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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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

Design for PBF Polymers

Welcome

20 JULY 2021

Maria DIMOPOULOU – LMS

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Get to know us

Before we start....

Go to sli.do

#562303

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Agenda

Day 1 (20.07.2021)

Welcome	09:00-09:15	15
Overview of Machines, Process Capabilities and Limitations	09:15-10:35	80
Break	*10:35-10:40*	*5*
Process Related Materials (Part 1)	10:40-11:55	75
Break	*11:55-12:00*	*5*
Process Related Materials (Part 2)	12:00-12:55	*55*
Lunch break	*12:55-13:40*	*45*
Specific Design Considerations (Part 1)	13:40-14:50	70
Break	*14:50-14:55*	*5*
Specific Design Considerations (Part 2)	14:55-16:00	55
Break	*16:00-16:10*	*10*
Specific Design Considerations (Part 3)	16:10-16:30	20

Agenda

Day 2 (21.07.2021)		
Case study	09:00-10:20	80
Break	*10:20-10:30*	*10*
Wrap Up	10:30-10:50	20
Break/preparation	*10:50-11:30*	*40*
Assessment	11:30-12:00	30

LMS: Introduction

The Laboratory for Manufacturing Systems & Automation (LMS) is oriented on research and development in cutting edge scientific and technological fields. LMS is involved in a number of research projects funded by the CEU and European industrial partners. Particular emphasis is given to the co-operation with the European industry as well as with a number of "hi-tech" firms. LMS employs approximately 100 researchers.

- Participation in more than **180 R&D Projects**
- Coordination of more that **50 EU Competitive R&D projects**
- Organization of more than **10 International conferences.**
- Publication of more than **700 Scientific articles**

LMS is organized in Three Different Groups

Manufacturing Processes

Manufacturing Automation, Robots & Virtual Reality Applications

Manufacturing Systems

SAM: The Project

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SAM is a European initiative that aims to address the workforce development for Additive Manufacturing (AM) by developing a shared skills vision and collaborative learning solutions for the sector at European level.

Objectives:

- Build a sector skills strategy in AM;
- Assess and anticipate skills (gaps and shortages) in AM;
- Support with data the AM European Qualification System and foster wideness of its scope;
- (Re)design professional profiles according to the industry requirements;
- Develop specific relevant qualifications to be delivered for the AM Sector;
- Increase the attractiveness of the sector to young people, whilst promoting gender balance;
- Strengthen education-research-industry partnerships and encourage creativity "in companies and relevant educational and scientific institutions";
- Track students, trainees and job seekers and promote match making between job offer and search.

Skills Strategy in Additive Manufacturing

Methodology for a sustainable assessment

Design, review and deploy of relevant qualifications

Promotion of Additive Manufacturing

One Online Qualifications Catalogue

Strenghten education-research-industry partnerships

Please find out more info at: www.skills4am.eu/

SAM: CU69 Design for PBF Polymers

Course structure

- 2-Day event
- Active participation of audience is expected
- Follow-up exam/assessment on 2nd day
- SAM certificate of attendance awarded to participants
  - Need to attend both days and successfully complete assessment
  - Will be issued after fulfilling the Satisfaction feedback form - 1 month to be issued
  - Will contain information about the attended CU and accomplished Assessment.

Assessment

- Multiple-choice questions directly related to the program of the Unit of Learning Outcomes / Competence unit
- Invigilator from EWF will give access to the exam the day of the exam, using MS Teams Forms as supporting tool for the assessment
- Students are advised to have good internet connection and cameras on to access the exam
- The students must wait for permission to initiate the exam (and access the link)
- Questions/doubts during the exam shall be addressed in the chat box ONLY
- In order to pass the exam, the student must reach at least 60% correct answers
- Failing the exam, the student will be entitled to a maximum of 3 reassessments
- If case of failing 3 times, the student must attend the CU again before repeating the exam
- Students who feel that the evaluation process was unfair have the right to appeal directly to EWF.
- The results of the exam will be released 1 week after the exam occurrence

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Evidences

- To prove attendance and participation, evidences will be collected during each training course
- Evidences include
  - Attendance list (including your names and e-mails)
  - Photographic evidence/screenshots
  - Results of the assessment
  - Results of the feedback surveys
- **Participating in the training course means that you automatically accept the aforementioned data collection policy!**

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

skills4am.eu

Laboratory for Manufacturing Systems and Automation (LMS)
Department of Mechanical Engineering and Aeronautics
University of Patras, Greece

Thank you

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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

Design for LPBF Polymers

SESSION 02: Process Related Materials

20 JULY 2021

FOTIS STAMATOPOULOS - LMS

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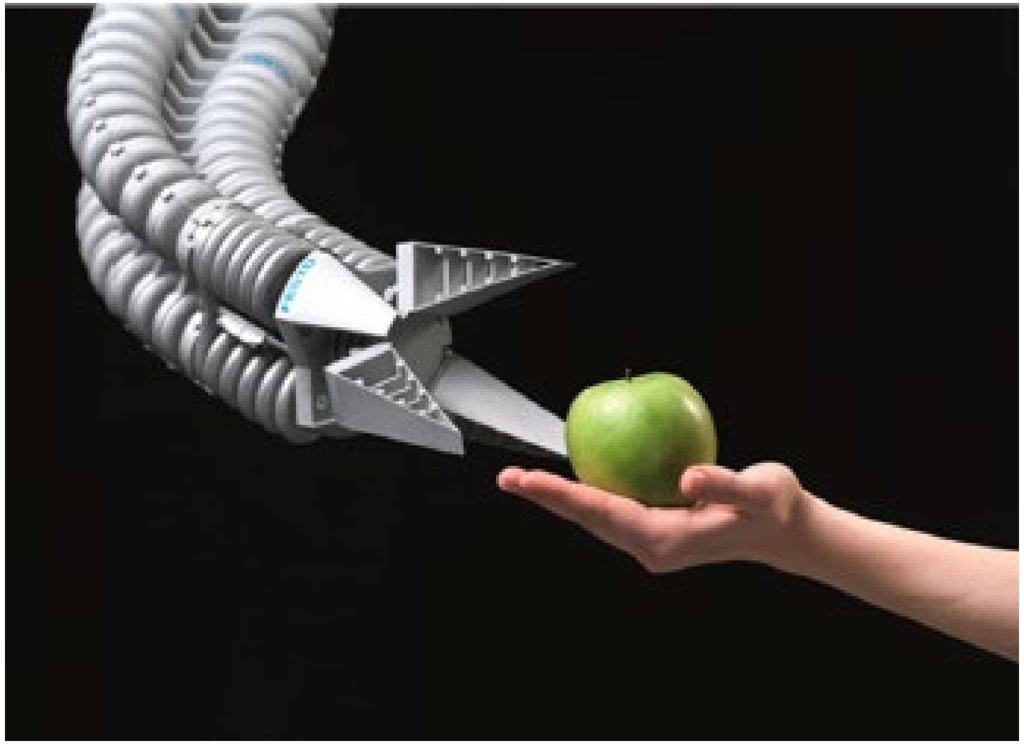
Agenda

- Learning Outcomes and Introduction
- Material Properties Overview
- Thermoplastics in PBF Overview
- Filled Thermoplastics
- Material Selection
- Powder usage, mixing & handling
- Biocompatibility
- Summary



PBF Printed Bionic Handling Assistant

Source: EOS

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

Learning Outcomes

- ✓ Basic understanding of all Material Properties and Characteristics important for the PBF printing process
- ✓ Familiarization with the most common Polymer Materials used in PBF and their respective properties and applications
- ✓ Brief overview of high end applications through the use of Filled Thermoplastics
- ✓ Ability to choose the right material for every PBF application
- ✓ Overview of proper powder usage, mixing & handling
- ✓ Introduction to Biocompatible Materials and high end Medical and Pharmaceutical Applications of PBF printing

Overview of PBF compatible Materials

Standard Materials	Specialty Materials
a. Polyamides (PA)-Nylon b. Polystyrenes (PS) c. Polypropylene (PP) d. Polyaryletherketones (PAEK) e. Polyetheretherketone (PEEK) f. Polycarbonate (PC) g. Thermoplastic Elastomers (TPE/TPU) h. ULTEM 9085, 1010	i. Nylon based composites ii. Fire retardant polymers

- PBF printing process is very adaptable => broad range of materials can be sintered
- Most common materials being **thermoplastics**
- Two-component thermosets and elastomeric materials also available
- Average Prices between 85-105 but may be considerably higher for high performance materials
- Market is **dominated** by polyamide **PA-12** (90% market share)

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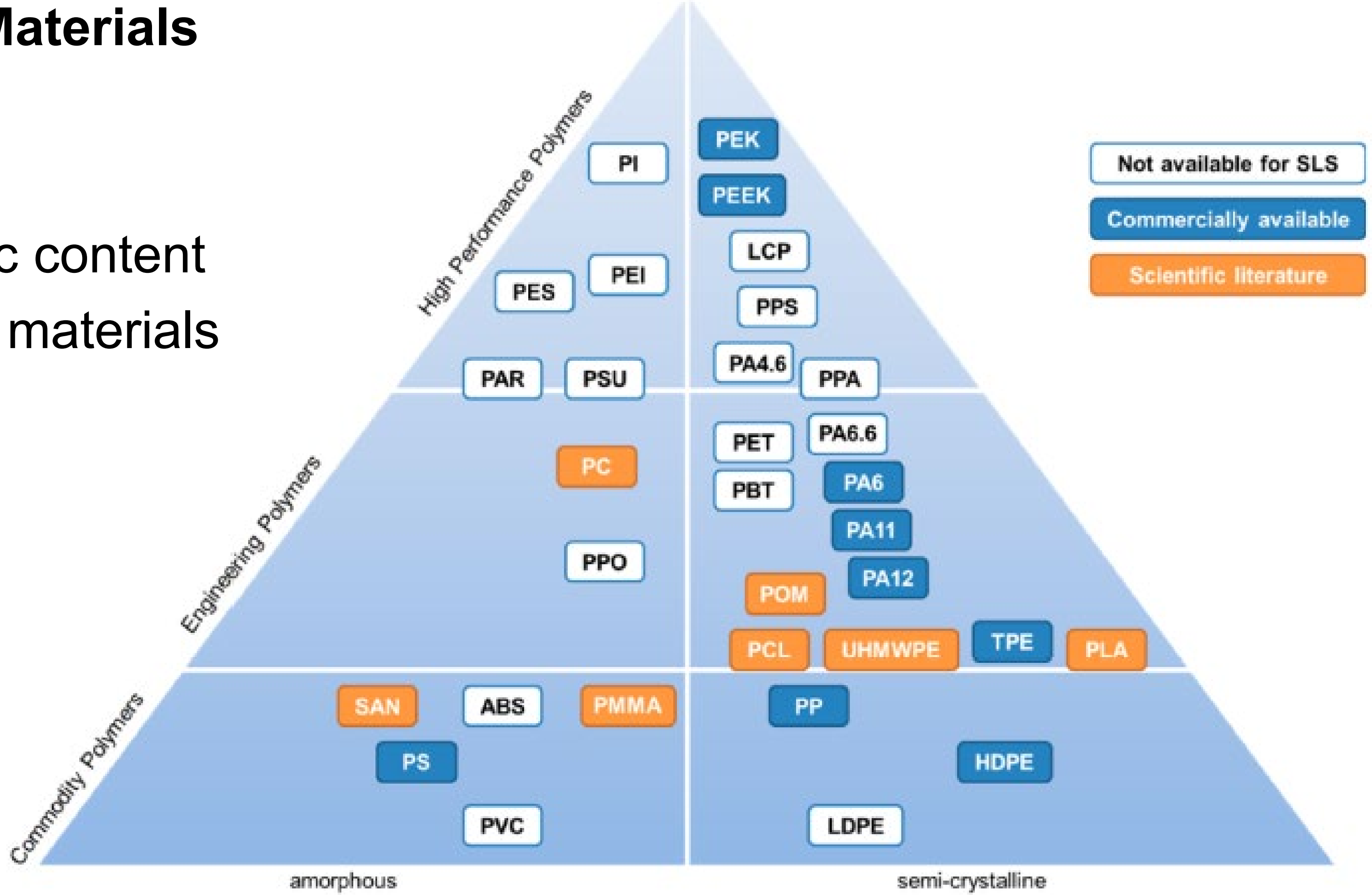
Classification of PBF Materials

According to:

a) Inorganic or polymeric content
b) Pyramid of polymeric materials



Source: Polymers for 3D Printing and Customized Additive Manufacturing, Samuel Clark Ligon, Robert Liska, Jürgen Stampfl, Matthias Gurr, and Rolf Mülhaupt, *Chemical Reviews* 2017 *117* (15), 10212-10290

SAM: Commercial Powders Overview

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trade name	supplier	polymer	filler	E [MPa]	σ_B [MPa]	ε_B [%]
Duraform PA	3D Systems	PA-12	unfilled	1586	43	14
NyTek 1200 PA	Stratasys	PA-12	unfilled	1700	46	15
Orgasol Invent Smooth	Arkema	PA-12	unfilled	1800	45	20
PA 2201	EOS	PA-12	unfilled	1700	48	15
PA650	ALM	PA-12	unfilled	1700	48	24
DuraForm EX	3D Systems	PA blend	unfilled	1517	48	47
Duraform GF	3D Systems	PA-12	glass beads	4068	26	1.4
NyTek 1200 GF	Stratasys	PA-12	glass	3585	44	3
PA 615-.GS	ALM	PA-12	glass	4100	31	1.6
PA 616-GS	ALM	PA-12	glass	4100	31	1.45
PA3200 GF	EOS	PA-12	glass beads	3200	51	9
Windform GT	CRP Techn.	PA	glass fibers	3290	56	14.8
Windform LX 2.0	CRP Techn.	PA	glass fibers	6248	60	2.3
CarbonMide	EOS	PA-12	carbon fibers	6100	72	4.1
NyTek 1200 CF	Stratasys	PA-12	carbon	3654	60	5.7
Windform SP	CRP Techn.	PA	carbon fibers	6219	76	11.4
Windform XT 2.0	CRP Techn.	PA	carbon fibers	8928	84	3.8
Alumide	EOS	PA-12	Al powder	3800	48	4
NyTek 1100	Stratasys	PA-11	unfilled	1647	47	21
PA 1101	EOS	PA-11	unfilled	1600	48	45
PA-850_NAT	ALM	PA-11	unfilled	1517	48	47
Sinterline	Solvay	PA-6	unfilled			
Sinterline Glassfilled	Solvay	PA-6	glass beads	6300		
Laser HDPE HX 17	Diamond Plastics	HDPE	unfilled	2000	21	6
Laser PP CP 22 weiß	Diamond Plastics	PP	unfilled	2500	25	8
PEEK-HP3	EOS	PEEK	unfilled	4250	90	2.8
DuraForm Flex	3D Systems	TPE	unfilled	9.2	2.3	151
Luvosint X92A-2	Luvosint	TPU	unfilled	27	20	520
PrimePart ST PEBA 2301	EOS	TPE	unfilled	75	8	200
CastForm PS	3D Systems	PS	unfilled	1604	2.84	
PrimeCast101	EOS	PS	unfilled	1600	5.5	0.4

Market is **dominated** by polyamide **PA-12**
(90% market share)

Source: Polymers for 3D Printing and Customized Additive Manufacturing, Samuel Clark Ligon, Robert Liska, Jürgen Stampfl, Matthias Gurr, and Rolf Mülhaupt, *Chemical Reviews* 2017 *117* (15), 10212-10290

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A **thermoplastic**, or **thermo-softening plastic**, is a plastic polymer material that becomes pliable or moldable at a certain elevated temperature and solidifies upon cooling.

Thermoplastics have a simple molecular structure comprising chemically independent macromolecules. Upon heating, they are softened or melted, then shaped, formed, welded, and solidified when cooled. Multiple cycles of heating and cooling can be repeated, allowing reprocessing and recycling.

- Thermoplastics have been in use long before Additive Manufacturing was invented
- Injection molding and plastics were invented in parallel, while AM is 100 years younger => Most plastics designed with molding in mind

Thermoplastics Reprocessing

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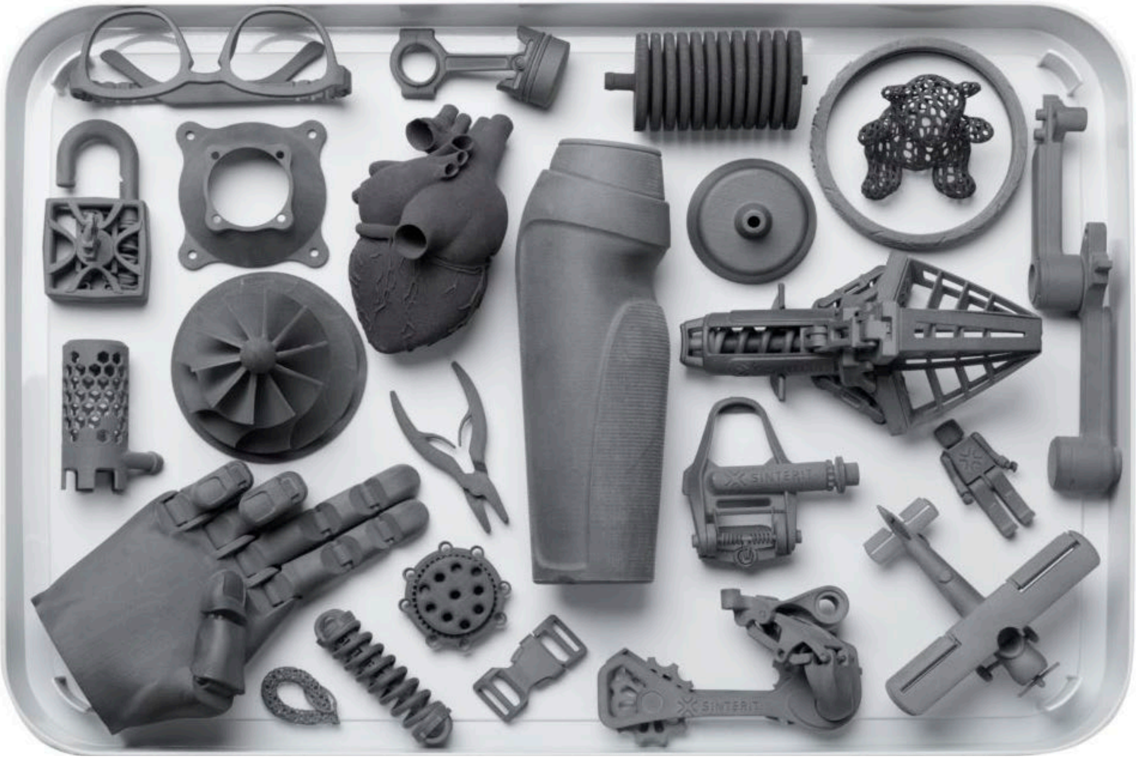
- The Powder Bed Fusion processes (PBF) are incredibly adaptable, however it **not all** thermoplastics are PBF processable.
- The thermoplastics that are printable, however, cover a massive range of compositions, final part constraints, and material properties.
- Additive Manufacturing Material market is **rapidly evolving** and sees the regular emergence of radically **new materials**.



PBF Polymer Printed Sample Parts

Source: Sinterit

SAM: Materials in PBF Introduction

- PBF Feedstock Materials typically come in a **powder form**
- The powder particle as well as the composition of the powder material, denotes the printability of the material.
- Resolution and surface roughness of parts manufactured are strongly dependent on the particle size of the utilized powder (larger particles generally cause lower spatial resolution and higher surface roughness)
- For safety and processability reasons, the average size of powder particles **cannot be reduced** below a certain limit.

PBF Polymeric Powder

Source: Sinterit

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Fabrication of Polymeric PFB Powders

a) Precipitation from polymer solution;

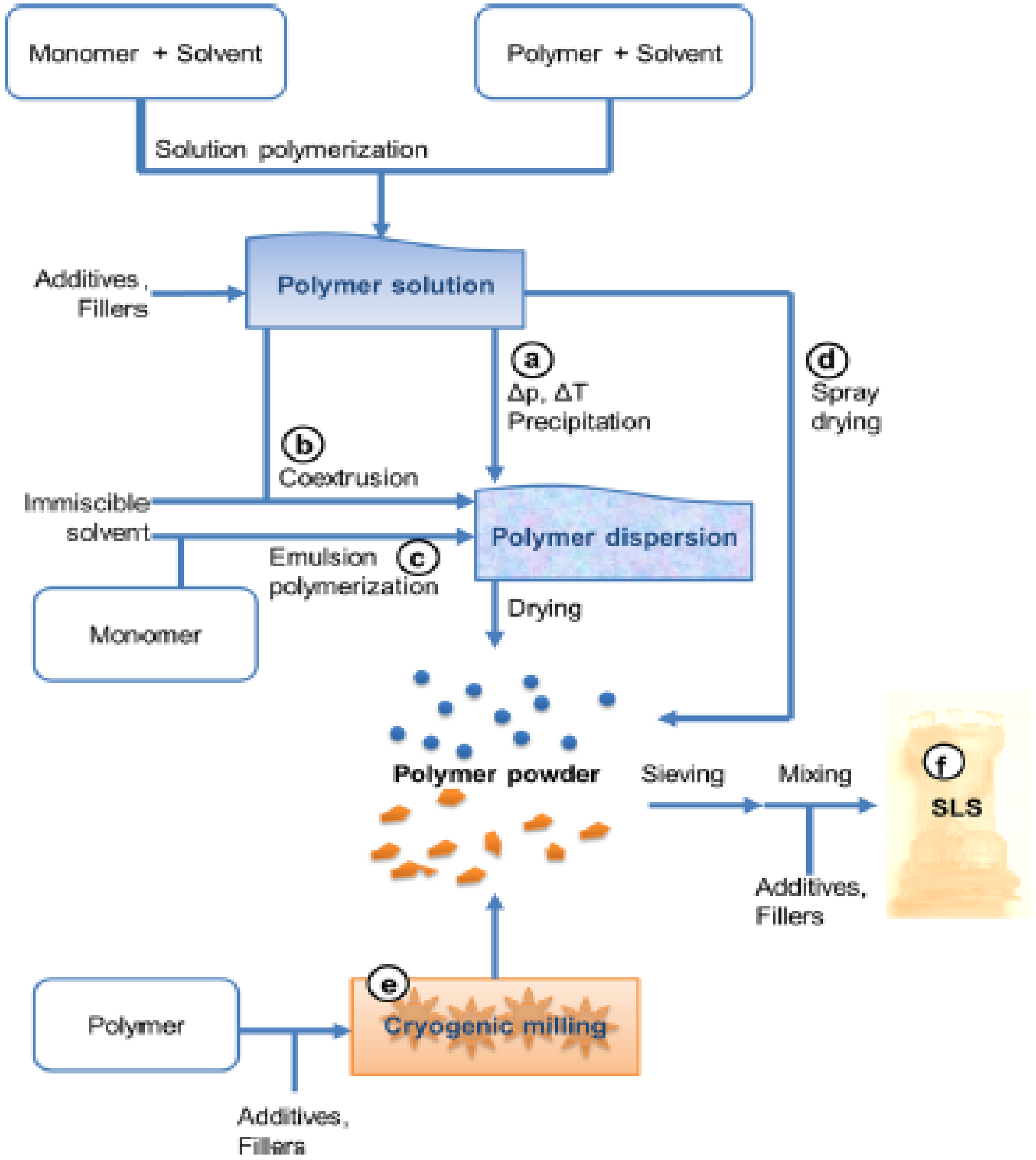
b) Co-extrusion of polymer solution with immiscible solvent;

c) Emulsion polymerization of water-insoluble monomers;

d) Spray drying of polymer solution;

e) Cryogenic milling of polymer powders;

f) PBF processing of powders with controlled size distribution and formulated additives.



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- **Material Properties Overview**
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Material Properties Overview

- Material properties describe how a specific material will behave under certain conditions
- Different categories of properties such as: chemical, optical, mechanical, thermal, electrical etc.
- As quantitative metrics, these attributes can help anyone to assess the benefits of one material versus another for a specific use case.

In the following, we'll provide a brief overview of:

- the most useful material properties linked with PBF printing
- their importance for specific applications

MECHANICAL PROPERTIES			
Tensile stress at yield and break	ISO 527	N/mm^2	45
Elongation at break	ISO 527	%	25
Tensile modulus of elasticity	ISO 527	N/mm^2	2500
Compression test			
- 1% strain after 1,000 hrs	ISO 899	N/mm^2	17
Charpy impact strength - Notched	ISO 179-1/1eU	KJ/mm^2	14
Charpy impact strength - Unnotched	ISO 179-1/1eA	KJ/mm^2	no break
Ball indentation hardness	ISO 2039	N/mm^2	85
Shore hardness D	ISO 2039	D	82
Coefficient of frition to steel[12]	ISO 8295	-	0.5
THERMAL PROPERTIES			
Melting temperature	ISO 3156	°C	105
Thermal conductivity at 23°C	ISO 22007.2	W/9km)	0.15
Deformation temperature[15]	ISO 75	°C	85
Coefficient of linear thermal expansion			
- average value between 23 and 60°C	ISO 11359	m(m.K)	90
Max. allowable service temperature in air			
- Continuously[17]	-	°C	90
- Short periods[18]	-	°C	100
Minimum service temperature[19]	-	°C	-20
Flamability			
- Oxygen index	ISO 4589	%	19
- according to UL 94 (3/6 thickness)	UL94	-	HB
ELECTRICAL PROPERTIES			
Dilectrical constant at 1 MHz	ISO 250	-	3.3
Dielectric strength	ISO 243	KV/mm	20
Volume resistivity	ISO 93	Ωcm	10^{15}
Dissipation factor tan Δ at 1 MHz	ISO 250	-	0.02

Source: plastim.co.uk

SAM: Material Properties Overview

Common Mechanical and Thermal Properties

- Tensile Strength
- Young's Modulus
- Elongation
- Flexural Strength
- Fatigue Strength
- Flexural Modulus
- Impact Strength
- Indentation Hardness (Shore)
- Compression Set
- Water Absorption
- Heat Deflection Temperature
- Vicat Softening Point
- Thermal Expansion

Other Useful Material Properties

- Chemical Resistance
- Electrical Properties
- Machinability
- Ease of Printing
- Layer Adhesion
- Optical Properties
- Recyclability/Biodegradability
- Biocompatibility
- Fire Retardancy

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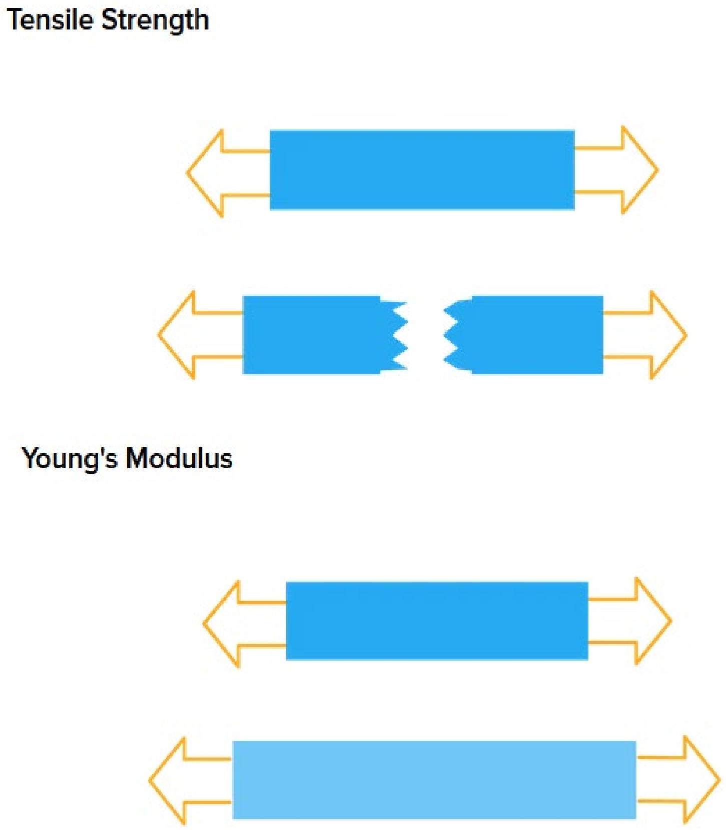
Tensile strength: Resistance of a material to breaking under tension

- Fundamental property that shows the ultimate strength of a part. High tensile strength is important for structural, load bearing, mechanical or statical parts

Young's Modulus: Resistance of a material to stretch under tension (stiffness)

- Good indicator for either the stiffness (high modulus) or the flexibility (low modulus) of a material
- Important for structural parts that are expected to remain inside their geometric specifications under load



Source: Formlabs

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Elongation: Resistance of a material to breaking when stretched

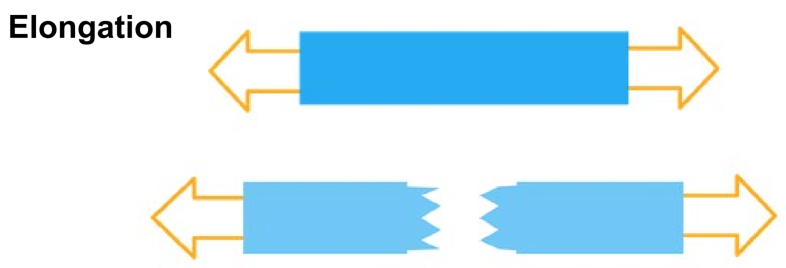
- helps you compare flexible materials based on how much they can stretch
- indicates if a material will deform first, or break suddenly

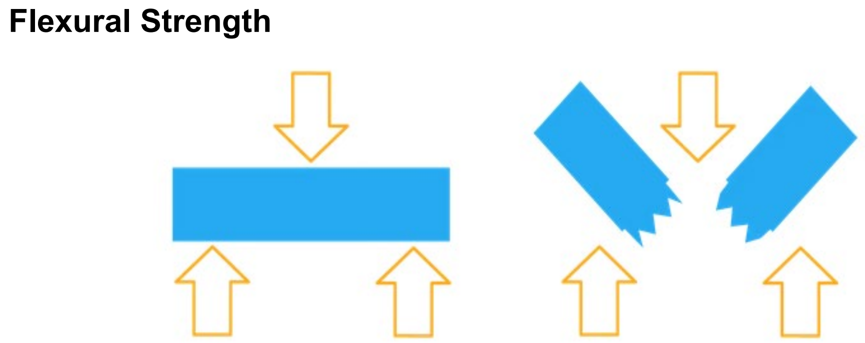
Flexural Strength: Resistance of a material to breaking when bent

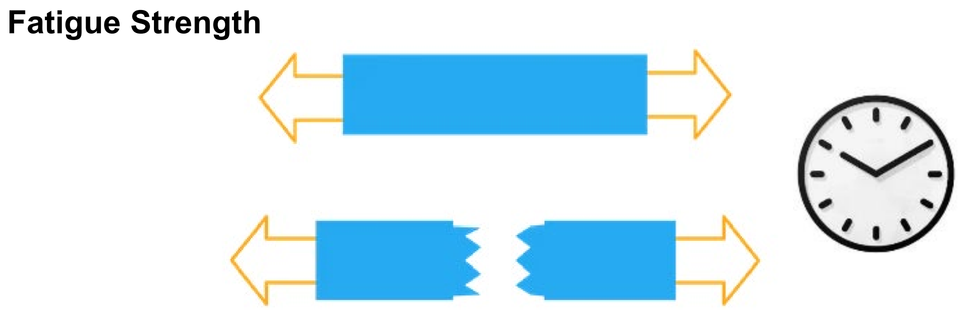
- strength versus bending loads
- good indicator if a material is isotropic (homogeneous)

Fatigue Strength: highest stress that a material can withstand for a given number of cycles without breaking

- indicator of durability
- important on repeated loads







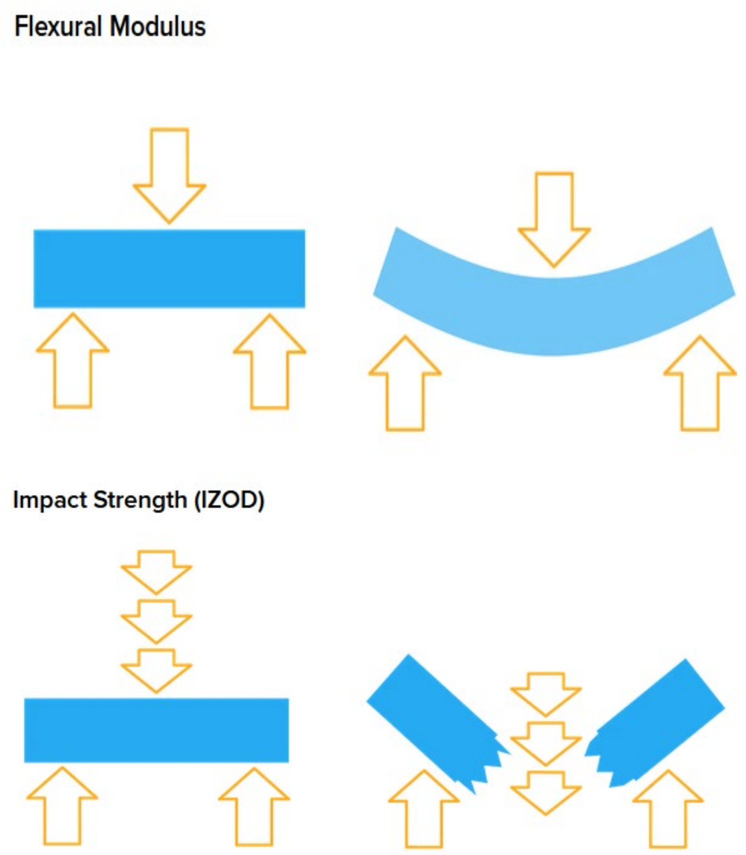
Source: Formlabs

Flexural Modulus: Resistance of a material to bending under load

- indicator for either the stiffness (high modulus) or the flexibility (low modulus) of a material

Impact Strength: Ability of a material to absorb shock and impact energy without breaking

- indicates toughness, helps you figure out if a part will survive when dropped on the ground or crashed into another object
- Important for applications like safety goggles



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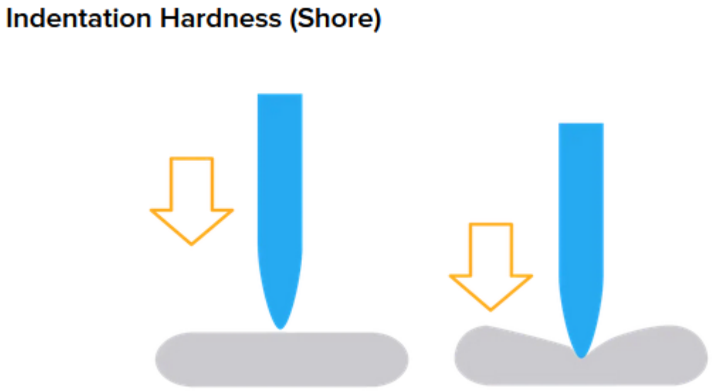
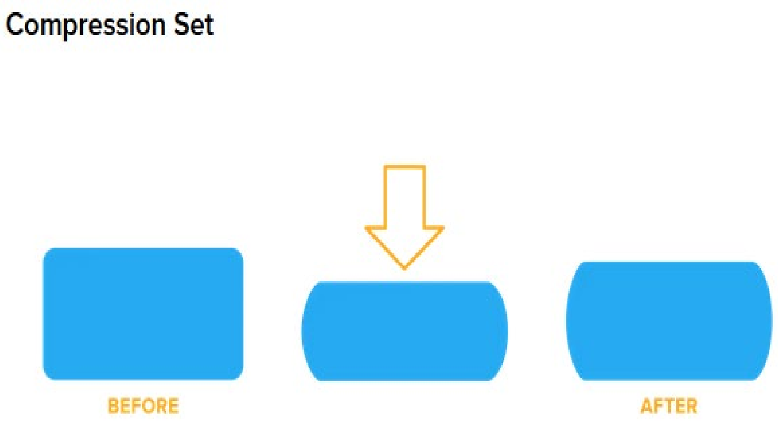
Indentation Hardness (Shore): Resistance of a material to deformation

- in practice synonymous with scratch resistance as well as resistance to indentation and elastic deformation
- helps you identify the right “softness” for rubber and elastomers for certain applications

Compression Set: Permanent deformation remaining after material has been compressed

- important for elastic applications, tells you if a material will quickly spring back into its original shape





Source: Formlabs

Water Absorption: Amount of water absorbed under specified conditions

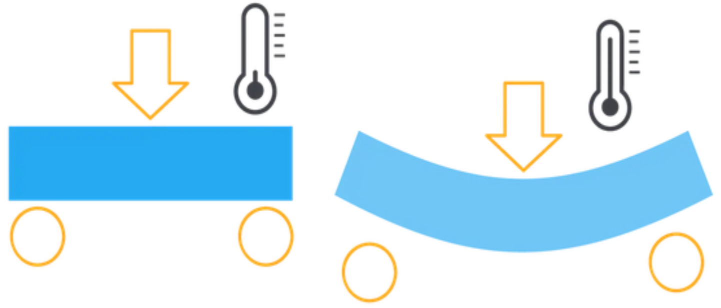
important during the processing of the raw material, high water absorption or humidity can lead to hydrolysis, which cracks long molecule chains into shorter ones and weakens the material properties

Water Absorption

Heat Deflection Temperature: Temperature at which a sample deforms under a specified load

indicates if a material is suitable for high temperature applications such as enclosures and mounts for heating elements, components which come in contact with hot liquids or gasses such as tooling for injection molds, fluidic connectors, valves, and nozzles.

