

Design and Manufacturing of Plastics Products

Integrating Traditional Methods
With Additive Manufacturing

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Chapter 7

Designing for additive manufacturing

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7.1 Part design: AM vs traditional techniques

7.1.1 Introduction

Additive Manufacturing (AM) technologies are relatively new and are rapidly changing the manufacturing industry. AM is still at a developing stage and is mainly present in the research environment; however, it is being foreseen that AM will dominate the manufacturing industry in just a few decades. AM is considered as one of the 10 technologies involving the Industry 4.0 paradigm (Fernández-Caramés and Fraga-Lamas, 2018; Bahnini et al., 2018). Its innovative and unconventional character redefines the product development chain and greatly contrasts with traditional technologies, often relying on subtractive manufacturing (SM) technologies. In SM a product or a tool is fabricated by taking a solid block and removing portions of material that correspond to the unnecessary part of the product or tool. Common SM technologies include drilling, milling, or grinding, for example.

AM operates in way opposite to SM. The ISO/ASTM 52900:2015 describes the AM as “a process of joining materials to make objects from 3D-model data, usually layer-upon-layer, as opposed to subtractive manufacturing methodologies. Synonyms of AM are: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication” (Frazier, 2014). This means that the product is started layer-by-layer by creating a positive portion instead of removing an undesirable one. The product is sliced on a build platform into several thin sections, the layers. The machine selectively adds material at prescribed locations to construct a layer. When a layer is complete, the build platform lowers one level, and a new layer is created on top of the previous one. The successive layers merge to form the final product.

The first form of AM was developed in the 1980s to rapidly create prototypes, therefore being called rapid prototyping. The ability to quickly create prototypes substantially reduced lead times from the initial design to the final product. The prototypes—without intermediary steps—are fabricated corresponding to a CAD model, so new design ideas or modifications only required an update of the CAD model. There is no need to reprogram CNC machines or make new molds, which are very time- and energy-consuming intermediary steps. However, the first AM machines had several limitations, resulting in fabricated parts of poor quality, only suitable for prototyping purposes. At present, as a result of continuous improvements that enhanced the capabilities of AM, it is possible to construct high-quality end-use products on short notice (Wong and Hernandez, 2012).

The AM process chain can be divided into eight general steps as in Fig. 7.1.

Step 1: CAD—All parts for AM must start from a model generated by software that allows a complete description of their geometry. In this step, a 3D-model of the part to be produced is generated from CAD programs (e.g., NX, SolidWorks, and CATIA.). The model can also be created using reverse engineering processes (e.g., laser or optical scanning).

Step 2: Conversion to STL format—Virtually all AM machines accept the STL (Standard Tessellation Language) file format, that became to be a standard format. STL is a file format that was created by 3D systems and allows a description of the closed external surfaces of the original CAD model and forms a basis for calculating the layers. The three-dimensional model is then converted to this standard format, as represented in Fig. 7.2.

Step 3: Transfer to an AM machine and manipulate the STL file—Each AM process has its own preprocessing program. In this program, the STL file of the model is manipulated to have the correct dimensions, position on the construction platform, and construction orientation, among other important aspects. This step is very important since the definitions established for the construction will be reflected in the finish, quality, and performance of the part.

Step 4: Machine setup—At this stage, the AM machine must be configured before the construction process starts. This configuration includes, for example, parameters, materials, and layer thickness.

Step 5: Construction—The construction of the part takes place layer-by-layer from the base of the construction platform. This process runs in an automated way until the model is complete.

Step 6: Removal—Once the production is completed, the parts are removed from the machine. This step requires some interaction with the machine.

Step 7: Postprocessing—Once removed from the machine, the part may require additional cleaning before it is considered ready for use. The parts can be fragile at this stage or have support structures that require removal. This removal takes time and must be performed carefully.

Step 8: Application—At this stage, the parts may be ready for use. However, in some cases, additional treatment may be required before approval for use.

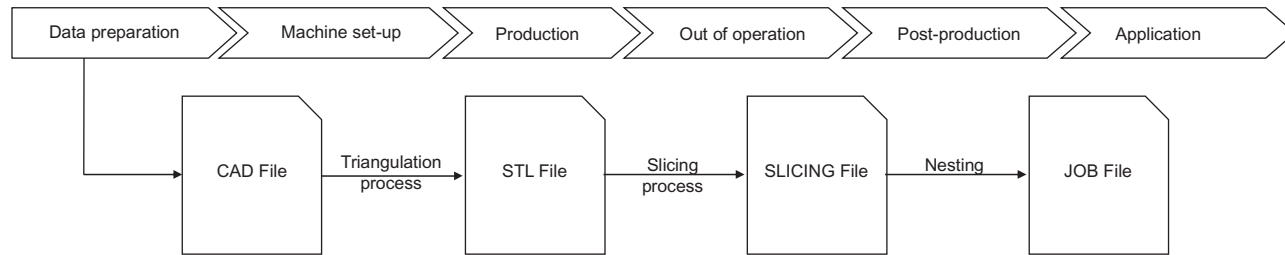


FIG. 7.1 Additive manufacturing process flow.

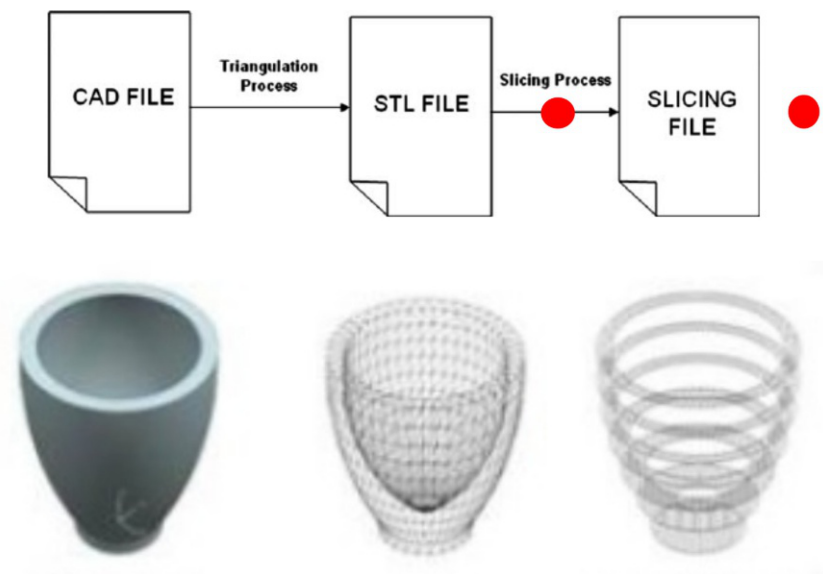


FIG. 7.2 CAD and slicing process.

For example, depending on the application, parts may need polishing, painting and other treatments to improve the texture and surface finish. The parts may require other types of treatments, such as coatings, heat treatments, micro-machining, and metallization. Depending on the processing technology, additional treatments may vary, as well as the time and labor associated with the treatment. In other situations, the part may need to be coupled with electronic or mechanical components to form the final product or model.

7.1.2 AM technologies

Over the past two decades, significant progress has been made in the development of new AM technologies. A classification may be based on a number of criteria, but for better understanding the ISO/ASTM 52900:2015 classification is commonly used.

The seven major technologies are described next.

VAT polymerization

A vat is filled with a liquid, photocurable polymer that solidifies when exposed to electromagnetic radiation, usually in the UV range. This process is called photopolymerization. A laser or light source generates a UV-beam-focused surface that cures areas point-by-point or layer-by-layer. When the UV beam has “printed” a complete layer, the building platform lowers by a one-thickness layer and a new layer can be scanned (Fig. 7.3).

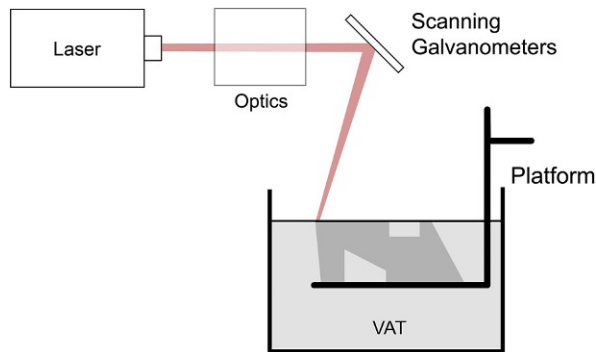


FIG. 7.3 VAT polymerization.

The materials used with this technology are photocurable epoxy or acrylate resins. Ceramics or metals are not suitable. The technology yields a superior surface quality but is expensive. Some technologies in the market are stereolithography (SLA), direct light processing (DLP) and two-photon polymerization (TPP). The latter is a layer-by-layer method and has great advantages in manufacturing arbitrary three-dimensional (3D) micro/nanostructures of various materials such as polymers, hybrid materials, and organically modified ceramics and metals with subdiffraction-limit resolution down to 100 nm (Kawata et al., 2001; Serbin et al., 2003; Doraiswamy et al., 2006; Ovsianikov et al., 2007; Formanek et al., 2006; Paz et al., 2012).

SLA was the first additive manufacturing process, introduced in 1988 by 3D-Systems, based on the work of Charles Hull. It is the most used vat photopolymerization technique.

Material extrusion

In this technology a polymeric filament is fed into an extruder. The chamber heats the material to achieve a viscous condition. The filament is pushed through a nozzle or orifice at a constant flow rate. The extruder head is typically carried on a plotting system that allows movement in the horizontal plane to make 2D contours. A layer is formed by printing a series of contours, as depicted in Fig. 7.4.

The technique is also known as fused filament fabrication (FFF). This technology is commercialized by Stratasys (Stratasys, Minneapolis, United States) under the name of fused deposition modeling (FDM). The popular low-budget 3D-printers operate according to this principle. In this process additional vertical support structures are required in overhanging details of the part being printed. The main drawback is the relatively low dimensional accuracy.

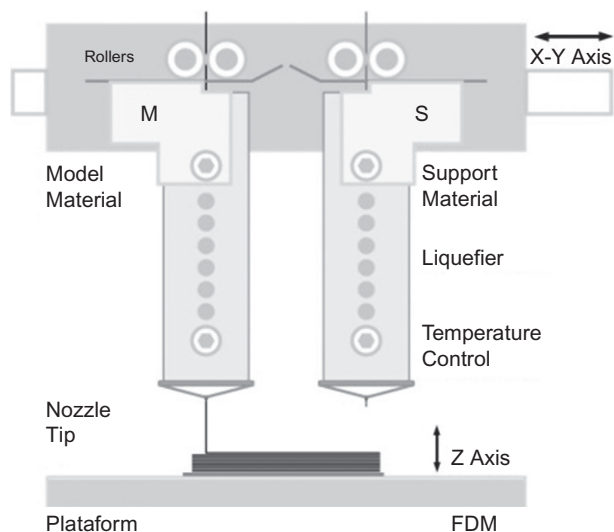


FIG. 7.4 Material extrusion.

