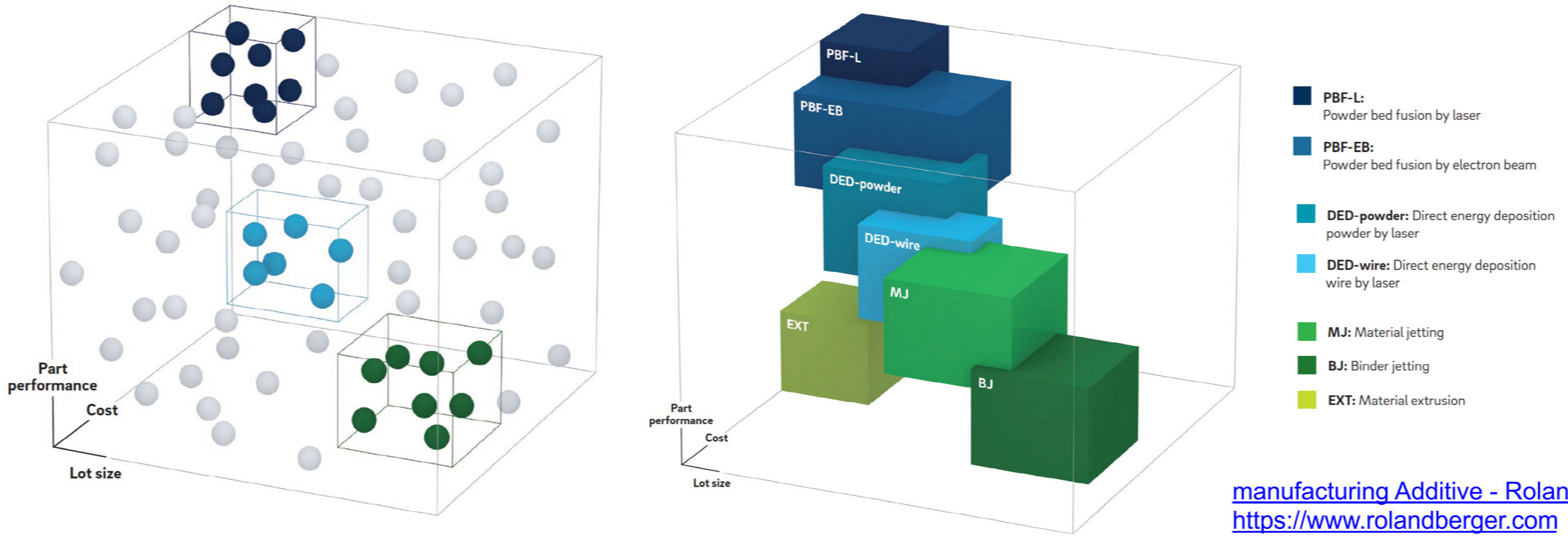
Each process has its own core business

- **Cluster 1:** High performance requirements at small lot sizes and high cost tolerance (e.g. PBF-L)
- **Cluster 2:** Medium to high performance requirements at small to medium lot sizes and medium cost tolerance (e.g. DED)
- **Cluster 3:** Lower performance requirements at higher lot sizes and lower cost tolerance (e.g. binder jetting)



[manufacturing Additive - Roland Berger](https://www.rolandberger.com)
https://www.rolandberger.com

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US005204055A

United States Patent [19]
Sachs et al.

[11] **Patent Number:** 5,204,055
[45] **Date of Patent:** Apr. 20, 1993

[54] **THREE-DIMENSIONAL PRINTING TECHNIQUES**

[75] Inventors: **Emanuel M. Sachs**, Somerville; **John S. Haggerty**, Lincoln; **Michael J. Cima**, Lexington; **Paul A. Williams**, Concord, all of Mass.

[73] Assignee: **Massachusetts Institute of Technology**, Cambridge, Mass.

[21] Appl. No.: **447,677**

[22] Filed: **Dec. 8, 1989**

[51] Int. Cl.[5] B22F 7/02; B29C 35/02; B29C 67/02; C04B 35/64

FOREIGN PATENT DOCUMENTS

226377 7/1973 Fed. Rep. of Germany .
WO90/03893 4/1990 World Int. Prop. O. .

OTHER PUBLICATIONS

Deckard, C. and Beaman, J., "Solid Freeform Fabrication and Selective Powder Sintering", NAMRAC Proceedings, Symposium #15, undated.
Kodama, H., "Automatic Method for Fabricating a Three-Dimensional Plastic Model with Photo-Hardening Polymer", Review of Scientific Instruments, vol. 52, No. 11, Nov. 1981.
Wohlers, Terry, "Creating Parts by the Layers", Cadence, Apr., 1989, pp. 73–76.

Abstract

A process for making a component by depositing a first layer of a fluent porous material, such as a powder, in a confined region and then depositing a binder material to selected regions of the layer of powder material to produce a layer of bonded powder material at the selected regions. Such steps are repeated a selected number of times to produce successive layers of selected regions of bonded powder material so as to form the desired component. The unbonded powder material is then removed. In some cases the component may be further processed as, for example, by heating it to further strengthen the bonding thereof.

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Home / Additive Manufacturing / Metal Additive Manufacturing / The year of the binder

3D Printer Hardware | 3D Printing Processes | Additive Manufacturing | Formnext 2022 | Metal Additive Manufacturing | Trends 2023

The year of the binder

HP 3D Printing, GE Additive, Desktop Metal/Exone, Markforged/Digital Metal, Ricoh (and others) are going all out in the exciting next phase of the metal AM market

Davide Sher · November 2, 2022 · 6 minutes read

Metal binder jetting technology, now also known by the acronym MBJ, is, at the same time, the first and the newest opportunity for binder-based metal AM processes.

Invented at MIT in 1993, the technology uses an inkjet printhead to apply binder to a bed of metal powder and form green parts which are similar to parts produced by metal injection molding (MIM). These parts then undergo a series of post-process (which differ for each specific technology), including sintering, to deliver final parts.

The **growing competition** in this segment, as the technology evolves to target larger batch production than metal PBF processes us clear. Desktop Metal and ExOne joined forces to compete against two large industrial groups that have already become leaders in different areas of production 3D printing: GE (GE Additive) and HP (HP 3D Printing).

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THE VOICE OF 3D PRINTING

What's the Deal with Metal Binder Jet 3D Printing?

December 8, 2022 • by Michael Block • 3D Printing • Editorials / Opinions • Metal 3D Printing • Post-processing • Quality Control

Size
Part quality
Materials
Speed
Ease-of-use
Supports

Deliveries of GE Additive metal binder jet Series 3 machine set to commence in 2023

GE Additive has announced that production deliveries of its metal binder jet Series 3 printer will commence in the second half of 2023.

19 OCT 2022 SAM DAVIES METAL ADDITIVE MANUFACTURING NEWS


GE Additive, GEADPR068

Desktop Metal receives $9 Million order from major German automaker for its binder jet systems

Desktop Metal has announced that the company has received a 9 million USD order from a major German automaker for its binder jet additive manufacturing systems that are used for mass production of powertrain components.

28 NOV 2022 OLIVER JOHNSON METAL ADDITIVE MANUFACTURING NEWS


Desktop Metal

METAL AM

HP launches modular Metal Jet S100 Solution for Binder Jetting

September 12, 2022

BINDER JETTING, THE AM TECHNOLOGY THAT CHANGED THE PRODUCTION DESIGN

Meeting Desktop Metal

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

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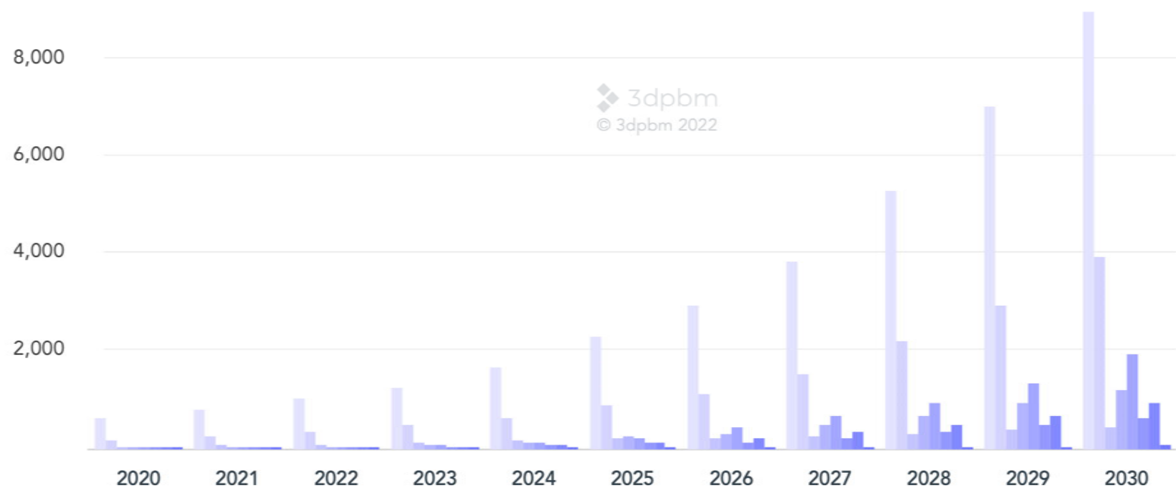
Davide Sher · November 2, 2022

In its first [Metal AM Market Report](), 3dpbm Research forecasted **overall metal AM hardware revenues to grow at 33.7% CAGR over the next 10-year period**, from just under $1 billion in yearly global sales in 2020 to just over $18 billion in yearly global sales by 2030.

10-year forecast of metal AM hardware revenues ($US M) by technology 2020-2030

Source: 3dpbm Research



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Total	996	1,381	1,758	2,234	2,994	4,280	5,585	7,516	10,450	13,911	18,176
L-PBF	640	846	1,036	1,268	1,681	2,315	2,951	3,823	5,264	6,980	8,900
L-DED	199	289	368	488	648	925	1,132	1,559	2,226	2,952	3,914
EBM	64	93	111	139	180	234	258	297	350	403	483
BMP	29	45	78	106	154	262	343	516	700	951	1,245
MBJ	25	42	72	99	143	251	453	676	975	1,356	1,955
WAAM	21	32	44	65	84	133	171	237	352	488	628
Cons.	12	27	41	57	86	138	248	372	521	703	950
EBAM	6	7	9	11	17	22	29	36	61	78	101

https://www.3dprintingmedia.network/the-year-of-the-binder/

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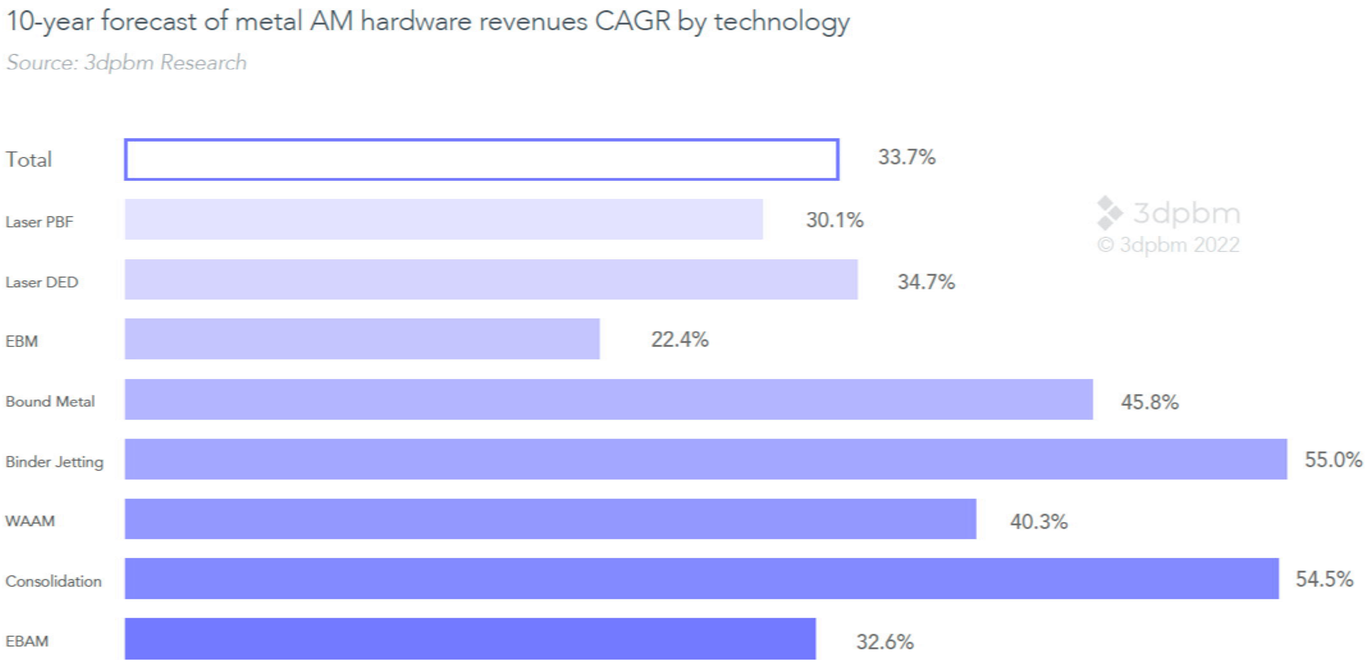
Davide Sher · November 2, 2022

«Binder jetting is expected to **grow at 55% CAGR**. This very high rate is down to a combination of binder jetting being only marginally commercially explored until now and its large adoption potential for the upcoming decade, supported by major investments.»



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Davide Sher · November 2, 2022

MBJ BENEFITS
•Higher productivity (up to tenfold compared to PBF)
•Several large operators entering the market with significant investments
•Does not require supports
•Potentially lower CapEx (compared to PBF)
•Produces net shape parts
•Very high-resolution potential

MBJ CHALLENGES
•Still unproven for large-scale production
•Requires lengthy sintering in a furnace as a post-process step
•Some MBJ processes require lengthy debonding
•Significant part shrinkage to account for
•Still mostly unproven for fully dense parts without additional infiltration steps
•Still limited selection of available materials (compared to PBF)
•Some processes require finer powders than PBF
•Challenging to produce large parts

https://www.3dprintingmedia.network/the-year-of-the-binder/

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Monday 12th Dec	link	9:30	10:00	Welcome & Introduction	prof B. M. Colosimo (POLIMI)
		10:00	12:30	MB Process steps	Dr P. Parenti (POLIMI)
		12:30	13:30	Lunch	
		13:30	14:30	MB Process steps	Dr P. Parenti (POLIMI)
		14.30	16.00	MBJ System - HW and SW	Dr P. Parenti / prof N.Lecis (POLIMI)
		16.00	17.30	MBJ Process Capability and Design	Dr M. Fernandez-Vicente (MTC)

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Time scheduling

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Tuesday 13th Dec	link	9:30	11:30	MBJ Feedstock and Characterization	Dr S. Hall (MTC)
		11:30	12:30	MBJ Process parameters	Dr P. Parenti (POLIMI)
		12:30	13:30	Lunch	
		13:30	15:30	MBJ Process parameters	prof N. Lecis (POLIMI)
		15.30	17.30	Sintering in MBJ (1)	Dr Y. Liu (MTC)

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Time scheduling

Thursday 15th Dec	link	9:30	11:00	Sintering in MBJ (2)	Prof D. Wimpenny (MTC)
		11:00	12:30	Post Processing	Dr. A. Kerwin / U. Attia (MTC)
		12:30	13:00	Lunch	
		13:00	16:00	Industrialization of MBJ	prof. B. M. Colosimo/P. Parenti (POLIMI)
		16.00	17.00	Recap	prof. B. M. Colosimo (POLIMI)

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Please do not forget to fill out our survey at the end

https://freeonlinesurveys.com/s/CU75

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SECTOR SKILLS STRATEGY
IN ADDITIVE MANUFACTURING

Metal Binder Jetting process

Overview on the Binder-Based technology and Introduction on the MBJ process steps

Date: 12nd Dec 2022

Lecturer: Paolo Parenti, PhD, POLITECNICO DI MILANO

paolo.paren

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Learning Outcomes

- Brief **overview** on all the **binder-based AM**
- Basic **understanding** of the Metal Binder Jetting process
- **Understanding** of the required **processing steps**

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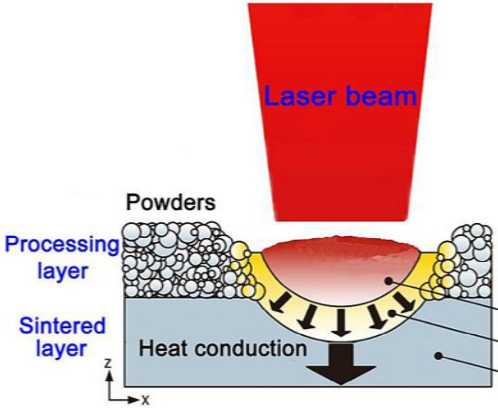
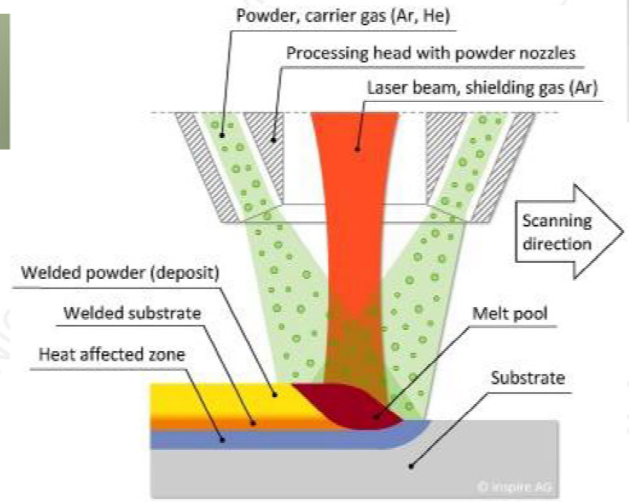


Additive Manufacturing Technologies

(Powder) Bed Systems	Nozzle Systems	Direct Energy Deposition (DED)	Liquid Resin Systems
Laser Powder Bed Fusion	Fused Deposition Modelling	Wire Feed Laser Beam Melting	Stereolithography
Electron Beam Powder Bed Fusion	Metal Droplet deposition	Laser Metal Deposition	Polyjet Process
Binder Jetting	Multi Jet Modelling		Continuos Liquid Interface Production
Multi Jet Fusion			



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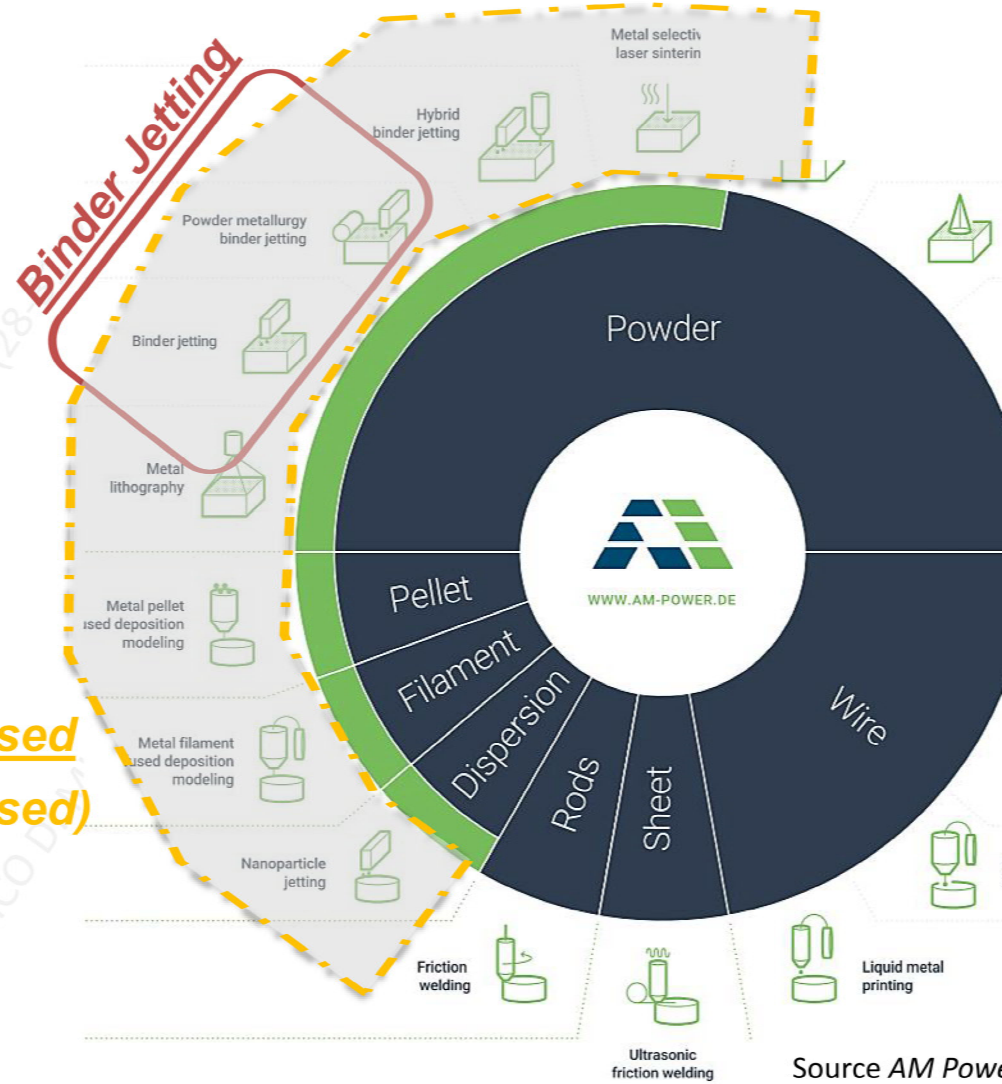
Among the many existing Metal AM processes on the market Binder-based AM (or sinter-based) for Metal and Ceramics are expanding considerably.



Source *AM Powe*

- Binder-Based AM techniques adopts the use of binder for **shaping** the powder parts at **"cold" conditions**

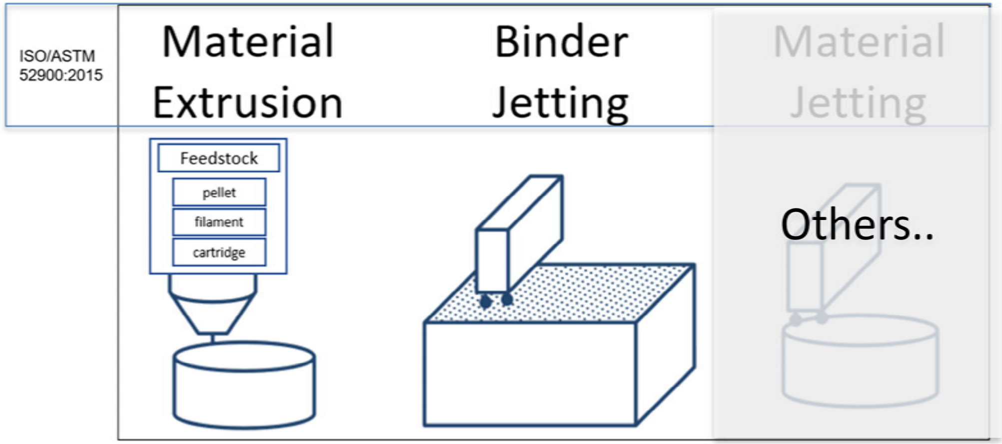
- **Thermal post-processing** and sintering can be run independently with better heat control, enhancing isotropic material properties with no residual stress and enabling the AM production of difficult-to-process materials

3D Printing

COLD

Part shaping

POWDER + BINDER

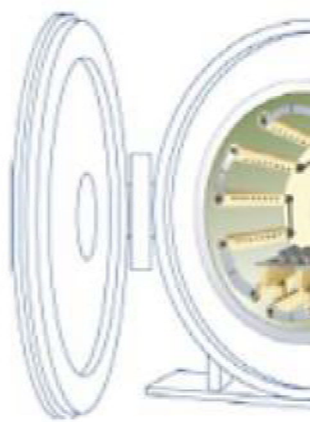


Adapted from AMPOWERINSIGHTS - Metal Additive Manufacturing with sinter-based technologies - Vol.3 - October 2018

HOT

Sinter

FURN



"Shaping and sintering phases are decoupled for better control of the sinterability p

"

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Theoretically, all the metal/ceramic materials can be processed by binder-based AM
“cold” deposition process and post-sintering.

→ Extended industrial material range:

- **Steel**
  Low-carbon, Stainless, Tool steel
- **Non-ferrous metals**
  Copper, Magnesium, Aluminum etc.
- **Ceramics & Carbides**
  Alumina, Zirconia, Tungsten Carbides, Silicon Nitrides, etc.

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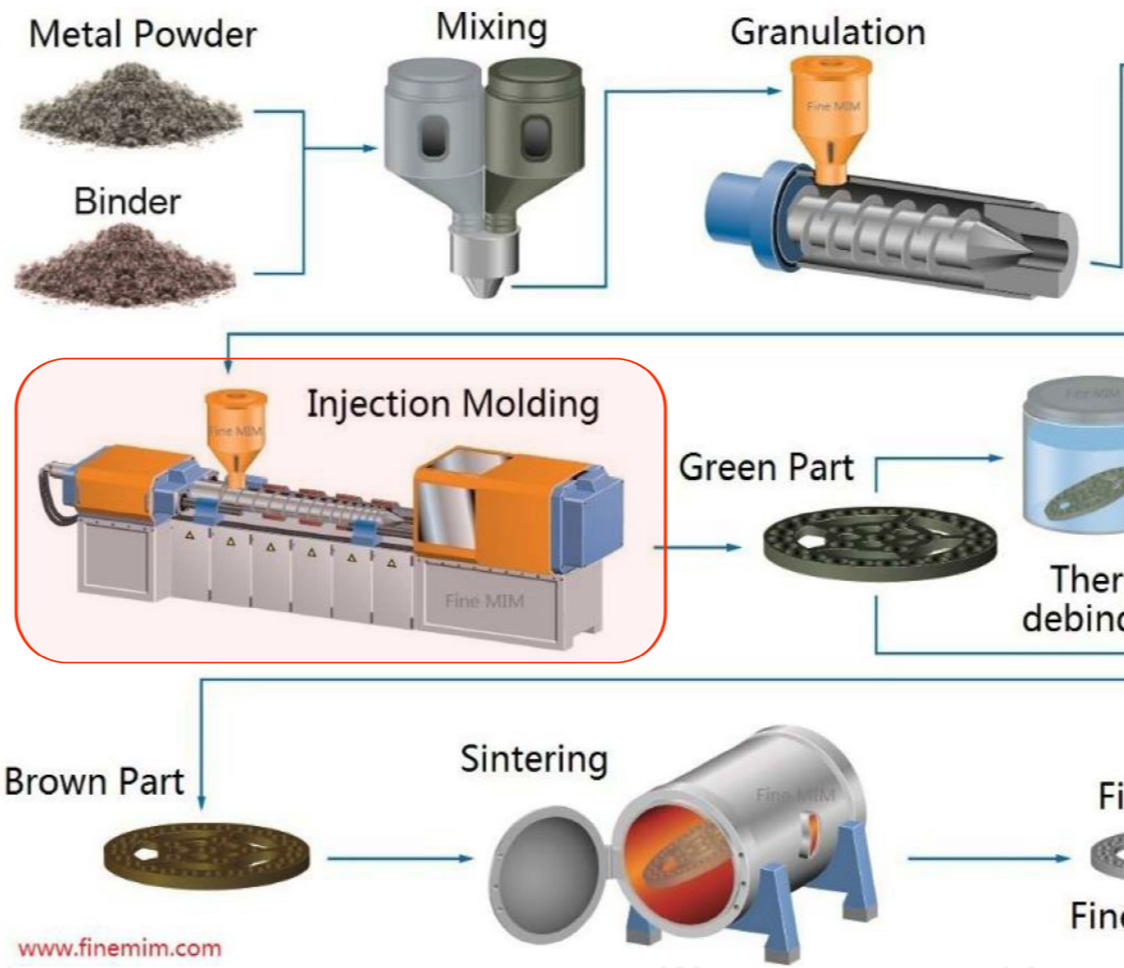
The week established ***Metal Injection Molding*** shapes feedstock trough a molding

Metal/Ceramic Injection Molding
MIM/CIM

- 1920s: ceramic injection molding processes (CIM)
- 1950s: metal injection molding (MIM)
- 1970s: sintering improvements, new binders, high density
- Small parts < 50 mm, Mass Production, Expensive molds
- Applications: medical instruments, jewellery, defense industry and electronic



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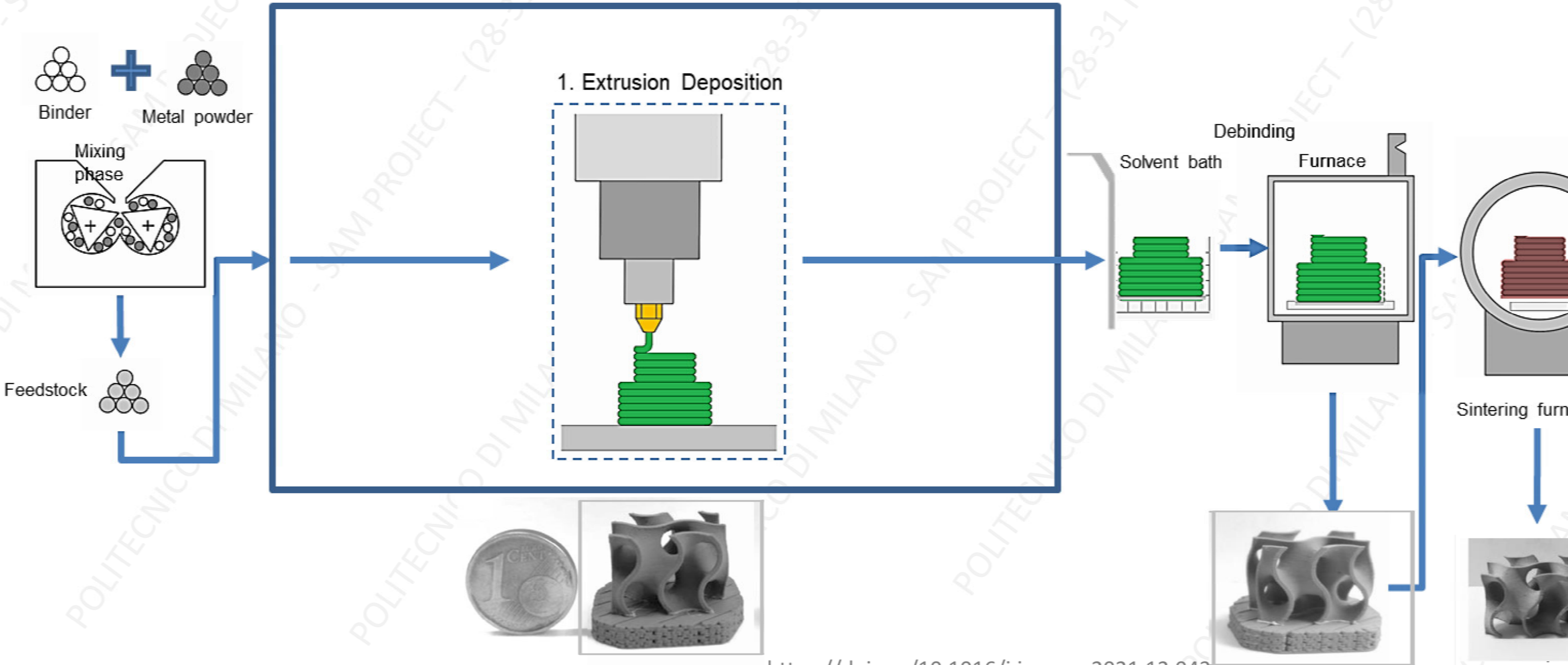
In **Metal FDM**, green parts are obtained by depositing highly-metal filled-polymers then requires debinding and sintering to achieve fully dense parts. In some cases additional printing head deposit dissimilar supports material.



https://doi.org/10.1016/j.jmapro.2021.12.043

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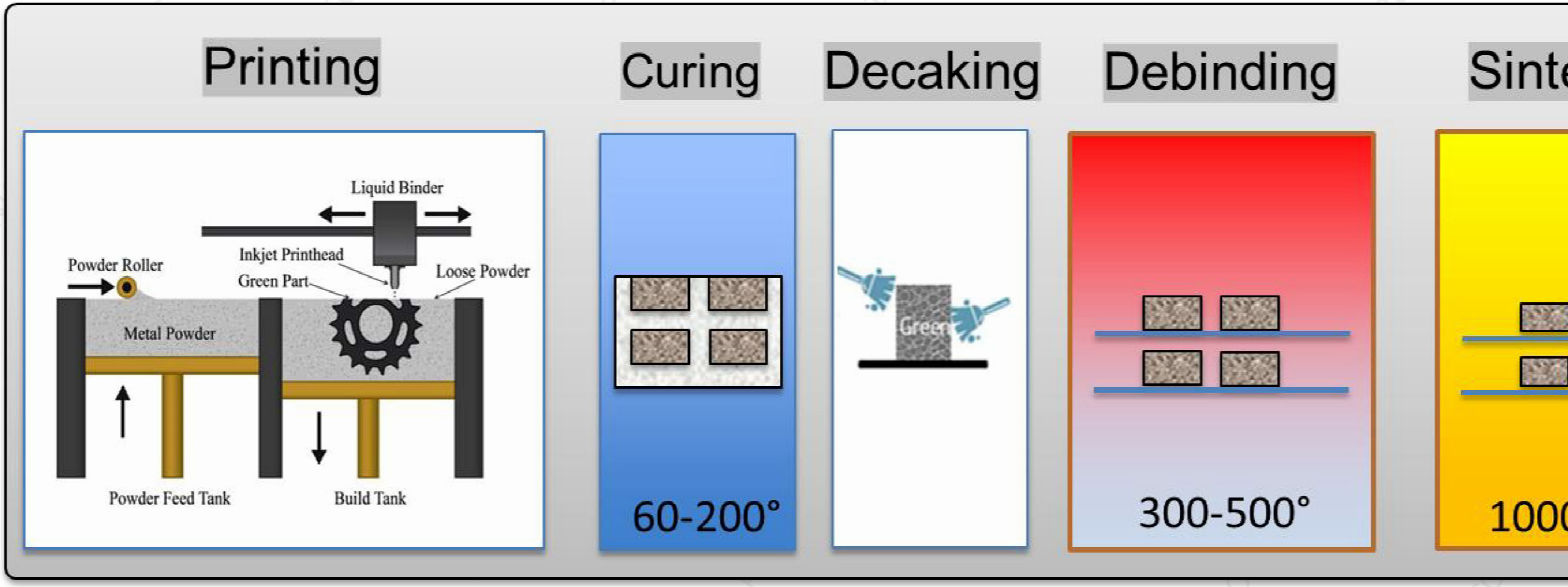
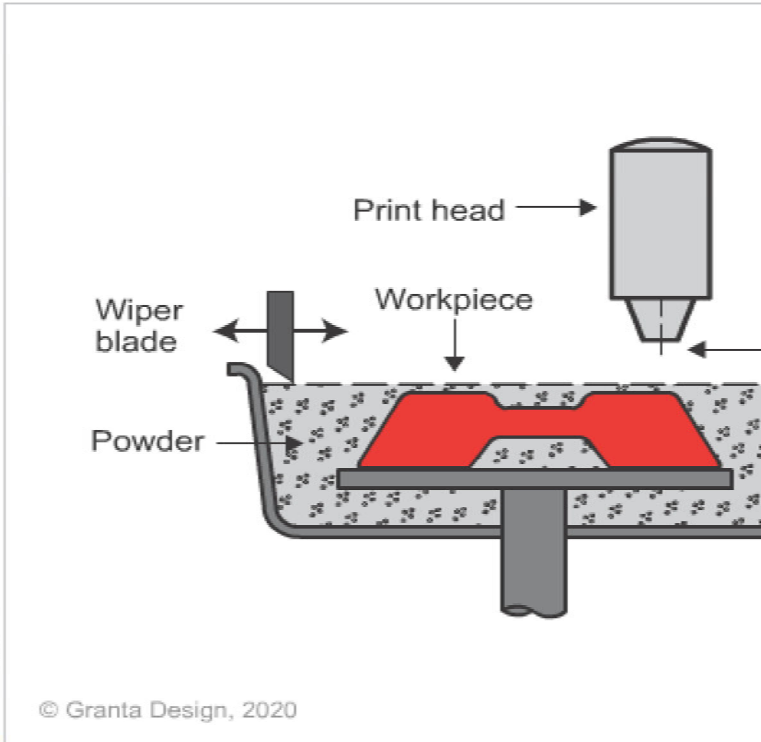
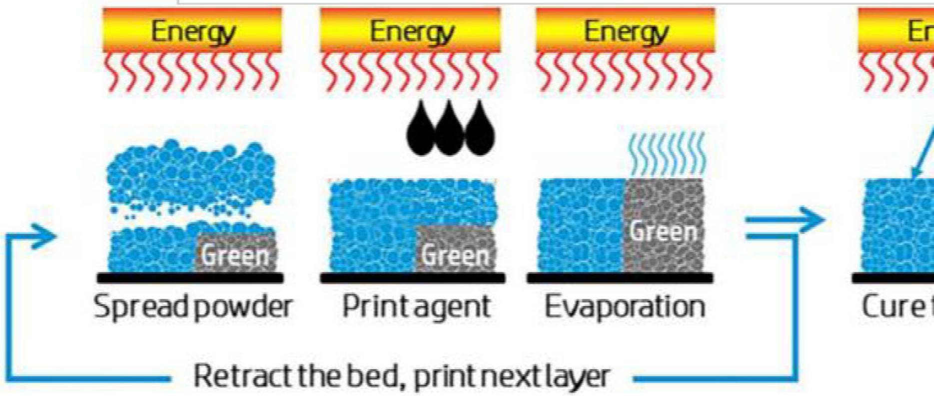
Binder Jetting

In the ***Binder Jetting*** a liquid binder is ejected by a printhead to selectively bind part
in a powder-bed. Green Parts are obtained layer-by-layer and then are cured, therma
debound and sintered to achieve full density.



1. **<u>Powder</u>** material is **<u>spread</u>** over the build platform using a roller.
2. The print head selectively **<u>deposits the binder</u>** liquid on top of the powder. The object is formed where the powder is bound to the liquid.
3. The **<u>heating lamp dries</u>** the layer evaporating volatile binder components (bed curing).
4. The build **<u>platform is lowered</u>** by the model's layer thickness.
5. **<u>Another layer</u>** of powder is spread over the previous layer. Unbound powder remains in position surrounding the object.
6. The **<u>process is repeated</u>** until the entire object has been made.





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Co
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of

Advantages

- Faster than LB-PBF systems;
- 20% less costs than LB-PBF systems;
- No support needed;
- Good resolution ~35µm;
- Achievable part Complexity;
- Powder recycling;
- Wide material range
- Residual stresses.