Heat Deflection Temperature (HDT)



Source: Formlabs

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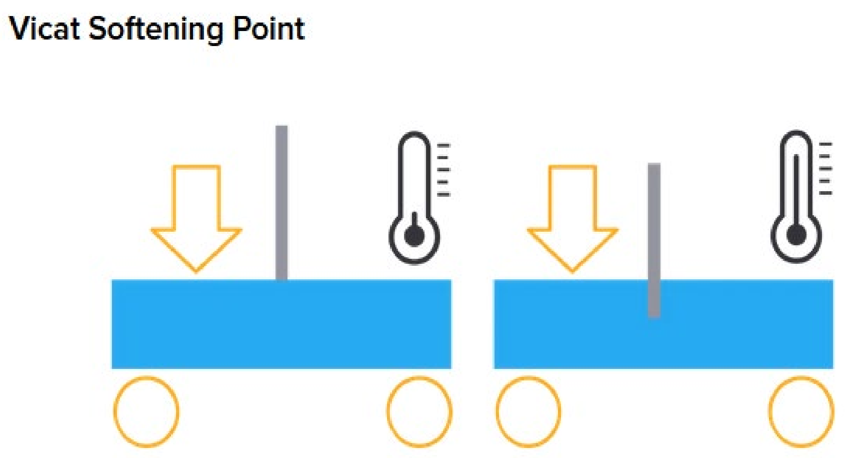
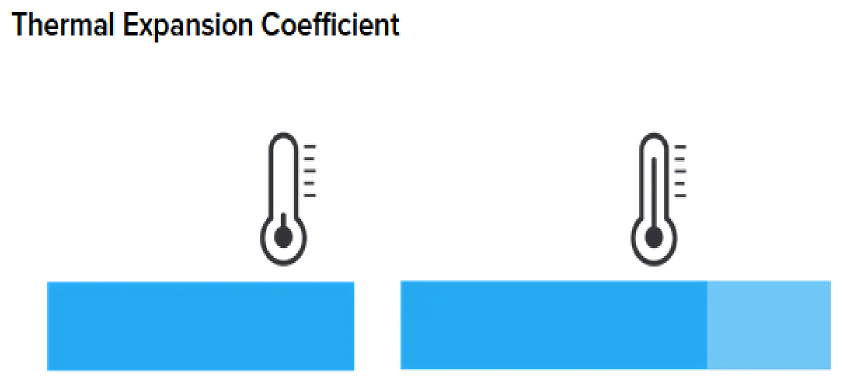
Vicat Softening Point: Temperature at which the material becomes noticeably soft

- used for materials that have no definite melting point. For high temperature applications it helps determine the upper temperature limit for continuous use

Thermal Expansion: Tendency of a material to expand (or shrink) in response to a change in temperature

- important for applications where a shape change in response to temperature is unacceptable or desirable
- if not taken into account can cause thermal phenomena such as hoop shrinkage, curling, and warping during printing





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Comparing Material Properties: Datasheets and Spider Web Diagrams

NYLON 12 MATERIAL PROPERTIES DATA

	METRIC[1,2]	IMPERIAL[1,2]	METHOD
Tensile Properties			
Ultimate Tensile Strength	50 MPa	7252 psi	ASTM D638 Type 1
Tensile Modulus	1850 MPa	268 ksi	ASTM D638 Type 1
Elongation at Break (X/Y)	11%	11%	ASTM D638 Type 1
Elongation at Break (Z)	6%	6%	ASTM D638 Type 1
Flexural Properties			
Flexural Strength	66 MPa	9572 psi	ASTM D790 A
Flexural Modulus	1600 MPa	232 ksi	ASTM D790 A
Impact Properties			
Notched Izod	32 J/m	0.60 ft-lb/in	ASTM D256
Temperature Properties			
Heat Deflection Temp. @ 1.8 MPa	87 °C	189 °F	ASTM D648
Heat Deflection Temp. @ 0.45 MPa	171 °C	340 °F	ASTM D648
Vicat Softening Temperature	175 °C	347 °F	ASTM D1525
Other Properties			
Moisture Content (powder)	0.25%	0.25%	ISO 15512 Method D
Water Absorption (printed part)	0.66%	0.66%	ASTM D570

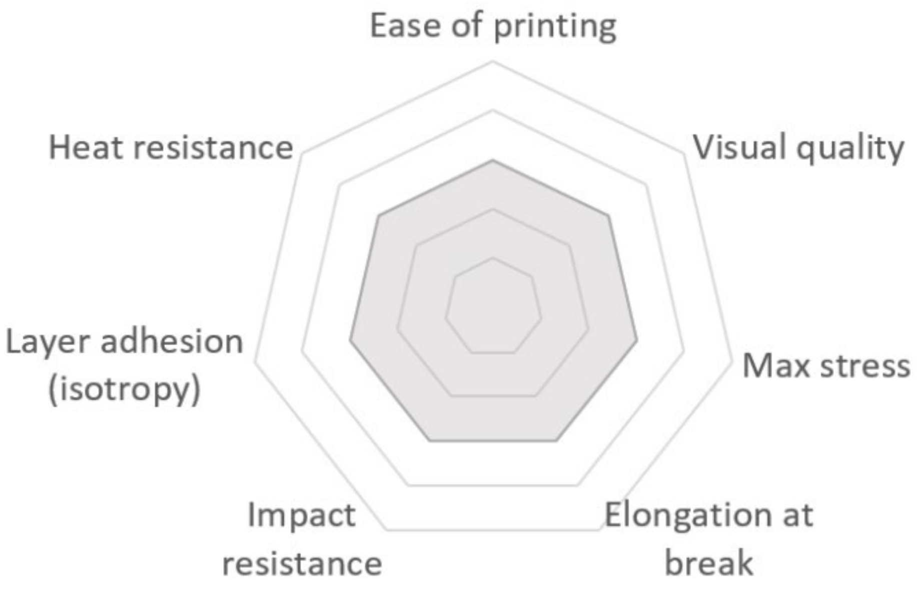
Evaluating Thermoplastics for Manufacturing

3 Major Categories

- Mechanical Performance
- Durability and Robustness
- Printability/Print Quality

Additional properties to be considered

- Cost/Availability
- Chemical resistance
- Humidity resistance



Material Properties Spider Web Graph

Source: https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/#conclusion

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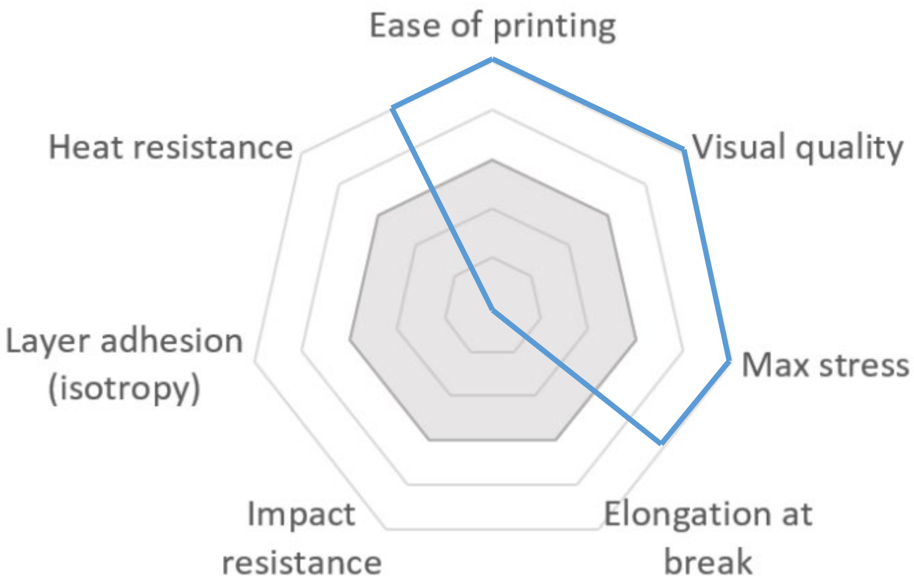
Visible/Tactile Attributes

- **Ease of printing:** How easy it is to print a material (bed adhesion, max printing speed, frequency of failed prints, flow accuracy, ease to feed into the printer etc.)
- **Visual quality:** How good the finished object looks
- **Max stress:** Maximum stress the object can undergo before breaking when slowly pulling on it



Material Properties Spider Web Graph

Adapted from: https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/#conclusion

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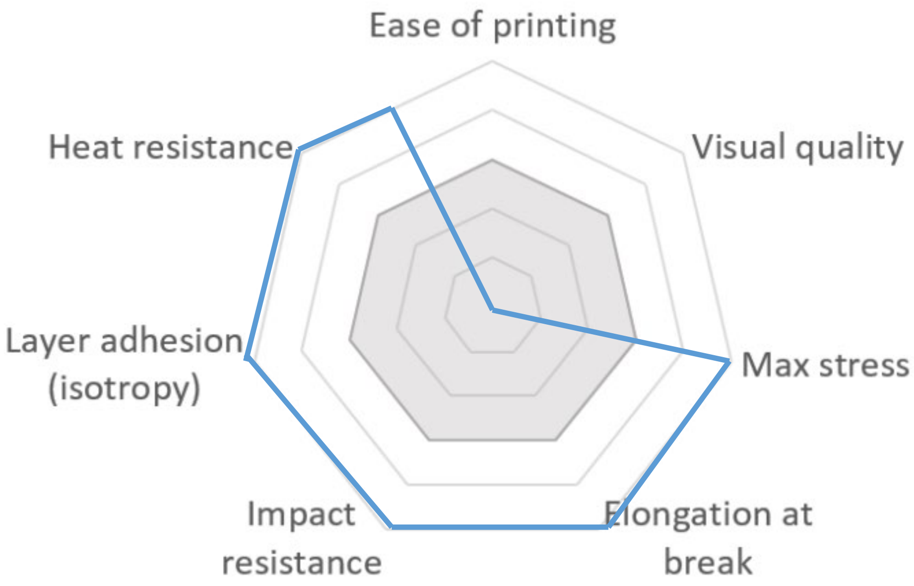
Mechanical/Thermal Properties

- **Max stress:** Maximum stress the object can undergo before breaking when slowly pulling on it
- **Elongation at break:** Maximum length the object has been stretched before breaking
- **Impact resistance:** Energy needed to break an object with a sudden impact
- **Layer adhesion (isotropy):** How good the adhesion between layers of material is
- **Heat resistance:** Max temperature the object can sustain before softening and deforming



Material Properties Spider Web Graph

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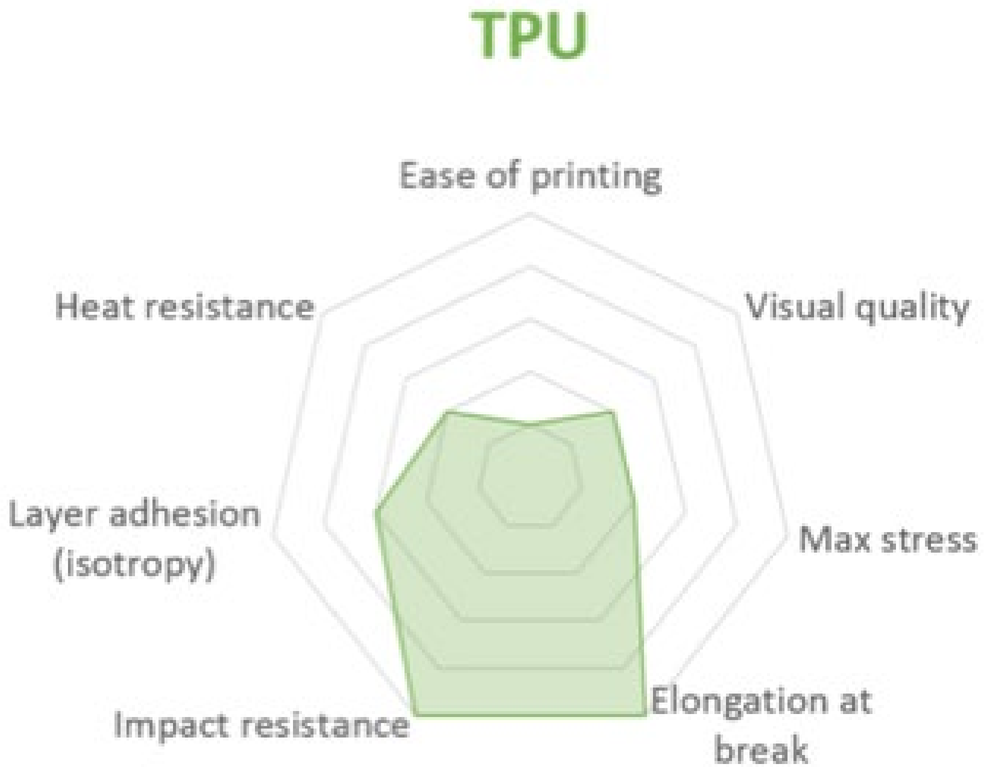
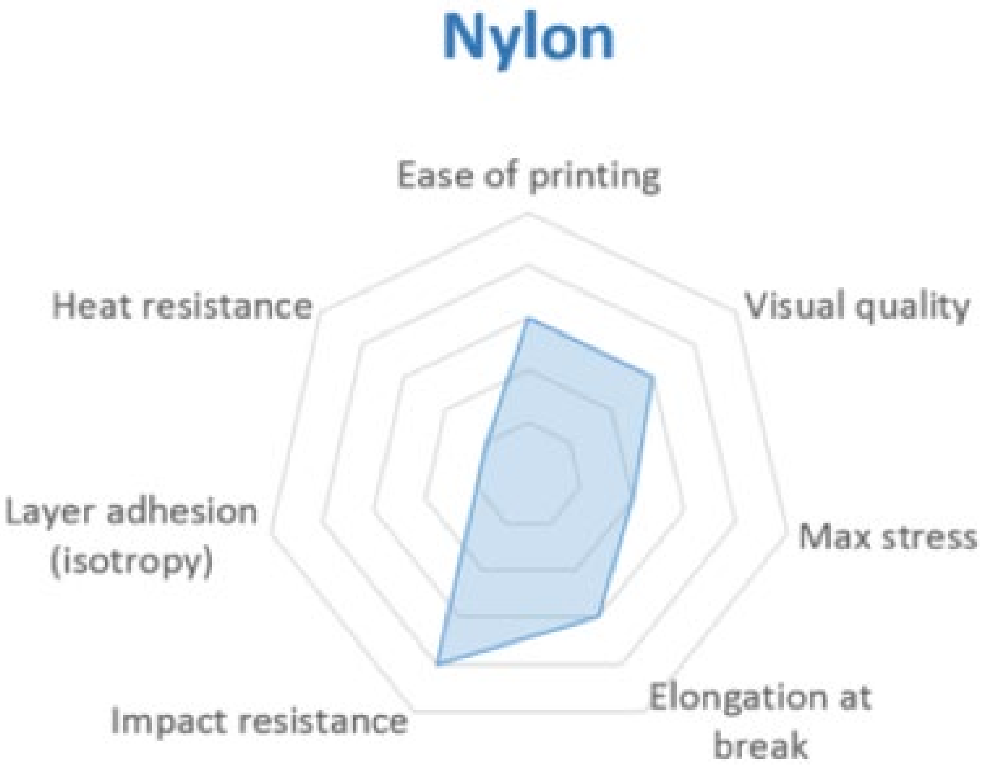
Evaluating Thermoplastics for Manufacturing with Spider Graphs Example





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- Thermoplastics in PBF Overview
- Filled Thermoplastics
- Material Selection
- Powder usage, mixing & handling
- Biocompatibility
- Summary

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Thermoplastics in PBF Overview

- As AM has expanded rapidly the recent years, so has the variety of printing materials
- The cost of an SLS machine as well as the cost of the raw materials indicates that without careful planning PBF could easily become a non affordable process
- The great majority of materials that are used for PBF machines are suitable for engineering applications
- Most PBF AM printable Thermoplastics fit into the below 3 categories:
  - **Standard (Commodity)Thermoplastics**
  - **Niche Thermoplastics**
  - **Engineering-grade or Performance Thermoplastics**

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Overview of Polymer Materials in PBF

PS (Polystyrene) - Hobbyist material with medium hardness and strength

PP (Polypropylene)- Functional prototypes, good chemical stability, several low-grade industrial applications

Standard (Commodity) Thermoplastics

Nylon - Tough, flexible niche material

TPE/TPU (Thermoplastic Polyurethane)- Flexible niche material

Engineering/Niche Thermoplastics

PAEK, PEEK, PEKK (Polyaryletherketone), PAFR– High Performance plastics, excellent for industrial applications and special applications where good resistant of heat load and fire resistance is required

High Performance Thermoplastics

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Standard (Commodity) Thermoplastics: These plastics can be acceptable in simple industrial applications and for hobbyist use. Alongside with nylons they are the most market available solutions for Polymer PBF.

- **PS (Polystyrene)** - Hobbyist material with medium hardness and strength
- **PP (Polypropylene)**- Functional prototypes, good chemical stability, several low-grade industrial applications

PP Belt Buckle

Source: additive3dasia.com

Source: https://i.materialise.com/blog/en/how-professional-3d-printing-works/

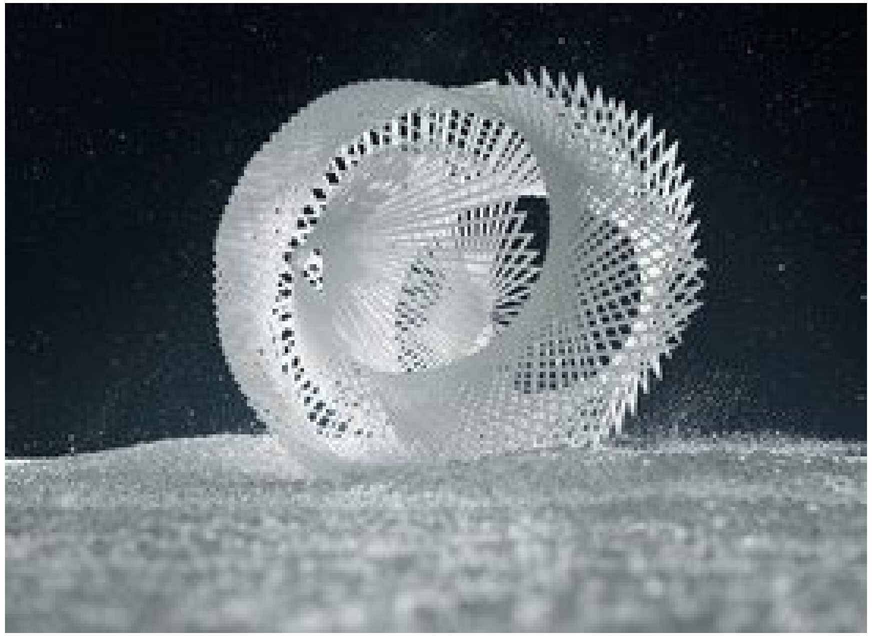
PS (Polystyrene)

Pros

- ✓ High rigidity
- ✓ Medium hardness
- ✓ Medium strength
- ✓ Excellent dimensional accuracy
- ✓ Transparent material

Cons

- Low humidity resistance
- Low impact resistance
- Low melting point, not suitable for high temperature applications



Polystyrene Sample Part

Source: EOS

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

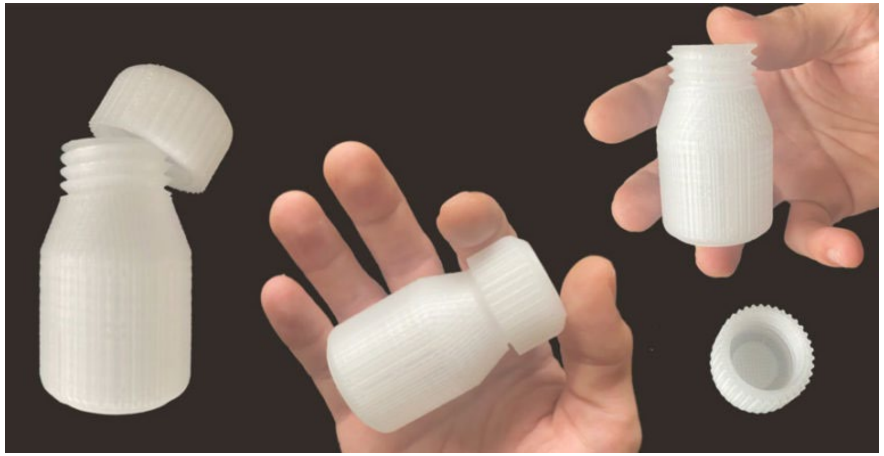
PP (Polypropylene)

Pros

- ✓ Products of high geometrical detail
- ✓ Melted but unused powder can be re-used, making the process more affordable
- ✓ Medium strength/Medium impact resistance
- ✓ Good operating temperature
- ✓ Electrical Insulation

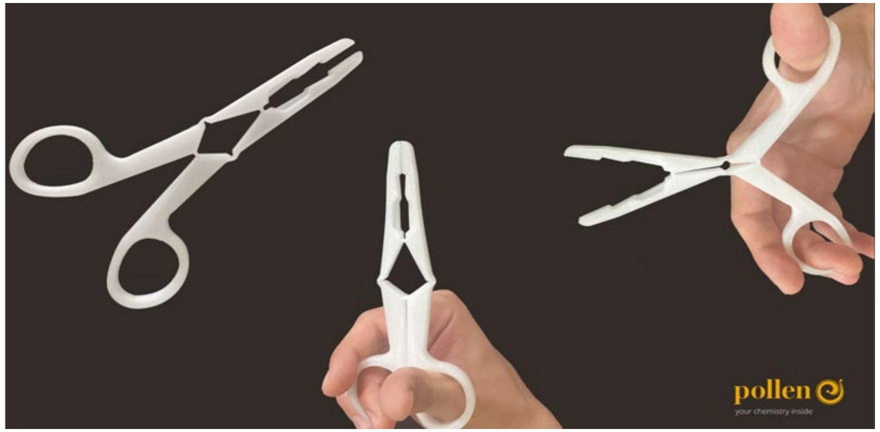
Cons

- Significant shrinkage
- Warping phenomenon
- Can't be glued easily/difficult post processing
- Low friction-Slippery surfaces
- Highly Flammable



Source: 3D natives

Gel Bottle with sealed function and functional threads



Source: Pollen AM

Polypropylene Scissors

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

Engineering Grade/Niche thermoplastics: Engineering grade properties sufficient for manufacturing environments, Niche thermoplastics have one or two excellent facets, making them very useful in specific applications.

- **Nylon also known as Polyamide:** it offers lightweight properties, strength and an acceptable durability. It is ideal for both rapid prototyping and production.
- **TPU/TPE:** an extremely ductile material that has similar properties to Nylon, while it is significantly more flexible.

Manifold

Source: 3D Print Western

Running Shoes

Source: Wanhua

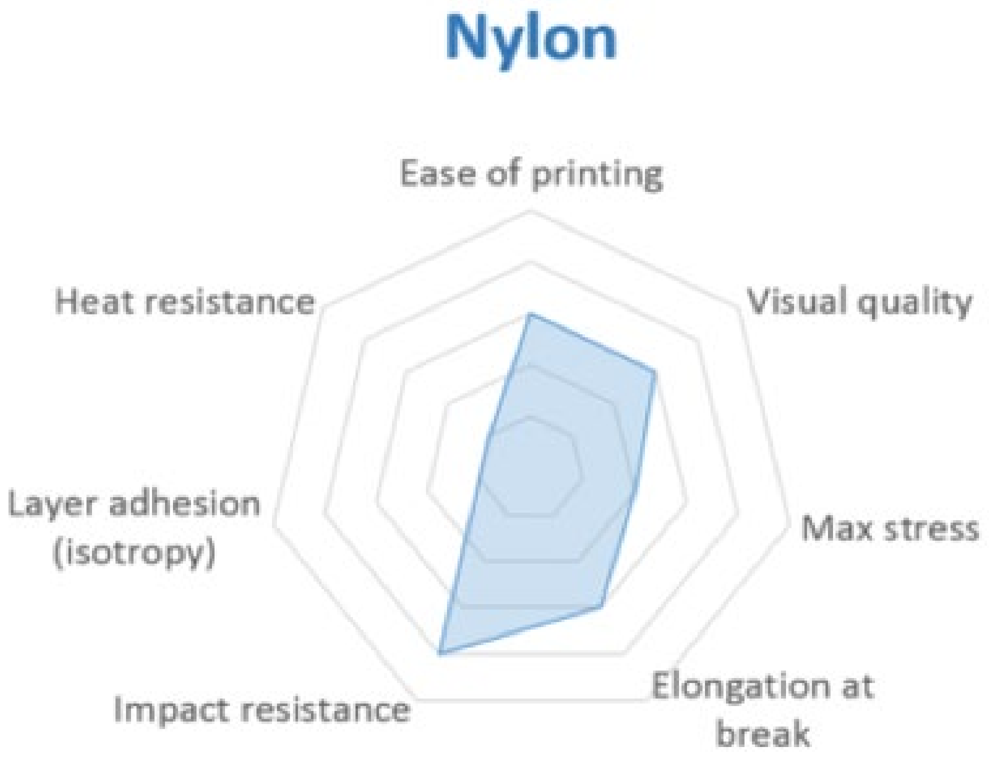
Nylon

Pros

- ✓ Best impact resistance for a non-flexible filament
- ✓ High Strength
- ✓ High Durability
- ✓ High chemical resistance
- ✓ Excellent wear resistance in contact with abrasive surfaces

Cons

- Absorbs moisture
- Potential high fume emissions
- Not stiff or heat resistance enough to be usable alone in high load environments
- Challenging layer adhesion



Source: https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/#conclusion

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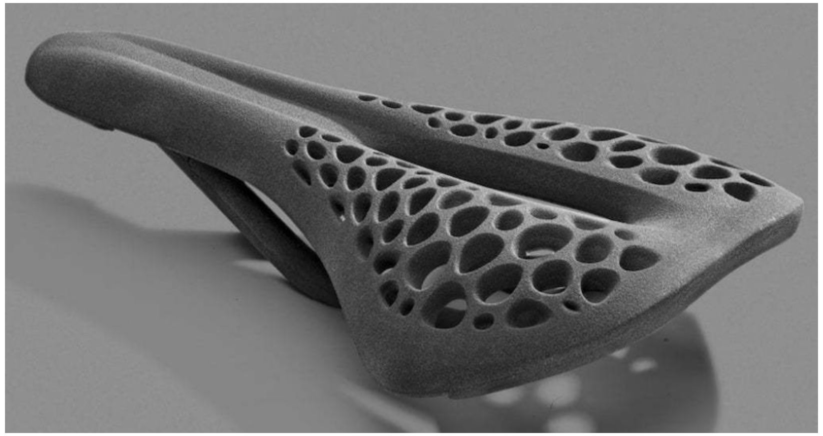
Nylon 6

- ✓ Good chemical resistance to hydrocarbon
- ✓ Good Strength
- ✓ Good Stiffness
- ✓ Excellent surface finish
- \- Significant water absorption
- \- Poor chemical resistance to strong acids and bases



Source: makexyz.com/

Bike Saddle

Nylon 11

- ✓ Ductile, strong, flexible material for when durability and performance are key.
- ✓ Impact-resistant prototypes, jigs, and fixtures
- ✓ Thin-walled ducts and enclosures
- ✓ Snaps, clips, and hinges
- ✓ Parts remain black even after significant abrasive wear

Hinge Mechanism

Source: EOS

SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING
Co-funded by the Erasmus+ Programme of the European Union

Nylon 12

- ✓ General purpose, versatile material with high detail and great dimensional accuracy
- ✓ High performance prototyping
- ✓ Small batch manufacturing
- ✓ Very good wear resistance
- ✓ Permanent jigs, fixtures, and tooling
- ✓ Suitable for general SLS parts

PA-12 textile Kinematic Dress

Source: Nervous System

PA-12 Sample Parts

Source: Dynamitism.com

TPU/TPE

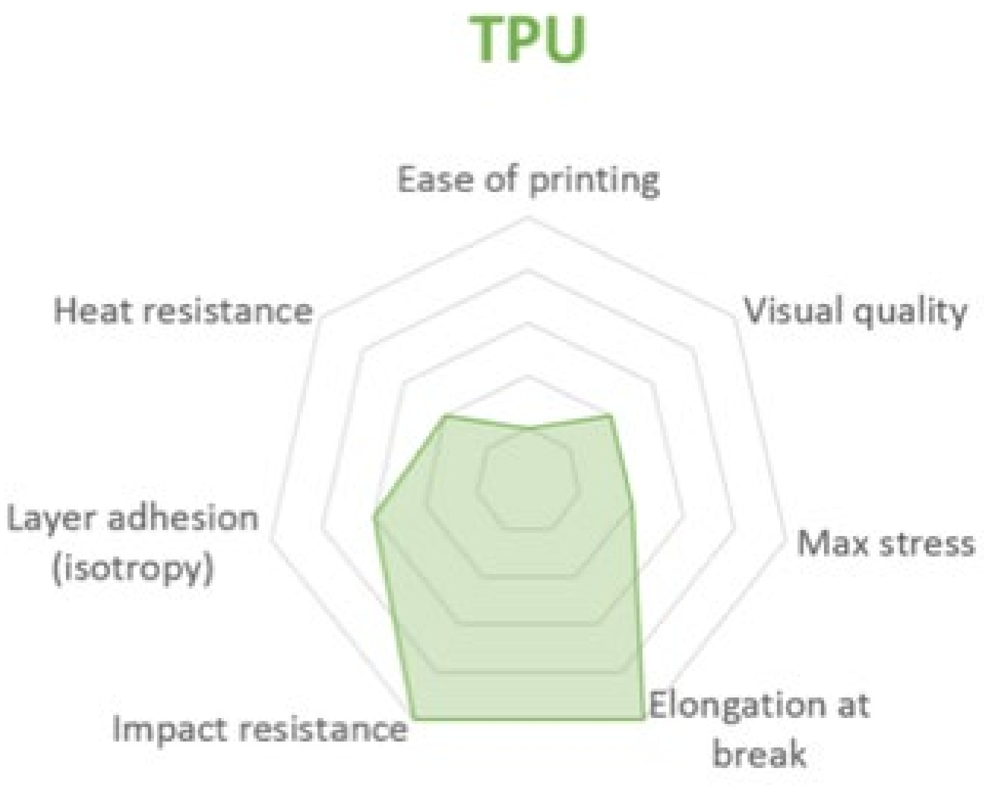
mostly used for flexible applications

Pros

- ✓ Very high impact resistance
- ✓ Good abrasion resistance
- ✓ Good resistance to oil and grease
- ✓ Highly flexible
- ✓ Highly Durable

Cons

- Difficult to post process
- Can't be glued easily
- Not strong enough to used in base industrial applications



Source: https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/#conclusion

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High Performance Thermoplastics: top of the line properties

❖ **PAEK/PEKK-PAFR (Polyaryletherketone)**

- High Performance plastics, excellent for industrial applications with great thermal resistant properties.
- It is a family of polyamides, which is suitable in applications such as aeronautics and aerospace where the resistance against high temperature and flames is of utmost importance.

❖ **PEEK (Polyetheretherketone)**

- combination of great mechanical properties, excellent temperature and chemical resistance making it useful for high performance applications

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PAEK (Polyaryletherketone)- PAFR

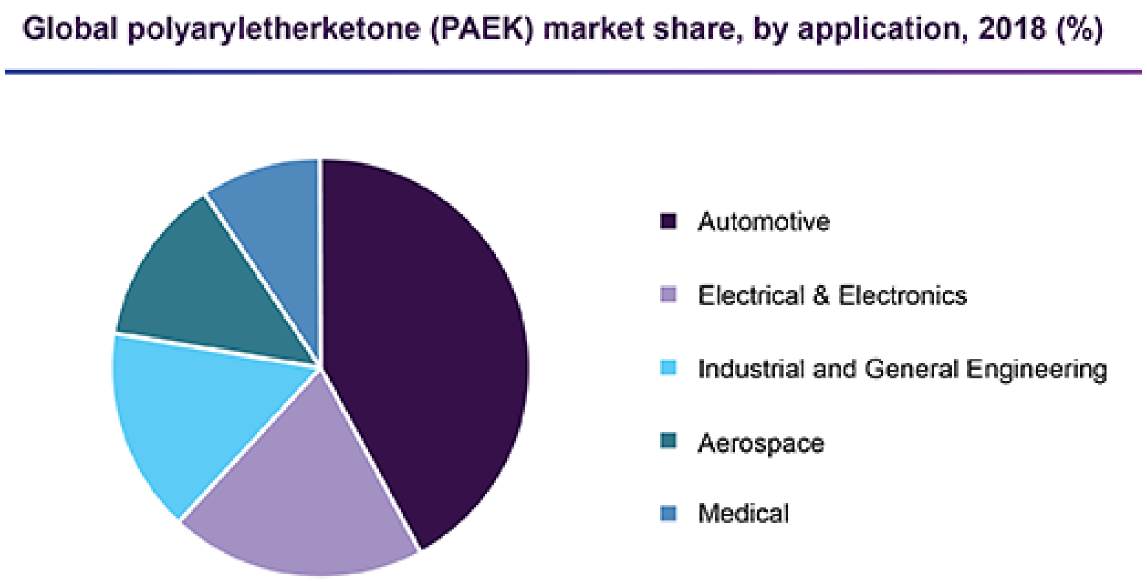
Used in high temperature applications and in applications where good abrasion resistance is required.

Pros

- ✓ Flame retardant
- ✓ Good chemical resistance
- ✓ Good Hydrolysis resistance
- ✓ Good tribological behavior
- ✓ Good thermal and mechanical properties
- ✓ UV Resistant

Cons

- Expensive
- Small recyclability
- Full refresh of the printing bed with new powder after each process



https://www.grandviewresearch.com/industry-analysis/polyaryletherketone-paek-market

PEEK

- Mostly used for high performance/high heat applications
- Also possessing great biocompatibility characteristics

Pros

- ✓ Very high allowable temperature (260℃)
- ✓ High mechanical strength
- ✓ High creep resistance at elevated temperatures
- ✓ Excellent chemical and hydrolysis resistance
- ✓ Excellent wear and frictional behavior
- ✓ Excellent dimensional stability

Cons

- Difficult to post process with conventional tools
- Can't be glued easily
- Poor interlayer bonding

https://etka.gr/product/ketron-peek/

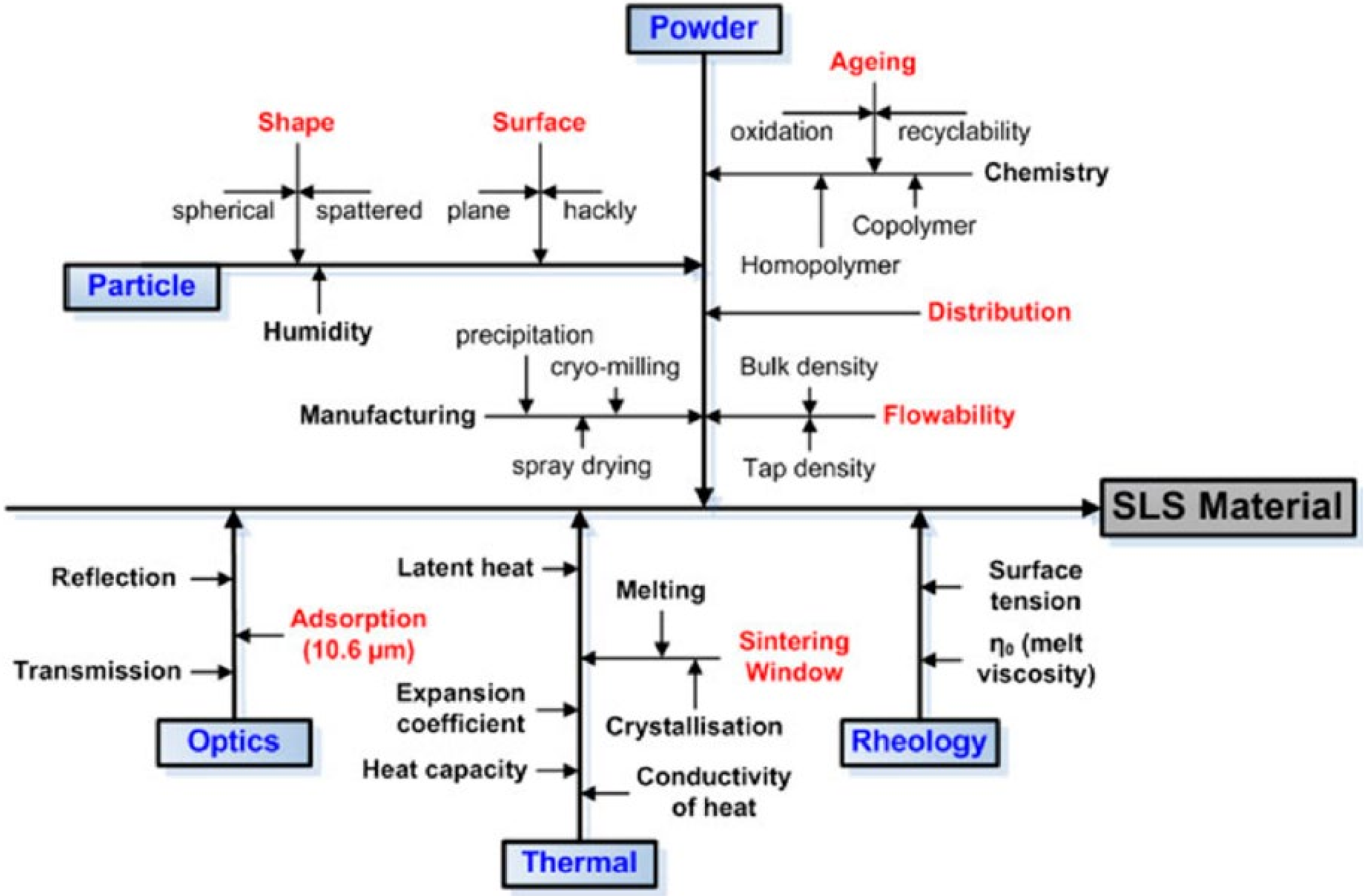
SAM: Thermoplastics in PBF Overview

Properties	PP	PS	Nylon	TPU/TPE	PAEK	PEEK
Tensile Strength (MPa)	33	34	40-50	26	71	90-100
Elongation	1.5	0.4	0.6-1.1	5.5-5.8	1.16	1.5
Tensile Modulus (GPa)	1.4	1.6	2.1	0.78	6.5	3.6
Density (g/cm^3)	0.90	0.77	1.06-1.14	1.21	1.39	1.32
Melting Point (^{o}C)	290	230	268	220	315	343
Biodegradable	Yes (under conditions)	No	No	Yes	No	No
Recyclable	Yes	Yes	Yes	Yes	No	No
Price (per kg)	15-30	15-45	50-100	90-100	200-400	200-400
Printability (1-10 scale)	9	8	8	3	4	4

https://www.materialise.com/en/manufacturing/3d-printing-technology/laser-sintering

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

Powder and Process Parameters Influencing Properties of PBF Polymer Parts



Source: Schmid, M.; Amado, A.; Wegener, K. Materials Perspective of Polymers for Additive Manufacturing with Selective Laser Sintering. J. Mater. Res. 2014, 29, 1824−1832.