Material jetting

This process creates objects in a method similar to the two-dimensional inkjet printer, using either a continuous or drop-on-demand approach.

A reservoir contains a liquid, that is, the supply material. The reservoir is provided with an actuator that induces pressure pulses. High pressure pushes the material out through a nozzle. In the reservoir a continuous stream of droplets is produced. Undesired droplets are deflected by a charging field and recycled. The nozzle generates individual pressure pulses at specific times. The process is comparable to a simple paper print system. PolyJet is a popular technology using this technique. Fabricated parts have a smooth surface and dimensional accuracy, but the capital investment is high (Gibson et al., 2014) (Fig. 7.5).

Material jetting is the only AM technology that can combine different materials in the same 3D-printed model in the same print job. Additionally, the multimaterial printing process can be used to construct functional assemblies, thereby reducing the need for multiple builds.

There are extensive number of materials available with material jetting. All materials are photopolymers and cover a wide range of characteristics from rigid to rubbery, transparent to opaque, or mimicking polymers like PE, PP or ABS (Vassos, 2019).

Binder jetting

Binder jetting, also referred to as the “real 3D-printing,” uses two materials: a powder-based material and a binder. The binder is usually in liquid form and

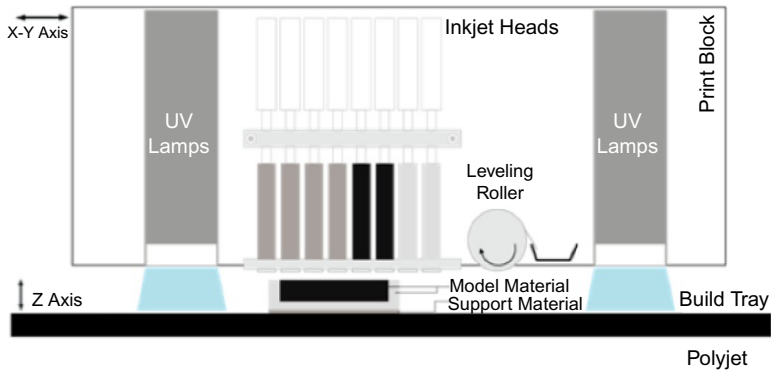


FIG. 7.5 Material jetting.

acts as an adhesive between powder layers. The part being printed is self-supported within the powder bed and, once completed, is removed from the unbound powder. Due to the method of binding, the material characteristics are not always suitable for structural parts. With the binder jetting process three types of materials can be used: metals (stainless steel), polymers (ABS, PA, and PC) and ceramics (glass).

In this process, a print head moves horizontally along the x - and y -axes of the machine and deposits alternating layers of the build material and the binding material. After each layer, the object being printed is lowered on its build platform (Fig. 7.6).

The benefits are the wide range of applicable materials and large dimensional possibilities. A drawback is the high porosity level which induces inferior mechanical strength.

Powder bed fusion

Powder bed fusion (PBF) methods use either a laser or an electron beam to melt and fuse material powders together. All these processes involve the spreading of the powder material over the previous layers (~ 0.1 mm) across the building platform. There are different mechanisms to enable this, including a roller or a blade. A hopper or a reservoir below or aside the bed provides fresh material supply. A CO_2 laser beam is focused directed onto the powder bed and moves using galvanometers to form a slice cross-section. The heat source facilitates the fusion of the particles. The atmosphere consists of an inert gas, e.g., Ar or N_2 (Fig. 7.7).

PBF includes the following commonly used printing techniques: selective laser sintering (SLS), direct metal laser sintering (DMLS), selective laser melting (SLM), electron beam melting (EBM), and selective heat sintering (SHS).

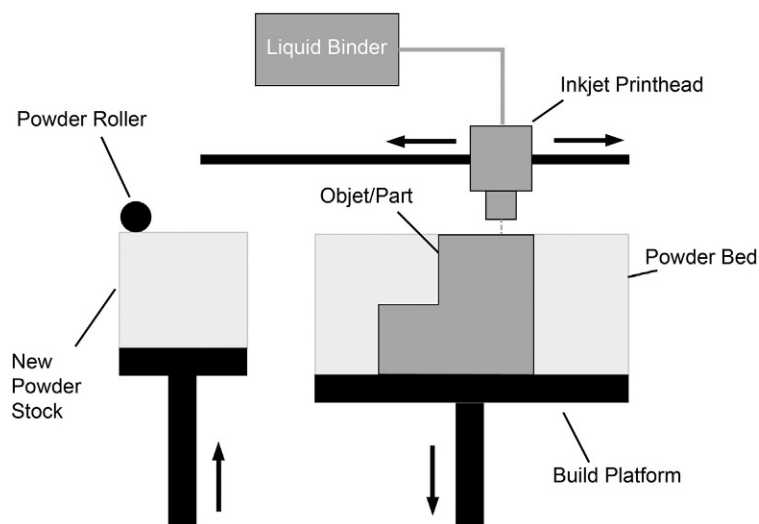


FIG. 7.6 Binder jetting.

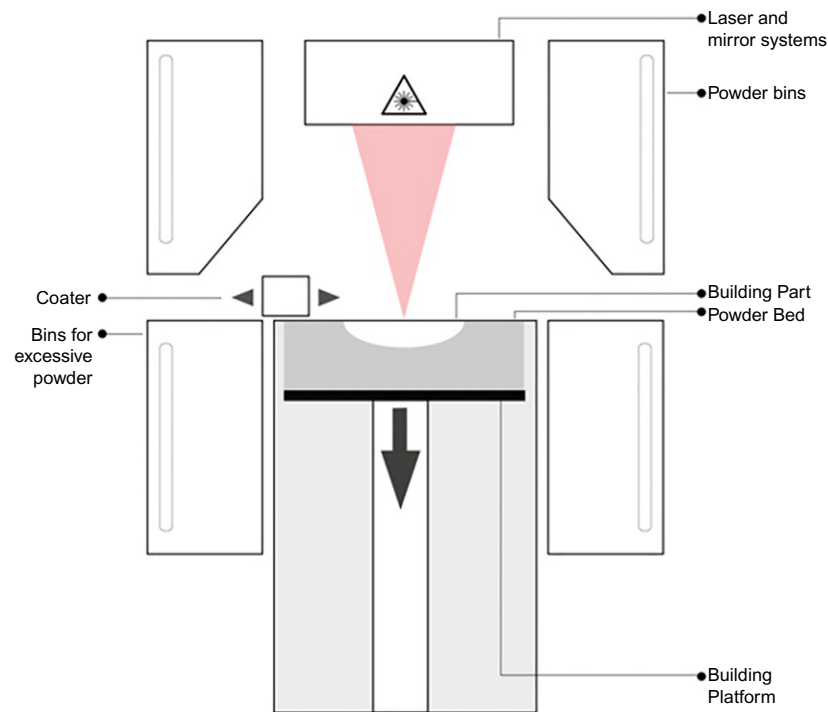


FIG. 7.7 Powder bed fusion.

Selective laser sintering (SLS) was patented in 1989 (Deckard, 1989) and uses an IR laser to promote the selective sintering of the powder material. The laser supplies energy for fusing neighboring powder particles and for bonding each new layer to those previously sintered. The sintering takes place in a sealed heated chamber at a temperature near the powder melting point and is filled with an inert gas to reduce oxidation of the powder being sintered. The powder that remains unaffected by the laser acts as a natural support for the model and remains in place until the model is complete. At the end, the nonsintered powder is discarded to reveal the solid object. Many types of materials, including polyamides, polycarbonate, ABS, metals, ceramics, and composites can be used with SLS. SLS is suitable for objects of small to medium size (10–800 mm, major dimensions) and geometrical complexity.

Direct laser metal sintering (DLMS) is also referred to as direct laser metal forming (DLMF) or selective laser melting (SLM). It is a powder bed fusion method developed jointly by Rapid Product Innovations (RPI, Finland) and EOS (Electro-Optical System, Germany) (Rahmati, 2014). DMLS is the same as SLS, but with the use of metal powders instead of plastics. The process utilizes a laser source to sinter metal powder by aiming the laser and layer-by-layer tracing a cross-section of the object. The dosing device adjusts the amount of powder for one layer and the blade arm spreads a uniform layer of powder on the surface of the platform according to the selected layer thickness. At the point of incidence of the laser beam, the metallic powder is locally melted, whereby the underlying layer is melted and then solidified. Each run partially overlaps the preceding run to form metallic bonds between the current and previous layers, producing a homogeneous solid. Previously solidified layers are re-melted and cooled several times at inconsistent levels of heat. The platform also removes heat, so the molten metal solidifies very quickly. The machine works with a protective nitrogen atmosphere in the build chamber. Postprocessing infiltration is not required because nearly dense parts are produced (Geiger et al., 2003).

SLM is a very high-energy process, as each layer of metal powder is heated above the melting point of the metal. In this AM process a high-power laser fully melts each layer of metal powder, rather than just sintering it, producing printed objects that are extremely dense and strong. Currently, SLM can only be used with specific metals, like stainless steel, tool steel, titanium, cobalt, chromium, and aluminum. Other metals do not have the correct flow characteristics required for SLM.

Electron beam melting (EBM) is an AM process similar to SLM. It also produces very dense models. The main difference between the two techniques is that EBM uses an electron beam rather than a laser to melt the metal powder. The raw material (metal powder or wire) is placed under a vacuum and fused together from heating by the electron beam. EBM and SLM are distinct from sintering processes as the raw material is let to complete melting or fusion.

Selective heat sintering (SHS) differs from other powder bed fusion processes for using a heated thermal print head to fuse powder material together.

As before, layers are added with a roller in between the fusion of layers. The platform lowers the model accordingly.

Another laser sintering process is ProMetal, a 3D-printing technology, developed by Extrude Hone Corporation (Irwin, PA) in cooperation with the Massachusetts Institute of Technology (MIT) in 1994. The principle of the process is based on metal components built by layer-by-layer selectively binding metal powder, but here the structural skeleton must be sintered and/or infiltrated with bronze to produce a finished part that is typically 60% steel and 40% bronze. The ProMetal 3D-printer uses a multiple electrostatic inkjet print head to eject liquid binders onto the metal powders, selectively hardening slices of the product. The parts are like a foundry part requiring only milling at some local areas to obtain a good, finished part.