Disadvantages

- Build box size approx. 400 x 300
- Post- processing steps
  - debinding /sintering;
- Sintering process difficult to contr
- Density (max 98-99%)
- Still relatively new;

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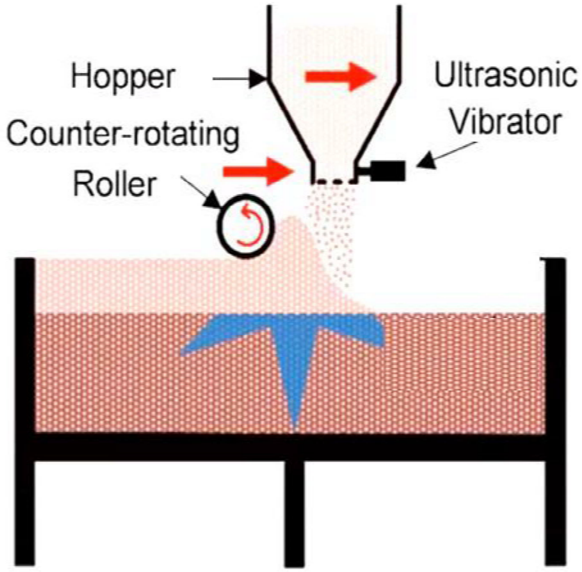
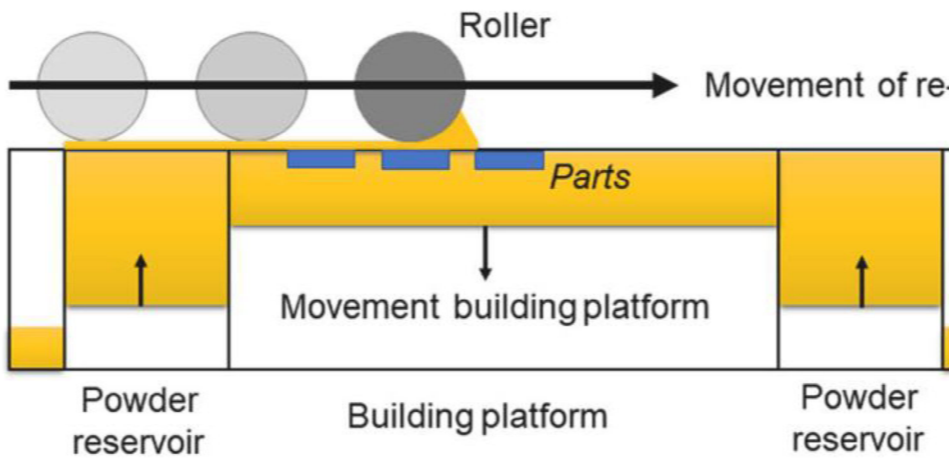
Two main types of powder dispensing systems

Moving hopper



Fixed Powder reservoir



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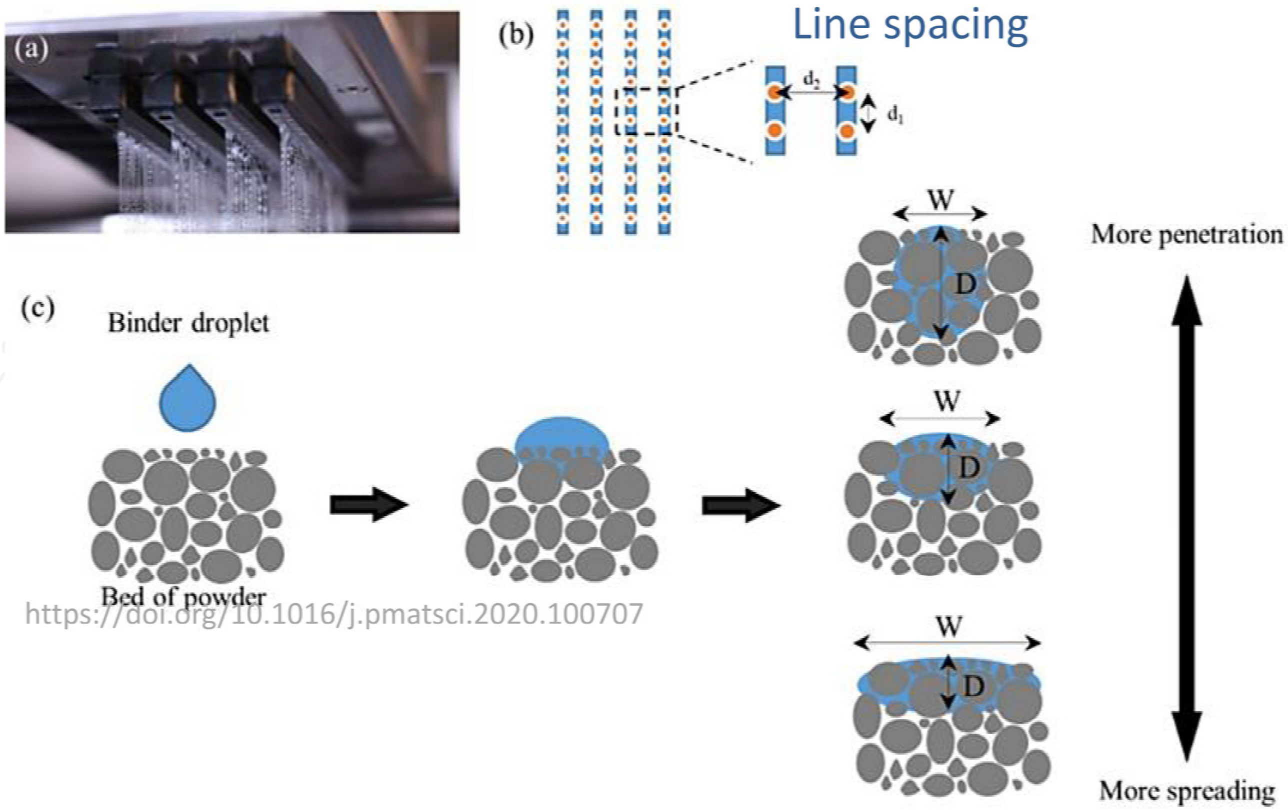
- A liquid binder (such as polymer in solvent or aqueous solution) is jetted from the p
head (or printing bar) onto each powder layer where the object is to be formed.



https://doi.org/10.1016/j.pmatsci.2020.100707

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The **Binder composition** should give enough cohesive force to brown part to guarantee shape and safe green part handling

Binder features (the most significant)

- Density and Molecular Weight
- Dynamic Viscosity
- Surface Tension

Binder Types

- Water-Based (Aqueous)
- Solvent-Based
- Resin-Based (Phenolic)

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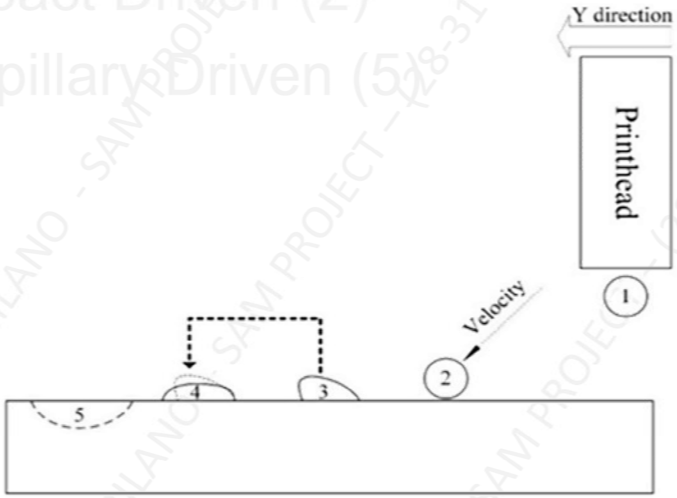
Drop dynamics on impact is divided in two phases

- Impact Driven (2)
- Capillary Driven (5)



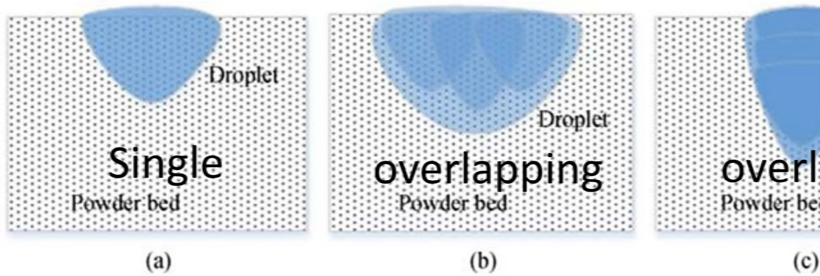
https://doi.org/10.1016/j.addma.2017.12.008

- The landing position of the droplets depends on print head speed,drop-to-drop distance and line spacing

Binder Saturation Level (BSL) c
printing stability: Green part stre

BSL can be controlled by

- Overlapping droplets
- Overlaying droplets



https://doi.org/10.1007/s1

Fig. 4 Saturation level control methods. (a) Single droplet; (b) overlapping droplet; (c)

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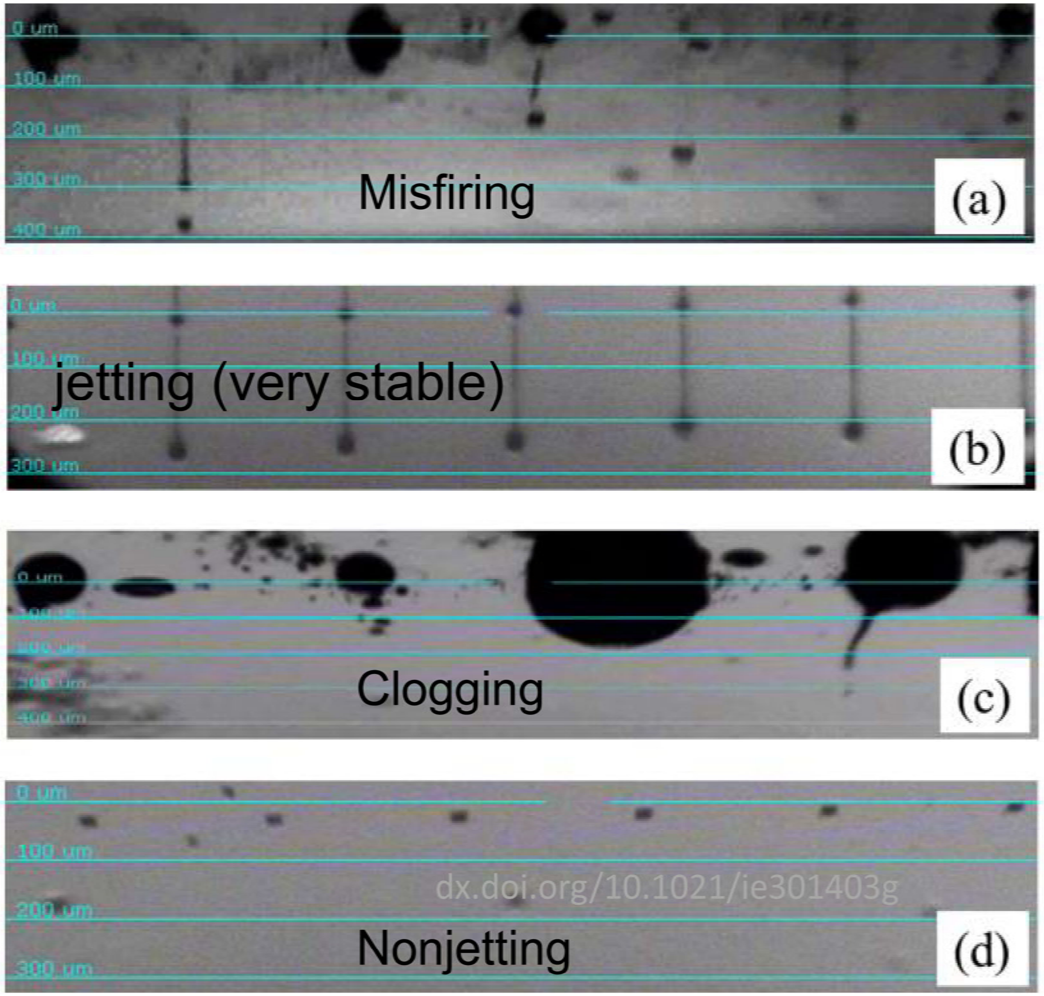
Nozzle Clogging

- Due to the fine size of the nozzles, malfunctioning can happen due to trapped air, dried ink, wear, etc..



Typical jetting behaviors: (a) misfiring, (b) stable drop-jetting, (c) nozzle clogging, and (d) nonjetting.

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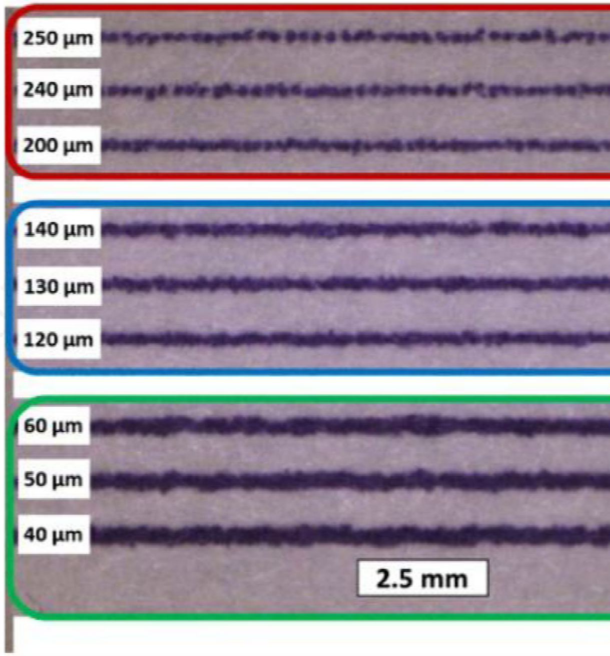
- Before and after printing it is suggested run a testing print on a sheet of coloured paper placed on top of the print platform.
- This engages all print nozzles to fire in a specific pattern as the nozzles cross the paper. The printed pattern allows for the quantification of all nozzle’s operational status
- Any jets that are not functioning can then be identified using the printer software and subsequently disengaged.
- Moreover, the printed sheet can serve for build Job certification purposes

DOI/10.1007/s00170-021-0712



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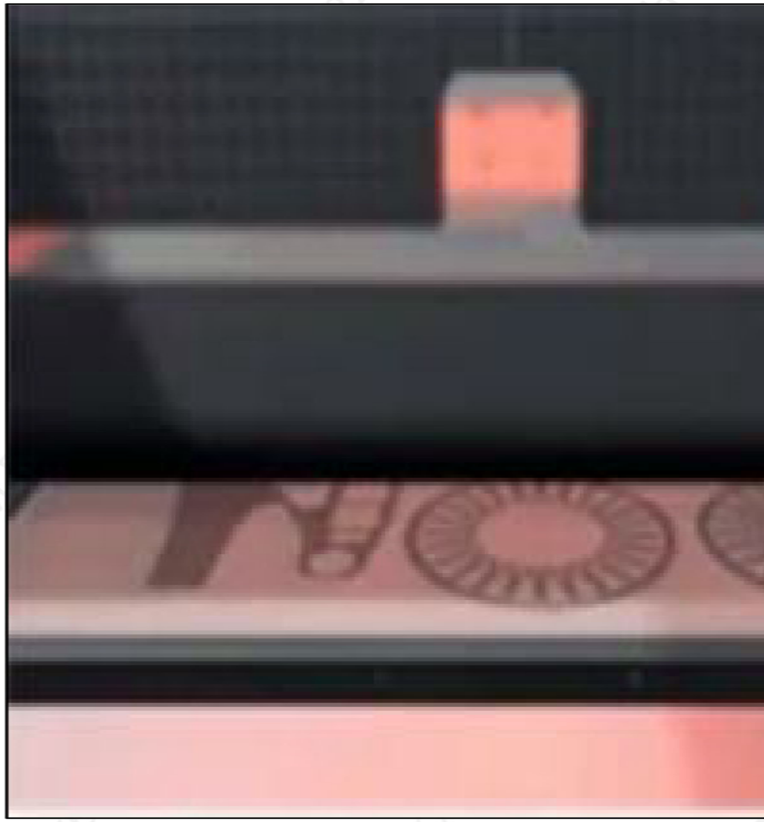
Drying

After the binder is deposited, most of the solvent contained in the binder is evaporated by air-drying or with the help of controlled bed temperature and electrical/Infrared heater that passes over the bed.

In some cases, partial or total binder cure can take place in this phase.

It is an important step, related with binder composition and saturation, that help pursuing correct part shaping with good quality, avoiding cracking of the bed or agglomeration/sticking of the powder on the roller



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Curing is a process that harden the binder increasing the strength of the bound pow
compact.

- Binder strength is enhanced inducing binder polymerization and the formation of the molecular crosslink network of bonds in the polymeric chain. No effects on the metal powder.

- It can be generated spontaneously by chemical reactions inside the binde components (resin and catalyst) or be triggered by an external source of energ such as heat (e.g. coming from infrared lamps or a furnace), pressure or suitabl radiation (such as UV light).

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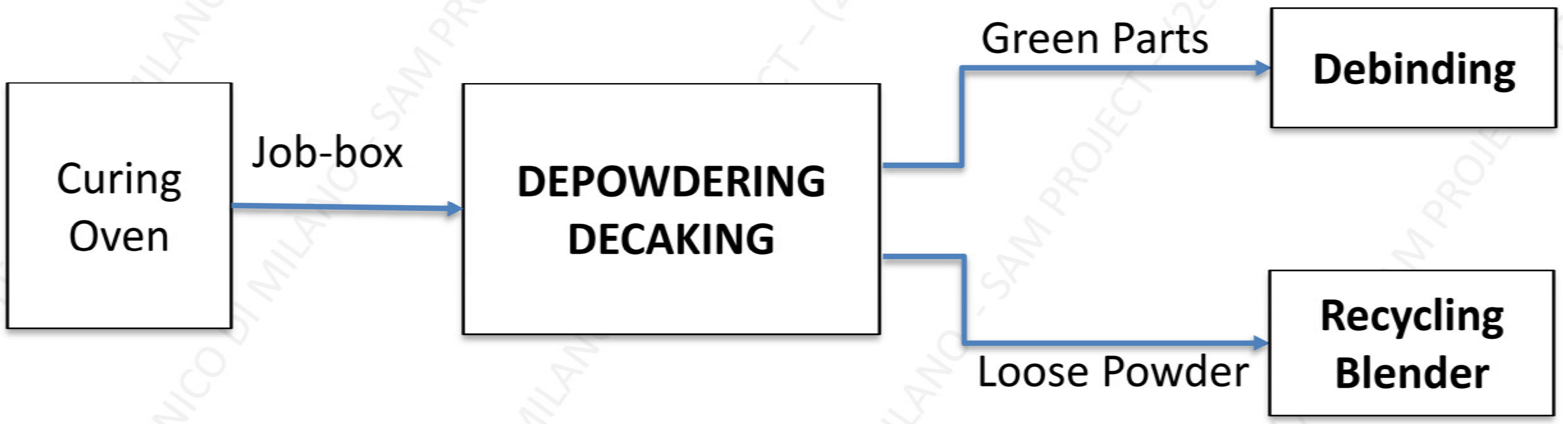
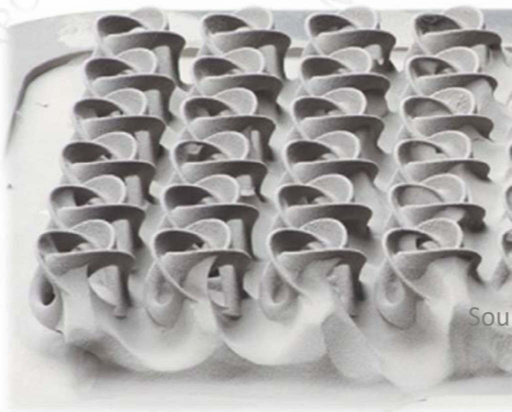
- In the depowdering the 3d **<u>printed and cured</u>** components are removed from the powder bed.
- All the excess of unbounded powder is removed and reused.





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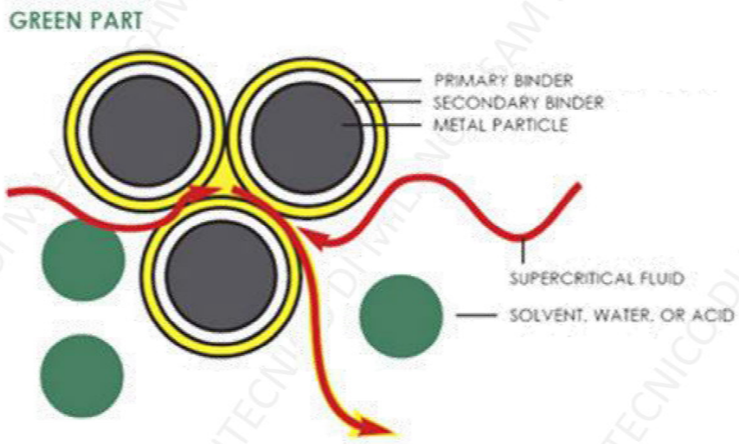
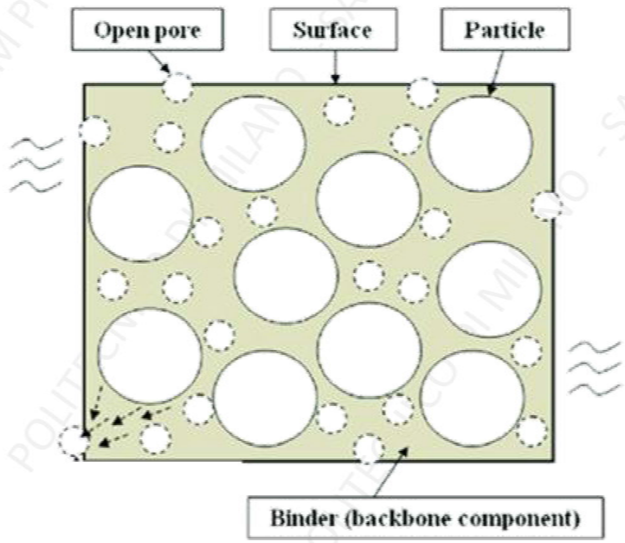
- Binder removal step is applied on the green part after the depowdering and prior t

- A controlled and "well-done" binder removal is necessary to avoid
  - Reduced Sinterability due to uncontrolled binder burnout (vapor formations / inhomogeneous particles bonding)
  - Chemical contamination of the sintered part (e.g., carbon in organic binders, c reduction).

Solvent debinding

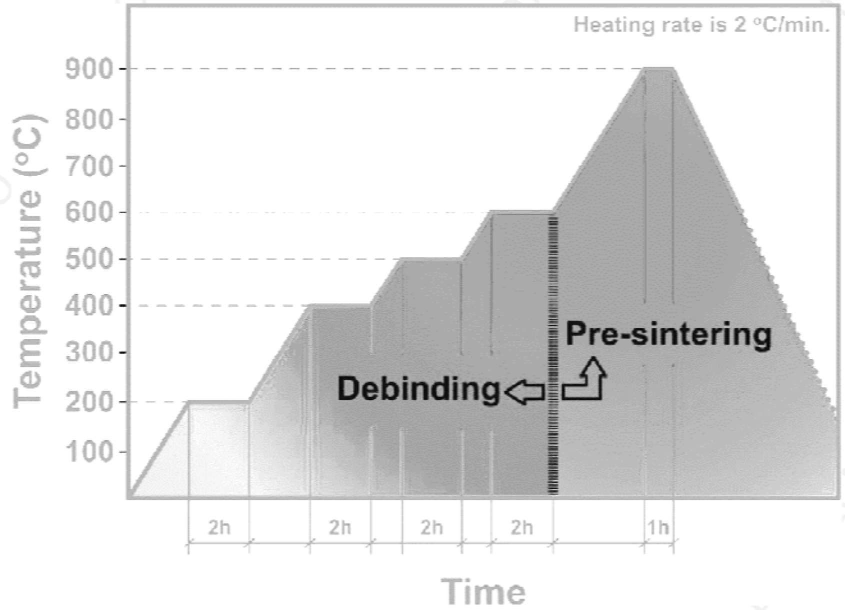




Therm

<u>Thermal debinding</u> generate binder removal by pyrolisis

- The <u>thermal decomposition</u> of the binder i.e., fracture of its molecular bonds, is affected by i) thermodynamics (what temperature, pressure), ii) kinetics (how fast)



Metal Binder Jetti
"green"
(Depowdered)

Thermal debinding
+
Sintering

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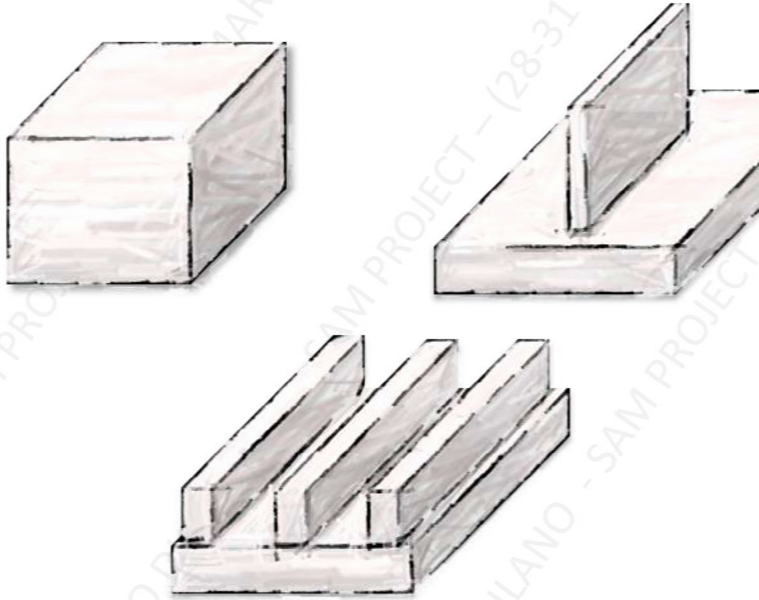
Factors that affect debindability:

Geometry of the parts

- ➢ thin sections are most desirable:



Pore structure

- ➢ Powder Particle
- ➢ solids loadings / packing density.

Processing cycle

- Heating Rates
- Atmosphere / Pressure

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Infiltration is a process where a part is heated so that its binders bake out and a low-melting-temperature metal like bronze is sucked up into the negative space via capillary action, creating a dense and strong composite.

Neither sintered nor infiltrated parts from a binder jetting printer are as strong as those from L-PBF type printers, but their surface roughness can be much lower, leading to more aesthetically pleasing finishes.

source: Xometry / Exone

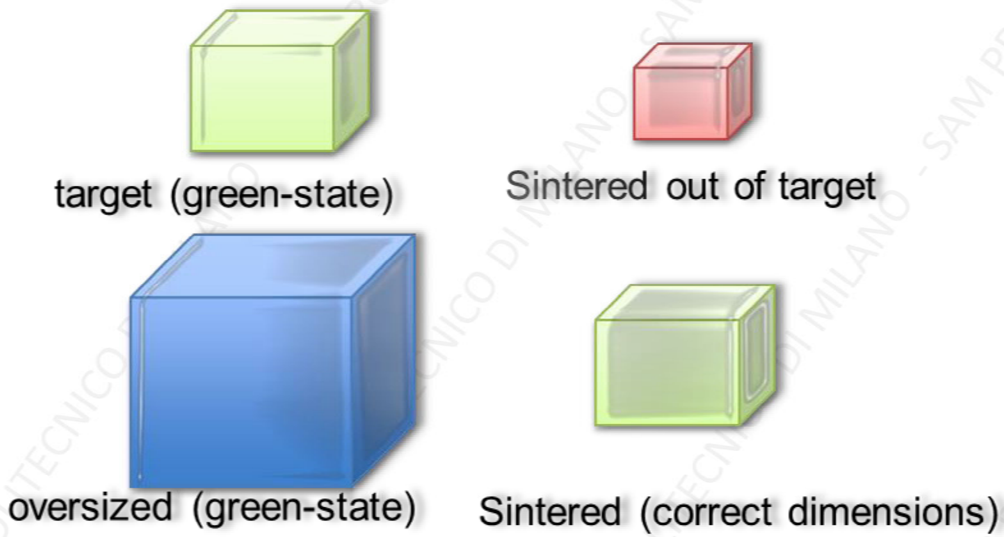
Sintering shrinkage is a direct effect of density increase (cannot be avoided!)

If the shrinkage is isotropic, the relative density ρ (at any time or temperature) can determined from the linear shrinkage*

$$\rho = \frac{\rho_0}{(1 - \Delta L/L_0)^3}$$

ρ_0 is the initial relative density, and $\Delta L/L_0$ is the magnitude of the linear shrinkage

Sintering shrinkage It is compensated via static Oversizing



*which is not equal to the volumetric shrinkage

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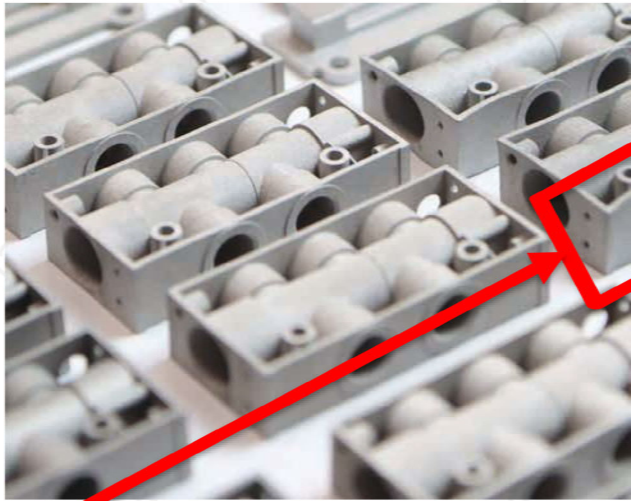
Shrinkage

- Sintering shrinkage compensation via oversizing limits the achievable dimension
accuracy (0.1-0.2 mm).



Sour

- High Aspect ratio parts can distort during furnace
- Thick-thin-Thich cross sections shoud be mitigated to avoid cracking!

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- Supports for Printing are usually not required with Metal Binder Jetting since loose is compact and can support the bound pars in the bed)

- To prevent distortions, parts are however suggested to have at least one flat surface to lie on.
  - if a chosen geometry does not allow such support, a matching sintering support may be needed.
  - The support must be in “green state” since it has to shrink with the part
  - Can be printed separately and coated with antiadhesive spray before the sintering.

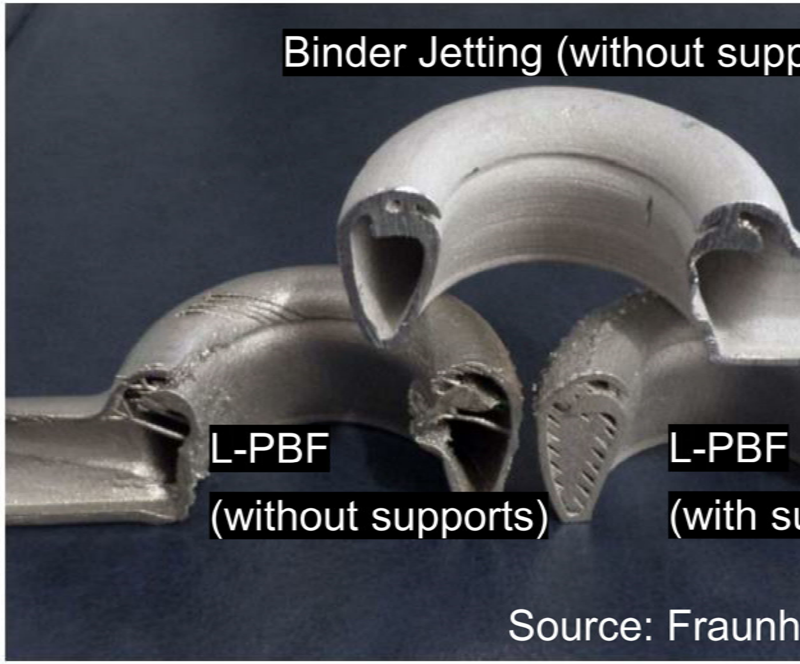

Fig. 1 Sections of circular nozzles, upper part by Binder Jetting without support struc LB-PBF with varying amounts of internal support structures

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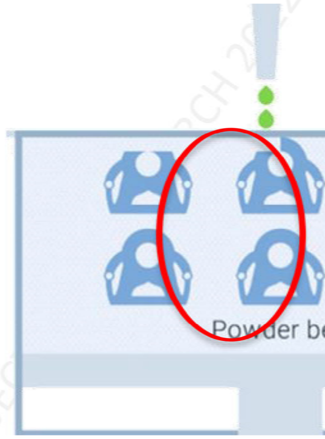
Batch Production (Printing Nesting)

- Additional <u>supports are not required</u> in printing
- No heat affected zone: parts can be placed close other (1 mm)



High Volume Part Nesting

(up to “different” 1000+ parts per printing batch)

↓ Productivity boost ↑ Layer-time is not affected by packing density* so that more packing reduce printing time per part

↓ Cost reduction ↑ Less printing time and less amount of powder to recycle

* True for high productive systems with full width printing bar

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IN ADDITIVE MANUFACTURING

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Thank you

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paolo.paren

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Metal Binder Jetting process

Hardware and Software

Date: 12nd March 2022

Lecturer: Paolo Parenti, PhD, POLITECNICO DI MILANO

paolo.parenti@polimi.it

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Learning Outcomes

- Basic understanding of the system hardware in Metal Binder Jetting process
- Understanding of the required system features
- Fundamentals of software for Sintering simulation

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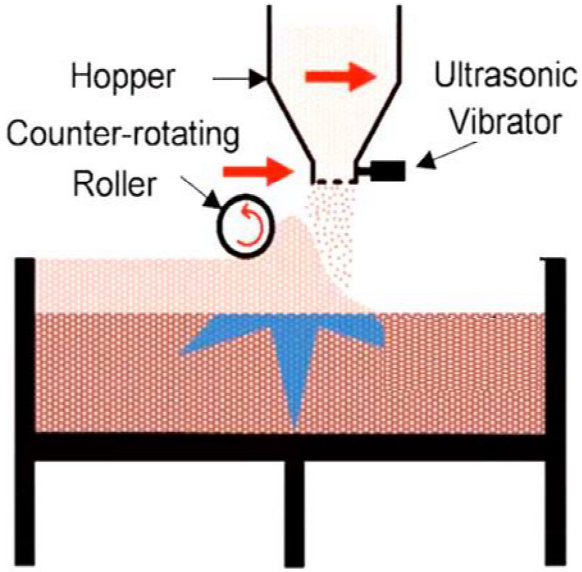
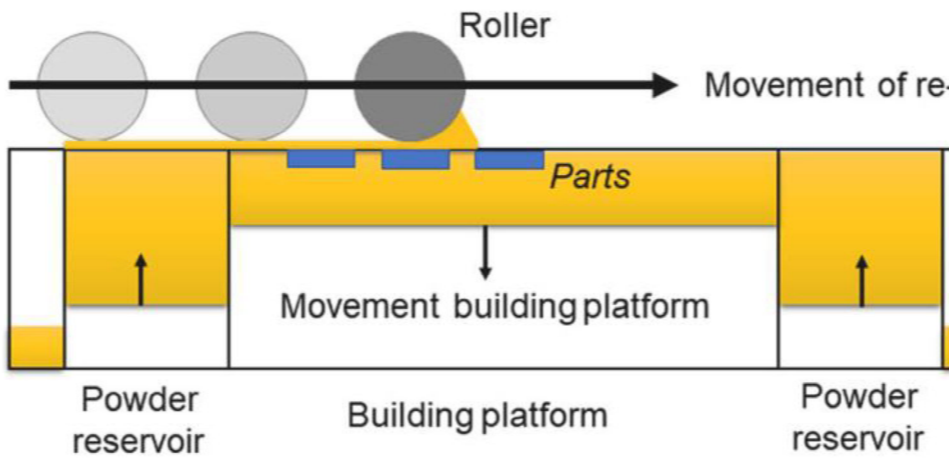
Two main types of powder dispensing systems

Moving hopper



Fixed Powder reservoir



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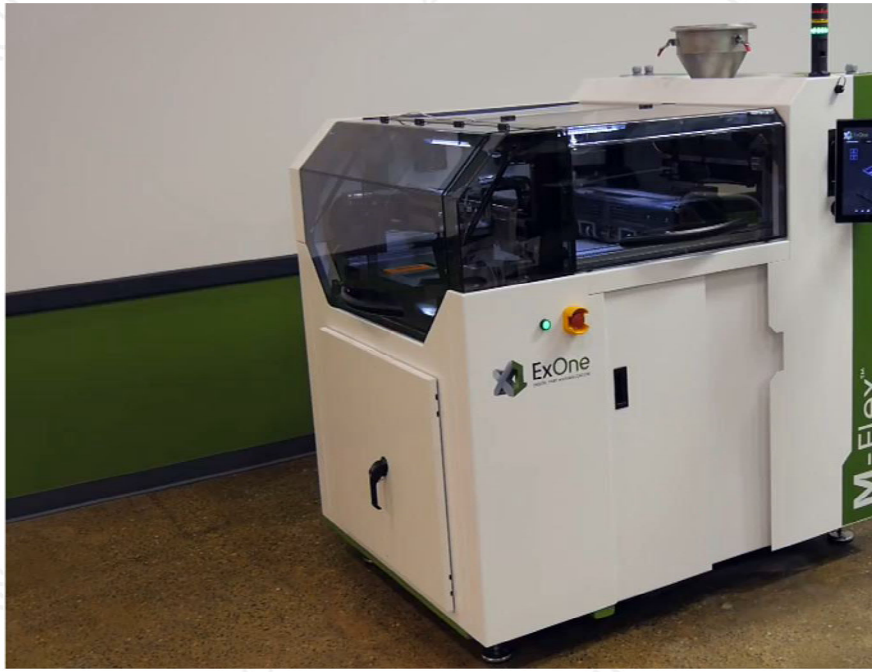
Digital Metal



Ex-One

"Printer Only" solutions

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Desktop Metal
“Integrated System” solution

Desktop Metal
“High Throughput” printer

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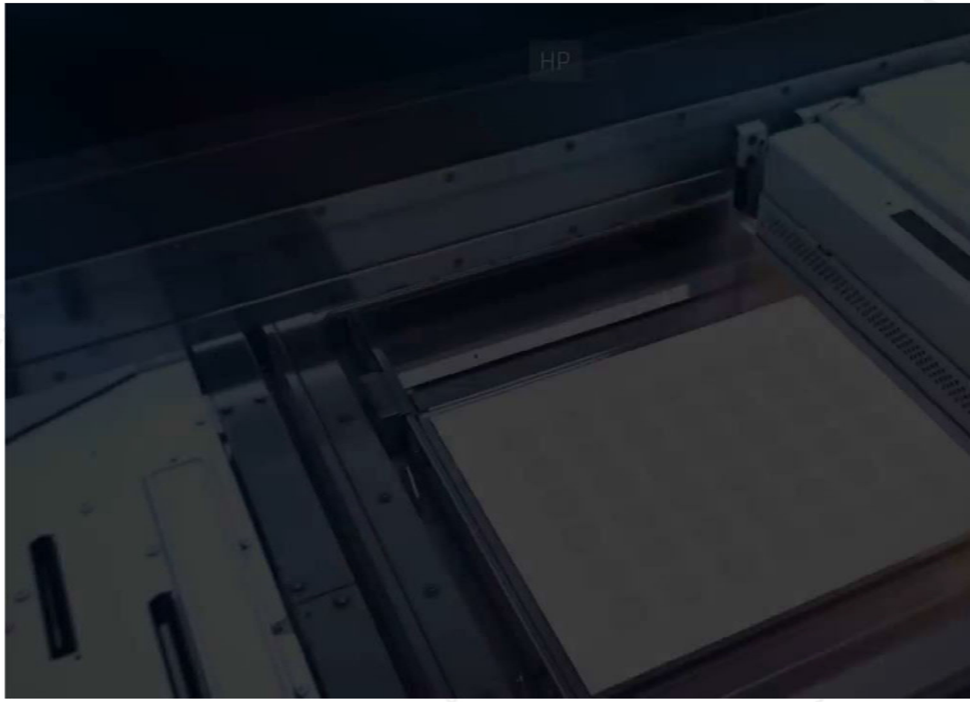
GE



HP

“Printer Only” solutions

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ExOne - X1 160Pro (August 2021)