- PBF is applicable to materials with vastly different bulk properties.
- Powders for the same bulk material can also vary in their morphology, sintering, and melting behavior.
- The powder characteristics strongly influence part properties such as accuracy, internal stresses, distortion, and response to mechanical load.
- The influence of intrinsic and non-intrinsic powder properties on PBF process parameters is summarized in the Figure above.

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Factors Affecting Quality and Mechanical Properties of PBF AM printed Parts

Process parameters
- Scanning speed
- Layer height
- Path planning strategy
- Stand of distance

SLS Printer-Specifications
- Laser power
- Laser spot diameter
- Laser focus
- Build Platform temperature
- Build Chamber Temperature
- Machine Calibration
- Machine Resolution

CAD Model
- Quality of STL File

Final Part Quality and Mechanical Properties

Part Build Orientation
- Z direction
- Y direction
- Z direction

Raw Material
- Powder Quality
- Density
- Mean powder particle size
- Manufacturer

Environment
- Temperature
- Humidity
- Oxygen content

Real AM Printed Parts might have **lower than expected** final properties

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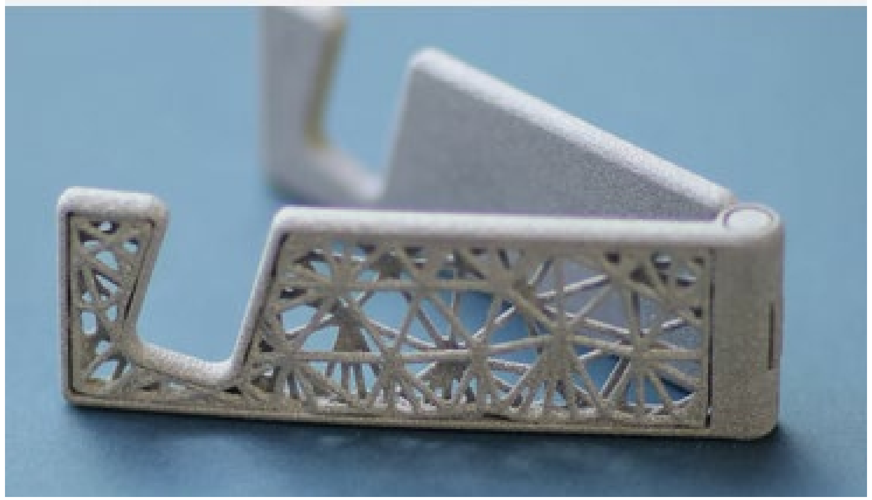
Overview of Filled Thermoplastics in PBF

Nylon based composites (PA-CF, PA-GF, PA-AF): The progress in material science has contributed to nylon-based composite materials mixed with carbon fiber, glass fiber and aluminum

Nylon based Composites

Glass bead – CF Sample Part

Source: EOS



Nylon-Alumide Smartphone Stand

Source: EOS

SAM: Filled Thermoplastics Overview

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Nylon-based composites: Materials which are mixed with glass, aluminum or carbon fibre improving the performance in terms of **structural** and **thermal** properties as well as **better dimensional stability** and **less shrinkage.**

- **PA-AF:** High Performance nylon mixed with aluminum, excellent for high performance industrial and structural applications.
- **PA-GF:** High Performance nylon mixed with Glass fiber, enhanced mechanical and thermal properties.
- **PA-CF:** High Performance nylon mixed with Carbon Fiber, similar performance with PA-GF (greater structural performance in comparison to glass when fibers are oriented in relation to the structural loads)

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Nylon Based Composites (PA-CF, PA-GF, PA-AF)

Each added component (aluminum, carbon fiber, glass) increases the mechanical and thermal properties of polyamide (Nylon) and provides better dimensional stability and reduces shrinkage

Pros

- ✓ Excellent stiffness and stiffness to weight ratio
- ✓ High density and high Tensile strength
- ✓ Wear resistance
- ✓ Good machinability
- ✓ Temperature resistant

Cons

- Harder to create parts with complex geometrical features
- Difficult post processing with conventional tools

CF Filled Nylon Manifold

Source: ams3d.co.za

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PA-AF (Aluminum Filled Nylon) vs PA (PA12)

MEASUREMENT	VALUE
Density	1.36 ±0.05 g/cm³
Tensile Strength	48 ±3 MPa
Tensile Modulus	3800 ±150 MPa
Flexural Modulus	3600 ±150 MPa
Charpy – Impact strength	29 ±2 kJ/m²
Charpy – Notched Impact Strength	4.6 ±0.3 kJ/m²
Shore D/A-hardness	D76 ±2
Heat Deflection Temperature	130 °C
Elongation at Break	3.5 ±1%

MEASUREMENT	VALUE
Density	0.95 ±0.03 g/cm³
Tensile Strength	48 ±3 MPa
Tensile Modulus	1650 MPa
Flexural Strength	41 MPa
Elongation at Break	20 ±5%
Flexural Modulus	1500 N/mm²
Charpy – Impact strength	53 ±3.8 kJ/m²
Charpy – Notched Impact Strength	4.8 ±0.3 kJ/m²
Izod - Notched Impact Strength	4.4 ±0.4 kJ/m²
Ball Indentation Hardness	77.6 ±2
Shore D/A-hardness	D75 ±2
Heat Deflection Temperature	86°C

SAM: Thermoplastics in PBF Overview

Properties	PP	PS	Nylon	TPU/TPE	PAEK	PEEK	Nylon based composites
Tensile Strength (MPa)	33	5.5	40-50	26	71	90-100	**50**
Elongation	1.5	0.4	0.6-1.1	5.5-5.8	1.16	1.5	**0.10**
Tensile Modulus (GPa)	1.4	1.6	2.1	0.78	6.5	3.6	**2.5-3.5**
Density (g/cm^3)	0.90	0.77	1.06-1.14	1.21	1.39	1.32	**1.00-1.3**
Melting Point (°C)	290	230	268	220	315	343	**260**
Biodegradable	Yes (under conditions)	No	No	Yes	No	No	**No**
Recyclable	Yes	Yes	Yes	Yes	No	No	**No**
Price (per kg)	15-30	15-45	50-100	90-100	200-400	200-400	**300-500**
Printability (1-10 scale)	9	8	8	3	4	4	**4**

https://www.materialise.com/en/manufacturing/3d-printing-technology/laser-sintering

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How to choose a material

1. **Determine performance requirements via intent of use**
   - Prototyping and R&D?
   - Validation or pre-production?
   - End-use parts?
2. **Translate performance to material requirements**
   - Stiffness/hardness
   - Toughness/tear strength
   - Temperature and chemical resistance
   - Creep and durability
3. **Select material**
   - Design Space/Operation Environment
   - Durability
   - Longevity
   - Cost

Test print and iterate!!

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Note: Function First, Materials Second

- People exhibit a tendency to focus on a material that a similar part has historically been made of.
- Because of the advanced possibilities of AM, it is often best to first think of the function the part must perform and design around that.
- Once the design is complete, one can then look at available AM materials to see if one of them is suitable for the function and the mechanical properties, that must be achieved.
- A component DfAM often requires substantially less material than a conventionally made part => you can manufacture the part using a higher-specification, more expensive material without raising the overall cost

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Example: Running Shoes

source: http://peaksportsusa.com/products/peak-3d-print-running-shoes-1

- **What are the performance requirements?**
- **How are those performance requirements translated into material requirements?**
- **What material would you use and why?**

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Example: V-twin Intake Manifold

source: https://www.3dsystems.com/customer-stories/briggs-stratton-uses-sls-printing-develop-and-qualify-engine-parts

- **What are the performance requirements if:**
  a) used for an early prototyping?
  b) used for a 2000hr on-engine testing?
  c) small batch production?

- **How do material requirements change when intent of use changes?**

- **What material would you use in case a) and case b) and why?**

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- **Thermoplastics in PBF Overview**
- **Filled Thermoplastics**
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- **Biocompatibility**
- **Summary**

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Powder Transport and Storage

- The exact storage conditions for the respective powder must be taken from the manufacturer's data sheets. In general, a dry storage location with a temperature of 20 degrees Celsius is recommended.

- The most important data for a powder is contained on a label, including the grain size, the filling content and the production date.

- It is important to secure that the container was properly closed and not opened during transport.

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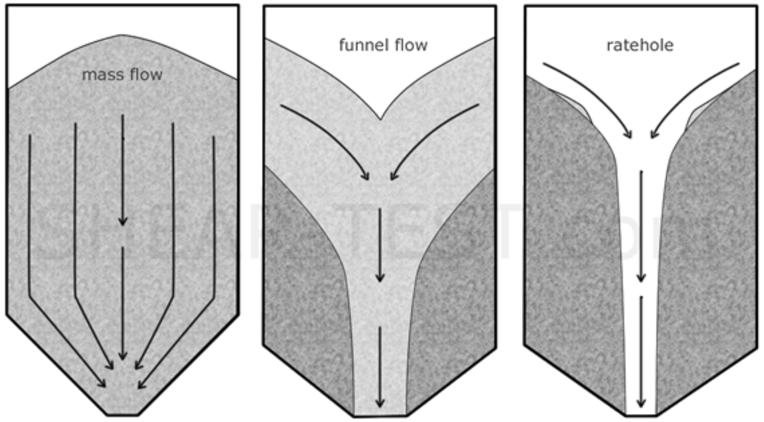
Powder Mixing

- The powder is mixed in suitable machines and checked each time in order to ensure that the desired result has been achieved, otherwise fresh powder is added.
- Powder flowability: It represents the ability of a powder to flow between certain channels
- Apart from the size of the powder particle, the interaction of it with the environment is capable to affect the flowability.



https://ip.festo-didactic.com/DigitalEducation/EITManufacturing/EMPOWDER/FDRenderer/index.html?LearningNugget=56ff8c9ebef5464792118b50b66f9ed9&Language=EN&FDEP=true

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Powder Usage

The PBF process comprises of **4 steps**

1. The Powder bed fusion process uses thermal energy to melt specific points on a layer of thermoplastic powder in the case of SLS.
2. The thermal energy melts the powder material, which then solidifies as it cools and each area of the part is manufactured.
3. After the melting of a layer, the platform lowers and the powder is recoated in order to form a new layer.
4. This process is repeated layer by layer until final part is complete.

https://www.sinterit.com/5-most-common-myths-about-sls-powder-handling/

The final part is found inside a box full of powder.

So, the next steps require to clean the part from the unsintered powder.

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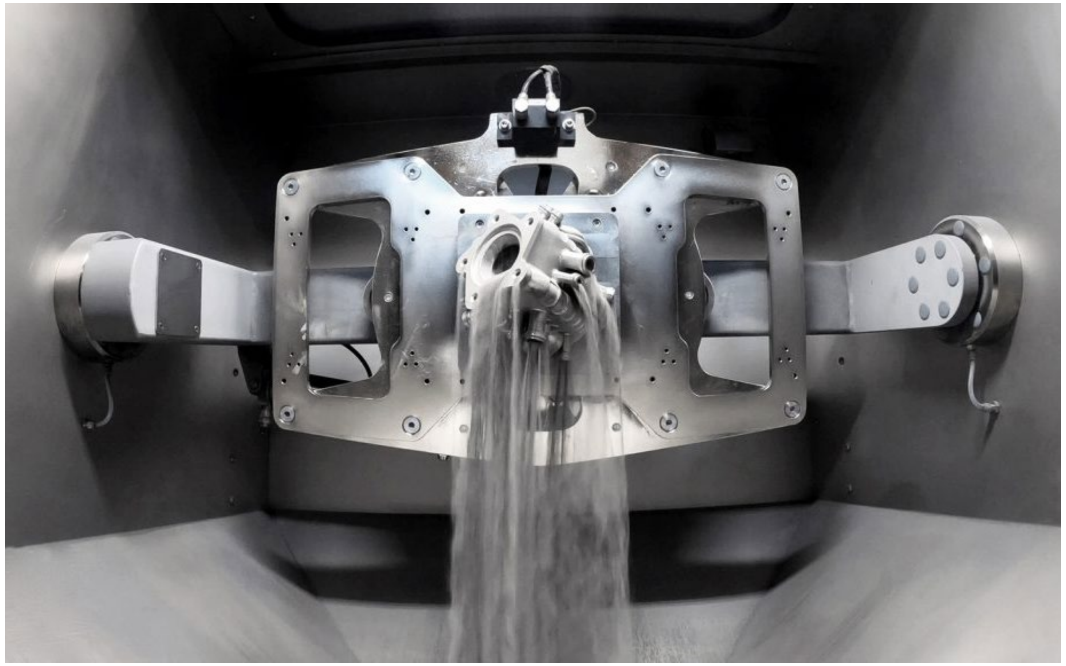
Powder Removal

- The unsintered powder is cleaned from the part body and based of the specifications of the material it can be reused after mixing with fresh powder. (up to ~90% recycling rate)
- In some cases, the heat affected zone during the sintering is large, and some portion of powder is sintered, reducing the mechanical and thermal properties of the raw material.
- The flowability and bulk density in particular play a major role and provide important information on the required mixing ratio.



https://www.metal-am.com/articles/powder-removal-in-powder-bed-based-metal-3d-printing/

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Powder Handling – Health and Safety Issues

The handling of powder requires also to take safety precautions, due to the very small particles of powder (45-100μm)

Extra care must be given when:

- Cleaning part and removing excess powder
- Cleaning Build chamber
- Refilling the reservoir of the machine
- Screening or blending used or virgin powder material

To this end standard operations have to be met:

- Standard Operating Procedures
- Hazard Identification
- Filtration/Disposal

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Powder Recycling

Some general metrics related to the handling and recycling or powder waste:

- Powder reclamation is pretty simple - any powder that is stuck to the part is waste, any that falls off is good to [re]use.
- A light tap is given to encourage the powder to fall off, but no more.
- A general rule of thumb determines 75% used powder, 25% virgin powder for a refill.
- **Nylon 11**: about 40% of the material is waste
- **Nylon 12**: amount of virgin powder required was reduced to 25%.
- Waste is **significantly higher** in composite materials

https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/life-times-selective-laser-sintering-powder/

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Outline

- Introduction
- Biocompatible Applications
- Biocompatible Materials Overview
- Advantages/Limitations of PBF Process
- Advances in Pharmaceutical Applications
- Conclusions

Cranial Implant

https://www.eos.info/en/3d-printing-examples-applications/all-3d-printing-applications/alphaform-medical-cranial-implants

SAM: Biocompatibility Introduction

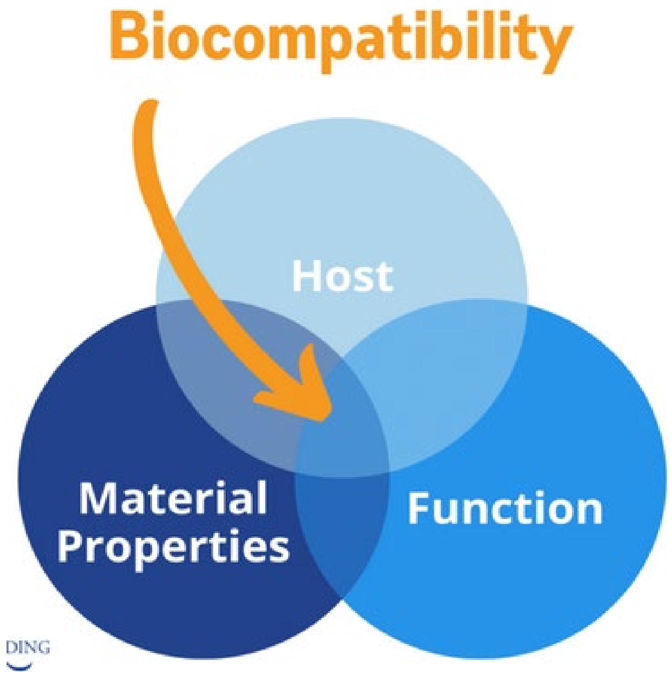
Biocompatibility: the ability of a biomaterial to sustain cellular activity including molecular signaling systems without provoking or arousing local or adverse effects to the host.

Biocompatible Material (Biomaterial): materials are biocompatible when they exert the expected beneficial tissue response and clinically relevant performance.

Components of Biocompatibility: cytotoxicity, genotoxicity, mutagenicity, carcinogenicity and immunogenicity.

Biocompatibility Standards

- United States Pharmacopoeia IV (USP Class IV) Biological Reactivity Test
- International Standards Organization 10993 (ISO 10993) Biological Evaluation of Medical Devices



https://www.cascobaymolding.com/biocompatibility

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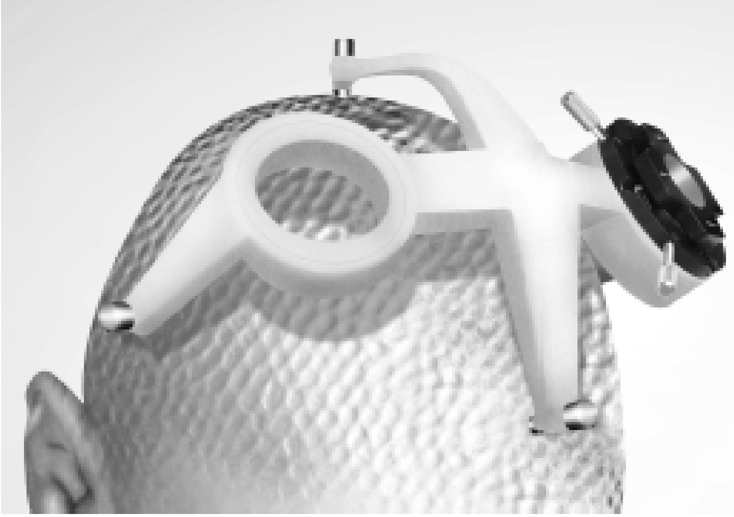
- Medical (devices, prosthetics, implants, dentures)
- Pharmaceutical (individualised dosage pills, drug delivery systems)
- Training Tools (Medical Modeling/Surgical Planning)

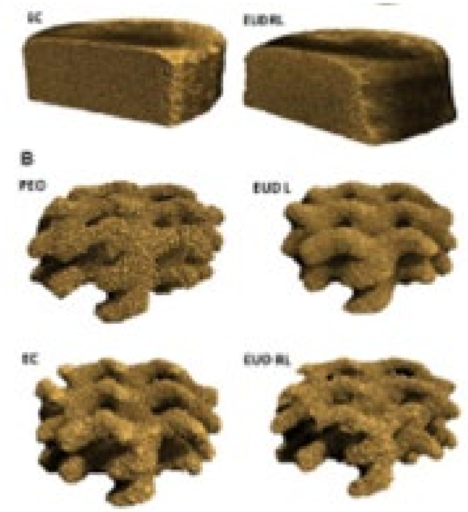


Customized Surgical Guide

Source: EOS GmbH/FHC

Hand Split

https://formlabs.com/blog/what-is-selective-laser-sintering/

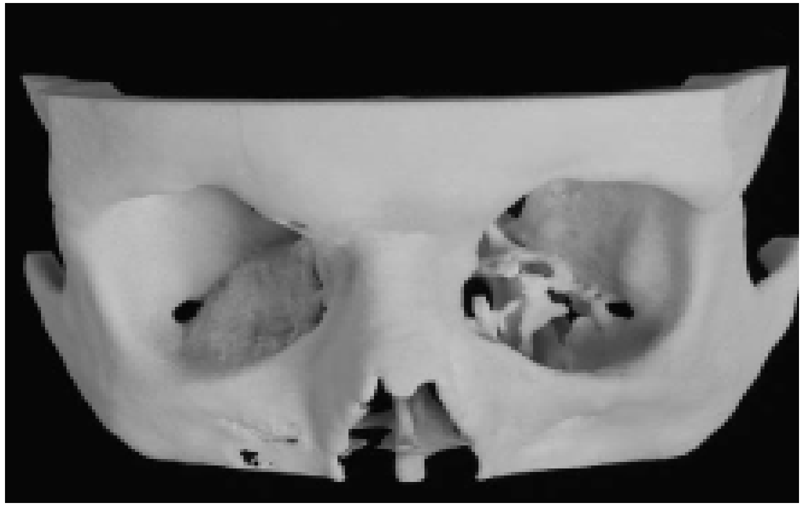


Solid Drug Tablets with different release profiles

Fina F, Goyanes A, Gaisford S, Basit AW. Selective laser sintering (SLS) 3D printing of medicines. Int J Pharm. 2017

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

Biomedical Applications



Model of Orbital Blowout Fracture used to construct titanium prosthetics

J. V. Williams, P. J. Revington: Novel use of an aerospace selective laser sintering machine for rapid prototyping of an orbital blowout fracture. Int. J. Oral Maxillofac.

Bionic Suite for Paraplegics

https://www.3dsystems.com/learning-center/case-studies/3d-systems-and-ekso-bionics-help-man-and-machine-walk-one

Prosthetic Hands

Source: 3dprint.com/70181/sls-3d-printed-prosthetic/

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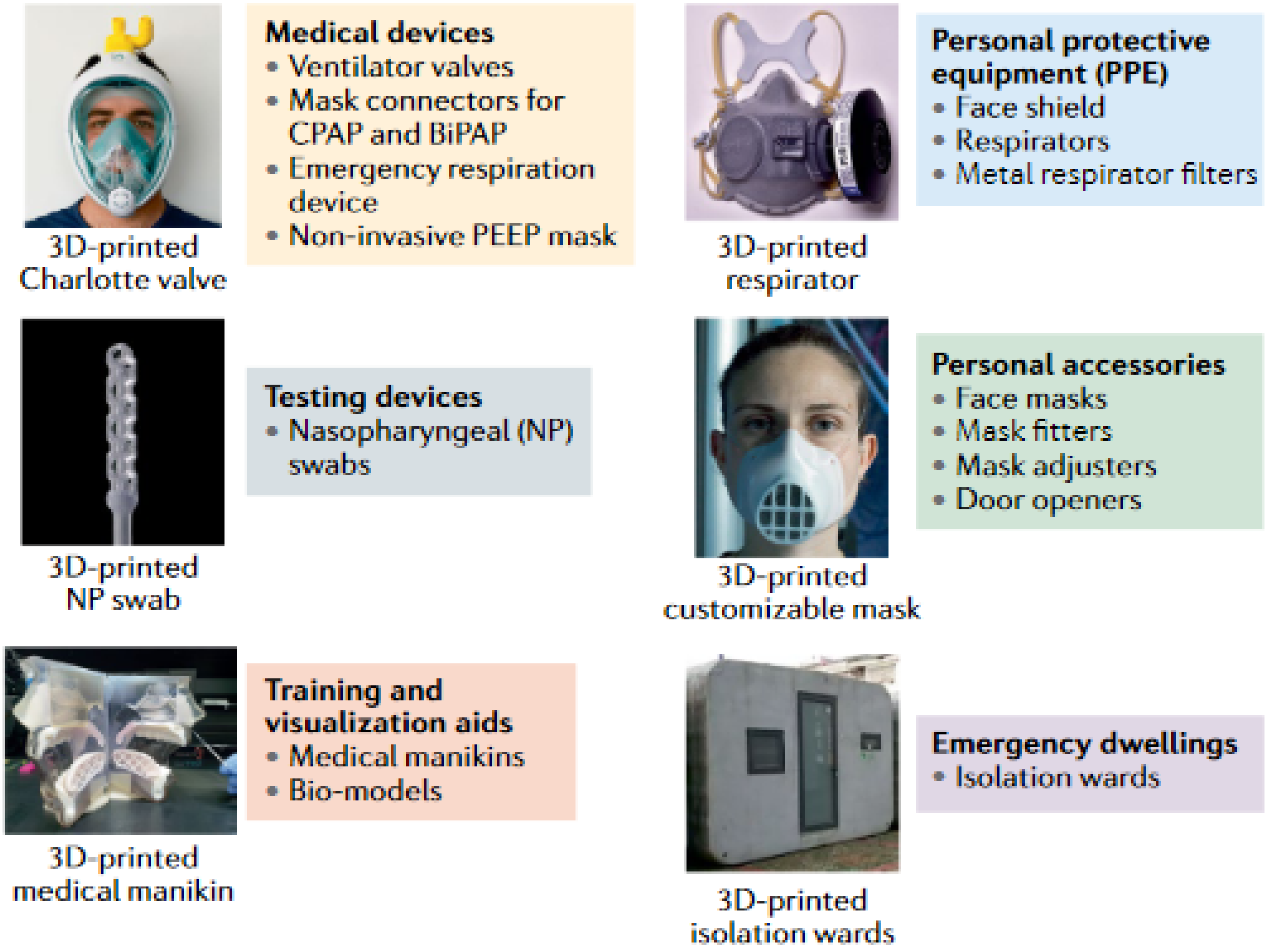
AM Printing Applications in the battle vs Covid-19



https://www.nature.com/articles/s41578-020-00234-3.pdf

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AM Printed parts used in the fight against Covid-19 overview:

Item	AM technologies
Face shields	FFF, SLA, SLS
Safety goggles	FFF, SLA, SLS
N95 respirators similar	FFF
Half-face masks	FFF, MJF, SLS
Antimicrobial mask	FFF
PAPR parts	FFF
Ear Savers	FFF
Mask fitters	FFF
Isolation chambers	FFF
Isolation wards	Not specified
Valves for CPAP	FFF
Splitter valves	Not specified
Valves for NIV helmets	Not specified
Venturi valves	FFF, SLA, SLS
Field Respirators parts	Not specified
Nasopharyngeal swabs	DLP, FFF, MJF, SLS, SLA
Hands-free door openers	MJF, FFF, SLS
Hands-free tools	FFF
Manikin for swab testing training	Not specified
Educational models	SLS, PolyJet
Mounts to point webcams downward	FFF
Bias tape makers	FFF
Mask pleaters	FFF
Copper filters	Binder jetting
Surgery mask	FFF

MEX Printing was the most used method

PBF was the second most used

Source: Longhitano, G.A., Nunes, G.B., Candido, G. *et al.* The role of 3D printing during COVID-19 pandemic: a review. *Prog Addit Manuf* **6,** 19–37 (2021). https://doi.org/10.1007/s40964-020-00159-x

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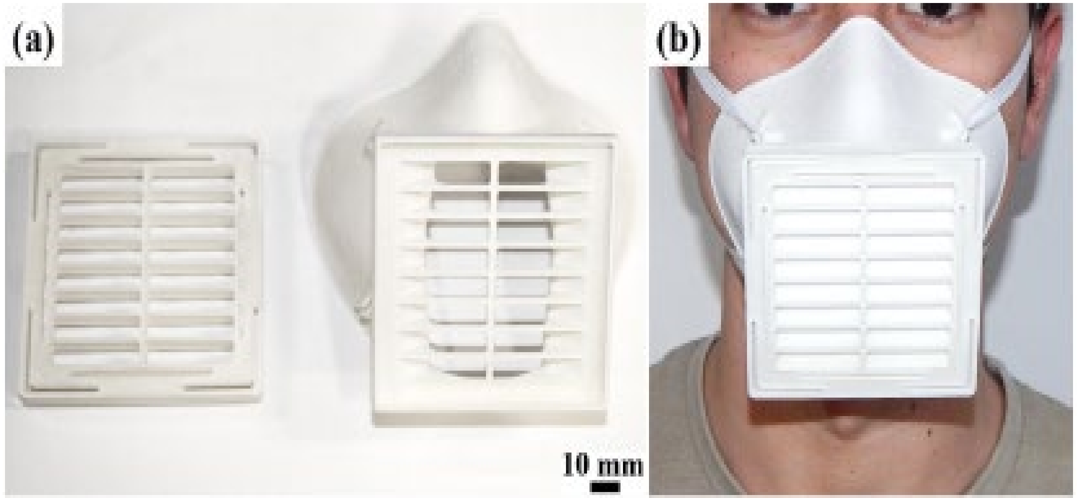
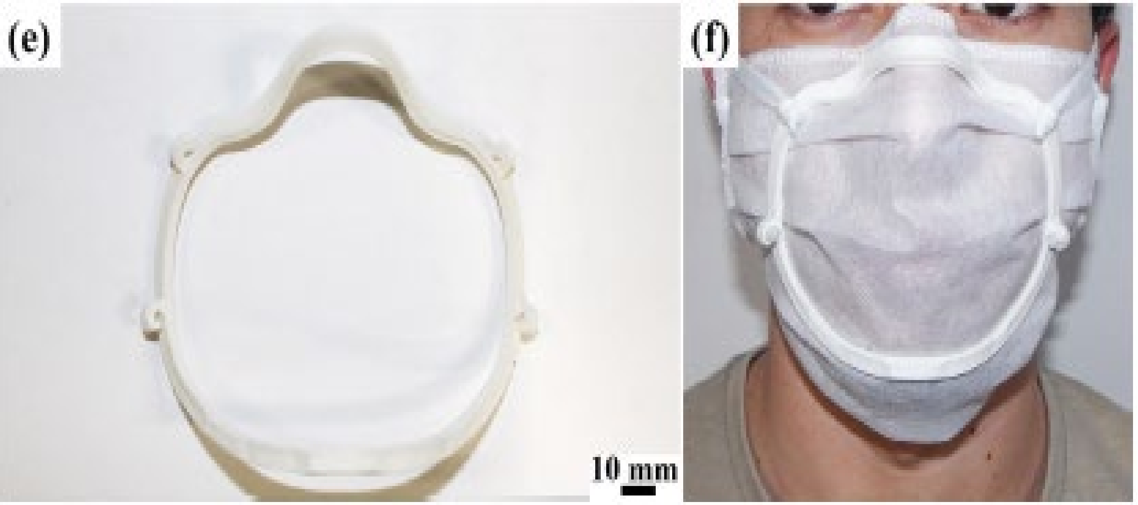
Face Masks and Support Parts

Stopgap Surgical Face Mask



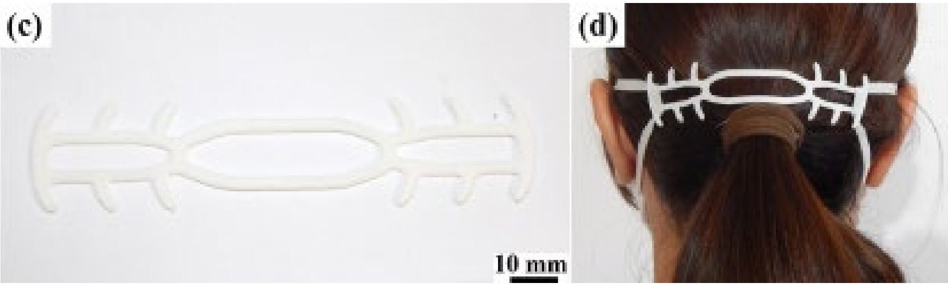
source: Stopgap Surgical Face Mask (SFM) Revision B|NIH 3D Print exchange (2020) https ://3dpri nt.nih.gov/disco ver/3dpx-014168.

Face Fitter



source: How to make Bellus3D's Face mask fitter|Bellus3D: High-quality 3D face scanning (2020) https ://bellu s3d.com/solut ions/facem ask.html.

Ear saver



source: Ear Savers for health workers|NIH 3D Print Exchange (2020) https ://3dpri nt.nih.gov/disco ver/3dpx-01386 0.

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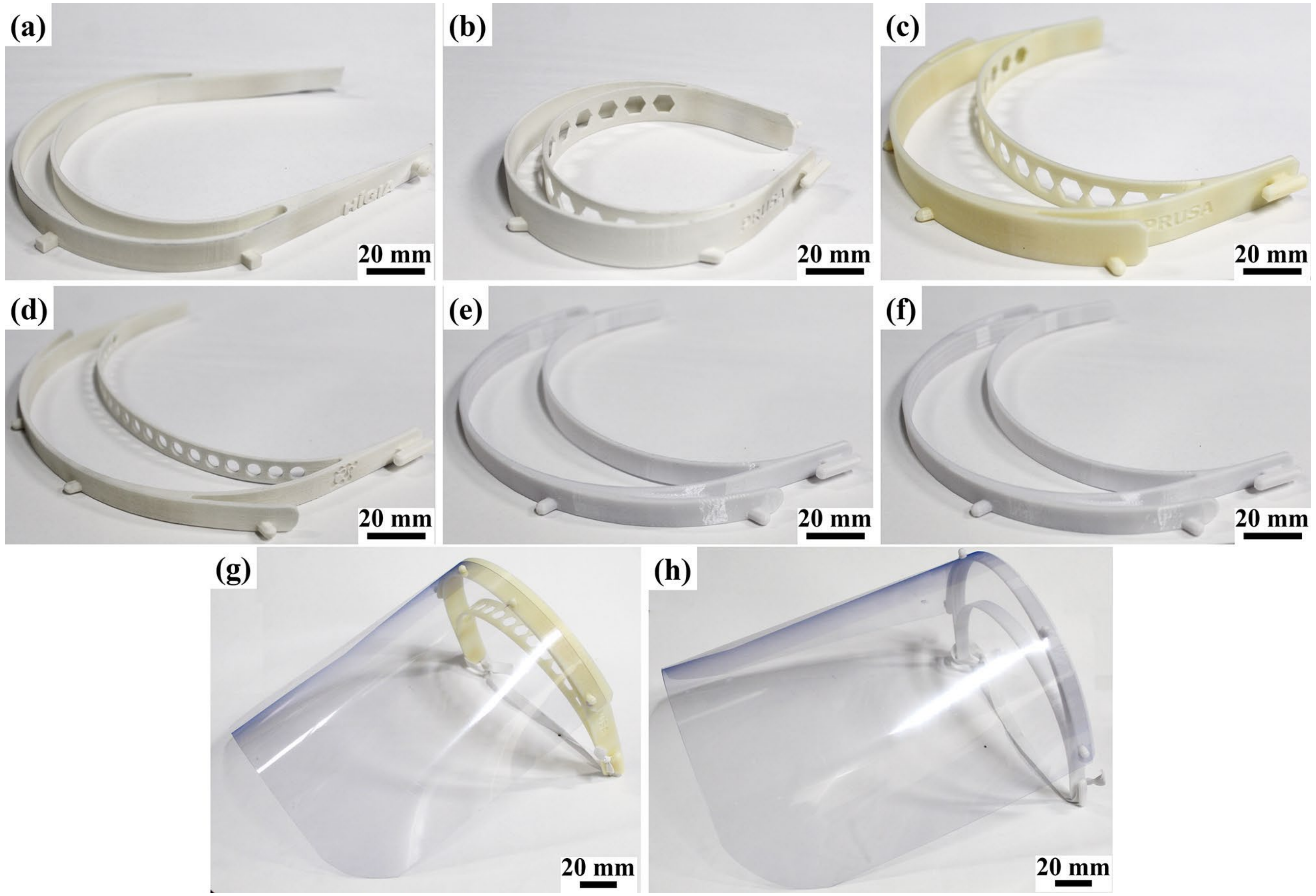
Face Shield Designs



PPE are the most printed devices during the pandemic because of:

- their relative simplicity
- low geometrical tolerance
- require lower-risk classification within Food and Drug Administration (FDA)

Designs (a), (b), (d) produced with PBF Printing

source: Longhitano, G.A., Nunes, G.B., Candido, G. *et al.* The role of 3D printing during COVID-19 pandemic: a review. *Prog Addit Manuf* **6,** 19–37 (2021).

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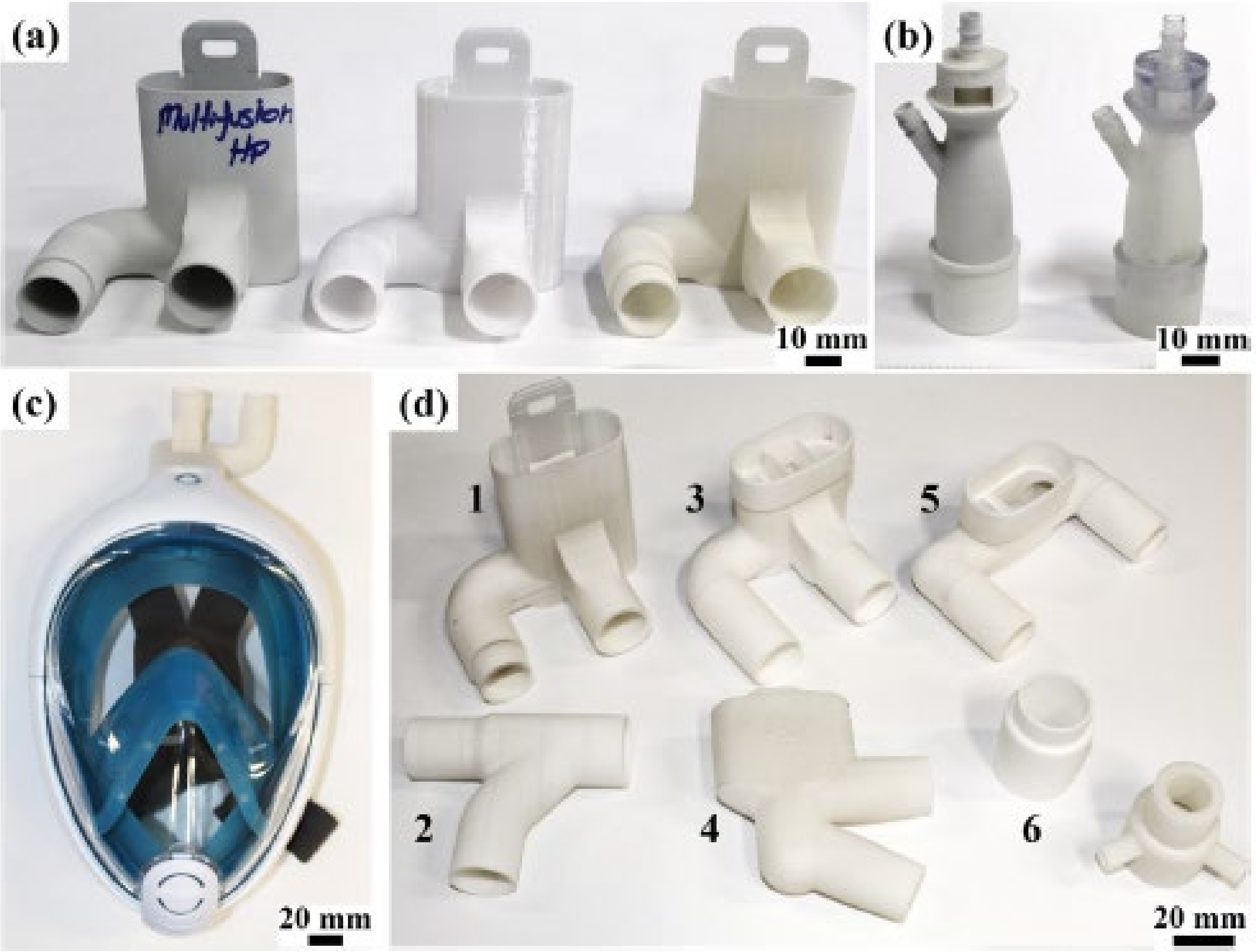

Valves and Adaptors

a) Isinnova's Charlotte Valve
b) Venturi Valves
c) Snorkelist Mark + Valve Assembly
d) Modified Valve/Valve Adaptors

source: Easy–Covid19 ENG|Isinnova (2020) https ://www.isinn ova.it/ easy-covid 19-eng/.

