AMPOWER

Course Booklet

Polymer Technologies

What you will get

- A deep-dive into the process characteristics of the following polymer technologies:
  - Laser Powder Bed Fusion
  - Material Extrusion
  - VAT Polymerization
- Typical application examples for each polymer technology
- Decision criteria for selecting the most suitable polymer technology for an application

November 2022

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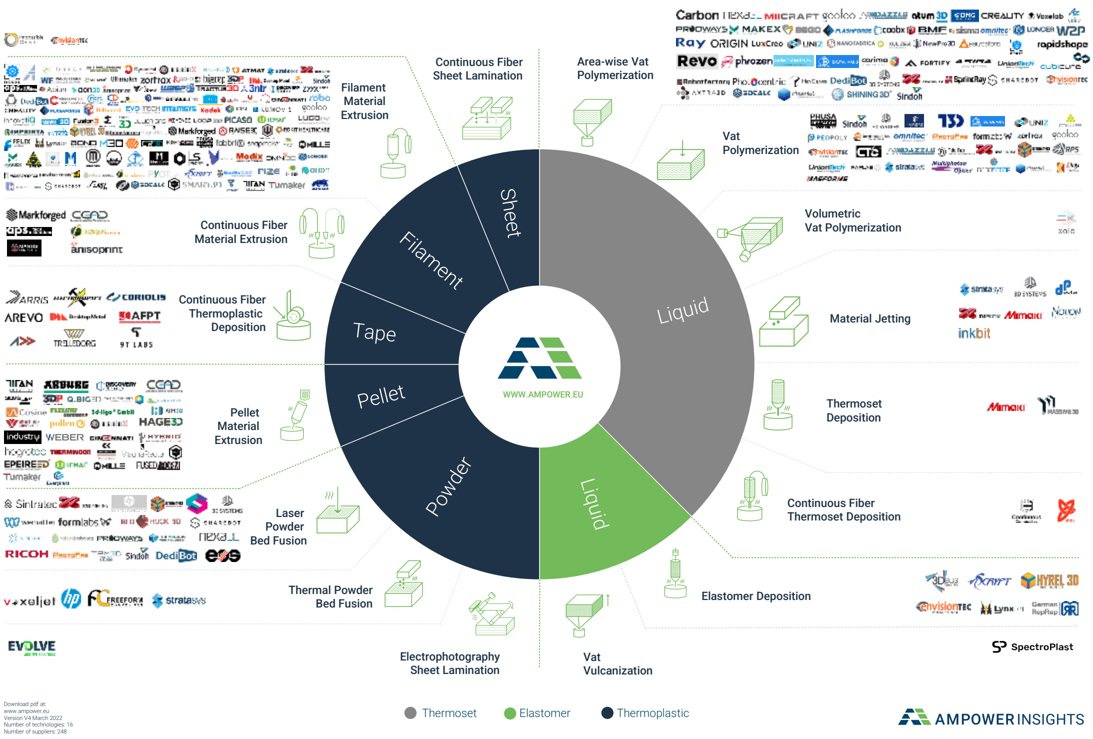
Polymer Technology Landscape

The development of the Additive Manufacturing landscape dates back to the early 80s and started with the invention of the Stereolithography process by Charles Hull. This Invention can be declared as the point of origin for the polymer AM market as well as the entire AM market. It paved the way for early adopters of the technology and the development of further technologies principles. Since then the number of processes and companies has exploded, making it hard to keep an overview.

The following map provides a good overview of the different processes divided by feedstock type.

Polymer Additive Manufacturing technology landscape



The map shows that out of 16 sub processes, 8 work with a liquid feedstock. VAT Polymerization is still leading in terms of number of suppliers. The classical VAT Polymerization process has later been modified into the area-wise process that cures an entire layer at once.

Filament-based Material Extrusion printers make up another large process category. The high number of suppliers is caused by the fact that such printers can easily be developed and are today amongst the most affordable printers.

The focus of this booklet

In this online learning we will focus on the **three most mature technologies** in an industrial context today:

- Polymer Powder Bed Fusion (LPBF)
- Material Extrusion (FDM)
- Stereolithography (SLA)

In the next section, we will provide and overview of the maturity of polymer technologies and discuss all of them in more detail.

In the following sections we collected the most important information for each technology, including functional principle, technical and economic characteristics as well as application examples.

After that, a comparison between the 3 different process categories that can help in identifying the right technology for an application can be found.