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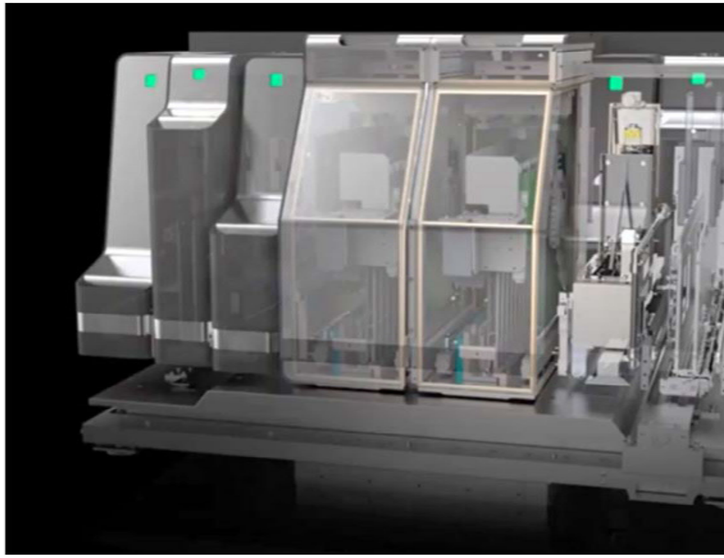
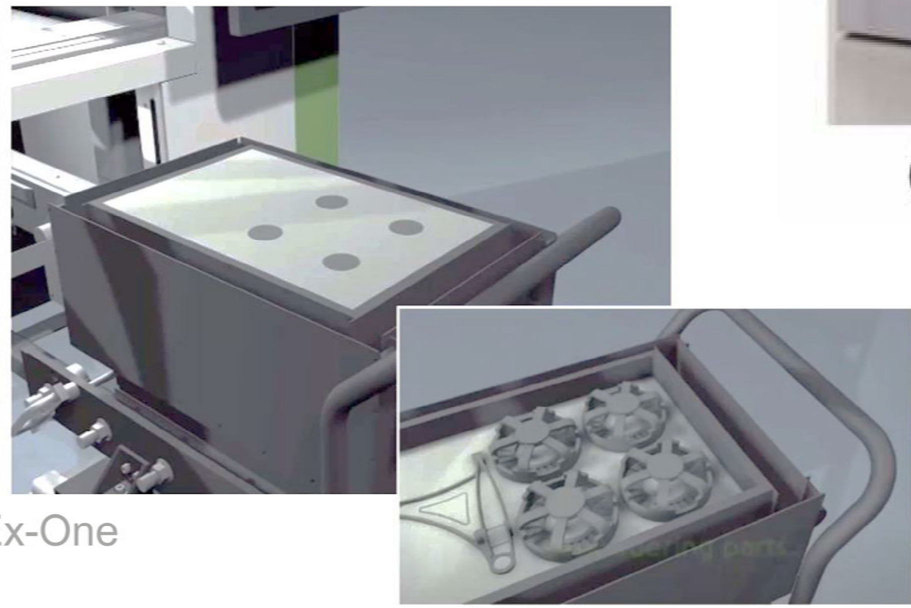
Desktop Metal Production System : Source INDO-MIM (June 2020)



Source : Desktop Metal Javelin techno

- Low Temperature Oven
- Size according to Job-Box
- Inert Atmosphere usually not adopted



Ex-One

Crosslink C

Deskt

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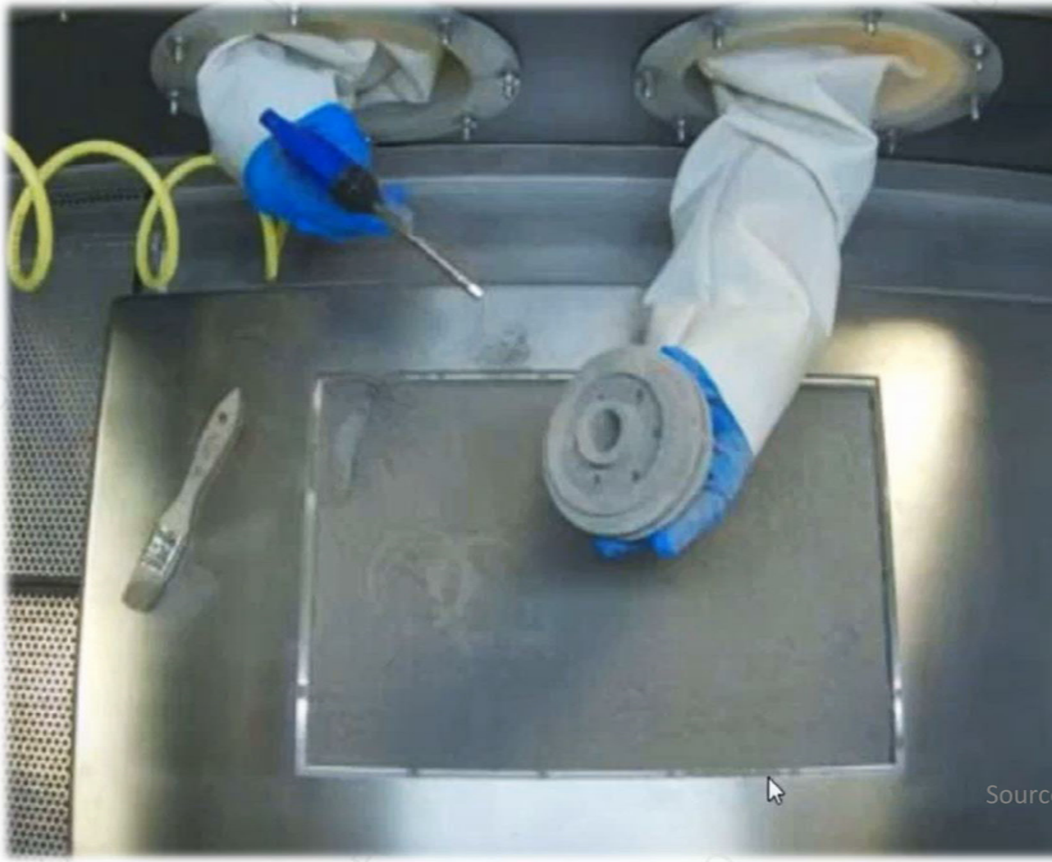
Depowdering / Decaking

- **Depowdering tools**
  - ✓ Brushes
  - ✓ Compressed air
  - ✓ Water Jets
  - ✓ Vacuum
  - ✓ Vibration
  - ✓ Cyclone
  - ✓ Wet methods (e.g. ultrasonic) if the binder is not soluble in the fluid



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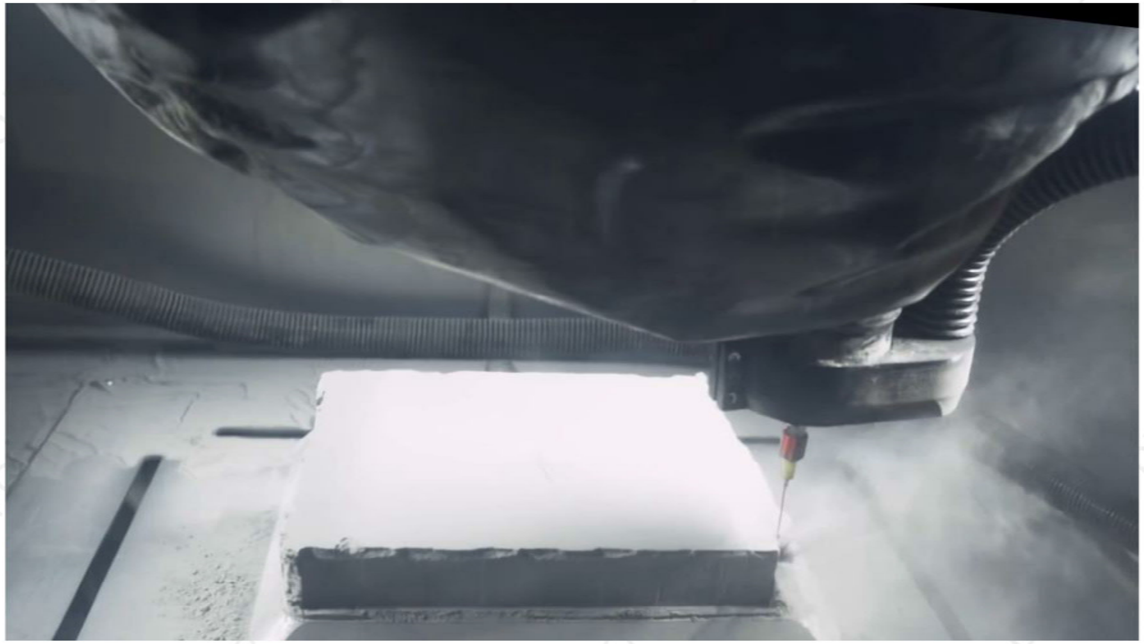
Semi and fully automatic machines allow to reduce time and labour work for depowd

- An automated depowdering nozzle removes the loose powder with compressed air starting from CAD planned toolpath



Digital Metal

https://digitalmetal.tech/digital-metal-first-depowdering-metal-binder-jetting/

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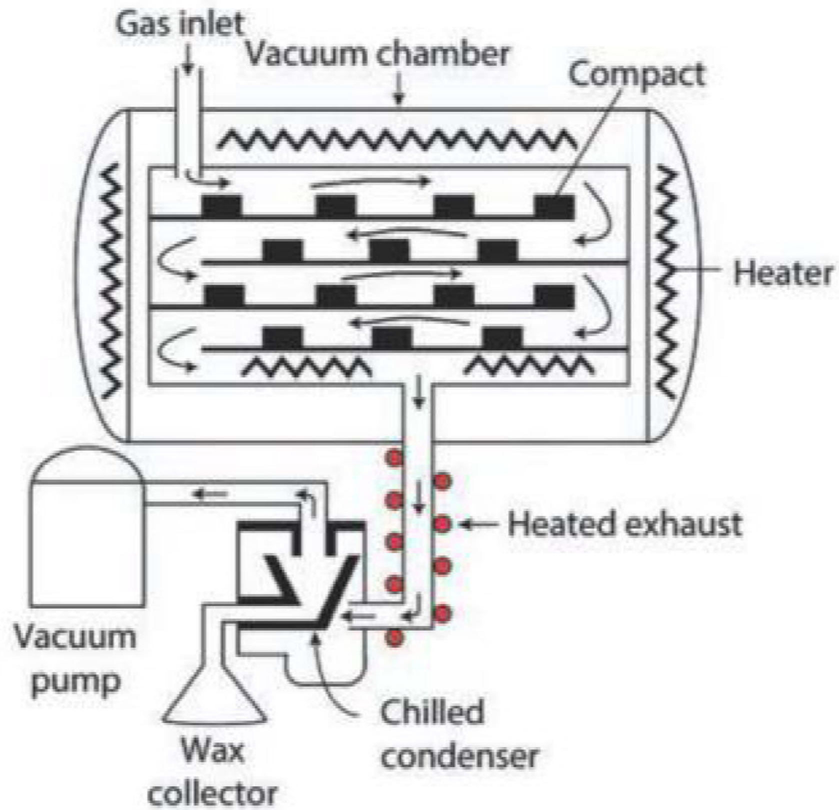
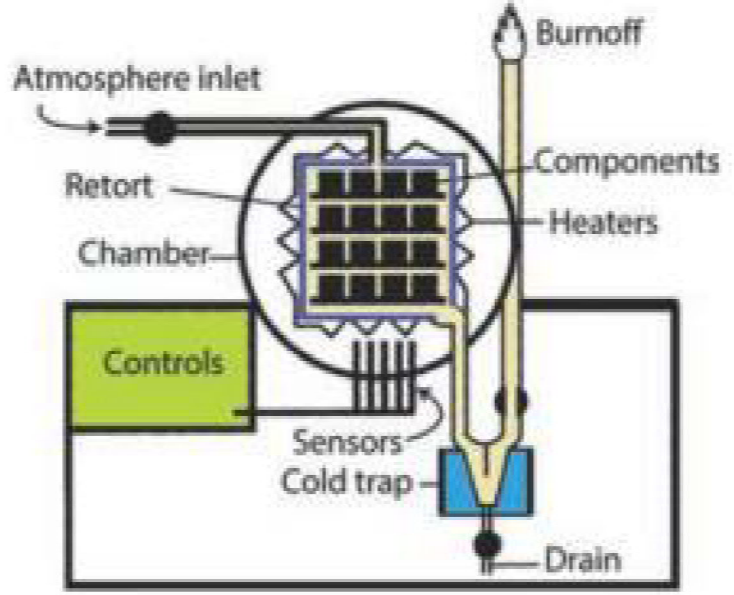


Vacuum Binder Removal



Binder Removal furnace (with post-con

https://doi.org/10.31399/asm.tb.bpapp.9781627083195

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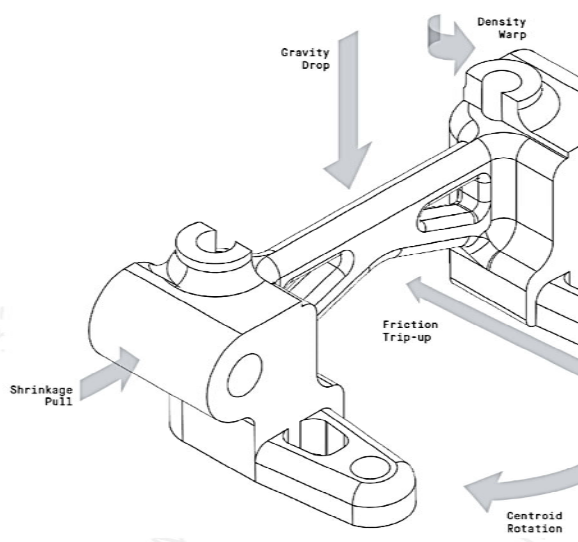
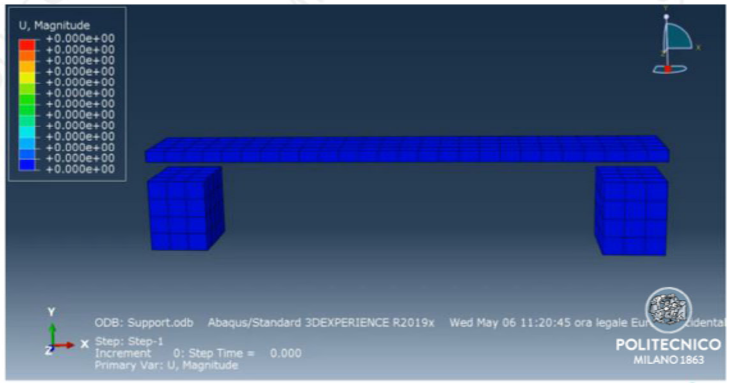
<u>Forces</u> experienced during Sintering:

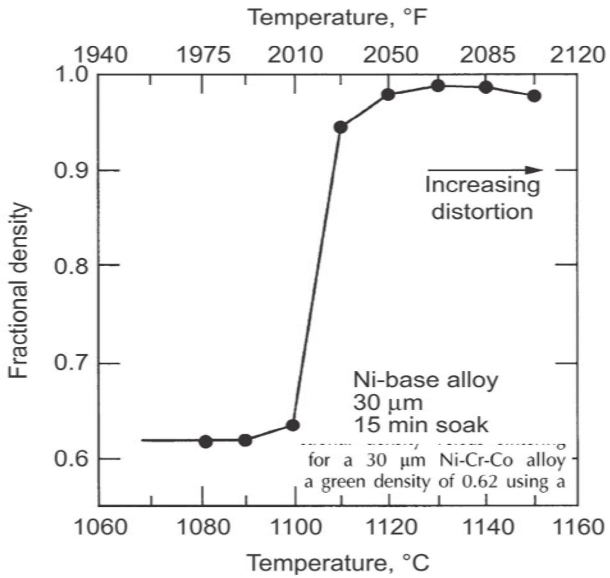
- **Gravity Drop:** Elastic and plastic motion downwards
- **Shrinkage Pull:** Multi-directional contraction
- **Friction Trip Up:** Stationary regions getting stuck against setters
- **Centroid Rotation:** Uneven weight distribution bending
- **Density Warp:** Varying shrinkage due to powder packing variations

Source : Deskt

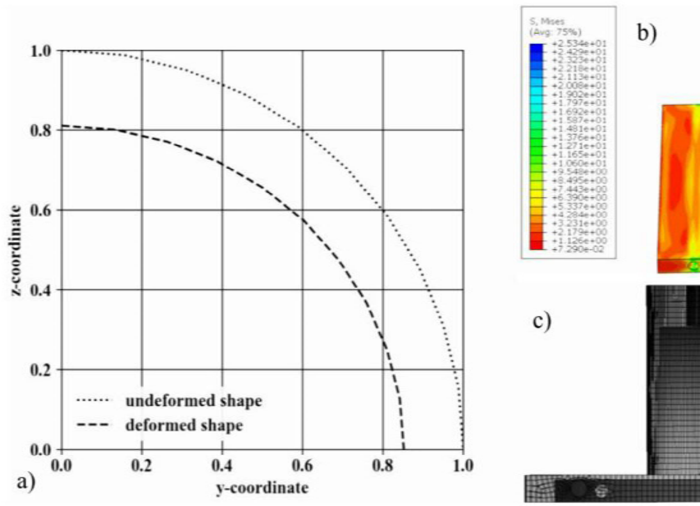




FEM densification simulation



DOI: 10.31399/asm.hb.v07.a0006117



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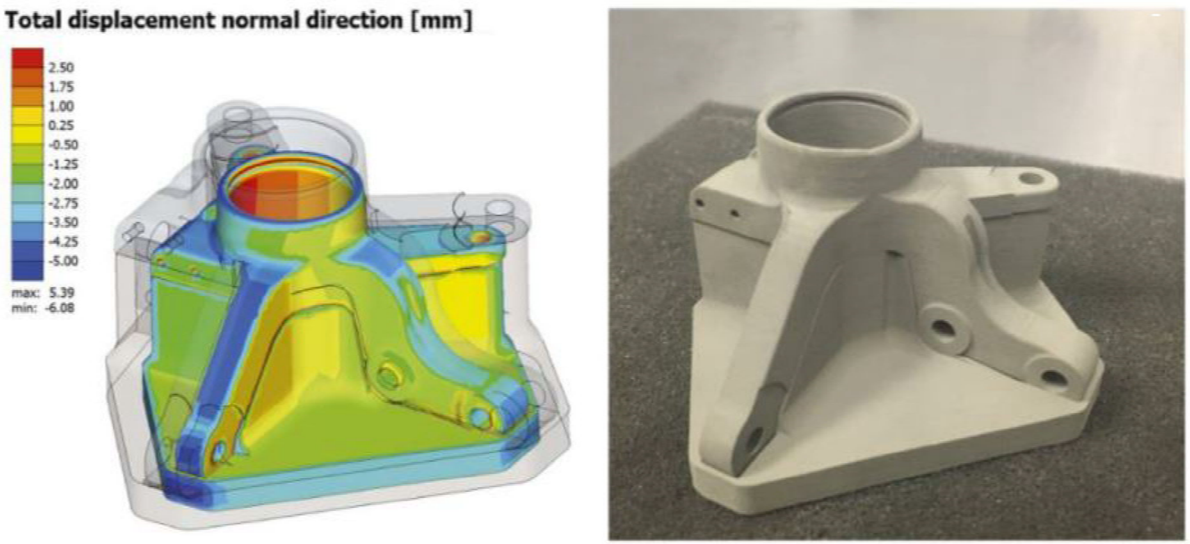

: 6 *Simulated deformation and actual sintered nominal steering knuckle geometry with live setter*

https://www.metal-am.com/articles/simufact-additive-accelerating-the-metal-binder-jetting-workflow-with-sintering-simulation/

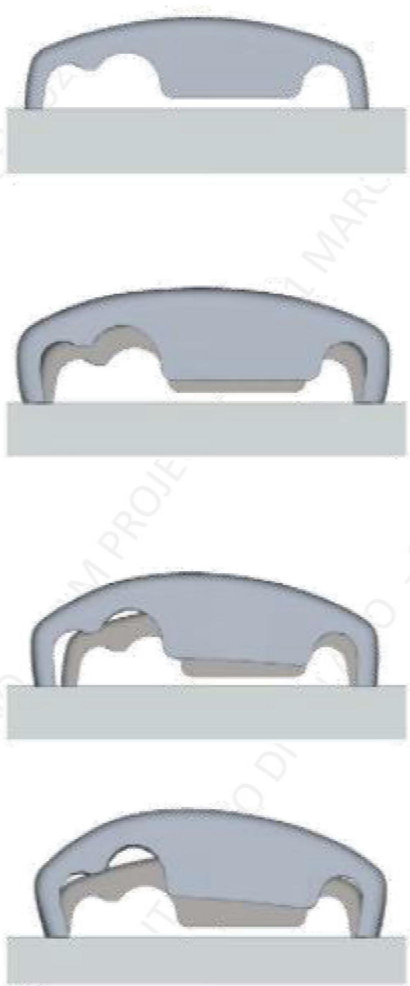

Fig. 3 Top to bottom: nominal geometry, first, fourth, sixth (final) compensation

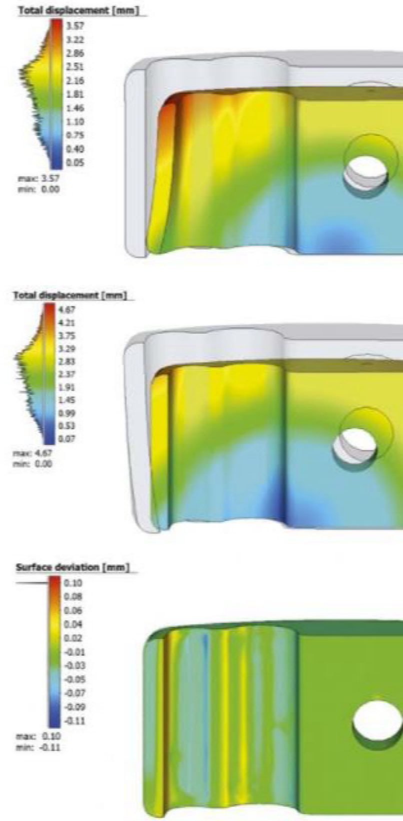

Fig. 2 Top: Distortion of nominal geometry, middle: Distortion of c
between compensated and nominal

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Thank you!

SECTOR SKILLS STRATEGY
IN ADDITIVE MANUFACTURING

Co-fu
Erasm
of the

Metal Binder Jetting process

Process Parameters

Date: 13rd Dec 2022

Lecturer: Paolo Parenti, PhD, POLITECNICO DI MILANO

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Learning Outcomes

- **Overview** on the printing parameters in MBJ
- Basic **understanding** of the interaction between them
- Basic **understanding** their influence on printing quality
- Basic **understanding** their influence on productivity

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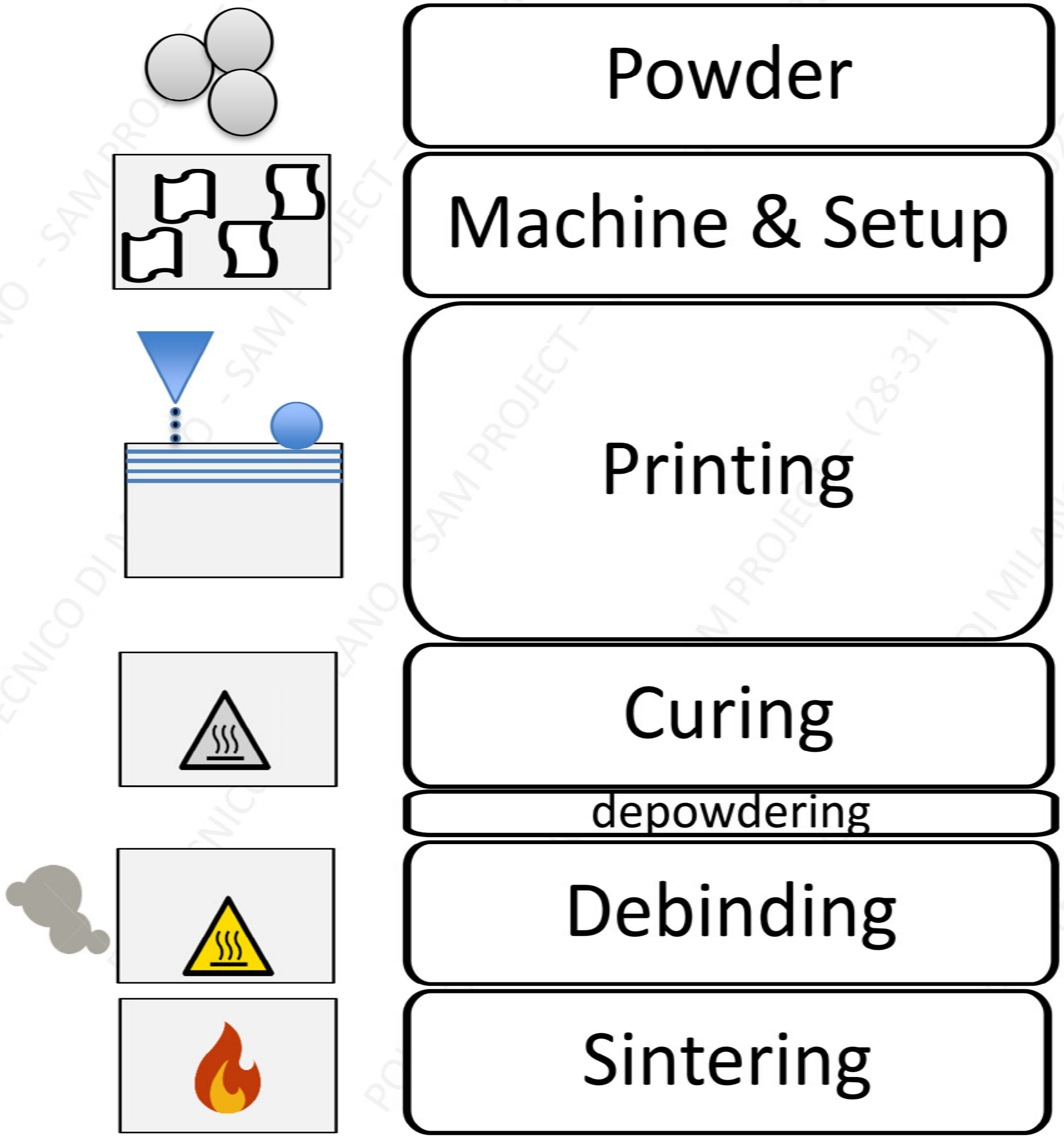

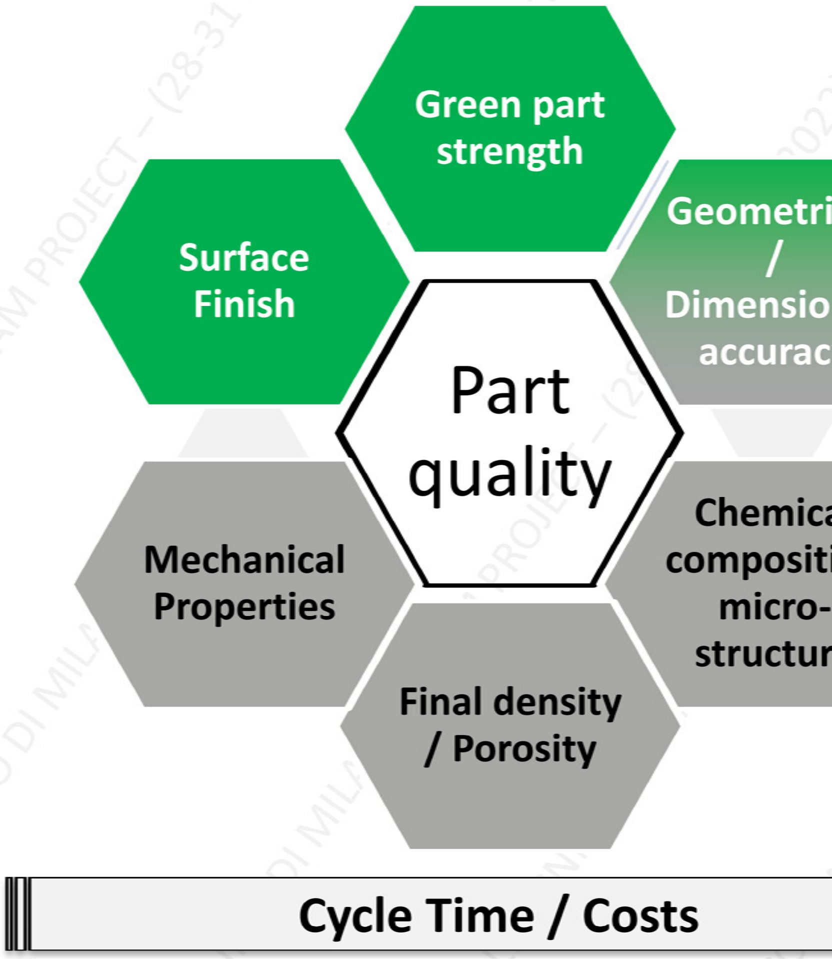

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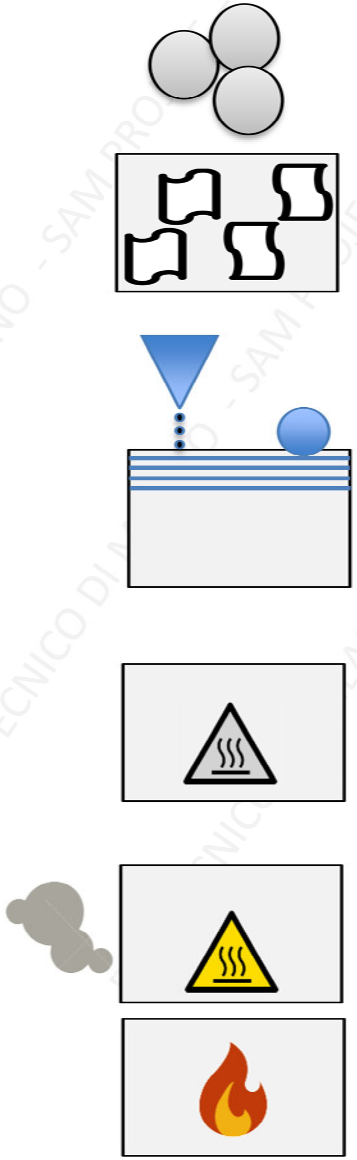

Powder
- Size Distribution / Shape
- Flowability / Compressibility (Tap / Bulk density)
- Chemical Composition & Humidity rate

Machine & Setup
- Parts orientation / location / margins / size
- Build Volume
- Humidity rate
- Binder Type / Printhead Cleaning cycles
- Shrinkage Compensation

Printing
- Powder spreading
  - Layer Thickness
  - Hopper Speed and Vibration Intensity
  - Type and Mesh of the Hopper sieve
- Powder compaction (Roller Travel / Rotational Speed)
- Binder Jetting
  - Binder Saturation Level
  - Drying parameters (Time, Target Temperature and Intensity)
  - Printing head Speed

Curing
- Energy Source
- Cycle time
- Cycle temperature

depowdering
- method

Debinding
- Mechanisms
- Cycle temperature
- Cycle times (Rate/Hold)

Sintering
- Atmosphere type & Pressure
- Cycle times (Heating Rate/Hold / Cooling Rate)
- Sintering Temperature

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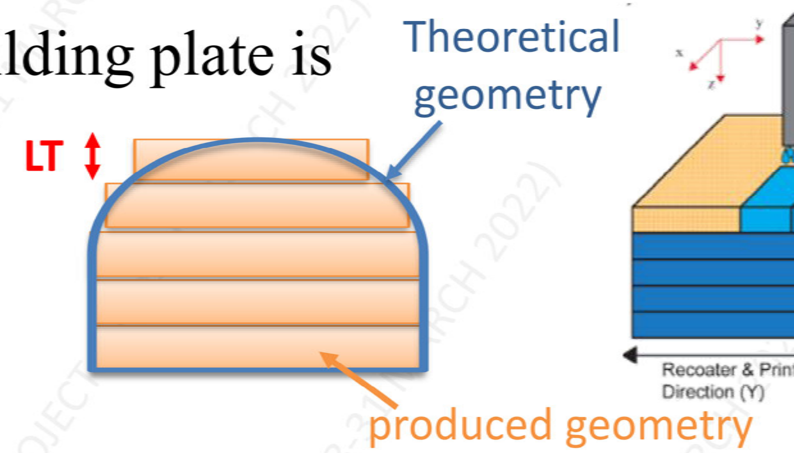
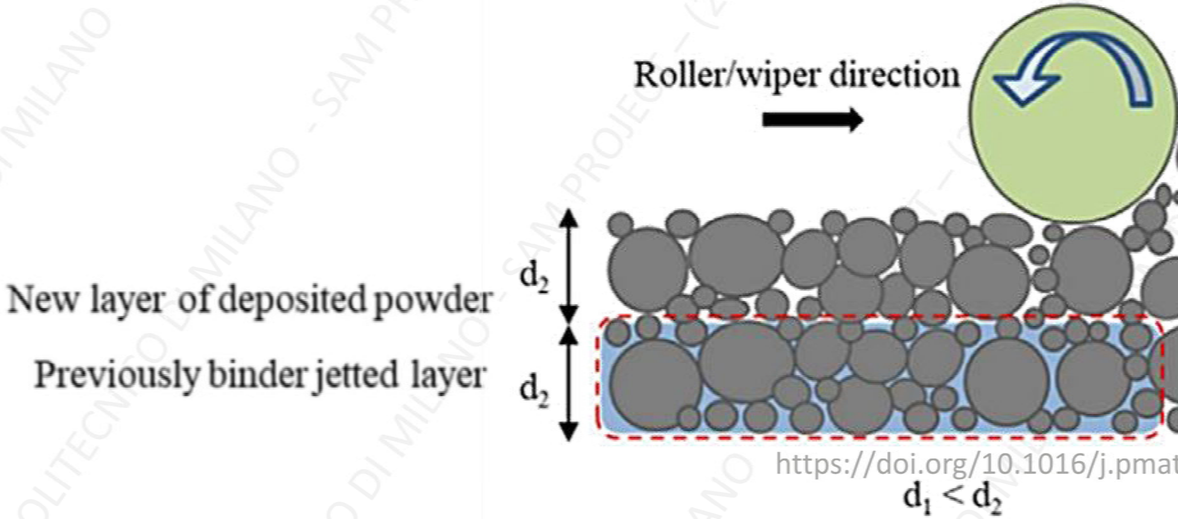
Layer thickness (LT) is the distance by which the building plate is lowered after printing a layer



Typical Values: 20-300 µm
Minimum value: Max Powder Particle Diameter
Optimal Value: 3* Powder Particle Diameter

Effects of LT ↓

- Resolution of the printed part (+)
- Surface quality (+)
- Geometrical accuracy (+)
- Powder bed density (+)
- Process time (-)



https://doi.org/10.1016/j.pmat

- Lower LT with Finer Powder (to facilitate droplet penetration)
- Setting of variable LT along the Z are possible in some BJ printer

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Effects of BSL ↑

- Powder bed density (+)
- Green part strength (+)
- Geometrical Accuracy (-)
- Dimensional Accuracy (-)
- Surface finish (+-)

EFFECTS ON SURFACE FINISH

UNDERSATURATION **OVERSATURATION**

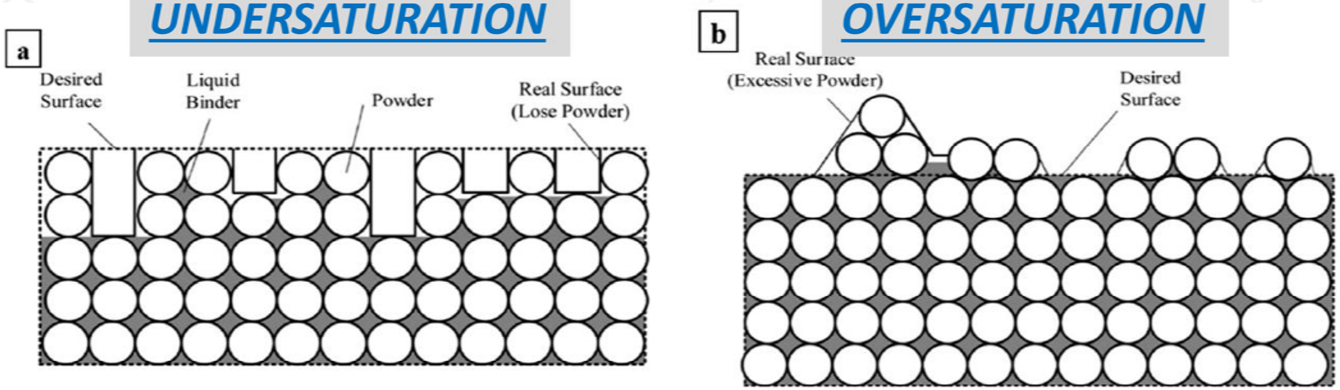
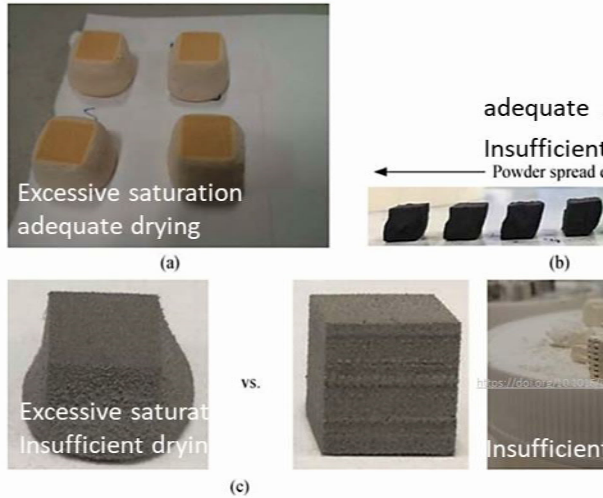


Figure 1 - Schematic of binder saturation effect on surface roughness: (a) low binder saturation leads to lack of binding and powder loss; (b) high binder saturation leads to excessive powder bond. From [25] and [41].

https://doi.org/10.3390/jmmp3030082

EFFECTS ON PART ACCUR



https://doi.org/10.1016/j.pmatsci.2

Fig. 9 Common BJ-AM in-process defects from saturation-drying setting. (a) Excessive satur saturation, insufficient drying; (c) excessive saturation, insufficient drying; (d) insufficient binder

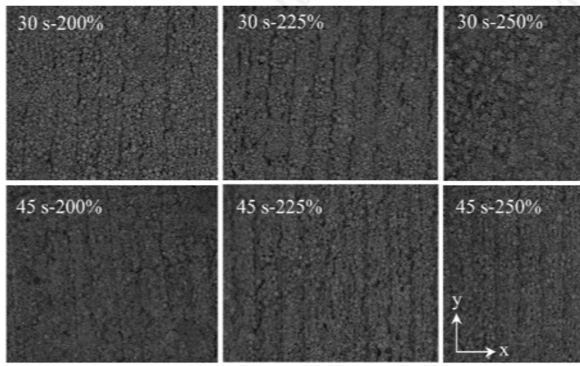


Fig. 3. Surface morphology of the 3D-printed coupons after curing at 200 °C for 8 h. Effect of printing processing parameters saturation was studied on the potential powder agglomeration during 3D-printing.

https://doi.org/10.1016/j.addma.2021.10

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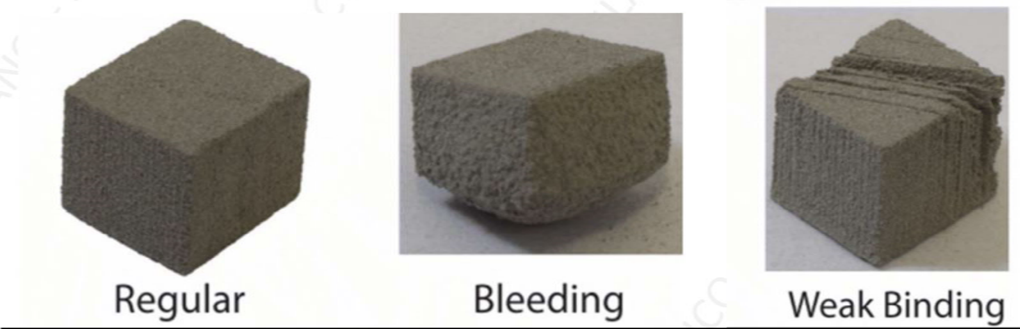
The optimal quantity of the **Binder Saturation** (BSL)

- Guarantees the geometrical / dimensional Part accuracy
- Produce adequate binding between layers and within them for (no delamination, no particles detachment, good mechanical resistance at green sintered state no pores)

- Avoid **Bleeding**: binder migration outside the defined controlled area that leads excessive powder bonding



DOI: 10.1007/s00170-021-08183-z

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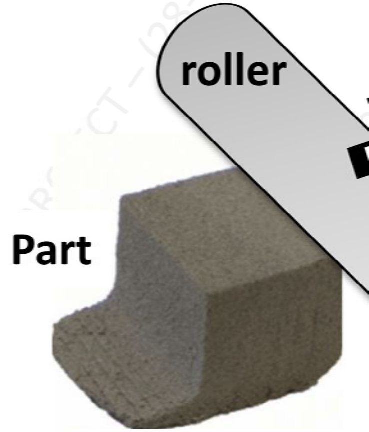
Drying Time

Drying time is the idle time between layers (in printers without Heating/drying Lamp (similar to **Drying Speed** parameter: speed of the Heating Lamps moving across the tray)

Typical Values: 0 /1 min

(Adapted) 10.100



LAYER SHIFTIN
DURING SMOO
(INCOMPLETE

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Drying Power

Drying Power is the intensity of the Infrared Heating Lamp used to to evaporate excess solvent from the binder solution

- Defined as **Heating Power Ratio** Rhc%=Pact/Pmax*100

Typical Values: 0/100%

The binder jet 3D printing process on GE Addi
Inc.