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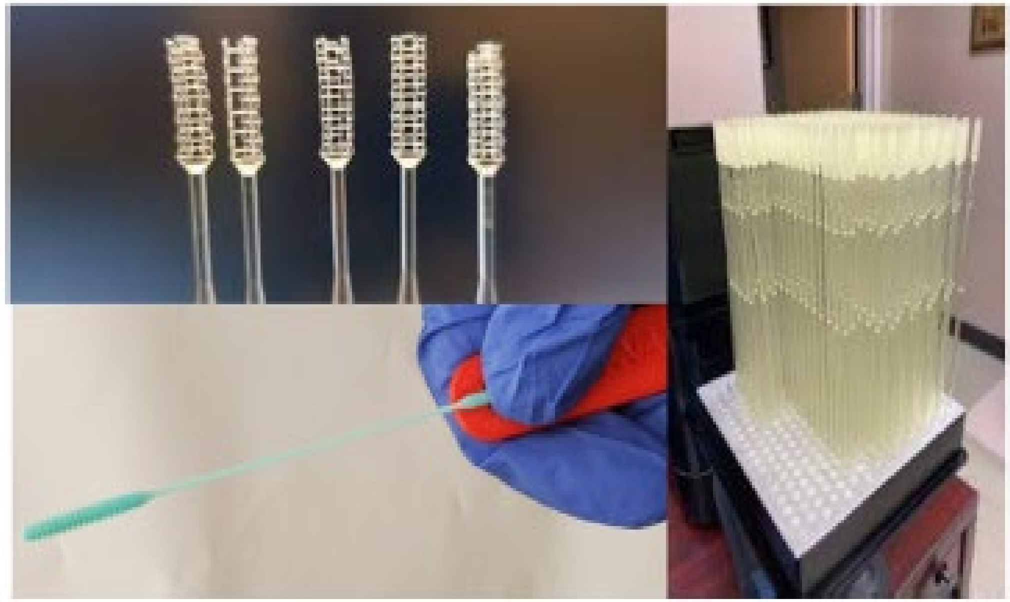
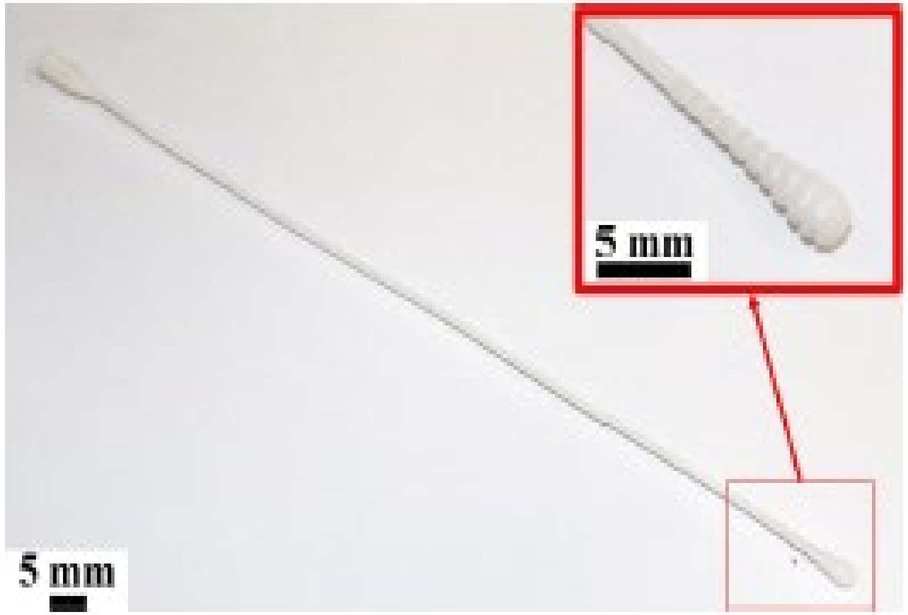
Medical Devices and Parts

Diagnostic Tools - Swabs



Source: Aydin, A., Demirtas, Z., Ok, M. *et al.* 3D printing in the battle against COVID-19. *emergent mater.* **4,** 363–386 (2021)

Nasopharyngeal Swab



source: NIH 3D Print Exchange (2020) https://3dpri nt.nih.gov/disco ver/3dpx-01373 0

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Misc.

Door Openers

source: Materialise Acts: Our 3D Printing Response to COVID-19 (2020) https ://www.mater ialis e.com/en/3d-print ing-responseto-covid -19.

Hands-free Tools

source: GB 3D—Hands Free—Door Pull Opener—Button Press—Door Open by bgiovanny—Thingiverse (2020) https ://www.thing iverse.com/thing :43101 10.

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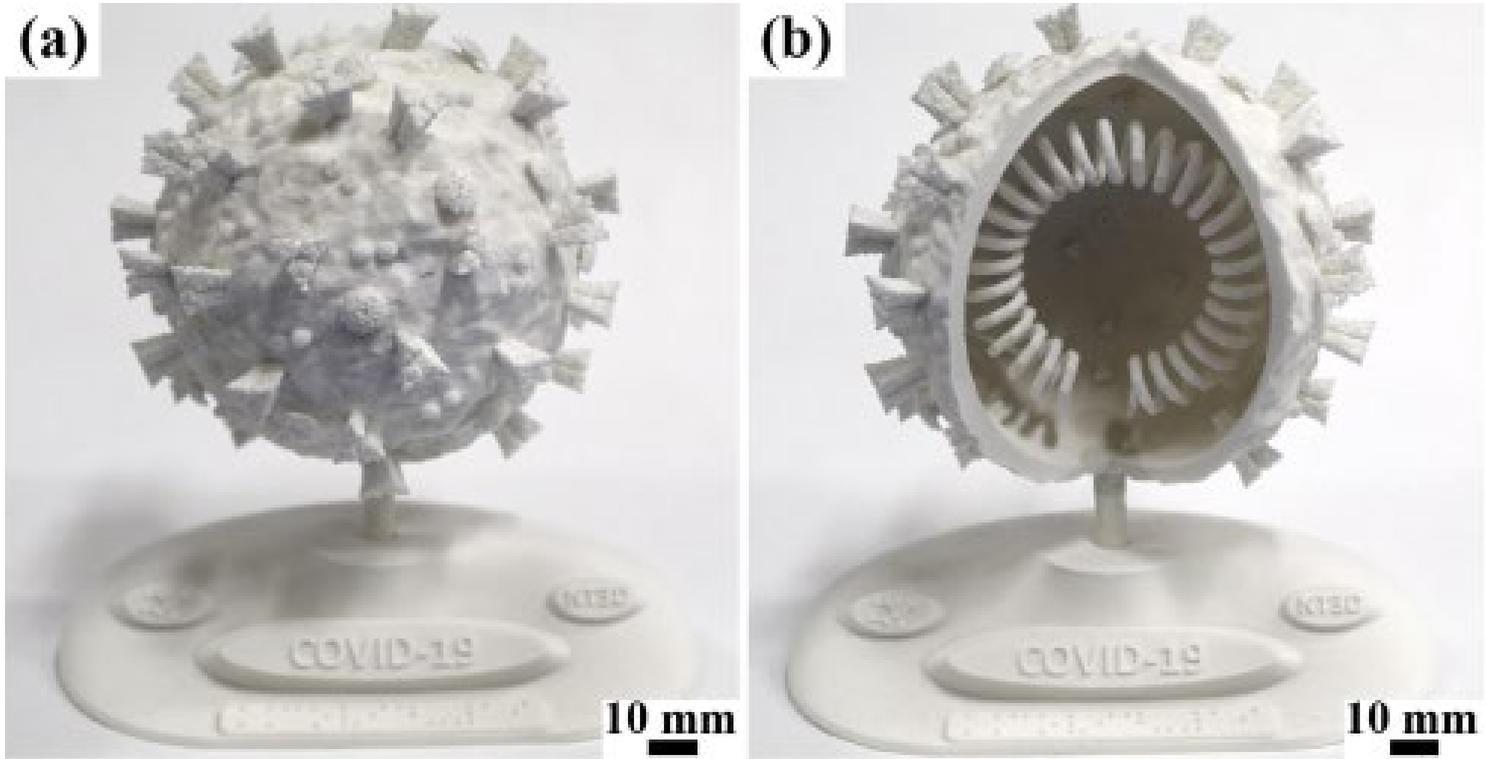
Training and Education



Visual Models of SARS COV-2 Morphology

source: Longhitano, G.A., Nunes, G.B., Candido, G. *et al.* The role of 3D printing during COVID-19 pandemic: a review. *Prog Addit Manuf* **6,** 19–37 (2021).

SAM: Biocompatible Materials Overview

Some of the most commonly-used biocompatible materials (or biomaterials) are **Thermoplastics**

- inherent flexibility
- tunable mechanical properties
- resorbable (ability to be absorbed into the circulatory systems of cells or tissue)
- degradation of by-products safe for psychological conditions

Polymer Biomaterials used in PBF

- Polycaprolactone (**PCL**)
- Polyetheretherketone (**PEEK**)
- Polyvinyl Alcohol (**PVA)** + Hydroxyapatire (**HA**)
- **PEEK** + **HA**
- Biocompatible **PA-12** Blends

Other Biomaterials used in PBF:

- Calcium phosphate
- Titanium
- TiAL6V4ELI – Titanium Dioxide

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PEEK:

+ advanced biomaterial with extremely good cell biocompatibility + good sterilization properties + resistant to organic and aqueous environments + high performance polymer • high melting temperature • high tensile strength • elastic modulus being comparable to that of cortical bone => great for reduced stress shielding for implant use • machinable • thermostable, good electric and thermal insulation	- higher price - not biodegradable - not recyclable - challenging to process with PBF

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PC:

+ highly transparent (light transmission comparable to glass ~90%) + high impact strength + high medical retention + can withstand repeated steam sterilization + high performance polymer • very high melting temperature • high tensile strength • thermostable, good electric and thermal insulation • flame retardant	- easily attacked by hydrocarbons - drying is required before processing - low fatigue endurance - yellowing tendency post exposure to UV - not biodegradable - challenging to process with PBF

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Sterilization Overview

Methods of sterilization

- Autoclave
- Dry Heat
- Ethylene Oxide (EtO)
- Gamma Irradiation
- Electron Beam

Polymer	Autoclave	Dry Heat	Ethylene Oxide (EtO)	Gamma Irradiation	Electron Beam
PA6 PA12	Fair Poor	Fair Poor	Good Good	Fair Fair	Fair Fair
PS	Poor	Poor	Good	Good	Good
PP	Good	Fair	Good	Fair	Fair
PEEK	Good	Good	Good	Good	Good
PC	Fair	Fair	Good	Good	Good
TPE	Poor	Fair	Good	Good	Good
PPSF/PPSU	Good	Good	Good	Good	Good
ULTEM 9085. 1010	Fair	Fair	Good	Good	Good

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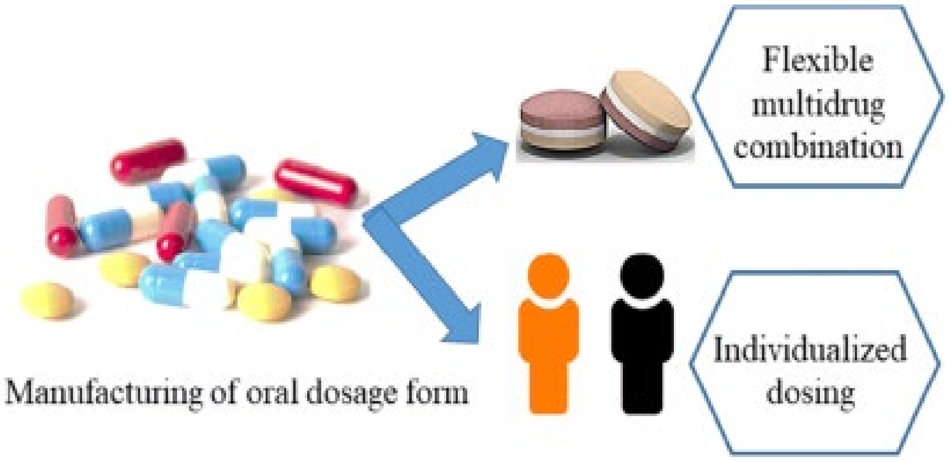
A new paradigm in Health Care - Individualised solutions for treatment

Production of medicinal products in smaller batches, on demand, personalized, and tailored for specific diseases.

Applications

- Drug Delivery Carriers
- Individualized - Single Dosing Pill Fabrication
- Polypill – Multidrug Manufacturing



2017 First SLS Printed Oral Dosage Form were fabricated using Two pharmaceutical grade polymers, Eudragit L100- 55 and Kollicoat IR to create paracetamol tablets.

Pandey, M., Choudhury, H., Fern, J.L.C. *et al.* 3D printing for oral drug delivery: a new tool to customize drug delivery. *Drug Deliv. and Transl. Res.* **10,** 986–1001 (2020)

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Advantageous Features of PBF in Pharmaceutical Applications

- Ability of creating **free-form** 3D objects (without the need for additional support)
- Creation of objects with high degrees of **porosity/pore** connectivity
- Does **not** require **the pre-processing** of its starting material (nor does it necessitate the inclusion of additional excipients that could pose potential toxicity)
- **Absence of solvents** enhances safety and provides better stability to drug substances that are liable to hydrolysis.
- **Most cost effective** for the production of personalised parts (when compared to other 3D printing technologies and conventional production processes (e.g. injection molding)
- Printed objects can **be stacked** on top of one another, increasing the capacity of the build platform and enhancing **productivity**
- Option of **recycling** and reprocessing feed material, reducing waste and supporting green pharmaceuticals

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Drug Delivery Carrier Improvement

- Manufacturing of porous caplets exhibiting accelerated release of the incorporated drug
- Accelerated release depends on porosity/pore connectivity

Single Dosage Pill Fabrication

- Flexible manufacturing of on demand, personalized pills with right amount of APIs

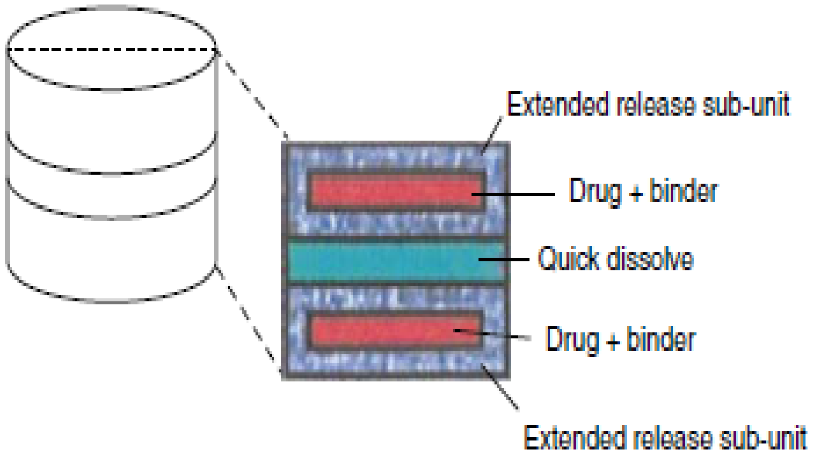

Illustration of Layers forming the break-away Tablet

Row et. al. Multimechanism oral dosage forms fabricated by three dimensional printing. J Control Release. 2000 May 3;66(1):11-7

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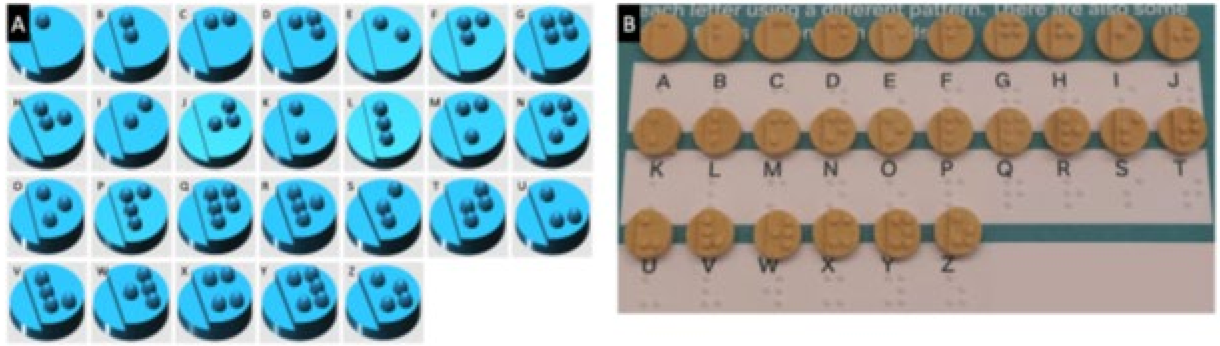
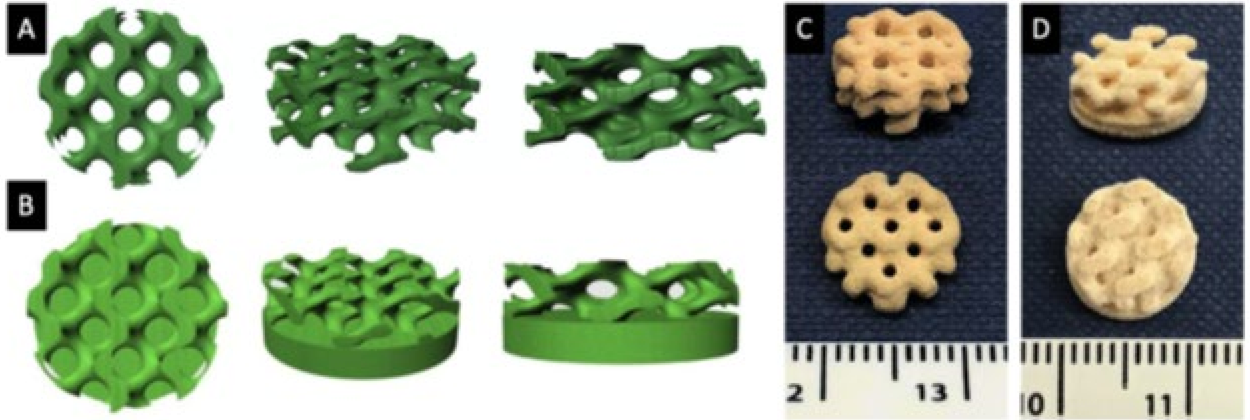
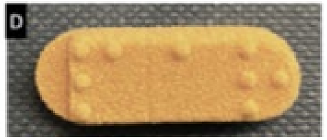
Pharmaceutical Creations using PBF

- Orally Disintegrating Printlets
- Immediate-release Printlets
- Controlled-release Printlets
- Multi-reservoir drug delivery system
- Tissue and bone regeneration implants
- Gyroid lattices and bi-layered Printlets
- Mini-printlets
- Intrauterine devices
- Printlets for the visually impaired







Awad et. al. 3D printing: Principles and pharmaceutical applications of selective laser sintering, International Journal of Pharmaceutics, Volume 586, 2020,

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Summary of Cutting-edge Pharmaceutical Creations using PBF

Pharmaceutical Application	Active Pharmaceutical Ingredients (APIs)	Polymer(s)	Other Excipients
Orally Disintegrating Printlets	Ondansetron Paracetamol Diclofenac sodium	Kollidon VA64 Kollidon VA64 Kollidon VA64	B-Cyclodextrin, Candurin, Gold Sheen, Manitol Candurin, Gold Sheen Candurin, NXT Ruby Red, Lactose monohydrate
Immediate-release Printlets	Paracetamol Paracetamol	Kollicoat IR HPMC	Candurin Gold Sheen Candurin Gold Sheen
Controlled-release Printlets	- Paracetamol Progesterone	PCL, PLLA Eudragit L100-55 PCL	- Candurin Gold Sheen -
Multi-reservoir drug delivery system	Progesterone	PCL	
Tissue and bone regeneration implants	5-flurouracil Ibuprofen 5-flurouracil	PE PCL PCL	- - -
Gyroid lattices and bi-layeted Printlets	Paracetamol	PEO, Eudragic L100-55, Eudragit RL and EC	Candurin Gold Sheen
Miniprintlets	Paracetamol, Ibuprofen	Kollicoat IR, EC	Candurin Gold Sheen
Intrauterine devices	Progesterone, 5-flurouracil	HDPE	-
Printlets for the visually impraired	Paracetamol	Kollidon VA64	Candurin Gold Sheen

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Agenda

- **Learning Outcomes and Introduction**
- **Material Properties Overview**
- **Thermoplastics in PBF Overview**
- **Filled Thermoplastics**
- **Material Selection**
- **Powder usage, mixing & handling**
- **Biocompatibility**
- **Summary**

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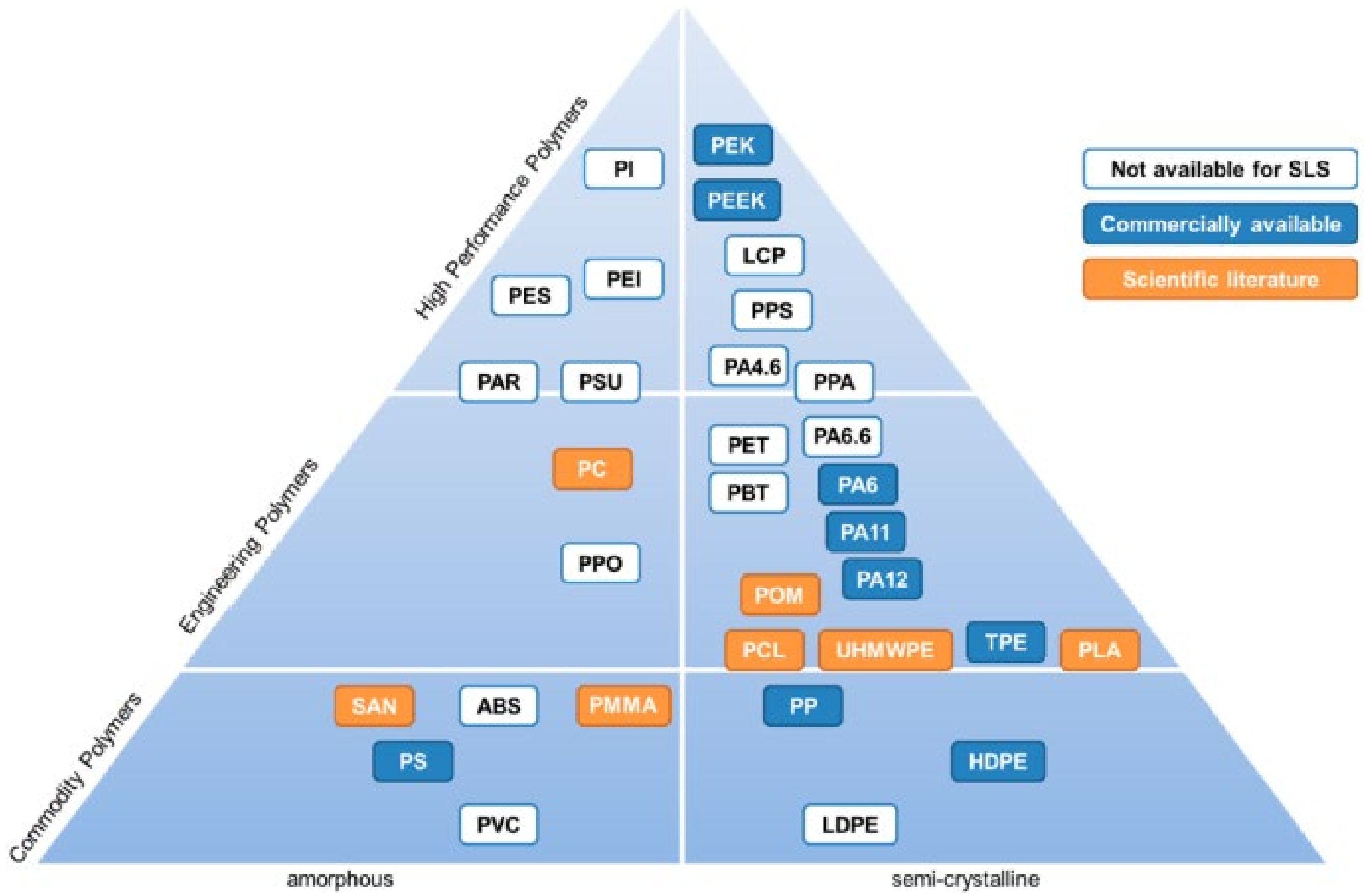

Most Commonly Used Materials

- Polyamide (Nylon) – PA6/11/12
- Polypropylene – PP
- Polyetheretherketone - PEEK

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Overview of Polymer Materials in PBF

PS (Polystyrene) - Hobbyist material with medium hardness and strength

PP (Polypropylene)- Functional prototypes, good chemical stability, several low-grade industrial applications

→ Standard (Commodity) Thermoplastics

Nylon - Tough, flexible niche material

TPE/TPU (Thermoplastic Polyurethane)- Flexible niche material

→ Niche thermoplastics

PAEK, PEEK, PEKK (Polyaryletherketone), PAFR– High Performance plastics, excellent for industrial applications and special applications where good resistant of heat load and fire resistance is required

→ Engineering Grade Thermoplastics (Superplastics)

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Properties	PP	PS	Nylon	TPU/TPE	PAEK	PEEK	Nylon based composites
Tensile Strength (MPa)	33	5.5	40-50	26	71	90-100	50
Elongation	1.5	0.4	0.6-1.1	5.5-5.8	1.16	1.5	0.10
Tensile Modulus (GPa)	1.4	1.6	2.1	0.78	6.5	3.6	2.5-3.5
Density (g/cm^3)	0.90	0.77	1.06-1.14	1.21	1.39	1.32	1.00-1.3
Melting Point (^{o}C)	290	230	268	220	315	343	260
Biodegradable	Yes (under conditions)	No	No	Yes	No	No	No
Recyclable	Yes	Yes	Yes	Yes	No	No	No
Price (per kg)	15-30	15-45	50-100	90-100	200-400	200-400	300-500
Printability (1-10 scale)	9	8	8	3	4	4	4

https://www.materialise.com/en/manufacturing/3d-printing-technology/laser-sintering

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Nylon Based Composites (PA-CF, PA-GF, PA-AF)

Each added component (aluminum, carbon fiber, glass)

- increases the **mechanical** and **thermal** properties of polyamide (Nylon)
- provides **better dimensional stability** and **reduces shrinkage**

  - ✓ Excellent stiffness and stiffness to weight ratio
  - ✓ High density and high Tensile strength
  - ✓ Wear resistance
  - ✓ Good machinability
  - ✓ Temperature resistant

CF Filled Nylon Manifold

Source: ams3d.co.za

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Material Selection Thought Process

1. **Determine performance requirements via intent of use**
   - Prototyping and R&D?
   - Validation or pre-production?
   - End-use parts?
2. **Translate performance to material requirements**
   - Stiffness/hardness
   - Toughness/tear strength
   - Temperature and chemical resistance
   - Creep and durability
3. **Select material**
   - Design Space/Operation Environment
   - Durability
   - Longevity
   - Cost

Test print and iterate!!

SAM: Biocompatible Applications of PBF Printing

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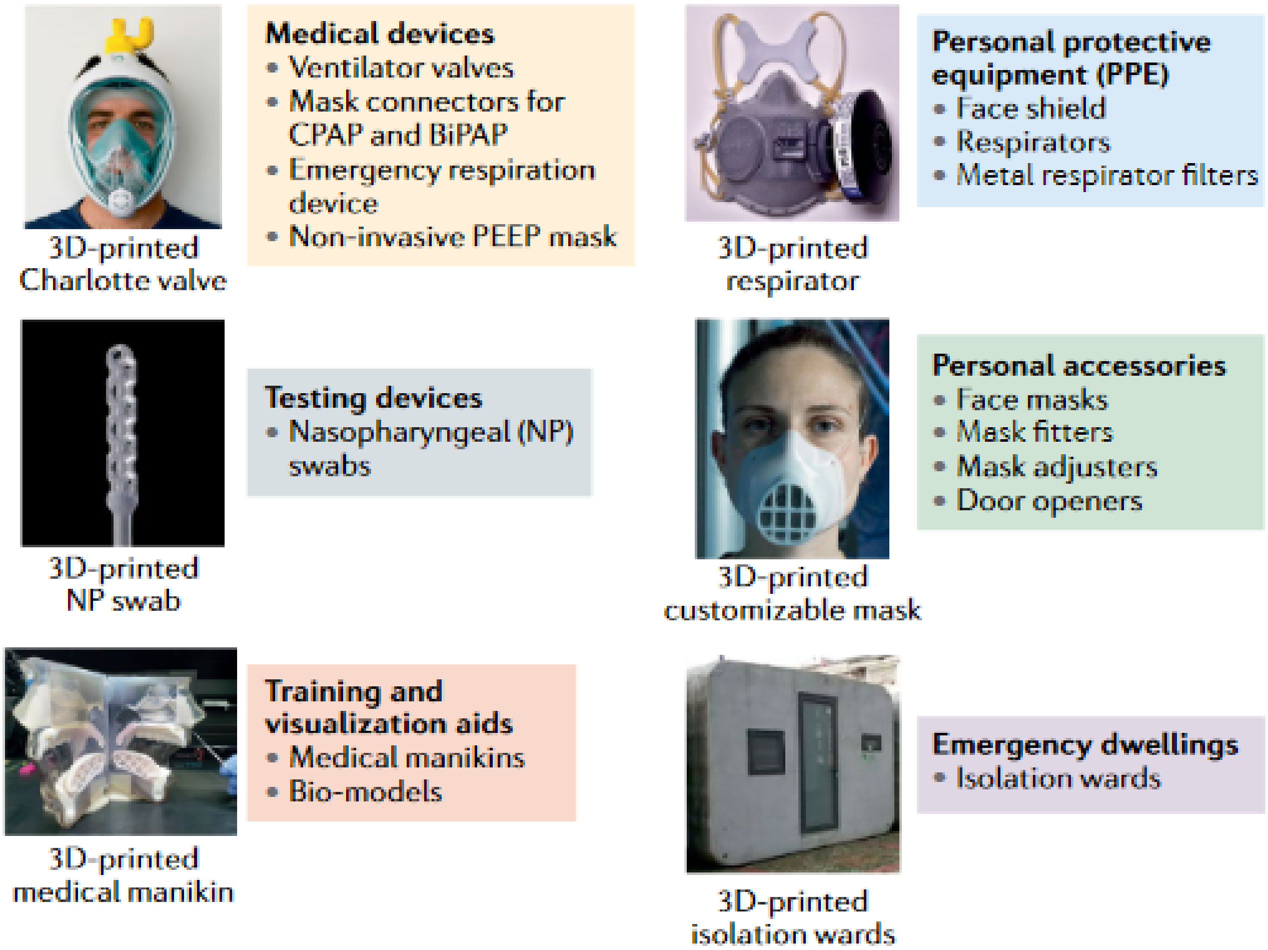
AM Printing Applications in the battle vs Covid-19



PBF Biomedical Applications

- Medical (devices, prosthetics, implants, dentures)
- Pharmaceutical (individualised dosage pills, drug delivery systems)
- Training Tools (Medical Modeling/Surgical Planning)

https://www.nature.com/articles/s41578-020-00234-3.pdf

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Advantageous Features of PBF in Pharmaceutical Applications

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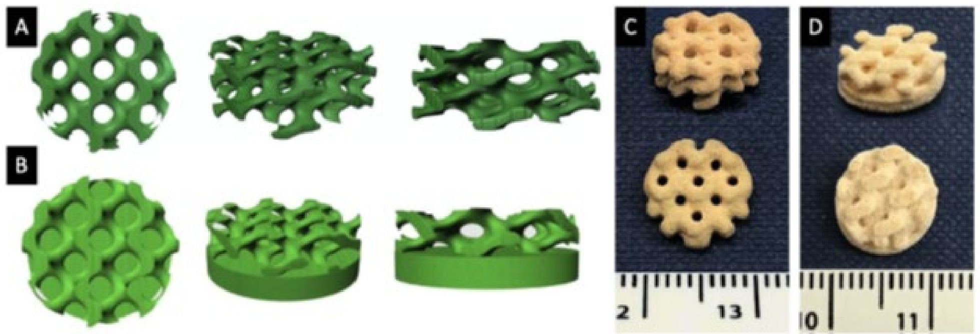

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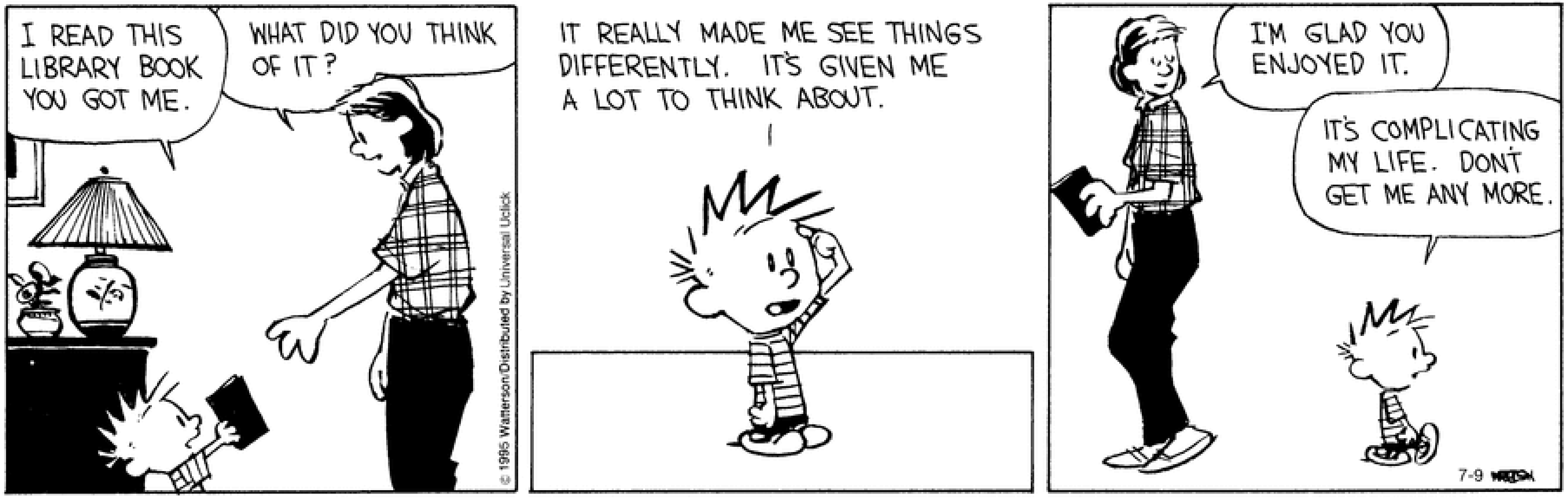
Questions?



Watterson, Bill. The Essential **Calvin and Hobbes**: A **Calvin and Hobbes** Treasury. , 1988. MLA (7th ed.)

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

skills4am.eu

LMS

Laboratory for Manufacturing Systems and Automation (LMS)
Department of Mechanical Engineering and Aeronautics
University of Patras, Greece

Thank you

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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

Design for Material Extrusion

SESSION 03: Specific Design Considerations

20 JULY 2021

Harry BIKAS – LMS

This project has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

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Agenda

- Introduction to DfAM
- Design aspects for PBF
- Design limits determination
- Design guidelines
- Design optimization methods
- Conclusions

Introduction to DfAM

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- Design for AM (DfAM) refers to **design optimization** following certain **rules and guidelines**, aiming to improve **AM manufacturability**
    - *Manufacturability* is not a duality nature of can-or-cannot be manufactured
    - *Manufacturability* is used to describe the ease to implement a manufacturing technology to realize a part design
    - *Manufacturability* for AM requires identification of the Design Aspects of the part and their comparison with AM capabilities

- Current design optimization methods (Topology Optimization/Generative Design) generate highly complex parts that are appealing for AM.

- Most complex geometries with structural purposes display low AM manufacturability due to the poor dimensional accuracy and surface quality of AM final products.

- Modifications are required on a second stage to address problematic aspects of the design (post-processing)

Introduction to DfAM

- When designing a part to be built using AM, the process characteristics must be considered.