The direct production of ProMetal parts created in CAD, follows several steps. First, the powered metal is spread onto the build platform. After that, the print head applies a layer of binder to form the first “slice” of the part. Before the part is lowered to allow the next layer of metal to be spread, a new layer of metal powder is collected while a binder driving lamp is applied to the built slice. The next layer of metal is then spread over. An additional binder is applied to bond the metal powder together and to the previous slice. The process repeats until the entire part has been printed (Fig. 7.8).

After the printing step, the “green” part, with a composition of approximately 60% of the base powder (stainless steel), 30% of the binder solvent

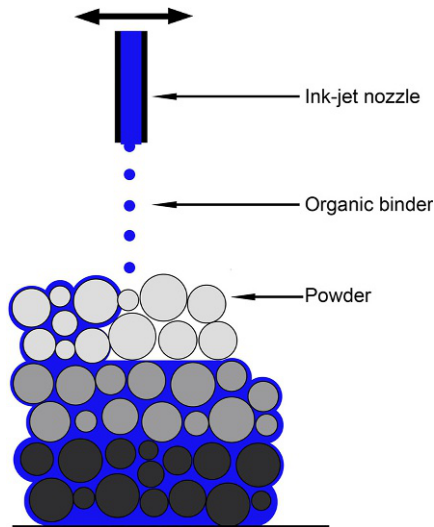


FIG. 7.8 Inkjet printing on the powder.

(bronze) and 10% of the binder active solvent, is placed into a furnace. It follows a 2-h cure at 180°C to guarantee minimal handling properties. The structural skeleton is then debonded and presintered (Dormal, 2004). In this phase the bronze infiltration takes place to produce a finished part that is 60% steel and 40% bronze. The shrinkage is very small, but the resulting alloy is not satisfactory for rapid manufacturing applications. The final mechanical properties are not excellent but good enough for many basic applications.

Alternatively, the last stage can be the fully sintering of the part to reach 95%–98% of the required properties and nearly the full material density. After that, the part is ready for postprocessing which may be polishing, milling, surface grinding, or any other way to reduce the bad surface quality produced by the 3D-printing process caused by the 120 µm layers.

The benefits of 3D-metal printing include:

- Fully dense metal printed parts, with complex geometries and precise internal features.
- Minimum material waste.
- Possibility of obtaining conformal cooling channels.
- Multiple, identical parts can be built at one time.

Directed energy deposition

Directed energy deposition (DED) covers a range of terminology (Gibson et al., 2010): laser engineered net shaping, directed light fabrication, direct metal deposition, and 3D-laser cladding.

A typical DED machine consists of a nozzle mounted on a multiaxis appendage, which deposits the melted material onto the specified surface. The process is similar to material extrusion, but the nozzle can move in multiple directions and is not fixed to a specific axis. The material, which can be deposited from any angle due to 4 and 5 axis machines, is melted upon deposition with a laser or an electron beam (Fig. 7.9).

The process can be used with polymers, ceramics, but is typically used with metals, in the form of either powder or wire.

Sheet lamination

Sheet lamination includes ultrasonic AM (UAM) and laminated object manufacturing (LOM). UAM uses sheets or ribbons of metal, which are bound together using ultrasonic welding. The process does require additional CNC machining and removal of the unbound metal, often during the welding process.

LOM uses a similar layer-by-layer approach but uses paper as the material and adhesive instead of welding. It uses a cross-hatching method during the printing process to allow for easy removal postbuild (Fig. 7.10).

Laminated objects are often used for esthetic and visual models and are not suitable for structural use (Friel and Harris, 2013). The process can bond different materials and requires relatively little energy, as the metal is not melted.

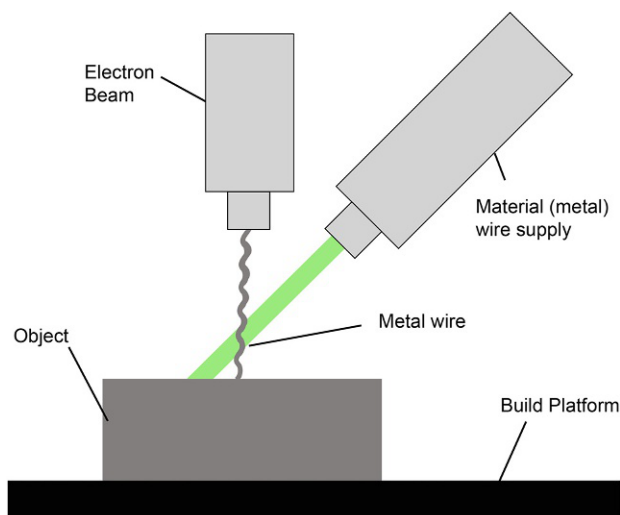


FIG. 7.9 Directed energy deposition process.

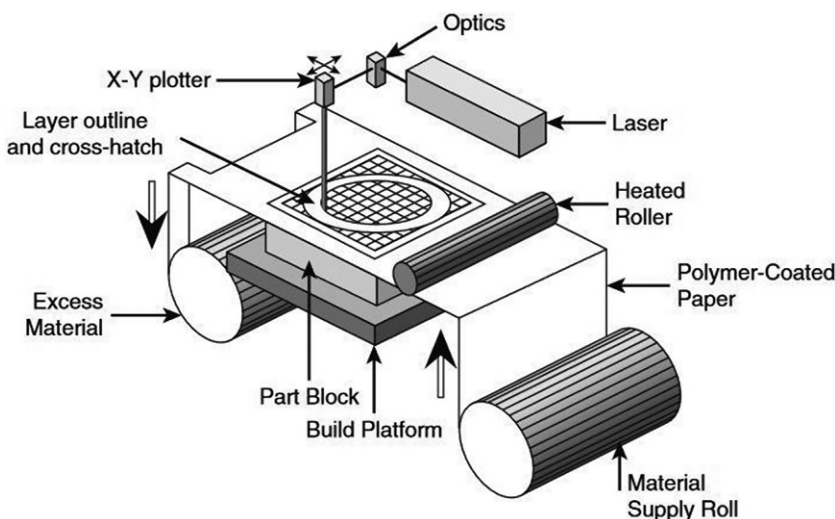


FIG. 7.10 Sheet lamination.

Any sheet material capable of being rolled, paper, plastic and some sheet metals can be used. For each technology, the same manufacturer can offer different machine models that vary in terms of the construction area, manufacturing speed, layer thickness, resolution, material range, precision, or cost (Table 7.1).

TABLE 7.1 Technologies and materials used in additive manufacturing.

Process category	Process/Technology	Material
Vat photo-polymerization	Stereolithography (SLA)	UV curable resins Wax Ceramics
	Direct light processing (DLP)	UV Curable Resins
	Continuous digital light processing (cDLP)	
Material jetting	Material jetting (MJ)	UV Curable Resins
	Nanoparticle jetting (NPJ)	Metals
	Drop on demand (DOD)	Wax
Binder jetting	3D-printing (3DP)	Composites Polymers Ceramics Metals
Material extrusion	Fused filament fabrication (FFF)	Thermoplastics Waxes Metals Composites
Powder bed fusion	Selective laser sintering (SLS)	Thermoplastics Metals
	Direct metal laser sintering (DMLS)/laser melting (SLM)	Metals
	Multi jet fusion (MJF)	Thermoplastics Metals
	Electron beam melting (EBM)	Metals
Sheet lamination	Laminated object manufacturing (LOM)	Paper Metals Composites Thermoplastics
Directed energy deposition	Laser metal deposition (LMD)/laser engineered net shaping (LENS) Electron beam AM (EBAM)	Metals

7.1.3 Benefits and weaknesses

Benefits

AM technologies overcome many limitations of traditional manufacturing techniques and design creativity. Traditional techniques are often restricted to basic shapes and geometries. AM offers the ability to build parts with a geometrical complexity that is limitless. This opens new opportunities for designers to focus more on geometrical optimization and functionality instead of machinability (Fig. 7.11).

Sustainability has become an important benchmark in every industry. Materials, energy and time became more valuable, therefore requiring careful management. AM only uses materials where needed, reducing material waste and energy consumption to an absolute minimum. Conventional subtractive manufacturing technologies need expensive and time-consuming recycling cycles to minimize the carbon footprint.

Product development is a thorough process from the initial idea to the final product. Designers come up with new design ideas, modifications etc. As previously mentioned, AM has the ability to fabricate parts directly from a CAD model. The creation of new and improved prototypes is a quick operation since the only requirement is an update of the CAD model. Traditional techniques require new molds or alternations of existent molds, or even modified CNC setups which can be expensive and time-consuming. AM technologies drastically accelerated the conceptual stage of product development.

Weaknesses

AM technologies developed extensively in the past decades. However, even though the techniques present improvements compared to initial versions, there remain some issues that require attention. Every AM technology has its specific drawbacks, but the following problems are common to all of them.

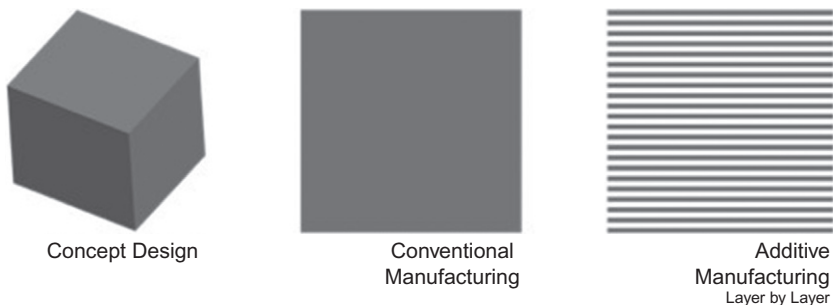


FIG. 7.11 From conventional to additive manufacturing.

AM inherently produces parts susceptible to high porosity levels. This can either be induced by the powder or the process. Void regions can be detrimental to structural integrity and firmness.

The heat-based AM operations are susceptible to residual stresses that appear when all external loads are withdrawn. They are usually unpredictable and undesired because they can negatively impact mechanical strength and cause warpage.

Pattern strategies, build orientation, or interaction between the layers can induce anisotropic properties. Adequate machine settings can minimize this problem.