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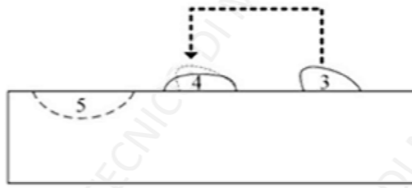
Printing Speed is the traverse speed of the printhead across the bed

Typical Values: 50/200 mm/s

- The higher speed, the shorter printing time
- It affects feature resolution and part accuracy
- It affects binding, higher speed can reduce the actual saturation leading to narrower printed tracks and unsaturated spots



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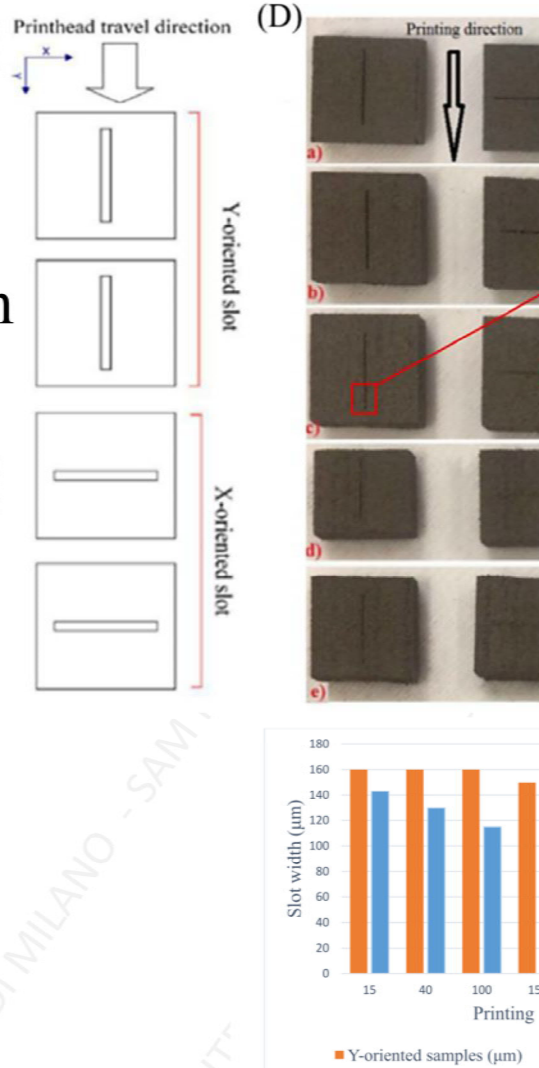
- It affects binding, higher speed can reduce the actual saturation leading to narrower printed tracks and unsaturated spots

printing speeds (a) 20 mm
(c) 300 mm/s (d) 700 mm/



https://doi.org/10.101

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Powder spreading parameters

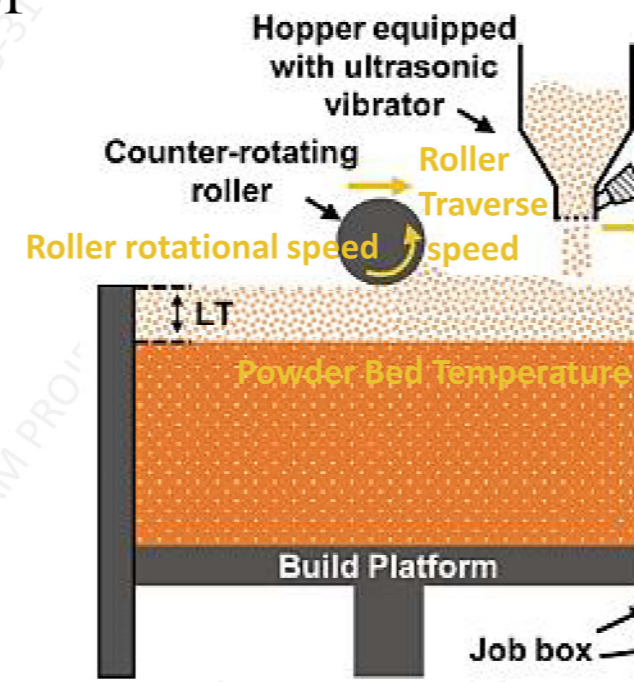
Recoat (Hopper) Speed (10-100 mm/s) is the traverse speed of the hopper while it is depositing powder on the print bed

Roller Traverse Speed (2-100 mm/s) is the traverse speed of the roller while it is smoothing the powder on the print bed

THEY AFFECT PRINTING TIME!

Roller Rotational Speed (100-1000 rpm) is the Rotational speed of the roller as it passes over the print bed. Coupled with Roller Traverse Speed

Vibration Intensity is the amplitude or frequency of vibration applied to the dispensing device at the hopper: It sets the rate of deposition of powder from the recoater



https://doi.org/10.1016/j.mfglet.2

Machines that do not use hopper adopt other synthetic parameters (e.g. Dosal Factor t the amount of powder deposited

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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Metal Binder Jetting HW/SW

Dr. Marco Mariani (POLIMI)

15:35 - 16:30, 12th December 2022

POLITECNICO MILANO 1863

Manufacturing Technology Centre

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Contents

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Printer Hardware Overview – ExOne Innovent+

On/Off Switch

Control S

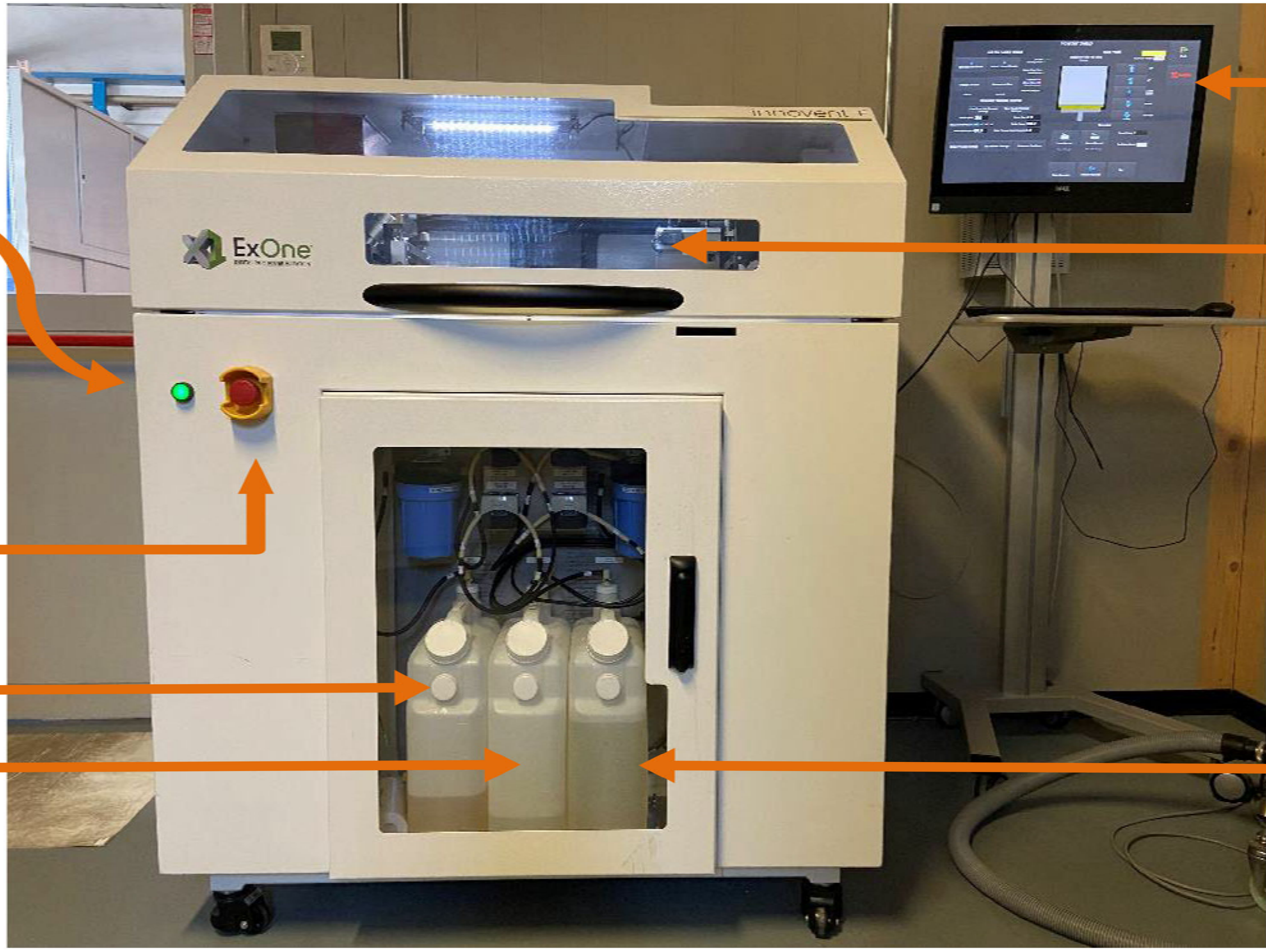
Building C

Emergency Button

Binder Tank

Cleaner Tank

Waste Liq



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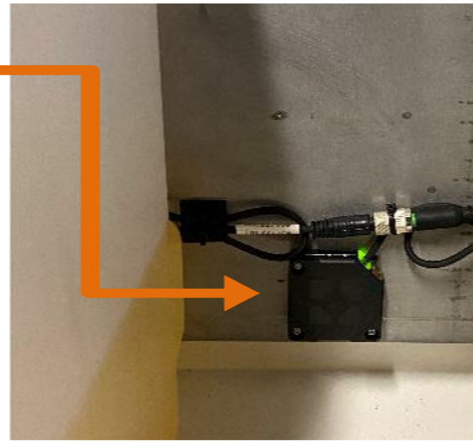
Liquids Reservoir

The binder and cleaner tanks are connected to **pumps** with multip
filtering systems to avoid tubes clogging

The waste tank is directly connected to the liquid sink in the buildi
chamber

All tanks are in contact with an optical **sensor** that stops the operations when:

- the binder and cleaner are too low
- the waste is too high



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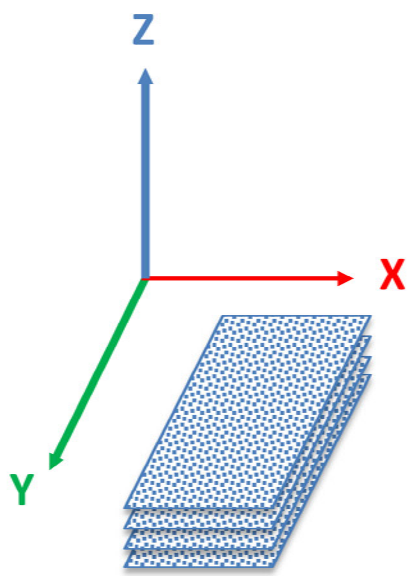
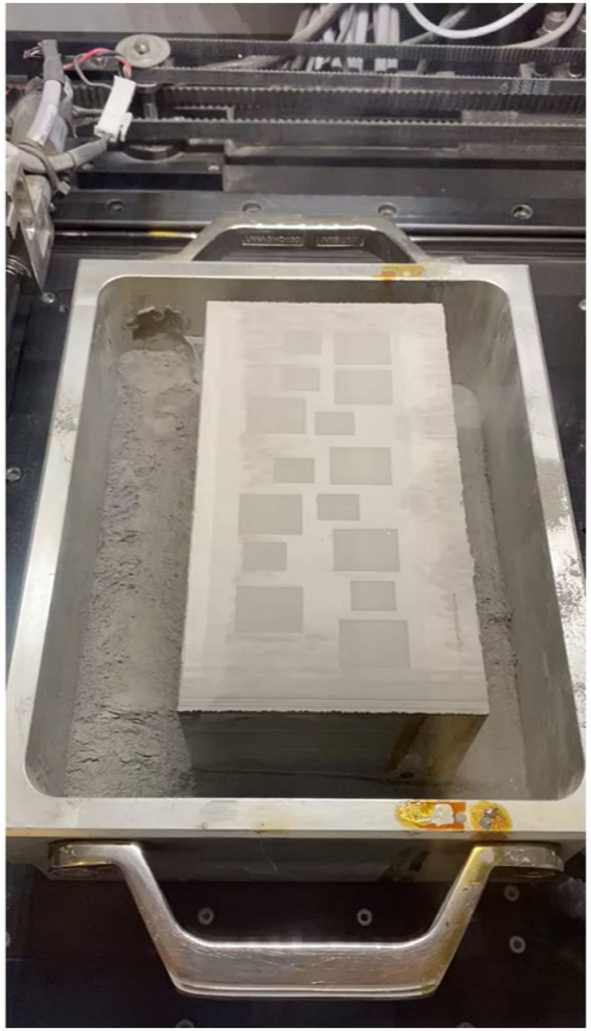
Three moving part are present:

- Powder dispensing and spreading apparatus (**X**)
- Printhead (**X**-**Y**)
- Vertical motor and job plate (**Z**)





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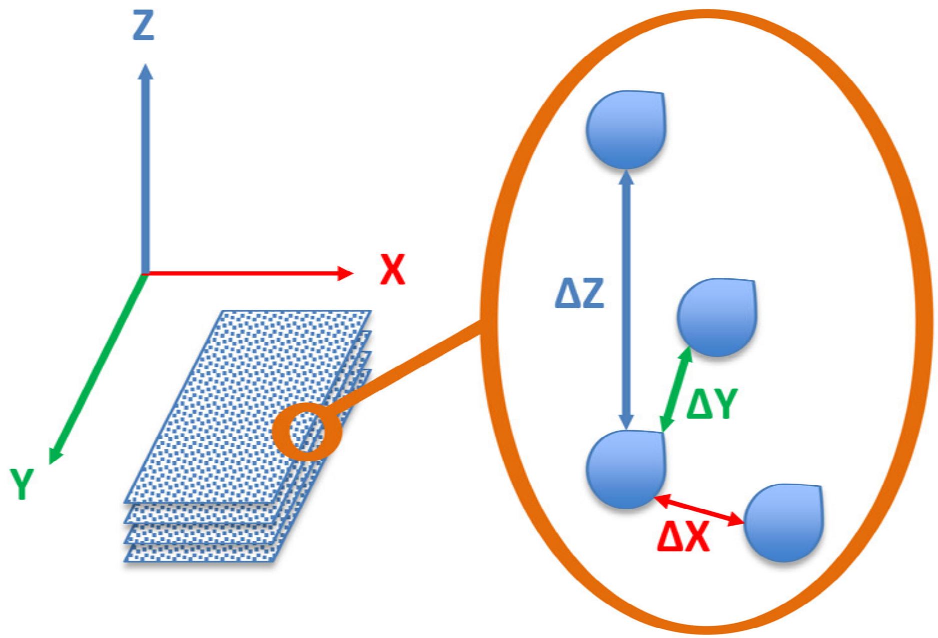
Three moving part are present:

- Powder dispensing and spreading apparatus (X)
- Printhead (X-Y)
- Vertical motor and job plate (Z)



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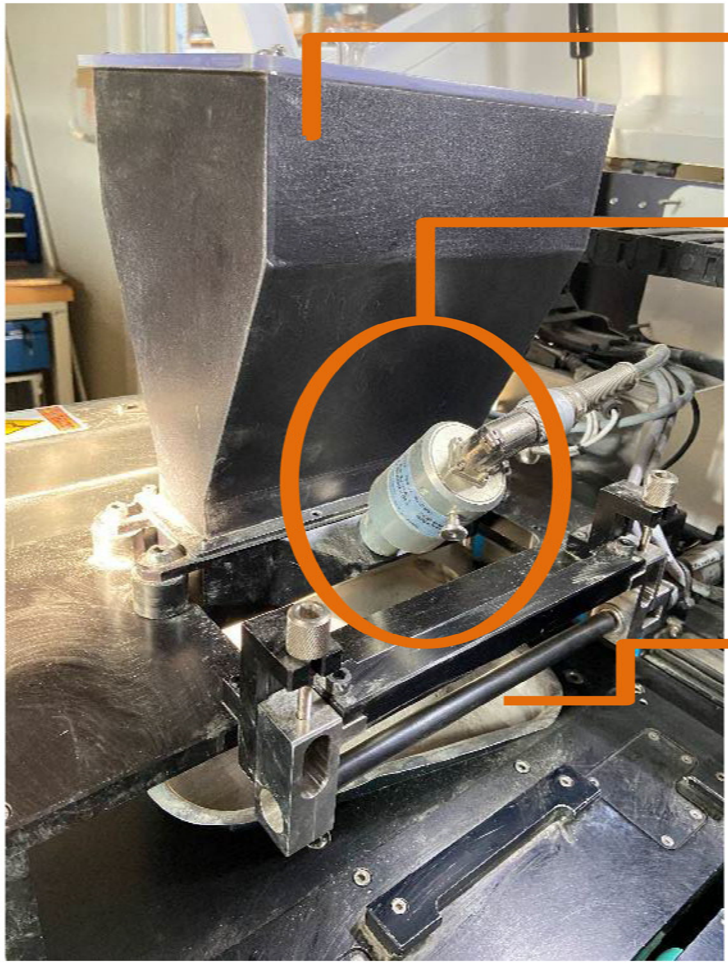
Building Chamber - Powder dispensing



The **powder hopper** can be manually filled to different levels depe
the amount of feedstock needed (proportional to the print height)

The **ultrasonic vibration** can be set at different levels, but it is usu
at maximum power and the material dispensing rate is controlled b
combining proper sieve size and recoating speed to ensure a high
productivity

The **roller** should always be clean to obtain a homogeneous powd
surface

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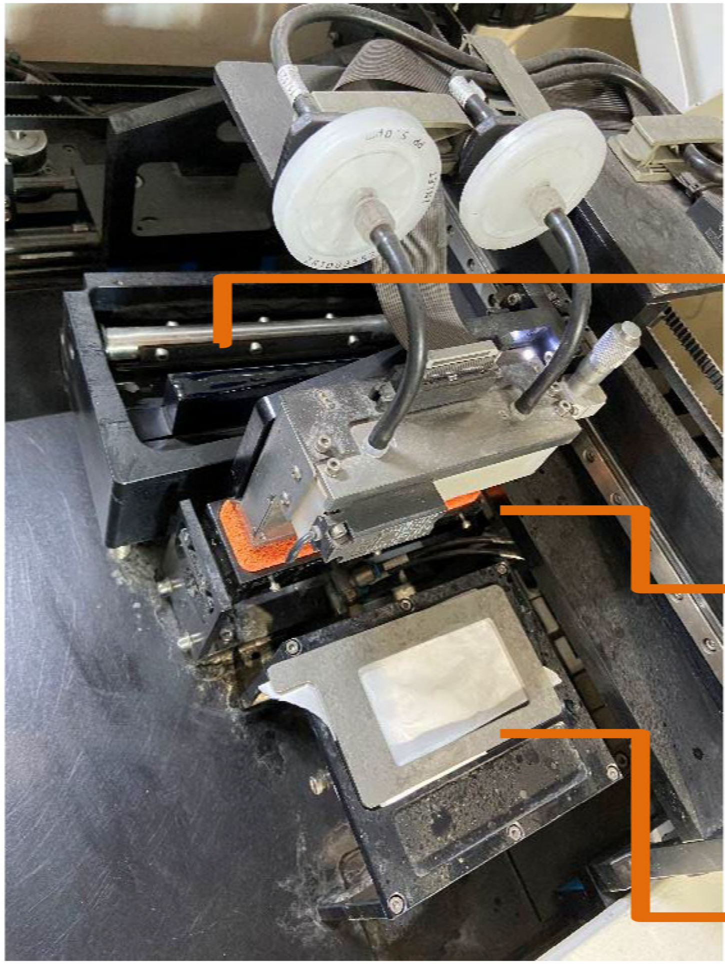

The printhead is the most critical component of the system be
directly affects the quality and the accuracy of the printed parts, t
keeping it clean is fundamental to ensure continuous operab

The liquid sink contains:

- A compartment with a wiper immersed in the cleaner
- A compartment connected to the waste tank to remove excess

The printhead standard position is on a **sponge**, **which keeps th nozzles moist and avoids clogging**, so it is advised to maintain cleaned by removing polymer debris and adding few cleaner drop day

Before starting the printing process, it is possible to test the nozzl status on a paper pad

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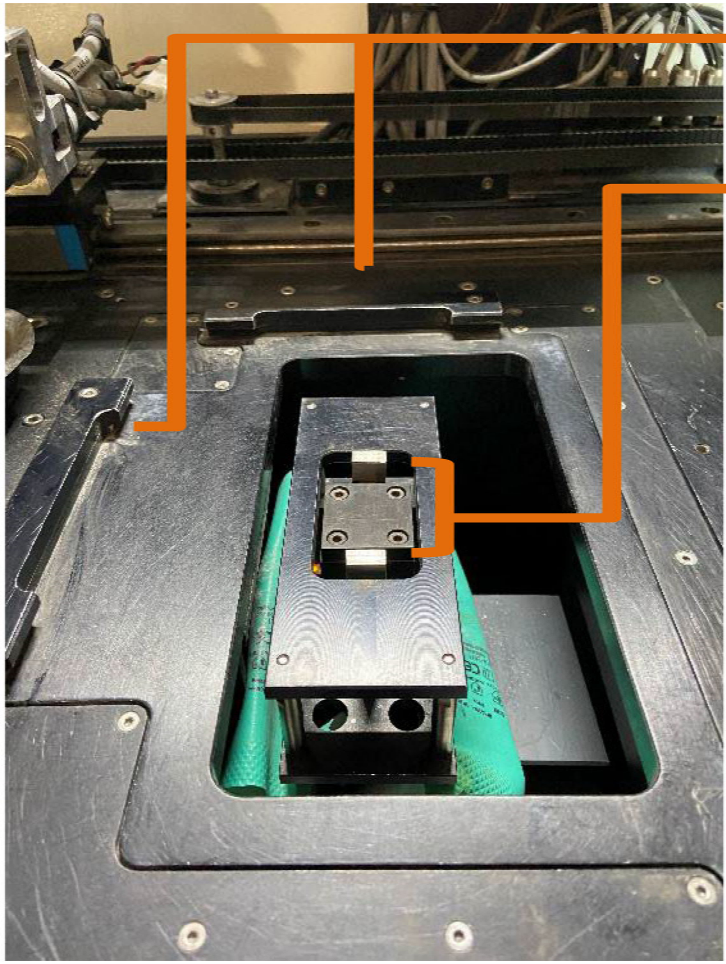

There are **guides** to ensure the correct placement of the job box

The printing plate is hooked to a **gripper** at the top of the vertical motor platform

The system is extremely **sensitive to the friction** between the jo and internal walls: it is important to place the box properly and to with care in between successive printing campaigns

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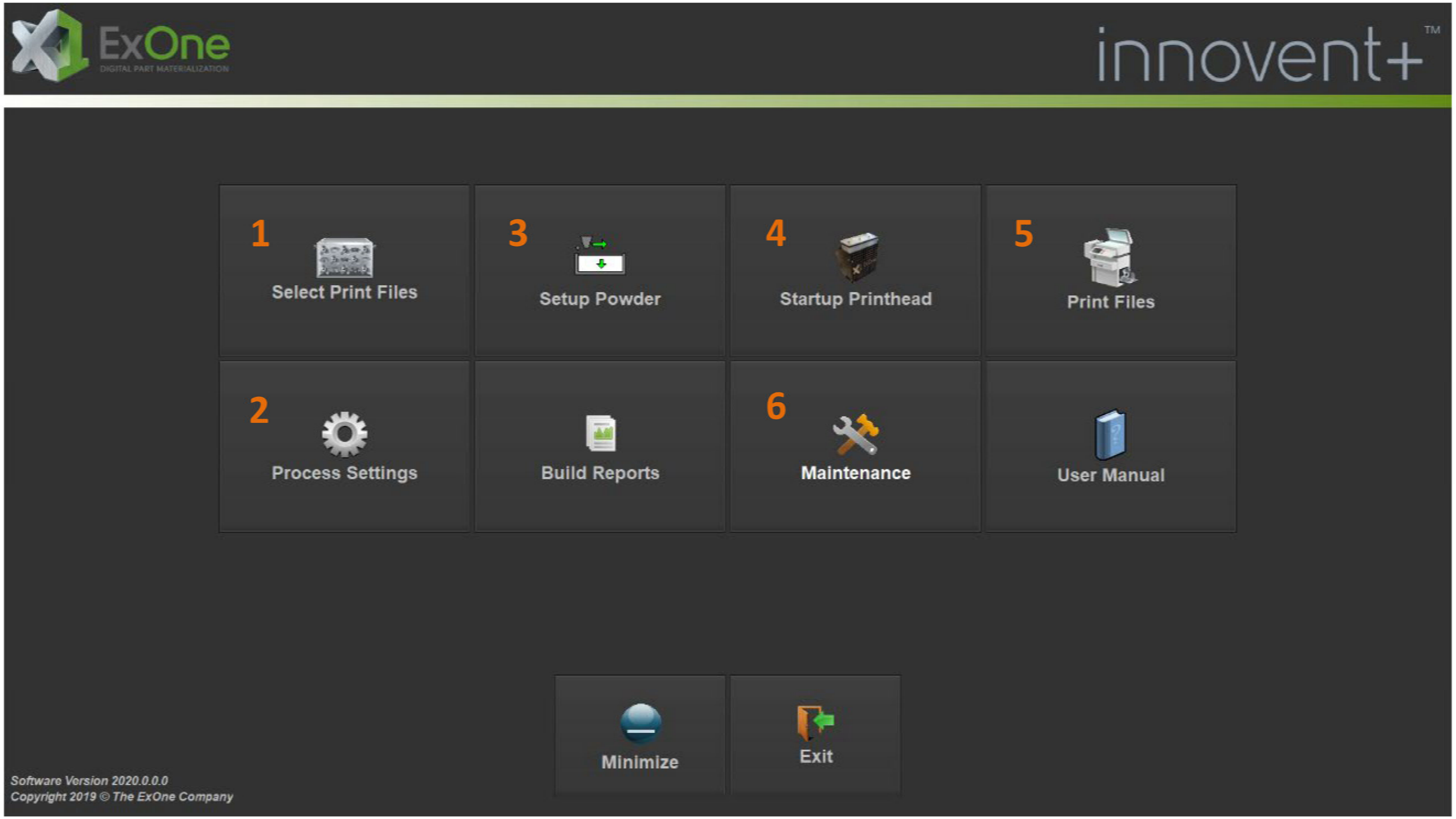

This is the **Home scre** appears after the initia the system

Each section deals wi different step of the pr process:

1-2) Layout and proce preparation

3-4) Hardware prepar

5) Printing process

6) Maintenance

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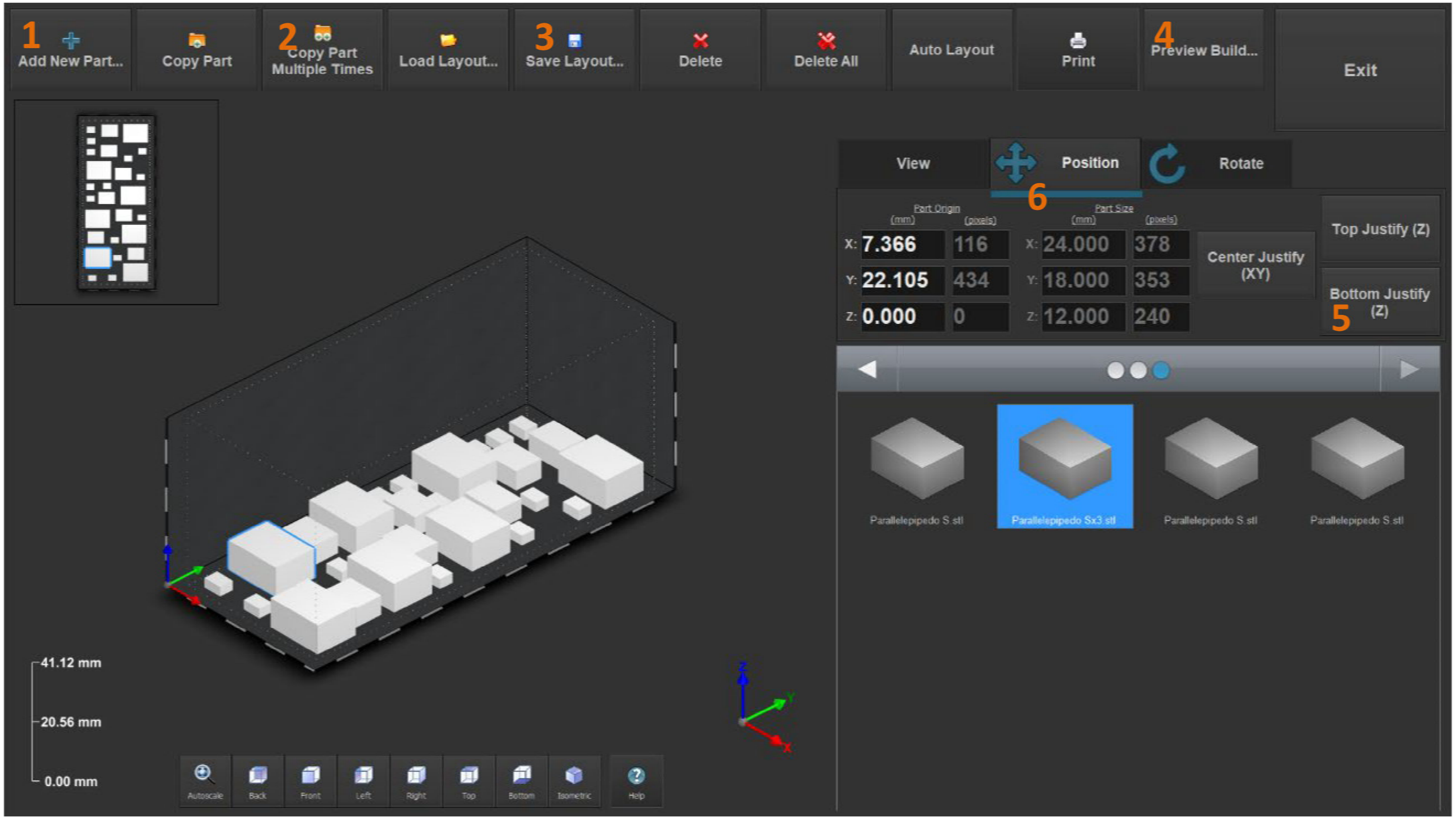

The lack of support str or limitations allows co freedom during the lay preparation

1) .stl files can be res added to the layou
2) Parts can be multip deleted
3) The whole layout c saved and loaded
4) A preview of the pr campaign is provid of layers)
5) All parts can be mo layer 1 to reduce th height
6) Fine positioning all maximise nesting

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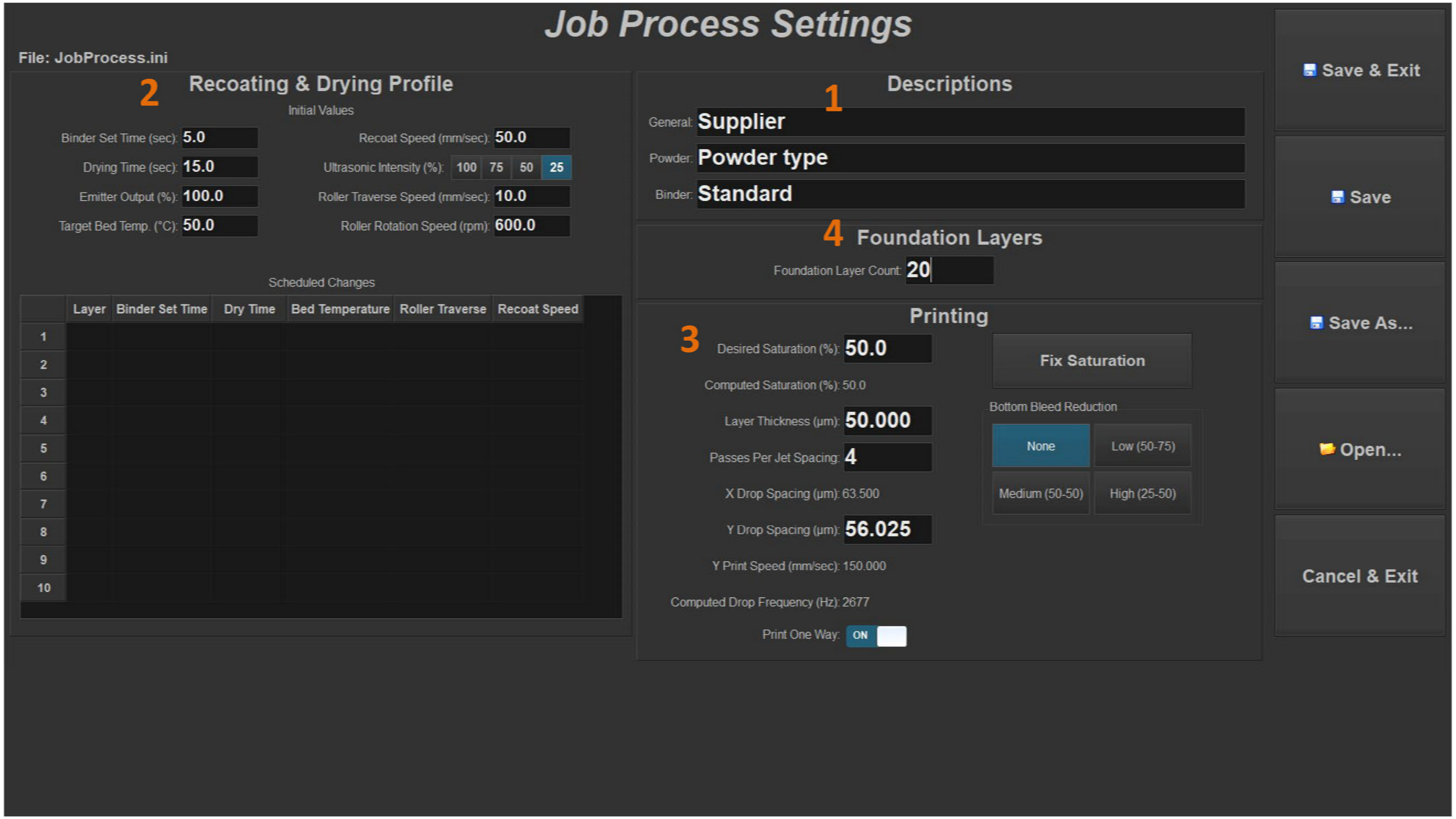

The process settings o
specific feedstock can
and loaded at need

1) Feedstock and bind
identification

2) Parameters affectin
powder bed formation
binder infiltration/sprea

3) Main printing param
layer thickness and bi
saturation)

4) Number of layers d
before starting the act
to avoid initial transitio

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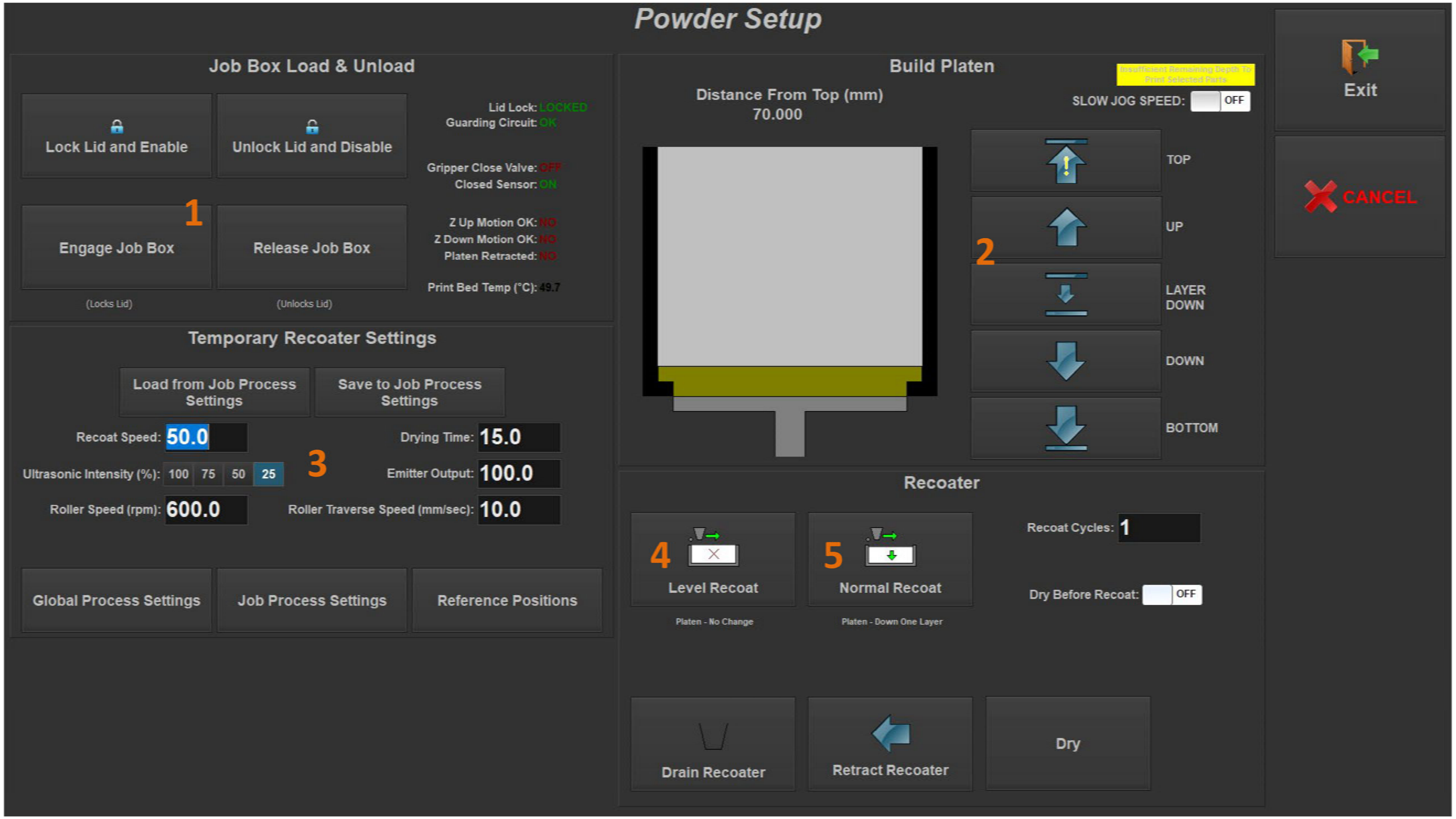