Maturity of polymer processes

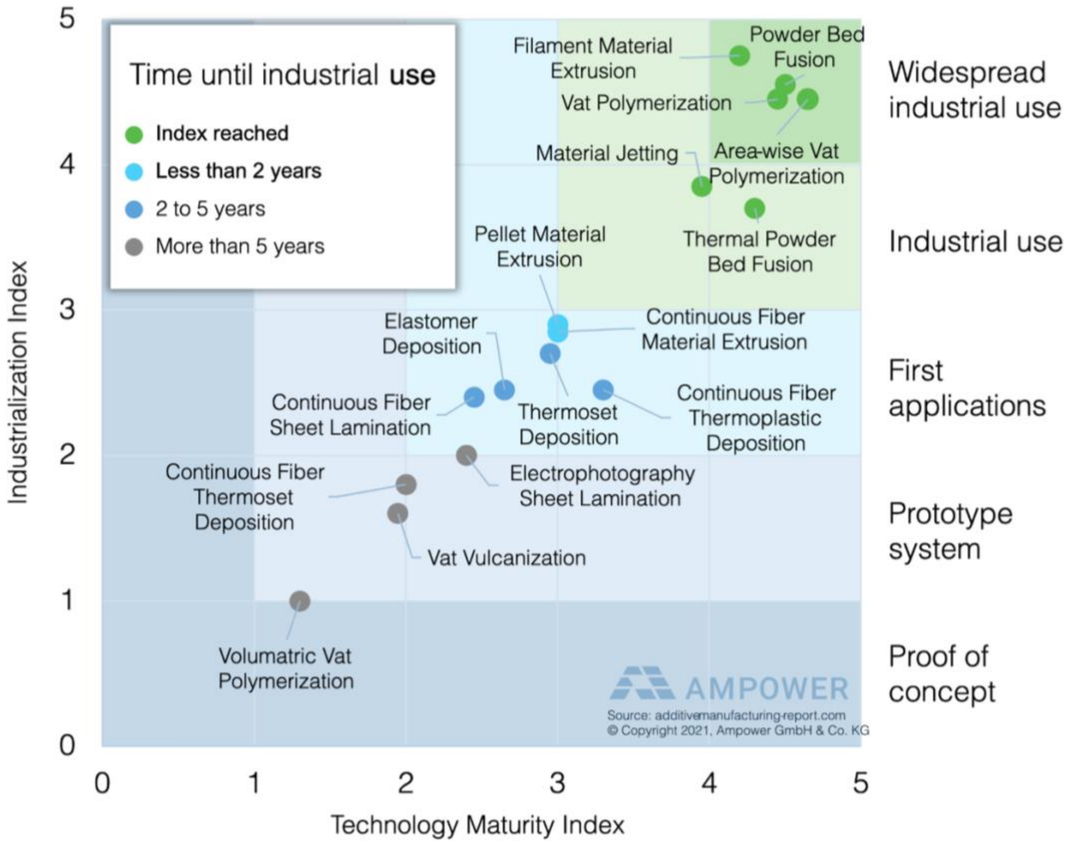
Industrialization and Technology Maturity Index

To evaluate the different AM technologies AMPOWER has developed a model to characterize the maturity of an Additive Manufacturing technology based on two indices. The **Industrialization Maturity Index** and the **Technology Maturity Index** describe and compare the capabilities and adoption rate of each AM technology in the industrial environment. Both indices are crucial factors for evaluating the current status of any AM technology.

- The Technology Maturity Index evaluates the process capability, system reliability and availability as well as implemented quality control measures.
- The Industrialization Index assesses the supply chain, material availability, installed system base, public knowledge and research as well as standardization of each technology.

Each category is weighted according to its specific importance. Typically, the technological maturity increases first, and the industrialization follows. A detailed description of the current state of maturity is given in the deep dive section for each technology.

Industrialization and Technology Maturity Index



Technologies with AM Maturity Index “Prototype system” are still at an early development stage with in-house systems only or on the verge of first systems at beta-customers. Many of the technologies in this corridor are proprietary AM principles or just recently made public.

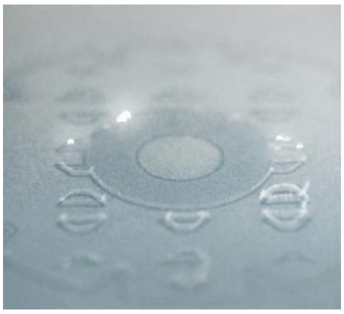
At a Maturity Index of “First application”, industrial adoption takes place and users introduce the technology in their R&D departments or machines are set up for pre serial production trials at beta-customers.