The surface finish highly depends on the involved AM platform, but it is generally inferior to traditional techniques, e.g., grinding, lapping, or milling. The different layers can be visible on the final product and skewed walls may appear in the form of a “stair-stepping” system. Postprocessing actions are sometimes required to smooth the surface.

The final issue is the price. Most advanced AM systems are not yet competitive with traditional techniques. Therefore, they are not considered by many companies.

Applications

Most applications of AM are still in development in research environment, but the extrapolation to mass production may be imminent, despite the elevated cost. Thanks to the wide range of available materials and capabilities to produce intricate geometries, the technology can be implemented in any industry. [Fig. 7.12](#) and some more in this chapter show examples produced at DONE Lab—Advanced Manufacturing of Products and Tools, located on the campus of the University of Minho, Guimarães, Portugal (www.donelab.uminho.pt), where AM techniques were used.

7.2 Design criteria for AM

7.2.1 FFF—Fused filament fabrication

FFF is particularly useful for functional applications because it matches 80% of the actual properties of the material in an injection-molded counterpart. FFF models are accurate and have an intermediate level of printed details. It is possible to have great freedom for the design of a model. However, the surface quality of the models is rougher compared to other technologies ([Fig. 7.13](#)).

FFF can be used to produce full functional models. Normally the material used is closest to the material of real production products. Extra finishing steps are possible if needed. Since the support material is dissolvable, complex designs are possible. The printing process is slow, but a printed model requires less manual finishing.



JIGS AND FIXTURES



ENCLOSURES/HOUSING



SOLES FOR SHOES



CONCEPTUAL PROTOTYPES



FUNCTIONAL PROTOTYPES



HIBRID MOULDS

FIG. 7.12 AM applications. (Courtesy of *DONE Lab - Advanced Manufacturing of Products and Tools*, Guimarães, Portugal.)

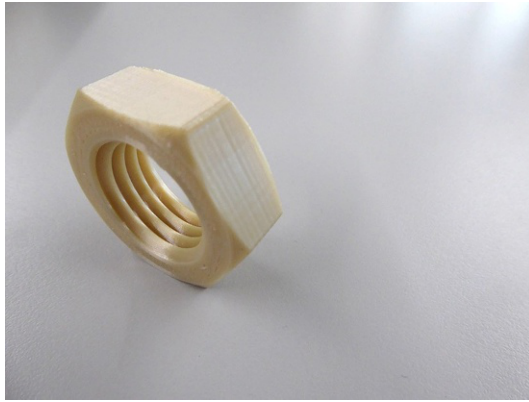


FIG. 7.13 FFF prototype molded in Ultem polyetherimide. (Courtesy of DONE Lab - Advanced Manufacturing of Products and Tools, Guimarães, Portugal.)

FFF basic rules

Wall thickness—In FFF, the wall thickness refers to the distance between one surface of the model and the opposite sheer surface. A model needs to be designed with a minimum wall thickness of 1 mm. The walls of larger parts need at least 1.2 mm thickness.

Surface quality and orientation—Many of the characteristics of the prototype will depend on the FFF process—the technology used to build the prototype. Since the model will be printed layer-by-layer, the printing orientation will influence the surface quality and strength.

In Fig. 7.14 there is an example of a part where the layer orientation can be seen. The printed model clearly shows the “staircase” effect of the printing process. Its surface is similar to that of a topographic map. If the model is printed vertically, the surface quality will be better.

It is necessary to think about which surface needs to have the best finish and choose the orientation accordingly when printing.

Anisotropy—Because the model is built up layer-by-layer, it will always have “weak points” caused by its printing orientation. These weak points can cause thin external elements of the design to easily break off. Therefore, features on the model that are parallel to the base or bottom plane and that will require strength to support them should be avoided (Fig. 7.15).

Dimensional accuracy—The general tolerance of the material is 0.1% with a minimum of $\pm 200\ \mu\text{m}$. Dimensional accuracy does not relate to the detail of the model but to the deviation from the nominal size.

Support—FFF takes place on a building platform. Since the models will be “built in the air” they must be attached to the supporting platform to prevent them from collapsing. This attachment is referred to as the “support” and is required for any model built using this technology. In addition to keeping the model in place, it also enables the construction of elements that stick out.

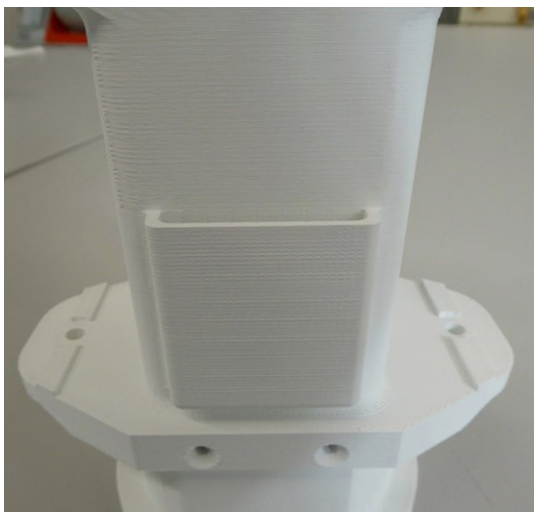


FIG. 7.14 Prototype finishing and orientation. (*Courtesy of DONE Lab - Advanced Manufacturing of Products and Tools, Guimarães, Portugal.*)

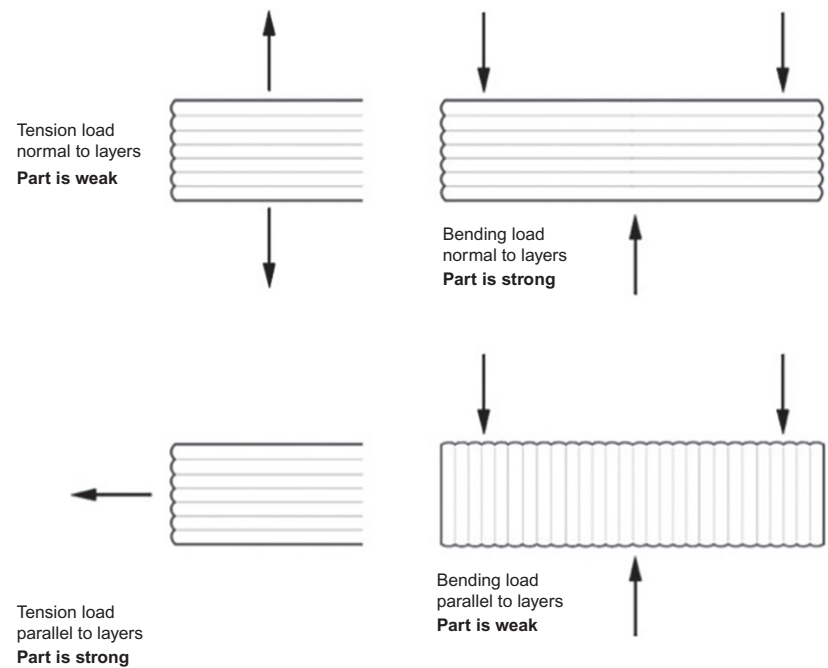


FIG. 7.15 Layer orientation and mechanical strength of the model.

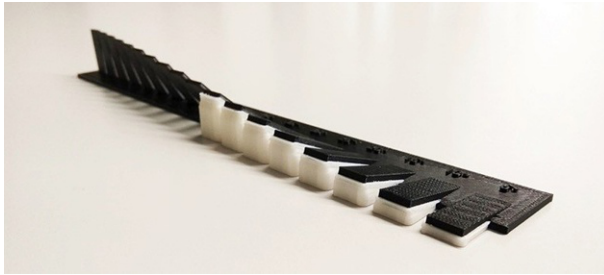


FIG. 7.16 Prototype support in narrower angles. (Courtesy of *DONE Lab - Advanced Manufacturing of Products and Tools*, Guimarães, Portugal.)

After the building process is complete, the support is manually removed. It is common that the model may show evidence of the removed support structures.

Base—To build the parts, they must be designed with a base on which to attach the support structure. With this in mind, it is convenient to consider that the bottom surface will be rougher than the rest of the model.

Rule of 45 degrees—To keep the model in place and prevent it from collapsing while being printed, models that have sections narrower than 45 degrees must be supported. The 45 degrees-rule also applies to the interior of the model. Any model with an interior section below 45 degrees must be supported. In Fig. 7.16, the model must be supported to prevent it from collapsing during the printing process.

Fig. 7.17 shows when a model requires support. The “self-supporting” or “safe” zone does not require any support when the model is printed. For most models, this area ranges from 45 to 135 degrees.

The right space between the (moving) parts—When it is necessary to design something like a hinge, the spacing between the surfaces is crucial. Spacing will determine the flexibility/bendability of the design. A minimum space of 0.4 mm must be kept between designed surfaces. In the example of a model with hinges, as shown in Fig. 7.18, the gap to be created between the surfaces will depend on their size.

Assembly—When designing models that need to be assembled, it is important to provide enough distance between the parts that will be attached

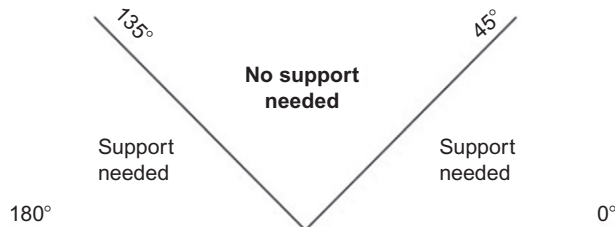


FIG. 7.17 Rule of 45 degrees.



FIG. 7.18 FFF right space between moving parts. (Courtesy of DONE Lab - Advanced Manufacturing of Products and Tools, Guimarães, Portugal.)

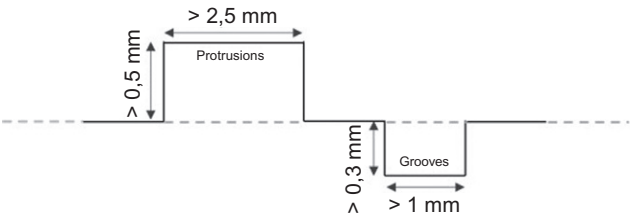


FIG. 7.19 Guidelines for FFF embossing and details.

together. A perfect fit in the software package does not mean a perfect fit after printing because the software ignores the friction present in the real world. Therefore, a spacing of at least 0.3 mm must be left between the different parts.