This section allows to the recoating and spre parameters

1-2) These functions a needed to clamp the p plate and put in positio

3) It is possible to mod recoating parameters Process Settings to ac

4-5) These functions deposit and spread l before printing to as powder behaviour ar the parameters

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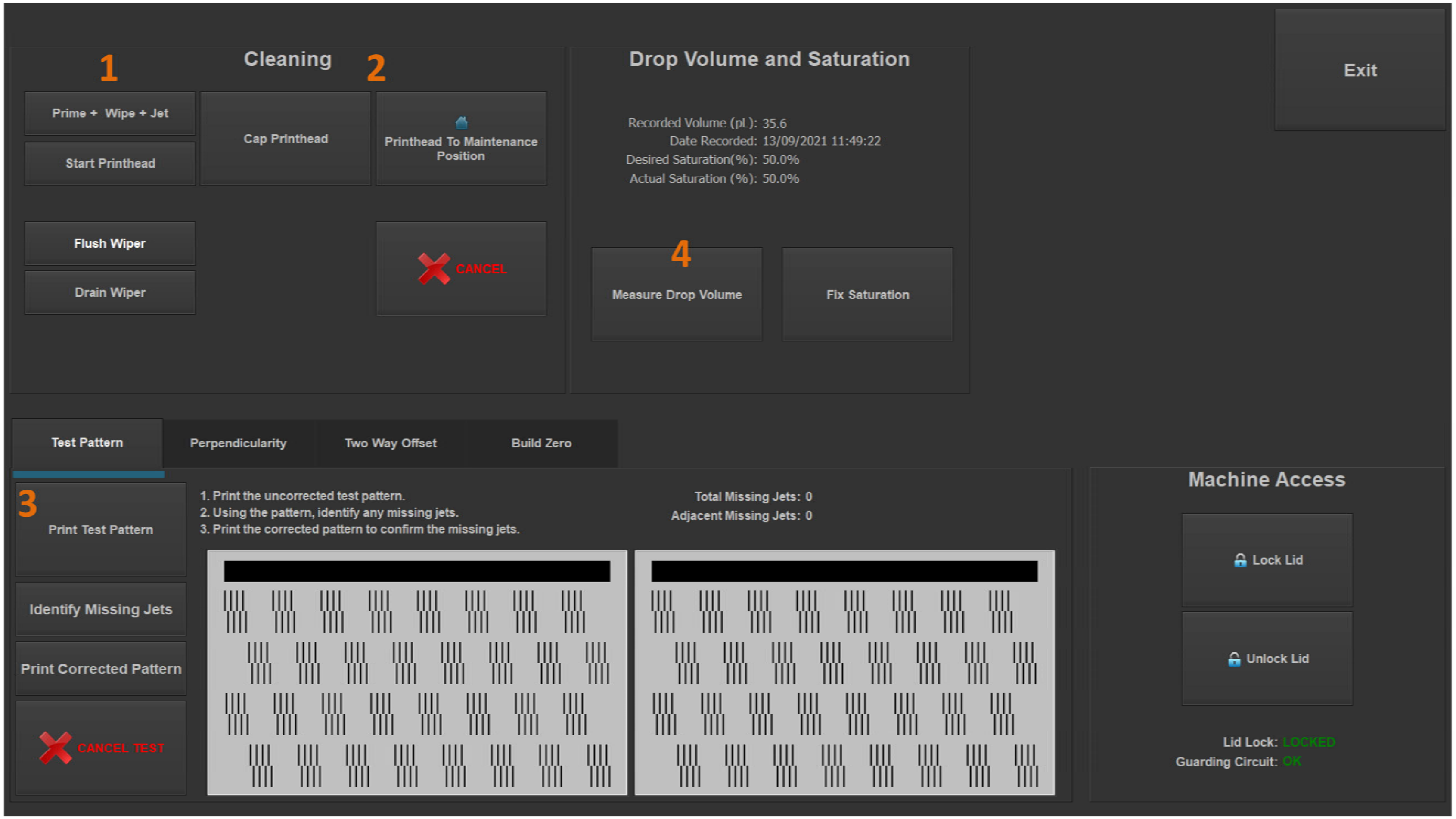
Printer Software Overview – 4) Printhead



1) Cleaning operation needed if the printh the sponge are kep day-by-day
2) "Cap" and "Mainter refer to the positior the sponge and on to allow nozzle clea
3) The nozzles cleanl be checked by prin pattern and correct be applied if neede
4) The actual binder c size can be calibra improve accuracy

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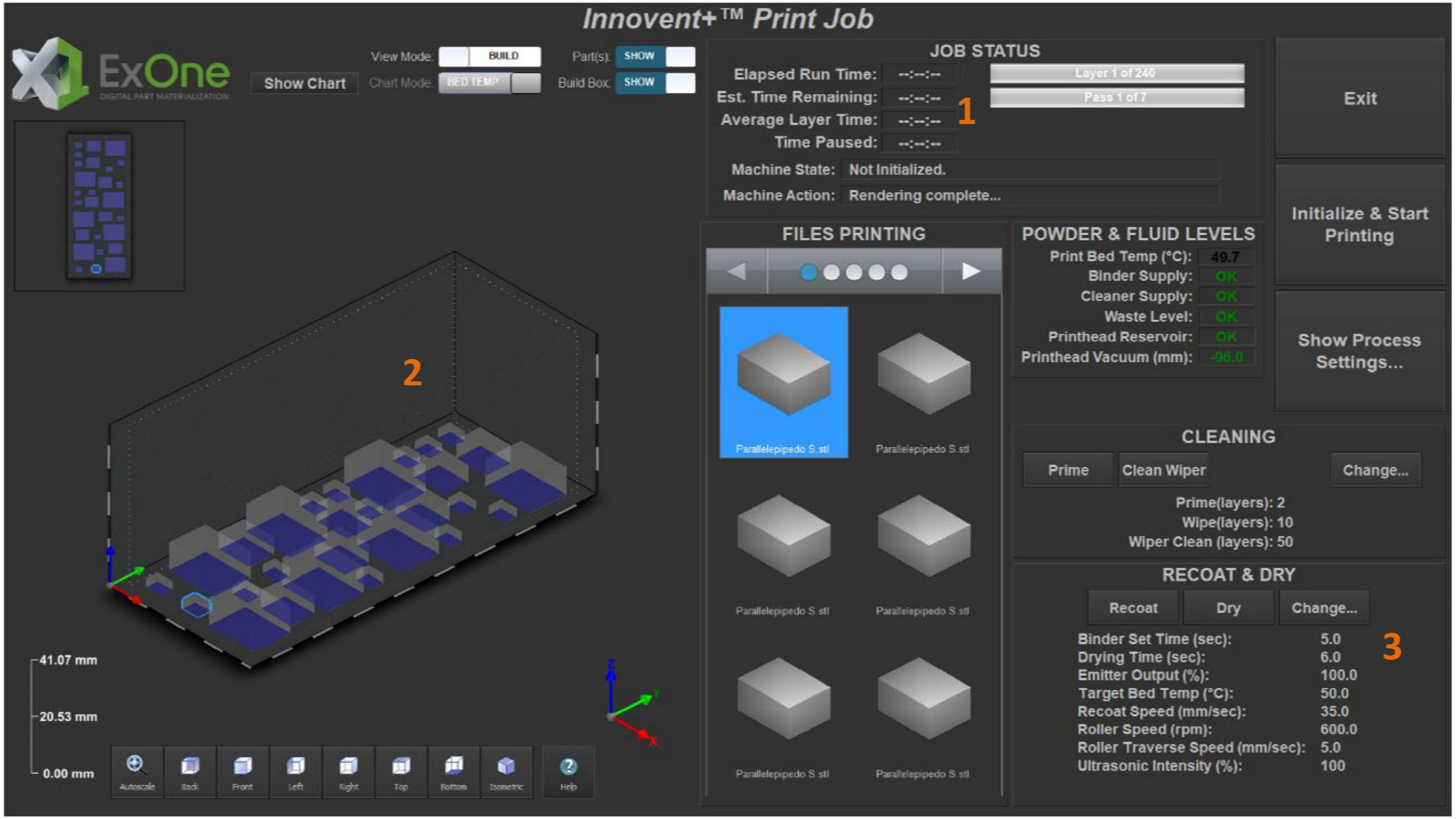
Printer Software Overview – 5) Print Campaign



1) The progress of th
process is shown h
2) The printed layer is
highlighted in blue
3) The recoating para
are shown and the
changed during the
in order to adjust th
deposition and spr
need
4) The Pause button
stop the print and c
printer if needed

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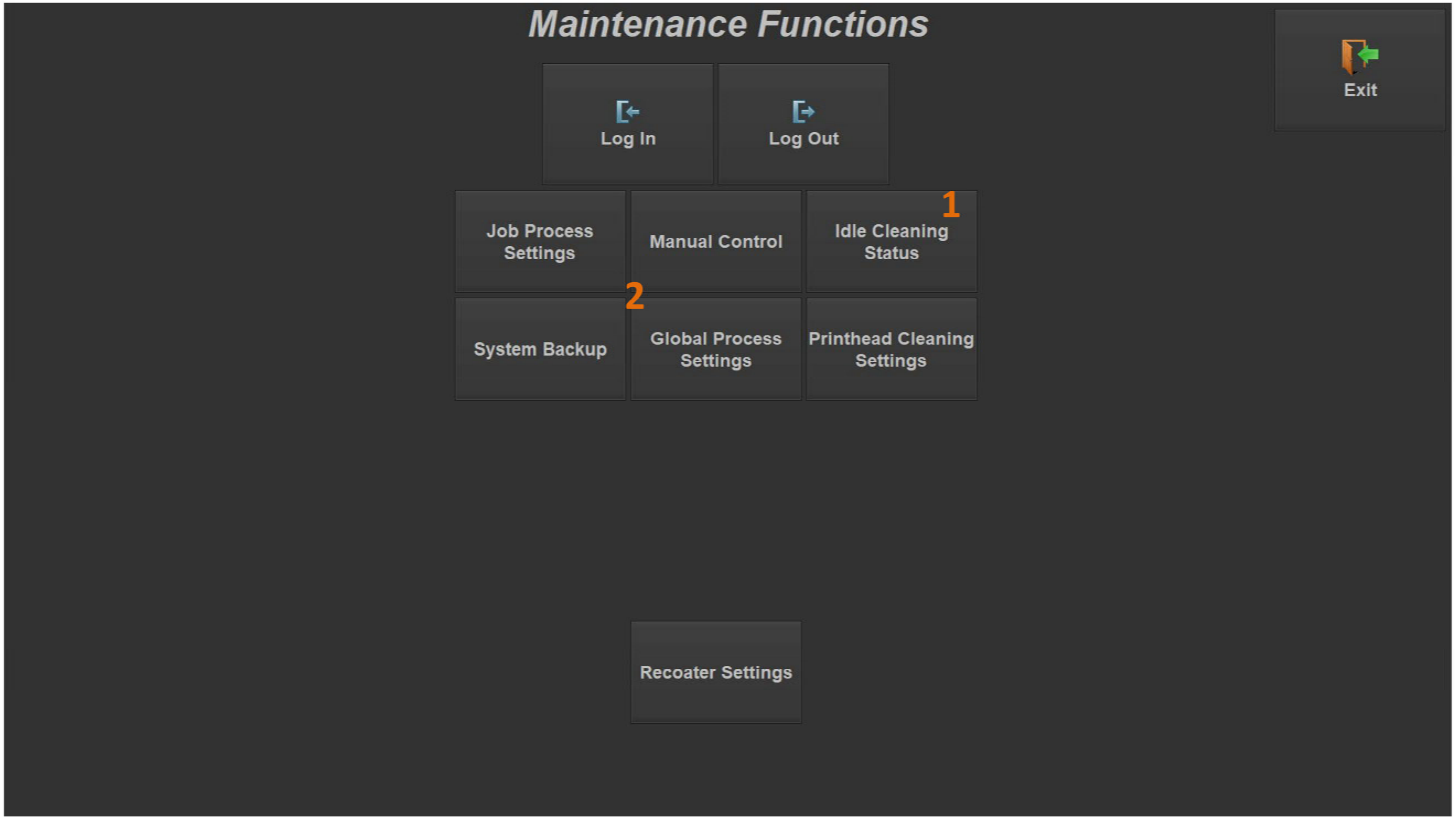
Printer Software Overview – 6) Maintenance



1) The “Idle Cleaning
function activates t
machine regularly
performs some cle
operations when th
is not operating (th
should never be sw
off)
2) Other parameters
can be done in this
but this should be
carefully to avoid e
deviations from the
machine operation

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Test

1) How many liquids are present in the machine?

A. 1 B. 4 C. 3 D. 2

2) In which directions is it possible to control the droplet spacing?

A. None B. All C. Z-X D. Y

3) Which limitations must be considered for parts placement?

A. Closed cavities
B. Minimum spacing among parts
C. Position in Z
D. All the previous answers

4) What is the purpose of the foundation layers?

A. Build an initial powder bed substrate
B. Stabilise the powder bed temperature
C. Check powder deposition and spreading
D. All the previous answers

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SAM
SECTOR SKILLS STRATEGY
IN ADDITIVE MANUFACTURING

Co-fu
Eras
of the

Metal Binder Jetting Process Parameters

Dr. Marco Mariani (POLIMI)

13:30-15:30, 13th December 2022

POLITECNICO
MILANO 1863

mtc
Manufacturing
Technology Centre

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Contents

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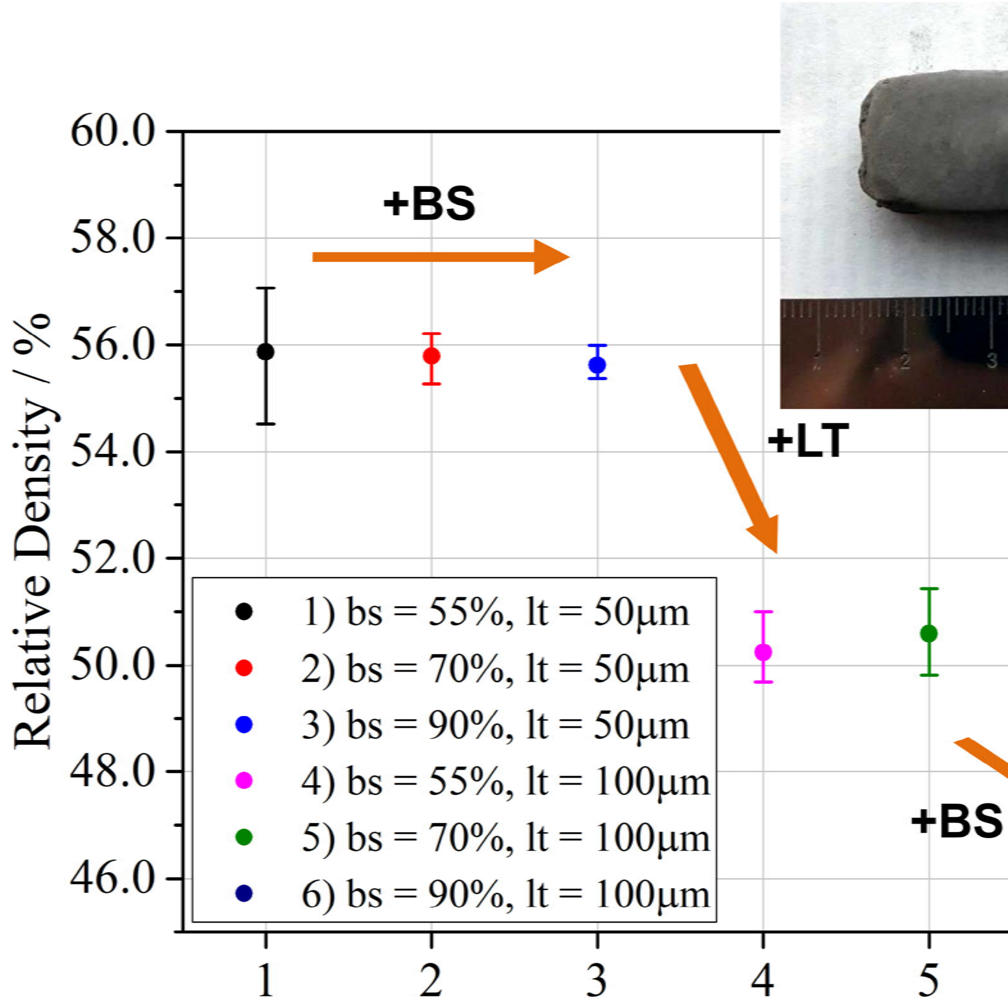
Stainless steel 316L: medium flowability

DENSITY

- Low LT + less probable to form macropores within the layer
- **High BS** + keeps the powder connected
  + increases the weight of the part
  - reduces geometrical accuracy



N. Lecis, R. Beltrami, M. Mariani, Binder jetting 3D printing of 316 stainless steel: Influence of process parameters on microstructural and mechanical pr
Metall. Ital. 113 (2021) 31–41.
https://www.researchgate.net/publication/352249008_Binder_jetting_3D_printing_of_316_stainless_steel_influence_of_process_parameters_on_micros
mechanical_properties.

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Density measurement

- Geometrical method - simple and effective when the geometry is regular
- Archimede's method - useful for complex shapes and accurate measurements

The main problem of the Archimede's method is that green parts have completely open porosity, so ir
is needed prior to measurement; however, this process could be detrimental to the green body and in
additional porosity, so we prefer to use the geometrical method on a wide set of pieces

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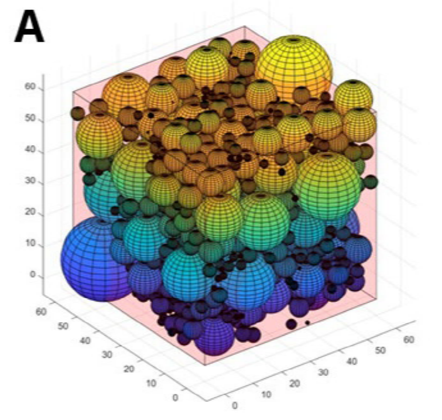
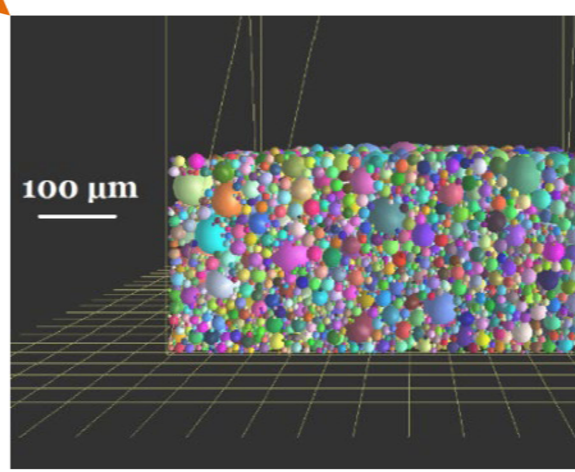
Packing simulation

- Lubachevsky-Stillinger (LS) Algorithm
- Discrete Element Modeling (DEM) with YADE software





Useful to have a rough prediction of the green density, which is mainly dependent on powder packing

Example fo alumina:

LS	68.4%
DEM	60.9%
Actual (LT50, BS55)	50.0%

M. Mariani, R. Beltrami, P. Brusa, C. Galassi, R. Ardito, N. Lecis, 3D printing of fine alumina powders by binder jetting, J. Eur. Ceram. Soc. 41 (2021) 53
https://doi.org/10.1016/j.jeurceramsoc.2021.04.006.

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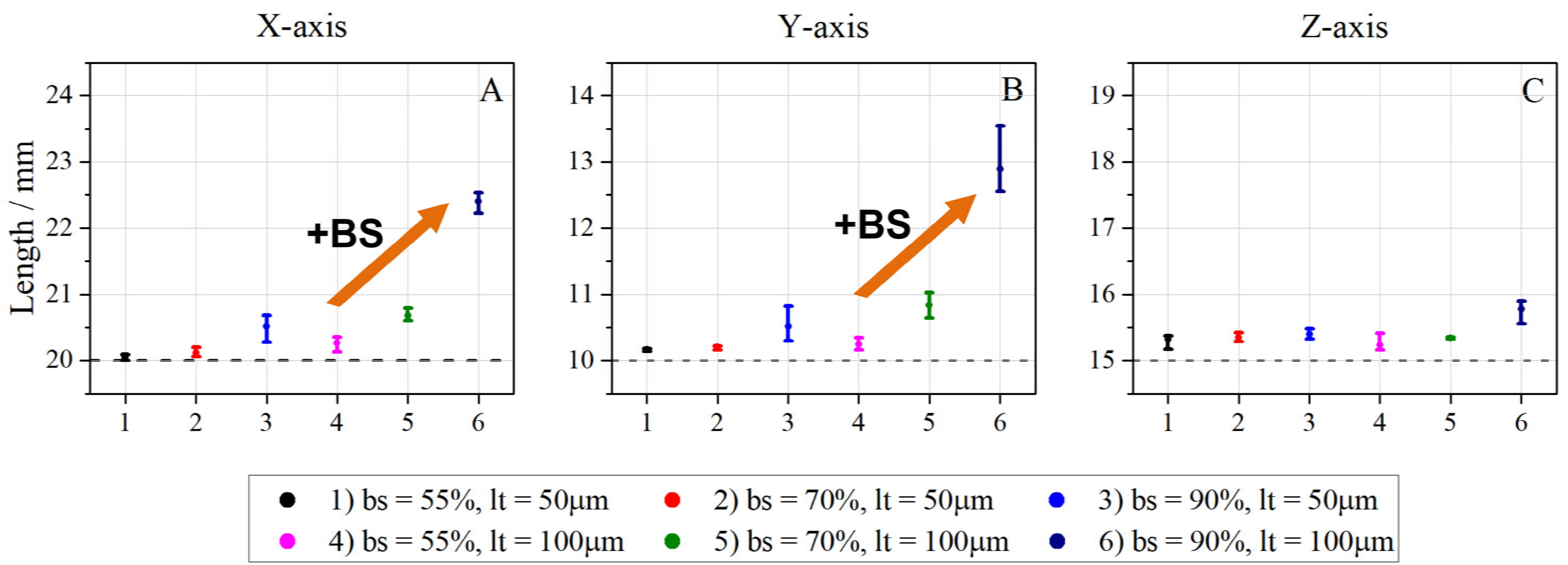
LT and BS on green parts

Stainless steel 316L: medium flowability



M. Mariani, R. Beltrami, F. Meneghetti, D. Azzolini, N. Lecis, Effect of printing parameters on the mechanical strength of green body from binder jetting a
manufacturing, in: Procedia Eur. 2020 Int. Powder Met. Virtual Congr. Exhib., EPMA, 2020.

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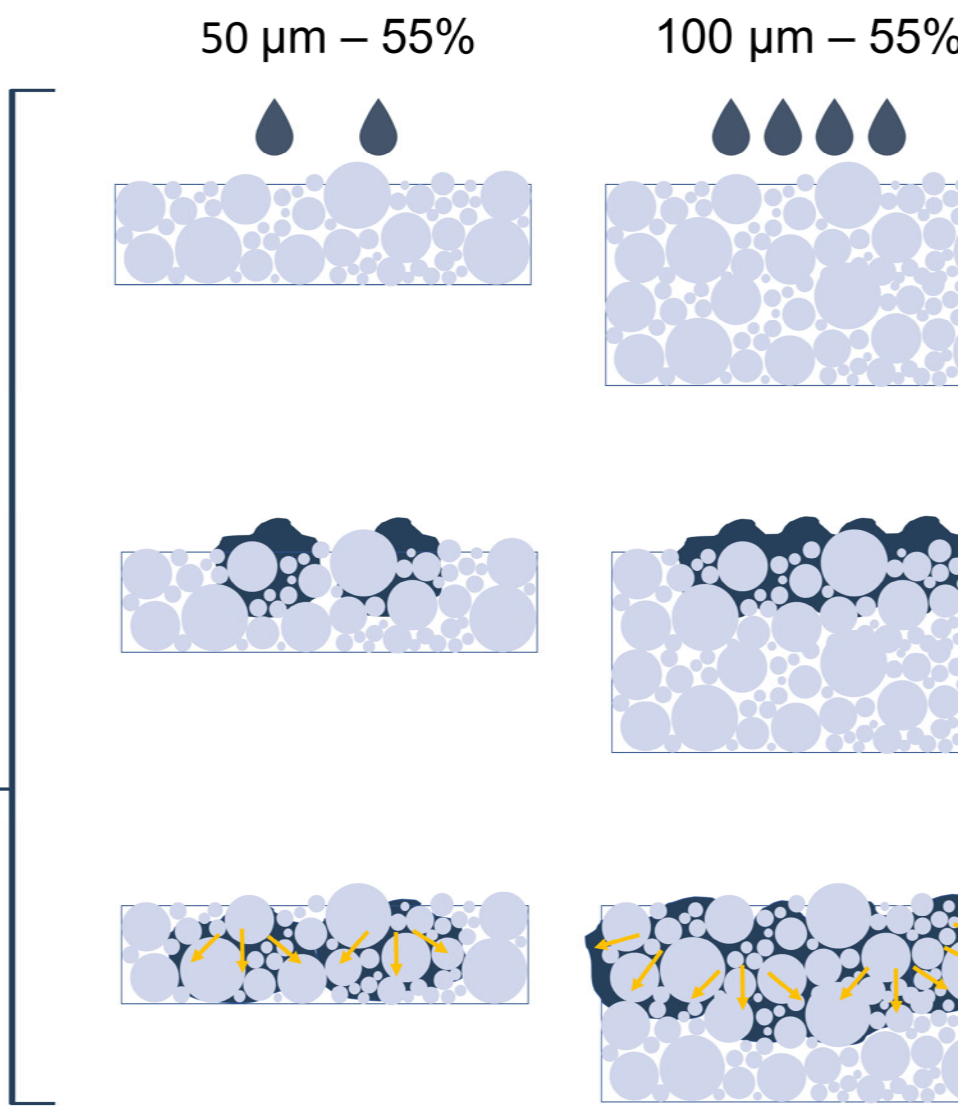
Layer thickness / µm	Binder Saturation / %
50	55
	70
	90

Low LT:

- **Improves the binder homogeneity** in the powder bed (thus mechanical strength of the green body)
- **Reduces lateral spreading and local oversaturation** (thus geometrical inaccuracy)



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Compensating for excessive BS

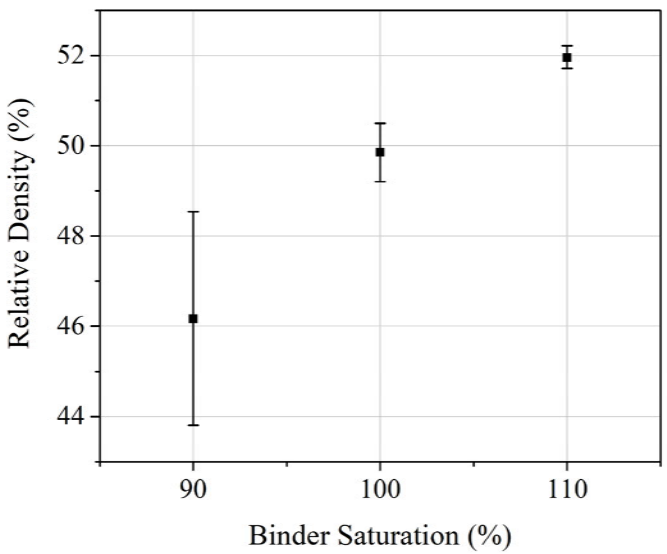
- Accelerating the solvent evaporation → increasing powder bed temperature
  → increasing the drying time
  → reducing the layer thickness

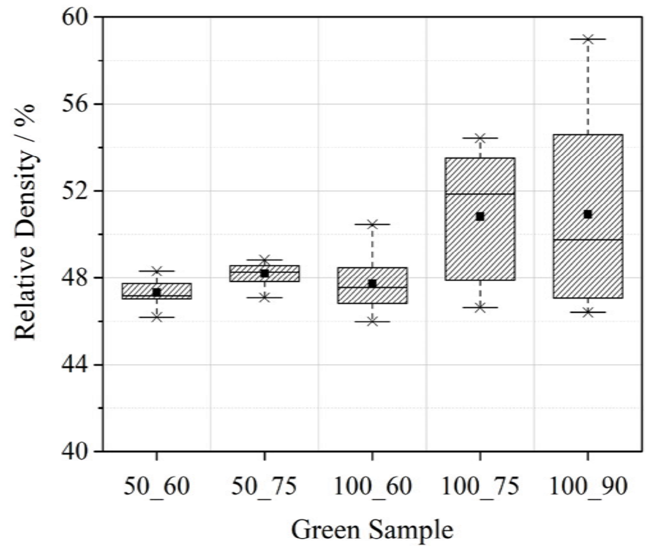
Pure Cu: medium-low flowability

High BS is needed to keep the green compact

WC-Co: high flowability

The powder flows so well that higher LT do
introduce macropores, but the binder distri
the part is worse (lower geometrical accura





T. Romano, E. Migliori, M. Mariani, N. Lecis, M. Vedani, Densification behaviour of pure copper processed through cold pressing and binder jetting unde
atmospheres, Rapid Prototyp. J. (2022). https://doi.org/10.1108/RPJ-09-2021-0243.

M. Mariani, D. Mariani, G.P. De Gaudenzi, N. Lecis, Effect of printing parameters on sintered WC-Co components by Binder Jetting, European Journal c

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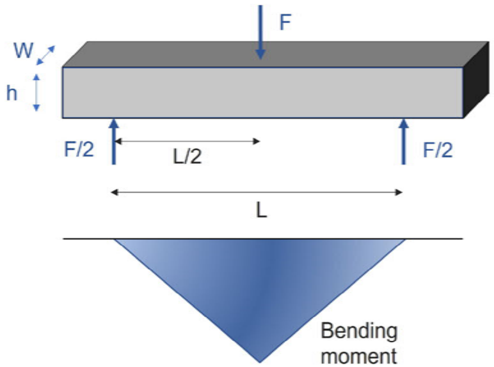
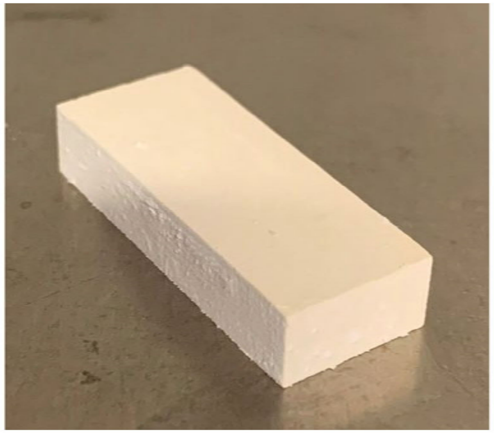
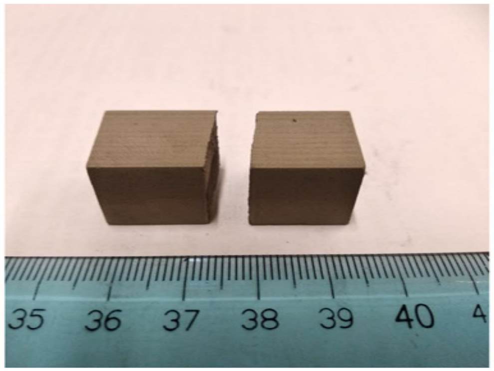
3-point bending test to assess the mechanical strength

Standard: **ASTM B312-20**

$$\sigma = \frac{3}{2}\frac{FL}{Wh^2}$$







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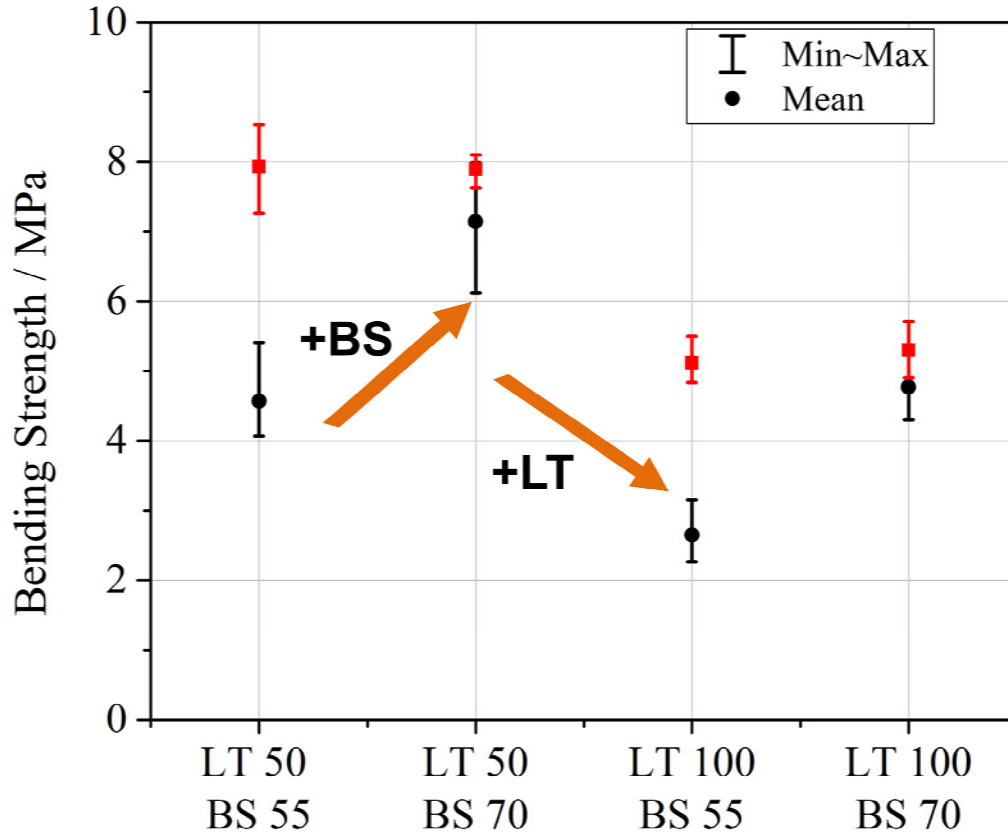
Stainless steel 316L

MECHANICAL STRENGTH

- High BS + the polymeric network is more spread and thicker
- Low LT + the powder is more packed so the polymer bridges are less stretched



N. Lecis, M. Mariani, R. Beltrami, L. Emanuelli, R. Casati, M. Vedani, A. Molinari, Effects of process parameters, debinding and sintering on the microstr
stainless steel produced by binder jetting, Mater. Sci. Eng. A. 828 (2021) 142108. https://doi.org/10.1016/j.msea.2021.142108.

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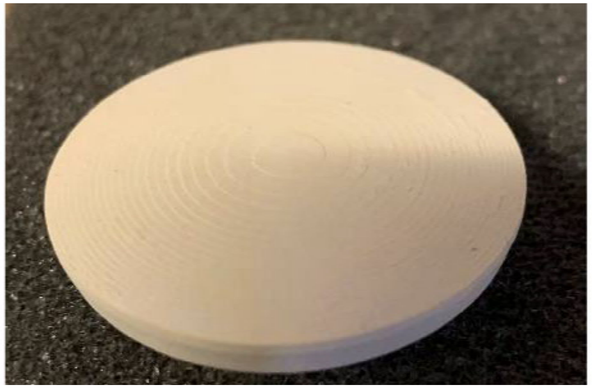
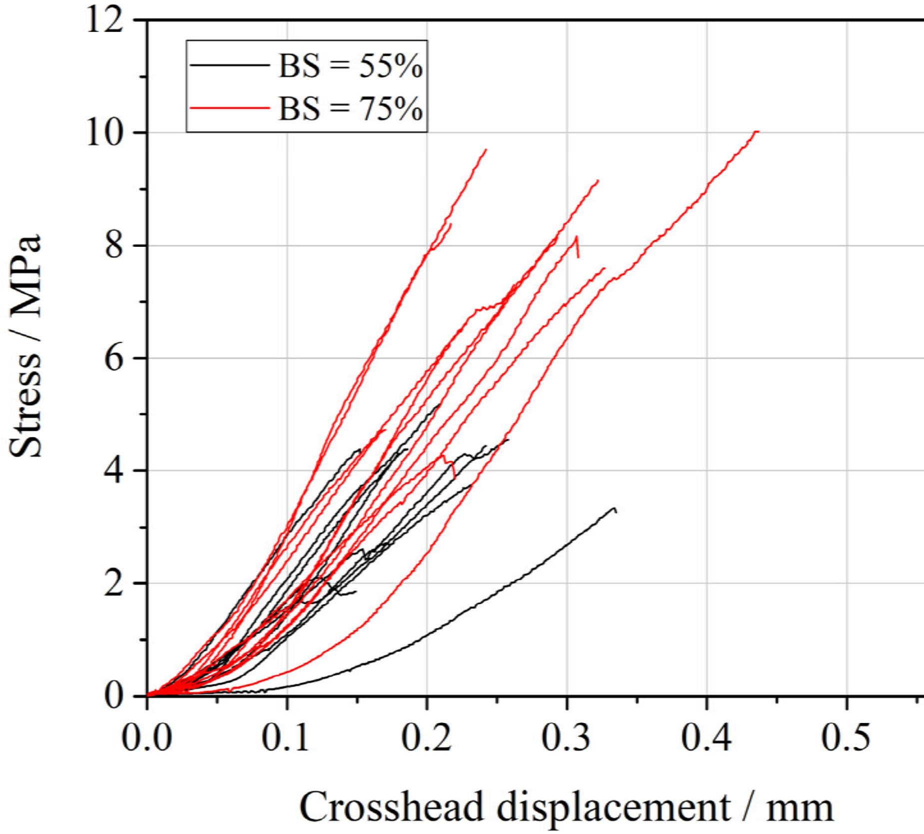
Alumina

MECHANICAL STRENGTH

The effect of binder is significant, however the **mechanical resistance** of the parts **is** still **limited**, so it is important to depowder and handle the components with extreme care





M. Mariani, R. Beltrami, P. Brusa, C. Galassi, R. Ardito, N. Lecis, 3D printing of fine alumina powders by binder jetting, J. Eur. Ceram. Soc. 41 (2021) 53
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Recoating and Spreading Parameters

Recoating and spreading parameters are difficult to analyse and have a minor effect on the parts qu

GOAL: deposit the strictly sufficient amount of powder and spread it slowly

Recoating **parameters** depends on system properties (fixed), powder (variable) and environmental conditions (variable), so they **should be optimised each time**

Powder flowability	Low	High
Recoat speed (mm/s)	5	100
Roller trasverse speed (mm/s)	3	10
Roller speed (rpm)	600	400

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Stainless steel 316L

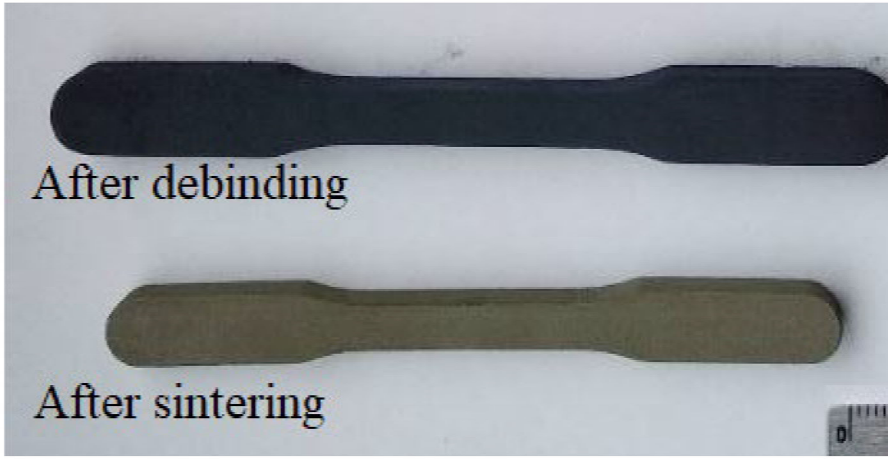
DENSITY

- High BS - after debinding the residual porosity increases, so the final density may be lower

REMEMBER

If density achieves +90%, shrinkage will be about 20% (higher in Z-direction)

Layer thickness – Binder saturation	Relative D
50 – 55	98
50 – 70	97
100 – 55	97
100 – 70	95



N. Lecis, M. Mariani, R. Beltrami, L. Emanuelli, R. Casati, M. Vedani, A. Molinari, Effects of process parameters, debinding and sintering on the microstr stainless steel produced by binder jetting, Mater. Sci. Eng. A. 828 (2021) 142108. https://doi.org/10.1016/j.msea.2021.142108.

