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INDUSTRIAL EXPERT

INDEX: Industrial Expert

Additive Manufacturing – Intermediate Module

About the course

The intermediate course starts with a detailed explanation of the general process of additive manufacturing (AM) and a brief look at its history. Afterwards, the course participant learns how to select the right AM process based on various framework conditions (e.g. required physical or optical properties of a component). Before moving on to detailed explanations of all relevant AM processes, the participant dives into the basis of AM: The 3D model itself. There, the participant learns about the most important properties that a 3D model must have in order to be printed successfully. Once the final 3D model has been exported, the various AM processes come into play. In this course, all relevant AM processes are explained in detail with their advantages and disadvantages. At the end of the course, the participant learns about the potential value of AM for companies and what opportunities AM offers.

Format

The form of education is e-learning with aprrox. 40 hours of lessons and 40 hours of self-studying. Weekly lessons include lectures, thematic videos and performing test tasks. An important part of this course is performing final exam in the form of multiple choices quiz, which contains answers based on study material. The course is set up in compliance with the ECVET System with possibility to obtain the Certificate of attendance.

Who can take this course

This course does not require any specific knowledge on Industry 4.0 and is designed for an audience, who want to learn about 4th Industrial revolution and smart technologies. This means, first of all, students (bachelors, masters), whose curricula include disciplines related to the industry 4.0 as well as specialists and mangers in the various application areas of smart technologies. The course will be of particular interest to:

- senior executives or a development department manager of your enterprise interested in the possibilities that additive manufacturing offers and whether the implementation could be useful
- professionals interested in choosing the right additive manufacturing process
- founders who want to quickly generate prototypes and functional models of their idea or want to build their entire production line on additive manufacturing
- engineers who want to get a deep understanding of additive manufacturing
- educators teaching graduate and postgraduate courses focusing on additive manufacturing
- students or postgraduates interested in additive manufacturing
- Hobbyists who want to expand their knowledge of additive manufacturing

Programme of the course

- 1. AM Process
- 1.1 Introduction into the processes of Additive Manufacturing methods
- 1.2 Choosing the right manufacturing technology
- 2. 3D Modelling/ CAD

- 2.2 3D modelling tools - Professional and free to use
- 3. Material extrusion
- 3.1 FDM
- 4. Photopolymerization
- 4.1 SLA
- 4.2 DLP
- 5. Powder bed fusion
- 5.1 MJF
- 5.2 EBM
- 5.3 SLS
- 5.4 SLM
- 6. Directed energy position
- 6.1 DED
- 7. Binder jetting
- 7.1 BJ
- 8. Material jetting
- 8.1 MJ
- 9.Value for your company
- 9.1 New possibilities in design and topology optimization

Course staff

Andreas Jahr

Professor of design theory and mechanics and director of the Institute for Product Development and Innovation (FMDauto) at Düsseldorf University of Applied Sciences, previously head of development, design and research in several mechanical engineering companies. Dr.-Ing. at RWTH Aachen University. R&D in the field of general and mechatronic product development. E-mail address: andreas.jahr@hs-duesseldorf.de

Lennard Müller

Research assistant at the Institute for Product Development and Innovation (FMDauto) at Düsseldorf University of Applied Sciences since 2019. Previously tutor in the area of production planning and control systems. E-mail address: lennard.mueller@hs-duesseldorf.de

Sven Markus

Research assistant at Institute of Product Development and Innovation (FMDauto) at the University of Applied Sciences Düsseldorf since 2021. Before graduating with a bachelor's degree, employed as a student assistant at FMDauto as part of several projects since 2019 as well as a technical product designer specializing in machine and plant design since 2017. E-mail address: svendavid.markus@hs-duesseldorf.de

Results

As the result of completing the Additive manufacturing intermediate level course, learners will know:

- how 3D models are created and what is important when creating 3D models with regard to additive manufacturing as a downstream process
- all relevant additive manufacturing, as well as their function and application
- materials and their properties and under which framework conditions they can be used
- possible production volume in additive manufacturing technologies
- advantages and disadvantages of the different additive manufacturing processes.

Competences

By completing the Additive manufacturing intermediate level course, learners will be able:

- to decide which additive manufacturing technologies are potentially interesting for the intended application
- to decide which of the different AM technologies will be the best for their use case and what problems and opportunities will occur
- to describe the different processes of additive manufacturing technologies

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Additive Manufacturing - Intermediate Module

Process of AM
Introduction into the Processes of Additive Manufacturing Methods

The Intermediate Course of Additive Manufacturing

Process of AM

The objects produced by 3D printing processes can have almost any shape or geometry. They are typically produced using digital model data from a 3D model or other electronic data source such as an STL (STereoLithography) file, one of the most common file types that 3D printers can read. The term 3D printing originally referred to a process in which a binder material was deposited layer by layer onto a powder bed using inkjet print heads. More recently, the term 3D printing has come into common usage to encompass a broader range of additive manufacturing processes. Among professionals, the term additive manufacturing remains more popular due to its broader meaning and longer existence. Other terms are also used, such as desktop manufacturing, rapid manufacturing, direct digital manufacturing and rapid prototyping. The invention of additive manufacturing can be traced back to the 1980s to Japanese, French and American researchers. The very first patent for 3D printing was filed in 1984 by Chuck Hull of 3D Systems Corporation. Hull defined the 3D printing process as a system for building three-dimensional objects by creating a cross-sectional pattern of the object to be formed. His invention consists of a stereolithography manufacturing system in which layers are added by curing photopolymers with ultraviolet light lasers. Stereolithography remains a very popular 3D printing manufacturing technique, also known as SLA.

However, the technology used by most 3D printers in the 2010s, especially by hobbyists and consumer-oriented products, is fused filament fabrication (FFF). It is also known as material extrusion or fused deposition modelling (FDM), the proprietary name of Stratasys. FDM was patented by S. Scott Crump in 1989, shortly before he founded Stratasys with his wife, Lisa Crump. Metal 3D printing did not become available until the 1990s with the invention of laser melting and sintering. Selective laser sintering (SLS) and selective laser melting (SLM) can also be referred to as direct metal laser sintering (DMLS) and direct metal laser melting (DMLM) when metal is the processed material.

General Process:

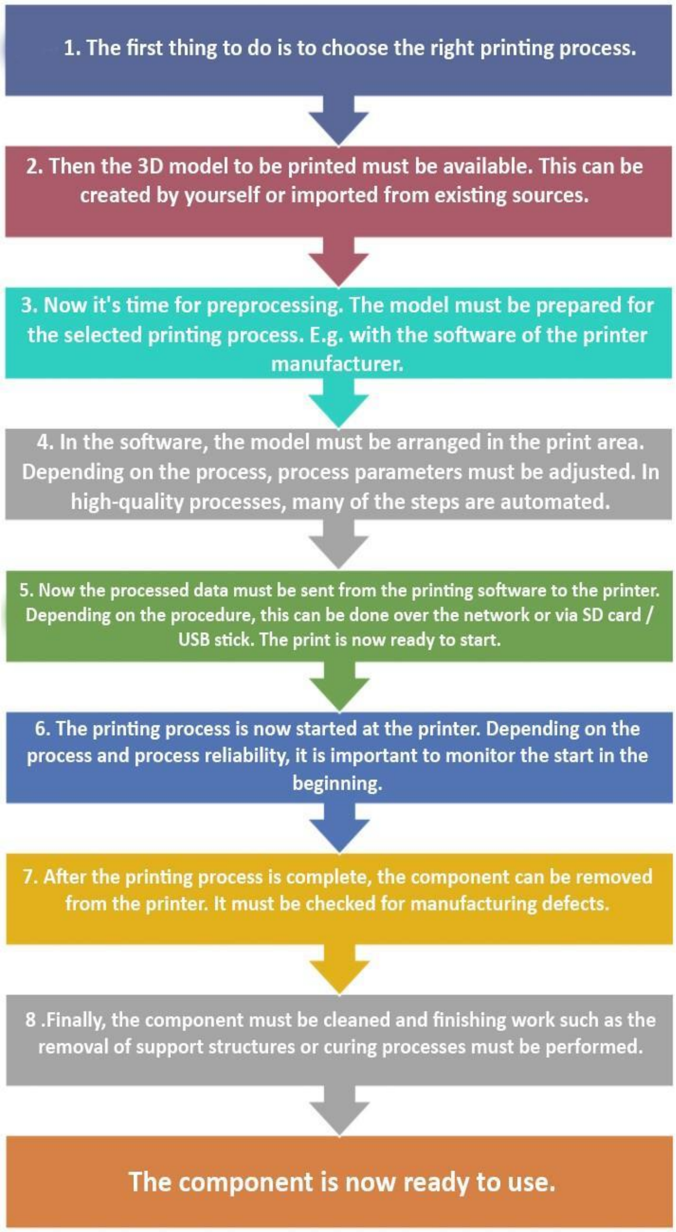

Figure 1. General process of AM. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

From an idea to part in one day

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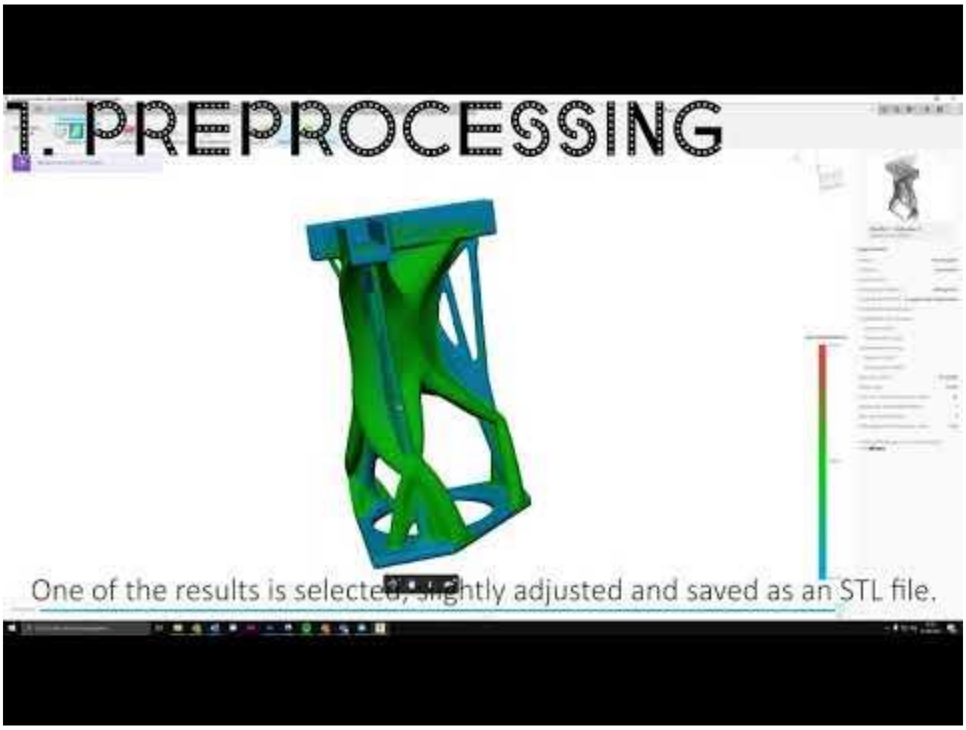


Choosing the right manufacturing technology

How do you choose the right 3D printing technology?

3D printing or additive manufacturing is an overall term that includes several processes. Most of them were developed in the 1980s-90s. Each 3D printing process has its advantages and limitations, and each suits better to a certain application than others. In this unit, we'll give you some easy-to-use tools to help you to choose the right 3D printing process for your needs.

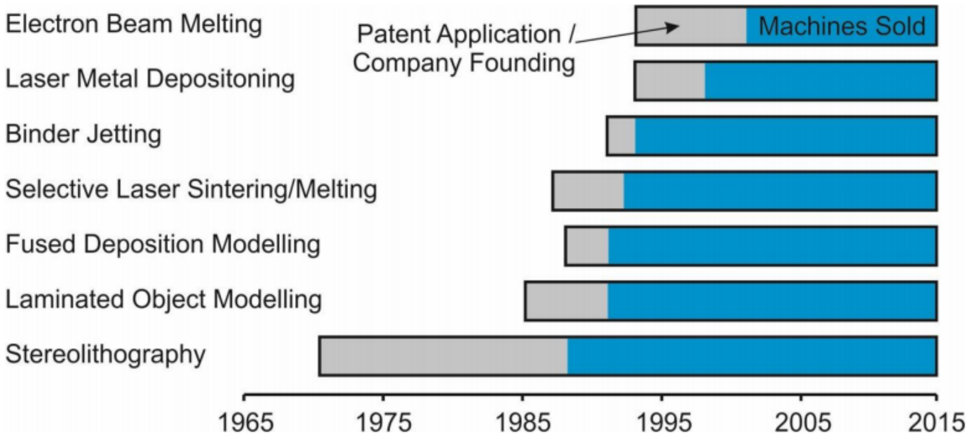


Figure 2. History of AM technologies. Source: B. Leutenecker-Twelsiek/Hochschule Düsseldorf.

Use the following figures and tables as a quick reference to identify the process that best meets your design needs.

Overview of relevant basic 3D printing technologies

- **(CJP)** Colour Binder Jetting | ColorJet ZPrinter 3D Printer for Concept Models

The ProJet CJP powder 3D colour printers, also known as ZPrinter and ColorJet 3D printers, offer a productive and cost-effective entry into 3D printing of full-colour communication models. They are also suitable for installation analysis and initial functional testing.

Figure 3. 3D Systems Projet CJP 660 Pro Printer results. Source: www.3dsystems.com

- **(MJP)** 3D Printer | MultiJet 3D Printer for Functional Prototypes.

The ProJet MJP photopolymer 3D printers use the MultiJet process and offer unbeatable detail resolution, smooth surface, high precision for 3D printing of functional assemblies and functional prototypes. The perfect departmental printer.

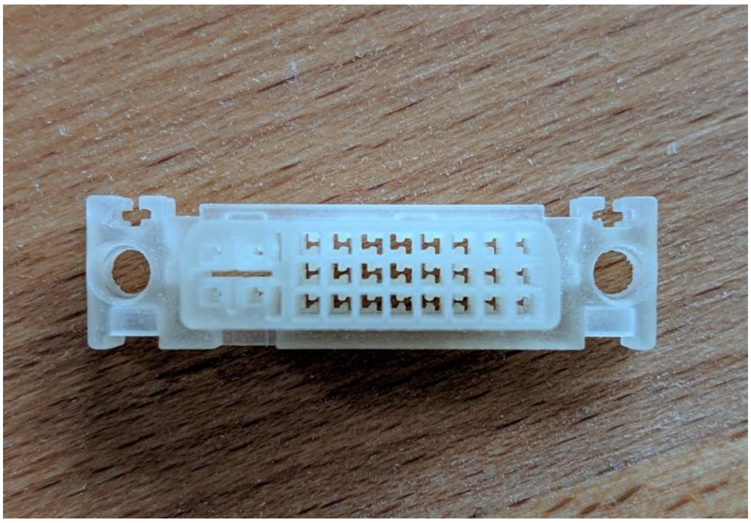


Figure 4. Highly detailed MJP Print. Source: L. Müller/Hochschule Düsseldorf.

- **(FDM)** 3D Printer | FDM for Functional Prototypes.

The FDM technology has attractive strength values in the strand direction and thus enables the printing of first functional prototypes.

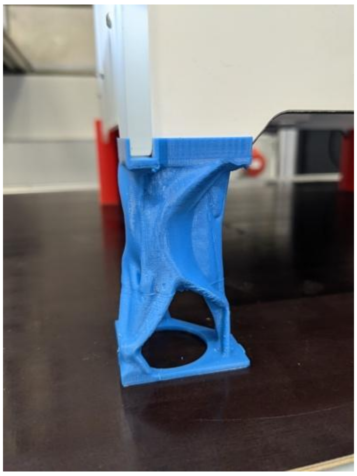


Figure 5. Quick and cheap FDM prototype. Source: L. Müller/Hochschule Düsseldorf.

- **(SLA)** 3D Printer | Stereolithography for functional prototypes and series parts.

The SLA stereolithography systems for functional prototypes and series parts are the entry into the world of PRODUCTION 3D printers and offer superior part quality and accuracy in generative layering. The wide range of materials from robust, flexible, black and transparent materials to dental, jewellery and high temperature materials qualify these 3D printers for a wide range of applications.

Figure 6. Formlabs SLA Printer. Source: www.formlabs.com

- **(MJF)** 3D printing systems | Multi Jet Fusion for prototypes, components and small series.

MultiJet Fusion technology fuses PLA plastic powders with superior productivity. With a shift time of 12 seconds / shift, independent of the number of parts to be printed, this technology produces plastic parts for final products and small series. High availability and perfect service.

Watch following video „PA12 part demonstration for MJF“

(This is an embedded video originally published on YouTube and complies with the standard YouTube license. If you want to re-use it, you should check the video owner’s copyright terms and conditions.)

- **(SLS)** 3D Printing Systems | Selective Laser Sintering for Series Parts.

The SLS Selective Laser Sintering in plastic and metal for end products and small series.

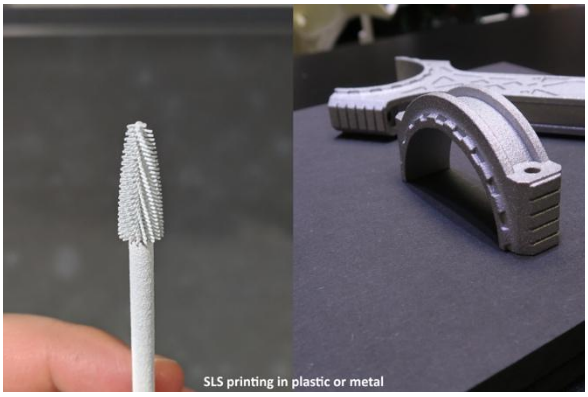


Figure 7. Possibilities of SLS printing with plastic or metal. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

Useful questions to help choose the right manufacturing technology

What's the purpose of the product?

It is important to determine early in the selection process whether the focus is on function or looks. This will greatly assist in selecting the most appropriate process. As a general rule of thumb, thermoplastic parts are better suited for functional applications, while thermosets are best for visual appearance. Some questions have to be asked to choose the right method.

Figure 8. Panton colour examples made out of thermosets by Stratasys. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

What functionality should the component have?

The flowchart below can help you identify the most suitable 3D printing process based on common design requirements for functional parts and prototypes. Technical constraints can dictate which process is most suitable.

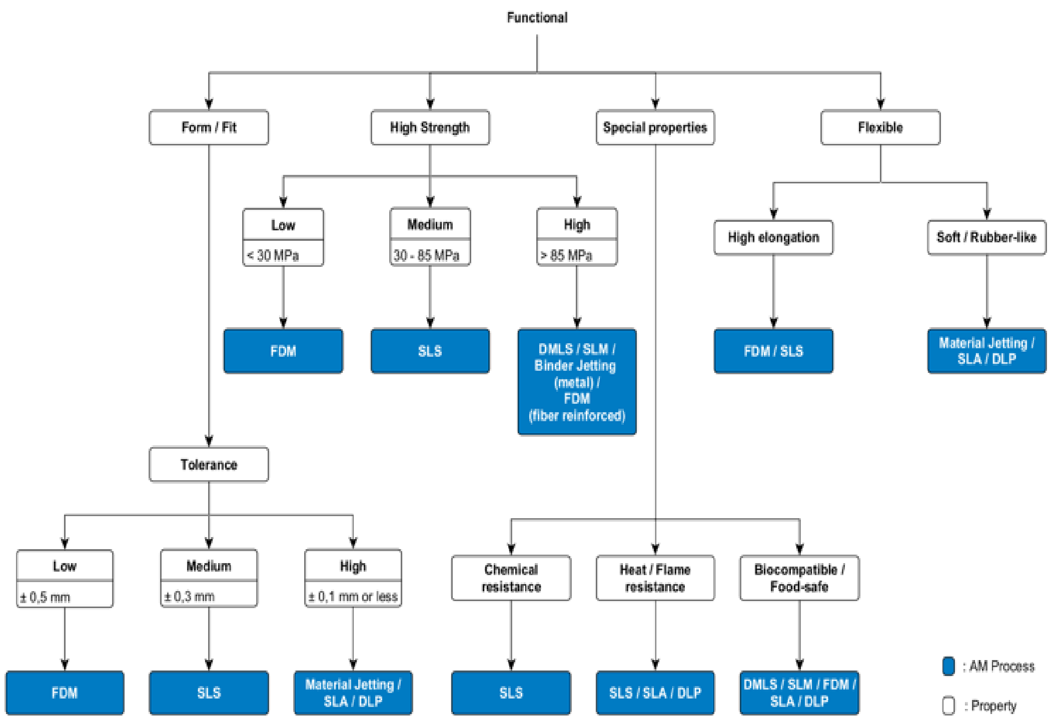


Figure 9. Decision tree by function. Source: (cc) BY-NC-SA S. Markus/Hochschule Düsseldorf.

Is the material already known?

3D printing materials usually come in filament, powder or resin form (depending on the 3D printing processes used). If the required material is already known, selecting a 3D printing process is relatively easy, as only a few technologies produce parts from the same materials.

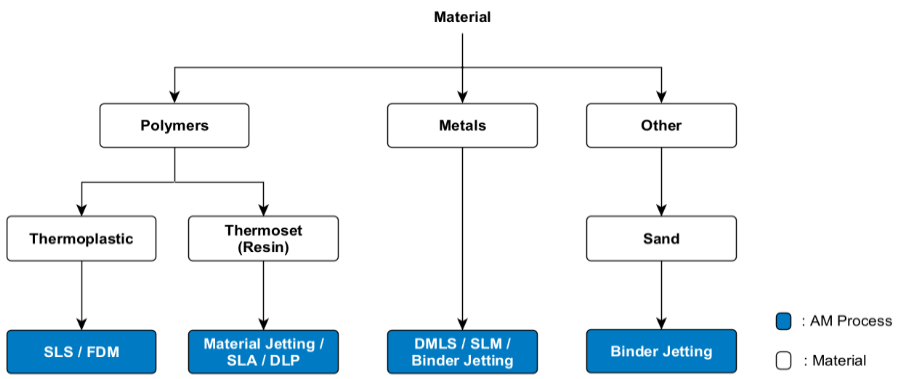


Figure 10. Decision tree by material. Source: S. Markus/Hochschule Düsseldorf.

How important is the design and appearance?

If you want to create visual models it is especially important to know which procedure leads to which result. Is it only about geometry or should colours etc. also be visible?

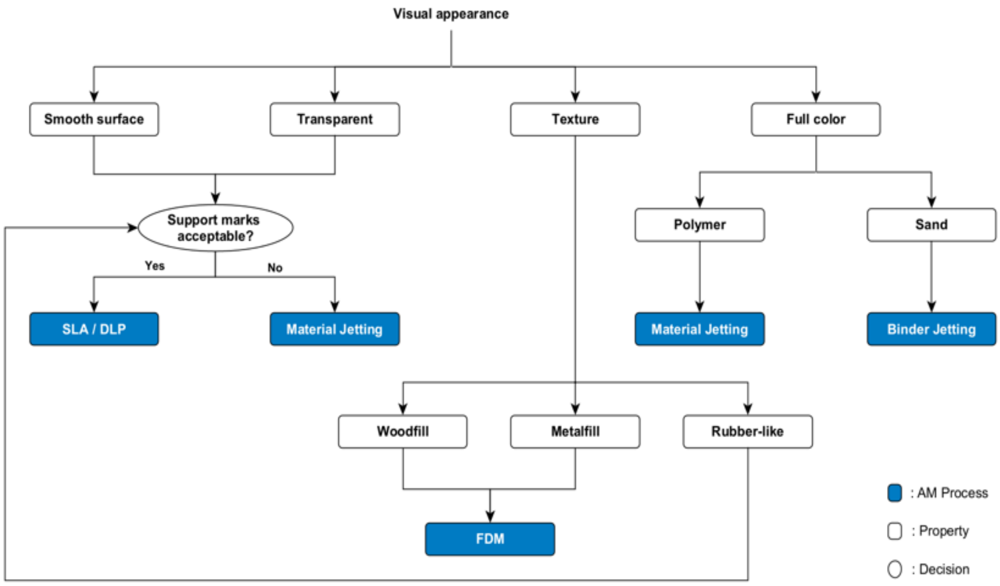


Figure 11. Decision tree by visual appearance. Source: S. Markus/Hochschule Düsseldorf.

How important are the costs and what volumes should be produced?

The following figure shows commonly used thermoplastics for 3D printing. The higher the material is positioned in the pyramid, the better its mechanical properties. In general, the better mechanical properties go hand in hand with higher demands on the printing technology.

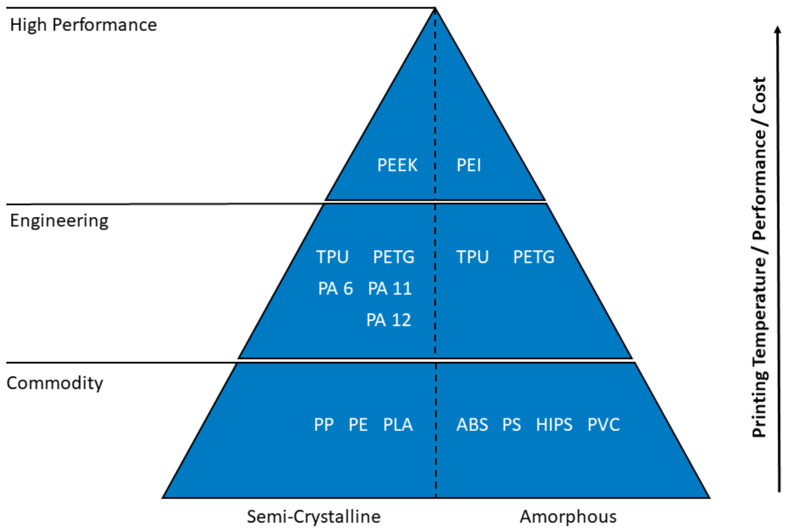


Figure 12. Material Pyramid. Source: (cc) BY-NC-SA S. Markus/Hochschule Düsseldorf.

Are there any specific requirements for the accuracies and sizes?

If you are printing for technical purposes, keep in mind that not every procedure reaches the same quality. Some procedures have a higher resolution or are particularly well suited to certain sizes.