Embossed and engraved details—In general, engraved text or details are preferable to embossed text or details. For engraved text or surface details, letters with a minimum line thickness of 1 mm and a depth of 0.3 mm are recommended. For embossed text and surface details, letters that have a line thickness of at least 2.5 mm and a depth of at least 0.5 mm are recommended (Fig. 7.19).

7.2.2 PolyJet

The models constructed from a photo-polymeric liquid are ideal for small and/or very finely detailed visual models. Although the functional use of this material is rather limited, the model will exhibit a smooth surface (Fig. 7.20).



FIG. 7.20 PolyJet prototype. (Courtesy of *DONE Lab - Advanced Manufacturing of Products and Tools*, Guimarães, Portugal.)

This technology can be used for small, detailed parts. The support material is printed together with the model (Fig. 7.21).

It has to be removed and it limits the freedom of design. Postfinishing a high detail model with paint is possible but leads to a possible loss of detail. The model must be kept out of direct sunlight to prevent discoloration. Painting or varnishing the model will prevent or limit discoloration.

PolyJet basic rules

Wall thickness—In PolyJet, the wall thickness refers to the distance between one surface of the model and the opposite sheer surface. A model made in PolyJet with a minimal wall thickness of 1 mm yields a strong solid surface.



FIG. 7.21 PolyJet prototype with support material. (Courtesy of *DONE Lab - Advanced Manufacturing of Products and Tools*, Guimarães, Portugal.)

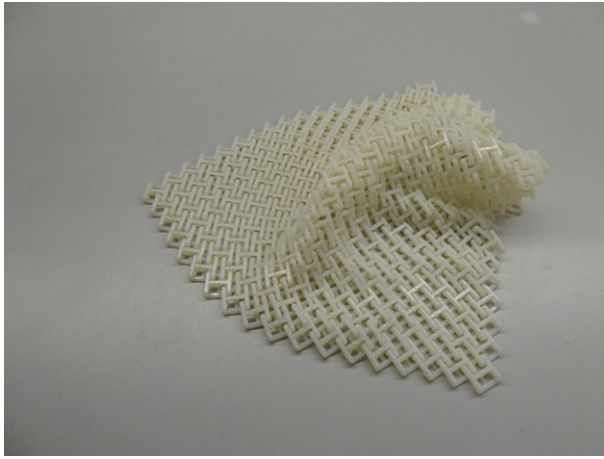


FIG. 7.22 PolyJet model showing the right space between moving parts. (Courtesy of *DONE Lab - Advanced Manufacturing of Products and Tools*, Guimarães, Portugal.)

Dimensional accuracy—PolyJet boasts one of the highest levels of accuracy among AM technologies. Thanks to the precise deposition of the tiny droplets of material, layers can be printed as thin as 0.013 mm, allowing for parts with a very smooth surface finish and enabling parts with small but highly accurate features to be produced.

The right space between the (moving) parts—When designing something like a chainmail, the spacing between the surfaces is crucial. It will determine the flexibility/bendability of the product.

At least 0.4 mm of space should be kept between the rings—it can always be more. The space created between the rings will purely depend on their size. With big rings, a lot of space can be created so that it will be possible to print more of them in a confined space. With small rings, there is a limit in the space to keep a distance between the opposite horizontal or vertical rings in the chain (Fig. 7.22).

Full-color and multimaterial parts—PolyJet can be used for full-color and multimaterial 3D-printing, as the printhead used in the printing process typically incorporates multiple nozzles. These nozzles can deposit different materials and/or different colors in a single printing process. Objects created through the material jetting printing process can therefore possess a range of material properties such as rigidity, flexibility, opaqueness, and translucency.

Assembly—When designing models that need to be assembled, it is important to provide enough distance between the parts that will be attached together. A perfect fit in the software package does not mean a perfect fit after printing because the software ignores the friction present in the real world. Therefore, a gap of at least 0.6 mm between the different parts must always be left.

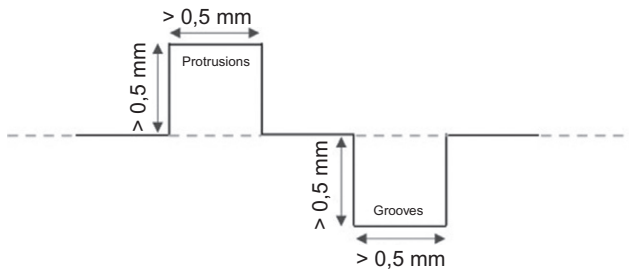


FIG. 7.23 PolyJet embossing and details.

Embossed and engraved details—For engraved text or surface details, the letters must have a minimum line thickness of 0.5 mm and a depth of 0.5 mm. For embossed text and surface details, letters with a line thickness of at least 0.5 mm and a depth of at least 0.5 mm should be used (Fig. 7.23).

7.2.3 SLS—Selective laser sintering

Models produced in SLS could be constructed in white, very fine, granular material powder (Fig. 7.24).

The result is a strong, fairly flexible product that can take small impacts. The surface has a sandy, granular look and is slightly porous.

SLS can be used for complex models, concept models, small series of models (several copies of a model), lamps, and functional models. This technique allows the greatest freedom of design of all 3D-printing techniques.

SLS with polyamide is perfect for beginning-designers who want a well-priced model, maximum freedom of creation, and who do not want to be bothered with the limitations of the printing process. The models produced with polyamide materials are not suited for outdoor use as they absorb moisture. However, in some cases the material can be treated to make it watertight.

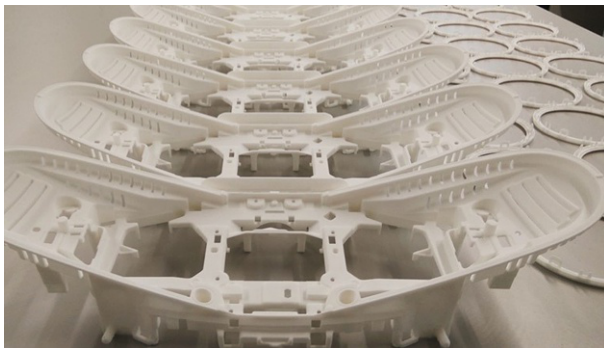


FIG. 7.24 SLS models printed in PA 12. (Courtesy of DONE Lab - Advanced Manufacturing of Products and Tools, Guimarães, Portugal.)

Some special attention should be given to models with large, flat surfaces or plates (<25 cm). When such a model cools down, it can deform and warp.

SLS basic rules

Wall thickness—In SLS, the wall thickness refers to the distance between one surface of the model and the opposite sheer surface. The wall thickness can either provide a strong solid surface, or a flexible and expandable surface.

A good example of when creating thin surface walls is ideal is when designing a spiral that needs some suspension properties. This makes the design light and flexible. The opposite effect can be achieved by making the surface walls thicker. This would be ideal for a more solid spiral-inspired flower vase (Fig. 7.25).

Hollow out the model—If possible, it is recommended to hollow out the model. This avoids deformation and discoloration during the printing process. It is possible to either hollow out the model and keep the powder material trapped inside or design a strategically placed hole (two is better) so that the powder can be easily removed after printing (Fig. 7.26).

Large flat planes can cause warping—Designing a big flat plain the size of an A4 page is a bad idea. In most cases, the model will deform. This process is called “warping”. Even if it is created support ribs under the plane, it does not



FIG. 7.25 SLS wall thickness.

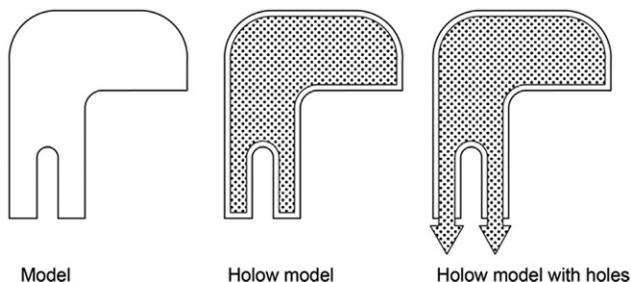


FIG. 7.26 SLS hollows.



FIG. 7.27 SLS flat planes. (Courtesy of DONE Lab - Advanced Manufacturing of Products and Tools, Guimarães, Portugal.)

solve the problem. It increases the possibility of deformation even more. The key here is to avoid large flat planes (Fig. 7.27).

The right space between the (moving) parts—When designing something like a chainmail, the space between the rings in the 3D-model is important. This will allow the powder between the rings to flow away when the model is taken out of the SLS machine.

At least 0.4 mm of space should be kept between the rings—it can always be more. The space created between the rings will purely depend on their size. With big rings, a lot of space can be created so that it will be possible to print more of them in a confined space. With small rings, there is a limit in the space to keep a distance between the opposite horizontal or vertical rings in the chain (Fig. 7.28).



FIG. 7.28 SLS chainmail model. (Courtesy of DONE Lab - Advanced Manufacturing of Products and Tools, Guimarães, Portugal.)

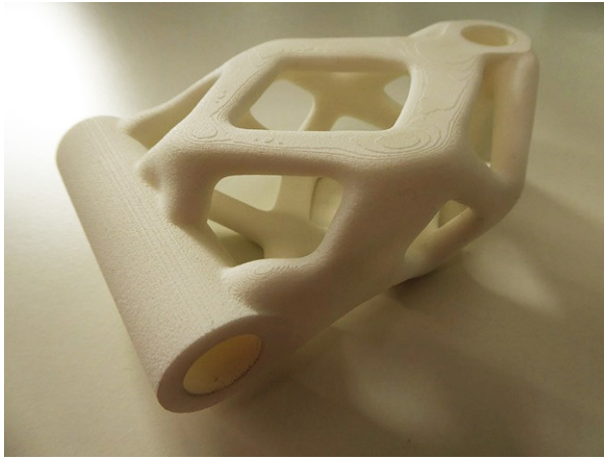


FIG. 7.29 SLS surface layer. (Courtesy of *DONE Lab - Advanced Manufacturing of Products and Tools*, Guimarães, Portugal.)

Using surface textures to hide building layers—Because of the nature of the SLS process, a visibly layered surface often remains on the designs. To remove these visible building layers, models are often polished. However, it is also possible to take advantage of the unsmooth surface by applying a surface texture to the model that will disguise the building layers (Fig. 7.29).

Assembly—When designing models that need to be assembled, it is important to provide enough distance between the parts that will be attached together. A perfect fit in the software package does not mean a perfect fit after printing because the software ignores the friction present in the real world. Therefore, always leave at least 0.6 mm between the different parts (Fig. 7.30).