Technologies at a Maturity Index of “Industrial use” are on the verge of full industrialization. Technologies in this area have not yet been widely adopted as a serial manufacturing technology across multiple industries.

To reach “Widespread industrial use” the technology must be established in multiple industries as a production technology for functional end parts.

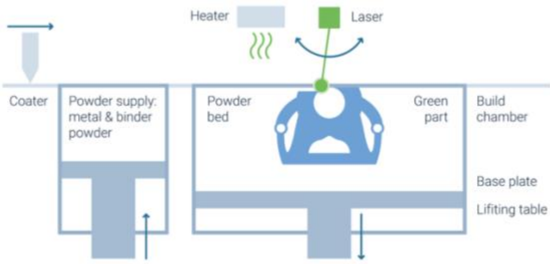
Laser Powder Bed Fusion (LPBF)

Polymer Laser Powder Bed Fusion (LPBF), often referred to as Selective Laser Sintering (SLS), is part of the Powder Bed Fusion family and among the most widely used polymer processes in an industrial context. SLS is used for the production of parts in low to medium quantities. SLS-parts show almost isotropic properties and are thus suitable for prototypes and functional parts.



Functional Principle

The material in the powder bed is pre-heated to just below melting point before the laser beam, usually a CO2-laser, scans the surface to melt the powder. Once the entire area is scanned, the powder bed moves down by a pre-defined layer thickness and the recoater adds a new layer of powder. This process is repeated until all parts are finished, resulting in the powder container filled with parts surrounded with powder.



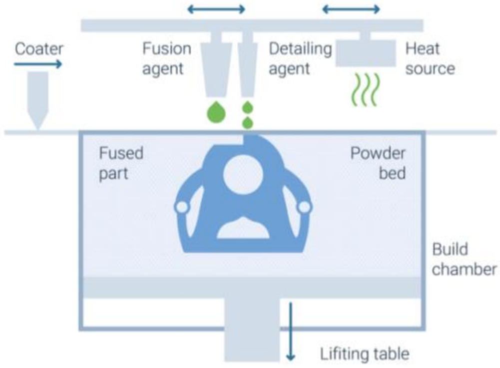
Laser Powder Bed Fusion (LPBF) versus Thermal Powder Bed Fusion

Thermal Powder Bed Fusion also known under the brand names of Multi Jet Fusion (MJF) or High-Speed Sintering (HSS) was patented by Neil Hopkinson in 2004. This technology stands out with its productivity and high production capabilities. Thermal Powder Bed Fusion was commercialized by HP as well as VOXELJET.

Like LPBF, Thermal Powder Bed Fusion is part of the Powder Bed Fusion family and the characteristics of the two processes are comparable. The main difference lies in the energy source used: Thermal Powder Bed Fusion spreads an ink that promotes light absorption on a powder and subsequently fuses inked powder with an infrared energy source.

Functional Principle

The powder bed is heated evenly by infrared light. The process of solidification of the powder is initiated by the application of a fusing agent or binder. This agent is a thermally conductive liquid that is applied as small droplets by a printhead. This process is repeated for each layer. A detailing agent is additionally applied to enclose the areas of the fusing agent. This isolation is used to generate sharp edges and details. It also prevents the fusing agent from diffusion in the unused powder.



Advantages and challenges

- Good mechanical properties (almost isotropic)
- High design freedom
- No support structures required
- High productivity compared to other polymer technologies

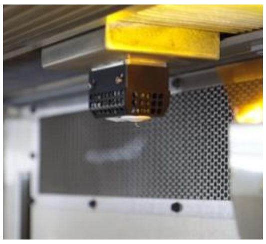
- Rough surface
- Limited temperature range for most materials
- More suitable for batch-production
- Often only up to 50% of powder reusable

Process Characteristics

The following values act as a general guideline. Exact values depend on the exact printer configuration.