Here is a rough overview of some of the most important boundary conditions and characteristics:

	Process	Stereolithographie	Digital light processing	Poly-jet modeling	Multi jet modeling	Selective laser sintering	Selective laser melting	Electron beam melding	Fused deposition modeling
	Acronym	**SLA**	**DLP**	**PJM**	**MJM**	**SLS**	**SLM**	**EBM**	**FDM**
Properties	Physical effect	Photopolymerisation	Photopolymerisation	Photopolymerisation	Melting	Sintern	Melting	Melting	Melting
Geometry generation	Beam	x	x			x	x	x	
Topology	Printhead			x	x			x	x
	Point	x		x	x	x	x		x
	Line							x	
	Surface		x						
Production	Volume	Mid	Low	Mid	High	High	Mid	Mid	Low
	Dimensional accuracy	± 0.5% (lower limit: ± 0.10 mm) - desktop ± 0.15% (lower limit ± 0.05 mm) - industrial		± 0.2 mm (± 0.3 mm for sand printing)	± 0.1% (lower limit of ± 0.05 mm)	± 0.3% (lower limit: ± 0.3 mm)	± 0.1 mm	± 0.25%	± 0.5% (lower limit ± 0.5 mm) - desktop ± 0.15% (lower limit ± 0.2 mm) - industrial
	Typical build size	145 x 145 x 175 mm for desktop Up to 1500 x 750 x 500 mm for industrial printers		400 x 250 x 250 mm (up to 1800 x 1000 x 700 mm)	380 x 250 x 200 mm (up to 1000 x 800 x 500 mm)	300 x 300 x 300 mm (up to 750 x 550 x 550 mm)	250 x 150 x 150 mm (up to up to 500 x 280 x 360 mm)	300 x 450 x 500 mm	200 x 200 x 200 mm for desktop printers Up to 900 x 600 x 900 mm for industrial printers
	Support	1500 x 750 x 500 mm for industrial printers		Not required	Always required (always dissolvable)	Not required	Always required	Not always required	Not always required (dissolvable available)
	Typical layer thickness	25 - 100 µm (most common: 50 µm)		100 µm	16 - 30 µm (most common: 16 µm)	80 - 120 µm (most common: 100 µm)	30 - 50 µm	50 µm	50 - 400 µm (most common: 200 µm)

Figure 13. Boundary conditions of AM technologies. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

Printing services

List of World Wide 3D Printing Services

If you want to try out 3D printing for yourself without investing directly in a printer you can easily upload a model online and print it. Providers such as Materialise, Shapeways and 3faktur provide quick cost estimates and quotes.

3D Printing Service	Shipping	Materials
3D Hubs	Worldwide	PLA, ABS, ASA, TPU (FDM), Resin, Nylon (MJF/SLS/FDM), Nylon 12-GF (SLS/MJF), PA 12-FR, PA 11 (MJF), HST, PETG (FDM), PEKK, Stainless Steel, Aluminum, Titanium
3D Print-Au	Australia, New Zealand	Nylon (SLS)
3D Printing Ally	Worldwide	ABS, Polycarbonate PC (FDM), Ultem, Nylon (SLS), Resin
3D Systems On Demand	Worldwide	ABS, Nylon, PA 11 (SLS/MJP), Polypropylene PP (SLA/MJF/SLS), Resin, Titanium, Stainless Steel, Maraging Steel, Cobalt-Chrome, Aluminum, Nickel, castable Wax
3DExperience Marketplace Make	Worldwide	PLA, ABS, PC ABS, ASA, PEI, PET, TPC, HIPS, TPU (FDM/MJ/SLS), TPE (FDM/SLS), PETG, Woodlike PLA, PEEK, PEKK, Nylon (FDM/SLS), PA 12-GF (SLS), Resin, Tough Resin, Polypropylene PP, ULTEM, Steel, Aluminum, Stainless Steel, Steel, Nickel, Cobalt, Titanium, Zinc, Copper, Silver, Gold, Titanium, Platinum, Castable Wax, Synthetic Sand
3Diligent	Worldwide	ABS, Ultem, PC-ABS, Polycarbonate PC (FDM), Nylon (FDM/MJF/SLS), PA 12-GF (SLS), Resin, Aluminum, Stainless Steel, Titanium, Nickel, Inconel, Paper, Sandstone
AutotivMFG	USA	Nylon (SLA/SLS/MJF), PA 12-GF (SLA/SLS/MJF), PLA, Resin, TPU (SLS), Ultem, Aluminum, Titanium

Beamler	Worldwide	ABS (FDM), TPU (FDM, SLS), TPE (SLS), PC (FDM), Nylon (FMD, SLS, MJF), PA 11 (SLS), Sand, Polymer (CLP), Silicone (SLA, DOD), Aluminum, Copper, Stainless steel, Tungsten, Tungsten carbide, Ceramic (SLA)
Beta Layout	Worldwide	Nylon (SLS), PA 12-GF (SLS), PEE, Alumide, Stainless Steel, Inconel, Cobalt Chrome
Craftcloud	Worldwide	PLA, ABS, PC-ABS, Nylon (FDM/SLS), PA 12-GF (SLS), PA11-CF (SLS), PA 11 (SLS/MJF), Resin, ASA, HIPS, PMMA, TPU (FDM, MJF), PPSU, Woodlike PLA, PETG (FDM/SLS), TPU (SLS), Polypropylene PP, ULTEM, Stainless Steel, Maraging Steel, Sterling Sliver, Aluminum, Alumide, Brass, Plated Brass, Copper, Gold, Titanium, Platinum, Wax, Multicolour, CNC-Milling
FacFox	Worldwide	PLA, ABS, TPU (SLS), ASA, Ultem, Nylon (FDM/SLS/MJF), PA 12-GF (SLS), Resin, Photopolymer PP, Stainless Steel, Bronze, Aluminum, Titanium, Maraging Steel, Cobalt Chrome, Sandstone
Fast Radius	Worldwide	ABS, PC, PC-ABS, ULTEM, ASA, PC-ISO, PPSF, Nylon (FDM), Resin (SLA, DLS), Nylon 12-PA (SLS), PP, Nylon 12-GF (SLS), Stainless Steel (L-PBF), Aluminum (L-PBF), Inconel (L-PBF), Titanium (L-PBF), Cobalt Chrome (L-PBF)
Fathom	Worldwide	ABS Ultem, Polycarbonate PC, ASA, TPU (FDM), Resin, Nylon (MJF/FDM), Acrylic, Nylon (SLS)
HK3DPrint	Worldwide	ABS, Nylon (SLS), Polycarbonate PC, Photopolymer PP, Resin
i.materialise	Worldwide	ABS, TPU, Nylon (SLS/MJF), Alumide, Polypropylene PP, Resin
Jawstec	USA, Canada, Mexico	Nylon (SLS, MJF), PA 12-GF (SLS)
Jomatik	Worldwide	Nylon (SLS), ABS, PMMA, TPE, Resin
Kraftwurx	Worldwide	ABS Plus, Ultem, Polycarbonate PC, Photopolymer PP, Nylon (SLS), Gold, Aluminum, Stainless Steel, Bronze, Ceramic, Copper, Acrylic, Palladium, Casting Wax

Materialise OnSite	Worldwide	ABS, Polycarbonate PC, PC-ABS, Ultem, Nylon (SLS/MJF), Polypropylene (PP), TPU (SLS), PA 12-GF, PA 12-FR, Alumide, Aluminum, Stainless Steel, Titanium, Inconel
Protolabs	Worldwide	ABS, Nylon (SLS/MJF), Polycarbonate PC (SLA), Polypropylene PP (SLA), Digital Photopolymer, Aluminum, Copper, Stainless Steel, Titanium, Inconel
Sculpteo	Worldwide	Nylon (SLS/MJF), PA12-GB, PA12 Carbon, PEBA, TPU, Alumide, Resin, Stainless Steel, Aluminum, Titanium, Brass, Bronze, Silver, Plated Metal
SD3D	Worldwide	PLA, ABS, PETT, PET+, PC-ABS, CF-PLA, CF-ABS, CF-PETG, CHETAH, PCTPE, FLEXSOLID, TPU, Nylon (SLS)
Shapeways	Worldwide	Nylon (SLS/MJF), PA 11, PA 12-GB (SLS/MJF), Resin, TPU (SLS), Aluminum, Steel, Plated Metal, Brass, Silver, Gold, Bronze, Sandstone
Star Rapid	Worldwide	Titanium, Steel, Aluminum, Maraging Steel
Stratasys Direct	Worldwide	ABS, ASA, Nylon (MJF/SLS), PA 12-GF (MJF/SLS), PC, PEKK, PPSF/PPSU, TPE, ULTEM, Resin, Aluminum, Cobalt Chrome, Copper, Inconel, Monel, Steel, Titanium
Treatstock	Worldwide	PLA, ABS, Nylon (SLS/FDM), Stainless Steel, TPU, Titanium, Aluminum, Brass, Polycarbonate, Castable Wax, PETG, Resin, Cobalt-Chrome
WeNext	Worldwide	Resin, Nylon (MJF, SLS) PA12-GF
WhiteClouds	No reply to our request	Nylon, Resin, full-colour Sandstone
Xometry	Worldwide	ABS, Nylon (SLS/MJF), PA 12-GF (SLS/MJF), Resin, Polycarbonate PC, Ultem, Stainless Steel, Aluminum

Table 1. List of 3D printing services. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

Quiz

Suitable AM technologies

Which technology is best suited for creating small series from PLA with a prior internal development process?

☐ SLA.
☐ MJP.
☐ MJF.
☒ FDM.

3D Modeling Tools - Professional or Free to use

3D-Data and Systems

Since additive manufacturing is a manufacturing process like any other, it is closely linked to industry and research. Therefore, you need a basic knowledge of 3D modelling and file extensions.

In this unit a short introduction to CAD Systems is given. The computer software used to design and manufacture products is called computer-aided design (CAD) or computer-aided manufacturing (CAM) software. CAD programs are used for design and documentation. On the other hand CAD/CAM systems can handle both the design and manufacturing processes, such as CNC and additive manufacturing. Usually, the design and the manufacturing processes are iterated until a desirable product is achieved. By considering the limitations of the layer-by-layer process, the number of iterations and modifications can be reduced.

For deep design knowledge you need to be proactive. But we will now show you the most important things. When you first start with additive manufacturing you need to know that the STL file format is the most important. It is suitable for most printing processes. The disadvantage of this high flexibility is that STL files cannot be easily edited or modified. For modifying 3D files other formats like STEP or IGES are preferred. Many software manufacturers have proprietary file formats that can only be processed with their software.

More informations: https://transmagic.com/choosing-the-best-cad-file-format/

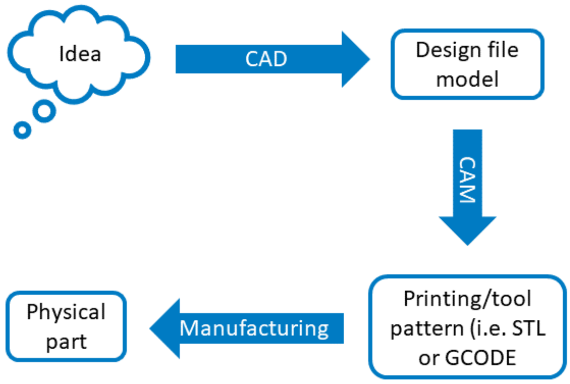


Figure 1. From the idea to the part. Source: (cc) BY-NC-SA L. Mueller/Hochschule Düsseldorf.

STL - Simple and nothing more

Ever since its invention, the STL (**S**tandard **T**riangulation/Tessellation **L**anguage) file format has been adopted by the rapid prototyping, 3D printing, and computer-aided manufacturing industries. It is still the most widely used file format in 3D printing. STL has the advantage and disadvantage that it only stores geometry information as polygons. This makes it very compatible, but also very simple and stupid. Ideal for exchanging files to print and protect them from modification. Easy to read, hard to edit. The format of choice in additive manufacturing unless you want to continue designing.

More information about STL: https://en.wikipedia.org/wiki/STL_(file_format)

Where to find 3D Models?

Where can I find suitable 3D data and models? To get started, it is recommended to look at websites that are specially designed for 3D printing.

The following websites are specialized in printable models.

https://www.thingiverse.com/
https://cults3d.com/en
https://www.cgtrader.com/
https://www.myminifactory.com/

You should always consider in which file format the models are offered, which licences they have and do they cost anything. Many of the models are from hobby designers and do not necessarily meet industrial standards. Nevertheless, the extensive search functions of the pages and the large offer are a good and convenient start. Many models are designed for printing with FDM printers, as these are particularly inexpensive and widely used by hobbyists.

Feel free to try our INDEX related files:

https://www.thingiverse.com/thing:4841877

https://www.thingiverse.com/thing:3977680

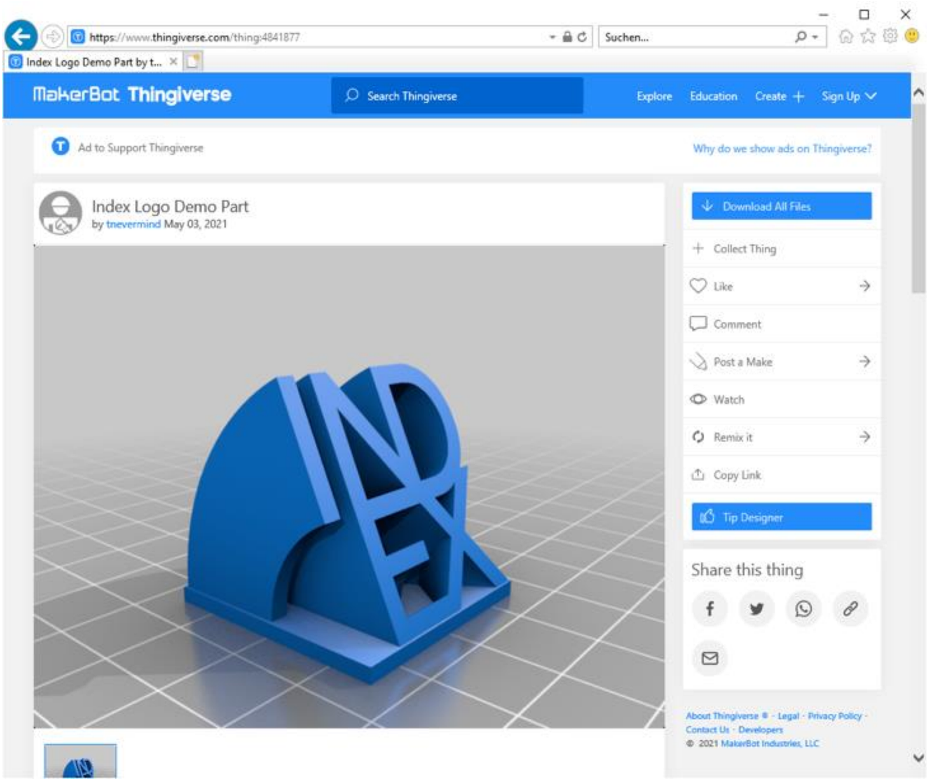


Figure 2. INDEX Logo STL-Data. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

If you are already an advanced user or looking for more professional sources of CAD data, the following websites are recommended as classic databases for professional use. In addition, manufacturers of technical components often offer the corresponding CAD files for their parts. The best known, for example, is the company 'Item' with its aluminium profiles.

The following websites are excellent if you are looking for standard parts or other professional parts:

https://www.traceparts.com/
https://www.3dfindit.com/
https://grabcad.com/

When using these websites, it is important to pay attention to whether the components must be purchased or are free to use. Sometimes the licences of the components are also free for private use, but not for business use.

Which CAD Program to use?

Beginner (Free to use): TinkerCAD

Tinkercad is ideal for absolute beginners and browser based.

Intermediate (Free to use): FreeCAD

FreeCAD is a free and open-source general-purpose parametric CAD program.

Advanced (Free trial): Fusion 360

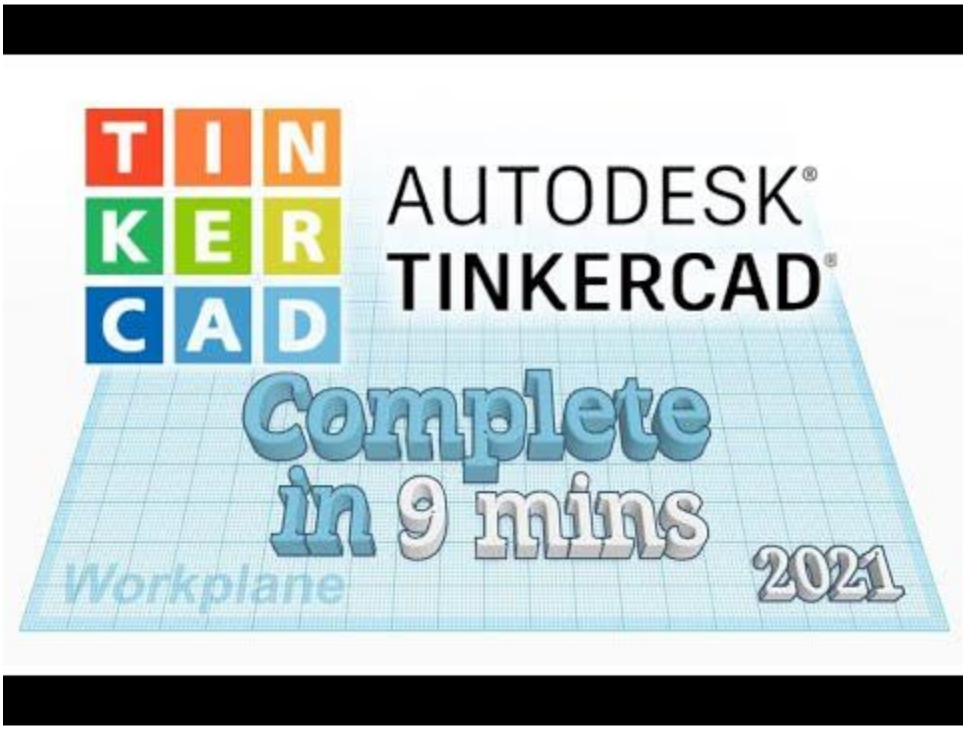
Fusion 360 is a cloud based CAD Software with free trial and generally free for students.

Enterprise: Onshape, Creo, Solidworks, Catia

Highly professional tools, recommended just for enterprises .

If you want to get started with Tinkercad or Fusion 360, the following videos are recommended.

TinkerCAD - Tutorial for Beginner



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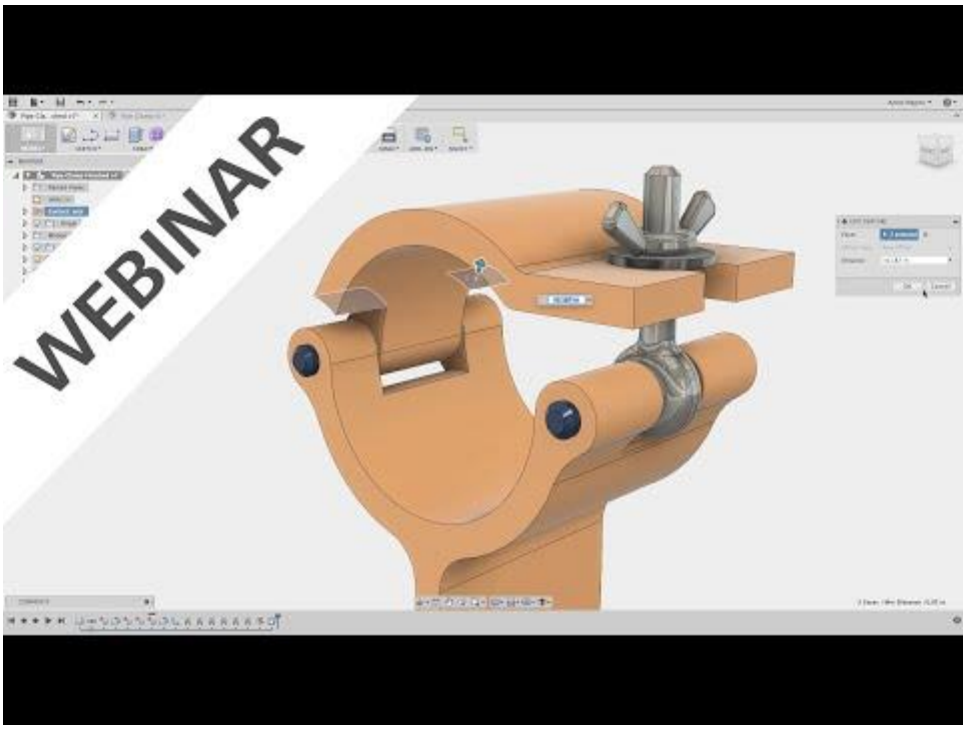
Fusion 360 For Beginners - Recorded Webinar



Quiz

Software

A part has already been developed and will now be created by machining. Which software is generally required to machine the part?

☐ CAD/CAM system.
☐ CAM.
☐ CAD.
☐ Fusion 360.

Basics in 3D Modeling and File Formats

CAD/CAM FOR ADDITIVE MANUFACTURING

All additive manufacturing technologies require a digital command file that contains all the necessary information for the AM machine to create the part. The file contains information about a 3D model that was either created in CAD software or scanned from a physical object with a 3D scanner. There are several essential steps and techniques that an AM operator must know in order to convert a 3D model into a format that AM machines can understand.

STL (Surface Triangulation/Tessellation Language/ STereoLithography).

- Standardized interface format for additive manufacturing.
- Describes component surface by individual triangles.

AMF (Additive Manufacturing File Format).

- Described in ISO/ASTM 52915.
- Component geometry, material properties, component arrangement / orientation.

3MF (Additive Manufacturing File Format).

- Developed by an industry consortium.

- Component geometry, material properties, part layout and orientation.

Watch the video Index - CAD and File Formats

Before importing the file into the AM program

It is always best to keep the design of a part simple and consistent. Defining unnecessary surfaces, over defining constraints, undefined units of measurement and zero thickness surfaces are prone to problems. A good designer considers the fabrication material, wall thickness constraints and volume. They should also consider the maximum dimensions the AM system can handle, as well as its resolution in the XY plane and the Z axis.

Before exporting an STL file

AM processes are capable of producing parts with complex geometries that are not possible with traditional manufacturing processes. Internal voids, lattice structures and variable porosity are all feasible. However, a designer must still consider the limitations that AM technologies bring, such as relatively slow production speed and the effect of different orientations on a part's strength. The following checks must be performed before exporting an STL file. More detailed recommendations can be found in the respective units on the manufacturing processes.

Is the Model Printable?

Different AM technologies have different maximum build dimensions. The operator must check the AM machine specification to ensure that the part is within these limits. The operator must also ensure that the smallest detail in the CAD model can be produced by checking the maximum resolution of the AM machine.

In the following you can see that the logo fits into the space of the printer, but the vase does not. This is automatically detected by the printing software. It should be noted that not all software recognizes this automatically.

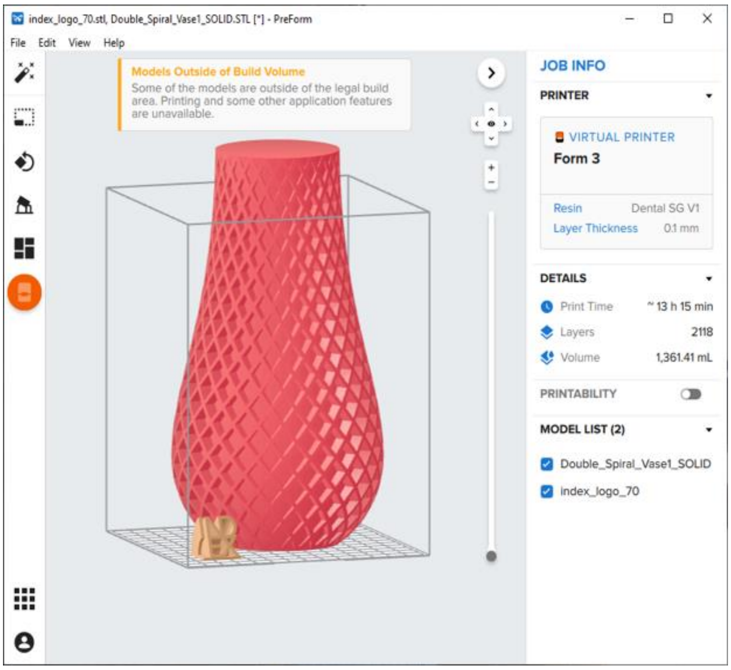


Figure 3. Be aware of the available workspace. Source: L. Müller/Hochschule Düsseldorf.

Is the Model Waterproof?

Digital 3D models for use in AM manufacturing must be tested for "watertightness". A watertight mesh is closed and does not contain any holes. There must be exactly two polygons on all edges. A good way to test watertightness is to imagine that the inside of the object is filled with water. The part is watertight if the water inside cannot flow out. Some AM software can automatically check the watertightness and correct the mesh if necessary. Your slicing software or distributor will often detect those problems automatically.

Is there Internal Overlapping?

The model should have one continuous outer shell, as any intersection or overlap can cause errors in the manufacturing process. Overlapping volumes create internal walls with zero thickness, which AM machines cannot manufacture. Most software can analyse parts for overlapping volumes.

Are the Walls Sufficiently Thick?

All surfaces in the 3D model must be assigned a thickness unless the part is completely solid. This is not advisable unless it is absolutely necessary. Solid parts consume more material and take longer to manufacture. The minimum allowable wall thickness depends on the material properties and the AM machine. It must also be large enough to support the part's own weight and withstand application-dependent stresses. Especially for FDM printing, make sure that the minimum wall thickness is at least as thick as the nozzle diameter used, better 2 x nozzle diameter. Otherwise, too thin walls cannot be drilled. You can try this out with our test component. In the following picture you can see how the thin test walls simply disappear.