Embossed and engraved details—For engraved text or surface details, it is recommended letters with a minimum line thickness of 1 mm, a depth of 1.5 mm, and an overall height of at least 4.5 mm. Embossed text or surface details should be thick enough that they will not break during production or transport. It is recommended letters that have a line thickness of at least 0.8 mm, an overall height of at least 3 mm, and a depth of at least 0.8 mm (Fig. 7.31).

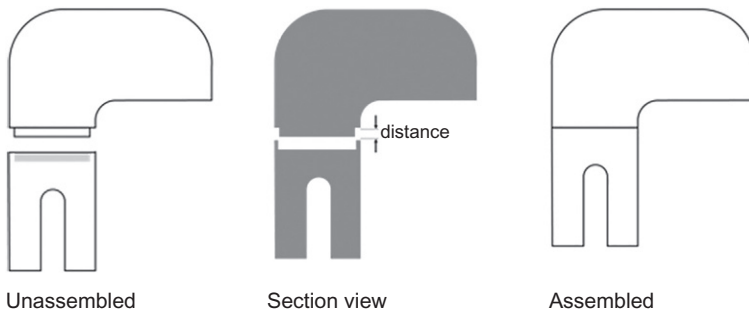


FIG. 7.30 SLS assembly.

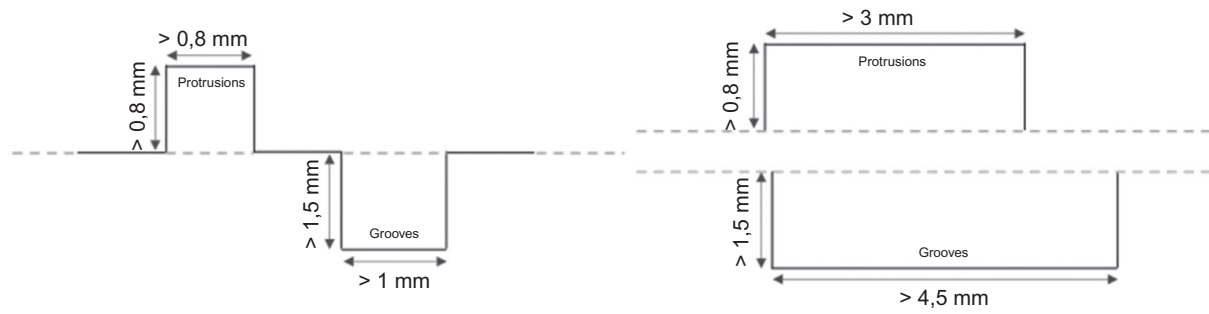


FIG. 7.31 SLS embossed and details.

7.2.4 DMLS—Direct metal laser sintering

The models made in DMLS are printed in powder material that is sintered together by a laser to produce end-use metal parts that are as equally good as machined models.

DMLS in aluminum does not look like the traditional shiny milled aluminum. Instead, it is a bit grayer and more matte with a slightly rougher and less defined surface. Models are strong, precise and can have a feature size as small as 0.25 mm. Aluminum can be used for full functional parts and spare parts (Fig. 7.32).

It is possible to make lattice structures, organically shaped objects that are not able to be produced by any other process (Fig. 7.33).

Because the supports have to be removed manually, some evidence of removed support structures might remain on the model. Any “overhanging” structures such as the bottom of a table built with this process will tend to be unattractive.

Any angles less steep than 35 degrees will tend to be less attractive with this process.

DMLS basic rules

Wall thickness—For DMLS, the minimum wall thickness is 0.5 mm for small surfaces or features up to 15 mm by 15 mm. However, if it necessary to make larger sections, the wall thickness should be increased to at least 1 mm.

Detail size—Small details, as small as 0.25 mm, are also possible when printing aluminum, using DMLS. Detail sizes refer to the distance between



FIG. 7.32 DMLS aluminum models. (Courtesy of DONE Lab - Advanced Manufacturing of Products and Tools, Guimarães, Portugal.)

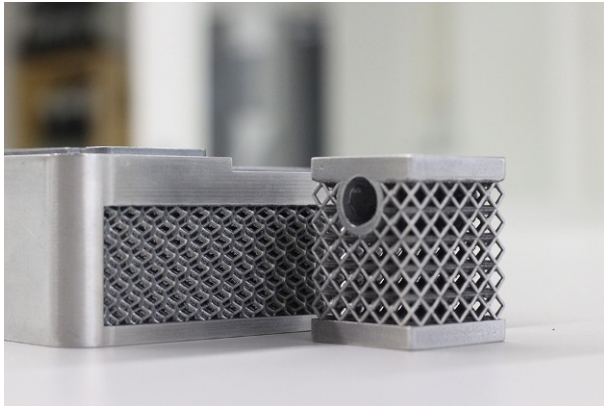


FIG. 7.33 DMLS lattice structures. (Courtesy of DONE Lab - Advanced Manufacturing of Products and Tools, Guimarães, Portugal.)

the surface of the model and the surface of the detail. Letters are also considered as details, but they have different specifications.

Geometry—Organic or freeform shapes, look more attractive in aluminum than angular shapes, right angles, and straight lines. Angles less than 35 degrees tend to lead to poorer surface quality, while steep angles of more than 35 degrees are likely to have better, smoother surfaces. An overhanging structure (e.g., the underside of a table) will be likely to have poor surface quality.

It is essential to avoid or minimize stress while printing the models, as it might eventually deform the model. It is advisable to round off or filet the edges in the design, and, also, avoiding sharp edges.

The ideal shape to make when using DMLS is that of lattice structures. These shapes are easy to design for this process and deliver the best results.

Dimensional accuracy—DMLS is the AM process for metals with very good dimensional accuracy. The general tolerance of the material is 2%, with a minimum of $\pm 200 \mu\text{m}$. Normally, the general tolerance for the AM process in aluminum is 0.2%.

Support—Support structures are also produced in aluminum. The support structures keep the model rigid during printing and prevent internal stress and deformations. Walls or overhangs with angles below 40 degrees typically need to be supported as they would otherwise collapse during the printing process. Afterward, the support is removed manually, and the part is sandblasted. Some evidence of the removed support structures may still be visible.

Powder removal—Models can be hollowed out. There should be used a minimum wall thickness of 1 mm and a minimum opening of 3 mm in diameter. This opening will serve as an exit for the extra, internal powder.

Larger and complex cavities need multiple holes and increased size. A minimum diameter of 7 mm is recommended. Holes in the center of the model are usually the best as they allow most of the powder to be removed.

Holes and threaded holes—The minimum recommended diameter for a hole is 1 mm. This is the minimum diameter needed to remove the internal powder; if the hole is smaller the powder will get stuck inside the geometry.

Complex and irregularly shaped holes or interior spaces are impossible to inspect or remove the powder from completely. Therefore, it cannot be guaranteed that these designs will come out of the printer looking exactly like their design. If perfectly straight holes are required, it is possible that the holes in the model are slightly smaller than designed. The hole to match the exact measurement can be drilled out once the part has been built.

Although dimensional accuracy is high, threads cannot be made of this material. If the design requires threaded holes, slightly smaller holes should be made in the 3D-design file and drilling and cutting out a thread into the holes of the 3D-printed part. Small adjustments to the final printed model can be made using traditional mechanical methods.

Nested objects, hinged and interlinking parts—Nested objects (objects floating within another object), hinged parts, and interlinking parts such as chains cannot be made using DMLS because this technology requires the use of support structures.

Engraved text and surface details—For engraved text or surface details, the letters should be designed with a minimum line thickness of 0.4 mm, a minimum overall height of 0.4 mm, and a minimum depth of 0.15 mm.

General tolerances—The general tolerances for DMLS parts are about ± 0.2 mm and the finish of DMLS parts as built is about 8 μm Ra.

Design guidelines—Parts can be manufactured using DMLS in a variety of metal and alloy materials. Geometries remain fixed to a base plate during the building process via a support structure and are separated afterward by breaking away the supports. It is not possible, however, to build detached parts, which can be done when making plastic laser sintered parts.

Overhangs with an angle greater than 35 degrees can be built without requiring a support structure. However, when supports are needed they must be easy to access or else they cannot be removed in secondary operations (Fig. 7.34).

When working with DMLS, only relevant geometries should be built. Excessive volumes should be avoided when using this technology. This is because build volume (the amount of material to be solidified) along with the number of layers is what determines the production time and costs, not the complexity of the geometry. For example, the tool insert displayed in Fig. 7.35 can be produced faster, and therefore more cost efficiently, if only the relevant geometry is built. The optimized version of the cavity, as shown, is also preferable for external corners to be round rather than sharp.

Unnecessary volume has to be sintered with a longer build time and will be more expensive.

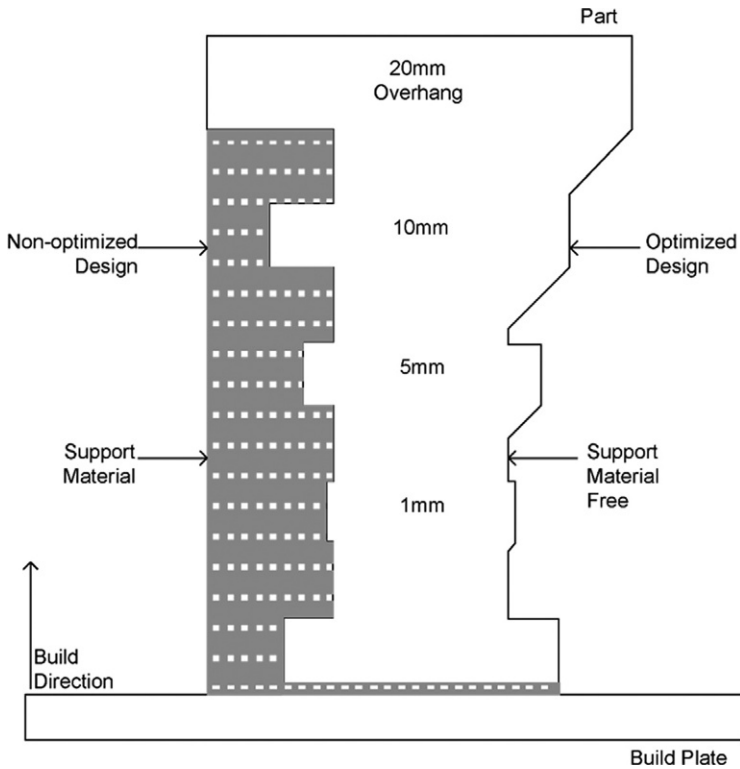


FIG. 7.34 Overhangs with an angle greater than 35 degrees can be built without support structures.