- Design for Additive Manufacturing (DfAM or D4AM) is defined as “the practice of designing and optimizing a product together with its production system to reduce development time and cost, and increase performance, quality, and profitability.” [2]

➢ The layer-by-layer nature of AM introduces some design limitations that are present in every AM process

➢ Some design limitations are presented on the following slides

[1] “Thompson, M. K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B., and Martina, F., 2016, “Design for Additive Manufacturing: Trends, Opportunities, Considerations, and Constraints,” CIRP Ann. Manuf. Technol., 65(2), pp. 737–760

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Determining AM part's Manufacturability

#Step	Indicator
1. Part's geometric features recognition	[from CAD/.STL file] 
2. Crosschecking Design features with the AM process capabilities	[Feature size, etc.] 0 1
3. Crosschecking Design Considerations with Part Specifications	[Surface roughness, poros 0 1
4. Magnitude of feature alternation to achieve manufacturable features	[Feasible-Impractical-Add Sup
5. Determine the actions for excess material removal	[Few-Numerous Suppo
6. Post-processing to reach parts requirements (post-treatment)	[Minimal-Major]

Introduction to DfAM: Benefits

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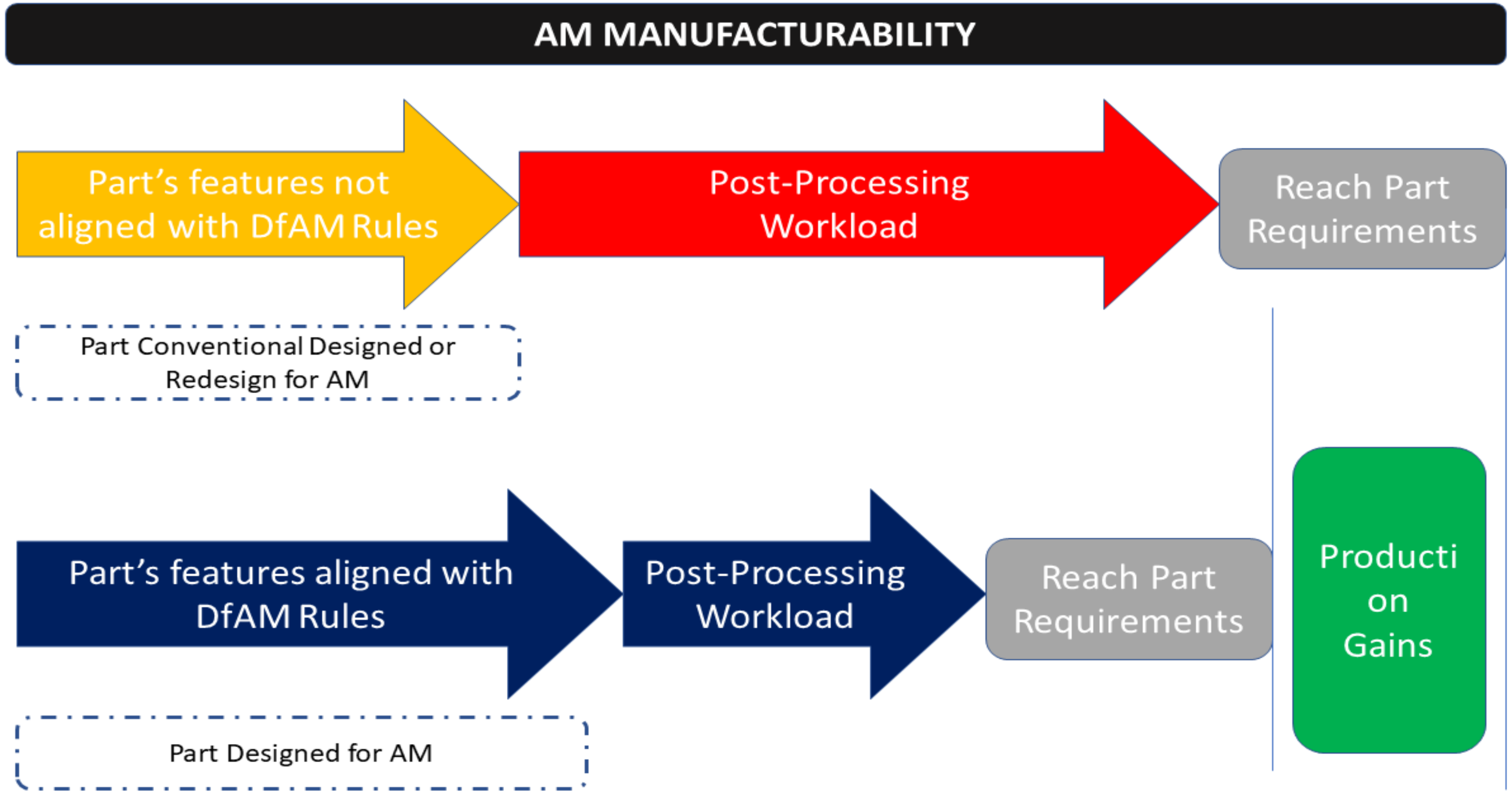

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DfAM considerations

Design aspect: feature which can be quantified at the design phase.

➢ The design aspects are divided into

- Geometric features (overhangs, bores, channels, etc.)
- Process variables/parameters (layer thickness, orientation, etc.)

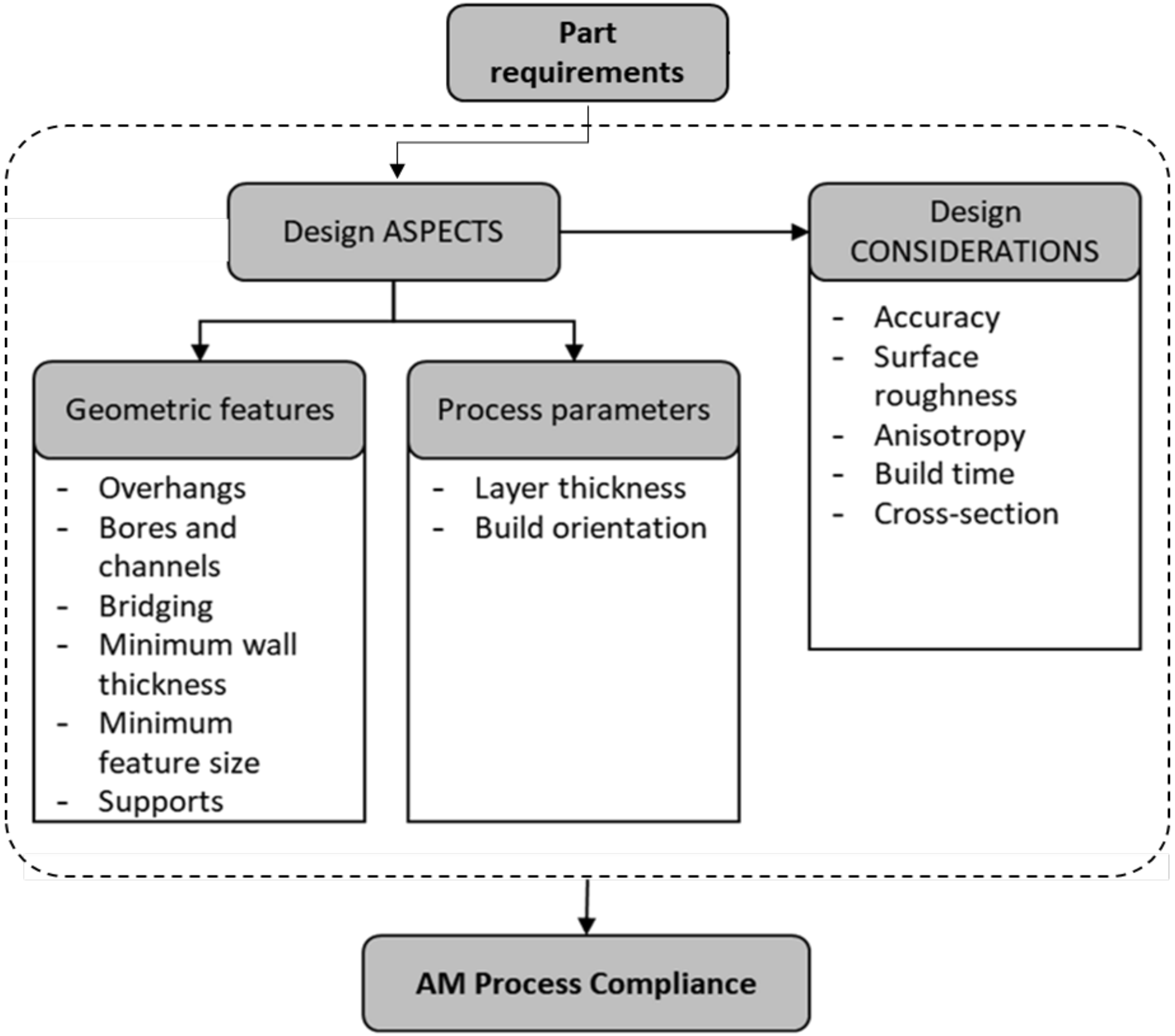
Design consideration: the result on the part

➢ The result is measured in terms of dimensional accuracy, surface roughness, built time etc.

Overall

➢ Need to map aspects (causes) to considerations (outcomes), in order to define design rules

➢ Design aspect effects and thresholds are dependent on the process mechanism and material



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Agenda

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Design aspects for PBF: Finishes and precision

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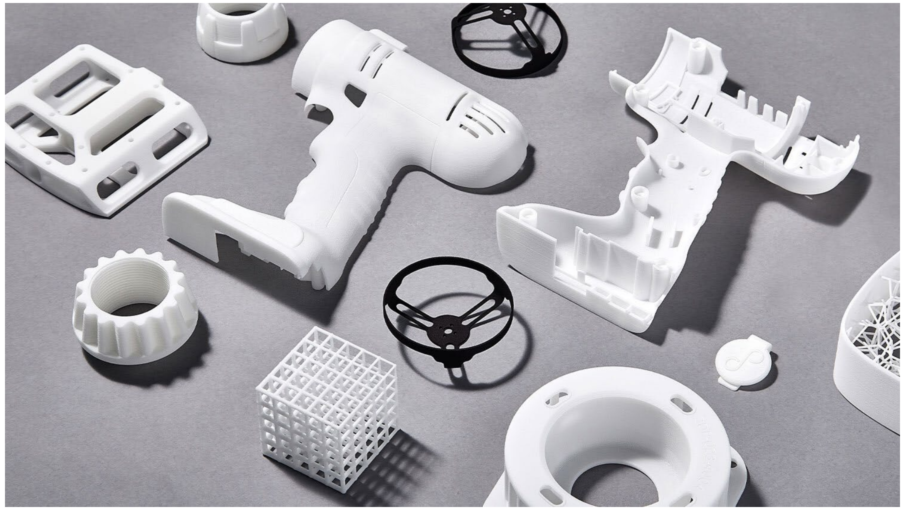
- PBF parts do not required support allowing for greater design freedom making PBF one of the easier 3D printing technologies to design for.
- PBF can be used to produce many functional features including axles, threads, tanks and hinges.
- The standard surface finish for PBF is a matte-like grainy surface.
- At the initial steps of the process selection the required precision (dimensional or surface) is determined
- Optimized process parameters can improve significantly the dimensional accuracy and appearance.

Source: http://renderfact.com/services/theed_printing



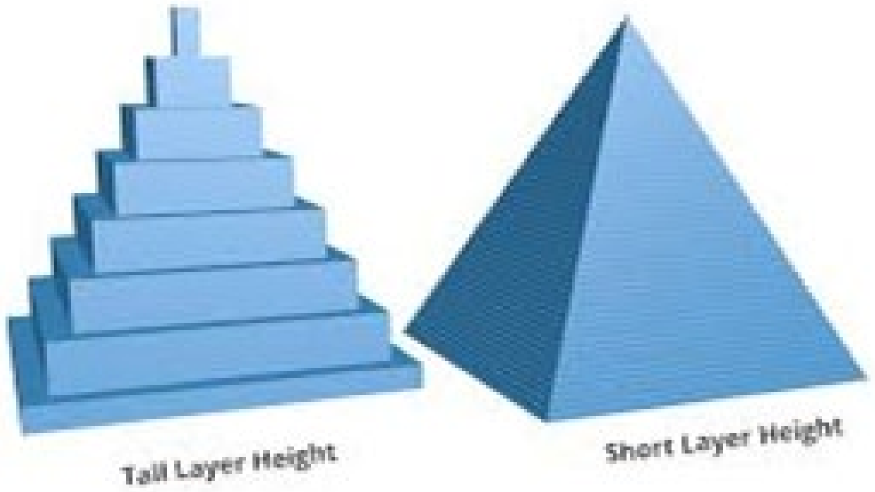
Source: http://renderfact.com/services/theed_printing/

Overall Considerations

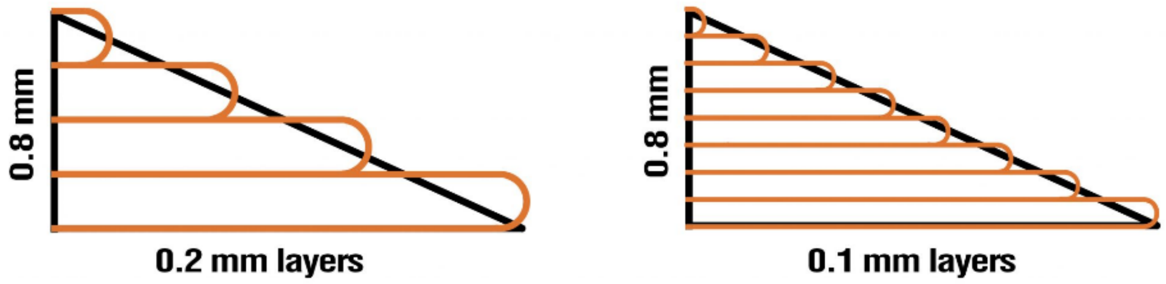
- ✔ Usually, small layer height and low deposition speed increase the quality of the final part.
- ✔ Post processing methods (media tumbled, sandpaper) are proposed to improve the surface quality.

Design aspects for PBF: Layer thickness

- A large layer height has less resolution but prints faster while a smaller layer height can create more fine features but is slower.
- The dimensional accuracy as well as the surface quality of the part are affected significantly with the choice of layer height.
- Very detailed features ask for the minimum layer height.
- The number of layers required to create an object determines the printing speed and thus the printing time required. The lower the layer thickness, the longer it takes to make a 3D printed object of a given height.
- Therefore, an object 1cm high requires 100 layers at 100μm or 167 layers at 60μm
- Model height must be an integer multiple of the selected layer height.



Source: https://3space.com/blog/what-does-resolution-mean-in-3d-printing/3d-printing-resolution-layer-height/



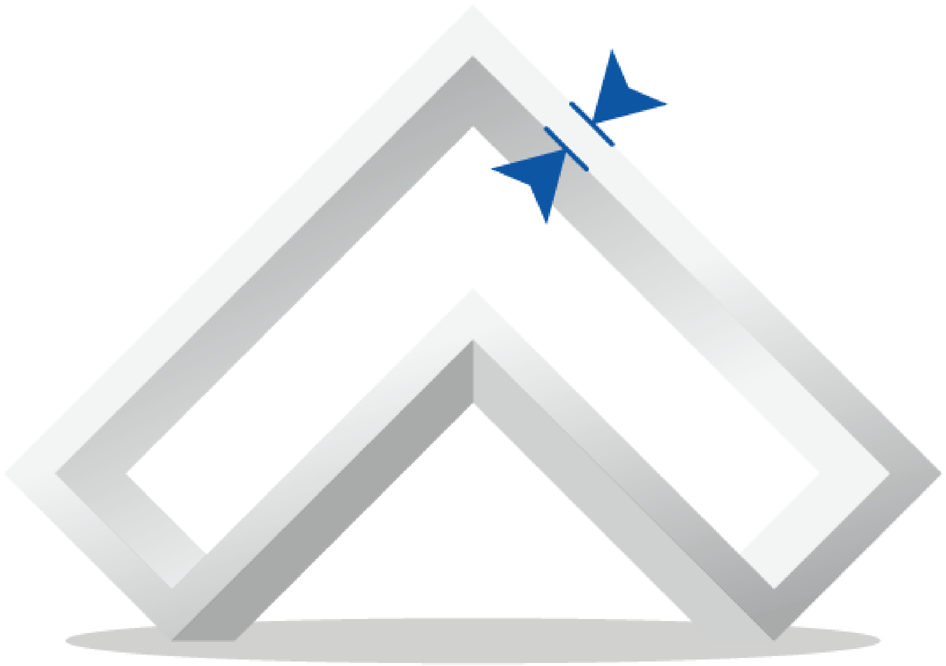
Source: https://blog.prusaprinters.org/everything-about-nozzles-with-a-different-diameter_8344

Design aspects for PBF: Wall thickness

- ✔ Wall thickness refers to the distance between one surface of your part and the opposite sheer surface.
- ✔ The infill lines are attached to the wall across the height of the part.

- ➢ High wall thickness can give a strong solid surface, while lower wall thickness can create a flexible and expandable surface, like when designing a spring that needs some suspension properties.

- ➢ Since PBF is a sintering-based process, cooling times may differ depending on the thickness of the part, causing thermal stress concentrations around features with sharp changes in cross sectional area.
- ➢ Therefore, there is a need for consistent wall thickness design along the whole part
- ➢ For PA 12, a recommended minimum wall thickness is 1 mm



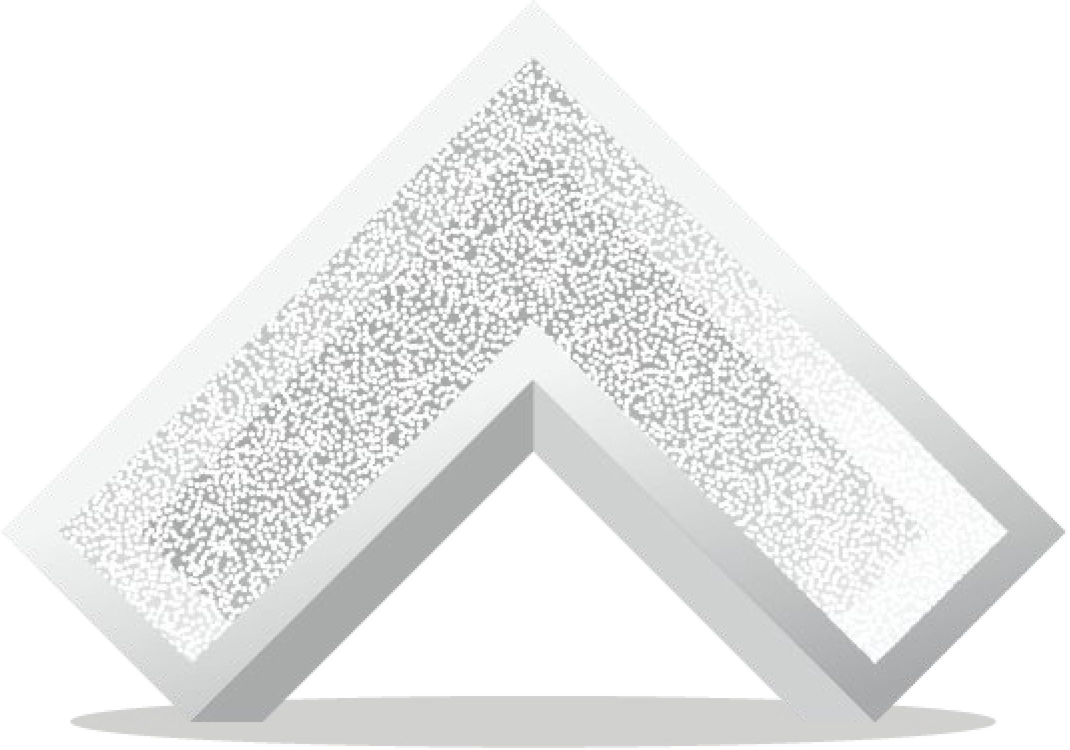
Source: https://www.materialise.com/en/manufacturing/materials/pa-12-sls/design-guidelines

Design aspects for PBF: Hollowing

- ✔ Hollowing a part aids to avoid deformation and discoloration during the printing process.

- ➢ A part can be hollow without a surface hole, which means that unsintered powder will remain trapped inside, or it can be designed with a strategically placed hole (two would be even better) so that the unsintered powder can be easily removed after printing.

- ➢ If the part needs to be reclosed, a lid can be designed with a diameter allowing for 0.5 mm play between the part and the lid.

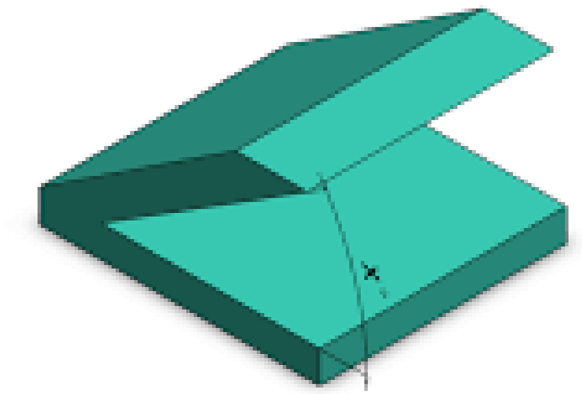


Source: https://www.materialise.com/en/manufacturing/materials/pa-12-sls/design-guidelines

[REF]: https://formlabs.com/blog/fuse-1-sls-design-guide/

Design aspects for PBF: Overhangs

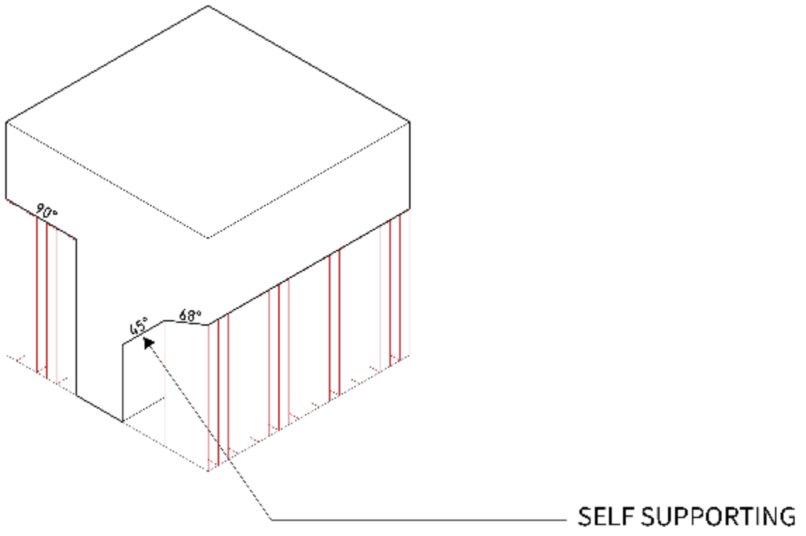
- **Overhangs** are shapes that extend outwards beyond the previous layer (cantilevers).
- In this case, a part is printed on a bed dense enough so that cantilevered section do not fall as they are printed. Material support needs to be more dense than the printed part.
- In the case of PBF it is the unsintered powder that acts as material support preventing parts to fall
- Therefore, overhangs require minimal support structure and in rare occasions when utilizing PBF additive manufacturing method

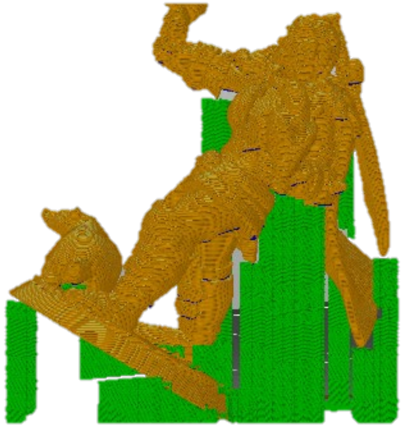


Source: https://3dl.tech/en/design-guidelines-sla-technology/

Design aspects for PBF: Supports

- Supports are sacrificial layers, generated to counter the effects of gravity on during printing.
- Essential part of 3D printing is understanding support angles, overhangs and bridges.
- In situations where an overhang is necessary, and the inclusion of supports will hinder a successful outcome.
- It is recommended to either incorporate artificial bridges (to be eliminated during post processing), or design the model undersides with an acceptable angle.
- The amount of support structures determine the sustainability of the process as well as the printability of the part.





Source: https://help.prusa3d.com/en/article/support-material_1698

Design aspects for PBF: Bores & channels

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

- Bores and channels are internal structures that are not visible from outside most of the times.

- The correct orientation of the part during the development ensure the successful creation of these structures.

- Channels are internal routes which can be used either in case of cooling fluids or for weight reduction

- Bores can be used to fit a bolt or a blind thread etc.

- It is difficult to manufacture these geometries with any other manufacturing process.

- Support removal should be taken into account.

Source: https://forward-am.com/material-portfolio/ultrasint-powders-for-powder-bed-fusion-pbf/pa6-line/ultrasint-pa6-lm/

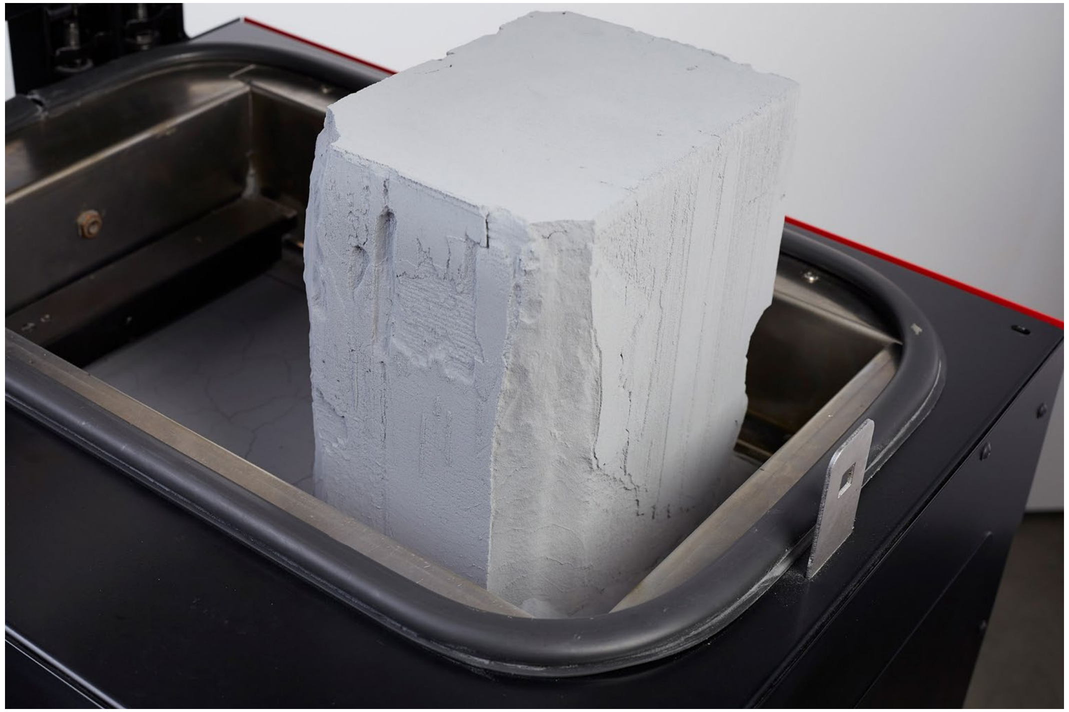
Design aspects for PBF: Bores and Channels

- Holes with a small diameter are exposed to a lot of heat during the sintering process and can cause the powder inside the holes to become fused.
- To make sure that holes in the parts remain clear, it is recommended to design with a diameter of at least 1 mm.
- Longer internal channels can be difficult to clear out, especially if the powder is partially sintered together.
- It is recommended to design a diameter of at least 3 mm for internal channels.

Source: https://forward-am.com/material-portfolio/ultrasint-powders-for-powder-bed-fusion-pbf/pa6-line/ultrasint-pa6/

Design aspects for PBF: Escape holes

- To save weight (and sometimes costs) PBF parts can be printed hollowed out. To remove unsintered powder after production escape holes must be included. Any enclosed cavities will remain filled with unsintered powder unless escape holes are designed into the part.
- To guarantee a clean internal surface, design your part so that the surface in question is easy to access with cleaning tools.
- Adding at least 2 escape holes to your printed enclosed cavities is recommended, while more and larger escape holes make it easier to remove unsintered powder from internal cavities.
- Escape holes must be a minimum of 1 mm diameter

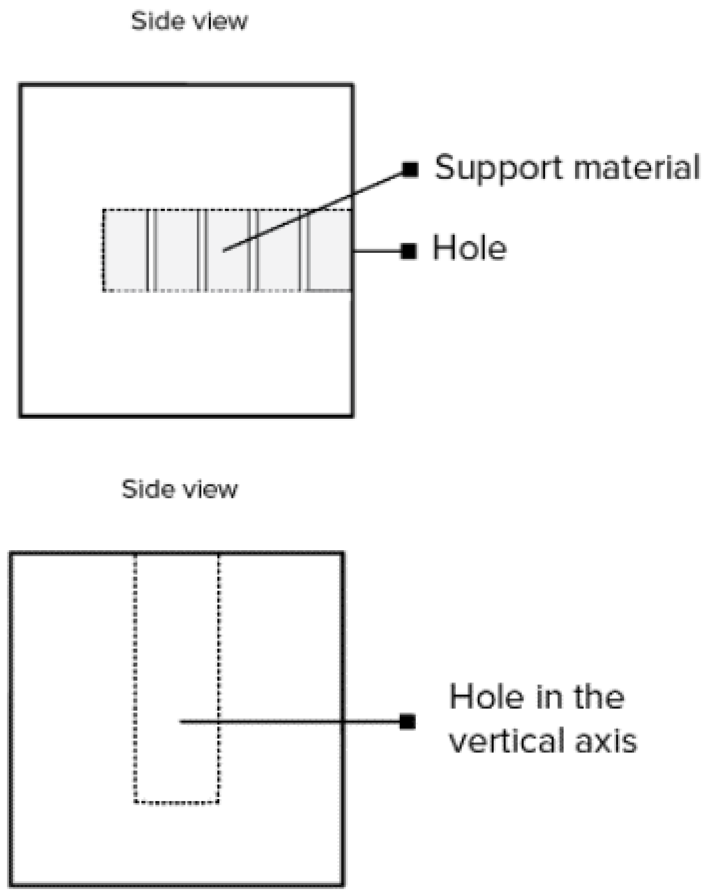


Source: https://www.sinterit.com/what-is-sls-3d-printing/

[REF]: https://formlabs.com/blog/fuse-1-sls-design-guide/

Design aspects for PBF: Build orientation

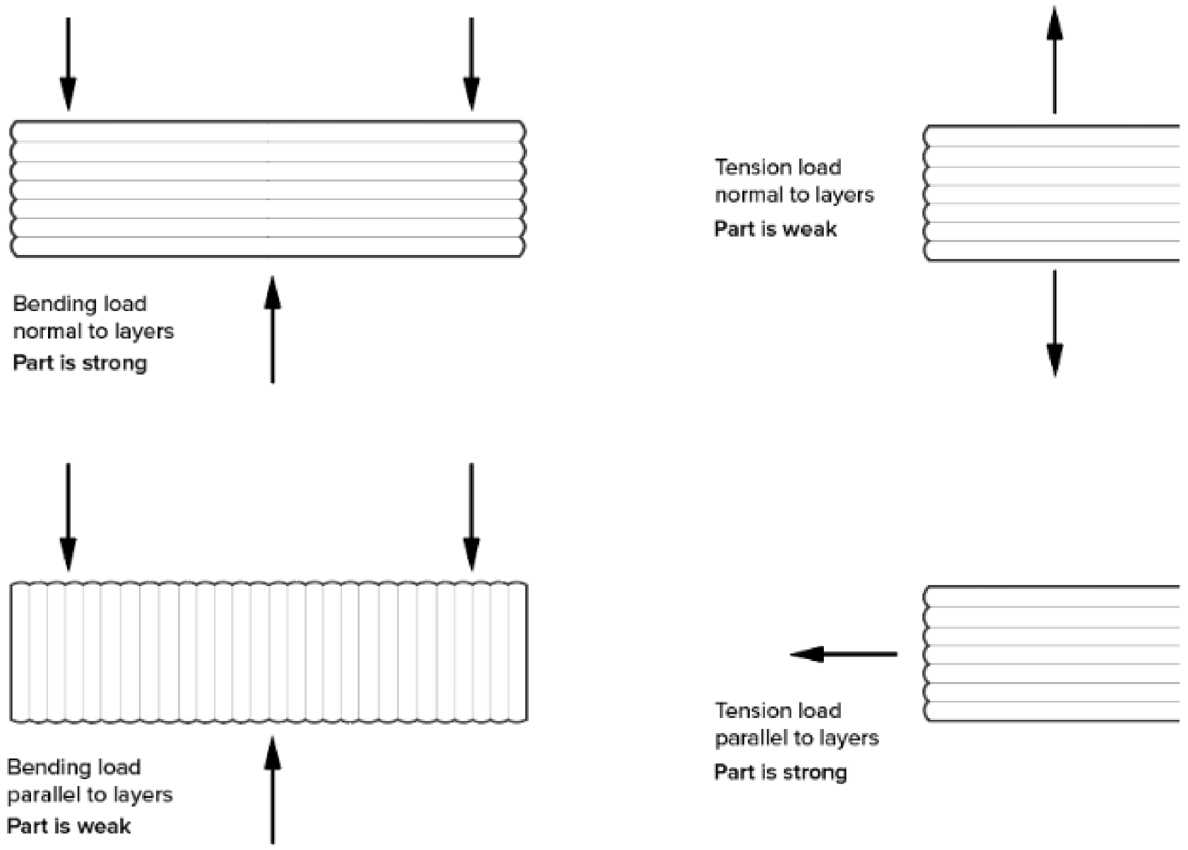
- Ideal orientation minimizes support material and achieves the best surface finish.
- Less material used means a more sustainable and efficient process considering also reduced build time
- As an example, support for holes is best avoided by changing the print orientation.
- For components with multiple holes in different directions, prioritize blind holes, then holes with the smallest to largest diameter, then criticality of hole size.



Source: https://wikifactory.com/+wikifactory/stories/ultimate-guide-how-to-design-for-3d-printing

Design aspects for PBF: Build orientation

- Upward facing surfaces tend to have a better surface finish.
- Since curved and angled surfaces are often prone to stair-stepping effect (rough surface texture), they can be oriented parallel to the build platform to minimize this effect.
- Long surfaces should be oriented in the x-y plane (large contact area with the bed).
- Loading of the part should be considered.
- Tabs should be oriented in x-y direction.



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Agenda

- Introduction to DfAM
- Design aspects for PBF
- Design limits determination
- Design guidelines
- Design optimization methods
- Conclusions

Limitations of PBF: Product size

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- ➢ The size a part is able to be printed at is limited by the size of the nylon container used in the PBF machines.

- ❖ The size of the largest available machines are 750x550x550 mm3.

- ❖ Risks of manufacturing very large parts (technology has to improve in reliability and speed).

- ❖ Cost of loading current equipment with material (cost of materials should go down).

Limitations of PBF: Large Production Runs

- The larger the tank, the more precision the laser loses at the ends of the plate.
- By having a larger tank and maintaining the same laser speed, the speed of the process is not increased.
- With a larger tank and the same laser technology, the laser exposure time can be so long that parts can be cooled down before the next recaoting.
- This leads to bad layer bonding and high anisotropic behaviour

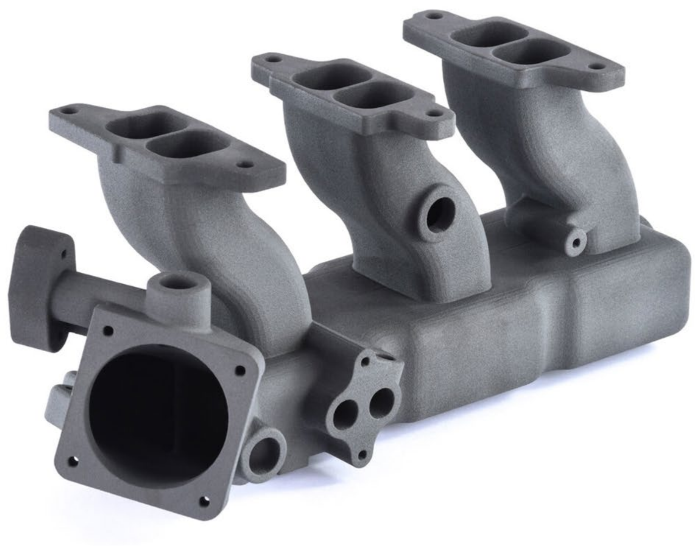
Limitations of PBF: Product quality and repeatability

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

- Since every PBF printed part consists of hundreds of layers, small variations between products can occur (dimensions, surface quality).
- In addition most post-processing steps are done manually.
- Furthermore, PBF includes very complex thermal processes happening, like micro fusions that generate tensions that give rise to deformations and can be combined with some lack of knowledge of the dynamics of the process
- All the above leads to incosistencies and minor variations (e.g. small color or coating variations).

✔ The user of a LBPF machine has to ensure that both the dimensional accuracy and the physical properties of the product (hardness, elasticity, breaking load, metallurgy ...) are equal (or within a tolerance range) in a production batch in order to have a consistency in the final product of a production batch

✔ Consistency is important in sectors such as: automobile, aeronautical, medical etc.



Source: https://www.eos.info/en/additive-manufacturing/3d-printing-plastic/eos-polymer-systems/eos-p-810

Limitations of PBF: Part Orientation and Chamber Packing

- Part layout within the build chamber is another aspect of the PBF 3D printing process that can affect design success.
- Distributing parts evenly across the build chamber reduces the potential for thermal buildup and keeping parts close to the bottom of the chamber keeps your print times low.