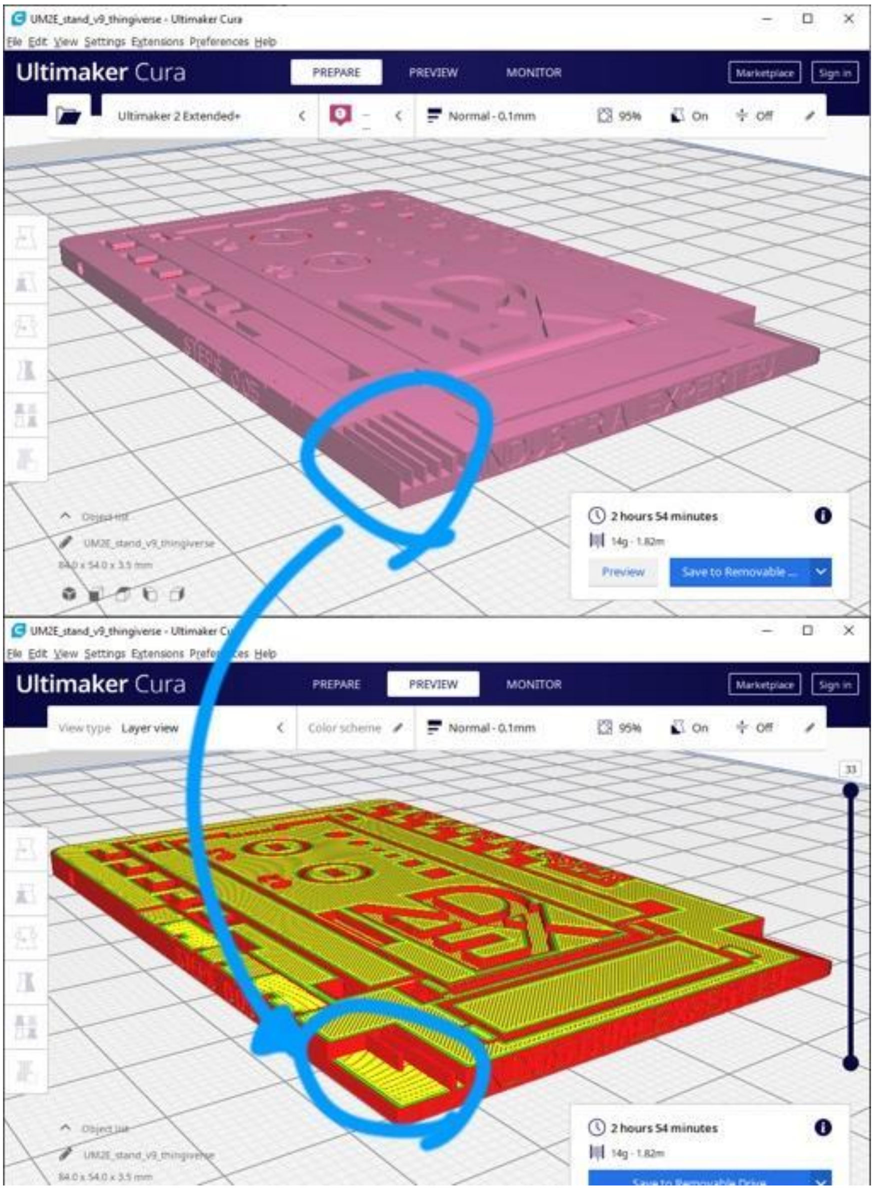


Figure 4. Too thin walls in FDM. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

Are There Escape Holes Where Necessary?

For some processes including powder bed and vat polymerisation methods, the digital 3D model needs to have escape holes, so that excess material is not trapped inside the part. More information is given in the unit about vat polymerisation.

Validate the model

You can easily test your CAD with slicing tools. Free tools are for example:

- Preform from Formlabs.
- Cura from Ultimaker.
- web services from 3Dhubs or i.materialise.

Feel free to test those services with our test model.

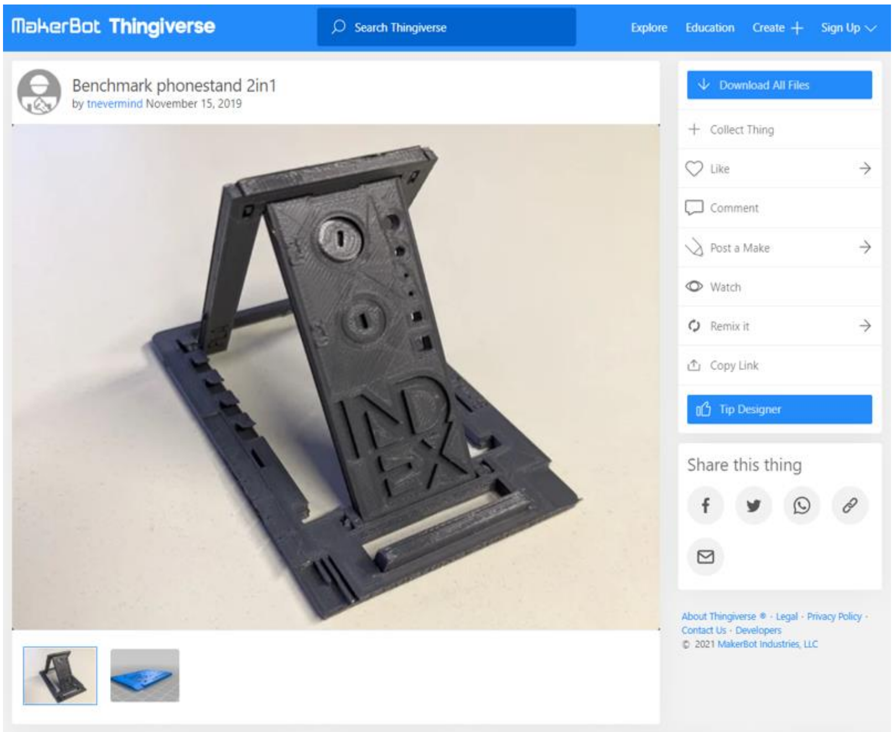


Figure 5. Free to use test file. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

Quiz

Escape holes.

Which AM technologies require escape holes for excess material?

☐ VAT Polymerization and SLS.
☐ SLS and FDM.
☐ DED and VAT polymerization.
☐ SLS and DOD.

FDM

Printer structure and components

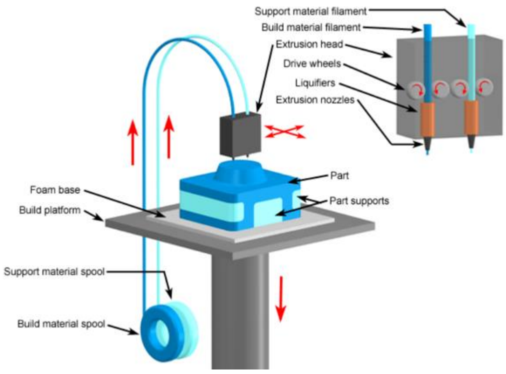


Figure 1. Structure of an FDM printer. Source: www.custompartnet.com.

General Process

Fused Deposition Modelling (FDM) sometimes referred to as Fused Filament Fabrication or FFF is the most commonly used 3D printing technology. FDM produces parts with strands of solid thermoplastic material that is in the form of a filament. The filament is pushed through a heated nozzle where it is melted. The printer continuously moves the nozzle around, depositing the melted material in precise locations that follow a predetermined path. As the material cools it solidifies and builds the part layer by layer. This unit will give you a good overview of FDM and what the technology's capabilities and problems are.

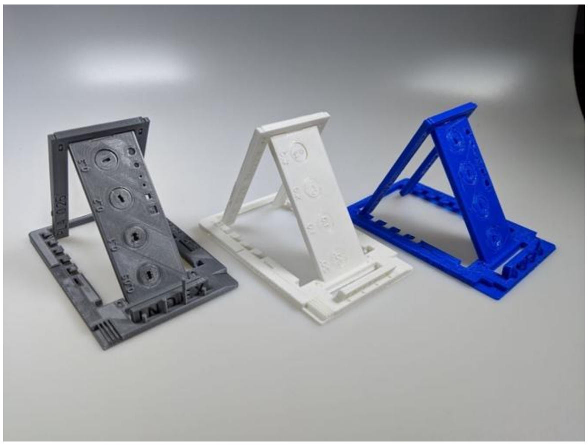


Figure 2. Smartphone stands printed with FDM. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

Material Feed System

Bulk material is either loaded directly into an extrusion chamber or continuously fed to the print head from a hopper or spool. Pellets are pushed through by a screw conveyor and filaments by rollers/wheels. Filament from a roll is most commonly used. As shown in the figure above, some printers use multiple nozzles. For example, multiple types of material can be used in one component. In the illustration, the construction material is used once, and a special wash-out material is used for the support structures. This process was mainly driven and developed by Stratasys.

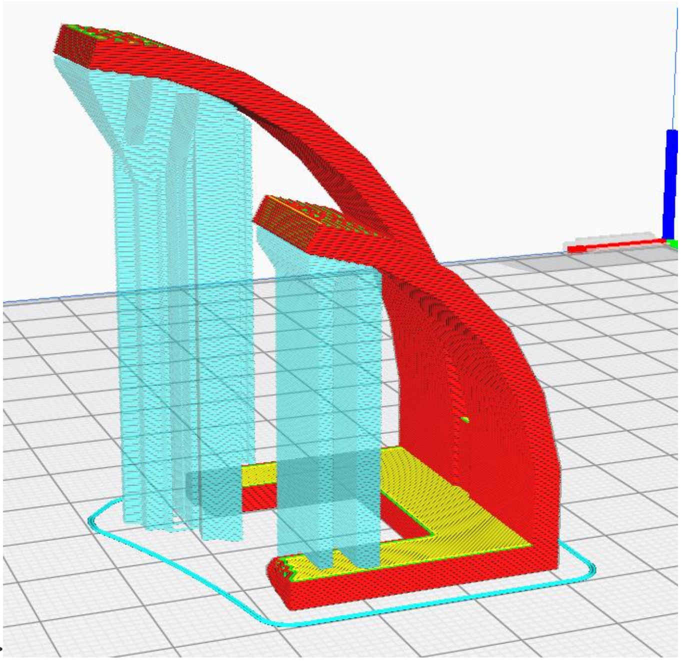
Deposition Characteristics

The shape and flow rate of the deposited material depends on the dimensions of the nozzle. There is a trade-off between the speed at which the system deposits the material and the quality of the part. The flow rate of the material and the movement of the extrusion head must be synchronized to ensure consistent deposition and accuracy. The direction of the extrusion head movement is subject to rapid accelerations and decelerations. Minimizing the weight of the extrusion head is important to reduce inertia and facilitate stopping, starting and changing directions. In post-processing, depending on the printer, it is possible to influence the flow speed and the travel speed of the print. Usually the pre-set profiles are sufficient and only for special materials or process optimization parameters should be adjusted. Experience shows that FDM processes in the low-cost range require some trial and error to achieve consistently good results.

Support Structures

Extrusion-based systems require support structures for overhanging and undercut parts during production. The support structures can be made from the same material as the rest of the part or from a different material. Colour variation helps to see the difference directly. Support material patterns can be automatically generated by the AM software. By design, support structures can be avoided. A rule of thumb is that overhangs up to 45° can be printed without support structures. Up to 65°, many printers also still achieve good results. To test which overhangs can be printed, test prints like the following are recommended. Our benchmark print also covers this. Go to Thingiverse and download our model or use this overhang test.

If you are designing your part yourself, design cleverly and try to change your overhangs so that they are a maximum of 65°. Less support material will result in shorter print times and less need for rework. In the following you can see how the actual component (red & yellow) is held by blue support structures from 65°.



>

Figure 3. Support structures displayed in a slicer. Source: L. Müller/Hochschule Düsseldorf.

Without support material, unsupported features can deform due to gravity. Powder bed systems that use polymer powder do not require support material because the excess powder holds the part. Extrusion-based technologies print the support structure in the same manner as the base material. Inexpensive printers usually print their support structures from the same material as the actual part. This has the disadvantage that it has to be removed manually close to the print and leads to less good surfaces. This is often used to save costs. In this section, two common substrate materials are presented, which are used to be able to be washed out, for example.

High Impact Polystyrene (HIPS):

High impact polystyrene is a polymer with strength and durability comparable to ABS. It is often used in conjunction with ABS as a substrate. HIPS filaments are inexpensive and can be dissolved in various solvents during post-processing. The main advantages are dissolvability in limonene and low toxicity, while the disadvantage is that the solvent can be costly.

Polyvinyl alcohol (PVA):

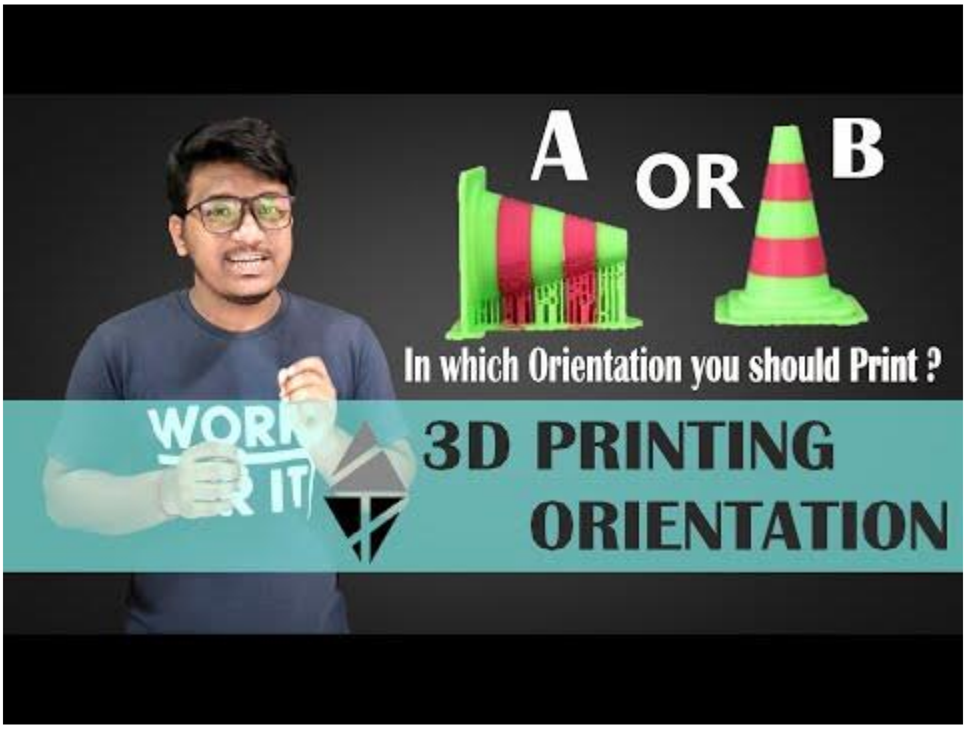
Polyvinyl alcohol or PVA is a synthetic polymer that is soluble in water. PVA is suitable as a carrier for PLA parts, but not for ABS, because PVA and ABS do not adhere well and have different extrusion temperatures.

Printing Patterns and Anisotropy

The outline of a cross-cross section is printed first at a slow rate to optimise the part's dimensional accuracy. Then, the system normally fills in the inner areas using a cross-hatch pattern. The nozzles have circular outputs, therefore it is challenging to plot corners. Different filling patterns and layering strategies can result in varying material properties in different directions (anisotropy).

FDM components are anisotropic. This means along the layers their load capacity is at 100%. Orthogonal to the layers, the tensile strength is reduced to approx. 30%. This is to be considered if you want to load components in a certain direction. Orient them so that the main load is along the layers.

Part orientation on a printer



Another useful video is „FDM Example -Timelaps"

Advantages and Disadvantages

Each manufacturing process has its individual advantages and disadvantages. The following are the main advantages and disadvantages of FDM.

Pros:

FDM parts are stable and suitable for functional parts.

- Machines are suitable for office environments.
- FDM parts are stable in the long term.
- Resistant to UV light, chemicals.
- Wide range of post-processing possibilities.
- Wide range of materials.
- Soluble support materials.

Cons:

- Fluted surface.
- Anisotropy of mechanical properties.
- Slow process.
- High part cost compared to other plastic AM processes.
- High demand for support structures.

Machine Costs

Home users and hobby

FDM is one of the most affordable ways to get started in additive manufacturing, even for home use. Cheap usable devices are available for **250€** (as of 2021) and very good hobby devices, which can also be found in small companies and startups, start at **1000€.** Simple printing material like PLA is already available from 20€/kg. Better materials can cost from 50-200 €/kg.

Entry-level devices are available from Anycubic for example. Especially recommended are the devices from Prusa. Typically, the build space is in a range from 200 x 200 x 200mm to 500 x 500x 500mm with a minimum layer thickness of 0.02mm.

Figure 4. PRUSA I3 MK3S+. Source: www.prusa3d.com

Prototype and Development

In prototyping and development, semi-professional FDM printers are a good way to achieve results quickly and comparatively cheaply. These devices require less maintenance than in the hobby sector and have been working very reliably for years. Typically, the devices cost between **5000€** and **25000€** (as of 2021). Manufacturers such as Stratasys, Ultimaker and Makerbot are more common here.

Figure 5. Stratasys F120. Source: www.stratasys.com

Manufacturing

In the large format and manufacturing there are FDM printers in the price range from **50000€** to **300000€**. The technology is only suitable to a limited extent to produce larger quantities, but very large models are feasible. Typically the Build space is in a range from 500 x 500 x 500mm to 1500 x 1500x 500mm with a minimum layer thickness of 0.04mm. Thus, FDM is also used in the field of architecture. The company Massivit offers large-format printers. The company Peri uses the FDM process for prints made of concrete.

Figure 6. Massivit 1800 Pro. Source: www.massivit3d.com

PROJECT | PERI 3D Construction Printing: First 3D-printed residential building in Germany (EN)

Materials and Properties

The following table gives an overview of the materials typically used in FDM. PLA is the most widely used material in the amateur and hobby sector. If there are high demands on the component, PEEK is used. However, this material can only be processed on professional equipment.

		Fused Deposition Modelling (FDM)						
		Tensile Strength	Flexural Strength	Elongation at break	Nozzle Temperature	Colours	Water absorption ASTM D570	UV resistance
		[MPa]	[MPa]	[%]	[°C]	-	[%]	-
Material	PLA	34.8 *1	98 *2	4.2 *1	180 ... 230	Multicolour	0.1	Poor
	ABS	22 *3	41 *4	6 *3	210 ... 250	Multicolour	1.8	Poor
	PET	33.4 *1	66.7 *2	2.7 *1	230 ... 250	Multicolour, Clear	0.2	Fair
	Nylon 12	53 *3	70.3 *4	9.5 *3	240 ... 260	Black	0.66	Good
	TPU	-	-	230	210 ... 230	Multicolour, Clear	0.4	Good
	PC	68 *3	-	4.8 *3	250 .. 310	Black, White	0.2	Fair
	PEEK	69 *3	124.1 *4	20 *3	360 ... 380	Multicolour	0.12	Good
	HIPS	18.4 *1	31.8 *2	1.4 *1	220 ... 240	Black, White	0.15	Poor

Note: All specifications are to be seen in proportion. The material properties depend strongly on the manufacturing and printing process
*1 ISO 527
*2 ISO 178
*3 ASTM D638
*4 ASTM D790

Figure 7. Materials for FDM. Source: (cc) BY-NC-SA S. Markus/Hochschule Düsseldorf.

Design Guidelines

If you are designing explicitly for additive manufacturing then there are some basic design rules to follow. In the following table you will find recommendations which will help you to design your component.

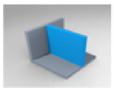
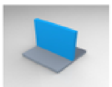
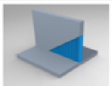
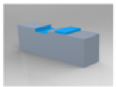
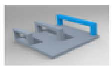
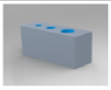
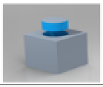
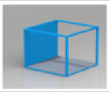
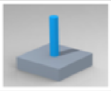
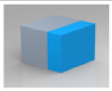
	**Supported walls** What's the minimum thickness?	2 x Nozzel diameter Most used nozzel 0.4 mm
	**Unsupported walls** What's the minimum thickness?	2 x Nozzel diameter
	**Support & Overhangs** Maximum angles of overhangs that can be printed without support	45°- 60°
	**Engraved and embossed details** Minimum dimensions to print deepenings and elevations.	1,5 x Nozzel Diameeter & 3 x Layer hight (often used 0.6 mm & 0.45 mm)
	**Horizontal bridges** Bridge span which is printable without support	10 mm - 15 mm
	**Holes** Minimum hole diameter	3 x Nozzel diameter > 1.5 mm
	**Moving/Connecting Parts** Recommended clearance between to parts	Horizontal to the layers > 0.3 mm Vertical to the layers > 0.5 mm
	**Escape holes** Minimum excaphole size	Not needed in FDM
	**Minimum features** Minimum size of small features to make them printable	2-3 x Nozzel diameter min. >1 mm
	**Minimum pin diameter** (For standalone pins)	5x Nozzel diameter
	**Tolerance** Expected dimensional accuracy	±0.5% lower limit 1,5 x nozzel diameter

Figure 8. Style-Guidelines for FDM. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

The following video shows you how to implement the design guidelines and check them in post-processing: **[Checking design guidelines for FDM]**

Preprocessing

Slicing Software and Orientation

Typical slicing software for your part can be found under the following links. If you are using professional equipment, the manufacturers usually offer specifically tailored software. However, one of the following is also suitable for checking your components. Cura from Ultimaker is especially beginner friendly and can be used for a large number of printers.

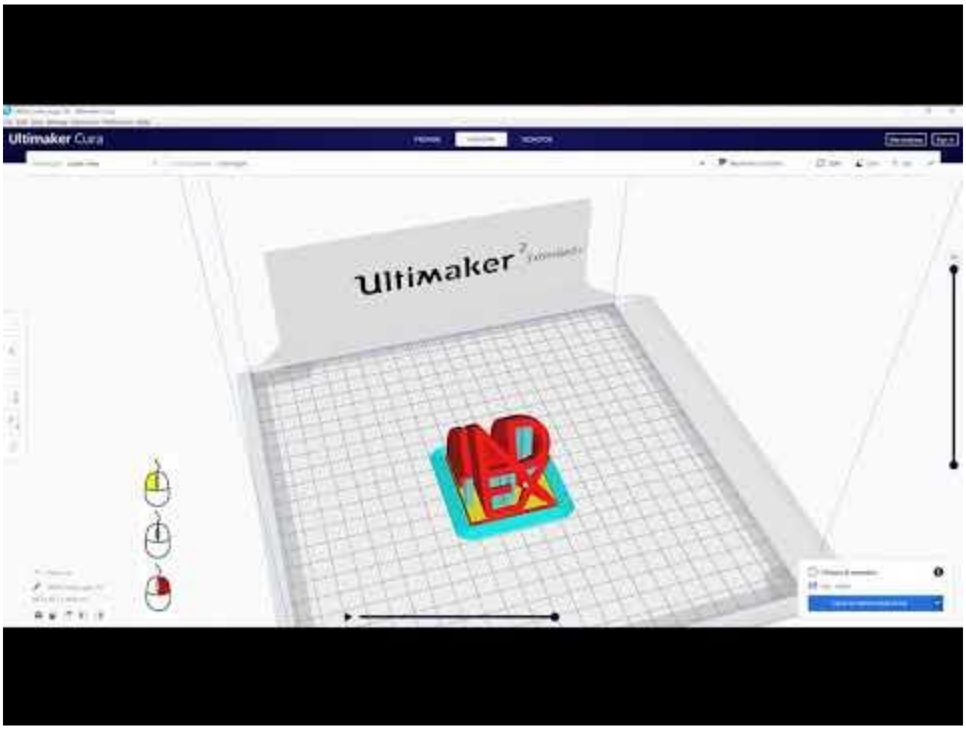
Cura by Ultimaker
Prusaslicer by Prusa3d
Simplify3d Slicer

Test your Setup

So that they can try out their printer or printing service once. Simply download our benchmark component. The best-known benchmark component is probably the Benchy. You can find it in the second link.

INDEX Benchmark
Benchy

Cura



Postprocessing

In the following video you can see how to remove support from a printer that works with dissolving support.

In the following video you can see the distance from classic support pressuretur from the same material.

Troubleshooting

If your component has errors which do not disappear even after renewed printing, you will find further information here or here. Try to find your error and adjust the printing parameters. If you have had your component printed by a service provider, this provider is responsible for the quality.

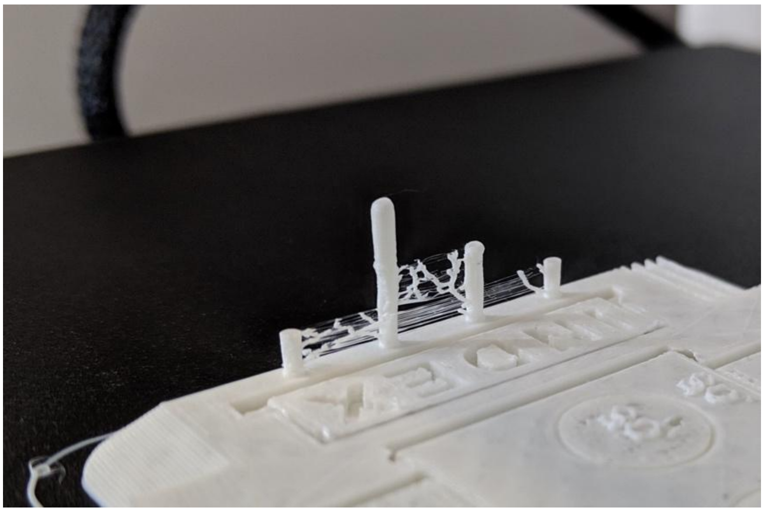


Figure 9. Example for stringing. Source: L. Müller/Hochschule Düsseldorf.

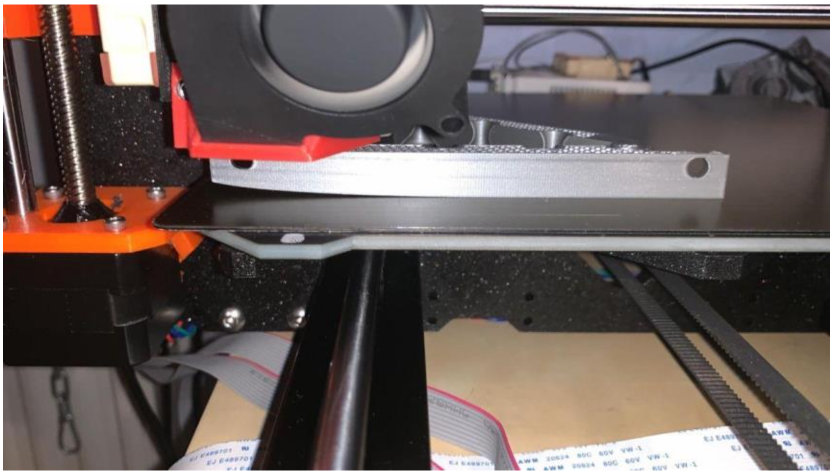


Figure 10. Buildplate detachment. Source: L. Müller/Hochschule Düsseldorf.

Industrial Case

Panels in Airbus Aircraft

In 2015, the first collaboration between Materialise and Airbus began with the order to manufacture plastic parts additively. Materialise was founded in 1990 and is one of the leading companies in the 3D printing industry. Since 2015, the collaboration has continued to grow and expand to include new programs and services. Among others, 3D printed panels for the cabin interior.