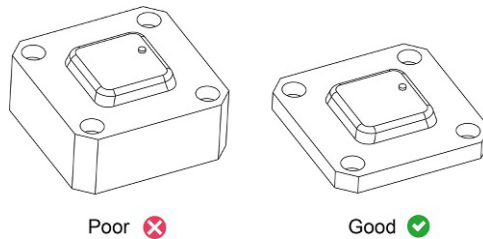


FIG. 7.35 *Left:* insert in original format; *Right:* insert optimized for reduced build time.

Overall, the most ideal geometries are small, self-supporting parts that would be difficult to manufacture through machining, are too expensive to investment casting, or are metal parts requiring short lead times.

7.3 Selection of AM technologies

The use of prototypes depends on each project, product, and product design elements. The success of a prototype depends on the AM and SM technologies selected to fabricate it.

There are five factors that should be considered during the prototype fabrication selection. The main factors of AM and SM technologies selection for prototype fabrication are as follows:

- 1. The purpose of the prototype
- 2. The quality of the prototype
- 3. The quantity needed
- 4. The complexity of the prototype
- 5. The cost or budget

7.3.1 The purpose of the prototype

During the process of designing and developing a product, prototypes are created for four main purposes (Ulrich et al., 2020): learning, communication, integration and milestones.

The purposes underlining prototyping vary depending on which phase of the product development is, and are: information design, concept design, detail design, preseries (Table 7.2).

Each phase has its feature and functionality requirement. This defines the specifications of the required prototype and its quality.

The planned tests or risk mitigation exercises, namely the types of test, the customer interaction feedback, and other issues will influence the selection. If the prototype is to go through rigorous testing and product verification, outside

TABLE 7.2 Product development phase vs type of prototypes used.

Product development phase	Type of prototype
Information design Research and getting information Definition of the specifications	Concept prototypes
Concept design Study and assessment of alternatives Selection of the concept to be developed	
Detail design Geometry definition Analyses of the functions Technical prototypes	
Preseries	Final products
Production	

the development team, then the type of material of the product plays a crucial part in the selection of the AM process. Another issue is the functional aspect of the prototype that needs consideration. The type of functional test, if any, and the existence of moving parts will significantly influence the selection and the assembly. Also, the changes and modifications required during the development phases should be considered. It is important to consider how easy or difficult it would be to make modifications to get the prototypes working.

Information design

This stage generally requires very early proof of concept mock-ups, demonstration units and industrial design prototypes. These can be produced by AM and SM techniques as follows: CNC machined foam models, cardboard mock-ups, or AM parts and assemblies (made by FFF, SLA, SLS and others).

Concept design

At this stage, it is probably necessary to have scaled parts or assemblies of the design with some user interface and limited functionality. FFF parts are adequate for getting a feeling for the shape and size. If more accuracy is required other AM technologies like SLA, SLS or PolyJet may be more appropriate to use. If the parts are metallic, then CNC or DMLS is more adequate. In some cases, sheet metal fabrication could also be considered.

Detail design

In this product development phase, it is needed to explore fully functional (form, fit and function) prototypes, therefore details are important. At this phase, the prototypes could go to work as assemblies consisting of several parts. It would also be necessarily more than one unit for testing purposes and considering the final manufacturing techniques. For this phase it is normal to consider vacuum casting and high-resolution AM techniques such as SLS and SLA for plastic parts.

Preseries

Any prototype made during the preseries production phase is probably meant to be used on functional testing and preproduction pilot runs. If they are to be injection molded, the parts can be produced using rapid tooling solutions like the “hybrid mold” concept. For more details on hybrid molds see [Chapter 9](#).

7.3.2 The quality of the prototype

The reliability or the accuracy of the required product will command what type of process and postprocessing will be applicable. The quality of the prototype as compared to the final product or integrated component also needs to be considered. As high-fidelity prototypes are more costly, they should be considered in

terms of return on investment. For example, if the part has a thread feature, then SLA is better than FDM, but it will cost more.

The lifetime of a prototype is also critical when deciding the technology. For example, if the parts have fasteners that will be used frequently, then machined or metal inserts are a better option than 3D-printed threaded or self-tapping holes.

The material selection also plays a vital role in the quality of the prototype. If the functional elements require specific material properties, such as surface finish and durability, then choosing AM parts might not be the best choice.

If the prototype is made of more than one part, then the tolerance of the prototype parts must be considered for ease of integration.

7.3.3 The required quantity

The required number of prototype parts in each phase of Product Development is important for the decision of which fabrication process is adequate since some of rapid prototyping technologies are only cost-effective for small quantities. For AM parts the volume also plays a crucial part in costing as bigger parts will require more time to print compared to smaller parts. As a general rule, the rules in Table 7.3 could apply.

7.3.4 The complexity of the prototype

The complexity and features of the part are the main factors to determine the rapid prototyping process selection. Additive manufacturing is good for producing complicated small parts, but one should be cautious about the final design because complicated means very expensive mass production.

TABLE 7.3 The number of prototypes required in each PD phase.				
	Quantity	Material	Geometry	Functional test
Concept design	1–2	Any	Not detailed	No
Geometry definition	1–2	Any	Detailed	No
Functional analysis	3–8	Near to final	Detailed	Yes
Technical model	10–20	Final or similar	Final or near	Yes
Preseries	100–500	Final	Final	Yes

TABLE 7.4 Tolerances achievable with AM processes.

Process	Tolerance (mm)	Minimum wall thickness (mm)
FFF	± 0.20 to ± 0.50	0.8–1.0
SLS	± 0.20 to ± 0.30	0.7–1.0
DMLS	± 0.10	0.4–0.5
Binder jetting	± 0.20	1.5–2.0
SLA	± 0.20 to ± 0.30	0.7–1.0
Vacuum casting	± 0.1	0.9–1.0

The tolerances and minimum wall thickness shown in [Table 7.4](#) are typical values that may vary with the material choice and feature design.

7.3.5 The cost or budget

The rapid prototyping processes available and the objective of the prototype are characteristics that determine the selection of the technology, either AM or SM. Time, cost, and man-hours to get the prototypes manufactured and working, need to be considered while choosing the rapid prototyping technology. The questions/factors to consider include:

- Is the time consumed by postprocessing or to get the part working from low-quality prototypes will be more than that of high-quality prototypes?
- Does the AM process need additional postprocessing time, and is it relatively short and cheaper?
- The cost of CNC is proportional to the complexity of the part while the cost of AM is directly proportional to the volume and size.
- The overall cost is tightly linked to the quantities, it being higher for a process like CNC because of the higher set-up cost

7.4 AM applications in the industry context

AM technologies are currently used for the rapid fabrication of prototypes of products and tools to be used in the development, manufacture and validation of new concepts is a reality. In this context, two examples are shown next, one where an AM technology was employed for the production of functional prototypes, and another for introducing a new design approach making use of the potential of AM.

7.4.1 FDM functional product

Automotive industries are constantly evolving to keep up with the technological advancements by introducing new products with added functionality. One typical example is the assembly of ESDS (Electrostatic Discharge Sensitive Devices) that require specific solutions for transportation and storage. Current solutions that guarantee adequate protection are based on tote boxes and loose lids made with electrostatic discharge (ESD) materials. The alternative concept that led to the development of AM prototypes with the ESD characteristics, started with conceptual design models based on the existent model with overall dimensions of $600 \times 400 \times 120$ (mm) (Fig. 7.36), considering predefined specifications.

The conceptual designs, as the example in Fig. 7.37, were developed and filtered until only a few are selected for further development and testing. Preliminary conceptual designs without relation to any processing technology were developed. These concepts present a series of features that fulfill the requirements defined initially. For instance, the smoothness and simplicity of the surface is an important design particularity that can greatly reduce the accumulation of particles. Different approaches were considered for the handling section, an integrated handle, and a grip surface to facilitate the handling. Regarding the loose lid, a unique reinforcing rib was designed with a reduced height, comparing to the actual loose lid, and corners with different curvature angles.

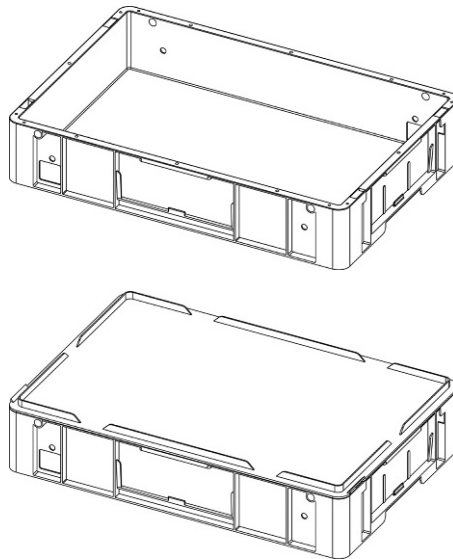


FIG. 7.36 3D CAD representation of the existent tote box (*left*), and the complete box with lid (*right*).



FIG. 7.37 Preliminary concepts of the tote box and loose lid.

The preliminary conceptual designs were changed to consider the fabrication technology design guidelines. Injection molding was the selected technology. Main design considerations to count with: uniform wall thickness to allow the mold cavity to fill more easily and to prevent warpage phenomena from uneven cooling; avoid features such as undercuts that require more complex molds that are consequently more expensive; avoid sharp corners which increase stress concentration and may not fill properly; structural ribs that assist in alignment with other parts and to increase the bending stiffness of a part without adding thickness.

Considering the optimized conceptual design, refined by iterative simulations to assess the structural strength when subjected to specific mechanical loads, and the feasibility with the final manufacturing technology, injection molding, a functional prototypes for usability testing and concept validation, in a real context of use, were fabricated in 80 h by FDM with ABS-ESD7 (Stratasys Ltd., United States), a static-dissipative ABS thermoplastic grade as building material using FDM Fortus 900mc equipment (Fig. 7.38).

After the full validation of this design concept, the fabrication of the mold tools, the process optimization, and the manufacturing of a preseries of products for a preliminary implementation took place.

This project brought breakthrough achievements including the development, manufacturing, and implementation of a solution with innovative features and characteristics, over a period of 12 weeks, that contributed to the improved logistical control of the product adequately protecting the electronic systems from electrostatic discharges, while assuring suitable structural performance and ergonomic quality.