Source: https://www.3dhub.gr/shop/3d-printers/professional/formlabs-fuse-1/

[REF]: https://formlabs.com/blog/fuse-1-sls-design-guide/

Limitations of PBF: Surface finish

- While PBF produces a consistent surface finish the surface appearance is a satin-like matte finish that is slightly grainy to the touch.
- The surface finish produced by PBF is a bit rougher than other 3D printing technologies—it typically ranges anywhere from 100-250 RMS—but it still works reasonably well for most functional prototypes.
- Some material offer better surface finish as-printed than others
- If a shiny and smooth finish is desired post-processing is recommended, like media tumbling

Source: https://support.xometry.com/hc/en-us/articles/115002092847-Surface-Finish-for-3D-Printed-Materials-Photo-Gallery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Agenda

- Introduction to DfAM
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PBF design guidelines: Residual Stresses

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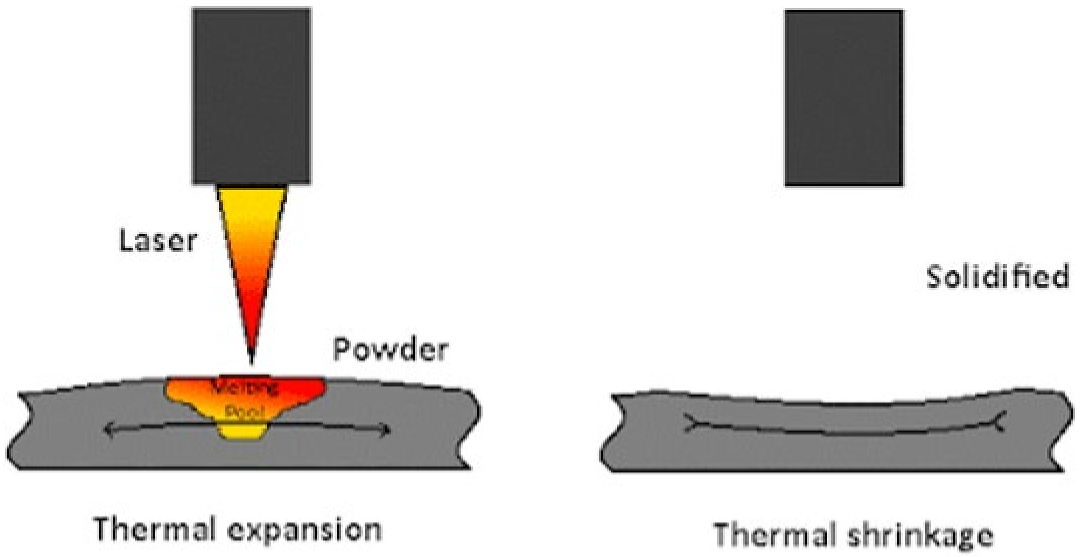
- ❖ They are inherent to the process, the rapid heating and cooling generate them

- ❖ There are two cases for the residual stresses to present a problem to the manufacturing:

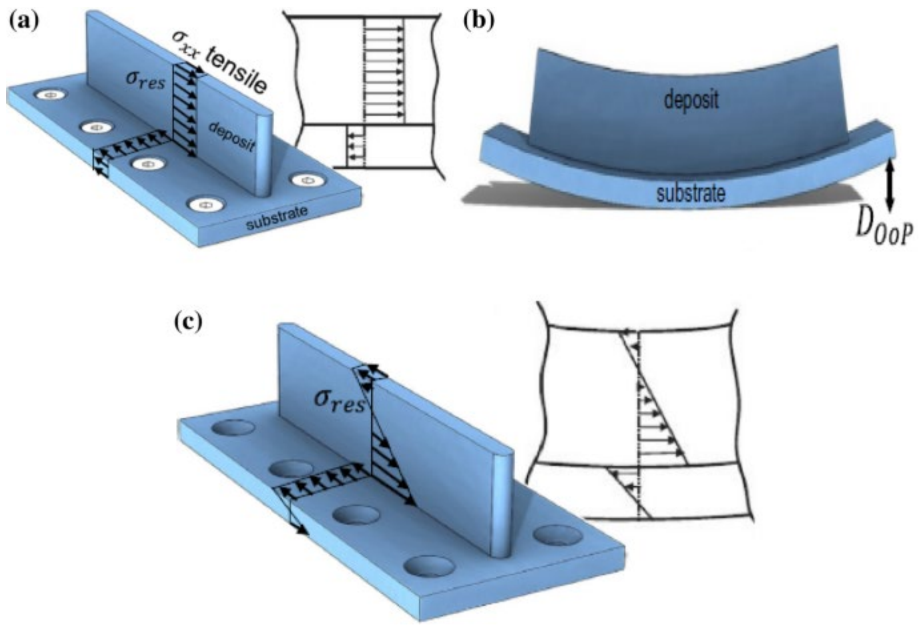
  - o The tension of the residual stresses exceeds the maximum strength of the supports
  - o The tension of the residual stresses exceeds the maximum strength of the material



PBF design guidelines: Residual Stresses

❖ The proposed solutions to overcome the residual stresses problem are:

✔ Orient the part on the build plate so that it in order to have the smallest possible sintering area per layer
✔ Modify the scan pattern in order to avoid long routes that the laser travels uninterruptedly. The longer the uninterrupted routes of the laser, the greater residual stresses there will be generated
✔ Preheating the manufacturing bed
✔ Post processing heat treatment stress relief
✔ Avoid of sudden section changes
✔ Add build pads thick enough because they can absorb stresses and dissipate more heat.



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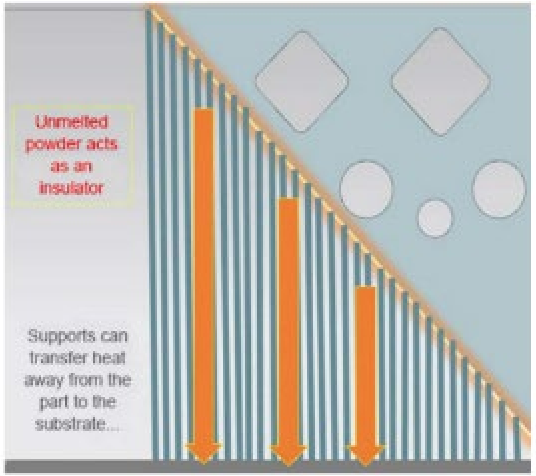
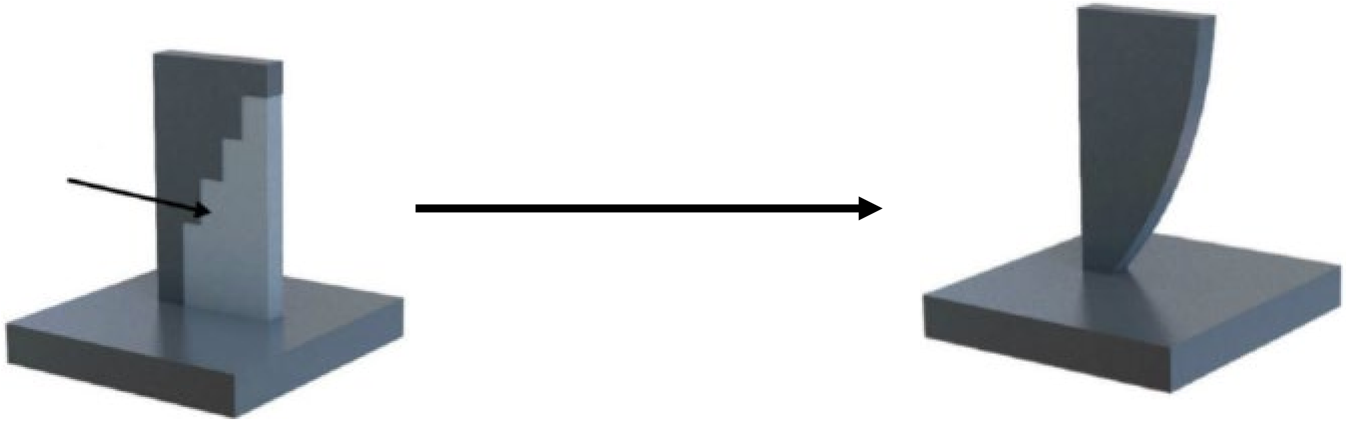
PBF design guidelines: Support Structure

- ❖ Although in PBF polymer manufacturing most surfaces can be supported by the unsintered powder, still some specific geometries require support.
- ❖ Besides the main function of the support structures, the can also fulfill other important missions:



- ✔ Serve as scaffolding to support cantilevered roofs and surfaces.
- ✔ Helps keep deformations caused by residual stresses in check
- ✔ Act as heat sinks to the build plate.



PBF design guidelines: Support Structure

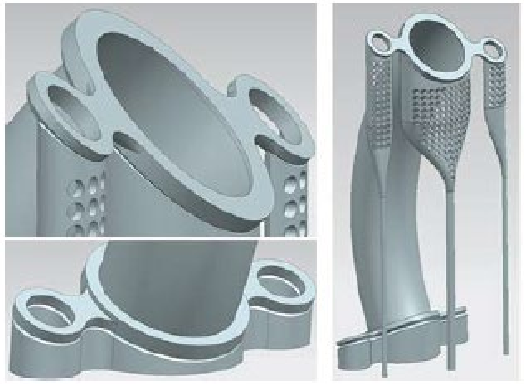
- ❖ Supports are categorized in two parts:
- ➢ **Primary**: those that are generated during the design of the part in the CAD environment.
- ➢ **Secondary**: generated in the manufacturing preparation software.

- ❖ Supports that are designed as a part of the product or as a separate solid provide a degree of flexibility if some design characteristics changes.

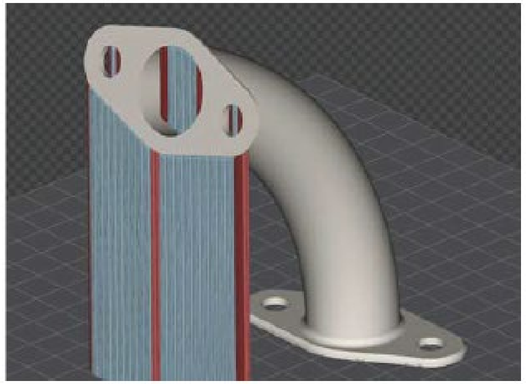
- ❖ The main reason to design the support structures as a separate part is that they can be analyzed by Finite Elements.

- ❖ Therefore, the heat dissipation and distortions can be calculated.

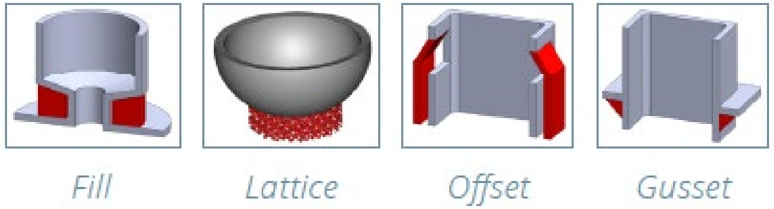
- ❖ The drawback is that the traceability and the repeatability are lost if there is a big design change.



Primary

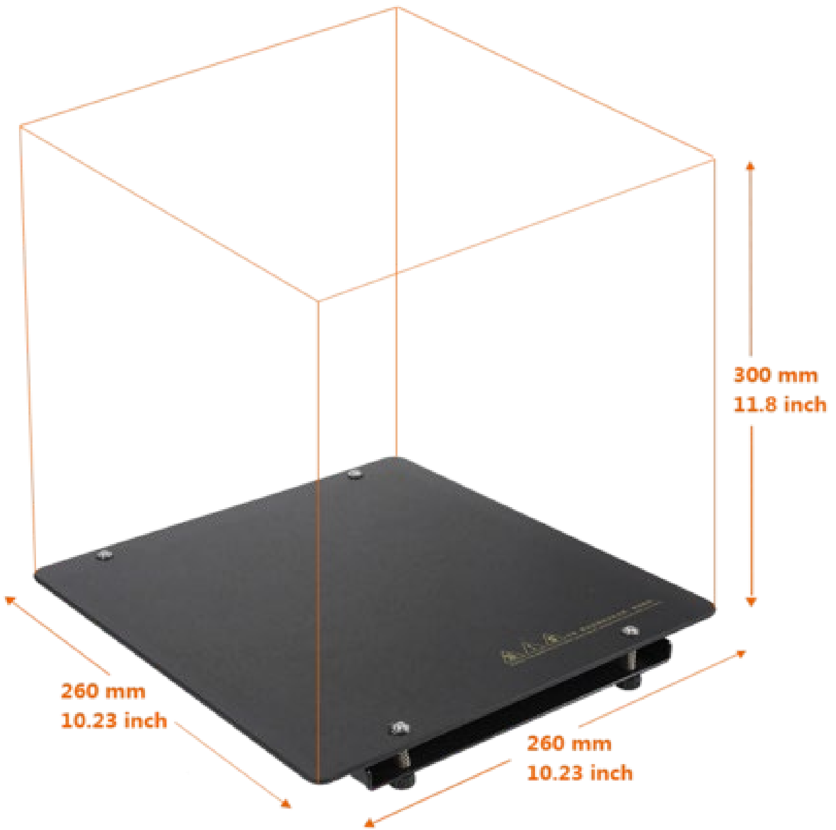


Secondary



PBF design guidelines: Part maximum dimensions

- The maximum dimensions of a part are somewhat overlooked while designing and the result is that the designed part will not fit the build volume of the available printer.
- In order to avoid that problem, the maximum dimensions of the build volume have to be considered while designing so the part will comfortably fit the printer or to be designed in split parts that will later be merged.
- However, during merging is significant to consider that if assembly bosses are used and the dimensions are equal in both sides the join will be considerably difficult.
- The dimensional accuracy of an PBF printer vary between certain limits.
- It is difficult to know a priori the exact accuracy so tight fit geometries are not suggested.



PBF design guidelines: Shrinkage & Warping

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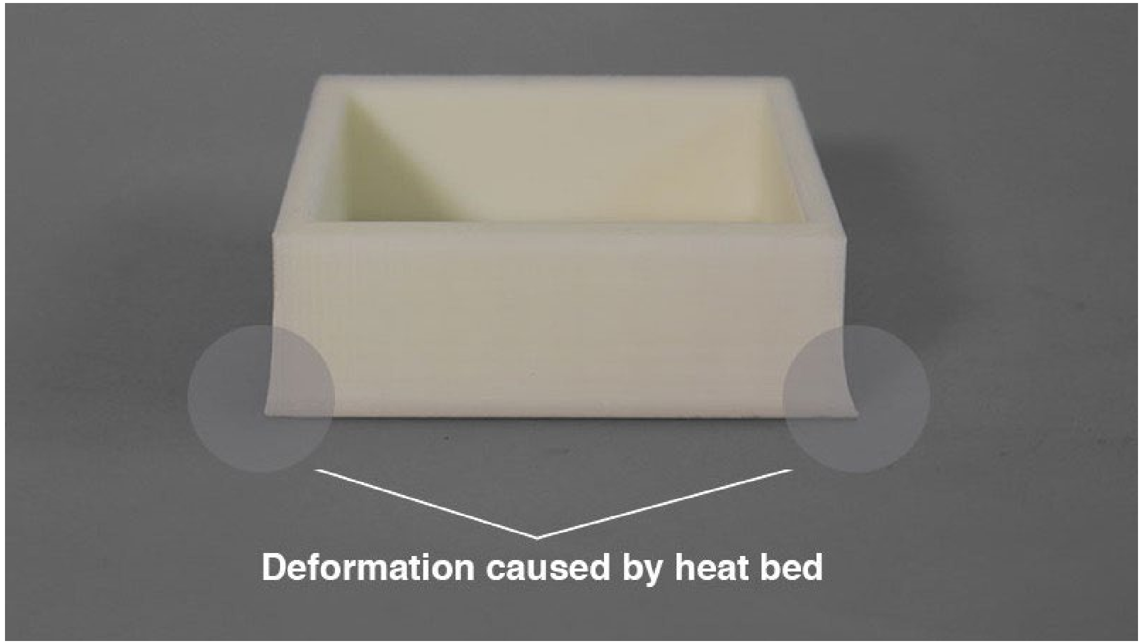
- Due to the high temperatures experienced by PBF components during the printing stage some shrinkage and warping can occur. PBF parts are typically cooled slowly to limit the impact of warping and shrinkage.

- Shrinkage - Most designs for PBF printing have overall dimensions increased by 3 - 3.5% at the pre-print analysis and conversion stage to accommodate shrinkage. This does not affect the design of a part.

- Warping - Large flat surfaces are most at risk. Consider adding ribs to increase stiffness. Part orientation during the printing stage can also help reduce the likelihood of warping.

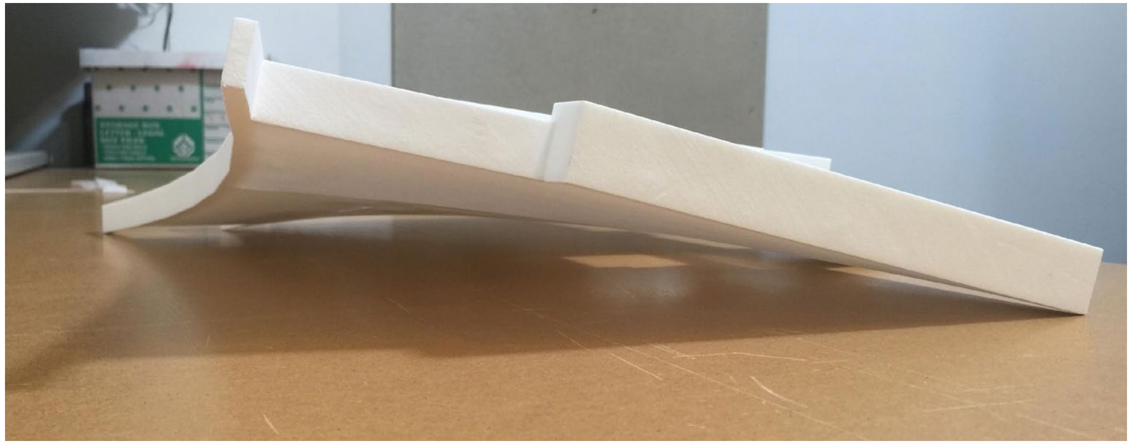


Source: https://printform.com/sls-design-considerations/

PBF design guidelines: Shrinkage & Warping

Shrinkage

- ❖ Due to the uneven heat inputs and the uneven cooling of the build plate (e.g. higher cooling near the edges), dimensional variation is not constant in the entire building area`
- ❖ As a rule of thumb, dimensional variation is lower at the outside than the inside and it is greater at the bottom of the build plate than at the top.
- ❖ Parts with thicker geometries, flat or broad parts, and parts with uneven wall thicknesses will be prone to significant deviations or warp due to variable thermal shrinkage and stress.



Source: https://www.shapeways.com/forum/t/badly-warped-sls-model.28903/

PBF design guidelines: Shrinkage & Warping

Warping

- ❖ Warping during PBF manufacturing occurs when the parts bend and twist due to inhomogeneous cooling of the parts
- ❖ This is caused by temperature differences during the building process
- ❖ Distortion during warping is also not constant in the entire building area, like shrinkage
- ❖ Like shrinkage, dimensional variation is lower at the outside than the inside and it is greater at the bottom of the build plate than at the top.

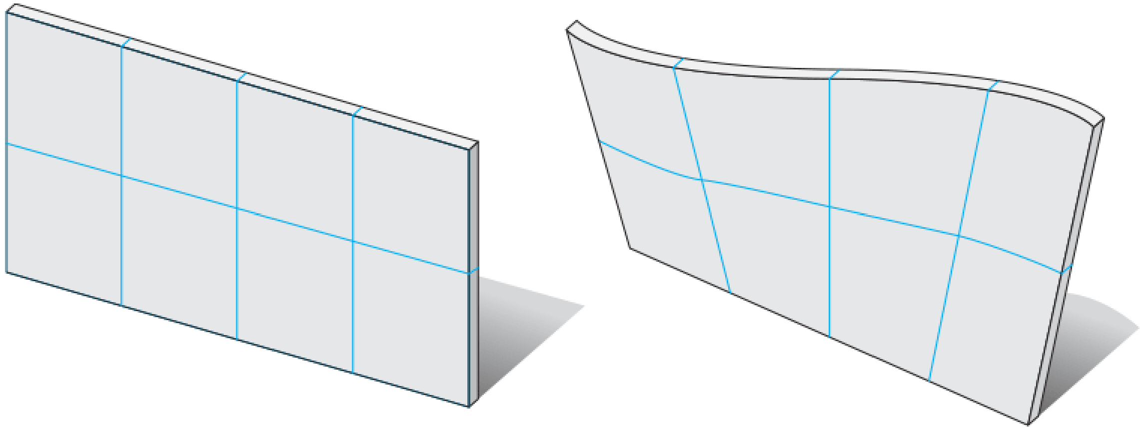
Source: https://support.formlabs.com/s/article/Warping-SLS?language=en_US

PBF design guidelines: Shrinkage & Warping

Warping

- It is strongly recommended to avoid large, flat plains in dimensions like a piece of paper (e.g. long and thin).
- In most cases, the model will deform. Even if aided by support ribs under the plane, most likely it doesn't solve the problem.

- Tall and thin towers often fail because the heat so this type of designs have to be avoided



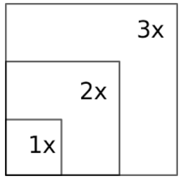
Source: https://i.materialise.com/en/3d-printing-materials/polyamide/design-guide

[REF] "https://www.materialise.com/en/manufacturing/materials/pa-12-sls/design-guidelines

PBF design guidelines: Shrinkage & Warping

Actions to minimize shrinkage & warping

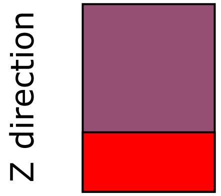
❖ Scale the parts to compensate for the shrinkage that occurs



❖ Retain parts position during production batches, since to achieve part accuracies (shrinkage) as reproducible as possible, the parts should be positioned in the same place in the building area as the first reference part.

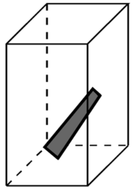
❖ Warm up machine properly, because the better the machine is warmed up before the building process, the more homogeneous the shrinkage behaviour and the lower the distortion.

❖ Parts critical for distortion and shrinkage should not be positioned in the bottom 1/3 of the job, as here shrinkage and distortion will increasingly occur due to the proximity to the cooler removal chamber

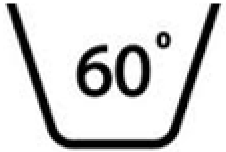


PBF design guidelines: Shrinkage & wrapping

Actions to minimize shrinkage & warping

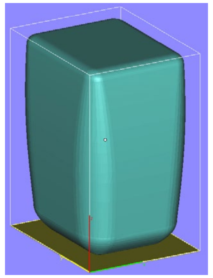


❖ Position on a corner: Parts critical for distortion with long surfaces should as far as possible be positioned diagonally in the building chamber.



❖ Unpack at < 60 °C: The job should only be unpacked at a core temperature in the exchangeable frame < 60 °C. Rule of thumb: Building time = cooling time (including cooling time outside the machine).

❖ Regenerate generously: For parts critical in relation to distortion, generously regenerated powder should be used. The higher the portion of new powder, the less distortion on the parts.

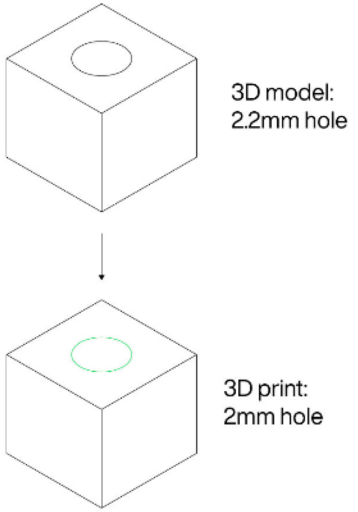


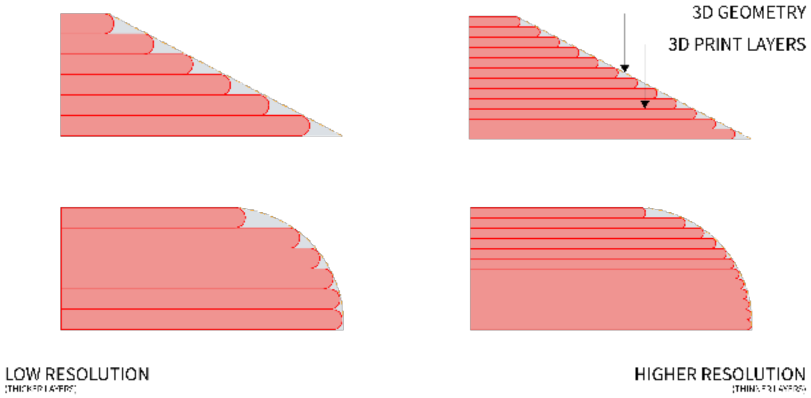
❖ Ideal positioning
Parts should be arranged in the area with the lowest tendency to distortion in the exchangeable frame ("Sweet Spot").

PBF design guidelines: Part dimensions

- **Precision (Dimensional accuracy, surface quality)**
- The quality of the final product can be quantified in terms of dimensional accuracy as well as the surface roughness
- Before proceeding to the creation of the desired part with specified specifications it is important to examine the accuracy of the machine as well as the consistency of providing the same output.
- This step may lead to design modifications in order to receive the desired output.
- Complex geometries with lot of geometrical features may need detailed slicing (very small layer height) in order to be achieved.
- The achievable surface roughness is found between 10-20μm.

- **Tolerances**
- Typical tolerances for PBF parts are ± 0.3 mm or ± 0.05 mm/mm, whichever is greater.





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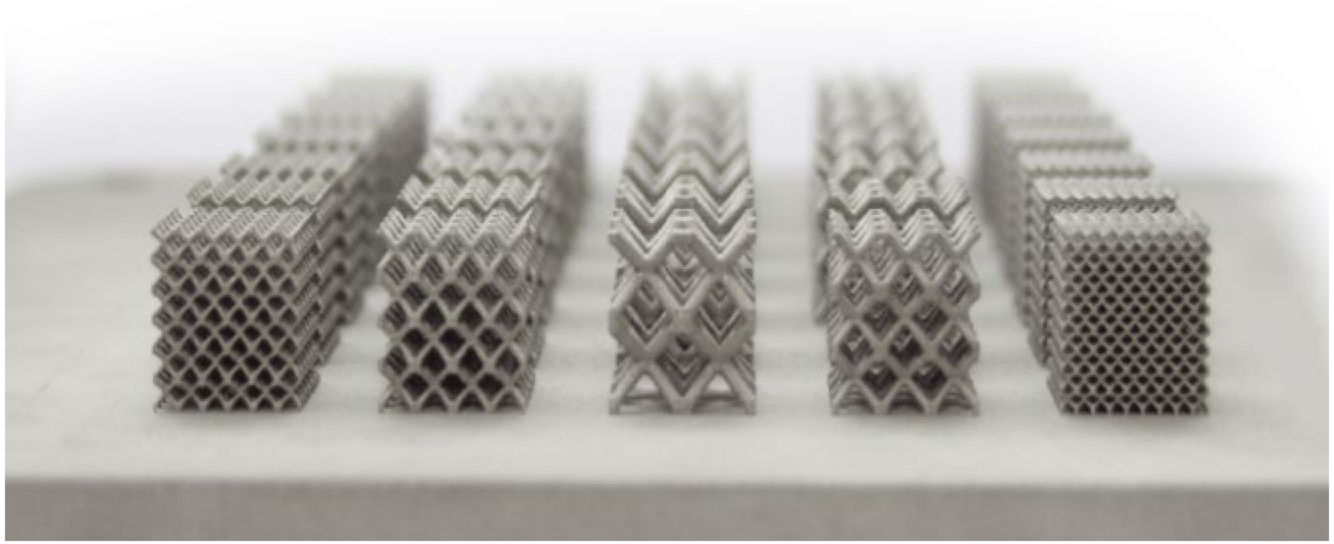
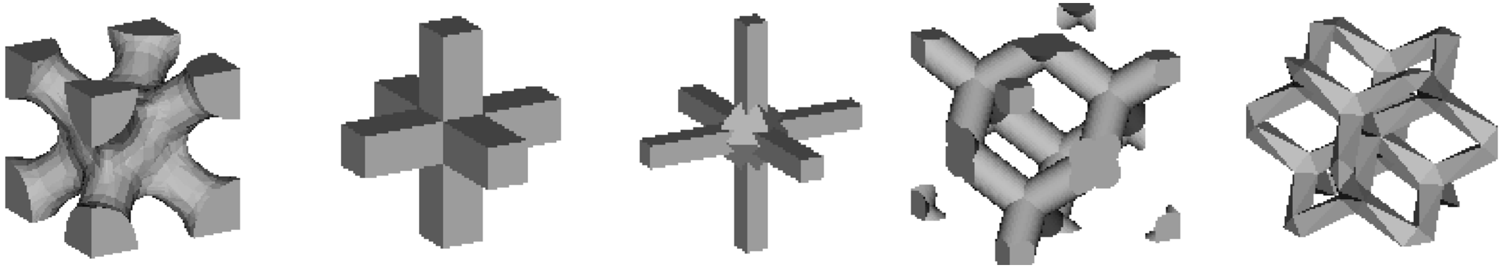
[REF] “Design Guidelines – FDM” https://www.materialise.com/en/manufacturing/materials/abs/design-guidelines
[REF] https://grabcad.com/tutorials/fused-deposition-modeling-fdm-design-guidelines

PBF design guidelines: Infill

- **Lattice structure**

- Lattice structures and other designed cellular materials enable designers to put material only where it is needed for a specific application.
- Lattice structures basically consist of a unit cell that is repeated throughout a volume.





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[REF] “3D Systems SLS Design Guidelines”

PBF design guidelines: Infill

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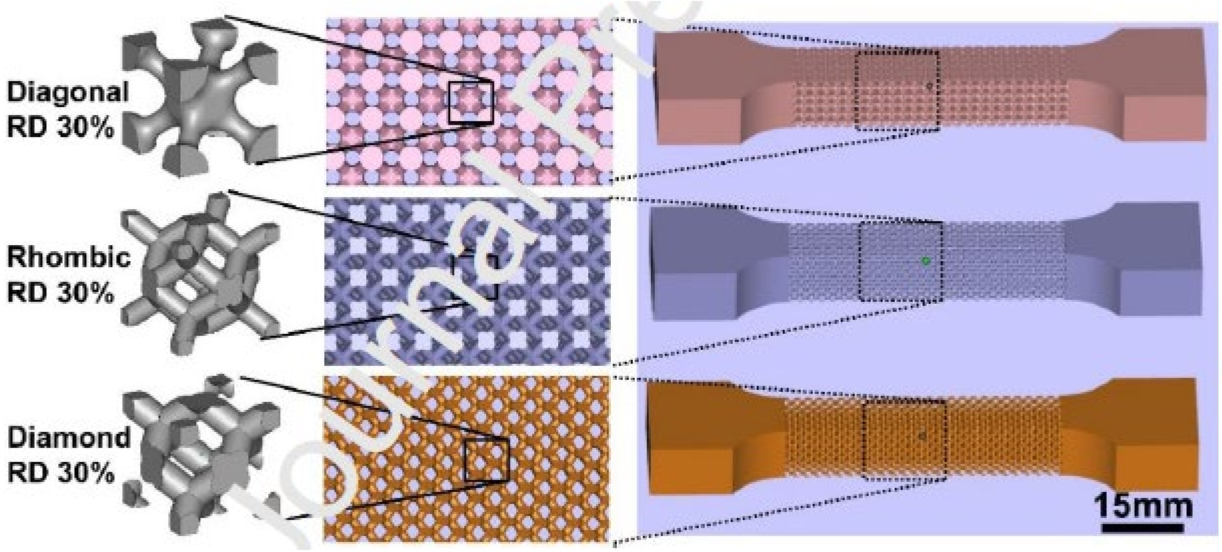
- **Lattice structure**

- A key advantage offered by cellular materials is high strength accompanied by a relatively low mass.
- These stuctures can also provide good energy absorption characteristics and good thermal and acoustic insulation properties as well.
- You can simulate the geometries of nature and place structures lattice inside 3D printed parts.



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[REF] “3D Systems SLS Design Guidelines”

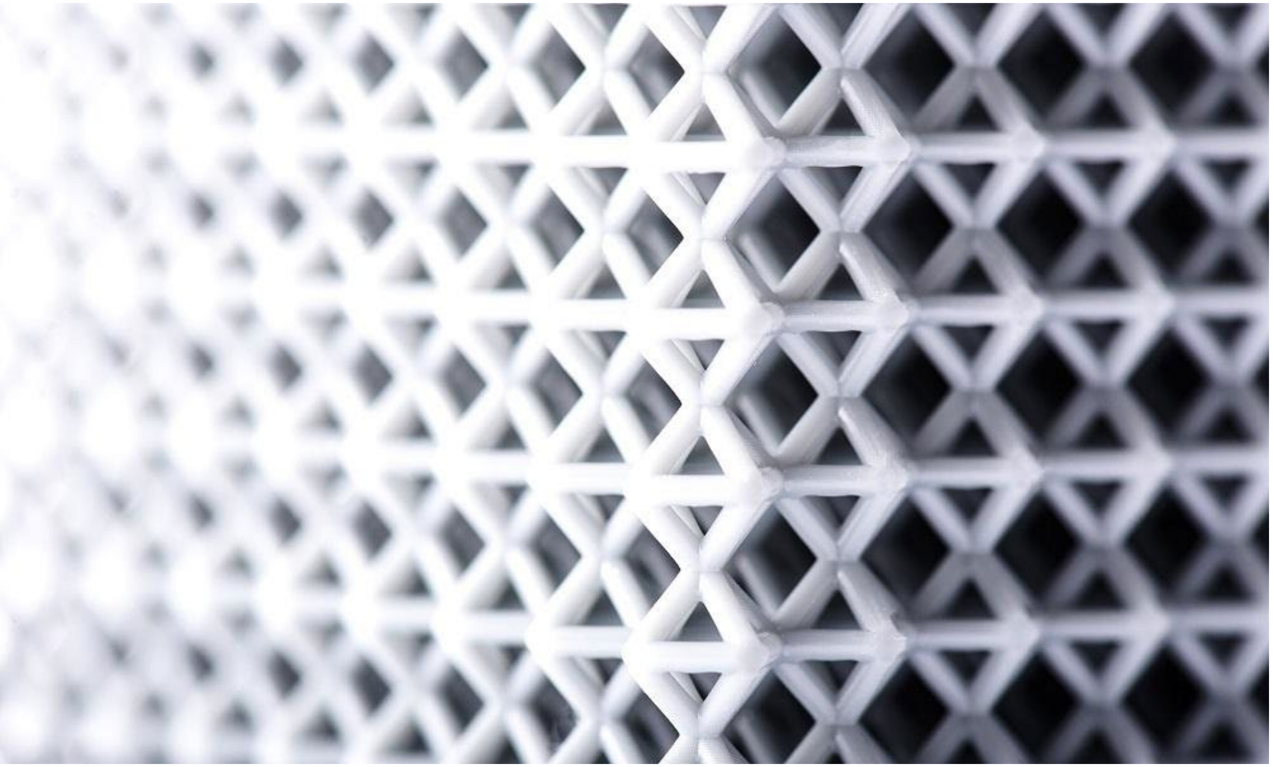
PBF design guidelines: Infill

➢ **Lattice structure**

❖ It can provide an added flexibility or impact resistance that solid material does not provide.

❖ A specialized software package is utilized that automates the design process of a lattice structure.

❖ PBF machines can fabricate lattice struts down to almost 0.5 mm in diameter.



Source: https://www.sculpteo.com/en/3d-learning-hub/3d-printing-software/lattice-generation-tools/

[REF] "3D Systems SLS Design Guidelines"

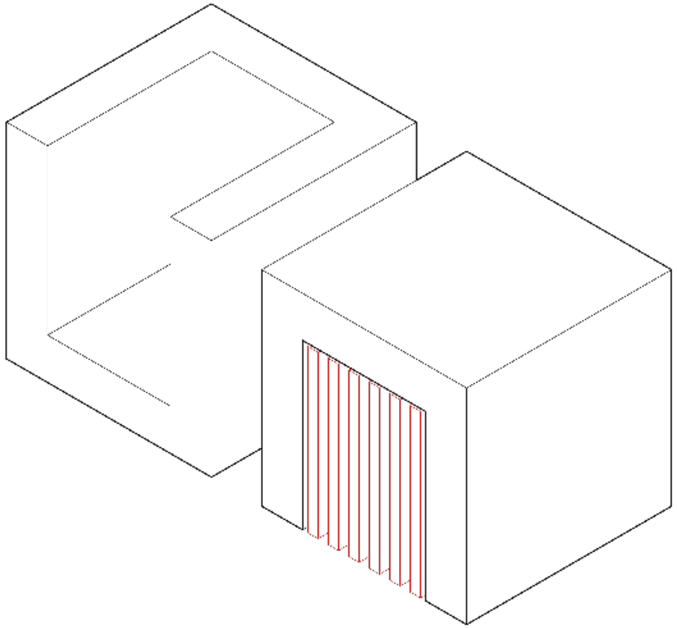
PBF design guidelines: Build orientation

➢ **Building orientation (Anisotropy, accuracy)**

❖ Build orientation dictates the directional behaviour of design requirements, like mechanical properties but also aesthetics & surface finish.

❖ The ideal time for choosing build orientation is after the concept design is completed but before detailed design requirements are implemented, in order to avoid features experiencing the staircase effect because of height layer height and overhang combination.

❖ The anisotropy of structural properties that arise of the building orientation is considered when the part is oriented for structural applications.



[REF] "Design Guidelines – FDM" https://www.materialise.com/en/manufacturing/materials/abs/design-guidelines
[REF] https://grabcad.com/tutorials/fused-deposition-modeling-fdm-design-guidelines

PBF design guidelines: Build orientation

➢ **Anisotropy**

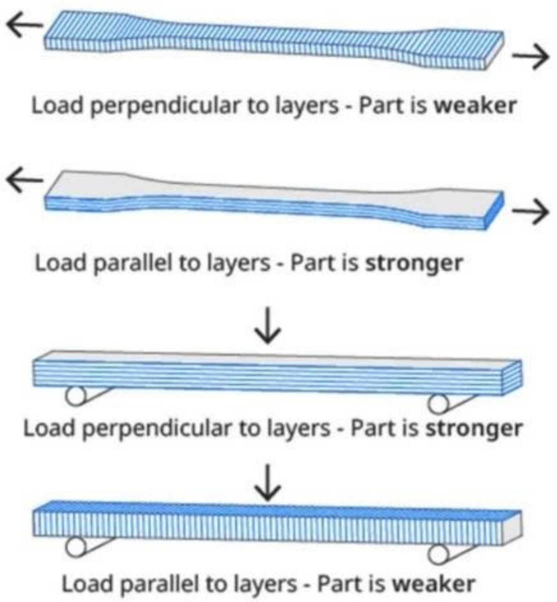
❖ Due to the anisotropic nature of PBF printing, understanding the application of a component and how it is built are critical to the success of a design.

❖ The lack of continuous material paths and the stress concentration created by each layer joint contribute to this weakness.