The panels installed in the cabin interior are used to cover luggage compartments and must meet the highest aesthetic requirements, as they are visibly installed. After a certain period of time, it is inevitable that the panels will have to be replaced. Repairs or maintenance of any kind incur costs of up to €100,000 per hour because the aircraft has to be grounded. Accordingly, it is essential that the components can be manufactured and delivered as quickly as possible when required. For retrofitting or upgrading, the panels have been manufactured additively by the company Materialise since 2015. The advantage of additive manufacturing is that small batches and individually adapted components such as the panels can be produced much faster with additive manufacturing than with conventional manufacturing (injection molding). No tooling or molding is required in advance. Another advantage compared to conventional manufacturing methods is a 15% reduction in the weight of the panels, thanks to the complex internal lattice structures used in the design. In addition, there are cost savings that would be incurred in conventional production due to more complex panels.

After the panels have been additively manufactured, they are further processed and painted in accordance with the relevant Airbus cabin guidelines.

The following figure shows the panel during 3D printing using the FDM process.

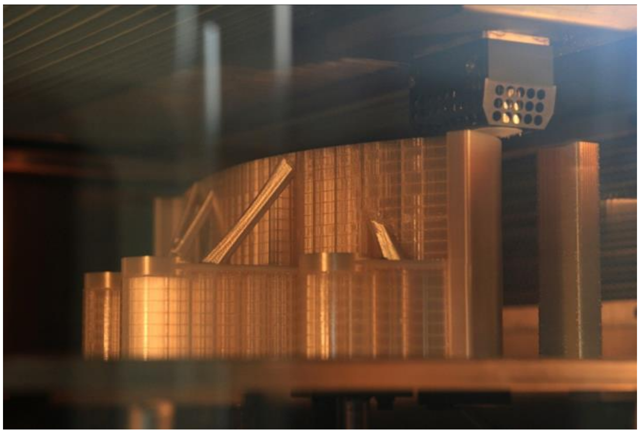


Figure 11. Panel during 3D printing in the FDM process. Source: www.materialise.com

The following figure shows the finished post-processed orifice plate in the interior view.

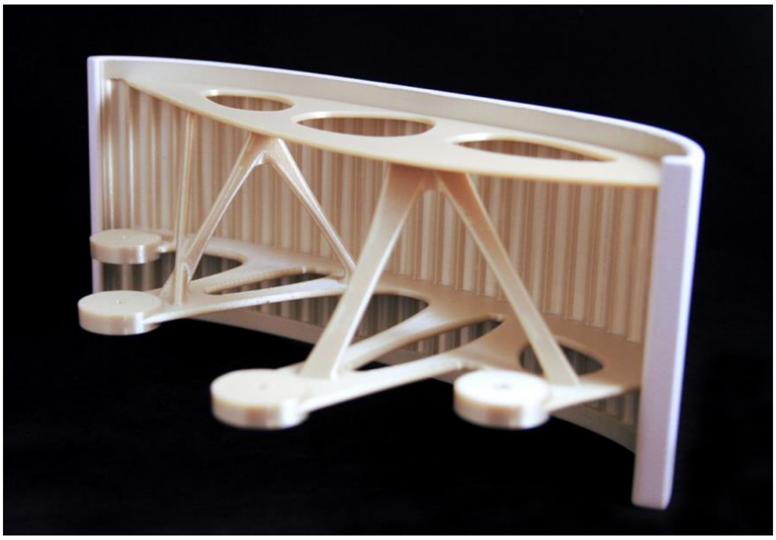


Figure 12. Finished post processed panel. Source: www.materialise.com

Quiz

Anisotropy.

How can the anisotropy properties of a part be influenced parallel to the printing platform?

☐ Printing pattern.
☐ Printing speed.
☐ Infill.
☐ Layer thickness.

SLA

Printer structure and components

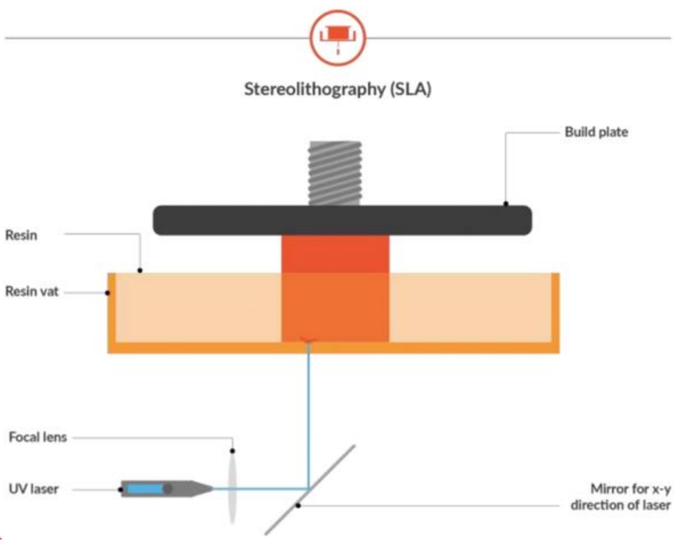


Figure 1. SLA structure. Source: B. Leutenecker-Twelsiek/Hochschule Düsseldorf.

General Process

Stereolithography (SL or SLA) is the oldest 3D printing technology, developed and patented by Charles W. Hull in 1986. In SLA manufacturing, a UV laser scanner system traces 2D contours of cross-sections of a 3D model on a tub of photopolymer resin. The scanner system consists of mirrors and a lens that direct and focus light in the XY plane. The build platform is submerged in the resin and moves the part down (in the Z direction) once a layer is scanned. The part can be made from the bottom of the vat up (consumer printer) or from the top of the vat down (professional printer). When the printer projects the light beam onto the bottom of the vat, the part is held at a layer distance from the bottom surface. The resin is forced under the part due to gravity and then cured with the UV laser before being peeled off so another layer can be applied. Alternatively, there are setups in which the resin is spread with a sweep blade. The part is at greater risk of being damaged during peeling, but is less susceptible to defects caused by uneven layer surfaces because new layers are always in contact with the bottom of the shell.

The liquid resin is solidified by a process called photopolymerization: during solidification, the monomeric carbon chains in the resin are activated by the light from the UV laser. The chains solidify, forming strong, unbreakable bonds between them. The photopolymerization process is irreversible and there is no way to convert the SLA parts back to their liquid form: when heated, they burn instead of melting. Unlike the thermoplastics that FDM uses, the materials produced with SLA are made of thermoset polymers. Tolerances on an SLA part are typically less than 0.05 mm, and it offers the smoothest surface finish of any additive manufacturing process. SLA is all about precision and accuracy, so it is often used where shape, fit and assembly are crucial. Given the level of quality that can be achieved with SLA, it is particularly useful for creating high-precision casting patterns (e.g., for injection molding, casting, and vacuum casting), as well as for functional prototypes, presentation models, and for performing mold and fit testing. It is the preferred choice for designer models and engineering reviews. SLA technology is extremely versatile and can be used in all areas where precision is required above all else.

With the SLA printing process, it is important to know how to post-cure your resin 3D prints. Post-curing allows parts to reach the highest possible strength and become more stable. This step is especially important for functional resins. For example, post-curing is required for successful burnout in castable prints, and flexible resin doubles its strength with post-curing. If you are using a stereolithography (SLA) 3D printer it is important to know how to post-cure your resin 3D prints.

Technology

In contrast to FDM, SLA printers are generally more professional. In the FDM field, there are extremely cheap and simple entry-level models, which require a variety of configurations for the printing results to be good. In SLA, less customisation is required. The manufacturer's software is highly optimised for the processes and materials.

However, there are some key elements that have a significant impact on print quality and speed. However, these can only be influenced by very experienced users. The accuracy of the components depends largely on the cure depth and width of the laser.

Cure Depth and Width

In stereolithography, the width of a cured resin line depends on the shape of the scanned line, with larger scan beams producing deeper depths of cure. The amount of energy transmitted by the laser beam also affects the depth of cure. If the energy is too low or the scan speed is too high, not enough energy is transferred to cure the polymer. A simple way to adjust the exposure energy is to adjust the scan speed. The minimum amount of energy required is called the critical exposure energy, which is a material property of the resin.

Photospeed

The photospeed is the speed at which the polymer is cured at a certain depth relative to the surface. It depends on the material properties, verified experimentally, including the critical exposure and the depth to which the laser can penetrate the resin.

Time Scales

The characteristic exposure time is the time required to scan a spot on the resin to cure it. It is usually between 50 and 2000 microseconds and depends on the scanning speed. After exposure, the resin continues to react and shrink. The chemical reactions can take anywhere from a fraction of a second to ten seconds. The shrinkage occurs because of the newly formed polymer occupying less space than the photopolymer resin.

Weave

In stereolithography, the beam solidifies a layer before adhering it to the previous one. This separation is made to prevent adjacent layers from affecting each other as they shrink at different times. The laser scans lines in the X direction first and then in the Y direction, to give the first lines just enough energy to adhere to the previous layer.

Weave Patterns

Scanning new lines directly on top of each other can improve part properties. On the other hand it introduces distortion at the corners and can create significant internal stresses. To solve these problems, a "star weave" pattern was introduced.

Supports

SLA always requires support structures. These consist of three components: rafts, scaffolds and touchpoints. The scaffold forms a base that adheres to the build platform. The scaffold protrudes from the plate to secure your part during printing. Touchpoints are contact areas where the framework meets the model.

If your model is not adequately supported, it can cause the following:

- Partially cured resin floating in the tank that needs to be filtered out.
- Misaligned layers.
- Detachment of the model from the framework and supports.
- Thin walls or features may warp.
- The model may fall off the build platform.
- The part may bend severely.
- The model may settle like a pancake on the bottom of the glass tray.

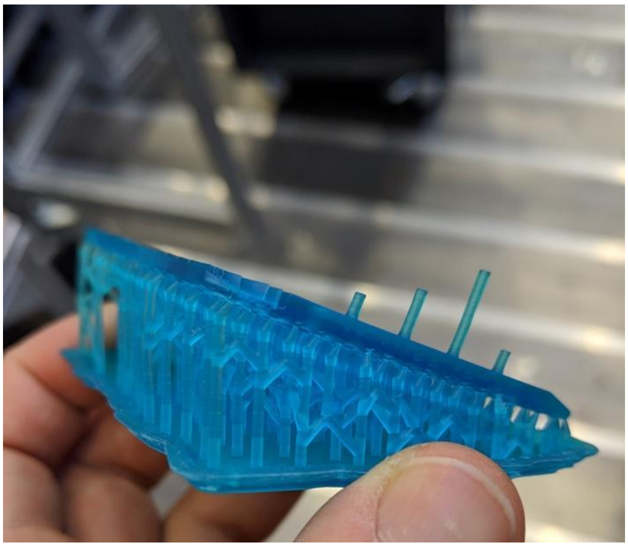


Figure 2. Support structures in SLA Printing. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

This is an embedded video originally published on YouTube and complies with the standard YouTube license. If you want to re-use it, you should check the video owner's copyright terms and conditions.

Advantages and Disadvantages

Each manufacturing process has its individual advantages and disadvantages. The following are the main advantages and disadvantages of SLA.

Pros

- Rapid implementation of very accurate prototypes in early stages of product development
- Production times comparable to FDM with higher precision
- Single-step production process produces smooth surfaces with almost no post-processing (supports must be removed)
- Low material consumption: uncured resin can be reused
- Production of both flexible and rigid 3D objects
- Wide range of materials

- Cost efficient production
- Multi-part assemblies are possible

Cons

- Supporting structures can restrict design freedom
- Depending on the material, components can be brittle
- Components are only UV-resistant to a limited extent
- Components are not as highly loadable as other processes
- Cleaning effort for material changes is often high

Machine Costs

Home users and hobby

Entry-level devices are available from Anicubic for example. Especially recommended are the devices from Formlabs. Typically the Build space is in a range from 140 x 140 x 200 mm to 300 x 300x 500 mm with an minimum layer thickness of 0.01 mm. Prices for usable beginner products start at **500 €** without accessories. It is recommended to purchase a wash station and a curing unit. In the hobby area, this can be replaced by a simple basin with isopropanol and a UV lamp. For an advanced entry-level system about **3,000 €** should be scheduled.

Figure 3. Formlabs Form 3. Source: www.formlabs.com

Prototype and development

In prototyping and development, (semi)professional SLA printers are a good way to achieve results quickly and comparatively cheaply. These devices require less maintenance than in the hobby sector and have been working very reliably for years. Typically, devices cost between **10,000 €** and **25,000 €** (as of 2021).Typically the building space is in a range from 275 x 150 x 400mm to 335 x 300x 500mm with an minimum layer thickness of 0.01mm.

Manufacturers such as Formlabs or Nexa3D are more common here.

Figure 4. Nexa NXE 400. Source: www.nexa3d.com

Manufacturing

In the field of production, there are mainly devices that are designed to produce high quantities in enormously good quality. These are often equipped with several lasers and can thus reduce unit costs. Prices range from **100,000 €** to **400,000 €**. Typical companies are 3D Systems, DWS and Nexa3D.

Figure 5. 3D Systems ProX 950. Source: www.3dsystems.com

3D Systems ProJet Series

Materials and their Properties

Stereolithography (SLA) is particularly well suited for parts that require high resolution and must meet tight tolerances. Thanks to the variety of resins available for SLA 3D printing, this process has found many applications in various industries. For example, in more simple applications, special technical applications or within medical technology. SLA materials have a wide range of mechanical properties and offer multiple applications for parts that require ABS or polypropylene-like properties, such as snap-fit joints, styling components for the automotive industry and master models. There are SLA materials for higher temperature applications and clear materials with polycarbonate-like properties. Casting resins, for example, are used for mold making: no ash is left when the hot cast is burned. Biocompatible materials are available for a variety of medical applications such as surgical tools, dental devices and hearing aids.

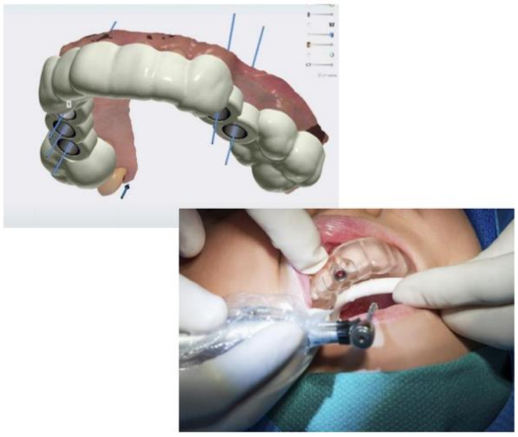


Figure 6. SLA in dental technology: (cc) BY-NC-SA B. Leutenecker-Twelsiek/Hochschule Düsseldorf.

The type of resin to be used always depends on the specific printer and thus cannot be answered in general terms. The manufacturers specify which resins are recommended.

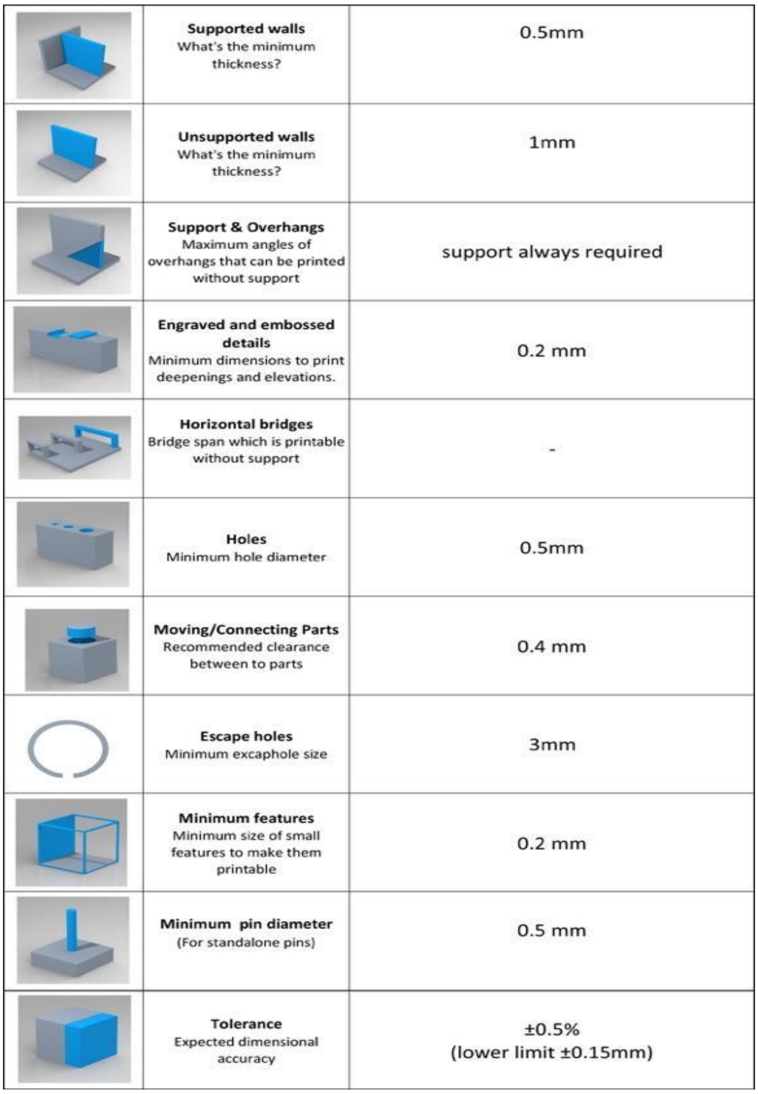
Some general material properties of commonly used materials can be found in the following table:

	Stereolithography (SLA)						
	Tensile Strength ASTM D638	E-Modulus ASTM D638	Elongation at break ASTM D638	Heat deflection temperature ASTM D648 (0.45 MPa)	Color	Water absorption ASTM D570	UV resistance
Material	[Mpa]	[Mpa]	[%]	[°C]	-	[%]	-
PC-like Accura 5530	50	3400	3	68	Clear amber	0,55	Generally poor
PC-like Accura 60	75	3500	7	53 ... 55	Clear	-	
ABS-like Renshape SL 7820	55	3000	5	93	Black	0,25	
ABS-like Watershed XC 11122	55	2900	6	45.9 ... 54.5	Clear	0,35	
ABS-like Accura Xtreme White 200	55	3300	9	47	White	0,65	
PP-like Somos 9120	35	1600	25	61	Clear white	-	
Note: All specifications are to be seen in proportion. The material properties depend strongly on the manufacturing and printing process							

Figure 7. Materials for SLA. Source: (cc) BY-NC-SA S. Markus/Hochschule Düsseldorf.

Design Guidelines

If you are designing explicitly for additive manufacturing, there are some basic design rules to follow. In the following table you will find recommendations which will help you to design your component.



Supported walls What's the minimum thickness?	0.5mm
Unsupported walls What's the minimum thickness?	1mm
Support & Overhangs Maximum angles of overhangs that can be printed without support	support always required
Engraved and embossed details Minimum dimensions to print deepenings and elevations.	0.2 mm
Horizontal bridges Bridge span which is printable without support	-
Holes Minimum hole diameter	0.5mm
Moving/Connecting Parts Recommended clearance between to parts	0.4 mm
Escape holes Minimum excaphole size	3mm
Minimum features Minimum size of small features to make them printable	0.2 mm
Minimum pin diameter (For standalone pins)	0.5 mm
Tolerance Expected dimensional accuracy	±0.5% (lower limit ±0.15mm)

Figure 8. Style-Guidelines for SLA. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

[**SLA - From Design to 3D Print With the Form 3**]()

Preprocessing

Slicing Software and Orientation

Typical slicing software can be found under the following links. If you are using professional equipment, the manufacturer usually offers specifically software. However, one of the following is also suitable for checking your components. Preform from Formlabs is especially beginner friendly and can be used to test your design. This works even if you are not using a Formlabs printer.

Download 3d Sprint Software Documents | 3D Systems
PreForm 3D Printing Software: Prepare Your Models for Printing | Formlabs
All-in-one SLA/DLP/LCD Slicer-HOME (chitubox.com)

Test your Setup
To test your printer or printing service you can download the following benchmark component. Our INDEX Component is especially hard for SLA Printers to print due to the design. But of course, you can have a try. Following the second link you will find the probably best-known benchmark component.

INDEX Benchmark
Benchy

Watch the video Prechecking your print

Watch the video 3DBenchy made on SLA printer

Postprocessing

Postprocessing in SLA printing is very manufacturer-dependent. In contrast to the FDM process, the various printer manufacturers have their own recommendations tailored to their products. Under the following links you can read the different recommendations of the manufacturers. 3D Systems and Formlabs represent the professional and semi-professional area very well.

Process Guide from 3DSystems:

QuickCast Post Processing Guide | Best Practices (3dsystems.com)

Hardening in post by Formlabs:

A Guide to Post-Curing Formlabs Resins | Formlabs

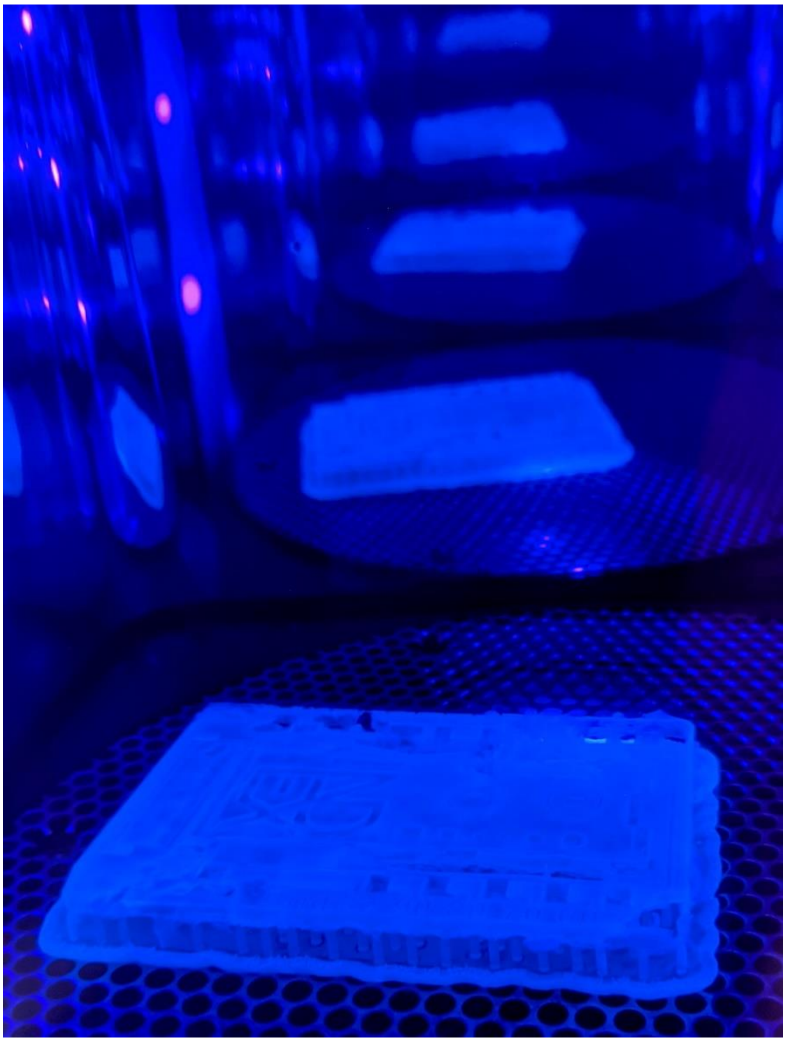


Figure 9. SLA Part while hardening in UV-light. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

Troubleshooting

If your component has errors which do not disappear even after renewed printing, the manufacturer typically gives futher information. For example Formlabs. Nikko supplies a general approach. If you have had your component printed by a service provider, this provider is responsible for the quality.

Figure 10. Failed SLA print due to laser erros caused by dirty buildplate. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

Industrial Case

Toothbrush

Razors, toothbrushes or even chessboard pieces are considered as simple objects of daily use. In prison, however, these products can be used as murder weapons or as suicide devices. Therefore, it is especially important to make such items consumer-friendly for prison inmates. Leading US correctional manufacturer Bob Barker has developed and produced daily used items with SLA printers. For example, a toothbrush, which is primarily intended to fulfil the function of brushing teeth, but still cannot be used as a weapon.

The following conditions should be ensured:

1. sufficient strength for brushing teeth, but still using elastic material

2. no sharp edges to minimise the risk of injury

3. fast implementation to accelerate development

4. little post-processing for production

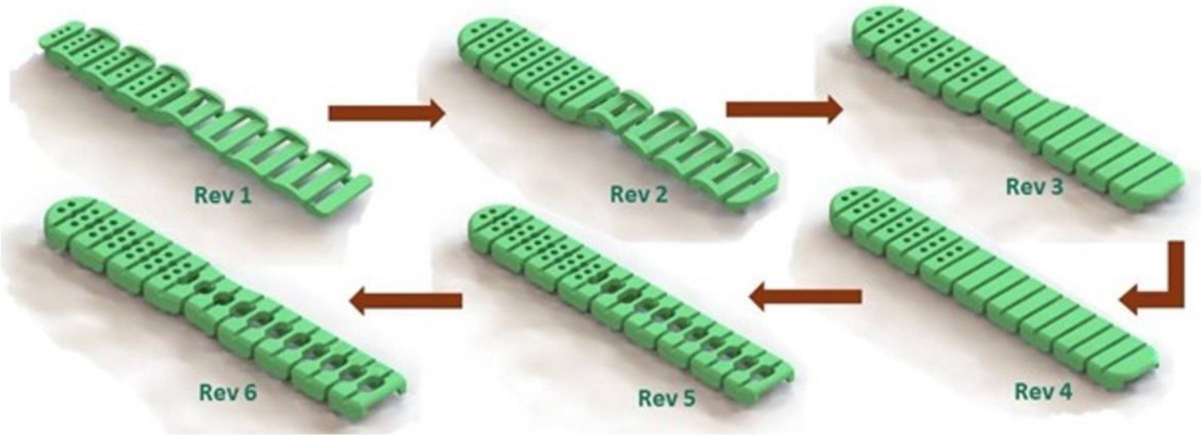


Figure 11. Design progress of the toothbrush. Source: www.formlabs.com/blog.

The models in the design process can be printed at short time. Therefore it was possible to evaluate the designs directly and implement ideas for improvement quickly. In total, it took six iterations to create the final product. Due to the rapid wear and tear of toothbrushes, it was decided in advance that the final product should be manufactured using an injection moulding process. This ensures a more effective production of lager quantities.

Special features and advantages

The simple implementation of the process made it possible to complete the toothbrush within a few process steps. The process was chosen because of the possibility of producing complex components or detailed objects. Since the toothbrush contains a particularly large number of narrow cuts, the possibility of creating complex components was an important criteria.

Quiz

Photopolymerization.

What is photopolymerization?

☐ Polymeric carbon chains in the resin are activated by the light from the UV laser. They solidify and form strong bonds.