Typical Build Size	• Build envelope small systems: 200 x 250 x 300 mm • Build envelope large systems: 700 x 400 x 600 mm
Materials	• **Mostly Nylon 12 and Nylon 11**, which is available with some filler materials (e.g. glass beads). • **High-performance plastics** such as PEEK, PEEK or HT23 are available for LPBF, but require a system capable to produce parts with a high melting temperature. • Other materials such as **Polypropylene (PP)** or **Thermoplastic Elastomers (TPE)** are available but not as widely spread.
Technical Characteristics	• Dimensional accuracy: ± 0.3 mm • Typical layer thickness: 60-180 µm • Typical build speed: 1 l/h – 6 l/h • Typical surface roughness: Ra 10-20 µm • Support structures: Not required
Economic Data	• Machine investment: 50.000 € to 500.000 € • Powder cost: around 60 €/kg (standard powders) • Additional cost: blasting cabinet, coloring equipment
Post Processing Operations	• Blasting to remove excess powder and to reduce surface roughness • Coloring (spray painting or dyeing) • Tumbling to create smooth surfaces
Suppliers	3D Systems (USA), EOS (Germany), Farsoon Technologies (China), Formlabs (USA), HP (USA) – MJF, Nexa3D, Prodways (France), Sintratec (Switzerland)
Applications	• Visual and functional prototypes • Complex parts in low-to mid volumes • Replacement of low-volume injection molding series

Material Extrusion

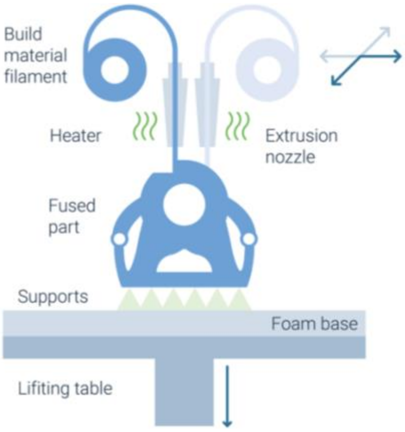


Material Extrusion, also known as Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF), was developed and patented by STRATASYS in the early days of AM. After the patent expired in 2009, this technology played a major role in the development of the consumer 3D printing market as well as the expansive adoption of Additive Manufacturing in the industry.

Besides filament based material extrusion, more recently several companies have introduced pellet based material extrusion machines. Using pellets instead of a filament leads to several advantages such as a higher productivity and lower material cost.

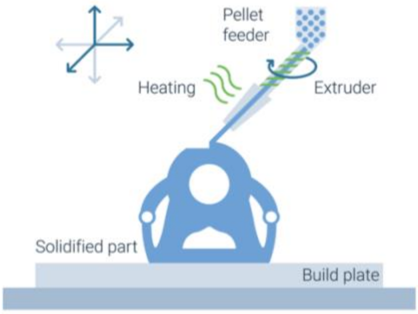
Functional Principle of filament based material extrusion

Filament based material extrusion is based on the extrusion of a thermoplastic feedstock through a heated nozzle. To generate the component the layer is generated by horizontal movement of the nozzle in the x-y-plane. To extrude the next layer, either the nozzle or the base plate is displaced vertically by the desired layer thickness.



Functional Principle of pellet based material extrusion

Plastic pellets are the basic feedstock for Pellet based Material Extrusion. The pellets are stored outside the machine and transported into the extruder screw by means of a feeding system. The extruder screw is heated and applies pressure to the pellets and at the same time melts the thermoplastic material. The molten material is then pressed through the extrusion nozzle layer by layer on the printing platform. This process is repeated until the part is completed.



Advantages and challenges

+ Advantages

- Low investment costs
- Easy to use hardware and software
- Wide range of materials available
- Water-soluble supports available

– Challenges

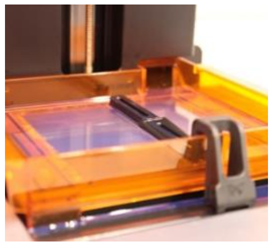
- Limited mechanical properties / anisotropy
- Lower detail accuracy compared to other polymer processes
- The build time per part does not decrease for batch production, thus the process is usually not suitable for high quantities
- No stacking of parts in build chamber

Process Characteristics

The following values act as a general guideline. Exact values depend on the exact printer configuration.