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Stainless steel 316L

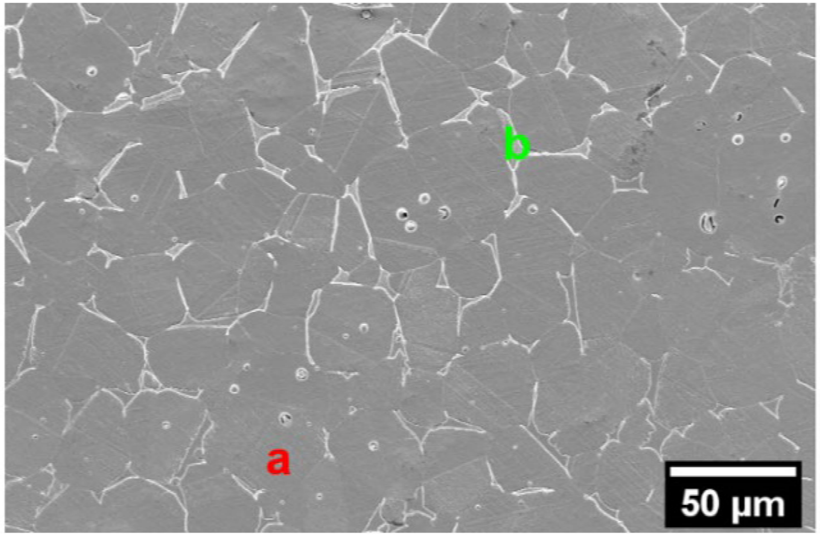
CARBON/OXYGEN CONTENT

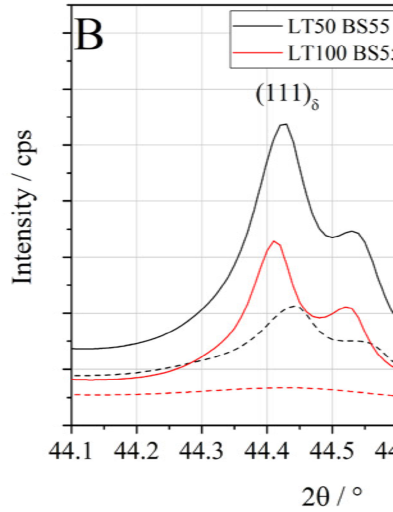
Organic material residuals may affect:

- Chemical and phase composition
- Formation of carbides/oxides

Effects on:

- Physical-chemical properties
- Mechanical performance





a-austenite b-ferrite

N. Lecis, M. Mariani, R. Beltrami, L. Emanuelli, R. Casati, M. Vedani, A. Molinari, Effects of process parameters, debinding and sintering on the microstr stainless steel produced by binder jetting, Mater. Sci. Eng. A. 828 (2021) 142108. https://doi.org/10.1016/j.msea.2021.142108.

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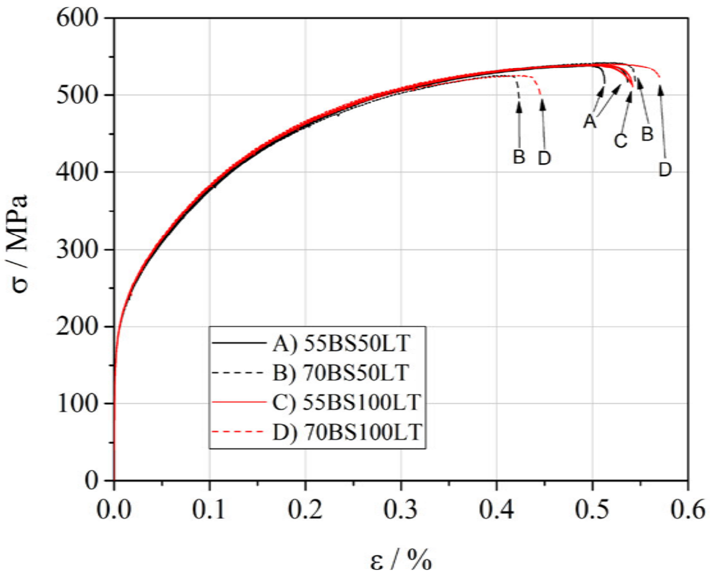
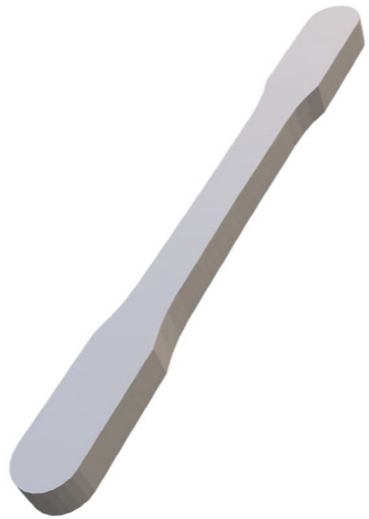
Stainless steel 316L

MECHANICAL PROPERTIES

Repeatable results regardless of the printing conditions



ASTM E8/E8M:
Tensile test on flat unmachined specimen



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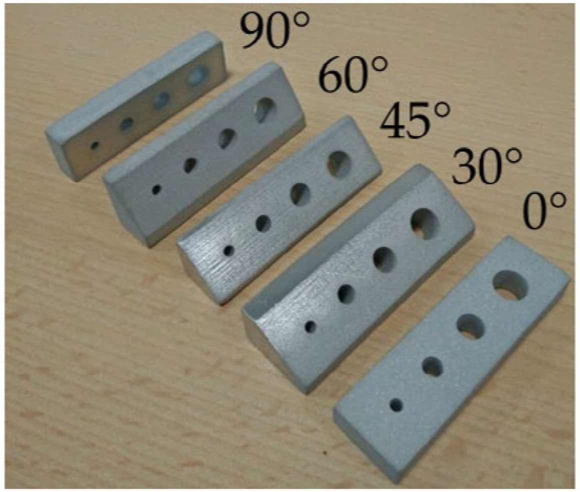
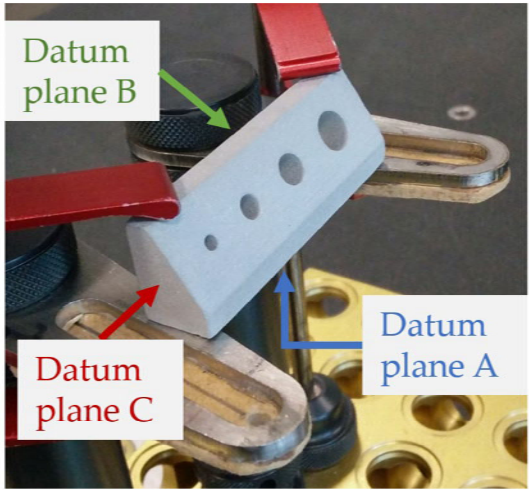
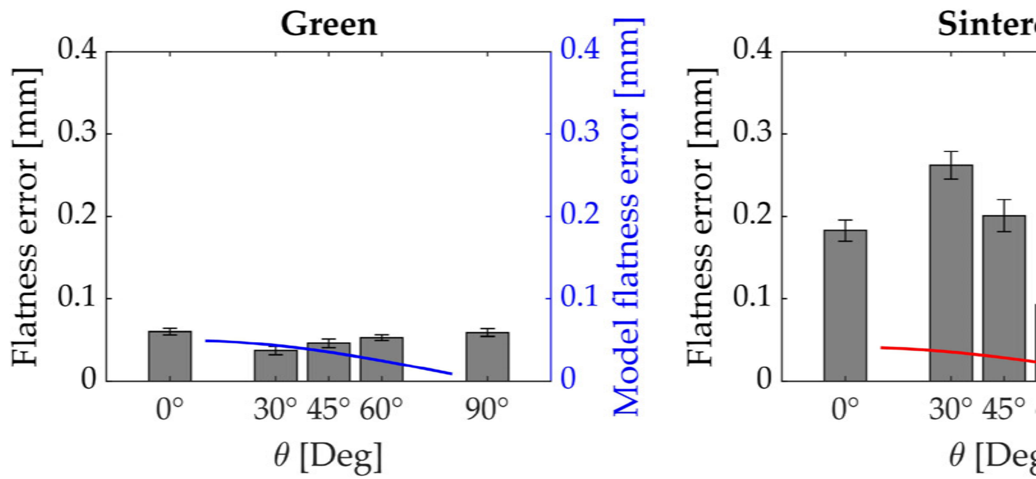
Stainless steel 316L

GEOMETRICAL ACCURACY

Large shrinkage rates may also be responsible for distortions in particular for complex geometries







M. Zago, N. Lecis, M. Mariani, I. Cristofolini, Analysis of the Flatness Form Error in Binder Jetting Process as Affected by the Inclination Angle, Metals (E
(2022) 430. https://doi.org/10.3390/met12030430.

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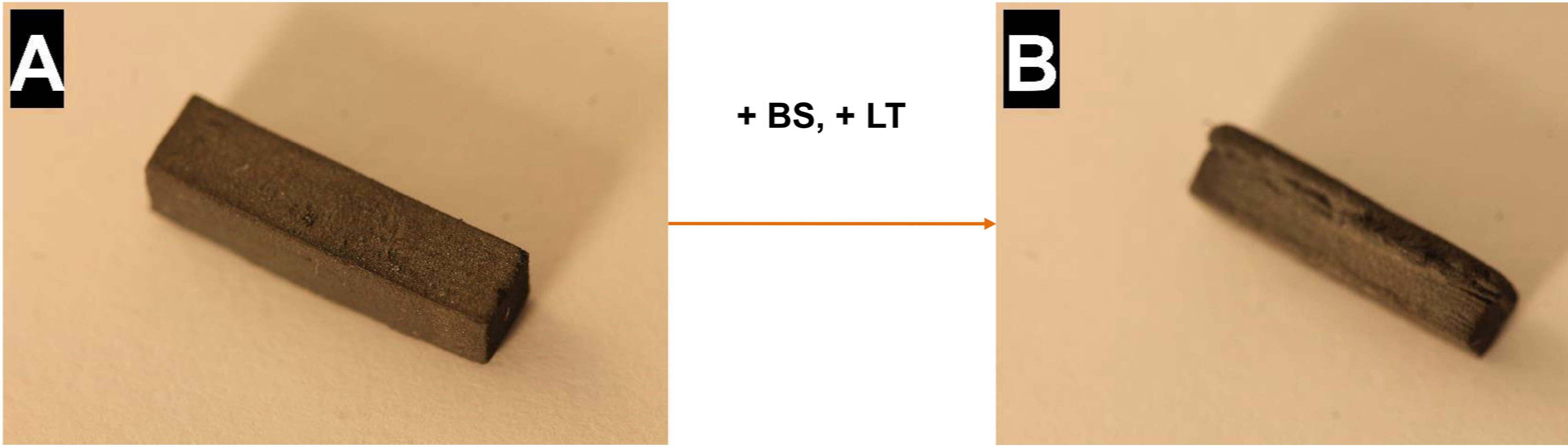
WC-Co

GEOMETRICAL ACCURACY

Defects in the green due to excessive BS and LT will be present also in the sintered parts



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Contents

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The curing process is binder-dependent

Our standard procedure:

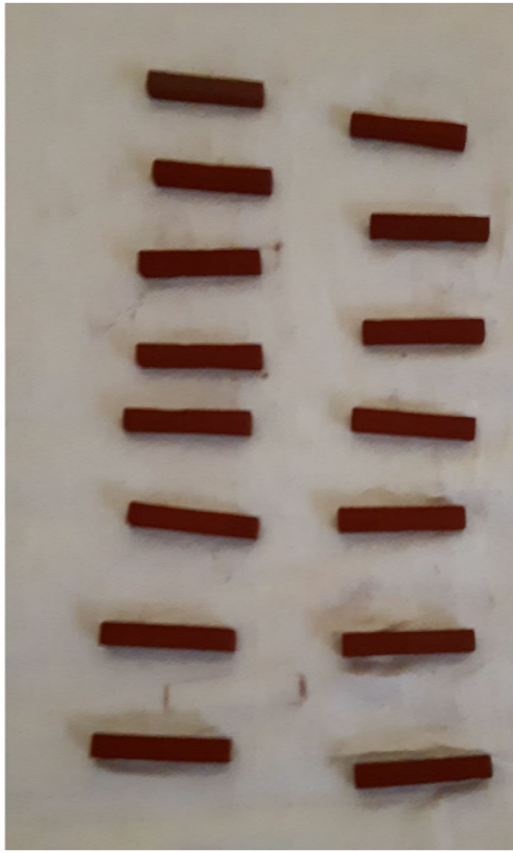
- 180 °C for 6 hours
- Air
- Simple natural convection oven

We obtain the evaporation of the solvents and the polymerization of the reactants to obtain polyethyleneglycol (PEG)

Main problem: curing may affect the properties of metallic alloys sensitive to **oxidative atmospheres** even at low temperatures (e.g. pure copper)

Consequences:

- Need for **reducing atmosphere/processes** later
- Reduction of the **recyclability** of the powders



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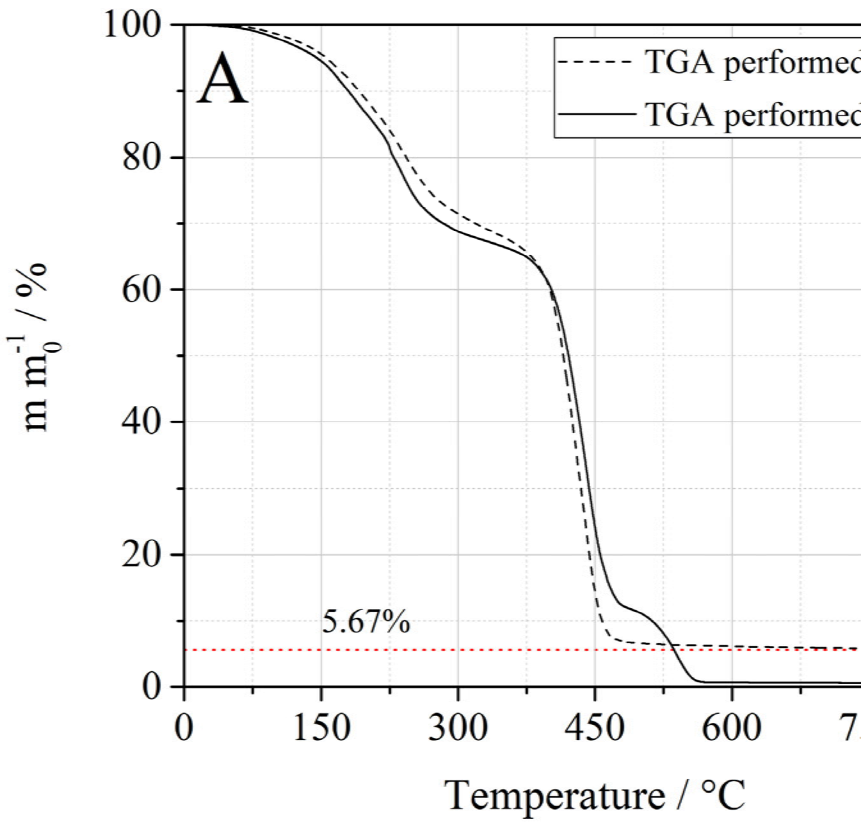
The debinding process is binder-dependent (BA005 or AquaFuse ®)

Our standard procedure:

- 470 °C for 4 hours
- Air / inert atmosphere

We obtain the progressive burnout of the polymer

Main problem: debinding may affect the properties of metallic alloys sensitive to **oxidative atmospheres**, but the polymer is not completely pyrolised under inert atmosphere



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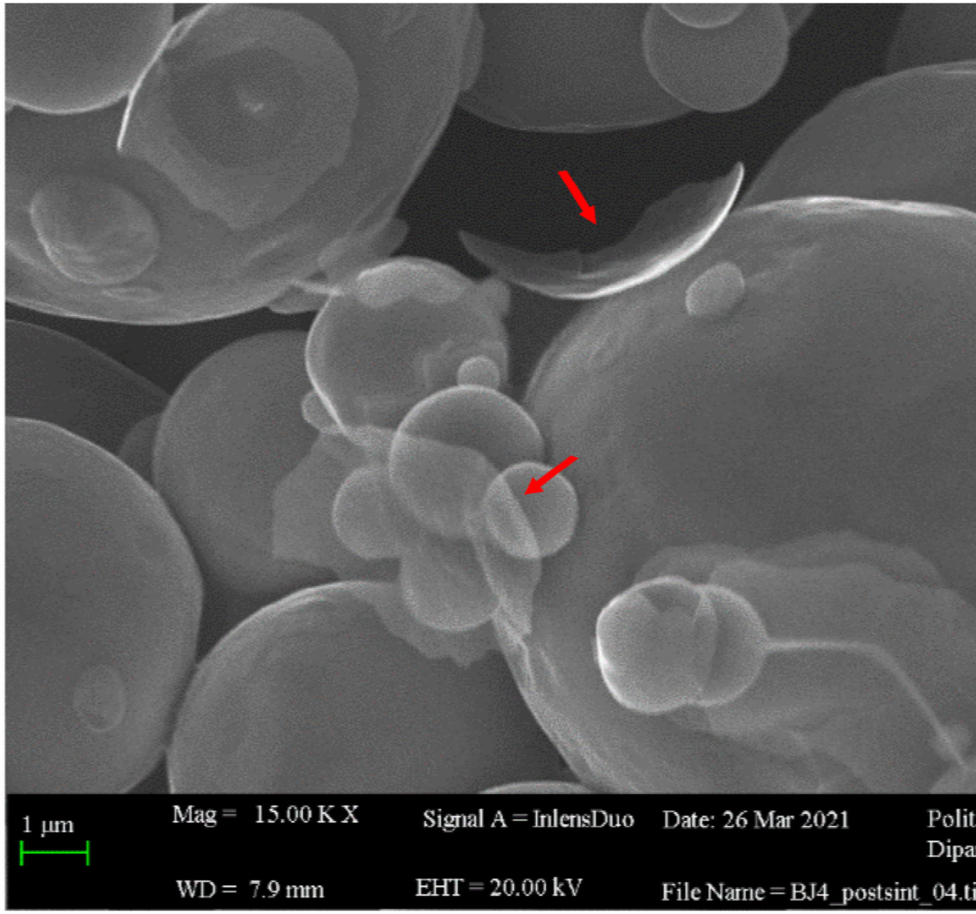
Debinding

Consequences:

- Need for **reducing atmosphere/processes** later if air-debinded
- Presence of **residual polymer ashes (C,H)** if argon-debinded

Sometimes debinding can be followed by pre-sintering to strengthen the component and avoid the collapse of the body under its own weight



The sintering process is material- and process-dependent

Each material needs an optimised thermal treatments, overall we observed:

- **The T_{sint} is much closer to the melting point** than typical temperatures of MIM or other powder m process because the densification needed is large (from 50% of the green to 98-99% after sintering
- The presence of **a liquid phase is desired** to fill residual porosity
- **Vacuum sintering may increase density** because it degasify the pores before their closure
- **Reducing atmospheres are needed in case of oxides formation** during curing-debinding

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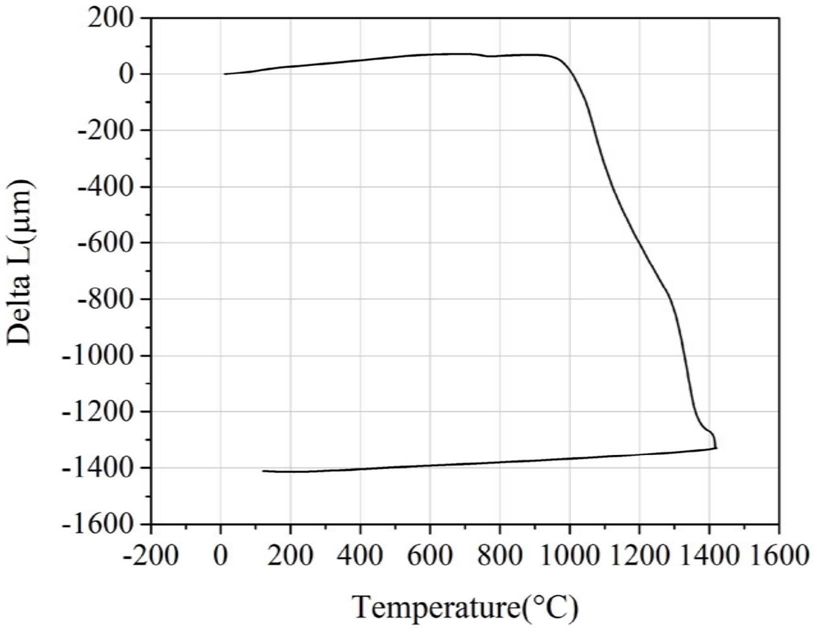
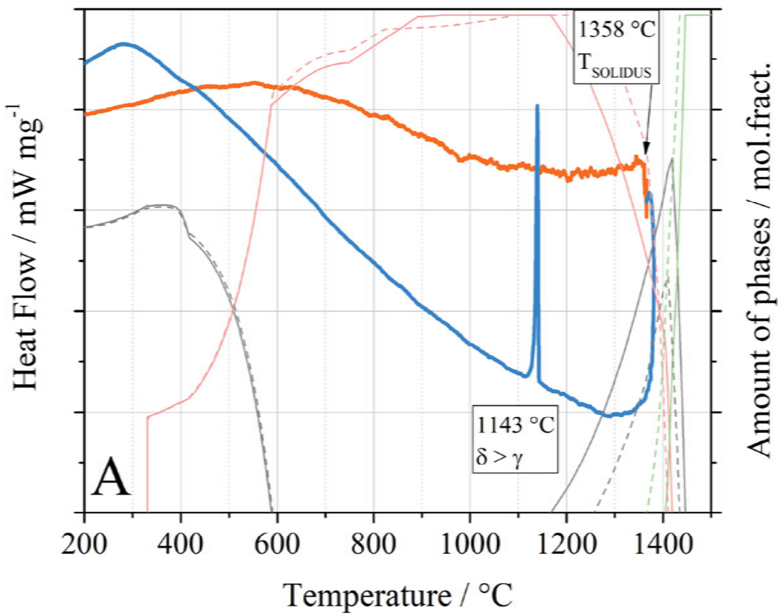
Liquid phase / supersolidus sintering study

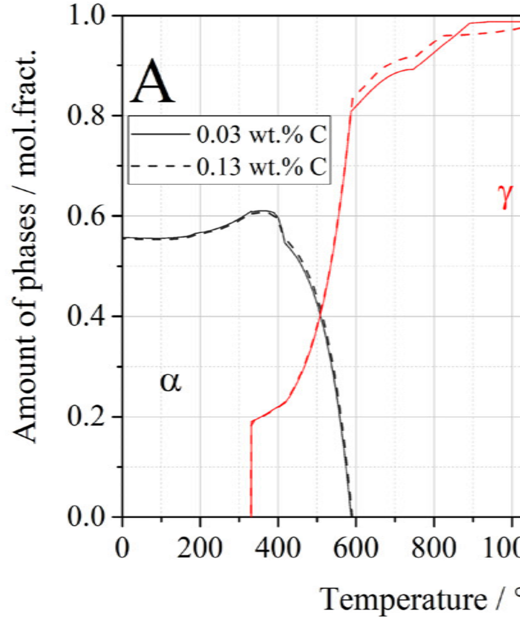
DILATOMETRY



DSC



THERMOCALC SIM



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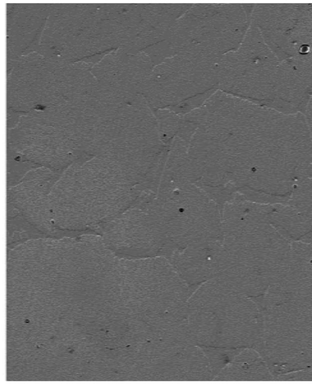
Stainless Steel 316L



Curing	Debinding	Sintering	
Air, 180 °C, 6 hours	Air, 470 °C, 4 hours	Argon, 1360 °C, 3 hours	OXIDES FORM
Air, 180 °C, 6 hours	Argon, 470 °C, 4 hours	Argon, 1360 °C, 3 hours	LIMITED DENSIF
Air, 180 °C, 6 hours	**Argon, 470 °C, 4 hours**	**Vacuum, 1360 °C, 3 hours**	**OPTIMAL R**
Air, 180 °C, 6 hours	Air/Argon, 470 °C, 4 hours	Ar+H_2, 1360 °C, 3 hours	ALTERNATIVE

N. Lecis, M. Mariani, R. Beltrami, L. Emanuelli, R. Casati, M. Vedani, A. Molinari, Effects of process parameters, debinding and sintering on the microstr stainless steel produced by binder jetting, Mater. Sci. Eng. A. 828 (2021) 142108. https://doi.org/10.1016/j.msea.2021.142108.

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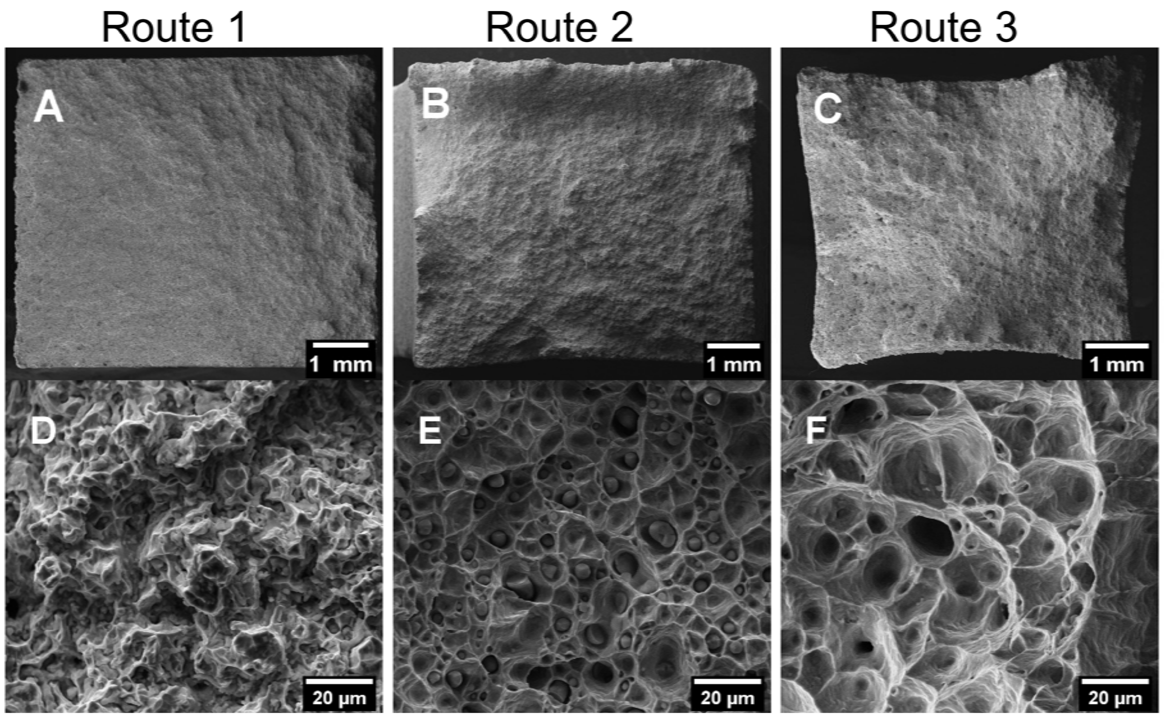
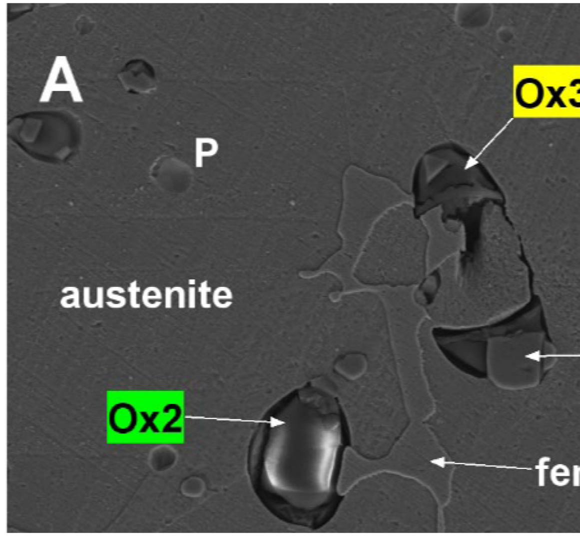
The presence of oxides hinders the densification process and affects the mechanical properties of the components





N. Lecis, R. Beltrami, M. Mariani, Binder jetting 3D printing of 316 stainless steel: Influence of process parameters on microstructural and mechanical pr
Metall. Ital. 113 (2021) 31–41.
https://www.researchgate.net/publication/352249008_Binder_jetting_3D_printing_of_316_stainless_steel_influence_of_process_parameters_on_micros
mechanical_properties.

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The combined effect of debinding and sintering it is relevant at high strain because precipitates and secondary phases facilitates the formation of voids and cracks

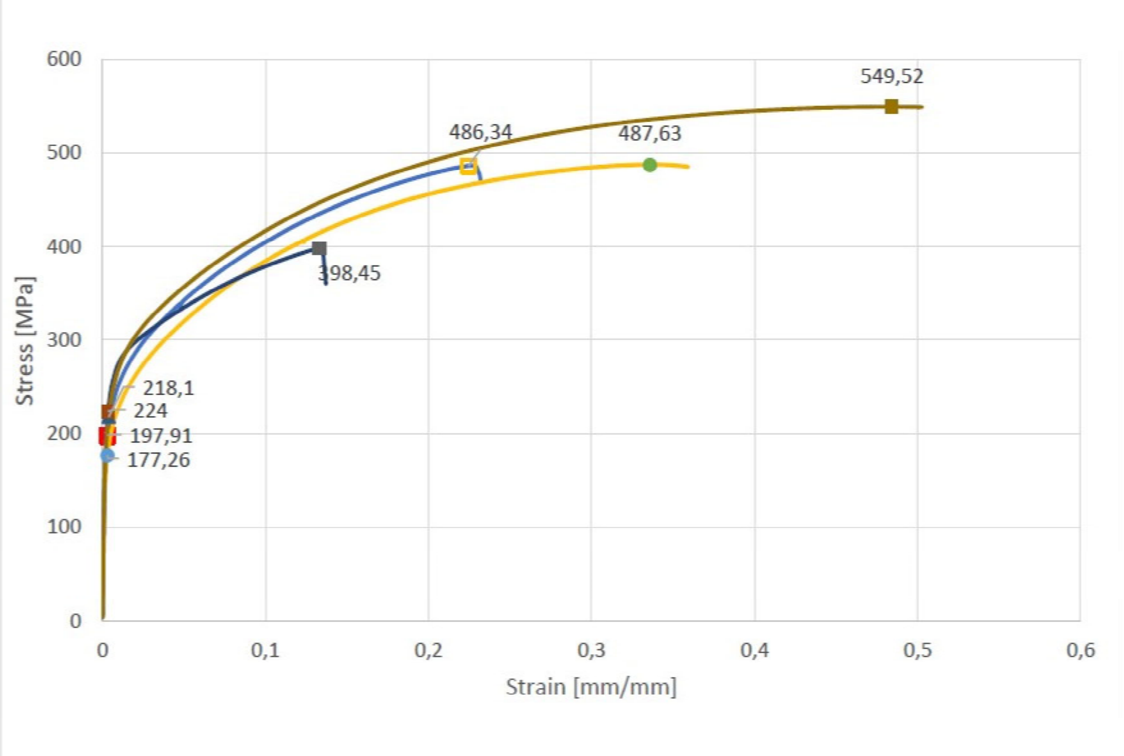

Figure 155: comparison stress/strain diagram for sample TAG (dark blue, debinded at 600°C in air); sample G4 (light blue, debinded in air at 470°C); sample H7 (yellow, debinded in argon at 470°C) and sample ExOne6 (brown, debinded in air at 470°C and sintered in hydrogen)

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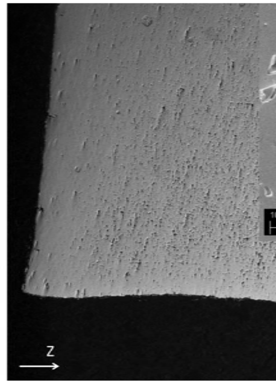
Pure Copper



Curing	Debinding	Sintering	
Air, 180 °C, 6 hours	Argon, 470 °C, 4 hours	Argon, 1000 °C, 3 hours	RESIDUAL
Air, 180 °C, 6 hours	Argon, 470 °C, 4 hours	Ar+graphite, 1000 °C, 3 hours	RESIDUAL
Air, 180 °C, 6 hours	**Argon, 470 °C, 4 hours**	**Air+graphite, 1000 °C, 3 hours**	**OPTIMAL**
Air, 180 °C, 6 hours	Argon, 470 °C, 4 hours	$Ar+H_2$, 1000 °C, 3 hours	ALTERNATIV

T. Romano, E. Migliori, M. Mariani, N. Lecis, M. Vedani, Densification behaviour of pure copper processed through cold pressing and binder jetting unde atmospheres, Rapid Prototyp. J. (2022). https://doi.org/10.1108/RPJ-09-2021-0243.

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Sintering

Reduction processes are often needed, possible solutions are:

- Reducing atmosphere (pure H_2 or gas mixtures)
- Adding a carbon source the furnace chamber to subtract O_2 by formation of CO and CO_2
- Exploiting residual C and H_2 from incomplete debinding to subtract O_2 by formation of H_2O, CO and
- Postprocessing (e.g. pickling treatments)

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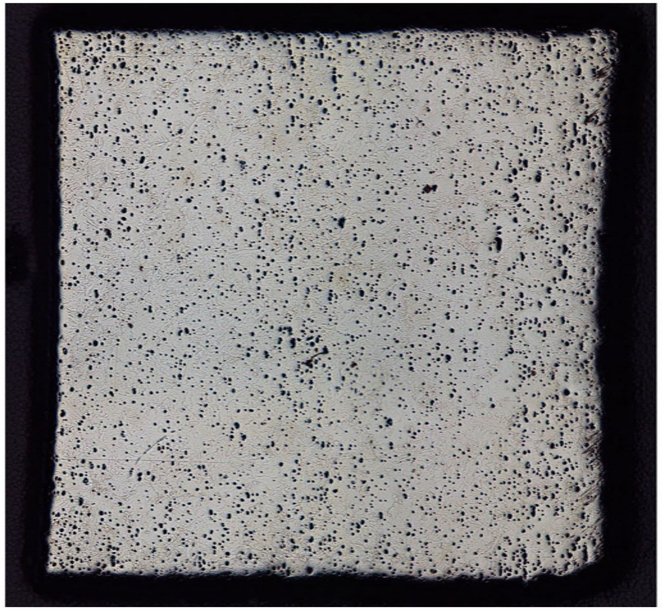
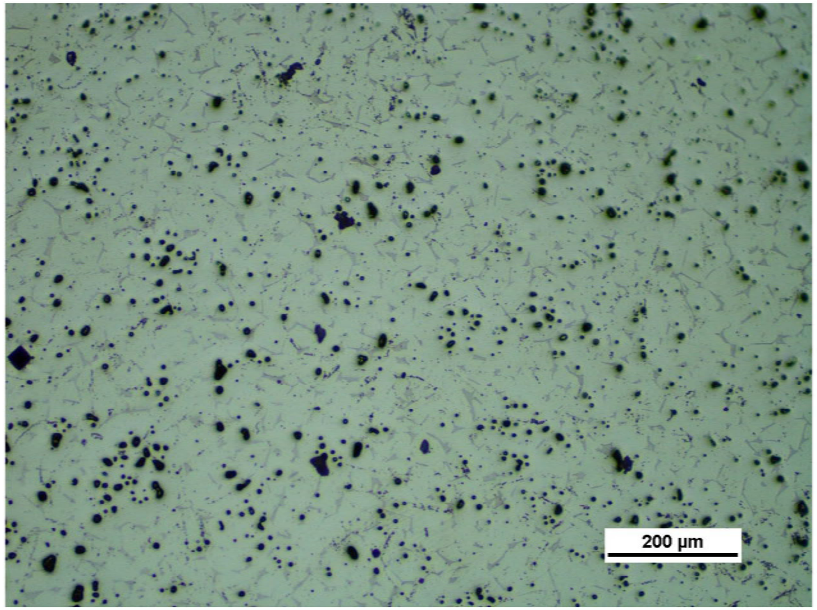
Hot Isostatic Pressing (HIP)

Helpful to remove the residual closed porosity when the sintered density is in the 90-97% range

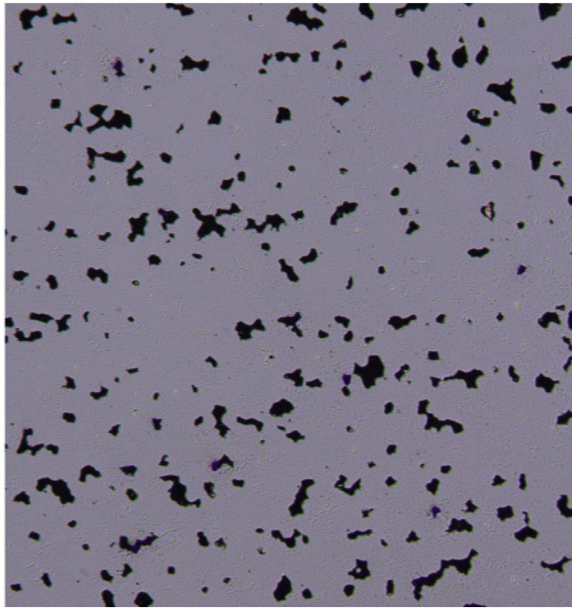
steel 17-4PH



steel 316L



WC-Co



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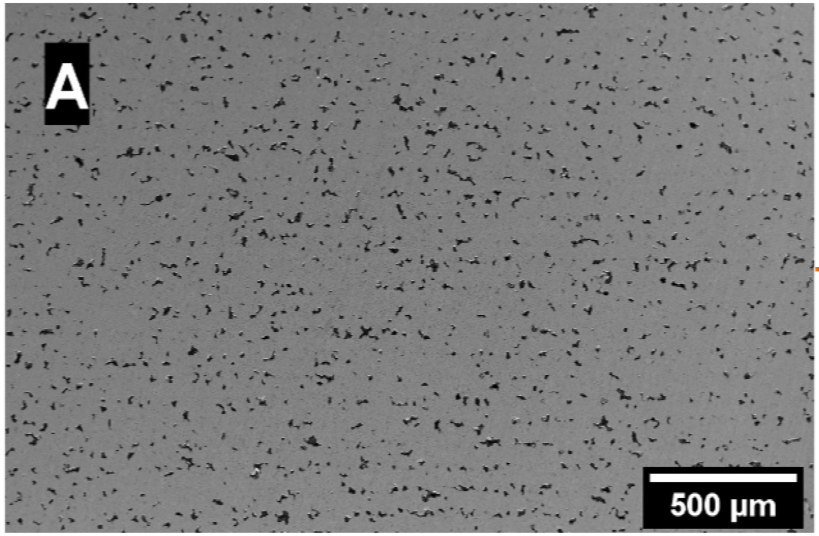
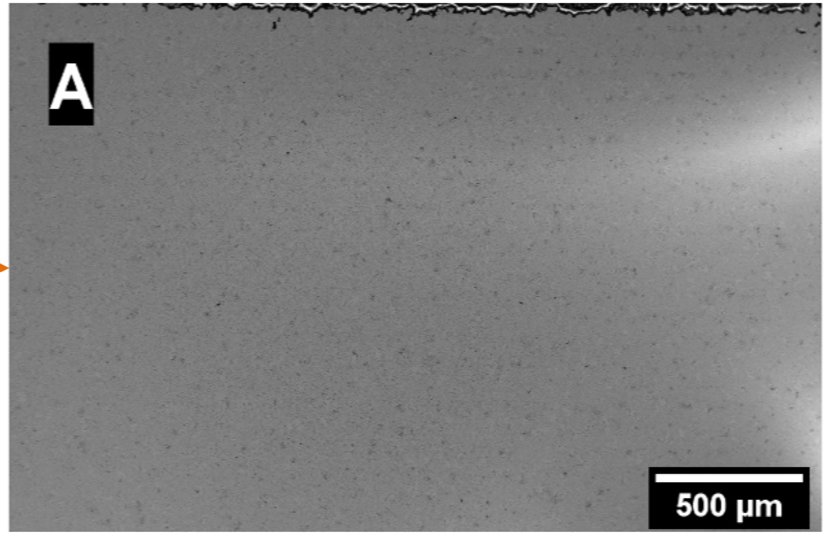
Hot Isostatic Pressing (HIP)

Helpful to remove the residual porosity, in particular in between layers

Case study: WC-Co, 35 bar at 1400 °C for 20 minutes





Density: 97.4% 99.3%

M. Mariani, I. Goncharov, D. Mariani, G. Pietro De Gaudenzi, A. Popovich, N. Lecis, M. Vedani, Mechanical and microstructural characterization of WC-consolidated by binder jetting additive manufacturing, Int. J. Refract. Met. Hard Mater. 100 (2021) 105639. https://doi.org/10.1016/j.ijrmhm.2021.105639

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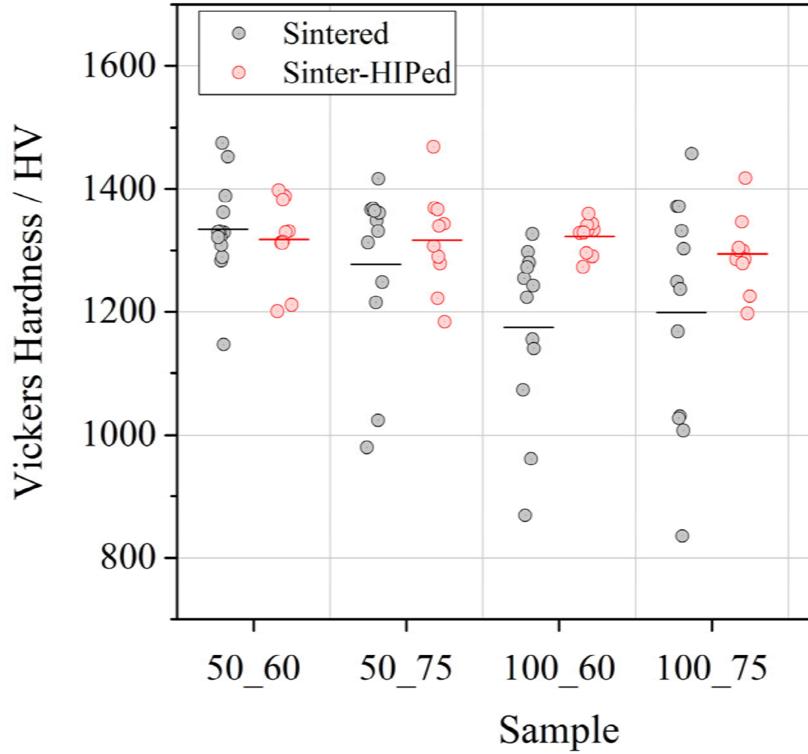
Hot Isostatic Pressing (HIP)

Case study: WC-Co, 35 bar at 1400 °C for 20 minutes

Removing porosity and all organic residuals allows to obtain comparable microstructure regardless of the initial printing conditions

For example, the average microhardness of WC-Co from 5 different printing parameters combinations becomes repeatable after removing the remaining 2-3% of closed porosity



M. Mariani, I. Goncharov, D. Mariani, G. Pietro De Gaudenzi, A. Popovich, N. Lecis, M. Vedani, Mechanical and microstructural characterization of WC-
consolidated by binder jetting additive manufacturing, Int. J. Refract. Met. Hard Mater. 100 (2021) 105639. https://doi.org/10.1016/j.ijrmhm.2021.105639

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Conclusions

Printing parameters

- Density, geometrical accuracy and mechanical resistance of the green components
- Residual porosity distribution and phase composition (thus mechanical properties) of the sintered components

Thermal treatments

- Possible presence of organic residuals in the microstructure
- Formation of oxides/precipitates/secondary phases
- Densification mechanism

Best practice

- Minimise layer thickness and binder saturation
- Reduce oxidation during curing/debinding to avoid the need of reducing atmosphere during sinterin
- Employ vacuum sintering to degasify porosity and achieve large densification

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1) Binder saturation should be

A. As low as possible
B. As large as possible
C. Optimised for depowdering
D. 50%

2) In which directions shrinkage is largest?