☐ Monomeric carbon chains in the resin are activated by the light from the UV laser. They solidify and form strong bonds.
☐ Monomeric carbon chains in the resin are activated by the light from the infrared laser. They solidify and form strong bonds.
☐ Monomeric carbon chains in the resin are activated by the light from the electron beam. They solidify and form strong bonds.

DLP

Printer structure and components

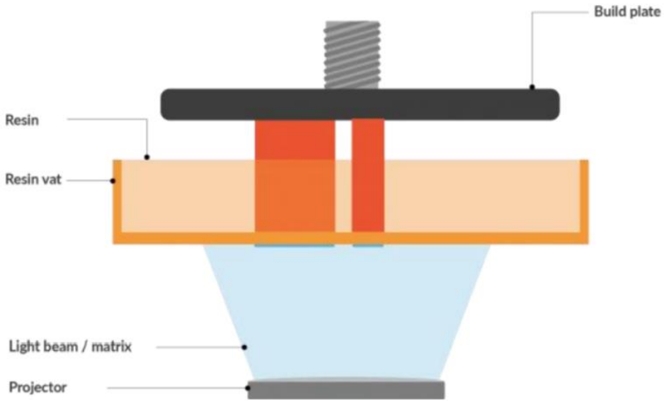


Figure 12. DLP structure. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

General Process

Similar to their SLA counterparts, desktop DLP 3D printers are built around a resin tank with a transparent bottom and a build platform that dips into the resin tank. The part is created layer by layer. In this unit, we will mainly show the differences to SLA. Design guidelines, error sources and material properties are similar. Those will not be discussed here.

Mask projection (MP) technologies were developed in the 1990s to project an entire cross-section of a model onto a resin surface. This method was preferred rather than using slower point-based techniques such as lasers or one-dimensional arrays. Early MP machines used LCD systems as projection devices. Modern commercial machines use digital light processing (DLP) chips to selectively direct UV light onto a resin surface to cure layers. DLP systems use digital micromirrors to turn pixels on or off in a projection. A semiconductor chip contains a large matrix of tiny digital mirrors that can be rotated ±12 degrees. At 12 degrees a mirror reflects the beam of light towards the resin. At -12 degrees the mirror blocks the light beam that illuminates a pixel at the base of the resin. The matrix of mirrors reflects a masked image of a cross-section of the part through a focusing lens and onto the resin. The illuminated pixels cure the resin and the off pixels have no effect. Once a layer is cured, the build platform moves vertically and the next cross-section is projected.

A more recent development in DLP technology is called **c**ontinuous **l**iquid **i**nterface **p**roduction (CLIP). With CLIP, the layers are cured at the bottom of the vat. Usually, this would mean removing the part from the bottom each time a layer is added. However, with CLIP, an oxygen-permeable membrane is used to prevent adhesion. Consequently, the part can continuously rise while the DLP system scans cross sections. With CLIP, uninterrupted material properties in the build direction are achieved.

Build Volume and Speed, the main differences between SLA and DLP

DLP printers can print faster than SLA printers, depending on the printer. SLA printers need a multilaser setup to increase their print speed, DLP printers do not, as they always expose a whole layer. However, there is a direct trade-off between resolution and build volume for DLP 3D printers. Resolution depends on the projector, which defines the number of available pixels/voxels. As you move the projector closer to the optical window, the pixels get smaller, which increases the resolution but limits the available build volume. You may know this phenomenon from your TV or a cinema.

Some manufacturers stack multiple projectors side by side or use a high-resolution 4K projector to increase build volume. This results in much higher costs that often push these devices out of the desktop market. DLP 3D printers are generally optimised for specific cases. Some have a smaller build volume and offer high resolution to produce small, detailed parts like jewellery, while others can produce larger parts but at a lower resolution.

The other main obstacle to increasing build volume for both SLA and DLP 3D printers is the pull-off force. When printing larger parts, the forces applied to the parts increase exponentially as a cured layer peels away from the tank.

Watch the video DLP - Timelapse on Zortrax Printer

Advantages and Disadvantages

Each manufacturing process has its individual advantages and disadvantages. The following are the main advantages and disadvantages of DLP. DLP and SLA share many advantages and disadvantages. Here are some differences.

Pros:

- Very delicate designs possible, especially with small build spaces and high projector resolutions- more accurate than FDM or SLS.
- Mostly faster than comparable SLA printers
- Slightly lower operating costs than SLA, as a shallower resin container is usually used, resulting in less waste.

Cons:

- Similar disadvantages to SLA, UV resistance low.
- Parts have poorer mechanical properties than FDM parts and degrade more over time
- Mostly poorer resolution than SLA for large parts
- Package size more limited than SLA

Machine costs

Entry-level models

Entry-level devices are available for example from Anicubic. Typically, the build space is limited (115 x 65 x 155 mm) with a minimum layer thickness of 25 ~ 100 um. Prices for usable beginner products start at **250 €** without accessories. It is recommended to purchase a wash station and a curing unit. In the hobby area, this can be replaced by a simple basin with isopropanol and a UV lamp.

Figure 13. Anycubic Photon S. Source: www.anycubic.com

Prototype and development

In prototyping and development, (semi)professional DLP printers are a good way to achieve results quickly and comparatively cheaply. These devices require less maintenance than in the hobby sector. Typically, the devices cost between 2,000 € and 10,000 € (as of 2021). Typically, the build space is small (up to 200 x 200x 200 mm) but with high XY pixel resolution (60 um) and low Layer Resolution (12 um). This makes them Ideal for high detailed models.

Typical manufacturers in this range are Flashforge and carima.

Figure 14. Flashforge Hunter. Source: www.flashforge.com

Materials and their properties

The following figure shows an overview of the materials that can be used for DLP. The difference between the materials that can be used in this process should become clear.

		Digital Light Processing (DLP)						
		Tensile Stength ASTM D638	Flexural Strength ASTM D790	Elongation at break ASTM D638	Heat deflection temperature ASTM D648 (1.81 MPa)	Color	Water absorption ASTM D570	UV resistance
Material		[Mpa]	[Mpa]	[%]	[°C]	-	[%]	-
	E-Perform	80*	146*	1.2*	119	Beige	0.1	Generally poor
	E-UA40	1.6*	-	120*	-	Clear white	-	
	E-IND147	84	126	3.2	166.7	Black	0,25	
	Loctite E-IND402	5.6	-	285	-	White	-	
	Loctite E-3955 FST HH	77	138	2,5	197	Black	-	
	KeySplint Soft for EnvisionTEC	-	44 ... 47	>110	61	Clear	-	
	BASF Ultracur3D ST 45	42	93	11	53	Clear	-	Long term UV resistant

* Unknown procedure
Note: All specifications are to be seen in proportion. The material properties depend strongly on the manufacturing and printing process

Figure 15. Materials for DLP. Source: S. Markus/Hochschule Düsseldorf.

Design guidelines

If you are designing explicitly for additive manufacturing there are some basic design rules to follow. In the following table you will find recommendations that will help you to design your component. DLP follows the same rules as SLA manufacturing.

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

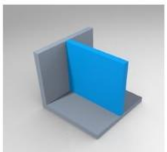
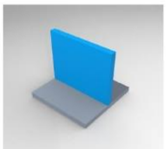
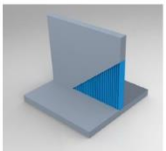
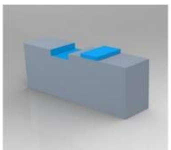
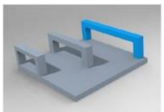
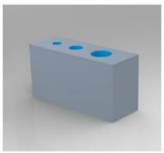
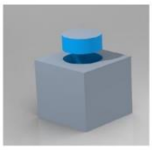
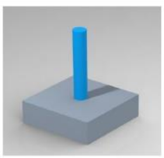
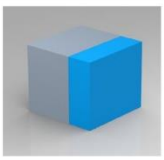
	**Supported walls** What's the minimum thickness?	0.5mm
	**Unsupported walls** What's the minimum thickness?	1mm
	**Support & Overhangs** Maximum angles of overhangs that can be printed without support	support always required
	**Engraved and embossed details** Minimum dimensions to print deepenings and elevations.	0.2 mm
	**Horizontal bridges** Bridge span which is printable without support	-
	**Holes** Minimum hole diameter	0.5mm
	**Moving/Connecting Parts** Recommended clearance between to parts	0.4 mm
	**Escape holes** Minimum excaphole size	3mm
	**Minimum features** Minimum size of small features to make them printable	0.2 mm
	**Minimum pin diameter** (For standalone pins)	0.5 mm
	**Tolerance** Expected dimensional accuracy	±0.5% (lower limit ±0.15mm)

Figure 16. Style-Guidelines for DLP. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

Industrial Case

Medical Applications

Models have so far been used in medicine primarily as visual aids or training aids. Especially with the possibilities of additive manufacturing, there is the additional possibility of generating highly precise, individual and scalable images from patient data. These can then be used to plan treatments and operations, as they accurately depict the case at hand and can thus make a significant contribution to treatment planning.

The advantages of Digital Light Processing (DLP) are the speed of printing and the high variability of printing parameters. The speed of printing is particularly important in surgical planning and treatment of intensive care patients. There, fast treatment is required and the time factor is therefore of high value. Furthermore, these models can also save costs, since much can already be aligned on the model rather than having to do it in surgery, which both saves costs and reduces the risk of the procedure for the patient.

Creating anatomic models

DLP offers many possible applications due to its high precision and fast printing time. Accurate images of body parts or organs can be created in a short time, which can provide opportunities for visualization of certain problems as well as for the production of templates or other aids. In addition, cross-sections can be created to visualize regions that are difficult to reach. These models can be used to test and preset aids for interventions, which in many cases can significantly reduce intervention time. The figure below shows a realistic replica of a heart. This enables, for example, the planning of intravenous interventions.

Figure 17. Anatomical model of a heart. Source: www.henkel.com

Example Scoliosis

Scoliosis is a common condition worldwide in which the spine is twisted and curved in the midsection. For treatment, a splint can be surgically attached to the spine, which performs a straightening and supporting function. A spine affected by scoliosis is shown below. It shows the complex misalignments that are possible with this disease.

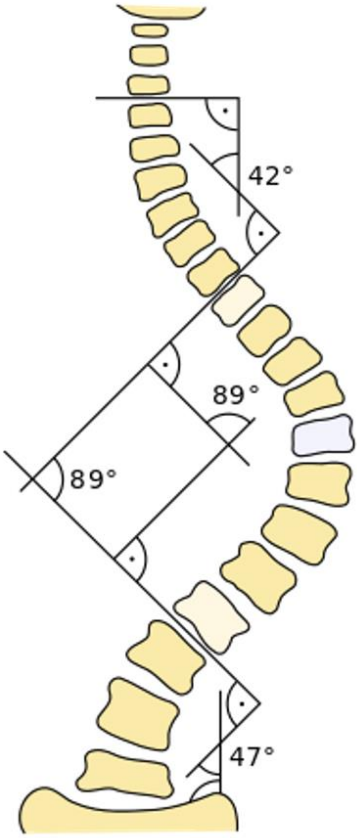


Figure 18. Distortion of a spine with scoliosis. Source: www.wikipedia.org

The illustration is only one of many possible ways in which scoliosis can develop. Each spine affected by scoliosis has its own individual misalignment, in which not only the angles but also entire curves can be different. For this reason, it is advisable to print a model of the affected spine in advance using DLP. With such a model, a general treatment method can be worked out. This can significantly shorten the duration of the operation and reduce the associated risk for the patient.

Quiz

DLP key advantage.

What is the key advantage of DLP in comparison to SLA?

☐ Support Structure.
☐ UV resistance of parts.
☐ Better resolution of all parts.
☐ Speed of printing.

MJF

Multi Jet Fusion

Multi Jet Fusion (MJF), introduced to the market by HP in 2016, is a fairly new technology moving toward industrial-scale ability. As with many 3D printing technologies, MJF is a powder-based 3D printing process. It is able to create functional prototypes as well as end-use production parts relatively fast. This technology is created for a professional environment and is not intended for the hobby sector – according to the current status. Correspondingly the machines are highly developed and designed for the highest demands.

This powder bed fusion 3D printing technology is often confused with two other types of 3D printing processes: SLS and Binder Jetting. None of the three processes are identical but similar in the sense that they all use thermoplastic powder, usually nylon. While Binder Jetting uses one binding agent to glue the powder particles together and SLS uses a laser to sinter the powder selectively, the MJF process works with a couple of different agents that interact with the powder in combination with an energy source to create parts.

Accordingly, MJF gets its name from the multiple inject heads that selectively apply fusing and detailing agents across a powder bed, which are then fused by heating elements into a solid layer. These agents aren't binders, rather they respond to the IR energy/ UV-light which is applied to it. After each layer, powder is distributed on top of the bed and the process repeats until the parts are complete. The fine-grained material, used within this process, allows very thin layers of 80 microns. This leads to parts with high density and low porosity. Because of that in combination with how the material is fused, the final parts exhibit quality surface finishes, fine feature resolution and isotropy (consistent) mechanical properties when compared to the other processes mentioned above. Isotropy properties means that there is no major difference between the x-, y-, and z-orientation, which make it superior to other (powder-based) technologies, especially with regard to the strength in the z-axis.

Figure 1. Part printed with the MJF process. Source: www.hp.com

Industries Using Multi Jet Fusion.

MJF has found use in several industries across the board because of its versatile application. This technology can be used for development processes, from prototyping to parts production. Typical industries, among others, are Automotive, Medical Engineering and Consumer Goods.

Pre-Processing

Before the actual print starts, the software, associated with the printer, takes over evaluating each part for selecting the optimal print orientation. They are then placed in the build envelope while the software takes care of a balanced height and pack density. In regards to this, the 3D file to be printed is rendered as voxels. Voxels contains the volumetric information to create the product. They represent essentially a three-dimensional equivalent of pixels that 2D printing relies on. Just like the principle of 2D printing, voxels are either fused into the final print or they aren’t.

Figure 2. Alignment of the components. Source: www.hp.com

General Process

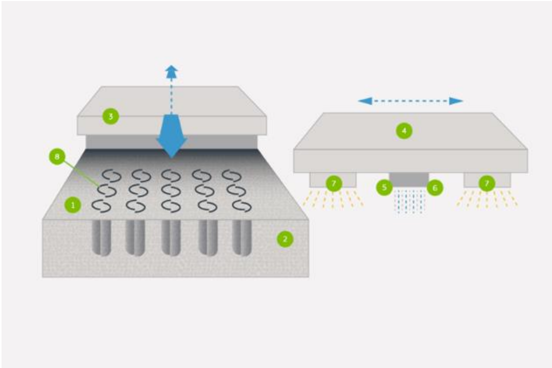


Figure 3. MJF printing process. Source: (cc) BY-NC-SA A. Hengstermann/Hochschule Düsseldorf.

After inserting the build unit into the processing station, the MJF printing process itself (seen in the picture above) starts by spreading a thin layer of powder across the build platform, where it is heated to a near-sintering temperature. The powder coating, applied by a recoater from top-to-bottom, has a thickness of 80 microns. Next, a carriage including the inkjet nozzles runs from left-to-right across the powder, jetting the agents onto it. A high-powered energy source passes over the building area in the same step. The process continues, layer-by-layer while the carriages change direction, until a complete part is formed.

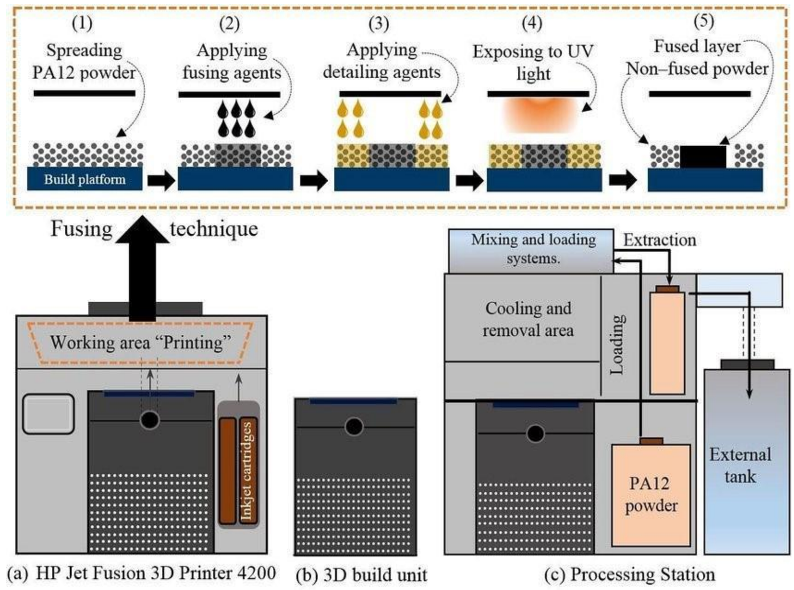


Figure 4. Overall MJF process. Source: (cc) BY-NC-SA A. Hengstermann/Hochschule Düsseldorf.

In terms of the fusion technique itself, there are effectively two agents that are printed onto the powder to increase the thermal selectivity during the printing process. The fusion agent is applied to the areas where the energy absorption should be increased. (2). The detailing agent is added to the boundaries of the part to prevent heat conduction from the part to the surrounding material. (3). That agent ensures a sharp and accurate part by effectively cooling down that area and stops the energies from being absorbed beyond the component boundaries. The fusion agent on the other hand absorbs IR energy and causes the sintering of the part areas. (4)

Post-Processing

After finishing the process, the 3D build unit (b) including the entire powder bed with the completed parts is moved to a processing station (c). There, the cooling process begins in a controlled manner to avoid deformation. A full build naturally cools in about 24 hrs. Following this, the parts are extracted while the loose powder can be removed by an integrated vacuum. The final step is bead blasting the parts to remaining unfused powder. Depending on the usage, an optional dyeing step can be applied to achieve a uniform black finish.

Watch the video "Multi Jet Fusion by HP"

Advantages and Disadvantages

Pros:

- Fast printing speed and production cycle
- Low cost per part
- Accurate printing, smooth surface areas
- Isotropy (consistent) mechanical properties
- Design freedom – no support needed
- High amount of recycled material (up to 80%) – less waste
- Ability to produce coloured parts

Cons:

- Expensive printer investment
- Limited material options
- Unable to produce hollow parts

Machine Costs

HP released various printer configurations that come with different hardware price tags, operation costs and yearly maintenance costs. The cost range of hardware across these machines is $57,000 -

$500,000. However, the less expensive machines typically have a higher cost of operation. In contrast, the more expensive machines have significantly lower operating costs at a higher number of pieces. The unit cost for 100 parts is about $13.99.

HP 300/500 series

Figure 5. JF 340. Source: www.3d-produktionsdrucher.de

The printer shown above is one of HP's more affordable machines, with a build volume of 254 x 190 x 248 mm. The cost of this AM machine is more than $57,000. For a printed part, which has a volume of about 15 cubic centimetres, the running costs are between $4 and $8, depending on the build height and packing density. Less than 100 parts per week can be produced. The yearly maintenance ranges from $10,000 - $15,000 per year. This includes remote problem diagnosis and support, onsite hardware support with all parts and labor included, and all firmware updates.

HP 4200 series

Figure 6. FJ 4200 and post-process station. Source: (cc) BY-NC-SA S. Markus/Hochschule Düsseldorf.

The price range for this series is $270,000 - $430,000. Because this series contains higher end machines than the 300/500 series, the printing costs are less expensive. They can achieve $2 - $4 per 15 cubic centimetres of printed part. The printer from this series can produce between 300 and 1000 parts per week and enables the entry into digital small batch parts production. With regard to the annual maintenance costs, which depend on the exact hardware configuration, such as the number of build units, printers and processing stations, these are generally higher at $35,000 to $43,000 per year.

HP 5200 series

Figure 7. FJ 5200 and post-process station. Source: www.3d-produktionsdrucker.de

The HP 5200 machines are the latest evolution of HP's Multi Jet Fusion technology. These machines are designed for actual manufacturing operations. The hardware costs are in range of $350,000 to $500,000, but the reliability, accuracy and low cost per part are unmatched in the industry. These machines can achieve a price of less than $1 per 15 cubic centimetres of printed part. With a build volume of 380 x 284 x 380 mm 300 to 1500 parts con be produced per week. The annual maintenance for this high-end production printers is $35,000 - $53,000.

Materials and their properties

The following figure shows an overview of the materials that can be used for Binder Jetting. The difference between the materials that can be used in this process should become clear.

Material	Multi Jet Fusion (MJF)								
	Powder Melting Point ASTM 3418	Particle Size ASTM 3451	Bulk Density of powder ASTM 1895	Colors	Stiffness	Elongation	Temperature Resistance	Chemical Resistance	Low Moisture Absorption
	[°C]	[microns]	[g/cm^3]	-	-	-	-	-	-
HP 3D HR PA 11	202	54	0.48	Black	Good	Good	Poor	Good	Poor
HP 3D HR PA 12	187	60	0.425	Black	Good	Fair	Fair	Good	Poor
HP 3D HR PP by BASF	138	62	0.34	Black	Fair	Fair	Fair	Best	Best
HP 3D HR PA Glass Beads	186	58	0.48	Black	Best	Poor	Good	-	Poor
HP 3D HR TPA by Evonik	152	77	0.42	Black	Poor	Best	Fair	Poor	Fair
HP 3D HR CB PA 12	189 *1	58 *2	0.442 *3	Multi-Color	Good	Fair	Fair	Good	Poor

*1 DIN EN ISO 11357
*2 ISO 8130/13
*3 ISO 60
Note: All specifications are to be seen in proportion. The material properties depend strongly on the manufacturing and printing process

Figure 8. Materials for MJF. Source: S. Markus/Hochschule Düsseldorf.

Design Guidelines

The following style guidelines should be considered when creating parts with MJF:

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

INDUSTRIAL EXPERT

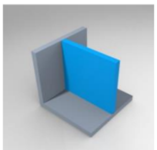
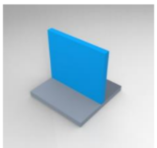
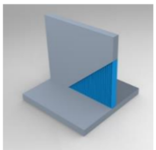
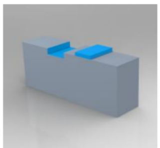
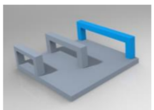
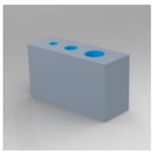
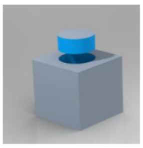
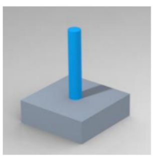
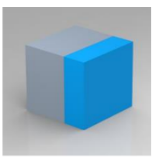
	**Supported walls** What's the minimum thickness?	0.5 mm
	**Unsupported walls** What's the minimum thickness?	0.5 mm
	**Support & Overhangs** Maximum angles of overhangs that can be printed without support	-
	**Engraved and embossed details** Minimum dimensions to print deepenings and elevations.	0.25 mm
	**Horizontal bridges** Bridge span which is printable without support	-
	**Holes** Minimum hole diameter	1.5 mm
	**Moving/Connecting Parts** Recommended clearance between to parts	0.5 mm
	**Escape holes** Minimum excaphole size	2.0 mm
	**Minimum features** Minimum size of small features to make them printable	0.5 mm
	**Minimum pin diameter** (For standalone pins)	1 mm
	**Tolerance** Expected dimensional accuracy	+0.3 mm / -0.002

Figure 9. Style-Guidelines for MJF. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

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https://all3dp.com/1/multi-jet-fusion-mjf-3d-printing-simply-explained/

https://www.materialise.com/en/manufacturing/3d-printing-technology/multi-jet-fusion

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https://www.hubs.com/knowledge-base/hp-mjf-vs-sls-3d-printing-technology-comparison/#what

http://blog.mastergraphics.com/expert_advice/how-much-does-the-hp-3d-printer-cost

https://www.hp.com/de-de/printers/3d-printers/software.html

Quiz

Steps in the MJF Process.

Why is step 4 (exposing to UV-light) in the process chain of MJF important for this process?

☐ The energy of the UV-light interacts with the applied agents to fuse the powder selectively.
☐ The UV-light by itself sinters the powder to get a solid part.
☐ The UV light is only used to heat up the chamber temperature.
☐ The UV-light hardens the parts after fusing them.

EBM

Electron Beam Melting (EBM)

The following figure shows the general structure of an EBM printer. The parts functions and the general process will be explained in the following.

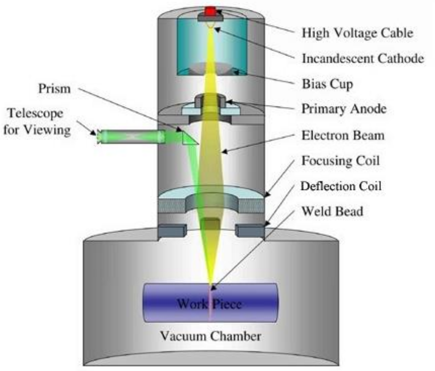


Figure 10. General structure Source: www.whiteclouds.com

Electron Beam Melting (EBM), first introduced to the market in 2002 by the Swedish company Arcam, is an additive manufacturing process for the production of metallic components from a powder bed and is therefore part of the "Powder Bed Fusion" family. As you have already learned, plastics are often used for industrial 3D printing. However, 3D metal printing in particular offers a wide range of advantages and is accordingly gaining more and more acceptance in the industry.

Like its name implies, this technology uses an electron beam as a heat source to fuse metal particles, primarily titanium alloys, and create the desired part layer by layer. The EBM process is performed in a vacuum, making it a suitable AM process for the production of materials that have a high affinity for oxygen. This technology is not able to print plastic or ceramic parts. This is because the technology is based on electrical charges. These charges create the reaction between the powder layer and the electron beam, causing the former to solidify. This process enables the production of complex, highly durable and at the same time lightweight structures. The technology is mainly used within the aerospace and medical industries and was developed for industrial application only. EBM produces parts faster than laser melting, but usually the result is less accurate and the surface is of lower quality because the powder is coarser-grained. It is worth mentioning that the company was acquired by GE Additive in 2016 and is now the only company marketing machines based on this process.

Pre-Processing

Before the actual printing process can begin, the 3D model is sent to a slicer software, which cuts the object into several layers corresponding to the material layers. The slicer, which was specially developed for the printer, sends all this information directly to the printer, which can begin its manufacturing process. The metal powder can then be filled into the machine's tank and the internal pressure has to be set to around 0.0001 mBar.

General Process

The printing process itself starts with spreading a thin layer of powder onto the build surface coating this area. Each layer is preheated with a defocused beam (700-1000 °C), and then the shape of the part is selectively melted, similar to SLM. The system repeats the process for each cross-section of the 3D CAD model until the shape of the required part is achieved.