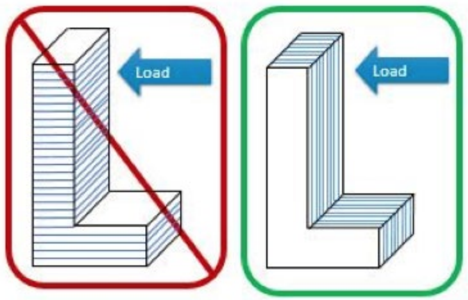
❖ PBF additive manufacturing maintains the least anisotropic effect compared to the other manufacturing methods

❖ With PBF, parts have their strongest strength at the tensile mode along the X-Y plane and the lowest strength in the Z-direction because of the technology's build style of one layer cooling and solidifying while the other is laid on

❖ Annealing can mitigate most anisotropic behavior



Source: https://ultimaker.com/learn/design-for-fff-3d-printing



Source: https://www.3dprintacademy.co.uk/fdm-3d-printing-tips-for-designers-tip-3-part-orientation/

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➢ **Geometry (e.g., corners, fillets and chamfers etc.)**

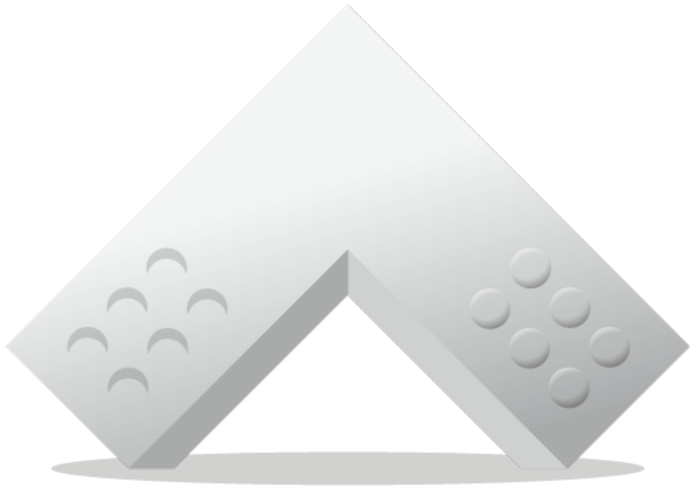
❖ **Rounded Edges**

❖ If your part contains sharp edges, these will be rounded off. Rounded corners and smooth transitions between surfaces will have a higher degree of polishing than sharp edges.

❖ This can be solved by adding small fillet radiuses in the corners

❖ **Embossed and Engraved Details**

❖ For engraved text or surface details, we recommend letters with a minimum line thickness of 1 mm, a depth of 1.5 mm, and an overall height of at least 4.5 mm. Embossed text or surface details should be thick enough that they will not break during production or transport. We recommend letters that have a line thickness of at least 0.8 mm, an overall height of at least 3 mm, and a depth of at least 0.8 mm.



Source: https://www.materialise.com/en/manufacturing/materials/pa-12-sls/design-guidelines

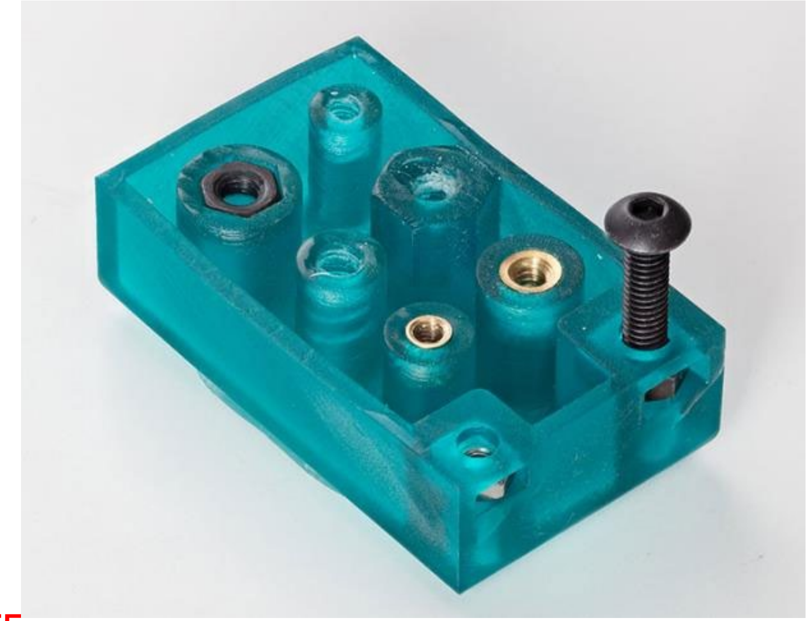
PBF design guidelines: Threaded holes

Threaded holes

- Should be limited only to blind holes, as bolt through hole and nut on the opposite side are generally stronger
- A flush insert (or pocketed nut) can be used in through holes where there is no space for a nut
- Bending along the axis parallel to printing should be generally avoided
- Double check your CAD model before adding fastening features

5 options for PBF processes

- Cutting threads (tapping)
- Print-in-place threads
- Self-tapping screws
- Inserts



How to select?

- Will you need to disassemble and reassemble the components?
- What are your strength requirements or holding forces?
- What are the geometric or spatial constraints inherent in the design of your parts?

PBF design guidelines: Threaded holes

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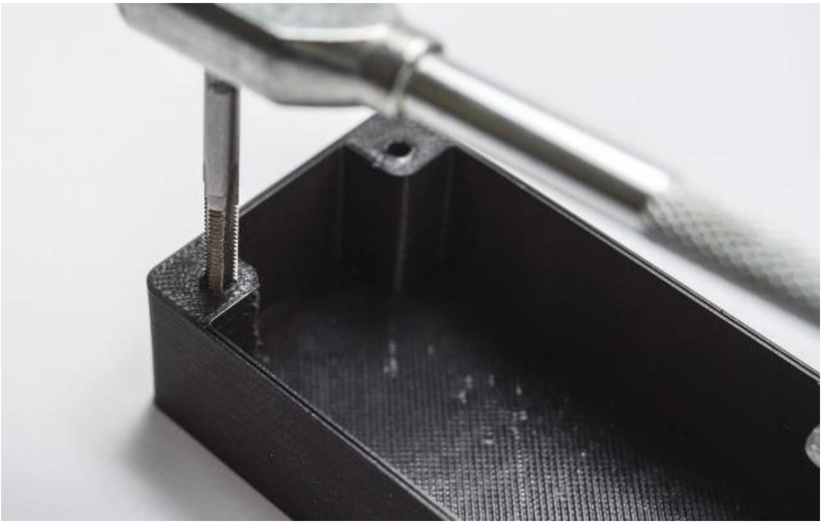
- **Cutting threads/tapping**

- Similar method to the one used for metallic parts

- Holes should be slightly undersized and drilled before tapping to the correct size (https://littlemachineshop.com/images/gallery/PDF/TapDrillSizes.pdf)

- Operation should not be forced, as the part could split between layers

- Minimum wall thickness around a thread should match the diameter of the fastener (e.g. an M5 fastener requires a minimum of 5mm wall thickness around the threaded hole).



Metric Tap & Clearance Drill Sizes		Tap Drill			
		75% Thread for Aluminum, Brass, & Plastics		50% Thread for Steel, Stainless, & Iron	
Screw Size (mm)	Thread Pitch (mm)	Drill Size (mm)	Closest American Drill	Drill Size (mm)	Closest American Drill
M1.5	0.35	1.15	56	1.25	55
M1.6	0.35	1.25	55	1.35	54
M 1.8	0.35	1.45	53	1.55	1/16
M 2	0.45	1.55	1/16	1.70	51
	0.40	1.60	52	1.75	50
M 2.2	0.45	1.75	50	1.90	48
M 2.5	0.45	2.05	46	2.20	44
M 3	0.60	2.40	41	2.60	37
	0.50	2.50	39	2.70	36
M 3.5	0.60	2.90	32	3.10	31

MEx design guidelines: Threaded holes

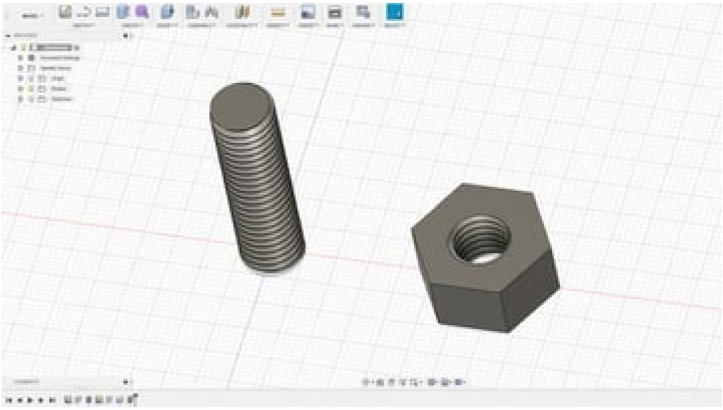
- **Print-in-place threads**

- Not suited for small threads and requires high printer detail/resolution to print accurately

- Thread usually requires clean-up with a tap after printing and before using

- Make sure the tolerance between internal and external threads is 0.15-0.2 mm

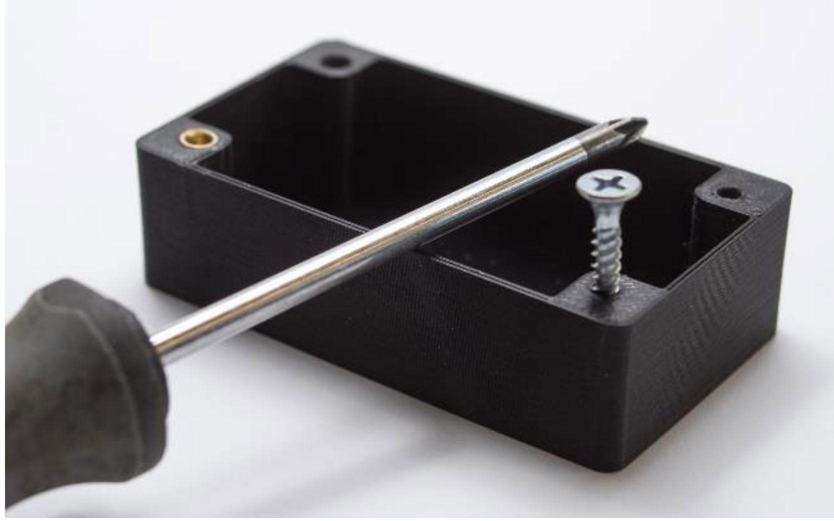
- Avoid sharp edges and 90-degree angles (stress concentrators) and include a radius on the root.



PBF design guidelines: Threaded holes

- **Self-tapping screws**

- Commonly used in IM parts
- Screw cuts its’ own threads while tightening
- A pilot hole size that provides 75% to 80% thread engagement is a good starting point; screw manufacturers usually list specifications
- Operation should not be forced, as the part could split between layers
- Special self tapping screws for plastic that limit the radial stress should be used whenever possible
- Minimum wall thickness around a thread should match the diameter of the fastener (e.g. an M5 fastener requires a minimum of 5mm wall thickness around the threaded hole)
- Suitable only for applications where parts will not be assembled/disassembled regularly



Nominal Size or Basic Screw Diameter		Threads per Inch	D Major Diameter Max.	D Major Diameter Min.	d Minor Diameter Max.	d Minor Diameter Min.	L These Lengths or Shorter Have AB Threads 90° Heads	L These Lengths or Shorter Have AB Threads Csk Heads
4	0.1120	24	0.114	0.110	0.086	0.082	3/16	7/32
6	0.1380	20	0.139	0.135	0.104	0.099	7/32	17/64
8	0.1640	18	0.188	0.161	0.122	0.116	9/32	21/64
10	0.1900	16	0.189	0.183	0.141	0.135	21/64	3/8
12	0.2160	14	0.215	0.209	0.164	0.157	3/8	13/32
1/4	0.2500	14	0.246	0.240	0.192	0.185	13/32	15/32
5/16	0.3125	12	0.315	0.306	0.244	0.236	5/8	3/4
3/8	0.3750	12	0.380	0.371	0.309	0.299	3/8	29/32

PBF design guidelines: Threaded holes

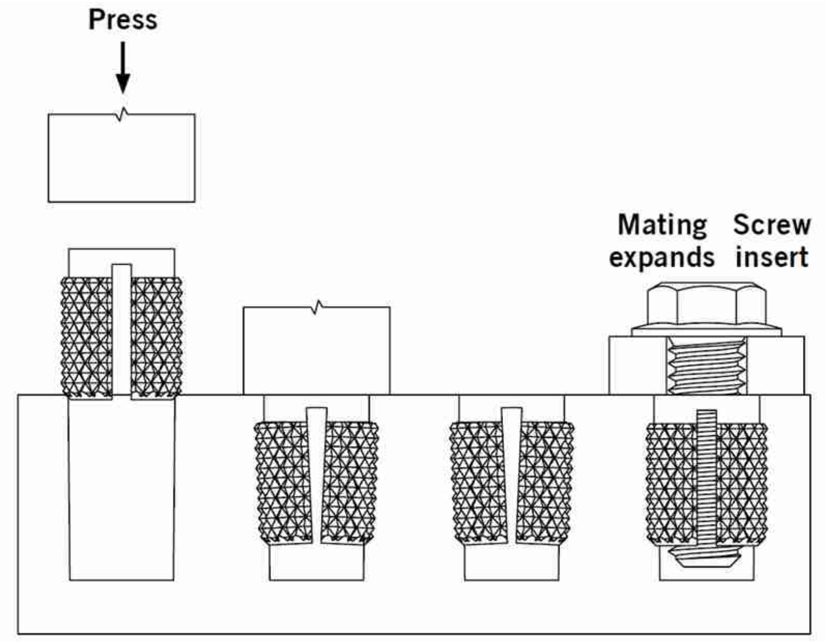
➢ **Press-fit inserts**

❖ Ideal for applications where parts will be assembled/disassembled frequently

❖ Expansion-type: When a mating screw is installed, the sides of these inserts are expanded and force the fins or knurls into the sides of the holes

❖ Hole size for the insert is provided by the manufacturer

❖ Minimum wall thickness around a thread should be at least half the insert diameter

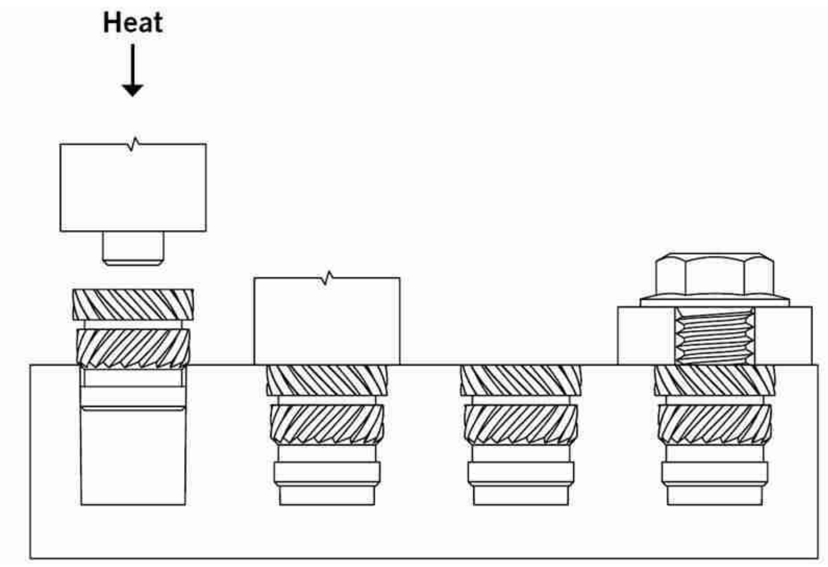


PRESS INSERT 240 SERIES — FLUSH BRASS						
Part Number	Thread Size	L (in.)	A (in.)	B (in.)	Hole Size* (in.)	Minimum Depth (in.)
240-000-BR	0-80	.125	.094	.104	.094	.130
240-002-BR	2-56	.156	.125	.135	.125	.173
240-004-BR	4-40	.188	.156	.166	.156	.215
240-006-BR	6-32	.250	.187	.199	.188	.259
240-008-BR	8-32	.313	.218	.230	.219	.302
240-008-BR.250	8-32	.250	.218	.230	.219	.302
240-3-BR	10-24	.375	.250	.262	.250	.345
240-332-BR	10-32	.375	.250	.262	.250	.345
240-332-BR.250	10-32	.250	.250	.262	.250	.345
240-4-BR	1/4-20	.500	.312	.326	.313	.432
240-5-BR	5/16-18	.563	.375	.389	.375	.518

PBF design guidelines: Threaded holes

➢ **Heat-set inserts**

- ❖ Ideal for applications where parts will be assembled/disassembled frequently
- ❖ Hole size for the insert is provided by the manufacturer
- ❖ The thread insert is heated via thermal conduction and pressed into the hole once the plastic reaches the proper melting temperature
- ❖ After the heated press tip is retracted, the plastic will become cool and solid, locking the thread insert into place
- ❖ Pressing against a cool flat surface until the plastic solidifies is encouraged to avoid plastic budging
- ❖ Minimum wall thickness around a thread should be at least half the insert diameter



TAPERED SINGLE VANE

Part Number.	Internal Thread	Overall Length (L)	Insert Diameter (W)	Pilot Diameter (N)	Rec. Hole Size* (D)	Rec. Hole Size* (S)	Minimum Wall Thickness
TH-002-SV	2-56	.115	.136	.122	.123	.118	.080
TH-004-SV	4-40	.135	.172	.157	.159	.153	.093
TH-006-SV	6-32	.150	.220	.203	.206	.199	.116
TH-008-SV	8-32	.185	.250	.230	.234	.226	.133
TH-124-SV	10-24	.225	.296	.272	.277	.267	.159
TH-132-SV	10-32	.225	.296	.272	.277	.267	.159
TH-420-SV	1/4-20	.300	.375	.354	.363	.349	.194
TH-428-SV	1/4-28	.300	.375	.354	.363	.349	.194
TH-518-SV	5/16-18	.335	.469	.439	.448	.431	.245
TH-316-SV	3/8-16	.375	.563	.530	.540	.523	.293
TH-324-SV	3/8-24	.375	.563	.530	.540	.523	.293
TH-M25-SV	M2.5-0.45	.135	.172	.157	.159	.153	.093
TH-M30-SV	M3-0.5	.150	.220	.203	.206	.199	.116
TH-M40-SV	M4-0.7	.185	.250	.230	.234	.226	.133
TH-M50-SV	M5-0.8	.265	.328	.308	.315	.303	.171
TH-M60-SV	M6-1.0	.300	.375	.354	.363	.349	.194

PBF design guidelines: Threaded holes

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➢ **Summary**

Type	Pros	Cons
Print-in-place	• Can design custom threads • Good when inserts aren't available (ie. M50 thread) • Works well with brittle materials	• Threads will wear down over time • Difficult to model accurately • Requires high resolution prints
Tapping	• Better assembly/disassembly than self threading screws	• Low strength • Plastic threads wear down over time • Time intensive
Self-tapping	• Easy installation • Minimal design requirements • Cheap	• Brittle material may break • Limited assembly/disassembly • Low strength
Inserts	• Fast, easy and clean • Unlimited assembly/disassembly • Production quality	• More expensive • Requires increased wall thickness

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➢ Design for Assembly

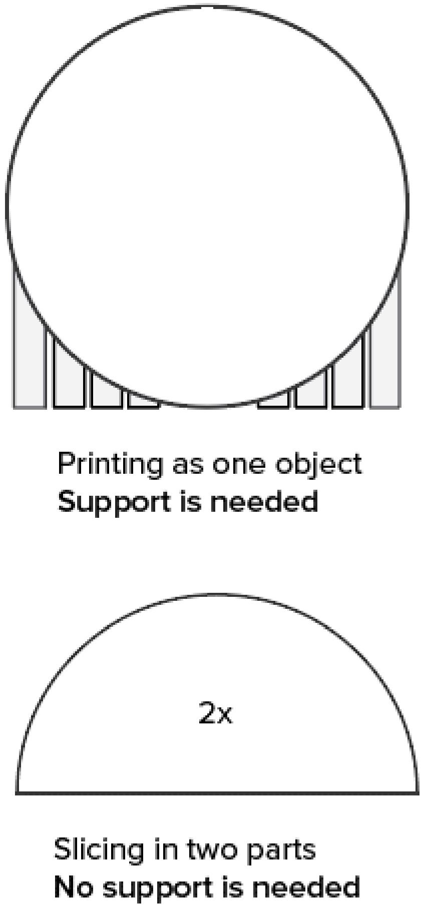
Key design aspects to consider when printing with PBF are:

- How to achieve optimal strength
- Direction the part is built on the build platform

Overhangs that require a large amount of support may be removed by simply splitting a complex shape into sections that are printed individually. If desired, the sections can be glued together once the print has been completed.

This results in:

✔ Reduction of the amount of supports
✔ Simplification of the post-processing
✔ Faster printing process
✔ Less material consumed



Source: https://www.hubs.com/knowledge-base/how-design-parts-fdm-3d-printing/#vertical-axis-holes

PBF design guidelines: Part splitting & DFA

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➢ **Design for Assembly considerations**

❖ What is the minimum number of parts that can be used?

❖ What would be the loads transferred between the parts?

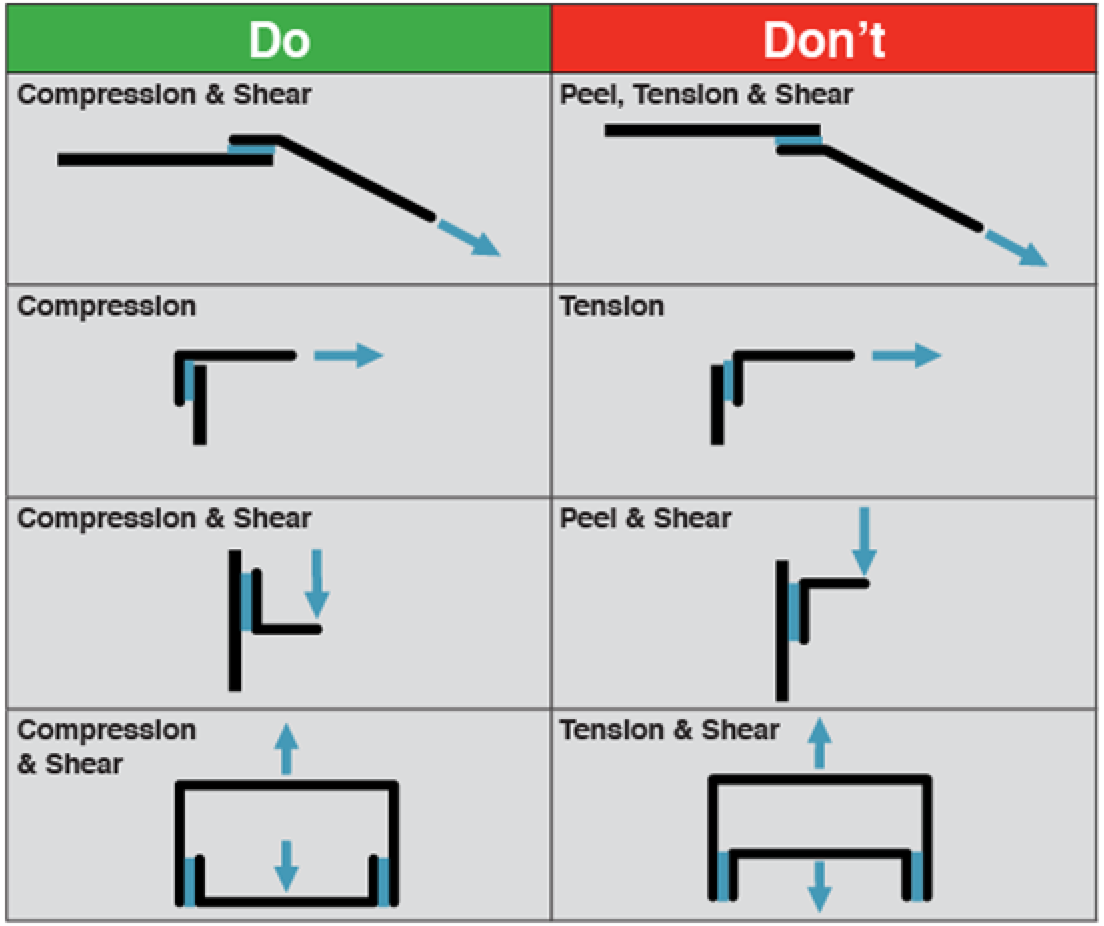
❖ How will the individual components be joined together?

- Clip together
- Screws
- Adhesive

❖ Adhesive is the most common way, however the joint should be designed properly to transfer forces effectively (shear)

❖ Locating features

- Parts can be designed to be self-locating/self-jigging
- Locating features can offer additional strength



Source: https://www.chemical-concepts.com/blog/2018/09/structural-adhesive-joint-design-guide/

PBF design guidelines: Print-in-place mechanisms

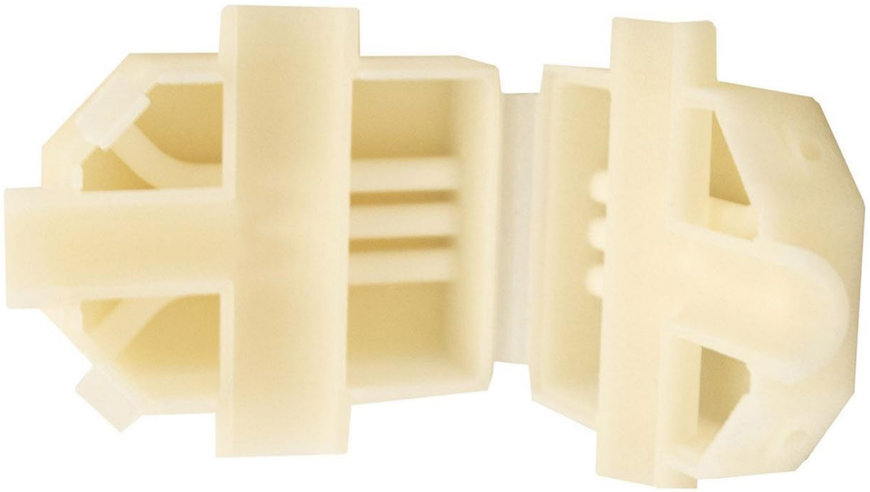
➢ **Interlocking Parts, Hinges & Clearances**

❖ If a 3D model that has multiple parts or pieces that will be assembled later will be created with PBF process, it is advised to ensure that there is enough space to join the pieces together.

❖ If it is planned to create a part in one piece without having to assemble afterwards, it is advised to check that there is enough clearance between any moving parts such as ball joints, hinges, gears, cogs or chain links.

❖ If minimum clearances are not met, the 3D model could possibly fuse together during the 3D printing process and making the 3D printed model solid instead of movable.

❖ Also consider that some materials allow to create complex assemblies of objects that 3D printing alone could not accomplish (flexible material etc.)



Source: https://3dprintingindustry.com/news/protolabs-expands-3d-printing-services-with-polypropylene-sls-163083/

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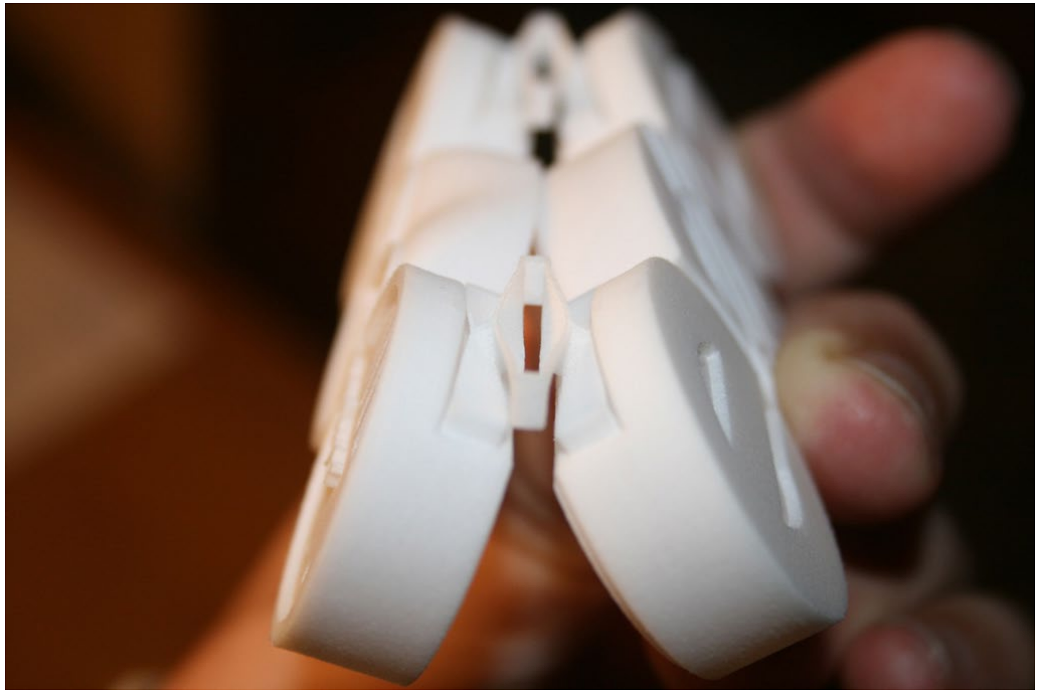
- **Living hinges**

❖ PBF is one of the only 3D printing methods that can produce functional living hinges.

❖ Conventional living hinges are designed and optimized for the thermoplastic injection molding materials and process

❖ This can be useful in applications where there is a one-time fold-to-use application and it makes sense to keep components connected together.

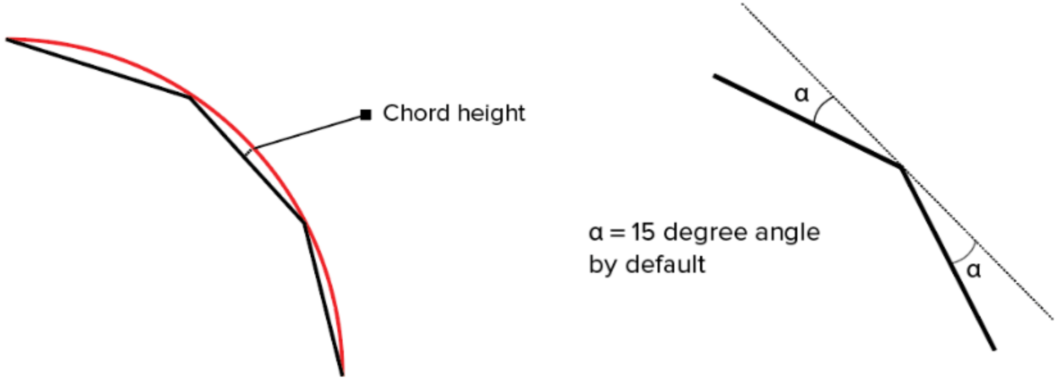
❖ It is recommended living hinges are 0.3 – 0.8 mm thick and a minimum of 5 mm in length



Source: https://printform.com/sls-design-considerations/

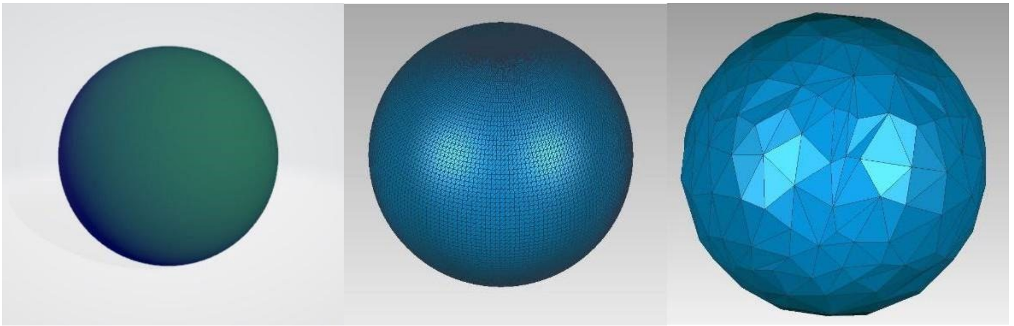
PBF design guidelines: STL files

- ❖ Polygon/model resolution when converting to STL is important for the final quality of the part
- Mainly defined by chord height & chord angle
- The chord height is the maximum distance that the software will allow between the surface of the original 3D model and the surface of the STL file
- The recommended value for the chord height is 1/20th of the 3D printing layer thickness and never below 0.001 mm
- Chord angle is the maximum allowable angle between the normals of adjacent triangles of the STL file



Source: https://www.hubs.com/knowledge-base/3d-printing-stl-files-step-step-guide/

- ❖ Many repair tool for watertight shapes and STL check exist and for each tool there are several examples on how to deal with common issues. Some of the tools are:
- Microsoft STL repair (Netfabb),
- Meshmixer, Meshlab,
- 3D Builder



Source: https://satori-tech.medium.com/why-is-stl-a-popular-file-format-for-3d-printing-f0ce3da45c52

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PBF design guidelines: STL files

➢ **Watertightness**

❖ Watertight part: It means that there are no holes on the surface of the 3D model.

❖ In order to manufacture a part with PBF process, it is obligatory for a part to be watertight

❖ Having a watertight design can affect the printability of a part — non-watertight models cannot be 3D printed — which is why it is vital to check the design before sending it to print.

❖ Some slicer automation software can easily check for watertight issues so it can be controlled before the actual print.

Source: https://www.sculpteo.com/en/materials/sls-material/pp-nat-01/

➢ **Non-Manifold Edges & Singular Points**

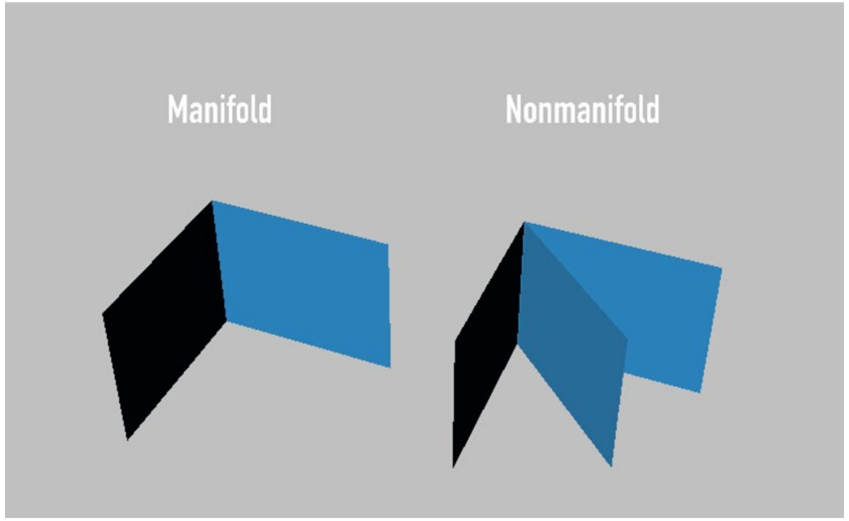
- ❖ During the conception of the 3D file, certain operations may create unattached, ambiguous surfaces which do not connect.

- ❖ Other operations may separate surfaces, creating singular point of connection.

- ❖ To define a clear volume, each side must be connecting two and only two adjacent faces.

- ❖ Similarly, singular points must arrive at the collection of multiple faces. If two faces share only one point (figure), the model is considered "non-manifold" and will not be able to be printed.

- ❖ These singularities can be eliminated by either disconnecting the non-manifold surface and giving it volume, or by deleting it completely.



Source: https://discourse.mcneel.com/t/manifold-vs-non-manifold-geometries/45265

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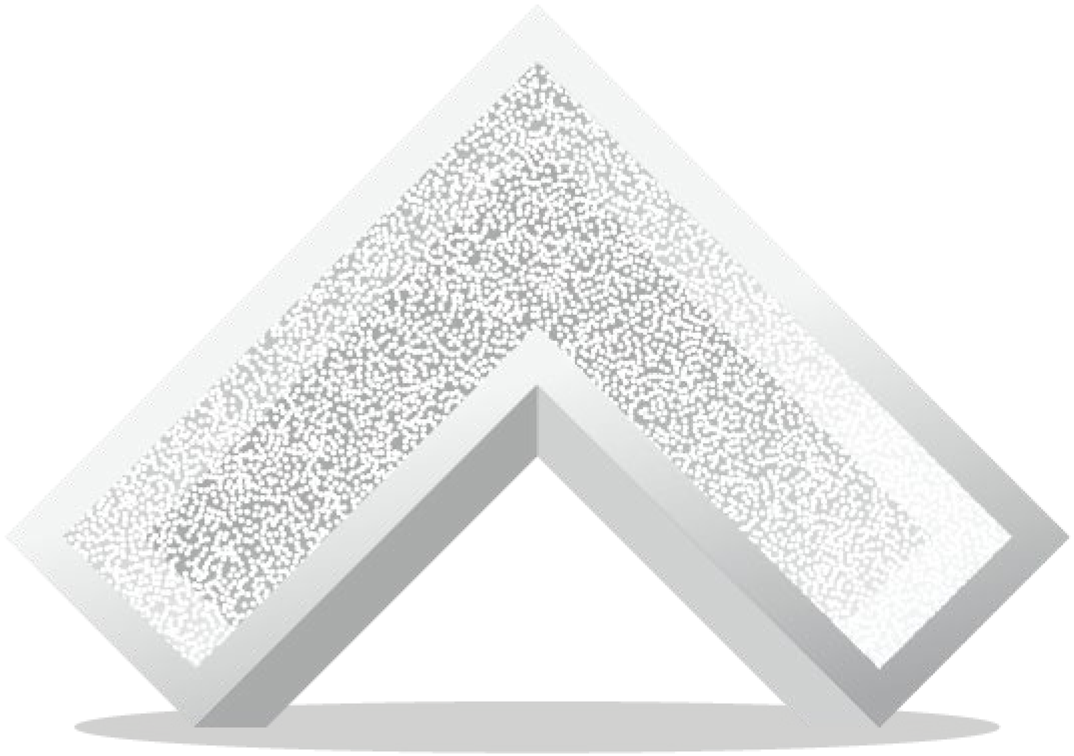
- **Hollowing**
- If a model is large or a decrease of the amount of material used for weight or cost savings is desired, then hollowing a model is the way to go.
- If some parts of the object canbe hollow, a hole in the model can be created so as to save significant portion of the material.
- Afterwards, an infill structure and infill percentage can be selected on the slicer software in order to strengthen the internal structure of the part.
- Do not forget to add an escape hole in order to extract the unsintered powder!