A. Z
B. All
C. X
D. Y

3) Which limitations must be considered for debinding?

A. Oxidation of metals
B. Efficiency of binder burnout
C. Production of resistant parts
D. All the previous answers

4) What is the purpose of pressure-assisted treatments?

A. Build an initial powder bed substrate
B. Remove residual porosity
C. Control the shape of the final components
D. All the previous answers

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Thank you!

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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Cost and Value analysis in MBJ

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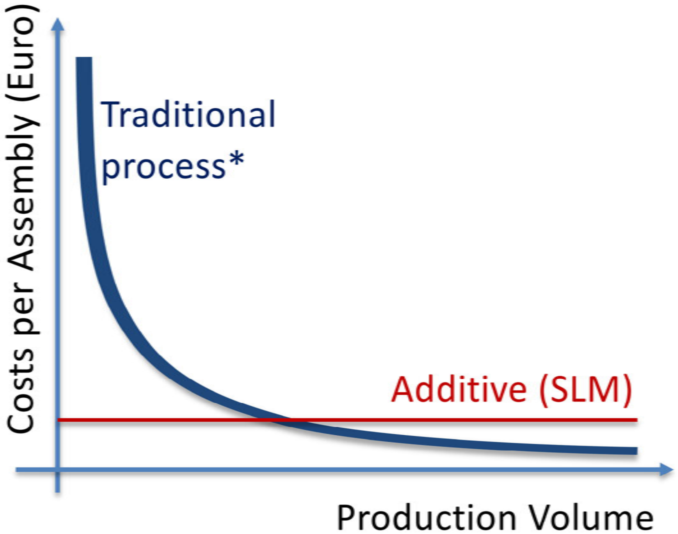
Value … and costs (SLM)

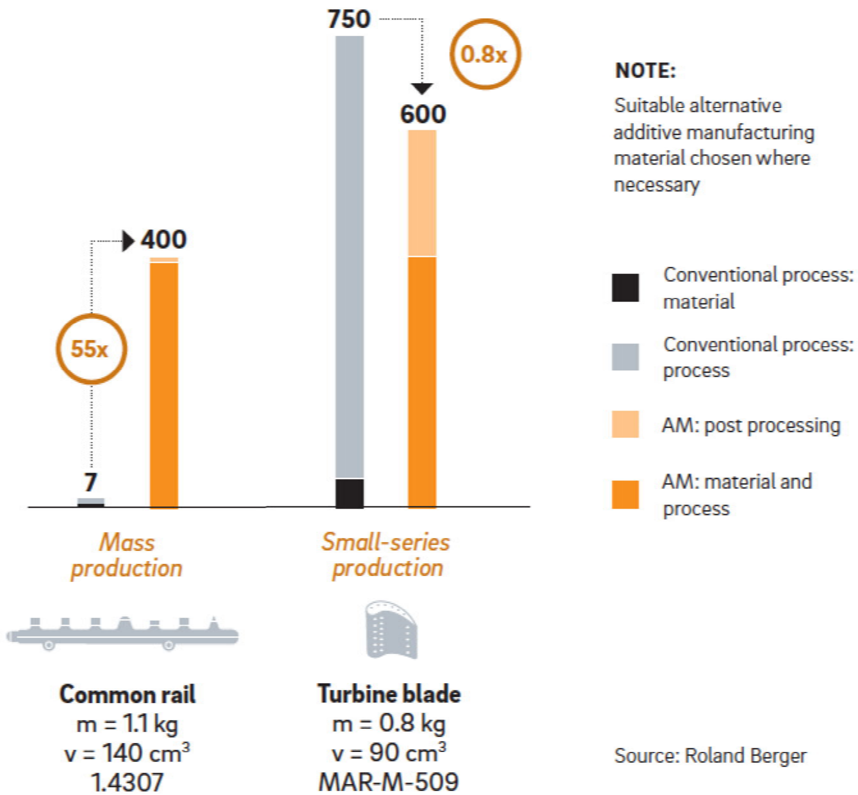


Atzeni & Salmi, 2011

*High-Pressure Die casting

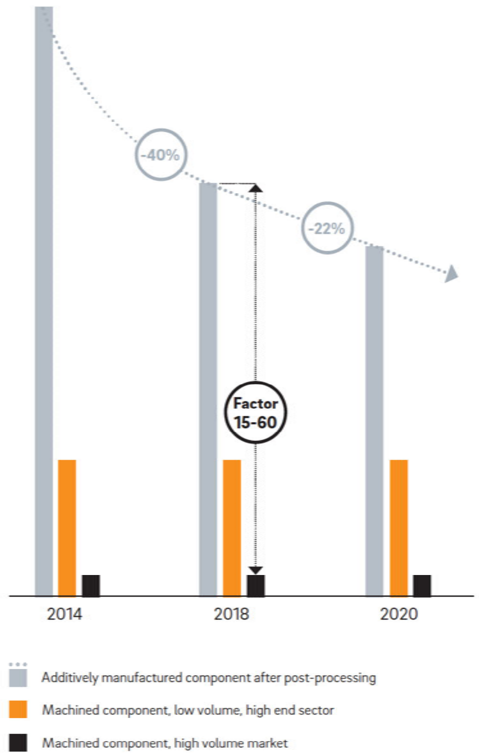
B: Cost comparison

Cost of conventional manufacturing vs. PBF-L, approximation assuming conventional geometries (EUR, schematic)



Source: Roland Berger

The gap is reducing but not so quickly



Different AM technologies for different requirements

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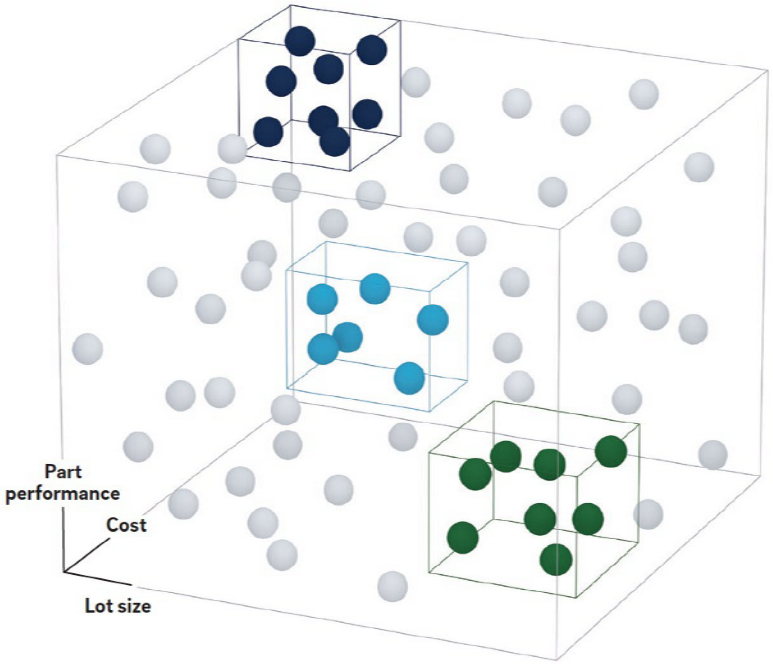
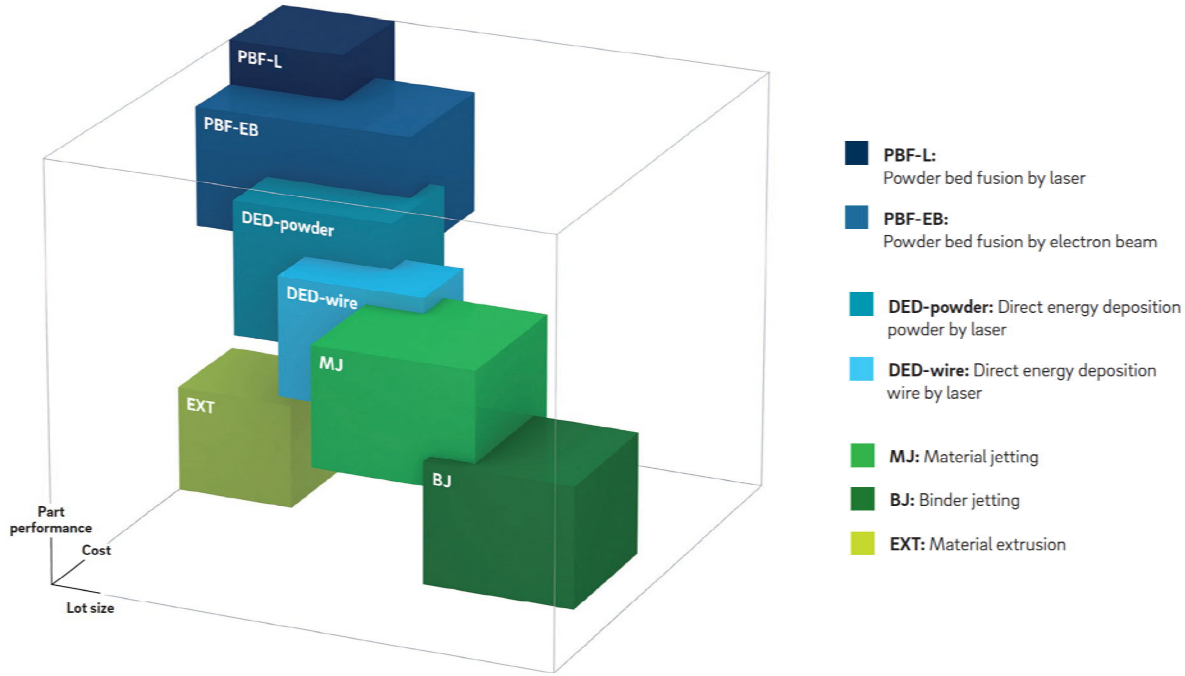
Cluster 1: High performance requirements at small lot sizes and high cost tolerance (e.g. PBF-L)

Cluster 2: Medium to high performance requirements at small to medium lot sizes and medium cost tolerance (e.g. DED)

Cluster 3: Lower performance requirements at higher lot sizes and lower cost tolerance (e.g. binder jetting)





What about VALUE?

AM should not be interpreted as a substituting technology!

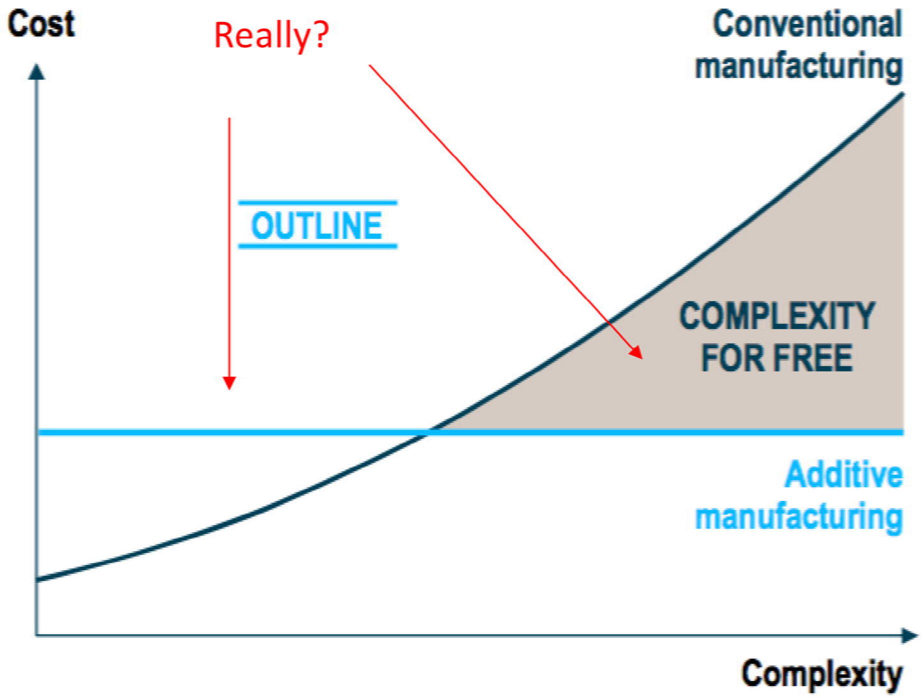
Costs

Flexibility
Easiness of use
Safety

Value
complexity for free (with the exception of the design cost):

- product improvement:
- Performances (thermo-mechanical; lightweight; reliability/durability, …)
- Number of components (supply chain)
- Spare parts
- Customization
- Sustainability (design&manufacturing)

Costs and values



Cost analysis of AM has to model dependencies of the process, and capture the value in use when compared to current alternatives

AM Costs

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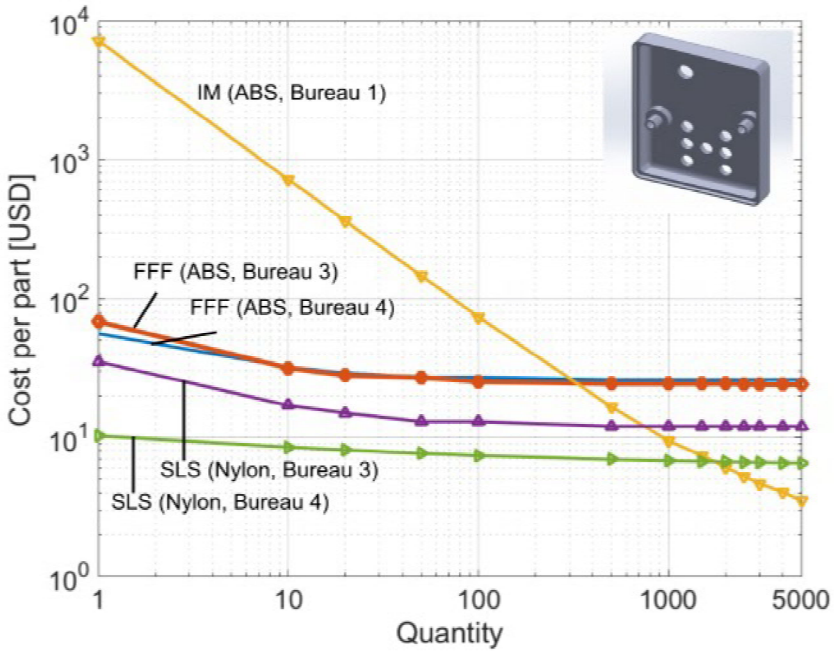
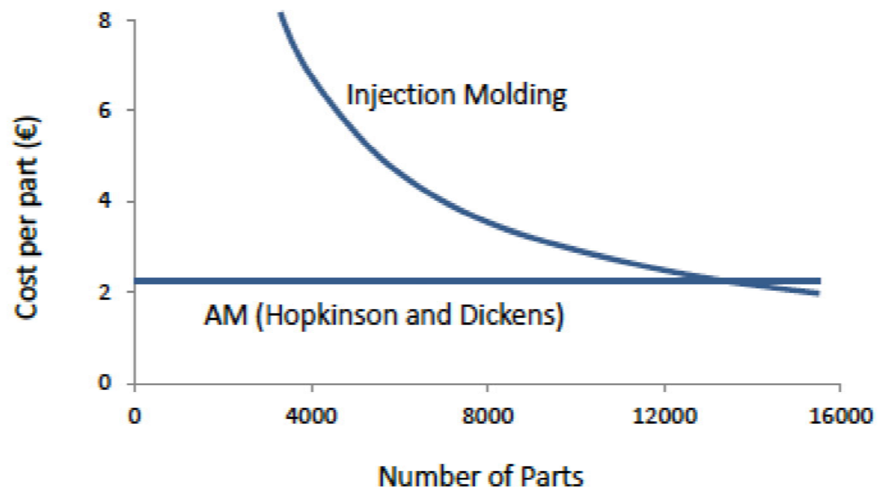


Figure 4.1: Hopkinson and Dickens (2003) Cost Model Compared to Injection Molding



Adapted from Hopkinson and Dickens (2003)

Quinlan, Hasan, Jaddou, Hart. Journal of Industrial Ecology, 2017.

A possible Cost model

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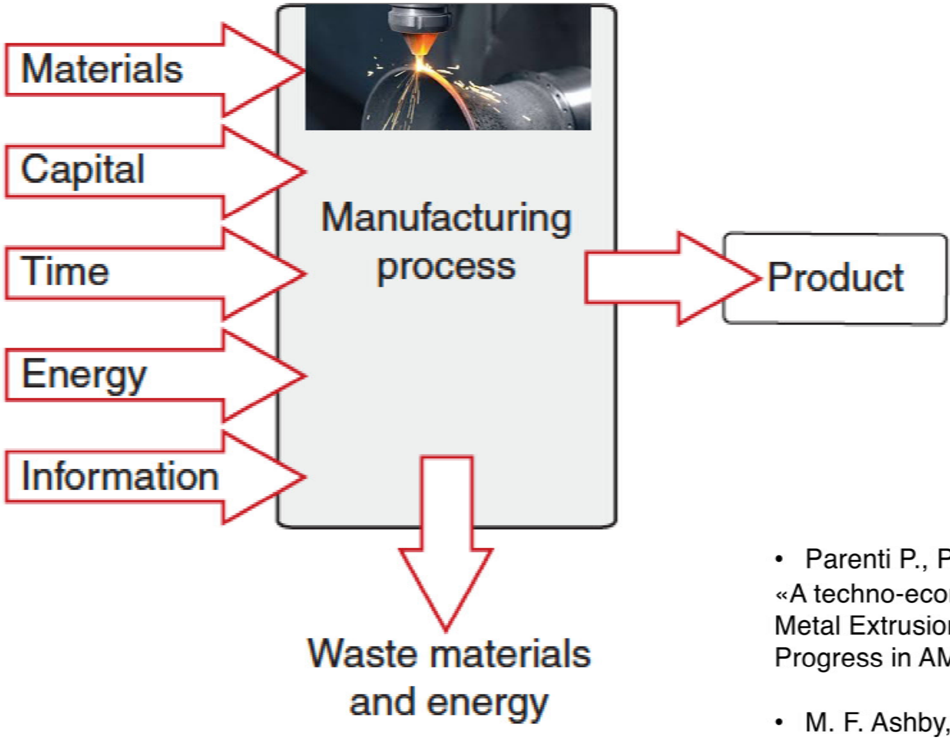

- Parenti P., Puccio D. Semeraro Q., Colosimo B.M. (2023)
«A techno-economic approach for decision-making in metal Additive 1 Manufacturing: Metal Extrusion versus Single and Multiple Laser Powder Bed Fusion – to appear in Progress in AM

- M. F. Ashby, "Materials Selection in Mechanical Design"
- The Cambridge Material Selector *(CES)* software -- Granta Design, Cambridge (www.grantadesign.com)

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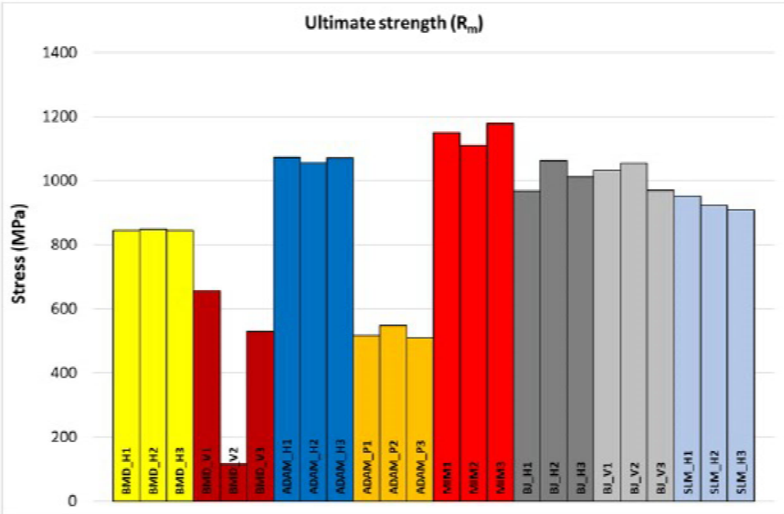
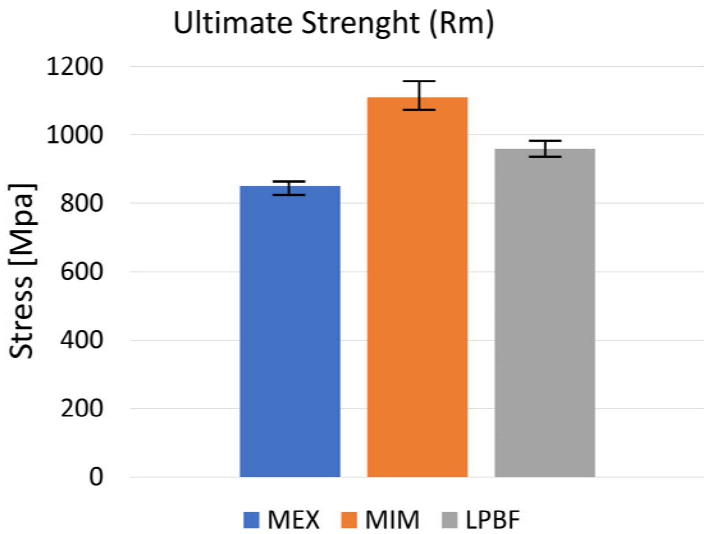
Assuming a frozen design to compare different technologies

Cost analysis is usually possible when it is assumed that the functional performances are satisfied

- Tensile
- Fatigue
- Ra
- Tolerances
- …





Differences in Stress/Strain and UTS, adjusted from Masurtschak et al. [28]

Assuming different processes respect the functional specifications, cost analysis can be used to assess a comparison

S. Masurtschak, U. Irastorza, U. Andres, M.I.M.T.A.S. L, A. Otaola, A Comparative Study of Mechanical Properties for MIM Standard 17-4PH Samples Manufactured via Binder Jetting and Material Extrusion, (n.d.) 2–7.

MAKE OR BUY?

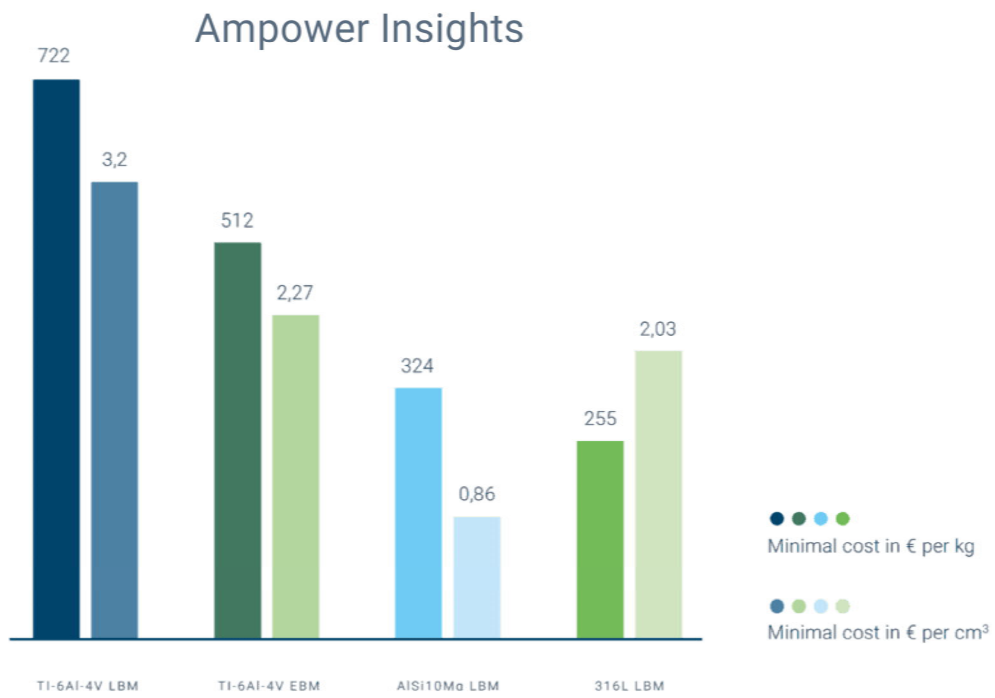
Co-funded by the Erasmus+ Programme of the European Union

AMPOWER

Cost Additive Manufacturing

The make or buy decision is becomes very important for success of the business case. Especially for SMEs, however, high part cost is still the main restriction for further wide-spread adoption of this production technology.
For Laser and Electron Beam Melting (LBM and EBM), a significant part of the (AM) manufacturing/ production costs results from high machine hourly rates of 40-50 €/h paired with relatively slow building speeds.

Ampower Insights gives a detailed calculation of production costs and introduces the ratio of cost per unit of volume for an easy comparison of technologies and materials. Today, the in-house production cost ranges between 0,86 €/cm³ for aluminum alloy AlSi10Mg to 3,20 €/cm³ for light-weight and medical grade titanium alloy Ti-6Al-4V.



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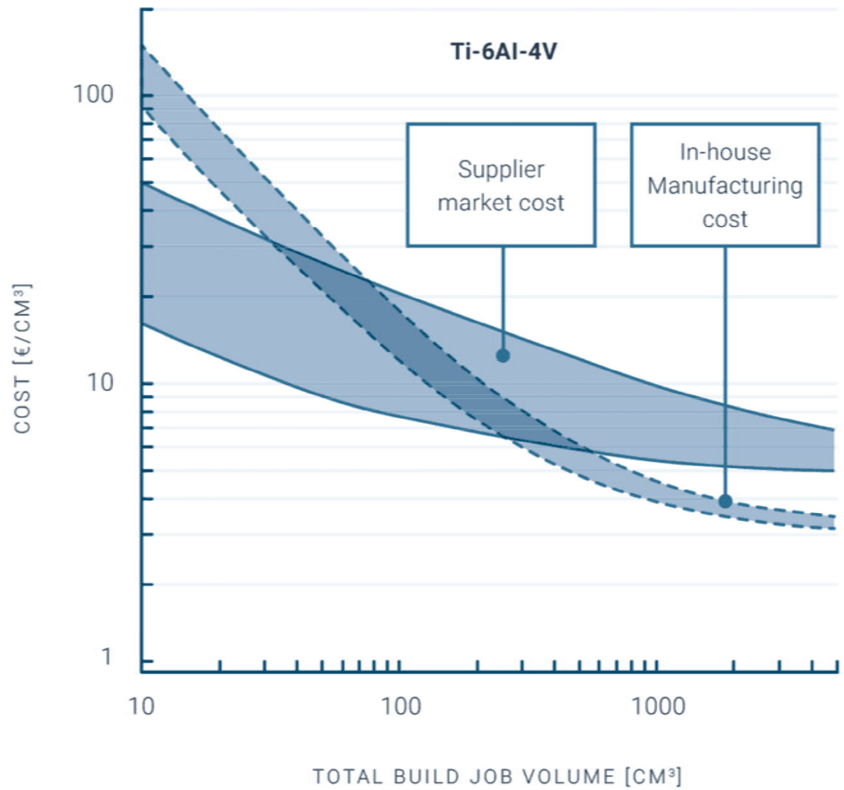
AMPOWER

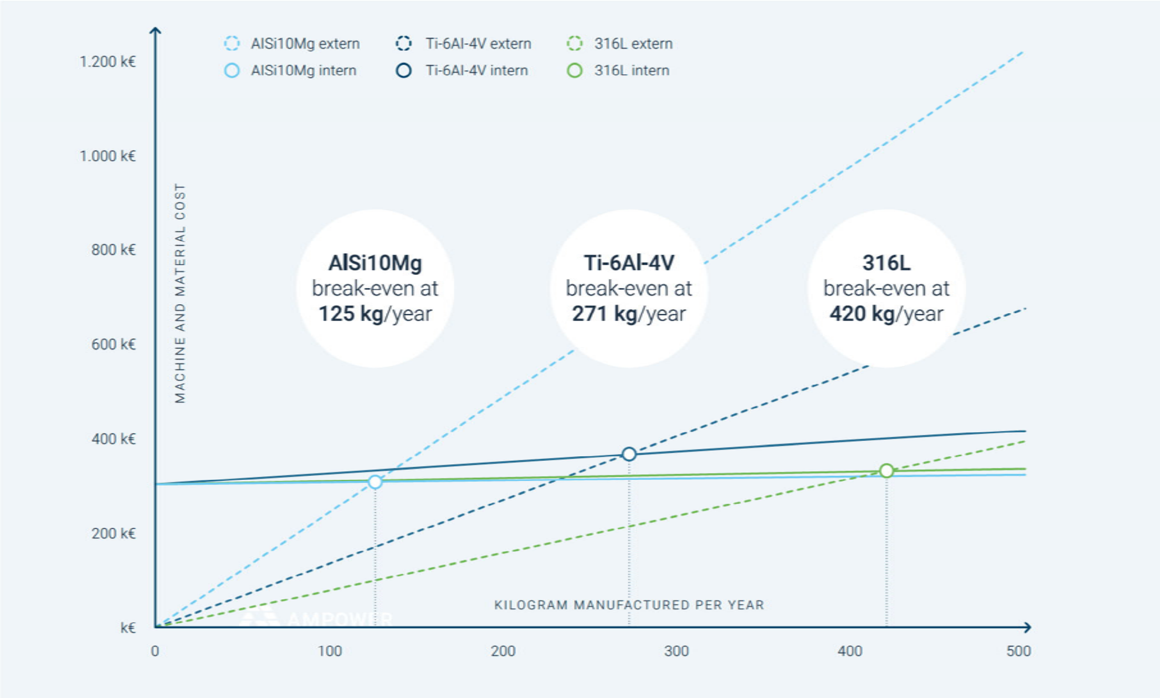
Cost of service bureaus

The existing market of metal service bureaus is analyzed for a representative depiction of market prices. The AM capacity at suppliers currently consists of a total of approximately 120 machines installed in service bureaus in the selected study region Germany, Switzerland, and Austria.

Market prices range between 3-10 €/cm³ for finished aluminum parts, representing a spread of 35-240% around the mean value. The price spread for titanium parts is significantly lower with market prices around 5-7 €/cm³.



Make or buy?



Make vs. Buy

Make	Buy
Large overheads increase production cost	Low investment in infrastructure
High initial investment and risk	Know-how transfer and synergies between partners
Development of protected material parameters	IP protection insufficient
IP on industrial production and quality assurance process	No developments in machine or material
High production integration increases quality	No increase of internal Know-how

Costs «ingredients»

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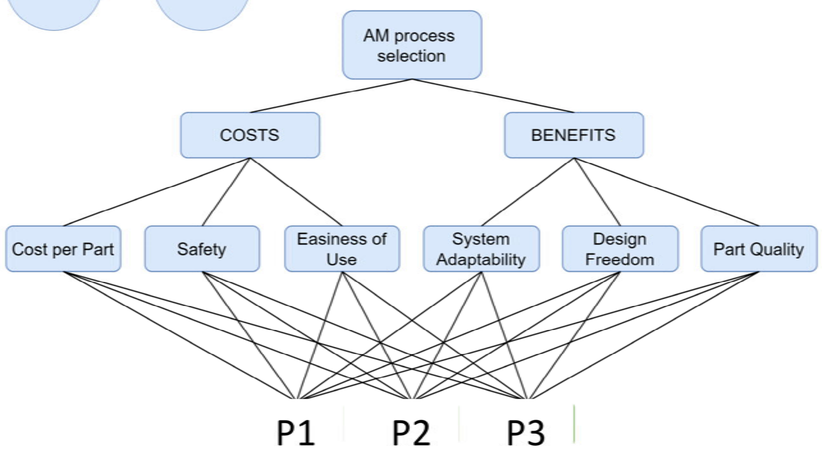

- Cost per part
- Safety (in use and maintenance)
- Easiness of use (skill levels)
- System adaptability (material range, material suppliers, and setup time).
- Design Freedom (maximum build size, lattice structures, or parts with internal features and thin walls).
- Part quality (dimensional/geometrical tolerances-post-processes required).

Assumptions (to be considered)

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a) Each build contains a fixed number of parts, and it is filled to saturation, depending on the part volume and build area constraints.

b) The yearly machine uptime *u* is 5400 h/y.

c) The baseline comparison in terms of maximum production volume is considered the saturation condition of the LPBF-SL system.

d) Different process systems are configured in a way to achieve the same production volume (for MBJ – define appropiate dimensioning of the system: printer, the debinder or the furnace)

e) The scrap rate *f* identifies the percentage of the out-of-spec parts produced.

f) Machine is totally dedicated to one part type

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TOTAL cost [€/part]

MATERIAL [€/part]

TOOLING [€/part]

$$C = C_{eq} + C_{mat} + C_{en} + C_{tool} + C_{OH}$$

COST OH [€/part]

COST OF ENERGY [€/part]

CAPITAL COST OF THE EQUIPMENT [€/part]

Cost of Equipment (AM machine)
(machine totally dedicated to one patrt type)

15

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$$C = \boxed{C_{eq}} + C_2 + + C_4$$

- Equipment = AM machine
- Represents all machines needed to meet desired production rate (for AM it might just be one – ideally it is at full capacity)

Cost per piece due to equipment

$$C_{eq} = \frac{c_{mac,eq}}{N \cdot (1-f)}$$

$$c_{mac,eq} = \frac{C_{machine}}{Lt_{op}} \ (€/y)$$

L: Load factor, fraction of time for which equipment is productive [-]

$\mathbf{t_{wo}}$: lifetime of equipment (simple straight line depreciation model) [h]

yearly investment for a new AM system, which includes the yearly depreciation cost of the machine and the accessory equipment (adopting a linear depreciation model over *y* years), plus the yearly maintenance and software costs

N (parts/y)

f the scrap fraction

General comments

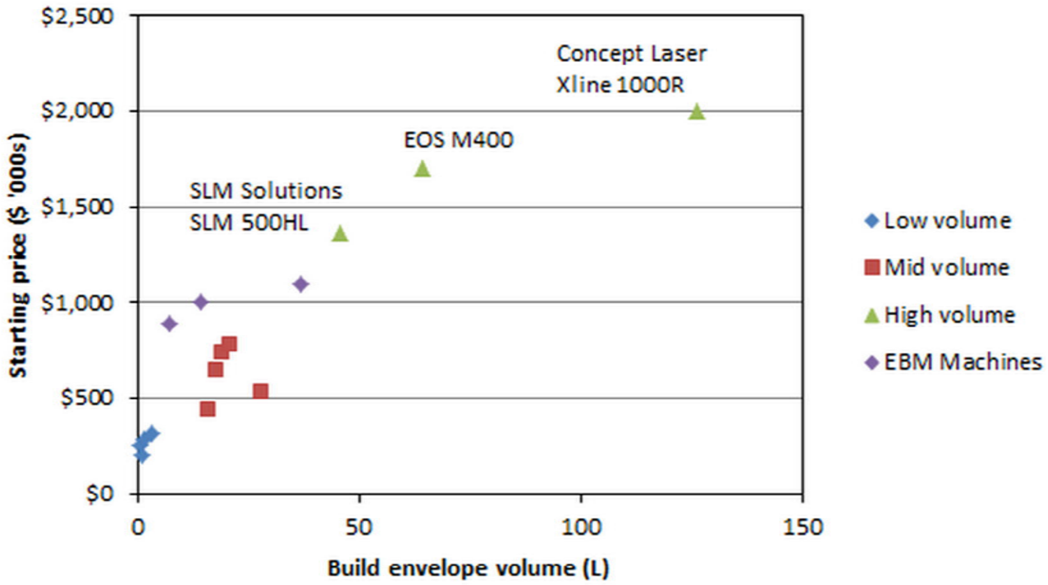
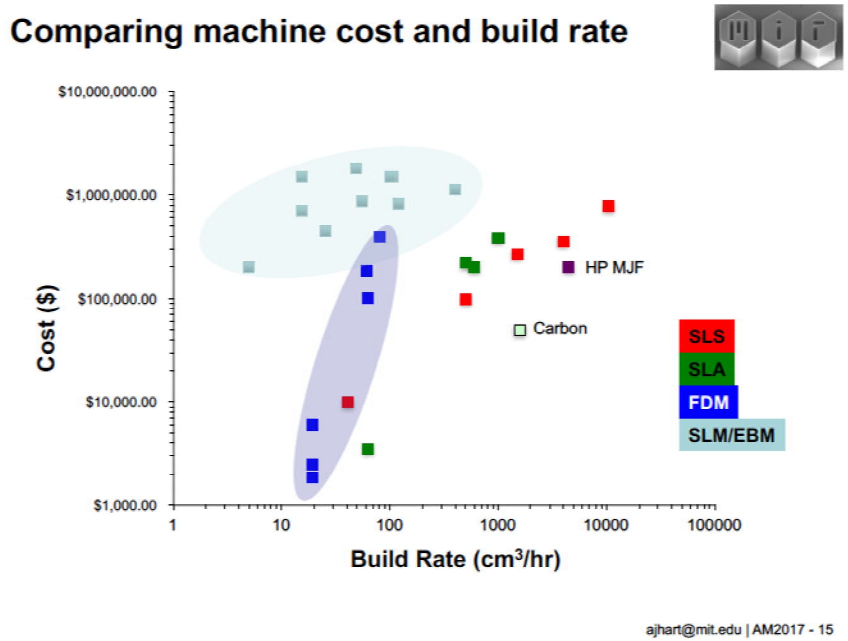


Figure 2.1: Starting price of SLM machines segmented into low, mid and large build envelope volume. Prices of EBM machines are shown as well.