Note that the entire manufacturing process must be done under vacuum to operate the electron beam properly. This also prevents the powder from oxidising when heated. At the end of the production process much of the unmelted powder can be almost directly reused.

For overhanging structures support structures are needed to help direct heat away from the molten powder to prevent wrapping and swelling of the part. However, residual stresses are low due to the preheating step for each powder layer, which helps keep heat in the build. In addition, both the energy density and scanning speed of the electron beam are generally much higher than SLM, making the build speed faster.

Post-Processing

After the manufacturing process is complete, the parts have to be removed from the machine. This starts by removing the excess powder with a blow gun for example. In the further process, the supports are removed, if any, and the components are detached from the plate. Further steps may include possible machining of the surfaces, polishing and coating using traditional techniques. In some cases, it may be necessary to heat the part in an oven for several hours to relieve the stresses slowly caused by the manufacturing process.

Watch the video [Direct Manufacturing with Arcam]

Advantages and Disadvantages

Pros:

- Production speed: The electron beam can separate to heat the powder in several places at once
- High density parts (up to 100%)
- High mechanical resistance of the printed parts
- Weight reduction
- Low risk of deformation
- Most of the unused powder can be recycled

Cons:

- Long cooling process
- Expensive to purchase and use
- Limited range of metals

- Rough surfaces
- Lower resolution and accuracy compared to Selective Laser Melting (SLM)
- Post-processing requires a lot of effort

Machine costs
Arcam Spectra H

Figure 11. Arcam Spectra H. Source: www.ge.com

The Spectra H from Arcam is an industrial 3D printer designed primarily for the aerospace industry. The price for the Spectra H is not listed on the official website, but is estimated to be between $100,000 and $250,000. The build volume of the Spectra H is one of Acram's smaller ones, with a diameter of 250 mm and a depth of 430 mm.
After printing, the entire build-up tank is removed and transferred to a powder recovery system. There, the parts are cleaned with compressed air as well as a newly developed magnetic separator. The costs for this system are not known, but represent without doubt a considerable additional investment.

Materials and their properties
Only a limited number of metals can be used within the EBM process, including titanium alloys, cobalt chrome, steel powder and nickel alloy 718. These materials have high strength, corrosion resistance and very good mechanical properties. For this reason, they can also be used for demanding applications in terms of load. It is important to note that any material used for EBM must be conductive, as the process relies on electrical charges.
Currently, EBM is the only commercial AM solution for additive manufacturing of titanium aluminide (TiAl) parts. This material is particularly known for its light weight, strength and heat resistance.
The following figure shows an overview of the materials that can be used for EBM. The difference between the materials that can be used in this process should become clear.

		Electron Beam Melting (EBM)						
		Ultimate Tensile Strength *1	Yield Tensile Strength *1	Elongation at break *1	Melting point *1	Size distribution by laser diffraction (ASTM B822)	Apperent Density ASTM B212	Flow Rate ASTM B213
Material		[Mpa]	[Mpa]	[%]	[°C]	[microns]	[g/cm^3]	[s]
	Cp-Ti grade 2	344	276 - 448	20-45	1,665	41 *2	2.6 *2	29 *2
	TI-6Al-4V grade 5	900	830	10	1,604 - 1660	38 *2	2.51 *2	26 *2
	Ni Alloy 718	1,100 - 1,375	980 - 1100	18 - 25	1,260 - 1,336	40 *2	4.74 *2	11 *2
	Al-Si10-Mg	360	220	7 - 12	-	28 *3	1.56 *3	76 *3
	316L	580	290	50	1370 - 1400	-	-	-
	CoCrMo	660 - 1280	450 - 840	8 - 35	1350 - 1430	-	4.0 *4	-

*1 The values represent general material properties. Not specifically for EBM powder. Unknown procedure
*2 SD: 15 - 53 microns; D50
*3 SD: 15 - 63 microns; D50
*4 SD unknown
Note: All specifications are to be seen in proportion. The material properties depend strongly on the manufacturing and printing process

Figure 12. Materials for EBM. Source: S. Markus/Hochschule Düsseldorf.

Design Guidelines

The following style guidelines should be considered when creating parts with EBM:

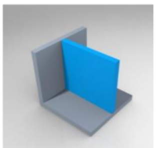
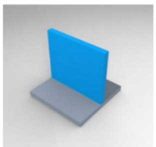
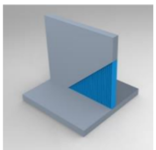
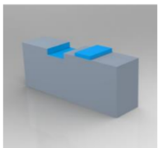
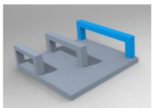
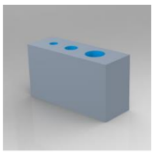
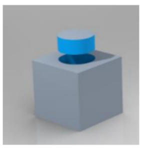
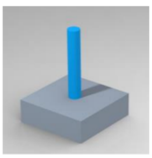
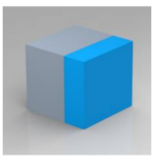
	**Supported walls** What's the minimum thickness?	0.6 mm
	**Unsupported walls** What's the minimum thickness?	0.6mm
	**Support & Overhangs** Maximum angles of overhangs that can be printed without support	45°
	**Engraved and embossed details** Minimum dimensions to print deepenings and elevations.	0.5 mm
	**Horizontal bridges** Bridge span which is printable without support	8 mm
	**Holes** Minimum hole diameter	0.8 mm
	**Moving/Connecting Parts** Recommended clearance between to parts	0.5 mm
	**Escape holes** Minimum excaphole size	2 mm
	**Minimum features** Minimum size of small features to make them printable	0.6 mm
	**Minimum pin diameter** (For standalone pins)	0.6 mm
	**Tolerance** Expected dimensional accuracy	±0.5 mm

Figure 13. Style-Guidelines for EBM. Source: L. Müller/Hochschule Düsseldorf.

Quiz

Pre-Processing in EBM.

What is an important step in pre-processing?

☐ Removing the build tank.
☐ Fill the machine tank with polymer powder.
☐ Setting the pressure to 0.0001 mBar.
☐ Use the software to divide the 3D object into vertical slices.

SLS

Printer structure and components

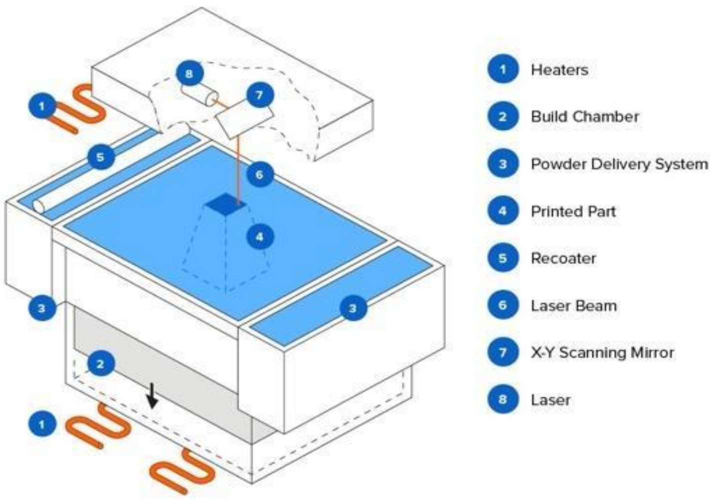


Figure 14. SLS structure. Source: www.formlabs.com

General Process

In selective laser sintering (SLS), a layering apparatus called a recoater distributes layers of powdered material, which are then fused together by a laser. This process allows a wide variety of materials to be processed, including plastics, metals and ceramics.

Other mechanisms involved in the process include a protective gas system and sometimes a powder preheating system. SLS can be used for polymers, metals and ceramics. SLS machines use a variety of lasers, including CO2, Nd:YAG, disk lasers and fiber lasers. This technology can create parts that are finely detailed, strong, durable, heat resistant and flexible (if needed).

Choosing the right laser is important because it significantly affects the way the powder fuses. The ability of the laser to absorb into the material depends on the laser wavelength used, while the densification of the powder depends on the correct laser energy density.

Selective Laser Sintering is mainly used in the professional environment. There is hardly any use in the hobby sector. Accordingly, the machines are highly developed and designed for the highest requirements. Traditional industrial SLS 3D printing systems use single or multiple high-powered lasers. The printing process requires an inert environment - nitrogen or other gases - to prevent oxidation and decomposition of the powder, which necessitates special air treatment equipment. These machines also require a dedicated HVAC system and industrial power, and even the smallest industrial machines take up at least 10 square metres of installation space.

Meanwhile, there are printers for the semi-professional area from about 10000€. Printer manufacturers of professional equipment often boast that SLS prints compete with injection molded products in terms of strength and precision.

Typical industries are the following:

- Automotive.
- Templates and fixtures.
- Sand casting models.
- Tooling.
- Aerospace.
- Medical and healthcare applications.
- Consumer electronics.
- Packaging.
- Military applications.

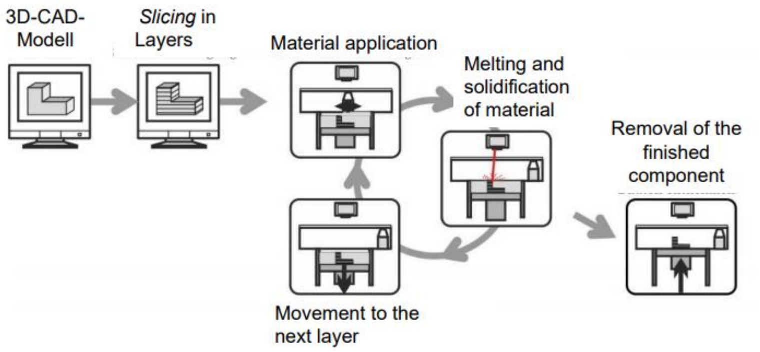


Figure 15. Process of SLS. Source: B. Leutenecker-Twelsiek/Hochschule Düsseldorf.

Figure 16. Example of SLS detail possibilities without supports. Source: L. Müller/Hochschule Düsseldorf.

SLS printers have a more limited plastic material range than technologies like FDM, mostly limited to nylon polyamide powder. Some are limited to black PA12 only, while others can print powders such as PA11 and PA6. In the industrial arena, glass blends, carbon fiber blends and even food-grade powders are also being used for niche applications. More and more SLS printers can print TPU, a flexible rubber-like material. Metal powders can also be sintered, but these are more commonly produced using the art-managing DMLS process.

Process flow - printing, cooling, finishing.

Printing: the powder is spread in a thin layer on a platform in the build chamber. The material is preheated to just before the melting point. The laser then scans a cross-section of the 3D model and heats the powder to just below or directly to the melting point of the material. This mechanically fuses (sinters) the particles together, creating a solid part. The unfused powder supports the part during printing, eliminating the need for special support structures. The platform then lowers one layer into the build chamber, typically between 50 and 200 microns, and the process repeats for each layer until the parts are complete.

Cooling: after printing, the build chamber cools in a controlled manner. This is done to avoid warping and to achieve the best possible material properties. This process can take longer than the actual printing process.

Finishing: the finished parts must be removed from the build chamber, separated and cleaned of excess powder. The powder can be recycled and the printed parts can be further processed by blasting or tumbling.

Watch the video [Process of SLS]

Advantages and Disadvantages

Each manufacturing process has its individual advantages and disadvantages. The following are the main advantages and disadvantages of SLS.

Pros:

SLS parts are stable and suitable for highly functional parts

- Complex geometries possible
- Integration of different part functions
- Prototypes & end user parts
- No support required / Self-supporting
- Low residual stresses
- Process stability
- Good mechanical properties
- Low anisotropy
- No tooling required

Cons:

- Rough surface of the parts
- Surface porosity of the parts (Solution: application of sealant)
- High cleaning effort after printing
- Protective equipment needed for very fine powders

Figure 17. Example of special wooden sintered material. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

Machine Costs

Prototype and Development

In prototyping and development, semi-professional SLS printers are a good way to achieve results quickly and comparatively cheaply. Typically, the devices cost between **5000€** and **25000€** (as of 2021). SLS prints at this price point are the first reasonable introduction to the technology and help evaluate whether the technology is a good fit for the business. Manufacturers such as Formlabs and Sintratec. Typical build volume in this price range is 110x110x110 mm to 200x 200 x 300mm with Layer Thickness around 0.1mm. Most of the time just a few materials are supported.

Figure 18. Sintratec Kit. Source: www.sintratec.com

Manufacturing

In the large format and manufacturing sector, SLS printers are available in the price range from **100000**€ to **500000**€. In industrial manufacturing, SLS shows its strengths. Typically, the build space is in a range of 300 x 300 x 300mm to 500 x 500x 1000mm with a minimum layer thickness of 0.1mm. Typical suppliers are EOS, Sintratec, Shining 3D and 3D Systems.

Figure 19. EOS P 770. Source: www.hartwiginc.com

Watch the video **EOS printer**

Materials and their Properties

Typical materials used in SLS are PA12, PA11, PEEK, PEBA (TPA), Alumide, Carbon filled polyamide and Glass filled polyamide. An overview of the properties can be found in the following table.

Material	Selective Laser Sintering (SLS): Ultimate Tensile Strength *1 *2	Yield Strength *2	Elongation at break *2	Melting point	Density	Heat Deflection Temperature (1.80 Mpa) *2	Color
	[Mpa]	[Mpa]	[%]	[°C]	[kg/m^3]	[°C]	-
PA 12 (PA 2200)	48	-	18	176	930	70	White
PA 11 (PA 1101)	48	-	45	201	990	46	White, Black
PEKK (HT-23)	71	-	1.16	302	1390	212	Gray
TPU (EOS TPU 1301)	7	-	250	138	1080	-	White
Polysterene (Primacast 101)	5.5	-	0.4	229 - 555 *3	770	-	Gray
AlSi10Mg	460	245	5	-	2670	-	Metal
Stainless Steel 316L	590	500	47	-	7980	-	Metal
Nickel Alloy In625	920	670	40	-	8400	-	Metal
Titanium Ti 64	1055	945	13	-	4400	-	Metal

*1 Tensile Strength for polymers
*2 Unknown procedure
*3 Decomposition temperature
Note: All specifications are to be seen in proportion. The material properties depend strongly on the manufacturing and printing process

Figure 20. Materials for SLS. Source: S. Markus/Hochschule Düsseldorf.

Design Guidelines

If you are designing explicitly for additive manufacturing then there are some basic design rules to follow. In the following table you will find recommendations which will help you to design your component.

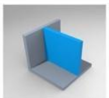
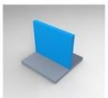
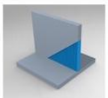
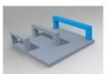
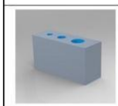
	**Supported walls** What's the minimum thickness?	0.6mm
	**Unsupported walls** What's the minimum thickness?	-
	**Support & Overhangs** Maximum angles of overhangs that can be printed without support	not needed at all
	**Engraved and embossed details** Minimum dimensions to print deepenings and elevations.	0.8mm
	**Horizontal bridges** Bridge span which is printable without support	-
	**Holes** Minimum hole diameter	1.5mm
	**Moving/Connecting Parts** Recommended clearance between to parts	0.3mm moving parts 0.2 connections
	**Escape holes** Minimum excaphole size	>4mm
	**Minimum features** Minimum size of small features to make them printable	0.8 mm
	**Minimum pin diameter** (For standalone pins)	0.8 mm
	**Tolerance** Expected dimensional accuracy	±0.3% (lower limit ±0.3mm)

Figure 21. Style-Guidelines for SLS. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

Watch the video "5 Reasons why Selective Laser Sintering could be the right 3D technology for you! – by Sintratec"

Pre-processing

Slicing Software and Orientation

You can find sample slicing software for your part at the following links. If you are using professional equipment, manufacturers usually offer specially tailored software. Sintratec Central and Formlabs

Preform can be used to get a feel for the SLS process. Especially in the industrial area you get customized software and support from the manufacturer.

[Sintratec Central](#)
[Formlaps Preform](#)

Test your Setup
So that they can try out their printer or printing service once. Simply download our benchmark component. The best-known benchmark component is probably the Benchy. You can find it in the second link.

[INDEX Benchmark](#)
[Benchy](#)

Watch the video Slicer in SLS

Post-Processing

Post-processing in the SLS field is an important area. Since the workpieces are enclosed in powder, they must be cleaned from the powder. The protective equipment recommended by the manufacturer is important. Extraction systems, gloves and recycling environments are strongly recommended. There are different finishing methods for SLS. The minimum is the removal of the powder, but tumbling methods are also common. These polish the surface through granules as in a kind of washing drum. The edges become rounder and the surfaces smoother. Dyeing in hot colour baths is also a common finishing process.

Problems

The temperature distribution in the printing chamber is decisive for the print quality. If hotspots form due to material accumulation, problems may occur. It is important to fill the build space evenly and to position the components slightly diagonally to the axes if possible. In this way, the laser does not remain in one position for too long and there are fewer hotspots in the powder.

Further troubleshooting help can be found here, for example.

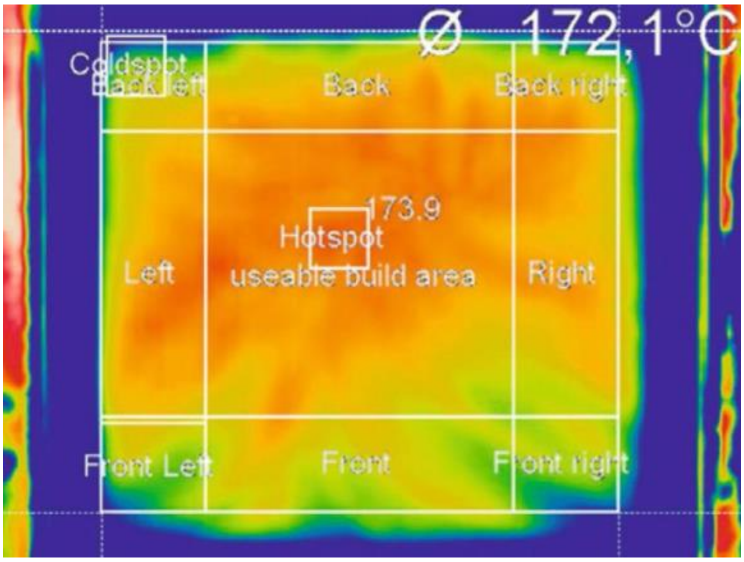


Figure 22. SLS heat map. Source: (cc) BY-NC-SA B. Leutenecker-Twelsiek/Hochschule Düsseldorf.

Industrial Case

Paddle wheel of a floating water pump

The process mentioned above is used e.g. for printing a prototype of a paddle wheel for a floating water pump used by firefighters.

Due to global warming, forests worldwide are becoming drier in the summer months. This makes forests more sensitive to fires. Regions where the number of forest fires is increasing due to global warming are, for example, California and Australia.

Here, the idea was to improve the performance of the water pumps used by designing a more powerful impeller. By improving the blade shape of the impeller, more pressure can be generated and water can be pumped into the water hoses more quickly, thus increasing efficiency.

Since an impeller is usually casted, different areas, such as design, machining and non-cutting manufacturing, have to work together. By the time a prototype is made, a relatively large amount of time is lost due to the traditional steps. By producing a prototype with the SLS process, one wanted to avoid these work steps.

The technological process could be accelerated by 30 percent just printing the prototype. The number of work steps to be carried out was also reduced from eight to two. In summary, the component is designed in CAD software and printed using the SLS process. Due to the high precision of the print, post-processing was not necessary in the use case. Likewise, no support structures are needed when printing with the SLS process, which contributes to the fact that cleaning the component takes less time. It should also be mentioned here that additive manufacturing allows relatively quick changes to be made to the model, so that different design variants can be tested more quickly.

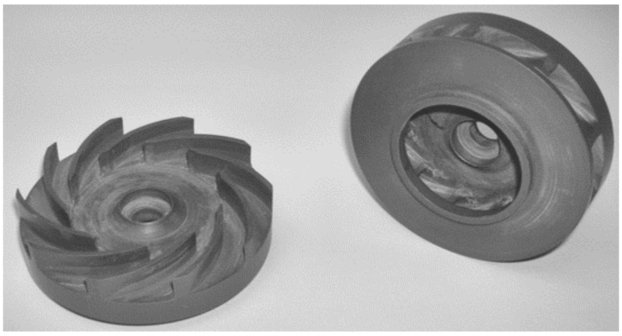


Figure 23. Impeller. Source: www.mb.uni-siegen.de

Quiz

Advantages of SLS.

What is not an advantage of SLS?

☐ No support structure needed.
☐ Smooth surface.
☐ Good isotropy properties.
☐ Functional parts for prototypes and end use parts can be produced.

SLM

Selective Laser Melting

Selective laser melting (SLM) started in 1995 at the Fraunhofer Institute ILT in Aachen, Germany, with a German research project. It is an industrial metal 3D printing process that builds objects layer by layer using high-power laser beams to fuse and melt metallic powder together. A range of metals produce final parts that can be used for end-use applications. These parts fulfil high material requirements, such as very good thermal resistance and mechanical resilience. Accordingly, SLM is considered one of the most versatile 3D printing processes and is a real alternative to welding, milling or casting material.

The innovation potential of laser melting is very high, because manufacturing no longer limits design possibilities. Components that were very expensive or impossible to produce are suddenly realisable, even for very small quantities. On the one hand, selective laser melting is often used in rapid prototyping. But on the other hand, the 3D printing process is also a valid option to conventional processes for the production of small series. In addition, this process is being used more and more for components that are based on a very complex or lightweight design.

Figure 24. Metal part with a complex shape produced via SLM. Source: www.phoenixdeventures.com

Therefore, it is not only the classic customers of high-tech components such as aerospace or the automotive industry who benefit from this. Sectors such as mechanical engineering, toolmaking or medical technology also enjoy the benefits of 3D metal printing today.

Pre-Processing

Similar to other layer additive manufacturing technologies, first a program takes the 3D CAD model and slices it into 2D cross-sections. These cross-sections contain the structure that the laser must follow in order to selectively melt the material at the right spots.

The metal 3D printing process has a high degree of freedom in the design of components. Nevertheless, SLM requires support structures to be added on any overhanging features which are generated by the software mentioned above. Otherwise, process errors can arise because of the material weight. Due to the large temperature difference between the new component layer and the already cooled layers, undesirable effects can occur, such as warping. To avoid this, the whole part is firmly welded to the base plate by support structures.

General Process

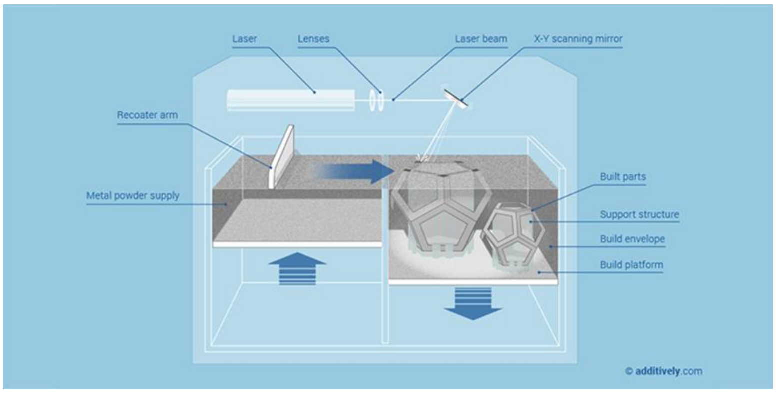


Figure 25. Selective Laser Melting process. Source: www.additively.com

To get started, loose powder is applied in a thin layer evenly on the building platform with the help of a blade or a roller. One or several laser beams are then deflected onto the powder surface so that the focus point of the laser traces the contours of the component layers. The cross-section area of the designed 3D part is then built by selectively melting and re-solidifying the metallic powders. To create another layer, the build platform is lowered by the layer thickness and a new layer of powders are deposited and levelled by the re coater again. To complete the building process, the steps are repeated until all layers have been fused and melted together according to the CAD Design.

Post-Processing

The completed part is then removed from the base plate which is often done with a bandsaw. After any support structures are detached, the part can be treated with an age hardening heat process to further harden it. In most cases, the parts are also sandblasted.

Because of the rough surface finish, this technology can be combined with conventional production processes for reworking steps such as surface treatment, welding, milling or eroding. This is also common to achieve fine tolerances for example.

Watch the video [Process of SLM]

Watch the video [Process of SLM with a Lasertec 30 SLM]

Advantages and Disadvantages

Pros:

- Dense functional parts made of various metallic materials.
- highly complex geometries and moving parts can be realised.

- Tool-free production, extremely fast and reliable.
- High mechanical resistance.
- Good reworking possibilities.
- Low waste.

Cons:

- Expensive.
- Special skills and knowledge in design and manufacturing are required.
- Relatively large machines.
- limited to relatively small parts.
- rough surface finish – post-processing needed.

Machine costs

Trumpf TruPrint 1000 LMF

Figure 26. Trumpf TruPrint 1000. Source: www.trumpf.com

This printer is an industrial metal 3D printer based on the SLM technology. The build chamber has a size of 100 x 100 x 100 mm. The price for this machine is about $250.000. Additional cost apart from the powder would include post-processing methods, like sanding and polishing.

SLM 125

Figure 27. SLM 125. Source: www.slm-solutions.com

SLM Solution is the leading provider of industrial 3D printing machines. The smallest base machine with a build chamber size of 125 x 125 x 125 mm is the SM 125 which uses a single laser for melting the powder. It is designed for the use of multi-materials. The price for this machine is around $400K to $500K.

SLM 500

Figure 28. SLM 500. Source: www.slm-solutions.com

The SLM 500 in contrast has a significantly bigger build chamber with a size of 500 x 280 x 365 mm. In addition, this machine uses multiple lasers (twin or quad) which makes the process much faster. It comes with features like automated powder handling and a turnkey system including a part removal station. This together is $1M to $2M worth.

Materials and their Properties

The following figure shows an overview of the materials that can be used for SLM. The difference between the materials that can be used in this process should become clear.

	Selective Laser Melting (SLM)						
	Tensile Strength *1 *3	Offset Yield Strength *1 *3	Elongation at break *1 *3	Reduction of area *1 *3	Build-up rate *2 *3	Particle Size *4	Density
Materials	[Mpa]	[Mpa]	[%]	[%]	[cm^3/h]	[microns]	[kg/m^3]
Al-Alloy AlSi10Mg	454	297	8	9	24.5	20 - 63	2670
Fe-Alloy 316L	682	591	39	66	10.4	10 - 45	7900
Fe-Alloy Invar 36	508	404	31	71	10.0	10 - 45	8100
Ni-Alloy In625	1072	737	31	35	10.37	10 - 45	8440
Ti-Alloy Ti6Al4V	1281	1076	8	19	18.14	20 - 63	4430
Co-Alloy CoCr28Mo6	1269	824	13	10	11.0	10 - 45	8470
Cu-Alloy CuNi2SiCr	314	260	36	79	11.7	20 - 63	8840

*1 Tensile test according to DIN EN ISO 6892-1
*2 Theoretical build up rate for comparison
*3 Layer thickness of 30 microns
*4 With respect to powder material
Note: All specifications are to be seen in proportion. The material properties depend strongly on the manufacturing and printing process

Figure 29. Materials for SLM. Source: (cc) BY-NC-SA S. Markus/Hochschule Düsseldorf.