Source: https://www.materialise.com/en/manufacturing/materials/pa-12-sls/design-guidelines

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Agenda

- Introduction to DfAM
- Design aspects for PBF
- Design limits determination
- Design guidelines
- Design optimization methods
- Conclusions

SAM: PBF Design Optimization methods

- Design from scratch provides the freedom to tailor material placement into the part to a high level of detail
- Conformance on both performance metrics (structural) and AM manufacturability
- **Design optimization techniques**
  - Several design optimization techniques with respect to different targets (structural, thermal, fluid dynamics) exist such as (Topology Optimization, Generative design, etc.)
  - However, these methods do not take into account manufacturability constrain
  - Although AM is the enabler of design freedom, it is not guaranteed that all designs can be built **effectively**
- AM manufacturability should be checked
- Addition of design elements to ensure AM manufacturability

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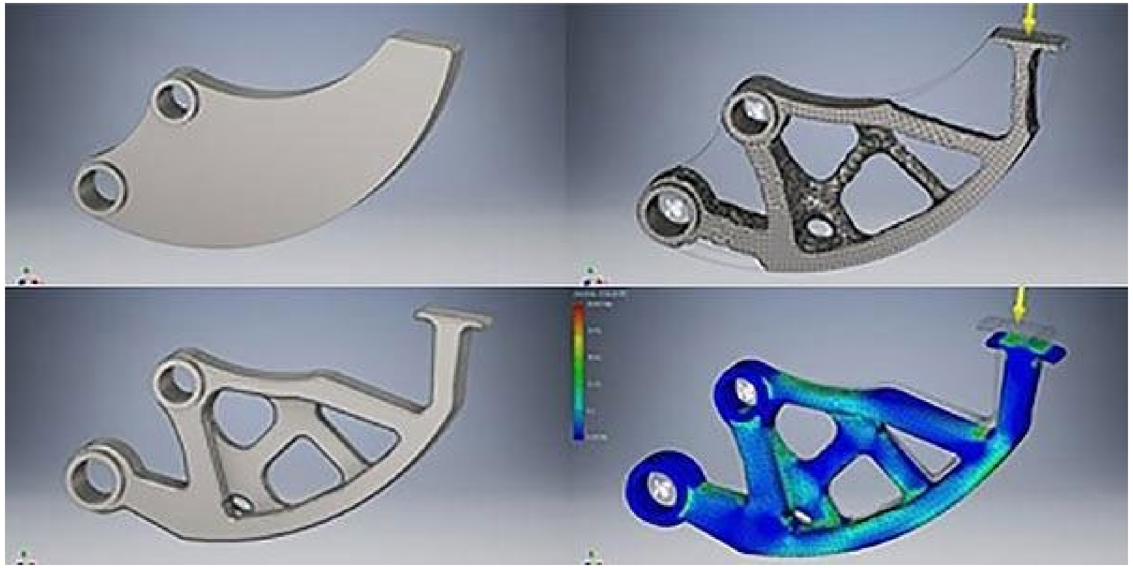
Topology: Area of mathematics concerned with properties that are preserved under continuous deformation of objects

Optimization: Selection of the best option from a set of available alternatives

Topology optimization: A mathematical approach that optimizes material distribution within a given design space (topology), for a given set of loads and boundary conditions, such as the result meets a prescribed set of performance (optimization) targets.

- An objective function needs to be defined, that needs to be maximized/minimized.
- A number of alternatives is produced, and the best one selected



PBF Design Optimization methods: Topology Optimization

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- **Preparation:** The input to the topology optimization software would the 3D cad of the part

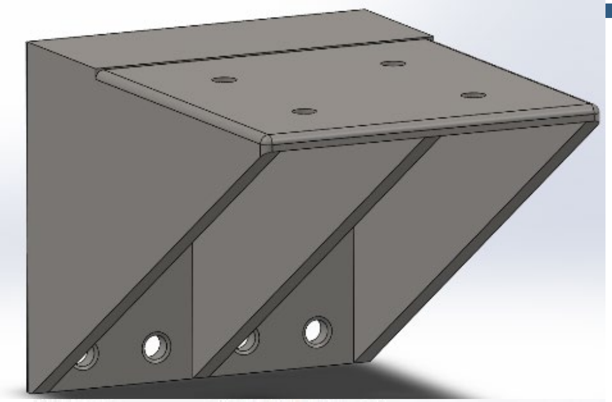
- **Defining the simulation parameters:** The applied loads and locations as well as the fixtures and the designed constraints are determined.

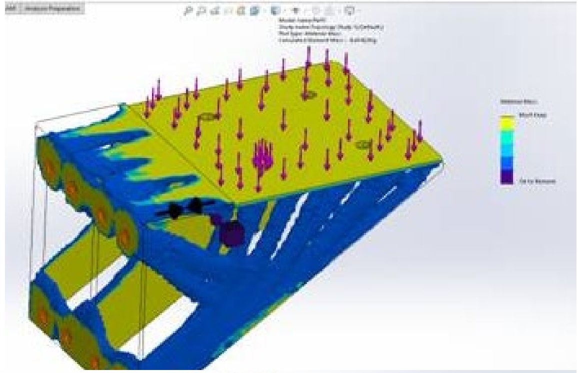
- **Goals and Constraints:** Selection of the optimization goal and constraints such as a) Best stiffness to weight ratio, b) Minimize maximum displacement and c) Minimize mass with displacement constraints.

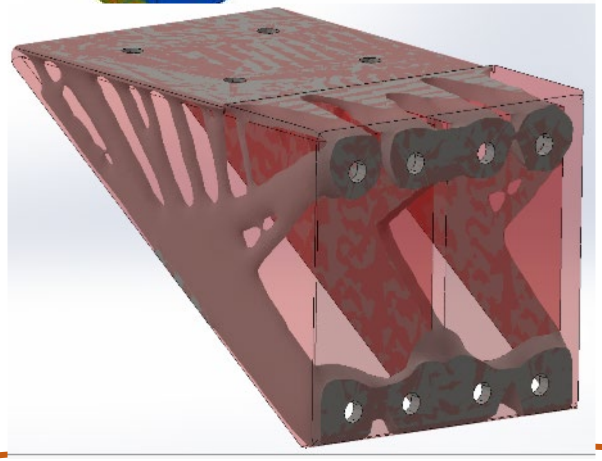
- **Manufacturing Controls:** Add constraints that assist with the manufacturability of the part and can be used to keep regions of material that you don't want removed by the optimization process

- **Mesh and run:** At this step the Mesh Density is controlled. A finer mesh will create a more accurate study but will take longer to mesh.

- **Results and analysis:** Identify which conditions provide the more optimized results. Iterations until the desired output come.







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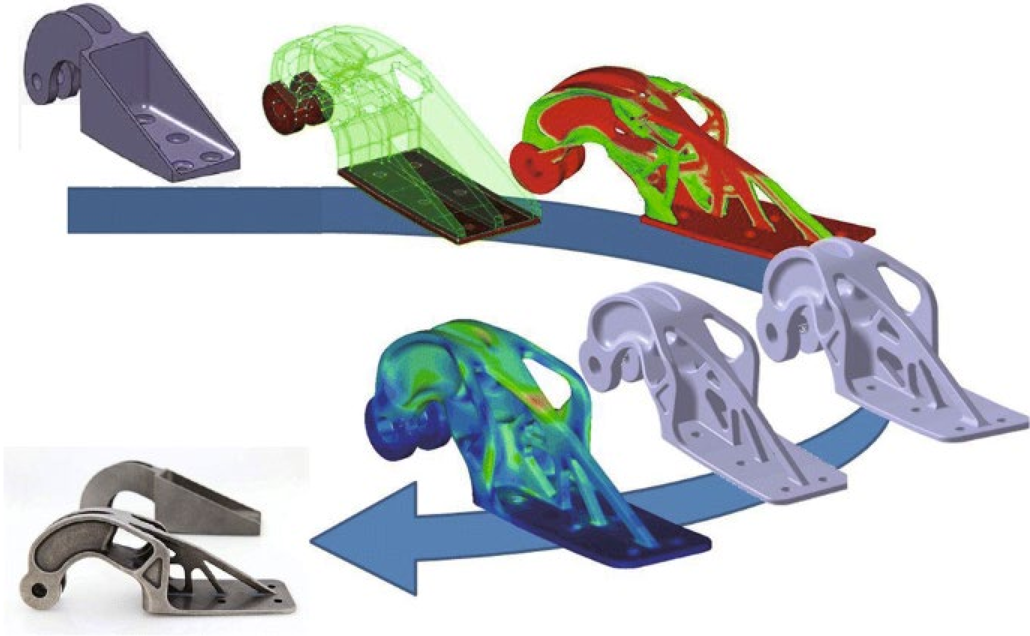
❖ **Dedicated software tools:**

- Altair OptiStruct
- Altair Inspire
- Ansys
- Dassault Systèmes
- Autodesk
- nTopology
- Tosca

❖ **Try for yourselves!**

http://www.topopt.dtu.dk/



❖ **CAD-embedded solutions:**

- Solidworks
- Creo
- Fusion 360

PBF Design Optimization methods: Generative design

- The typical design process, requires the knowledge and expertise of the designer to craft products that meet the needs of the end user.
- Combine this with the next generation of products that are emerging, which require ultra-high-performance characteristics and are too demanding for the traditional design process, and this is where generative design will help create the optimized designs of the future.
- Designers or engineers input design goals into the generative design software, along with parameters such as performance or spatial requirements, materials, manufacturing methods, and cost constraints.
- With the emergence of technologies such as artificial intelligence algorithms and infinite computing, which are much more accessible that any time in the past, designers and engineers can co-create designs using parameter driven optimization.
- The software explores all the possible permutations of a solution, quickly generating design alternatives.

Source: https://www.autodesk.com/solutions/generative-design

Source: https://knepublishing.com/index.php/KnE-Engineering/article/view/612/1903

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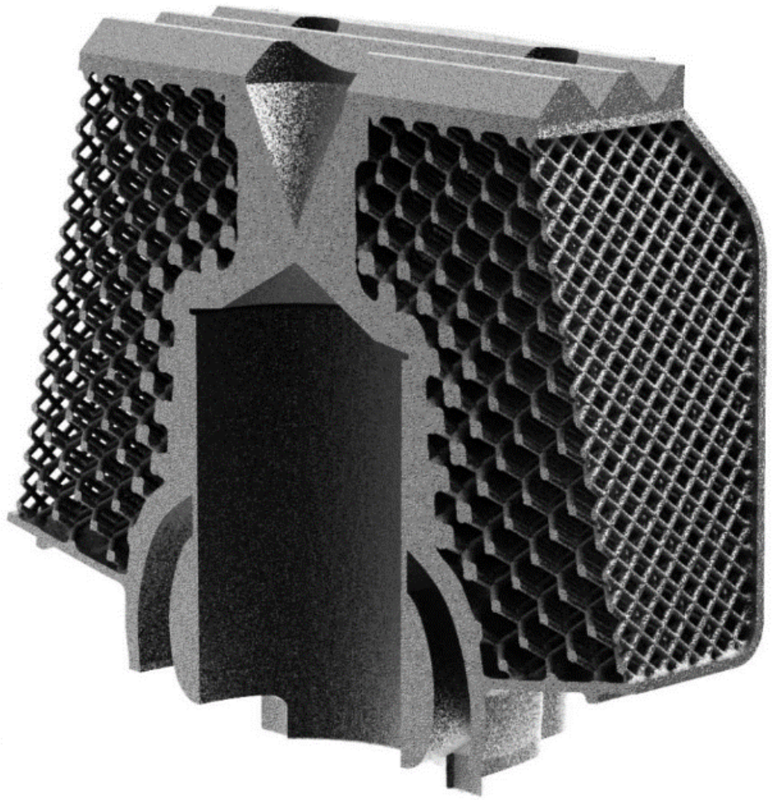
❖ **Dedicated software tools:**

- Ntopology
- MSC software
- CIDEON
- Ansys
- Dassault Systèmes
- Autodesk
- Tosca
- Altair Inspire

Try for yourselves!

https://www.layopt.com/truss/



❖ **CAD-embedded solutions:**

- Siemens NX
- FUSION 360
- Solidworks

PBF Design Optimization methods: Topology vs Generative

- For the topology optimization, the software generates a single optimized mesh-model concept ready for an engineer's evaluation.
- In other words, topology optimization requires a human-designed model from the outset to function, limiting the process, its outcomes, and its scale.
- In a way, topology optimization serves as the foundation for generative design.
- Generative design takes the process a step further and eliminates the need for the initial human-designed model, taking on the role of the designer based on the predefined set of constraints.

Source: https://formlabs.com/blog/generative-design/


Let's have a
COFFEE
BREAK

3. Top-Down geometric optimization

- A number of voxel stages is defined
- A voxel is candidate for removal when both following criteria are valid:
  - ✔ Load is below the allowable stress threshold
  - ✔ The resulting geometry conforms to 3 main DfAM rules

Voxels Status	Description
1	Stressed element that needs to be part of the mass domain
0	Non-stressed element
0C	Non-Stressed element Candidate for extraction
1C	Non-stressed element that was added to the mass domain to secure manufacturability

FE analysis of the build envelope → Build orientation determination → Top-down geometric optimization → AM manufacturable optimized part

[A. K. Lianos, H. Bikas, P. Stavropoulos, "A Shape Optimization Method for Part Design Derived from the Buildability Restrictions of the Directed Energy Deposition Additive Manufacturing Process", (2020)]

PBF Design Optimization methods: AM optimiser

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3. Top-Down geometric optimization
Rule 1: HB Ratio

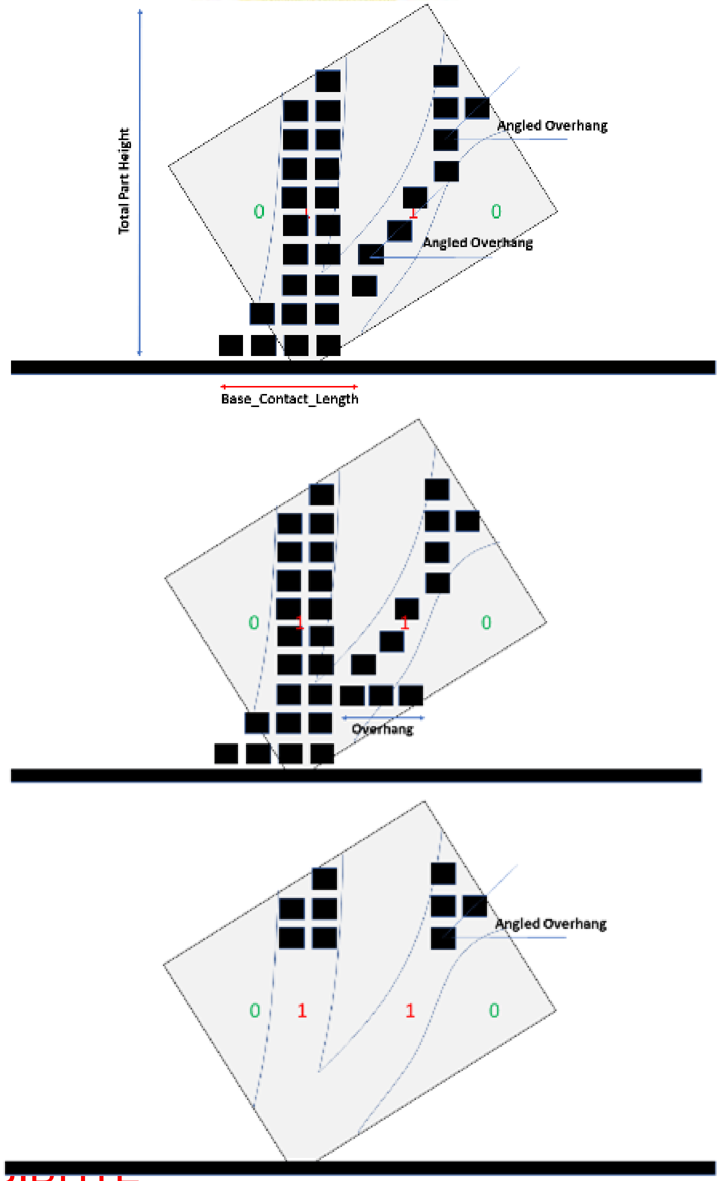
- Ratio of total base area to total part height
- Used as a mechanical connection to the build plate
- Used as a heatsink to the build plate
- Threshold to be experimentally determined for each process/material

Rule 2: Overhang length

- Maximum length of a unsupported structure
- Threshold to be experimentally determined for each process/material

Rule 3: Overhang angle

- Maximum angle of a unsupported structure
- Threshold to be experimentally determined for each process/material



HB ratio

Overhang

Overhanging angle

PBF Design Optimization methods: AM optimiser

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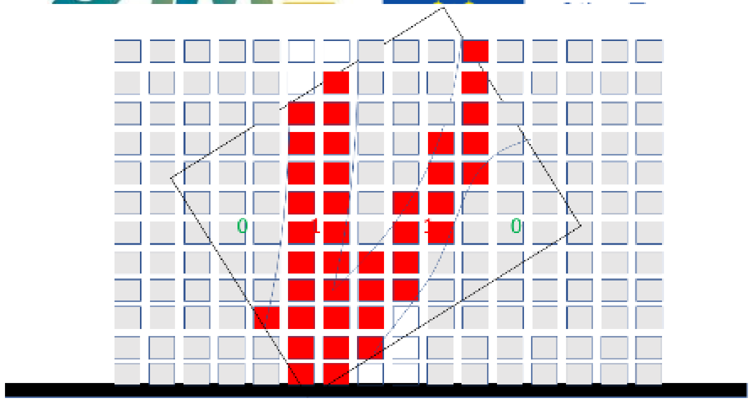
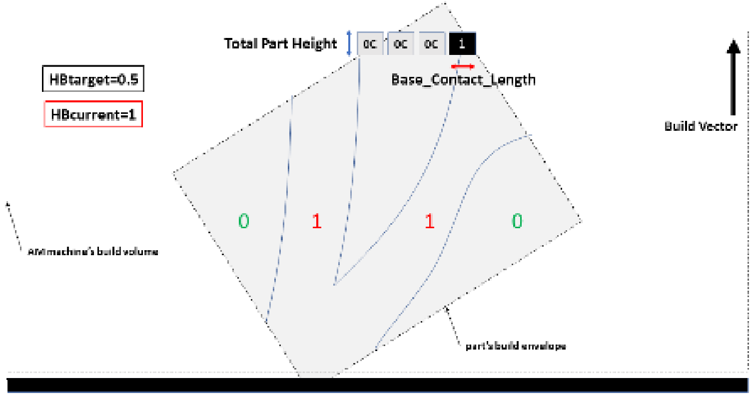
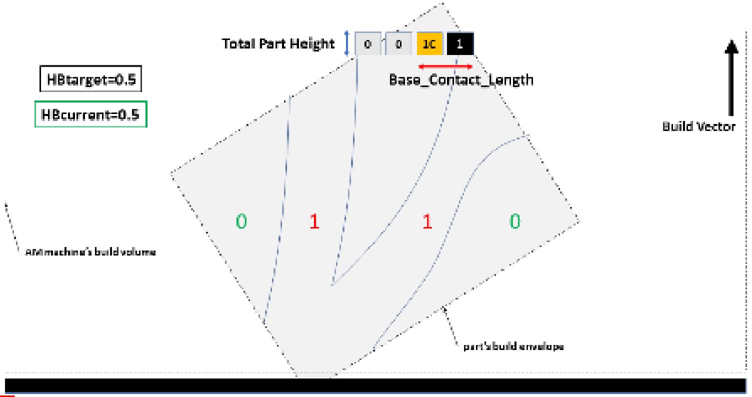
3. Top-Down geometric optimization

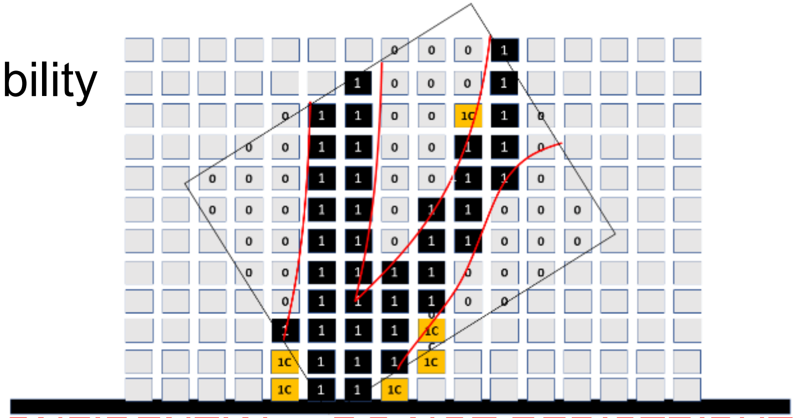
- The only factors morphing the part are the target HB ratio and the elements that are loaded
- The loaded element gets a value of 1
- The rest get a value of 0C
- DfAM rules are checked
- Candidate elements needed for manufacturability change their status from 0C to 1C
- Newly calculated domain now consists of
  - 0, 0C (material is subtracted)
  - 1,1C (material remains)

- 1C elements increase manufacturability









PBF Design Optimization methods: AM optimiser

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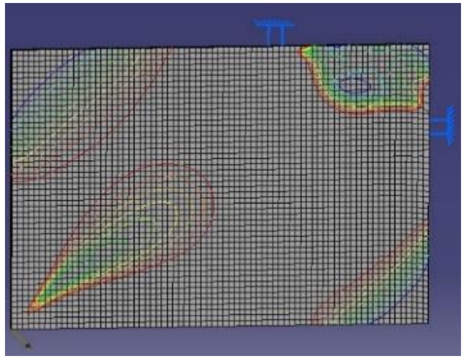
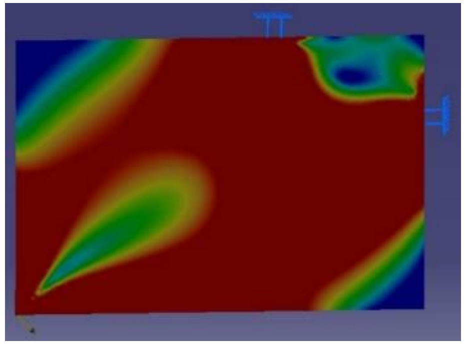
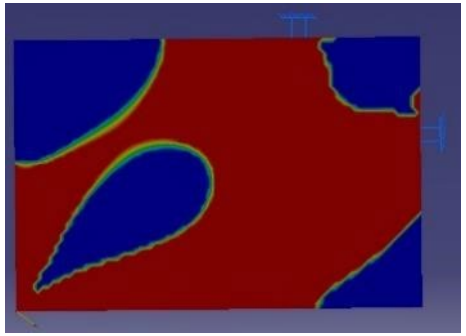
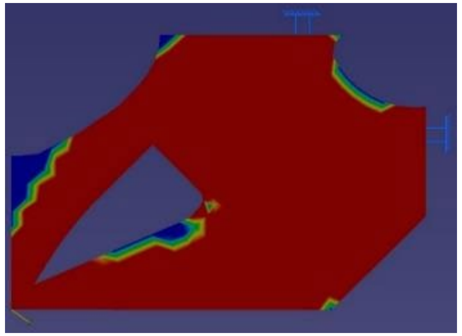
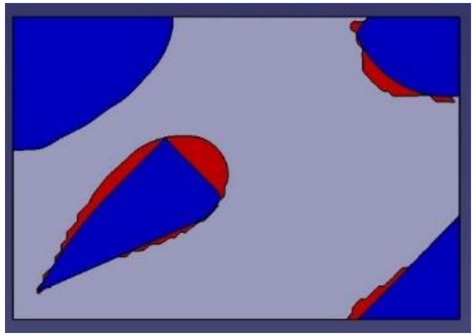


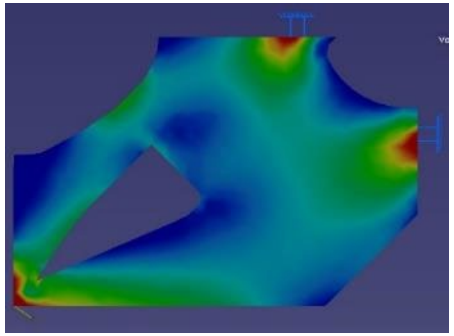


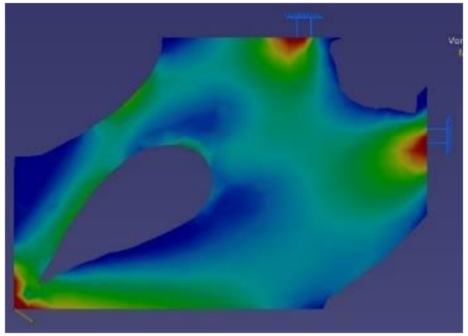
- Simplified 2D cross-section of a part under load
- 100x150mm with a load case of F_x=10N and F_y=-7.5N
- **Results:**
  - Differences on overhangs in the lower left and upper right corners
  - TMI = 95.0%
  - Added material serving AM Manufacturability is far less than the material used for the part to receive the developed stresses
- **Conclusions:**
  - Method compensates for both optimal material distribution based on load-case and manufacturability for AM at early design stages
  - Resulting geometry is not 100% material optimized as additional voxels are used to secure manufacturability
  - Additional design aspects/rules for specific AM technologies can be integrated











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Agenda

- Introduction to DfAM
- Design aspects for PBF
- Design limits determination
- Design guidelines
- Design optimization methods
- Conclusions

SAM: Conclusions

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- In this presentation all the aspects of designing a part in order to be manufactured with PBF processes have been presented
- It is very important to understand the mechanisms of the process and the machine specifications in order to extract the most from the process
- However, the user has to be sure about the functionalities of the part in order to be happy with the final part of an PBF process.
- The well-known benefits of a part which have been made with AM, have been improved further by investigating optimization techniques such as Topology Optimization and Generative Design
- The future of PBF process and the related outputs depends mostly on these techniques as well as on the improved performance of machines in order to be capable to provide satisfactory products.

SAM: Conclusions

- Do tests to determine the limits of the machine & material combination, using standard test artefacts
- Scale/oversize/undersize features based on the obtained results from testing
- Pockets and height should be an integer multiple of layer thickness
- Avoid sharp edges (stress concentration) and add fillets/ribs

Thickness

- Recommended thickness depends on the machine and material
- For PA 12, a recommended minimum wall thickness is 1 mm
- Maintain a consistent wall thickness design along the whole part

Holes or gaps

- Avoid holes with a small diameter because the powder inside the holes can become fused.
- It is recommended to design holes with a minimum diameter of at least 1 mm.
- It is typically recommended to increase a hole diameter by 2% to 4% for holes up to 10mm.
- If the accuracy of a hole diameter is critical, the hole can be 3D printed undersized with enough perimeters to drill through, especially under 3mm (Higher accuracy of the drill diameter)

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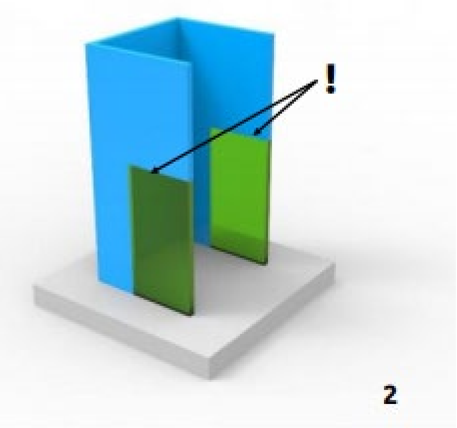
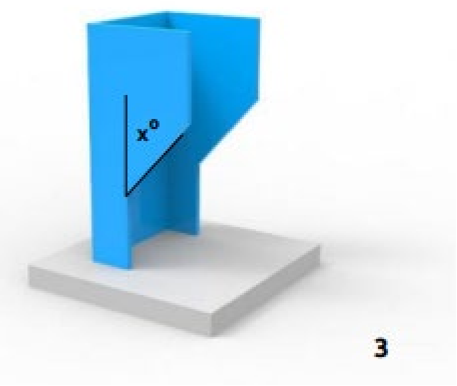
❖ Angles and overhang

- In general, supports are not neeeded in most cases of overhangs
- Reduce need for supports via design or with correct orientation of the part
- Orient the part correctly against the passage of the recoater
- Machine the small details to avoid difficult to remove supports.



❖ Part orientation

- Orient the part to obtain sufficient strength (consider anisotropy)
- Orient the part to ensure holes and bores are vertical if possible
- Orient the part to improve surface finish
- Orient the part to minimize supports (if not feasible, splitting the part might be an option)



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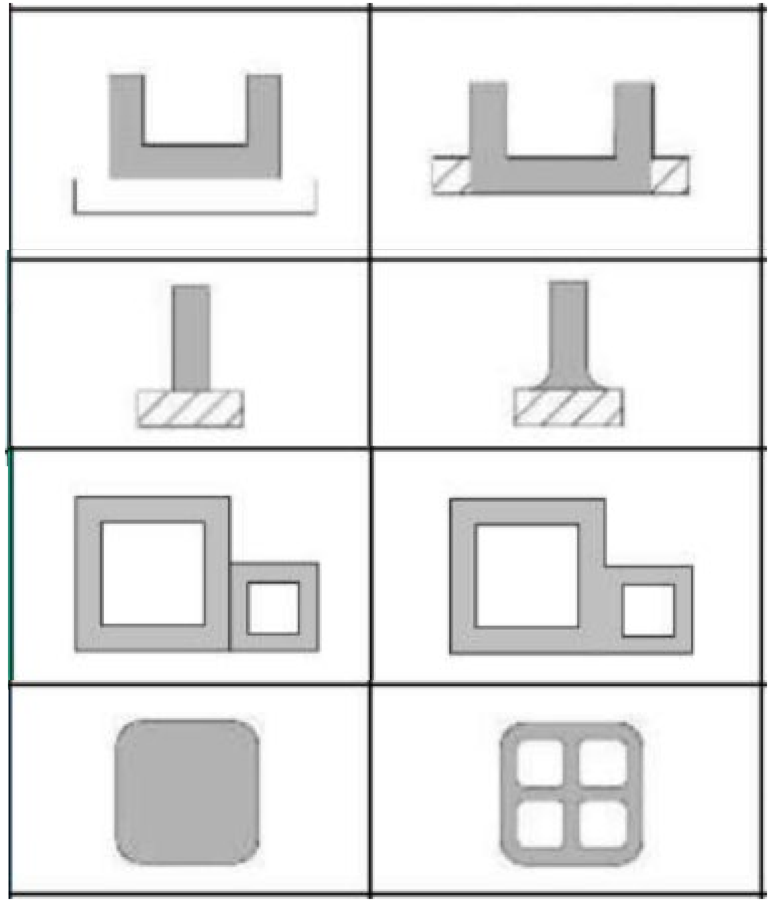

Leverage build plate

Improve connection with the manufacturing platform

Join components in just one

Reduce part mass with infil structures

SAM: Conclusions

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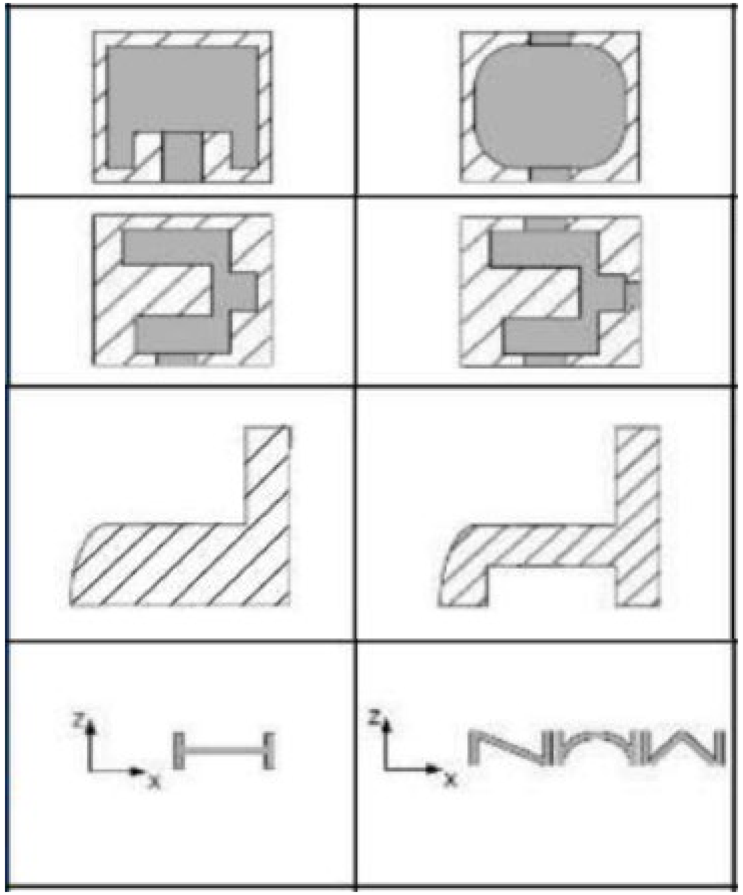


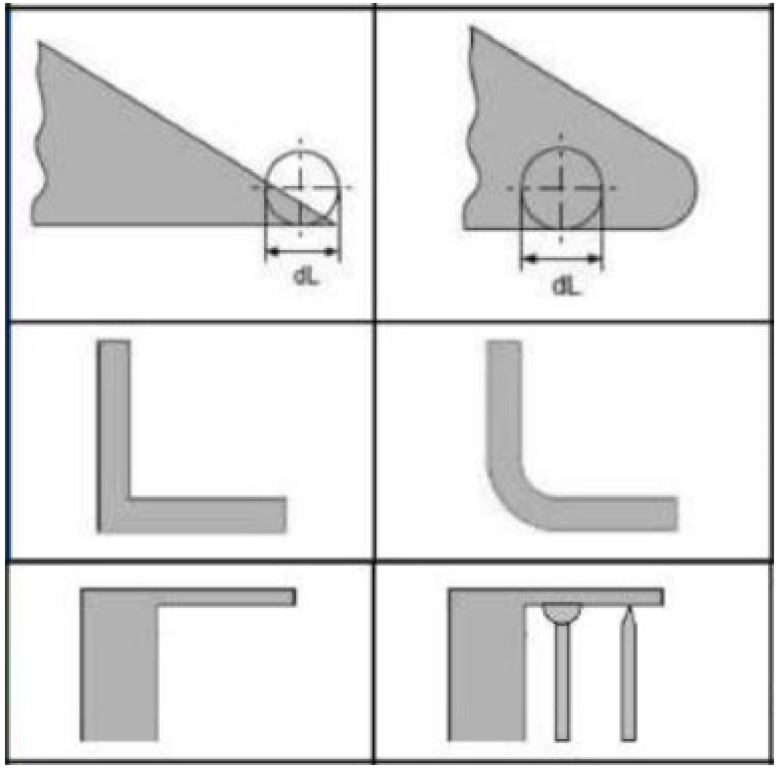
Designs that favor dust extraction

Consider multiple extraction points on complex geometries

Reduce component mass by clever design

Avoid large horizontal sections

SAM: Conclusions



Consider the focal diameter of the laser

Avoid geometries that reduce residual stresses

Consider structures that favor the extraction of heat

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- ❖ Include a 45^{o} degree chamfer or radius on all edges of an PBF part touching the build plate.
- ❖ Do not forget to add an escape hole in order to remove the unsintered powder off the part
- ❖ If part needs to be split, pay attention to aligning features and design for bonding.
- ❖ Consider bolted connections only when disassembly is needed.
- ❖ Plastic threads are weaker and not suitable for multiple cycles.
- ❖ Polygon/model resolution when converting to STL is important for the final quality of the part
- ❖ Many repair tool for watertight shapes and STL check exist and for each tool there are several examples on how to deal with common issues. Some of the tools are:
- Microsoft STL repair (Netfabb),
- Meshmixer, Meshlab,
- 3D Builder

Overall Comment

- ❖ Splitting a model, re-orientating holes, and specifying build direction are all factors that can lower cost, speed up the printing process, and improve the strength and print quality of a design.

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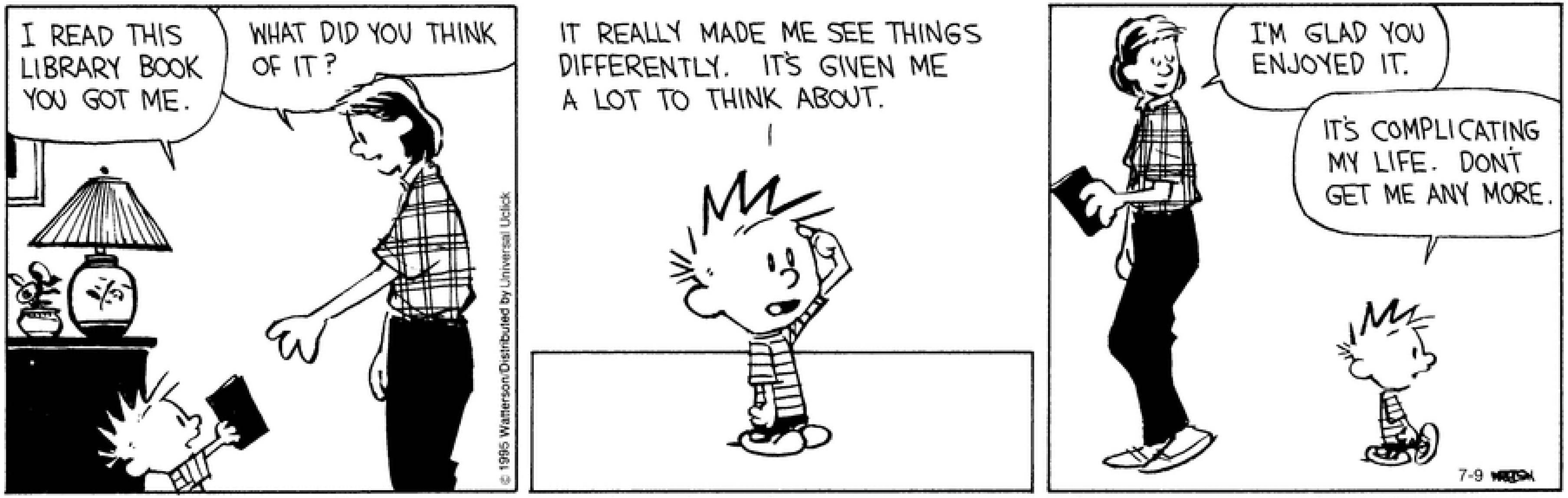
Questions?



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