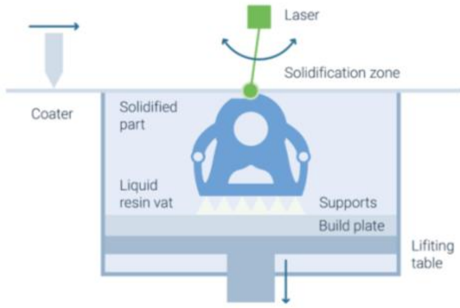
Typical Build Size	Desktop printers: 200 x 200 x 200 mm Large-scale printers: >1.000 x 1.000 x 1.000 mm
Materials	Wide range of materials available, both semi-cristalline and amorphous polymers can be printed with extrusion. • Commodity polymers: PP, ABS, PLA • Engineering polymers: PA6, PA11, PA12, POM, TPU • High-performance polymers: PEEK, PPSU, Ultem
Technical Characteristics	• Dimensional accuracy: ± 0.2 mm or ±0.2% • Typical layer thickness: 50 – 300 µm • Build speed: 5-150 mm/h • Typical surface roughness: Ra 1-5 µm • Support structures: Required for overhangs
Economic Data	Machine investment: • Desktop printers: 2.000 € to 10.000 € • Industrial printers: >100.000€ Feedstock cost: • Low-cost filament: 20 €/kg • Engineering filament: >200 €/kg • Pellets: ~50 to 90% cheaper than filaments
Post Processing Operations	• Support removal (manual or dissolvable supports) • Reduction of surface roughness through sanding, polishing, vapor smoothing
Suppliers	BLB Industries (Sweden), Intamsys (China), Markforged (USA), Stratasys (USA), Ultimaker / Makerbot (USA)
Applications	• Visual and functional prototypes • Production aids, jigs & fixtures • Low-volume end-use parts (e.g. housings, aircraft interior components)

Vat Polymerization (SLA)



Vat Polymerization also known as **Stereolithography** (SLA) is the origin of the 3D printing technology. Variations of the process have been developed over the last 40 Years to increase the efficiency and the accuracy of the process. Especially the medical sector is taking advantage of the various polymerization processes.

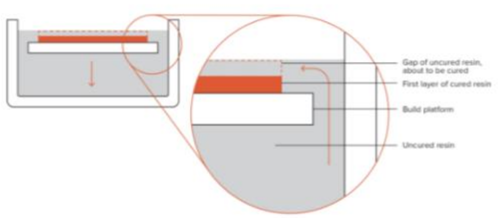
Functional Principle



The origin of this technology is the polymerization process, in which a liquid photopolymer is cured by a UV laser to initiate the solidification. The laser selectively generates the x-y-contour of the part within the liquid resin vat. The initial layer of the component is connected to the baseplate by support structures. After each cycle the base plate is lowered by the means of the defined layer thickness and a new layer is applied by a coater.

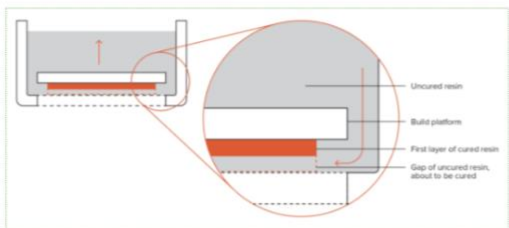
Bottom-up vs. top-down printers

Top-down printer



Source: 3D Hubs

Bottom-up printer



Source: 3D Hubs

Most **desktop SLA printers use a bottom-up process** as described below, whereas **industrial printers usually work with a top-down process**, basically turning the entire process upside down. Bottom-up printers are cheaper to produce but have a limitation in the part size, since gravitational forces during the process might cause the part to detach from the build platform. Top-down printers come at a higher cost, but are capable of producing larger components with a higher productivity.

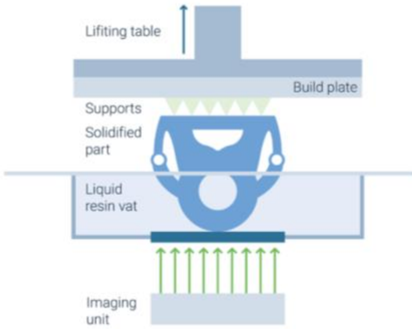
Area-wise Vat Polymerization

Area-wise Vat Polymerization, known also as **Digital Light Processing** (DLP), is a modification of Vat Polymerization. Instead of selective curing of a photopolymer by laser, a UV projector is used that cures an entire layer at once. This technology was first introduced by ENVISIONTEC and its founder Al Siblani.

Nowadays this process is especially popular in the medial sector. Dental aligners, hearing aids and other customized products are produced via this technology in high numbers and take advantage of the accuracy and speed of this technology.