Design Guidelines

The following style guidelines should be considered when creating parts with Binder Jetting:

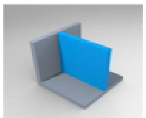
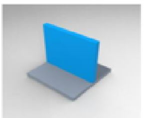
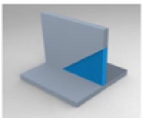
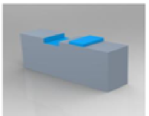
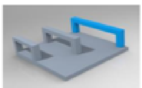
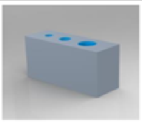
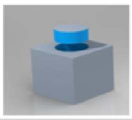
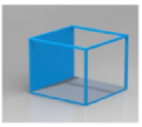
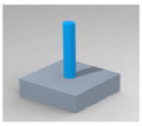
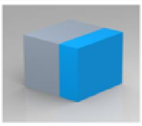
	**Supported walls** What's the minimum thickness?	0.5 mm
	**Unsupported walls** What's the minimum thickness?	0.5 mm
	**Support & Overhangs** Maximum angles of overhangs that can be printed without support	45°
	**Engraved and embossed details** Minimum dimensions to print deepenings and elevations.	0.2 mm
	**Horizontal bridges** Bridge span which is printable without support	1 mm
	**Holes** Minimum hole diameter	0.5 mm
	**Moving/Connecting Parts** Recommended clearance between to parts	0.5 mm
	**Escape holes** Minimum excaphole size	>2.0 mm
	**Minimum features** Minimum size of small features to make them printable	0.5mm possible; >1.0mm recommended
	**Minimum pin diameter** (For standalone pins)	1.0 mm
	**Tolerance** Expected dimensional accuracy	XY- Direction ±0.125 mm,1 Layer in Z-Direction

Figure 30. Style-Guidelines for SLM. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

Industrial Case

Orbex Raketenantrieb

Selective Laser Melting makes it possible to manufacture rocket boosters completely in a single printing process. The fast iteration times of the SLM process also lead to time and cost savings: c ost savings of 90% in machining time and of more than 50% compared to traditional CNC machining had been achieved. The Orbex rocket engine was manufactured in the SLM-800, which has an installation space of 500x280x850 mm.

Figure 31. Rocket booster. Source: www.industrieanzeiger.industrie.de/news

Quiz

Process of SLM.

How are the objects produced in this process?

☐ Powder is fused together with a binding agent.
☐ An electron beam is used to melt metallic powder.
☐ Deflected UV-light causes heat to fuse the metallic powder selectively.
☐ High-power laser beams are used to fuse and melt metallic powder together.

DED

Printer Structure and components

There are several **D**irected **E**nergy **D**eposition (DED) processes in existence. Among the most relevant are **L**aser **E**ngineering **N**et **S**hape (LENS) and **E**lectron **B**eam **A**dditive **M**anufacturing (EBAM). The following figure shows these two processes and their structure. The core element of LENS is the nozzle, which delivers a combination of inert gas and powder towards the base plate. The powder is then melted by a laser. EBAM, on the other hand, uses wire that is provided by a wire feeder. This wire is melted by using an electron beam. Therefore, the process must take place in a vacuum, otherwise the electron beam would interact with electrons from the atmosphere.

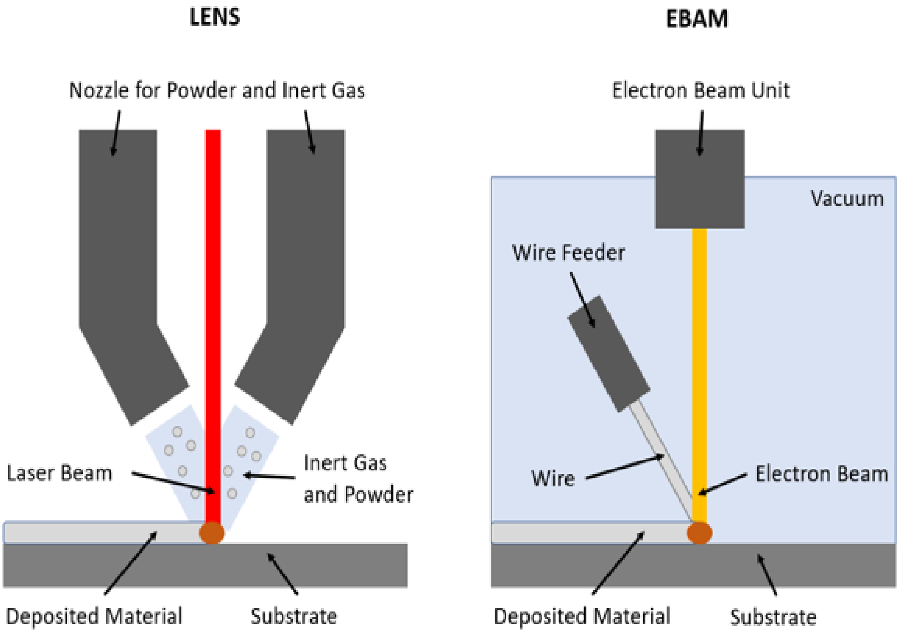


Figure 1. DED in the form of LENS and EBAM. Source: (cc) BY-NC-SA S. Markus/Hochschule Düsseldorf.

General Process

The Directed Energy Deposition (DED) uses an energy beam to directly melt material onto a substrate. This energy beam can be a laser or an electron beam. The energy beam used depends on the exact process that is chosen. The processes are generally based on a nozzle or a feeder with a beam unit that is mounted to a multi axis arm and a base plate which, depending on the machine, can be static or also multiaxial.

In general, DED often uses metal wire or powder to process. The variety of possible metals is high: titanium, Inconel, tungsten, stainless steel, steel, aluminium, copper and nickel as well as many other metals. The metal wires can vary between 1-3 mm and the diameter of the powder between 50-150 microns. Also, polymers and ceramics are possible to manufacture but play a rather subordinate role. Due to its fixed cost structure, post-processing requirements and low resolution DED is used in low volume manufacture of middle or big sized parts. Some industry sectors where these boundary conditions for near-net-shape parts are present are aerospace, defence, energy and marine. Feature addition and repair bring revolution to a market. Previously, these tasks could only be done manually.

With DED already existing parts can be modified or repaired automatically with a good accuracy.

Watch the video [What is DED?]

Advantages and Disadvantages

The following list shows the main advantages and disadvantages of DED in general, without differentiating into further subcategories such as LENS or EBAM. The other manufacturing methods serve as a reference for comparison. If a point refers to something specific, this is indicated in brackets.

Pros:

- High build rates
- Dense and strong parts
- Material and manufacturing costs are low
- Near net shape (cf. machining)
- Wide range of metal materials
- Large build size
- Editing and repairing existing parts

Cons:

- Low print resolution
- Low volume manufacturing
- Gas / vacuum chamber or local shielding needed
- High energy consumption
- High capital cost

Machine Costs

Optomec CS 250 System - Printer with Powder and Laser: 200,000 $

Suitable for Research and development, alloy development, prototyping and repairing. Parts to process can have dimensions up to 250 x 250 x 250 mm. The printer has an All-in-One compact machine enclosure, a 3-5 axis CNC control system, up to 4 integrated powder feeders and 500 to 2000 W fibre lasers.

Figure 2. Optomec CS 250 System. Source: www.optomec.com

Sciaky EBAM 300 System – Printer with Wire and E-Beam: 2,000,000 $

This metal 3D printer provides the largest build envelope in the market with a working space of 5791 x 1219 x 1219 mm. The printer also has X, Y & Z Servo axes with multiple part positioner and CNC control–joint scanning and digitizing system.

Figure 3. Sciaky EBAM 300 System. Source: www.sciaky.com

Materials and their properties

The following figure shows an overview of materials that can be used for DED. Material for DED can be in wire or powder form. Therefore, only the general mechanical and physical properties are given in the following table.

		Directed Energy Deposition (DED)				
		Ultimate Tensile Strength *1	Yield Tensile Strength *1	Elongation at break *1	Density *1	Melting point *1
Material		[Mpa]	[Mpa]	[%]	[kg/m^3]	[°C]
	Cp-Ti grade 2	344	276 - 448	20-45	4510	1,665
	TI-6Al-4V grade 5	900	830	10	4430	1,604 - 1660
	Ni Alloy 718	1,100 - 1,375	980 - 1100	18 - 25	8190	1,260 - 1,336
	Al-Si10-Mg	360	220	7 - 12	2670	570
	316L	580	290	50	8000	1370 - 1400
	CoCrMo	660 - 1280	450 - 840	8 - 35	8300	1350 - 1430

*1 The values represent general material properties. Not specifically for DED powder. Unkown procedure
Note: All specifications are to be seen in proportion. The material properties depend strongly on the manufacturing and printing process

Figure 4. Materials for DED. Source: S. Markus/Hochschule Düsseldorf.

Design Guidelines

The following style guidelines should be considered when creating parts with DED:

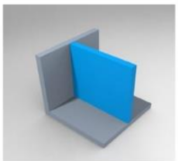
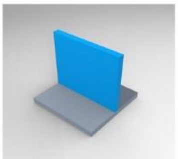
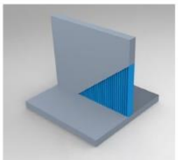
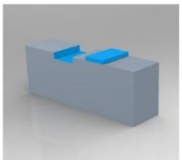
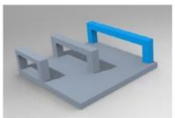
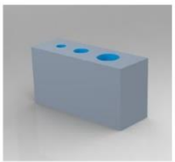
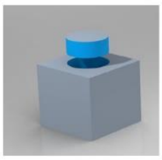
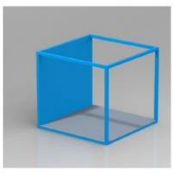
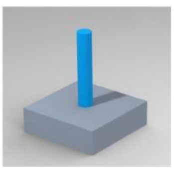
	**Supported walls** What's the minimum thickness?	0.4 mm
	**Unsupported walls** What's the minimum thickness?	0.5 mm
	**Support & Overhangs** Maximum angles of overhangs that can be printed without support	always needed
	**Engraved and embossed details** Minimum dimensions to print deepenings and elevations.	0.1mm
	**Horizontal bridges** Bridge span which is printable without support	2.0 mm
	**Holes** Minimum hole diameter	1.5 mm
	**Moving/Connecting Parts** Recommended clearance between to parts	-
	**Escape holes** Minimum excaphole size	5.0 mm
	**Minimum features** Minimum size of small features to make them printable	0.6 mm
	**Minimum pin diameter** (For standalone pins)	1 mm

Figure 5. Style-Guidelines for DED. Source: L. Müller/Hochschule Düsseldorf.

Pre-Processing

As in all additive manufacturing processes, a 3D model is needed. This 3D model (mostly an STL-file) will then be transformed in a GCODE-file. A slicer software is used to realize this. After importing the 3D model to the slicer, the process settings have to be adjusted. Some important settings for DED are hatch spacing, laser power, layer height and scan speed. In most of the programs it is also possible to show the deposition of material onto the substrate. This is a good way to validate the settings.

One of the most important process properties is the heat transfer. It can be influenced by the geometry but also by the process settings. The following video shows how important it is to choose appropriate processing settings for certain geometries:

Watch the video Errors in the DED process due to Pre-Processing

Post-Processing

In general, DED is used to create near-net-shape parts.

This means that the part that is being created in the process is not in its final shape, but instead in a shape that is very close to the final part. To finish the part post-processing is needed e.g., machining. If the part does not have to meet precise geometry requirements, you can dispense with post-processing like machining, because the material properties are already in its final state after the DED process.

The substrate removal, must be performed for each created part instead. In general, it is not a feature of the created part and therefore must be removed. The substrate's function is to serve as a building plate and additionally helps with heat transfer. Because of the heat that is acting on the substrate, distortion or even cracks are a serious issue. This issue can be solved through integrating the substrate into the final part and compensating the residual stresses by alternating the layer deposition between both sides of the substrate.

Since DED is primarily creating parts out of metallic materials, such as steel, it is possible to perform a heat treatment to further improve the mechanical properties of the part. A heat treatment can also be useful when adding features to an already existing part. The newly added features have different material properties than the rest of the part. A heat treatment can help to converge the properties of the new and already existing part.

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

INDUSTRIAL EXPERT INDEX

Quiz

Environment of EBAM.

What environment is needed to use the EBAM process?

☐ Argon.
☐ Vacuum.
☐ Oxygen.
☐ Atmosphere.

Binder Jetting

Printer Structure and Components

The following figure shows the general parts of a Binder Jetting (BJ) printer. The parts' functions and the general process will be explained in the following.

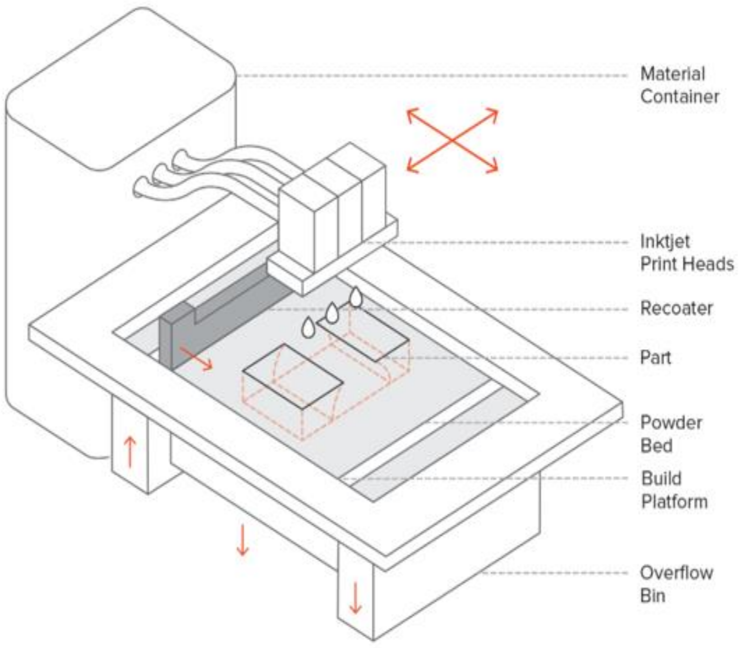


Figure 1. Structure of a Binder Jetting printer. Source: www.hubs.com

General Process

In general, Binder Jetting uses a binding agent which is applied on powder to glue it together. This powder can be made out of metals or ceramics (sand). Furthermore, it is possible to not only provide binding agent through the nozzle but also multi-colour ink to create colourful parts. Colours are generally used with ceramics to create prototypes, visual models, or decorative items. It is also possible to create sand casting cores and molds with BJ, as well as metal parts. When using metal powder to create final parts it is important to note that BJ only creates green parts. These must then be post-processed to reach good mechanical properties. Processes to increase the mechanical properties are infiltration and sintering.

As all additive manufacturing processes, BJ is also a layer-by-layer process. Therefore, the recoater is used to provide the build platform with a thin layer of the chosen powder. The powder is provided by a powder bin and the excess powder is stored in an overflow bin. In the next step the inkjet print head travels over the powder bed and supplies specific areas with binding agent and optionally also with coloured ink. The areas where the binding agent must be applied in every layer is defined by the pre-processing software. After finishing a layer, the build platform will be lowered by one layer and the recoater again provides the build platform with new powder. This process will be repeated until the part is fully built. Depending on the chosen material, post-processing is needed after removing the parts from the building plate and the excess powder from the part with pressurized air.

One of three big application areas are **sand casting models**. Models created by BJ can have an intricate shape because of the powder that surrounds the printed part. This allows the creation of casting models that are not possible with conventional processes. As a binding agent, furan binder is commonly used. Also, large casting models can be created at relatively low cost. Furthermore, there is no need for post-processing. The printed cores and molds can directly be used for casting.

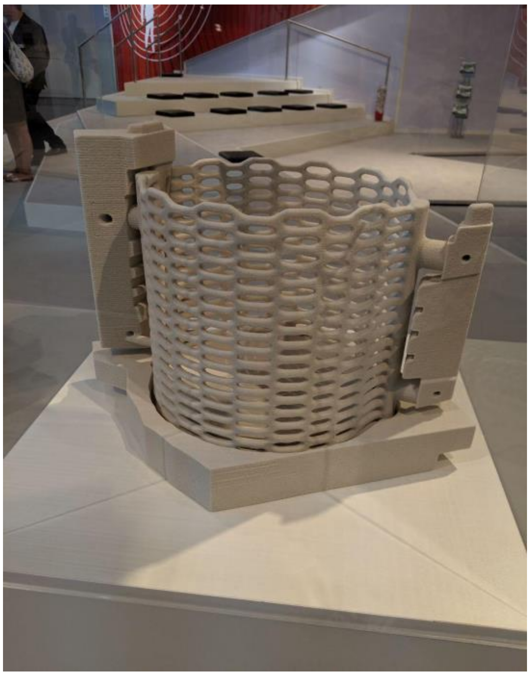


Figure 2. Example of a casting core. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

Also, it is possible to print **multicolour models** with BJ. These multicolour models can function as prototypes, visual models (e.g., in architecture) or decorative items and are widespread because of the low costs. The models are generally made from sandstone or PMMA powder. Phenol and silicate binder are commonly used as a binding agent in this area of application. After the printing process is finished, cyanoacrylate is often used to improve the mechanical and visual properties of the part.

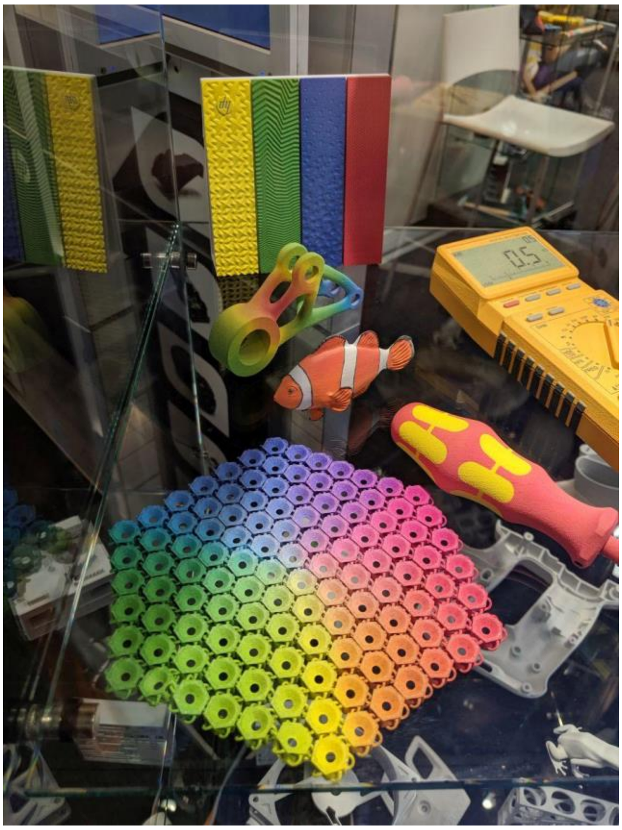


Figure 3. Example of multicolour models. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

The third area of application is **models out of metal**. Metal powders which can be used for BJ are stainless steel, inconel, copper, titanium and tungsten carbide. A liquid polymer binder is generally used in the process as a binding agent. Metal Binder Jetting can be used in low-to-medium production and enables one to create intricate shapes without the need of support material. During the BJ process green parts are being created. Therefore, post-processing is needed in the form of infiltration or sintering. The post-processing must be taken into account in the modelling process, because it has an impact on the geometry due to shrinking.

Watch the video [Binder Jetting with Metals]

Advantages and Disadvantages

The following list shows the main advantages and disadvantages of Binder Jetting, without differentiating into further subcategories such printing ceramics, metals and composites. The other manufacturing methods serve as a reference for comparison. If a point refers to something specific, this is indicated in brackets.

Pros:

- Multifunctional (Prototypes, final metal parts, sand casting cores and molds)
- High resolution (up to 30 microns)
- Low cost printed parts
- No distortion or curling during the process
- Full color options
- Large build volumes
- Multiple parts at once printable
- No support structures needed

Cons:

- Metal parts need to be sintered or infiltrated
- Metal parts have lower mechanical properties than DMLS/ SLM parts
- Limited material selection
- Shrinking during infiltration and sintering
- Low mechanical properties in green state

Machine Costs

The Binder Jetting process can be used for industrial and research application. For private use it is generally not suited because of high acquisition costs and printing metal requires additional post-processing that can only be done by other machines.

ExOne Innovent+: 100,000 – 250,000 $

This is a small multi-purpose 3D printer that can print a wide range of metals powders as well as ceramic, composite and other powders. The printer is ideal for printing in a research or training environment, but also in the industry for development. The build volume is 160 x 65 x 55 mm and the layer height can be varied from 30 – 200 microns. This printer also has a build rate of 166 cc/h.

Figure 4. ExOne Innovent+. Source: www.exone.com

Digital Metal DM P2500: > 250,000 $

This printer has a very good accuracy of 1 micron and is therefore perfectly suited serial production and precise prototyping. The build volume of this printer is 203 x 180 x 69 mm and layer height can go down to 35 microns. The printer has also a build rate of 100 cc/h.

Figure 5. Digital Metal DM P2500. Source: www.digitalmetal.tech

ExOne X1 160Pro: > 150,000 $

This is the largest printer of the company ExOne that can print metal, ceramic and composite powders and is especially suitable for ultra-fine powder which leads to very dense green parts. This density is important when considering the post processing. The denser the green part is, the less distortion takes place. X1 160 Pro has a build volume of 800 x 500 x 400 mm and the layer height can be varied between 30 – 200 microns. It also prints at a very high build rate of more than 10,000 cc/h.

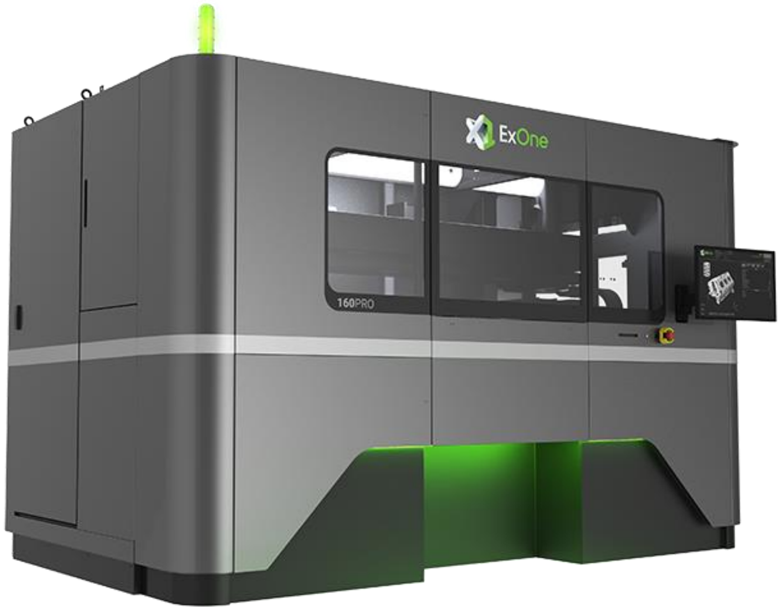


Figure 6. ExOne X1 160Pro. Source: www.exone.com

Materials and their properties

The following figure shows an overview of the materials that can be used for Binder Jetting. The difference between the materials that can be used in this process should become clear.

Material			Binder Jetting (BJ)					
			Tensile Strength *1	Yield Strength *1	Elongation at break *1	Relative Density *1	Density	Color
			[Mpa]	[Mpa]	[%]	[%]	[kg/m^3]	-
Material	Poly-mer	PMMA	25 *2	-	2.5 *2	> 85	1000	White
	Sandstone	Visijet PXL with ColorBond Infiltrant	14.2 *3	31.1 *3 *4	0.23 *3	-	-	Multicolor
		Visijet PXL with StrengthMax Infiltrant	26.4 *3	44.1 *3 *4	0.21 *3	-	-	Multicolor
		Visijet PXL with Salt Water Cure Infiltrant	2.38 *3	13.1 *3 *4	0.04 *3	-	-	Monochrome
	Metal	17-4PH Stainless Steel	1070 - 1310 *5	970 - 1030	4 - 12	96 - 99	7500 - 7700	Metal
		316L Stainless Steel	450 - 580 *5	140 - 220	40 - 55	96 - 99	7600 - 7900	Metal
		316 Stainless Steel with Bronze Infiltrant	580 *5	283	14.5	~ 95	7860	Metal
		Inconel 718	1310 *5	1069	15	99.2	8130	Metal
	Casting material	Sand/Ceramic with Furan Binders	Chemically-cured, furfuryl-alcohol based binders and acid activators. Suitable for making high strength cores & molds in a wide variety of silica sand & ceramic casting media.					
		Sand/Ceramic with CHP Binders	Ester-cured alkaline phenolic resole binder. Best suited for specific core & mold geometries that requiring maximum desandability. Compatible with a wide variety of silica sand & ceramic casting media.					

*1 Unknown procedure
*2 Test standard ISO 527-1
*3 Requires 24 hrs of drying time at 37.8°C
*4 Flexural Strength
*5 Ultimate Tensile Strength
Note: All specifications are to be seen in proportion. The material properties depend strongly on the manufacturing and printing process

Figure 7. Materials for Binder Jetting. Source: BY-NC-SA S. Markus/Hochschule Düsseldorf.