Please do not share – courtesy of John Hart – MIT

Material costs

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$$C = C_{eq} + C_{mat} + C_{en} + C_{tool} + C_{OH}$$

$$C_{mat} = \left(M + \frac{m_w}{n_b}\right) \cdot \frac{c_m}{1-f}$$

- c_m is the cost of the material (€/kg),
- m is the final part mass (kg/part), which includes the material used for the part and all the supports,
- m_w (kg/build) represents the mass of material wasted
- n_b (part/build) number of parts fabricated in one single build

The material waste consists of non-recyclable powder for the LPBF process and wasted metal-binder mixture for MBJ/MEX (e.g., the material lost for purging and cleaning the extrusion nozzle).

Energy costs

$$C_{en} = c_{en} \frac{e \cdot t_b}{n_b \cdot (1 - f)}$$

- c_{en} (€/kWh) is the unit cost of the energy,
- e is the machine power consumption (kW),
- t_b is the time of machine-related activities in a building job (h/build)
- n_b represents the number of parts fabricated in one build job.

he percentage of energy lost to process defective parts is included via the scrap rate f.

Cost of Tooling (less important to AM)

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C_{tool}

- Tooling_dies, molds, fixtures
- Assume dedicated to the project

molds

Die casting molds

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C_{tool}

Machining
(special tool)

fixture

Cost of Tooling (less important to AM)

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- Tooling_dies, molds, fixtures
- Assume dedicated to the project

Cost per part produced due to tooling

$$C_{tool} = \frac{C_t}{n}\left[roundup\left(\frac{n}{n_t}\right)\right]$$

Number of tools needed

C_t: cost of one set of tooling [€]

n: number of units in production run in fixed time (e.g., per year) [pieces]

n_t: Number of units which each tool set can make before wearing out (tool life). [pieces]

Less important for AM

OVERHEAD COST

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C_{oH}= labor (direct and indirect), facilities, energy, etc…

$$C_{oH} = \frac{\dot{C}_{oh}}{\dot{n}}$$

Cost per piece due to overhead

$\dot{\mathbf{C}}_{\mathbf{oh}}$: Overhead rate[€/h]

n: Production rate [pieces/h]

For AM, overhead cost is dominated by pre- and postprocessing operations, and energy cost.
n ↑ C4↓

MODEL COST – dominant factors

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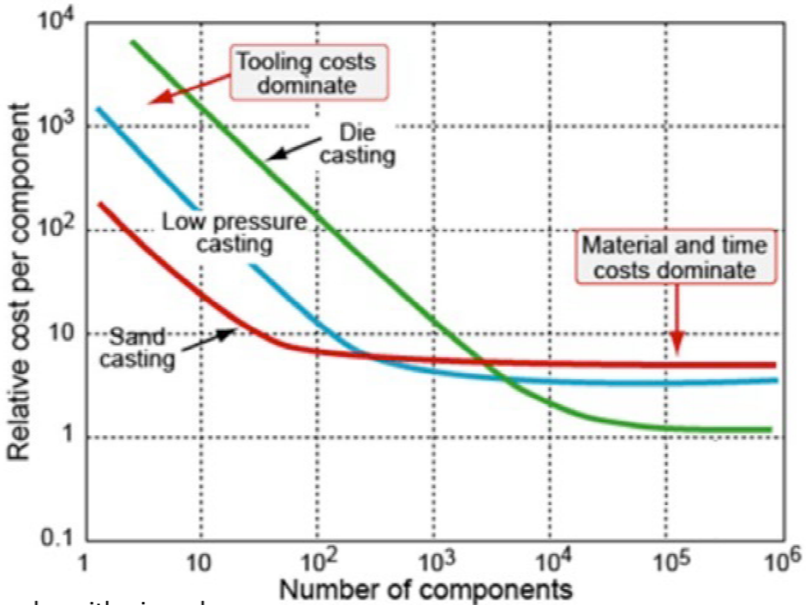

The graph uses logarithmic scale

$$C_{tot} = \boxed{C_{mat}} + \boxed{\frac{C_{dedicated}}{n}} + \boxed{\frac{\dot{C}_{capital} + \dot{C}_{overhead}}{\dot{n}}}$$

- C_{mat} is constant with n
- $C_{dedicated}$ varies as 1/n
- Capital and overhead costs vary with production rate
- Economic batch size

TYPES OF COST

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TOTAL cost [€/part]

MATERIAL [€/part]

TOOLING [€/part]

$$C = C_{eq} + C_{mat} + C_{en} + C_{tool} + C_{OH}$$

COST OH [€/part]

COST OF ENERGY [€/part]

CAPITAL COST OF THE EQUIPMENT [€/part]

TYPES OF COST

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TOTAL cost [€/part]

MATERIAL [€/part]

TOOLING [€/part]

CONSUMABLES (print heads, recoaters,…)[€/part]

LAB OP (depowdering, support removal) [€/part

SETUP [€/part]

$$C = C_{eq} + C_{mat} + C_{en} + C_{tool} + C_{sec} + C_{cons} + C_{pp} + C_{lab} + C_{fac} + C_{setup}$$

FACILITY [€/part]

POST-PROCESSING (heat treat, EDM)[€/part]

SECONDARY costs (gas and solvents)[€/part]

COST OF ENERGY [€/part]

CAPITAL COST OF THE EQUIPMENT [€/part]

$$C_{sec} = \frac{t_b}{n_b \cdot (1-f)} \cdot c_g + \frac{w_{dfl}}{n_b \cdot (1-f)} \cdot c_{dfl}$$

In the **secondary costs** C_{sec} (€/part),
working gas consumption
debinding solvent consumption

c_g (€/h) and c_{dfl} (€/l) are the costs of gas and solvent, respectively, and w_{dfl} (l/build) is the volume of solvent fluid consumed per each debinding cycle

$$C_{cons} = \sum_{i=1}^{n_{cons}} \frac{c_{cons,i}}{N_{b,i} \cdot n_b \cdot (1-f)}$$

$c_{cons,i}$ (€) represents the cost of the i-th consumable (i=1,..,n_{cons}) for the specific technology, whilst $N_{b,i}$ represents the number of builds that can be produced with that consumable.

$$C_{pp} = \frac{c_{HT} + c_{EDM}}{n_b \cdot (1-f)}$$

heat treatment costs for stress relief c_{HT} (€/build), and the wire-EDM cutting operations c_{EDM} (€/part

$$C_{lab} = \frac{c_{op} \cdot t_{post}}{(1-f)}$$

The **labour cost** C_{lab} (€/part) considers the time t_{post} (h/part) needed to perform the support removal operation (if any) and depowdering on each part

$$C_{fac} = \frac{c_S \cdot S}{N \cdot (1-f)}$$

amount of space S (m^2) occupied by the production systems, where c_S (€/(y·m^2)) is the cost per square meter in the facility

$$C_{setup} = \frac{c_{start} + c_{op} \cdot n_{op} \cdot t_{start}}{N \cdot (1-f)} + \frac{c_{op} \cdot t_{b,prep}}{n_b}$$

C_{setup} (€/part):
to the fixed yearly investment costs c_{start} (€/y) and variable costs due to operators' activities ($c_{op} \cdot n_{op} \cdot t_{start}$) when a new production has to start;
($c_{op} \cdot t_{b,prep}$) is related to the operator costs devoted to a new build-job preparation

Dedicated versus generla purpose machine what does it change

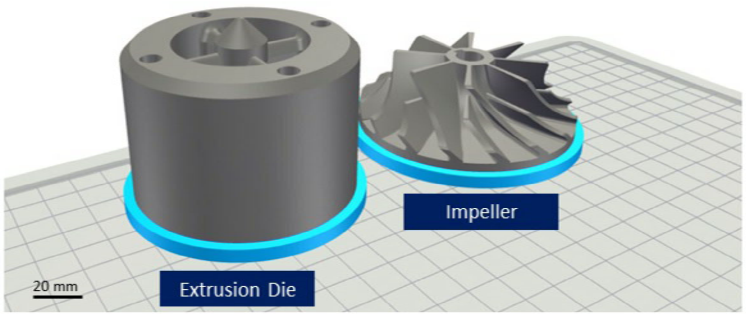
$$C_{eq} = c_{mac,eq} \cdot \frac{t_{b,eq}}{u \cdot (1-f)}$$

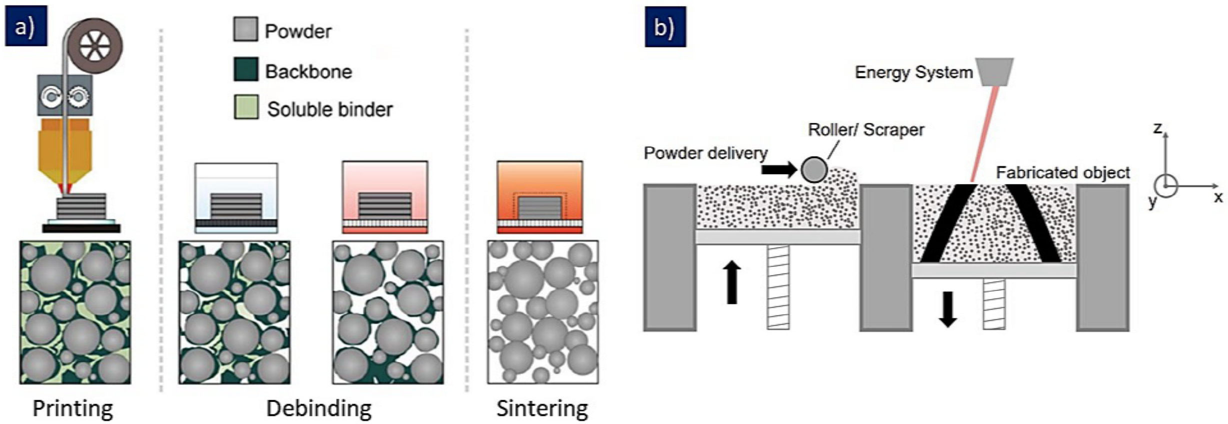
$$C_{fac} = c_S \cdot S \cdot \frac{t_{b,eq}}{u \cdot (1-f)}$$

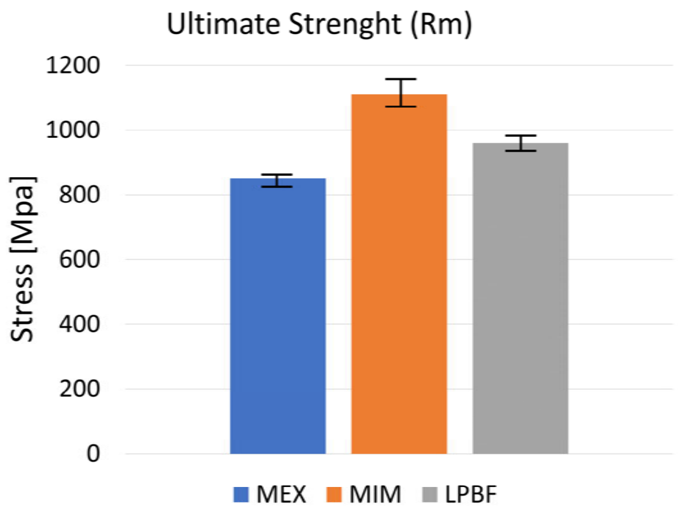
$t_{b,eq}$ (h/part) is the time to manufacture the part and

u (h/year) is the yearly machine uptime.

MEX vs LPBF


Impeller
Extrusion Die
20 mm


a)
Powder
Backbone
Soluble binder
Printing
Debinding
Sintering
b)
Energy System
Roller/ Scraper
Powder delivery
Fabricated object
z
y
x



	Extrusion die	Impeller
Build material	17-4 PH	17-4 PH
Dimensions [mm]	58x58x44	63x63x20
Market sector	Tooling	Mechanical components
Mass [kg]	0.5	0.2

Equip. Material Energy Second. Cons.
Post-proc. Labor Facility Setup

the maximum production volume achievable with one LPBF-SL system is 460 units per year (this value is set as the upper limit of the investigation) while the LPBF-QL system presents higher potential productivity, reaching up to 1800 parts yearly.

On the contrary, the MEX system in a 1-1-1 configuration can guarantee only 250 units per year.
Therefore, in order to reach the target production volume of 460 parts per year, a different layout including 2 printers, i.e., a 2-1-1 layout, must be considered.

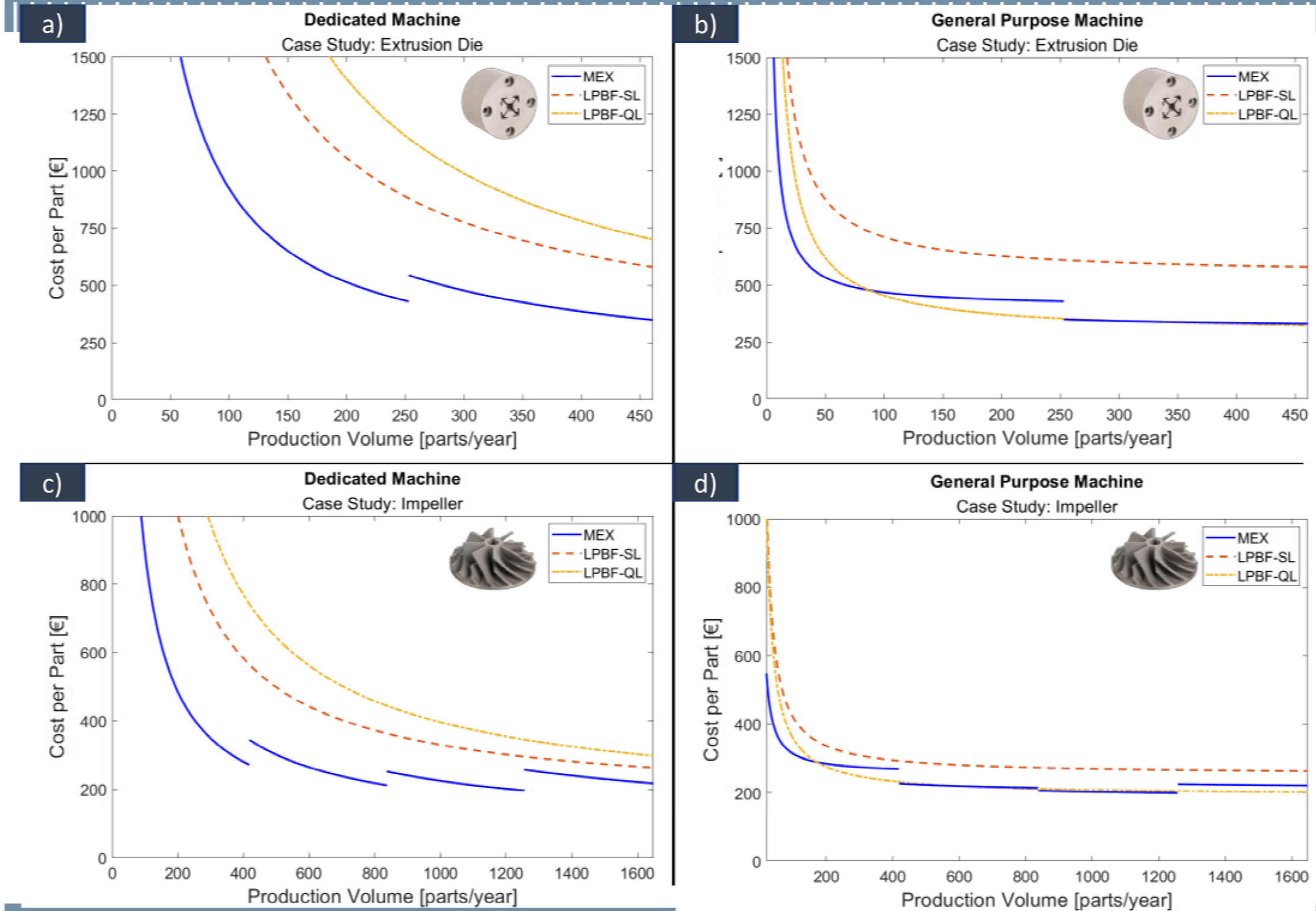
Equip. Material Energy Second. Cons.
Post-proc. Labor Facility Setup

The equipment cost is the most important contribution for all the three AM systems, while MEX presents a material cost higher than the LPBF cases.

This can be related to the specific market approach of the studied commercial MEX solution (i.e., the *BMD* from *DM*), which forces the use of its own building materials. There are other MEX system alternatives for metals that allow the use of open materials, such as the low-cost MIM pellets material, and that could result in cost savings from the material viewpoint.

Another different element between the two technologies is represented by **consumable costs**, which are higher for the LPBF processes because of the replacement of some machine elements, such as the recoater or the powder filter etc., which is required frequently (at every build or after a few builds). The contribution of the secondary cost is instead particularly high in the LPBF-SL system, due to a higher gas consumption. This is mainly because LPBF-SL has lower productivity with respect to LPBF-QL, thus leading to longer processing times and consequent larger use of gas quantities.

Dedicated vs General-purpose



Comments: pay attention to Uncertainty/sensitivity

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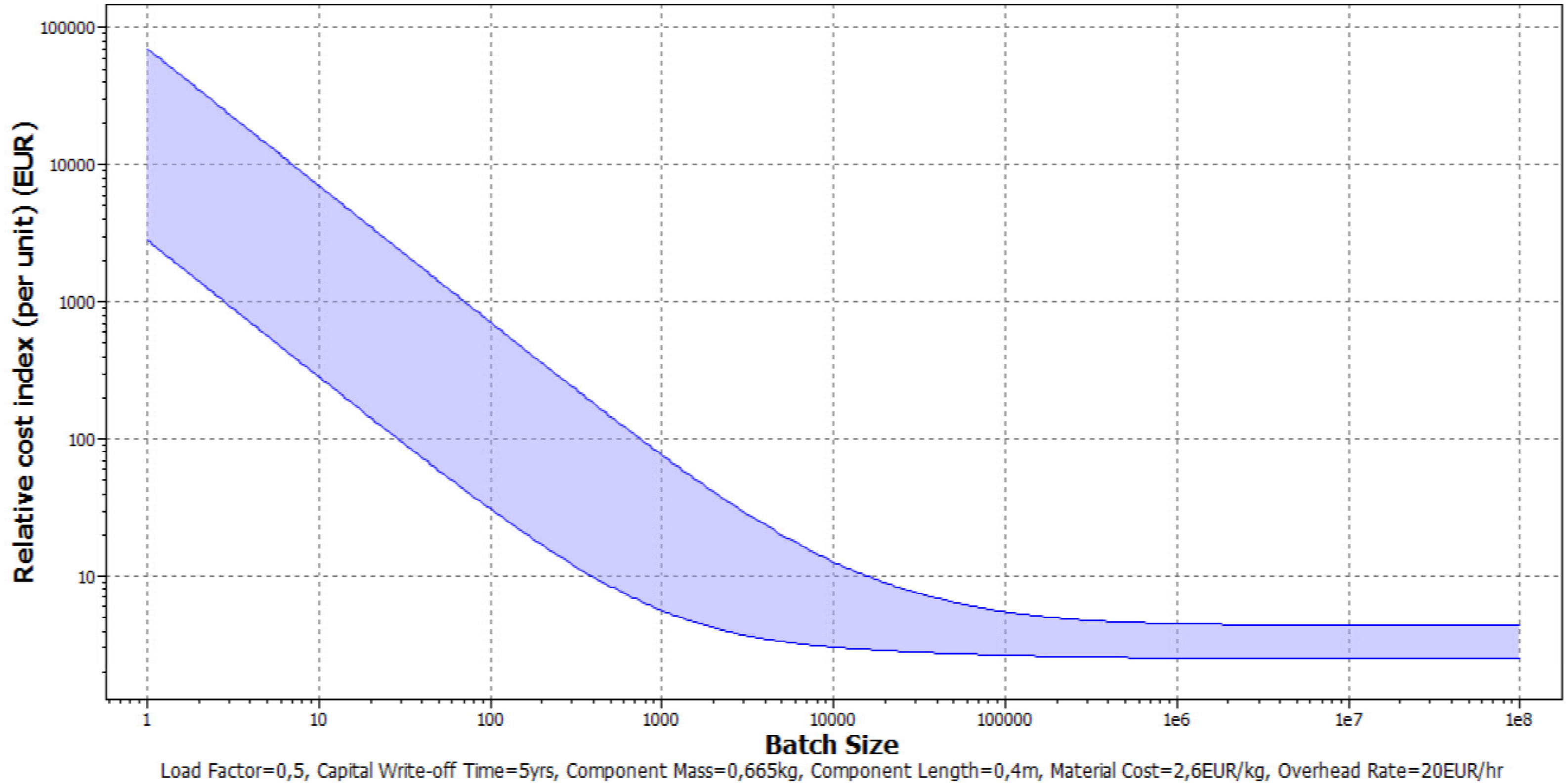
Uncertainty/sensitivity



What about VALUE?

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AM should not be interpreted as a substituting technology!

Costs

Flexibility
Easiness of use
Safety

Value
complexity for free (with the exception of the design cost):

- product improvement:
- Performances (thermo-mechanical; lightweight; reliability/durability, …)
- Number of components (supply chain)
- Spare parts
- Customization
- Sustainability (design&manufacturing)

A classification system for evaluating additive manufacturing suitability

SAM SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING
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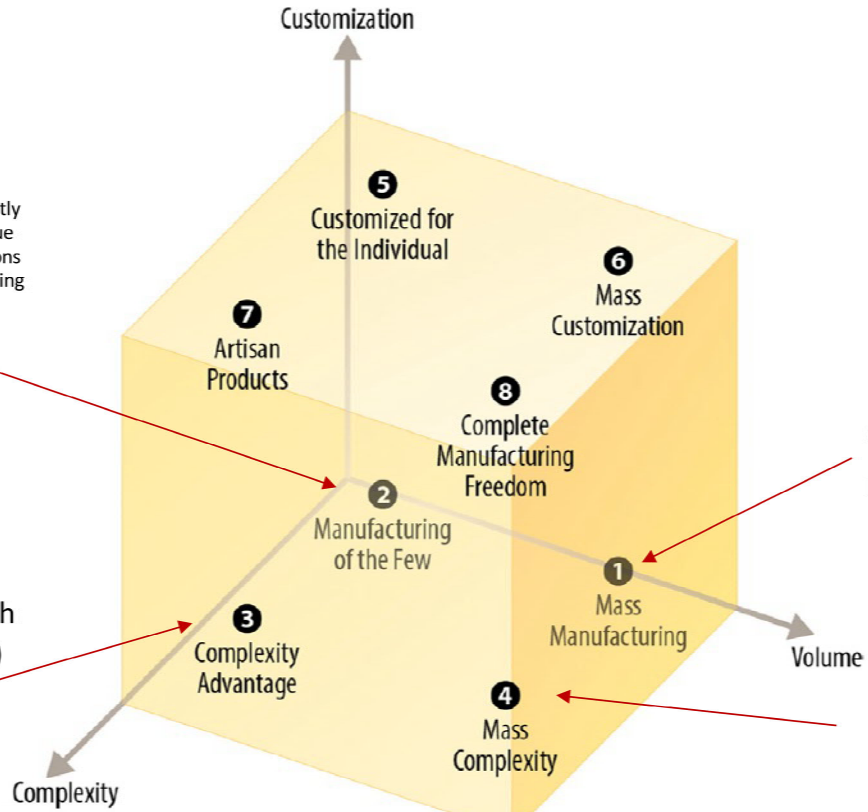
Manufacturing of the few

product prototypes subsequently mass manufac- tured, high value parts for low volume applications like ships or satellites, and tooling and fixturing.

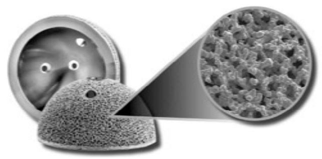


Conventional manufacturing

Additive

or conventional with welding (high costs)

Additive



Modeling Complexity

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Part volume ratio (C_{PR})

V_p is part volume

V_b is volume of bounding box

$$C_{PR} = 1 - \frac{V_p}{V_b}$$

Part area ratio (C_{AR}):

A_s is surface area of a sphere with identical volume

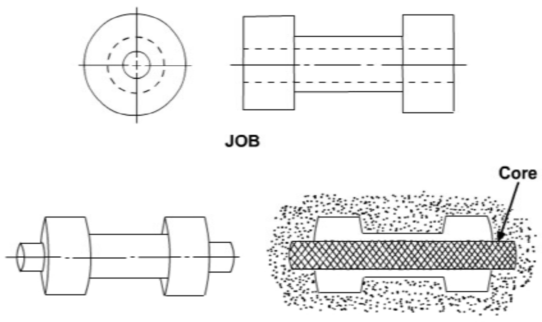
A_p is part surface area

$$C_{AR} = 1 - \frac{A_s}{A_p}$$

Cores parameter (C_{NH})

N_H number of cores required to produce part

$$C_{NH} = 1 - \frac{1}{\sqrt{(1+N_H)}}$$



Modified Complexity Factor

$$MCF = 5.7 + 10.8C_{PR} + 18.0_{AR} + 32.7C_{NH}$$

Multiple regression analysis of 40 cast parts of varying complexity used to determine weights of equation

B.P. Conner et al. / Additive Manufacturing 1–4 (2014) 64–76

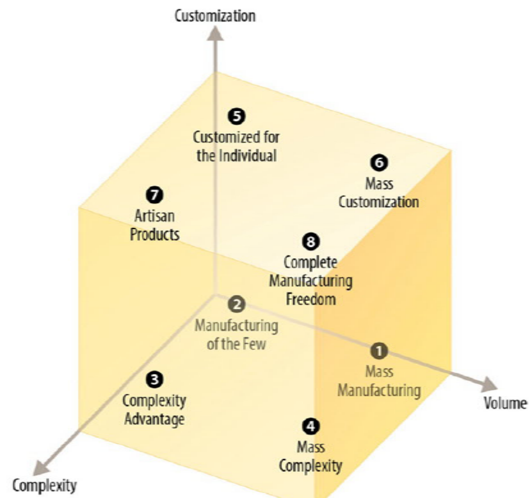
Modeling customization

Customization level	
0	No customization. Examples are commodity products
1	Pre-defined options. For example, allowing choice of laptop case color
2	Limited customization/many restraints. For example, text incorporated into the geometry of a part
3	Greater freedom of customization. An increasing number of features defined by customization but not a random level of customization
4	Fully unique parts. Random customization, for example a part with design features and overall geometry to fit human or animal anatomy, such as Invisalign brace molds

B.P. Conner et al. / Additive Manufacturing 1–4 (2014) 64–76

Part	Process	Material	MCF	Customization	Production volume	Map region	Cost per part
Lever	Injection molding	Polycarbonate	31.6	Level 0	18,000	1	€ 1.75
Lever	Laser sintering	Nylon	31.6	Level 0	18,000	1	€ 2.20–3.44
Lever	Injection molding	Polycarbonate	31.6	Level 0	1000	2	€ 27.59
Lever	Laser sintering	Nylon	31.6	Level 0	1000	2	€ 2.20–3.59
Lever	Injection molding	Polycarbonate	31.6	Level 3	1000	5	€ 27,300
Lever	Laser sintering	Nylon	31.6	Level 3	1000	5	€ 2.20–3.59
Braces Mold	Stereolithography	Photopolymer	19.1	Level 5	17,000,000	6	<$400
Suspension	4-Axis CNC (RP)	Ti-6Al-4V	51.8	Level 0	4	3	$1358.25
Suspension	Electron beam melting	Ti-6Al-4V	51.8	Level 0	4	3	$1254.65

B.P. Conner et al. / Additive Manufacturing 1–4 (2014) 64–76



	Part	Process	Material	MCF	Customization	Production volume	Map region	Cost per part
1	Lever	Injection molding	Polycarbonate	31.6	Level 0	18,000	1	€ 1.75
	Lever	Laser sintering	Nylon	31.6	Level 0	18,000	1	€ 2.20–3.44
2	Lever	Injection molding	Polycarbonate	31.6	Level 0	1000	2	€ 27.59
	Lever	Laser sintering	Nylon	31.6	Level 0	1000	2	€ 2.20–3.59
3	Lever	Injection molding	Polycarbonate	31.6	Level 3	1000	5	€ 27,300
	Lever	Laser sintering	Nylon	31.6	Level 3	1000	5	€ 2.20–3.59
4	Braces Mold	Stereolithography	Photopolymer	19.1	Level 5	17,000,000	6	<$400
5	Suspension	4-Axis CNC (RP)	Ti-6Al-4V	51.8	Level 0	4	3	$1358.25
	Suspension	Electron beam melting	Ti-6Al-4V	51.8	Level 0	4	3	$1254.65

B.P. Conner et al. / Additive Manufacturing 1–4 (2014) 64–76

1. For making 18,000 levers (mass manufacturing), AM is not competitive
2. For producing 1,000 levers (manufacturing of the few), AM is competitive because fixed tooling costs are eliminated.
3. AM is highly favorable for producing 1,000 individually customized levers (customized for the individual), since tooling is avoided.
4. AM is the only option for making braces molds, each of which must be individually customized, despite high production numbers (mass customization).
5. AM and CNC are similar for producing a suspension part that is geometrically complex but does not require customization (mass complexity). However, AM may be able to produce a better suspension part.

Ex: ENVIRONMENTAL effect
Compare CNC machining with optimized AM

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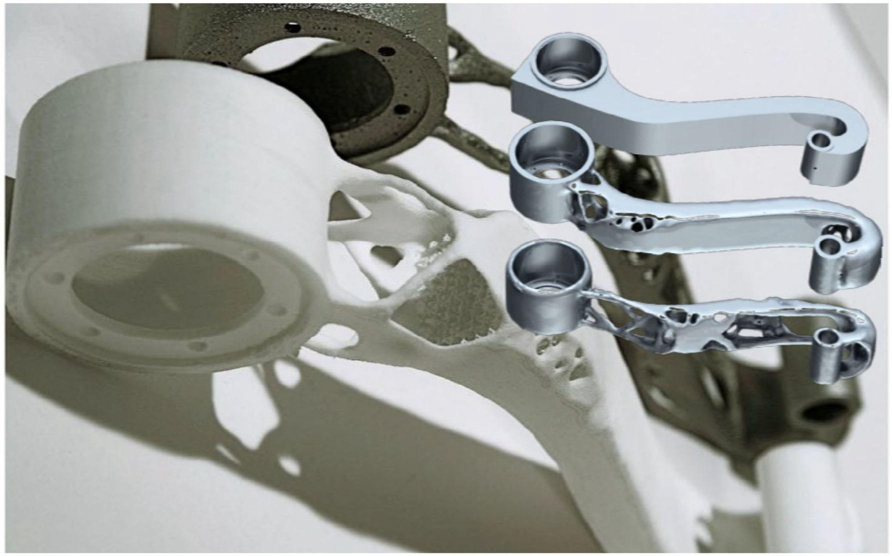
Aircraft monitor arm case study (U. Nottingham)



- part manufactured for ‘Virgin Atlantic’ and is being investigated by Econolyst and Loughborough University.
- the original geometry, or the use of topologically optimised parts and lattice structures.

C. Tuck (U. Nottingham), “The AM Sustainability Issue”
http://www.enlighten-toolkit.com/App_Themes/Enlighten/Documents/MonitorArm-processing.pdf

Environmental effect

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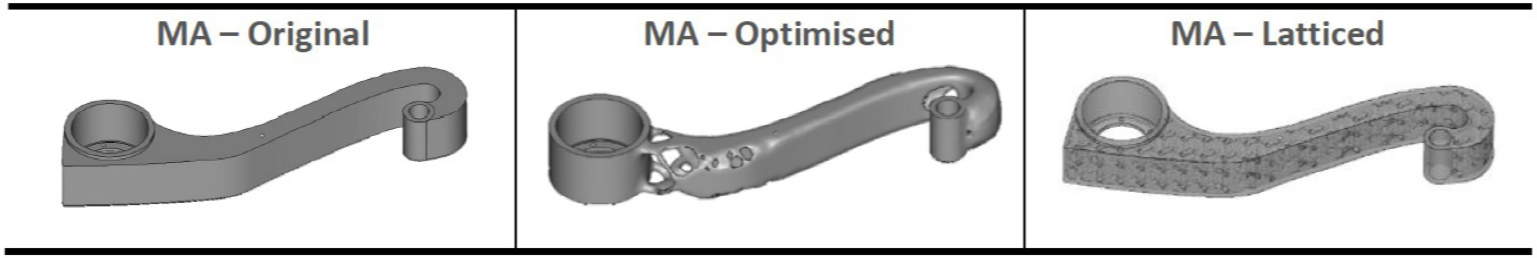
the original design, which will be produced from billet using conventional machining;

a coarse lattice design with a full solid skin, that will also be produced using AM technology



a geometry which has been topologically optimised and produced via AM

Previous study: aluminium =best metal x lifecycle carbon emissions and energy usage (when compared to stainless steel and titanium).

MA – original (2.91 kg of material is used; primary process: CNC machining; the final part weighs 0.86 kg and is 307,188 mm3.)

MA – Optimised (0.53 kg of material is used; primary process is SLM+an ancillary atomisation process, the final part weighs 0.34 kg and is 120,703 mm3.

MA – Latticed (0.58 kg of material is used; the primary process is SLM+ancillary atomisation process; the final part weighs 0.39 kg and is 138,862 mm3)

Common assumptions:

•raw material is sourced from India (Aluminium, S380.0: LM24-M, cast (Al/8Si/3Cu/Fe));

•the part is for use on a long haul, aeroplane, anticipated to travel 90,000,000 km over its lifetime;

•the part is not designed to be replaced over the lifetime of the vehicle.

•the part ends its lifecycle in Huntsville, TN, USA.

Impact Categories by LIFECYCLE

SAM Sector Skills Strategy in Additive Manufacturing
Co-funded by the Erasmus+ Programme of the European Union

The totals emissions and energy values can be categorised into 5 main stages of the parts lifecycle;

	Raw materials	Manufacture	Distribution and retail	Usage	End-of-life
MA – Original					
CO_2	163	1	6	47,052	0
%	0%	0%	0%	100%	0%
CO_2 / kg	190	1	7	54,900	0
MJ	639	9	90	690,113	1
MA – Optimised					
CO_2	30	7	2	18,490	0
%	0%	0%	0%	100%	0%
CO_2 / kg	88	21	5	54,900	0
MJ	116	50	25	271,188	0
MA – Latticed					
CO_2	33	8	2	21,270	0
%	0%	0%	0%	100%	0%
CO_2 / kg	84	20	6	54,900	0
MJ	128	55	31	311,960	0

Ed Morris, director of NAMII (National Additive Manufacturing Innovation Institute), the US federally-funded initiative set to define and promote the future of the industry:

"In terms of impact on inventory and logistics," he says, "you can print on demand. **Meaning you don't have to have the finished product stacked on shelves or stacked in warehouses anymore.** "Whenever you need a product," he explains, "You just make it. **And that collapses the supply chain down to its simplest parts, adding new efficiencies to the system."**

Those efficiencies run the entire supply chain, from the cost of distribution to assembly and carry, all the way to the component itself, all the while reducing scrap, maximizing customization and improving assembly cycle times.

Effect on the supply chain

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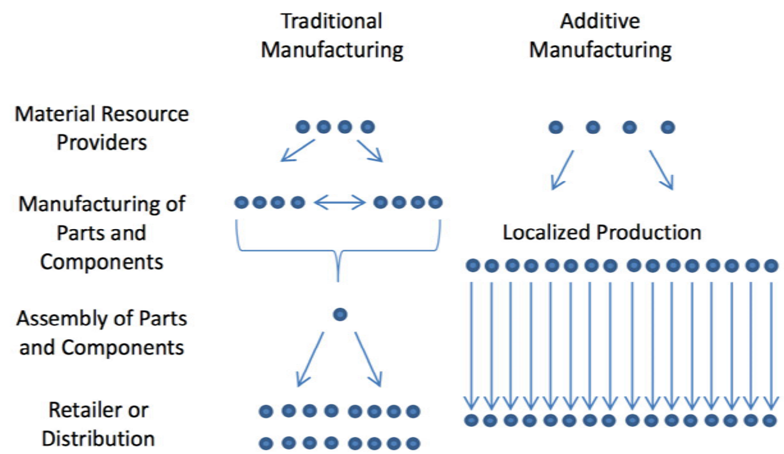
Figure 3.2: Example of Traditional Supply Chain Compared to the Supply Chain for Additive Manufacturing with Localized Production



The **traditional** supply chain model is, of course, founded on traditional **constraints** of the industry, the efficiencies of mass production, the need for low-cost, high-volume assembly workers, real estate to house each stage of the process and so on.
But additive manufacturing bypasses those constraints.

3DP finds its value in the printing of **low volume**, **customer-specific** items, items that are capable of **much greater complexity** than is possible through traditional means
…, the efficiencies of that traditional model stop making sense, it is no longer financially efficient to send products zipping across the globe to get to the customer **when manufacturing can take place almost anywhere** at the same cost.
The **raw materials today are digital files and the machines that make them are** wired and connected, faster and more efficient than ever

Deloitte consulting

ramework for understanding AM paths and value

Graphic: Deloitte University Press

Path I: Companies do not seek radical alterations in either supply chains or products, but explore AM technologies to improve value delivery for current products within existing supply chains.

Path II: Companies take advantage of scale economics offered by AM as an enabler of supply chain transformation for the products they offer.

Path III: Companies take advantage of the scope economics offered by AM technologies to achieve new levels of performance or innovation in the products they offer.

Path IV: Companies alter both supply chains and products in the pursuit of completely new business models previously not possible without AM.

http://dupress.com/articles/additive-manufacturing-3d-printing-supply-chain-transformation/#end-notes