Functional Principle of Area-wise Vat Polymerization

This process is based on the polymerization of a photopolymer. To cure the liquid polymer a UV light source or projector is used. A transparent and permeable window allows transmission of light. A series of cross-sectional images using UV light cures the resin during the up movement of the plate. This process repeats after every layer. After the process is completed, the part is removed from the vat. The generated part must be cleaned and support structures need to be removed. Usually, the parts are also post processed with an UV curing oven to solidify the part completely.



Advantages and challenges

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- Low investment costs
- Easy to use hardware and software
- Wide range of materials available
- Water-soluble supports available

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- Limited mechanical properties / anisotropy
- Lower detail accuracy compared to other polymer processes
- The build time per part does not decrease for batch production, thus the process is usually not suitable for high quantities
- No stacking of parts in build chamber

Process Characteristics

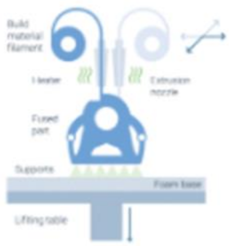
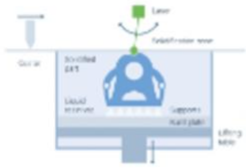
The following values act as a general guideline. Exact values depend on the exact printer configuration.

Typical Build Size	• Desktop printers: typically 300 x 200 x 300 mm • Industrial printers: up to 1.500 x 750 x 550 mm
Materials	Materials for the SLA process come in the form of liquid resins and the availability is limited. • High-temperature (e.g.Accura 5530) • Tough and durable (e.g. Accura Xtreme White 200, Formlabs Tough 2000) • ABS-like material (e.g. Accura ABS White) • Flexible (e.g. Formlabs Flexible 80a)
Technical Characteristics	• Dimensional accuracy: ± 0.01 mm or ±0.15% • Typical layer thickness: 16 – 200 µm • Typical build speed: 50 – 200 cm3/h • Typical surface roughness: Ra 5-15 µm • Support structures: Required for overhangs
Economic Data	Machine investment • Desktop printer: 2.000 -20.000 € • Industrial printer: >200.000 € Resin cost • Low-cost resin: 50 €/l • High-performance resin: 200 €/l
Post Processing Operations	• Washing in a solvent to remove extra resin • Curing in a UV-oven to increase strength • (Manual) support removal • Polishing to achieve a shiny and transparent surface finish
Suppliers	3D Systems (SLA), Carbon3D (DLP), Cubicure (SLA), EnvisionTEC (DLP), Formlabs (SLA), Nexa 3D (DLP), Prodways (DLP), Stratasys (SLA)
Applications	• Visual prototypes • Investment casting patterns

How to choose the right polymer technology

Choosing the right technology can be tricky. Selecting the right process always depends on your **application** and its **requirements**.
We therefore created an overview of the three main polymer technologies below that will help you choose the right technology for your needs. You can dive deeper into the different polymer technologies at the bottom of this page.
Keep in mind that the values should only be seen as a general rule of thumb and exact values depend on the application, the printer and the material.

Polymer technology comparison

	FDM	SLA	LPBF
Functional Principle			
Process Category	Extrusion	Vat Photopolymerization	Powder Bed Fusion
Build size	*Desktop printer:* 200x200x200 mm *Large printer:* >1x1x1m	*Desktop printer:* typically 300x200x300 mm *Industrial printer:* up to 1500x750x550mm	*Small printer:* 200x250x300 mm *Large printer:* 700x400x600 mm
Materials	Thermoplastics (Semi - Crystalline and Amorphous)	Thermoset Resins	Thermoplastics (Semi-Crystalline)
Surface Finish	Slightly rough	Smooth and shiny	Rough and grainy
Dimensional Accuracy	±0.2mm or ±0.2%	±0.01mm / ±0.15%	±0.3 mm
Typical Applications	Functional parts	Visual prototypes	Functional parts

How to get started

The above table should provide you a general guideline how to get started selecting the right process. Keep in mind that often there is **more than one process for your application**. In such cases, the selection depends on topics such as cost, quantity or mechanical properties.

The way in which you select your process depends on the type of information that you have available. If you have a concrete material in mind and this cannot be changed, start by identifying all processes that are capable of working with this material. This usually narrows down the number of technologies to 1 or 2.

In other cases, the final part properties are known. In this case, there are different databases, such as the Senvol Database of Industrial AM machines and materials. These databases will allow you to narrow down the list of possible machines or materials by applying filters such as your material category, part dimensions or required part properties.

Once you have one or several technologies in mind, the next step is to reach out to an AM expert to discuss this in more detail.