Design Guidelines

The following style guidelines should be considered when creating parts with Binder Jetting:

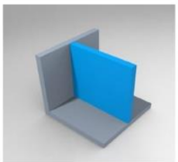
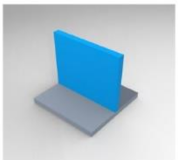
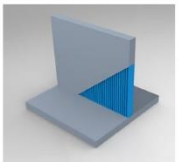
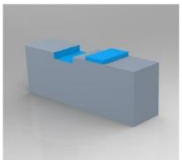
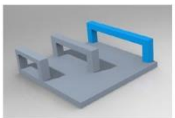
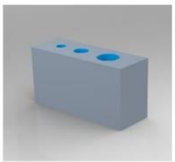
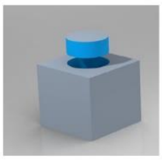
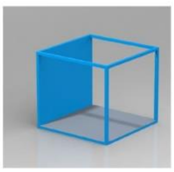
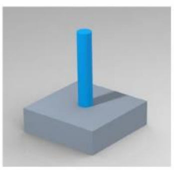
	**Supported walls** What's the minimum thickness?	2.0 mm
	**Unsupported walls** What's the minimum thickness?	3.0 mm
	**Support & Overhangs** Maximum angles of overhangs that can be printed without support	-
	**Engraved and embossed details** Minimum dimensions to print deepenings and elevations.	0.5mm
	**Horizontal bridges** Bridge span which is printable without support	-
	**Holes** Minimum hole diameter	1.5 mm
	**Moving/Connecting Parts** Recommended clearance between to parts	1.5 mm
	**Escape holes** Minimum excaphole size	5.0 mm
	**Minimum features** Minimum size of small features to make them printable	2 mm
	**Minimum pin diameter** (For standalone pins)	2 mm

Figure 8. Style-Guidelines for Binder Jetting. Source: (cc) BY-NC-SA L. Müller/Hochschule Düsseldorf.

Preprocessing

While pre-processing the part it is important to consider which material is used and how the post-processing will be done. If the part is printed out of metal powder and furthermore gets sintered during post-processing it is crucial to pre-calculate the shrinking of the part to correspondingly increase the dimensions of the model.

It is also important to consider the usage and the production size of the part. When printing larger batches you have to fill in the build volume as much as possible with duplicates of the part to higher the efficiency.

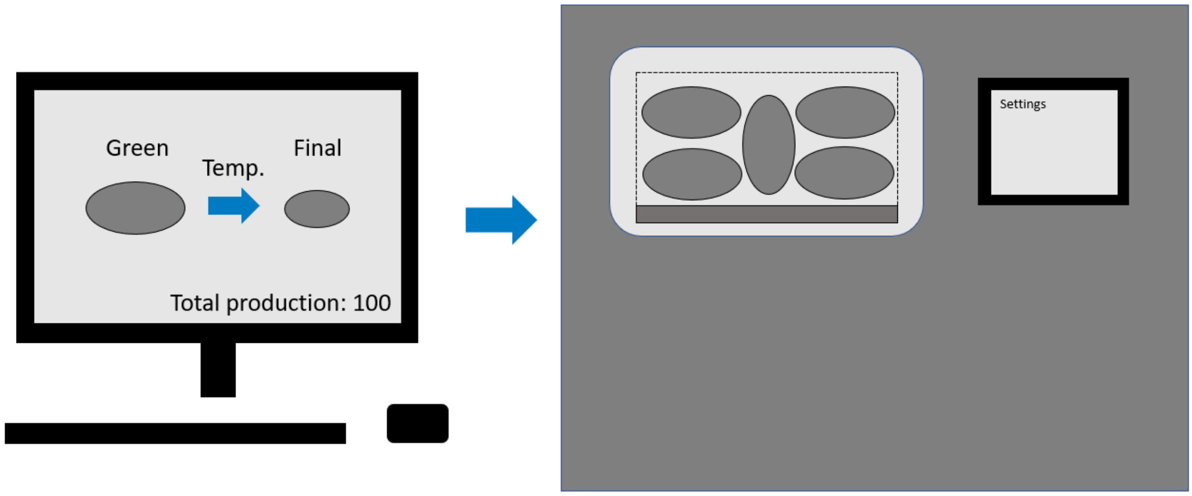


Figure 9. Schematic Pre-Processing of Binder Jetting . Source: (cc) BY-NC-SA S. Markus/Hochschule Düsseldorf.

Postprocessing

As stated at the beginning of this unit, post-processing is not always needed. When creating prototypes or visual models with Binder Jetting, post-processing is generally not needed because of the low mechanical requirements of the parts. Instead, if you want to print functional metal parts with Binder Jetting, post-processing is crucial for obtaining parts with appropriate mechanical properties. The reason of this, lays in the process itself, because Binder Jetting uses a binding agent to glue the metal powder together.

Curing is the first step that must be done when using metal powder in the Binder Jetting process. It increases the strength of the green part slightly so that the part can be removed from the build platform and can be freed from the excess material by pressurized air.

After curing there are two options two further process the part. One of these options is **infiltration**. To start the infiltration firstly the binding agent must be removed through a heat treatment. Through the removal of the binding agent the density of the part decreases significantly. Bronze then is commonly used to infill the cavities to higher the density again and increase the mechanical properties of the part.

Another way to increase the mechanical properties of the part is **sintering** it. In this process no additional material is needed. The parts get heated to the point where the material fuses together and thereby eliminating the cavities. The density of the parts then increases to well over 90 %. The disadvantage is that the increase of density simultaneously leads to shrinking of the whole part. This must be considered during preprocessing.

Quiz

Post-Processing of Binder Jetting.

What must be done in Post-Processing, when creating a metal part that must consist completely out of stainless steel?

☐ Cure the part first to remove it from the build platform, and then infiltrate it.
☐ Cure the part first to remove it from the build platform, and then sinter it.
☐ Cure the part exclusively to prepare it for use.
☐ Infiltrate the part first and then sinter it.

Material Jetting

Printer Structure and Components

The following figure shows the general parts of a Material Jetting (MJ) printer. More precisely, a polyjet printer is shown. It is often the case that Material Jetting and Polyjet are equated, as this is the first patented process in this field.

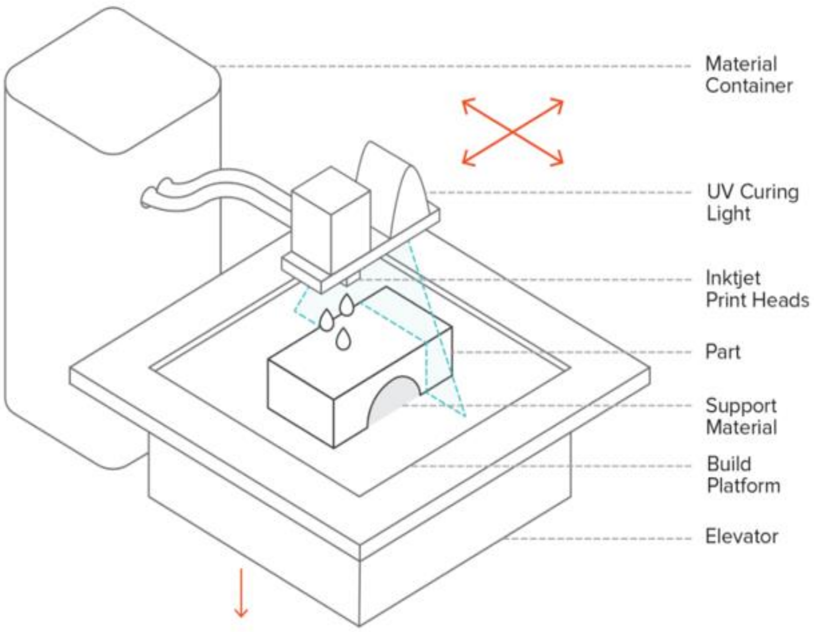


Figure 1. Structure of a Material Jetting printer. Source: www.hubs.com

General process

Material Jetting is divided in three main subcategories. These subcategories are: Drop on Demand, NanoParticle Jetting and Polyjet. Polyjet was the first and is still the most important process in Material Jetting. Therefore, this unit will give a quick overview about all three subcategories and will then focus on Polyjet.

Drop-on-Demand (DOD)

DOD printer use two print heads. One that provides the build platform with the liquid build material and the second one that provides the platform with support material. These printheads only deposit dots on the build platform where it is needed. That is the name giving property of DOD. Additionally, DOD printers flatten each printed layer after the material is deposited, so that the next layer has a flat surface to build on. Because of the use of viscous liquid, wax is commonly used in this process. This process is often used in the manufacture of jewellery or generally to produce molds.

Watch the video DOD Printing Process

Process: Nano Particle Jetting (NPJ)

NPJ uses, as the name implies, nano particles that are surrounded by a liquid. This is called dispersion. The dispersion is then jetted on the build platform to create very thin layer of build material as well as support material. The build platform is constantly in a high temperature environment so that the liquid in which the nano particles are dispensed evaporates and only a dense layer of nano particles is left on the build platform. After the building process is finished the parts must be sintered to reach the desired properties and the support structures must be removed. The process is used to create parts out of ceramics or metals in a technical environment. The metal parts are very dense, and they can have the same properties as the parts from ordinary manufacturing processes after sintering.

Watch the video NPJ Printing Process

Process: Polyjetting

Polyjetting or generally also called Material Jetting (MJ) is a multi-purpose and fast printing technology. The technology uses photopolymer resin droplets and a UV light source to build complex parts in the typical layer-by-layer process. Generally, the layer thickness is very thin. Because of this and because the material used is present in the liquid phase, the resolution of this process is very high and the surface very smooth.

The process of Polyjetting begins with preheating the resin, so that the viscosity is sufficient to further process it. Then the print head navigates above the build platform and a nozzle deposits the liquid resin droplets of the photopolymer. After depositing the liquid resin droplets, UV light cures the resin on the build platform through photopolymerization. The resin is now solidified. After this process is done for the whole layer, the platform is lowered by the layer height and the process starts again. The difference of this process compared to many others lies in the deposition of the material. Polyjetting uses multiple inkjets to deposit multiple materials at the same time. Therefore, it is possible to create multicolour parts and parts out of different materials as well. The support structures that are produced in the printing process must be removed in post-processing.

Watch the video Polyjet Printing Process

Keyfeatures and Applications of Polyjetting

The versatility of Polyjtetting is one of its key advantages. It is possible to create multi-color as well as multi-material parts in one process. Therefore, it is possible to save many steps that are normally needed in post-processing to finish the part or assembly. Processes like painting and coating are redundant because the parts already have the needed color or color gradient. Furthermore, the assembly of parts is also redundant. When printing with a Polyjet printer it is possible to create multiple parts out of different materials that are already assembled by defining the correct settings during pre-processing. Due to these properties of Polyjet it is possible to create multi-color and multi-material parts like the following model bust that is semitransparent and also shows inner veins and arteries.

Figure 2. Bust printed with a Polyjet printer: BY-NC-SA L. Müller/Hochschule Düsseldorf.

In general, Polyjetting is used to create realistic, smooth surfaced, colored, and multi-material prototypes or visual models. Application areas for these models can be civil engineering, architecture or teaching e.g. in medicine. Another application area are molds as well as everyday items and wearings. But because of the poor mechanical properties and the UV sensitivity the parts created with Polyjetting are not suited for mechanical applications or long-term outdoor usage.

Advantages and Disadvantages

The following list shows the main advantages and disadvantages of Material Jetting, without differentiating into further subcategories such as DOD, NPJ and Polyjet. The other manufacturing methods serve as a reference for comparison. If a point refers to something specific, this is indicated in brackets.

Pros:

- Multi-color
- Multi-material
- Very smooth surface finish
- Very good resolution
- Homogeneous mechanical and thermal properties
- High production rate (multiple parts at once)

Cons:

- Low mechanical properties (Except NPJ parts)
- UV sensitive
- Support structures needed
- Brittle parts
- High costs
- Properties degrade over time

Machine Costs

The following printers are Polyjet printers because they find the broadest application in the industry. DOD and NPJ printers are not listed.

Stratasys Objet30: 31,000 $

The Objet30 is a very accurate and versatile Polyjet printer. The printer has a build area of 294 x 192 x 148.6 mm. The printer also has layer thickness and general resolution up to 16 microns. The XY resolution is 600 x 600 DPI. Application for this printer lays in prototypes with specialized properties ad smooth finishes as well as medical devices out of biocompatible materials.

Figure 3. Stratasys Objet30. Source: www.stratasys.com

Stratasys J4100: Contact supplier for price

The J4100 is a highly productive Polyjet printer that can print up to 3 materials at the same time. The user can choose between a wide variety of materials. The selectable materials can be categorized in neutral shades, transparent materials, flexible materials, and digital materials. The printer also has a large building area of 1000 x 800 x 500 mm. The layer thickness and general resolution go up to 27 microns. The XY resolution is 300 x 600 DPI.

Figure 4. Stratasys J4100. Source: www.stratasys.com

Materials and their properties

The following figure shows an overview of the materials that can be used for Material Jetting. The difference between the materials that can be used in this process should become clear.

		Material Jetting (MJ)					
		Tensile Stength ASTM D638	Flexural Strength ASTM D790	Elongation at break ASTM D638	Heat deflection temperature ASTM D648 (1.82 MPa)	Color	Water absorption ASTM D570
		[Mpa]	[Mpa]	[%]	[°C]	-	[%]
Material	Stratasys Durus	20 - 35	30 - 40	40 - 50	32 - 34	Ivory	1.5 - 1.9
	Stratasys Agilus 30 [*1]	2.1 - 3.1 [*2]	4 - 7 Kg/cm [*3]	185 - 270 [*2]	-	Black, White, Clear	-
	Stratasys Digital ABS plus	55 - 60	65 - 75	25 - 40	51 - 55	Green, Ivory	-
	Stratasys Rigur	40 - 45	52 - 59	20 - 35	45 - 50	White	-
	Stratasys Tango [*1]	0.8 - 5 [*2]	2 - 12 Kg/cm [*3]	45 - 220 [*2]	-	Black, Gray, Clear	-
	Stratasys Biocompatible MED610	60 - 65	75 -110	10 - 25	45 - 50	Clear	1.1 - 1.5

[*1] Multiple material variants included
[*1] ASTM D-412
[*2] ASTM D-624: Tensile Tear Resistance
Note: All specifications are to be seen in proportion. The material properties depend strongly on the manufacturing and printing process

Figure 5. Materials for Material Jetting. Source: (cc) BY-NC-SA S. Markus/Hochschule Düsseldorf.

Design Guidelines

The following style guidelines should be considered when creating parts with Material Jetting:

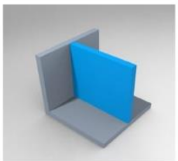
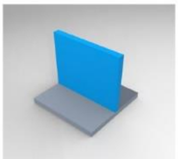
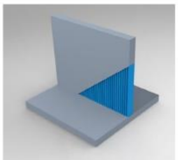
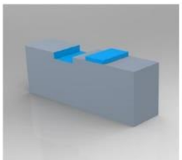
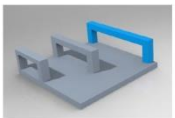
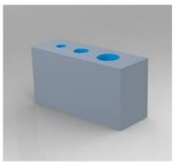
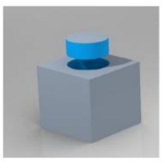
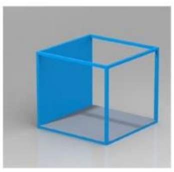
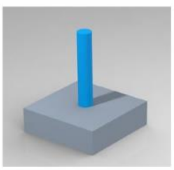
	**Supported walls** What's the minimum thickness?	1.0 mm
	**Unsupported walls** What's the minimum thickness?	1.0 mm
	**Support & Overhangs** Maximum angles of overhangs that can be printed without support	always needed
	**Engraved and embossed details** Minimum dimensions to print deepenings and elevations.	0.5mm
	**Horizontal bridges** Bridge span which is printable without support	-
	**Holes** Minimum hole diameter	0.5 mm
	**Moving/Connecting Parts** Recommended clearance between to parts	0.2 mm
	**Escape holes** Minimum excaphole size	-
	**Minimum features** Minimum size of small features to make them printable	0.5 mm
	**Minimum pin diameter** (For standalone pins)	0.5 mm

Figure 6. Style-Guidelines for Material Jetting. Source: L. Müller/Hochschule Düsseldorf.

Pre-Processing

The pre-processing settings which are made in Material Jetting are highly depending on the material. Therefore, many settings are preset when selecting the material. An Example for this is the layer height that can be reached.

In general, the pre-processing begins with selecting material for the printed part. When printing multi-color or multi-material parts it is important to divide the CAD-model into shells. Each shell is a separate volume, which can be assigned material and color. The next step is to place the part on the build platform and choosing the surface finish, whether it should be matt or glossy. Depending on the orientation of the part and the look desired look of the surfaces, choose the support type. At the end choose the printing mode. It defines the speed and accordingly the resolution. The faster the printing process is done, the lower is the resolution.

Post-Processing

The two major parts of post-processing are removal of support structures and finishing the surface. The support structures are out of a different material then the main part. Most of the materials for support structures are removable with a water jet or sometimes soluble. Because of the fact, that support structures are always needed in Material Jetting the post-processing is a big part of this process. But the advantage is, that the surfaces, where support structures were attached, show commonly no damage after the removal. Instead, their visual appearance is matte. When there is a need for glossy surfaces the surfaces with the removed support structures must be polished.

Watch the video Polyjet Post-Processing

Quiz

Multi-Material Parts.

Which material jetting process is needed if you want to produce a multi-material part from different polymers in one step?

☐ NanoParticle Jetting.
☐ Binder Jetting.
☐ Polyjetting.
☐ Drop-on-Demand.

Value for your company

Today, Additive Manufacturing processes are so far developed that they can be used for the industrial production of components as well as for end customer products. This technology opens up great potential in many areas thanks to its digital process chain and the special freedom of geometry. Compared to other conventional manufacturing processes, AM is still a relatively new technology. However, due to further improvements in productivity and quality, AM will be used in more and more areas in the future. Additive manufacturing processes are often only one production step in a longer process chain of manufacturing. Either a part geometry can be additive manufactured and, together with other processes, it forms the final component or the additively manufactured part is indirectly involved in the creation of the end-use product.

Additive manufacturing can be used in various areas of industries to increase value so that an integration of the AM technology for producing components can make economic sense. One example is the already widespread use and benefit of AM as a prototyping technology. The graphic below shows the growth rate of the top six industries embracing 3D printing technology.

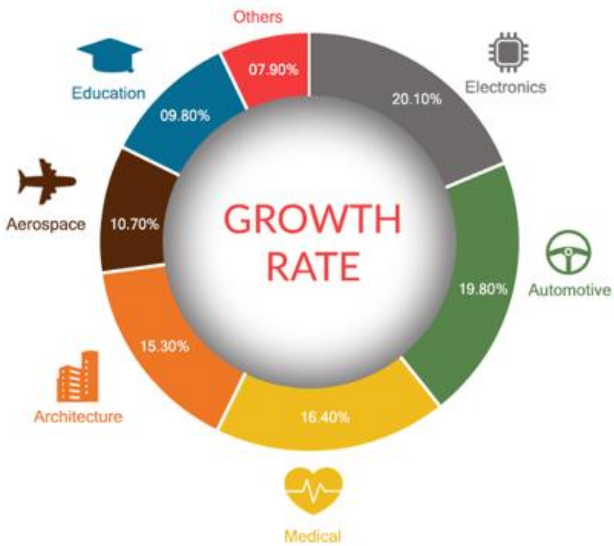


Figure 1. Growth rate of industries embracing AM. Source: www.3ding.in

Nevertheless, there are various factors for an integration of this technology that have to be considered, as not only the cost structure of additive manufacturing differs significantly from that of conventional manufacturing processes. These factors are discussed in the following.

The cost estimation for an additively manufactured product itself is usually done per cubic centimetre of manufactured components, which contains the overall cost structure of additive manufacturing processes. This is largely determined by the cost of the AM machines, followed by the cost of materials. In addition, the post-processing of the additive components is another cost factor that must be considered. In particular, machines for powder-based manufacturing methods such as laser sintering and laser melting are very expensive, which drives up the total cost per cubic centimetre. The cost of powder bed-based processes is often compared with that of tool-intensive conventional manufacturing processes such as injection moulding and die casting, or even with machining processes such as CNC milling. In most cases, parts produced with the powder-based technology are higher in price. Nevertheless, the use of additive processes in manufacturing can make sense in terms of fixed costs. The differences of AM, with conventional manufacturing technologies, the tools, molds, etc. that are only used to manufacture a specific product must be included. For this reason, conventional manufacturing processes depend even more on fixed costs than additive processes. If only a few units are produced or only small batches are manufactured, the fixed costs can far outweigh the variable costs, so that additive manufacturing is more cost-effective than manufacturing with conventional processes.

Moreover, the design of the additive components themselves has the potential to reduce the operating costs. Next to the costs of production and operation, these costs are combined in the Life Cycle Costing (LLC). For this reason, the LLC method should be included in the decision-making process for and against additive manufacturing. It should also be noted that the integration of AM technology requires not only experienced developers, comprehensive technological know-how and a deep understanding of the entire process chain (from the initial concept to the creation of a CAD model to post-processing), but also an adaptation of existing processes and internal company routines. Therefore, it is important for developers and managers to know the possible application fields of additive manufacturing in their company ahead, to understand how a specific implementation is possible.

- **Prototyping**

With AM, prototypes of different levels can be produced: from very simple to highly complex.

- **Product Improvement**

AM offers a completely new kind of freedom in product design, providing the opportunity to develop lighter and more efficient products as well as functional integration.

- **Incremental Launch of a Product**

AM offers the possibility to start production without specially manufactured production equipment to adjust the product before the actual mass production begins.

- **Customization**

AM allows a high degree of customisation of products without incurring additional costs in manufacturing.

- **Tool/ Mold Making**

AM can be used indirectly for manufacturing end products by using it in tool and mold making for conventional production processes.

- **Flexibility**

For components whose production changes quickly or which are only required in very small quantities, a migration to AM can be very profitable.

To sum up, AM can be a great chance to improve manufacturing processes. But on the other hand, changing the manufacturing process is always an investment for a company. The first and most important question is: what benefits are expected from additive manufacturing for the company? In most cases, this involves a comparison of the current conventional manufacturing possibilities with the possibilities of additive manufacturing.

Based on these considerations, two basic ways of introducing additive manufacturing can be determined:

- Use of additive manufacturing without changing the component design: this approach takes advantage of the independent batch size and the digital process chain of additive manufacturing.
- Use of additive manufacturing with a change in component design: this procedure uses the high design freedom of additive manufacturing to achieve improved system properties.

Adapting the design and setting up a new supply chain causes costs and requires a learning process within the company. Therefore, it would be recommended to establish a business case, for the selection of components for additive manufacturing, that compares costs and benefits.

Examples of Applications

- Transition piece for a high-efficiency heat exchanger

Figure 2. Heat exchanger produced with SLM. Source: See References

This component is characterised by a very complex shape combined with a delicate honeycomb structure. The ideal shape of a heat exchanger is often so complex that it is difficult or impossible to implement with conventional manufacturing processes.

- Architectural models.
- Bionically optimised components (e.g. armrests in planes).
- Hydraulic components.
- Injection molds.
- Transparent braces
- Prostheses and Orthoses.
- Toys.
- …

Quiz

Cost estimation.

How is the cost estimation for an additively manufactured product usually done?

☐ By weight of the component.
☐ Per cubic centimetre
☐ By time to build a component.
☐ By energy you need for the whole process.

Final Exam

First Patent.

What was the first AM technology patented in 1984?

- Selective Laser Sintering (SLS).
- Stereolithography (SLA).
- Fused Deposition Modeling (FDM).
- Selective Laser Melting (SLM).

Post-Processing

What technique can not be considered post-processing?

- Removing support structures.
- Deforming.
- Sanding and polishing.
- Painting.

Choose AM Technology

What technology should be used to create parts with medium tolerances and a good chemical resistance?

- FDM.
- DLP.
- Material Jetting.
- SLS.

Choose AM Technology

What technology should be used to create a multicoloured polymer part with good surface conditions?

- Material Jetting.
- SLS.
- Binder Jetting.
- DLP.

Watertight

What is meant by watertightness in the context of additive manufacturing?

- The 3D model consists of one enclosed volume.
- The 3D model is actually watertight.
- The 3D model is fully defined and ready to print.
- The 3D model has no modelling errors

Rotative limits for digital mirrors in DLP

How much can the digital mirrors in DLP rotate in total?

- +12.
- +10.
- +-12.
- +-10.

Pros and Cons of SLA

What advantages and disadvantages fit SLA completely ?

- Wide range of materials; Cost efficient production; good UV resistance.
- Multi-part assemblies are possible; low material consumption; production of only rigid 3D objects.
- High material consumption; limited UV resistance; wide range of materials.
- Cost efficient production; low material consumption; limited UV resistance.

Post-Curing in SLA

What is post-curing used for?

- To reach the highest possible strength and become more stable.
- To remove support material and finish the surface.
- To finish and coat/ paint the surface.
- To make the parts UV resistant.

Advantage of SLA

Which process feature gives SLA an advantage over all other additive manufacturing processes?

- Fastest printing speed.
- Best material variety.
- Smoothest surface finish.
- Strongest parts

Support Material in FDM

What are common materials for support structures?

- PLA and ABS.
- PET and PETG.
- PLA and PVC.
- HIPS and PVA.

Advantages of SLM

What is not an advantage of SLM?

- Tool-free production of metallic parts.
- Low waste – high amount of recycling material.
- High density of the parts.
- Inexpensive production.

Detailing agent in MJF

Why is a detailing agent added to the boundaries of the actual part within the MJF process?

- To glue the outer contour.
- For support structures.
- To prevent heat conduction from the part to the surrounded material.
- As a binding agent it fuses the material together to get a more detailed part boundary.

Parts of a SLS printer

What is the name of the layering apparatus used to distribute the powder onto the print area?

- Distributor.
- Pusher.
- Recoater.
- Spreader

Solidification in EBM

What causes the metal powder to solidify within the EBM process??

- UV-light.
- Binding agent.

- CO2-Laser.
- Electrical charges.

LENS

What kind of material-energy combination is used in LENS?

- Wire and E-Beam.
- Powder and E-Beam.
- Wire and Laser.
- Powder and Laser.

Green Parts in Binder Jetting

What are green parts?

- Green parts are finished parts that are ready to use.
- Green parts need to be coated and then are ready to use.
- Green parts must be post-processed to obtain final properties.
- Green parts is another word for CAD models.

Pre-Processing Settings in Material Jetting

Which pre-processing settings are important when printing multi-material parts?

- Define shells and assign materials.
- Convert the volume model into a surface model.
- Define surface areas and assign materials.
- Create a file with a model for each material.

Post-Processing in Material Jetting

What post-processes are commonly redundant when printing a part with a Polyjet printer?

- Assembling and Polishing.
- Painting and Removing support structures.
- Painting and Polishing.
- Painting and Assembling.

Cost reduction in AM

What is an important factor to reduce the cost of AM components?

- Design of the components.
- Temperature during the printing process.
- Weight of the components.
- Tools needed for the process.

Integrating AM into a company

What does AM not need before integrating into a company?

- An adaptation of existing processes and internal company routines.
- Experienced developers.
- Comprehensive technological know-how.
- Deep understanding of the entire process chain.

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