7.4.2 Hybrid products

As it was already highlighted, the resource to AM technologies facilitates the advancement and optimization of processes related to product development, either by the rapid fabrication of products and tools directly or by resorting to hybrid molds. Further to these established features, AM technologies and parts may also be used as a manufacturing technique for the fabrication of

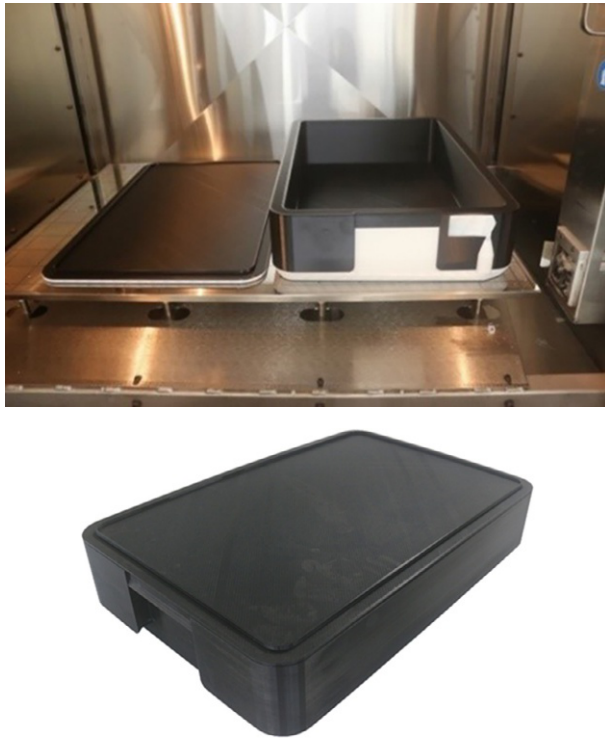


FIG. 7.38 Functional prototype produced in FDM equipment.

“hybrid” products. In this case, the qualifier “hybrid” indicates that the product results from the combination of either the distinct manufacturing process or materials to achieve unique and individual features.

One approach to the manufacturing of hybrid products consists in the integration of one or multiple external systems (e.g., sensors, actuators, tracking devices, mechanical fasteners, and parts manufactured by other processing techniques) within a part during its AM building process (Ota et al., 2016; Espalin et al., 2014; Kataria and Rosen, 2001).

The methodology of obtaining hybrid products includes various stages of the design of new products that include planning, developing, and manufacturing, all interconnected by specific activities and tasks (Lima et al., 2017).

In the first activity, during the planning stage, the product requirements are defined. This activity comprehends two tasks: the definition of the insert typology and possible embedding constraints, and the selection of the most adequate manufacturing technology.

The second activity is the CAD preparation and takes place over the planning and developing stages. It includes the model CAD optimization, considering the product requirements, the insert to be incorporated and the AM technology.

The third activity is the data preparation, in which the setup of the files (slicing, support definition, tool path definition, and building) is defined. The setup definition is based on the selected AM technology, the product orientation, and the pausing layer for the placement of the insert to be embedded. This activity occurs during the developing and manufacturing stages. Finally, the last activity is the production, which consists of the following tasks: (i) pretreatment for adhesion improvement (if necessary); (ii) insert placement that must be as fast as possible to avoid disturbances in the surrounding environment, and in perfect alignment with the upper surface of the insert part being built.

One example of the application of this methodology is the embedding of metallic objects like, standard M6 nut and standard plain M12 washer using 2 AM technologies: FDM with ASA and PolyJet with a VeroBlack rigid opaque resin (Objet, Canada). In the beginning the dimensional tolerance was identified for each technology, 0.15 mm for FDM and 0.10 mm for PolyJet. A pretreatment step, prior to the embedding process, consisting of cleaning and coating with an acrylic spray was performed to the metallic inserts. The positioning of the metallic inserts in the static building platform was both vertical and horizontal. The hybrid parts embedded with metallic inserts are shown in [Fig. 7.39](#).

This concept is an alternative approach that combines AM technologies with conventional injection molding, by including an over-molding step in the injection molding cycle, to fabricate hybrid products. The benefits inherent to this hybrid method, its design possibilities, material combinations, and embedded functionality are described next.

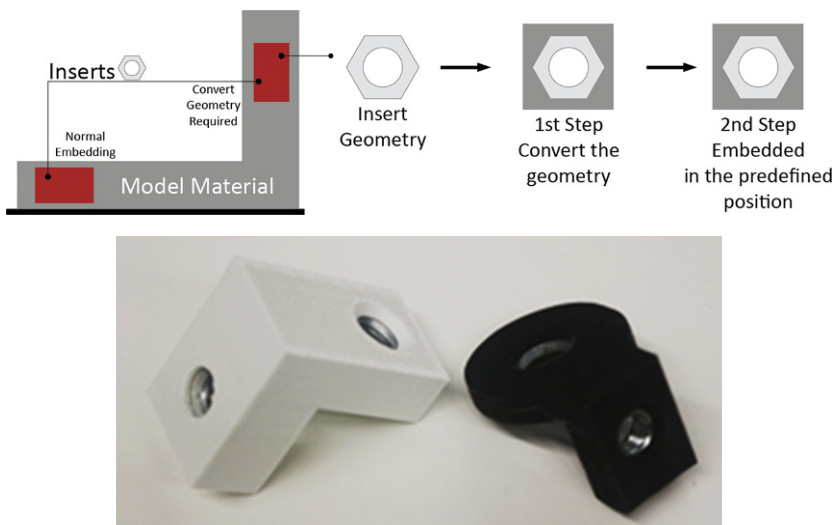


FIG. 7.39 Schematic representation of the embedding method steps (*top*); and resulting hybrid parts from FDM (*white*) and PolyJet (*black*) (*bottom*).

The design of a hybrid product combines the design freedom for lightweight, complex, and efficient structures ability from AM technologies with the tight dimensional precision and closed tolerances, along with the high-quality surface mold finish (e.g., high gloss, and matte) characteristic of injection molding (Guo and Leu, 2013; Attaran, 2017).

Hybrid products with particular aspects and reinforcement in intended areas will be possible based on a simplified processing manner. The method is also appropriate to customize an existent product, for it is possible to easily personalize details and features with no need for tool development or alterations of the existent ones.

Regarding material possibilities, both AM and injection molding are viable with a wide portfolio of materials. For AM, it is possible to use a single building material (e.g., plastic, metallic alloy, and ceramic), while also generating parts with particularities, such as continuous fiber per layer, variations of a polymer formulation across the built part, and also the combination of different materials during the manufacture (in the same technology or by combining technologies through embedding) (Guo and Leu, 2013; ISO, 2015).

For injection molding, the portfolio of materials has been continuously growing for many decades, and includes plain thermoplastics, foams, elastomers, and modified plastics with an endless variety of additives, reinforcements, and fillers. With the hybrid method, it is possible to assure specific properties at predefined locations of a multimaterial product and therefore, improve its overall performance.

The benefit of obtaining hybrid products is achieved by the embedding operation during the AM building process. The joining of the AM and the insert materials may occur through molecular diffusion based on welding when materials are compatible, or by structural interlocks for dissimilar materials, or by the combination of both.

An example of hybrid product based on an existent molding tool is shown in Fig. 7.40. In this case, the manufacturing technologies were FDM and injection molding. The adhesion between the materials from each processing technology and also the effect of the processing conditions were observed. The joining between the insert and the AM build part, if their materials are compatible, is better when the insert is heated up to a temperature near to the glass transition temperature of the plastics insert molded part material. With regard to noncompatible materials, the temperature is irrelevant and mechanical interlocking is required. The design of the mechanical interlocking must comply with injection molding design guidelines (e.g., fillets, and draft angles) and allow the embedding by the molten material while avoiding air traps.

The insert could be designed and manufactured by FDM with ASA as a building material. The insert part is positioned and locked in the mold core (Fig. 7.40, left image). After closing the mold, the overmolding took place by injecting an ABS material. The resultant hybrid product is ejected (Fig. 7.40, right image).

Further exploration with regard to this method for the production of hybrid products includes resourcing to other AM technologies and materials, and also

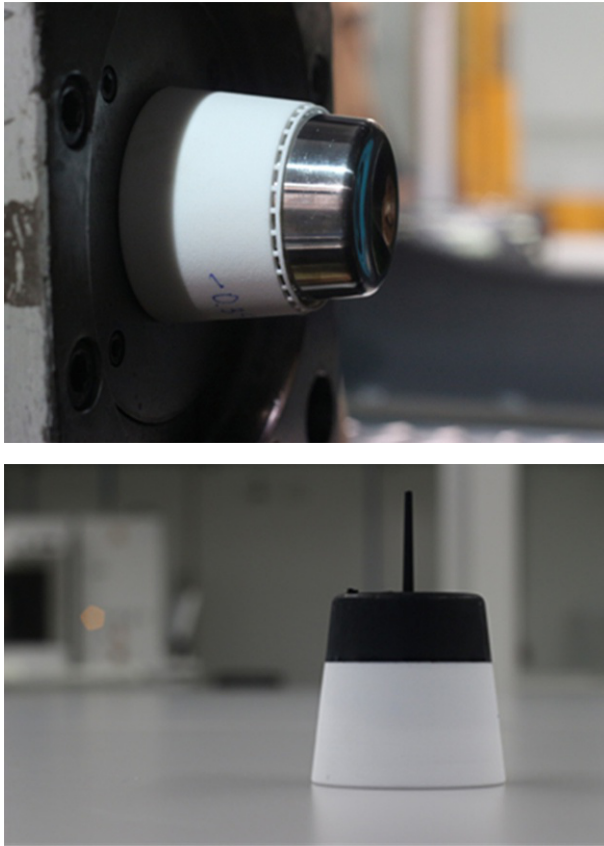


FIG. 7.40 Overmolded hybrid product. On the *left image* it is shown the insert part positioning in the mold core and on the *right image* the resulting hybrid product.

performing embedding operations during the layer-by-layer production for added functionality. This way, it will be possible to expand the possibilities to generate functional and personalized hybrid products based on multimaterial products, for applications in various fields.

7.5 Final remarks

Product development usually involves making prototypes to test ideas, functionalities, etc. However, the quality of the testing and the subsequent decision-making will highly depend on how well the prototype simulates the final product. Therefore, selecting the right process to make the prototype is fundamental to the success of any engineering product.

Once a clear understanding of the key factors is established, a decision can be made on the type of process to explore. There are several AM processes and materials to produce prototypes and every prototyping process will have its advantages and limitations, as summarized in [Fig. 7.41](#).

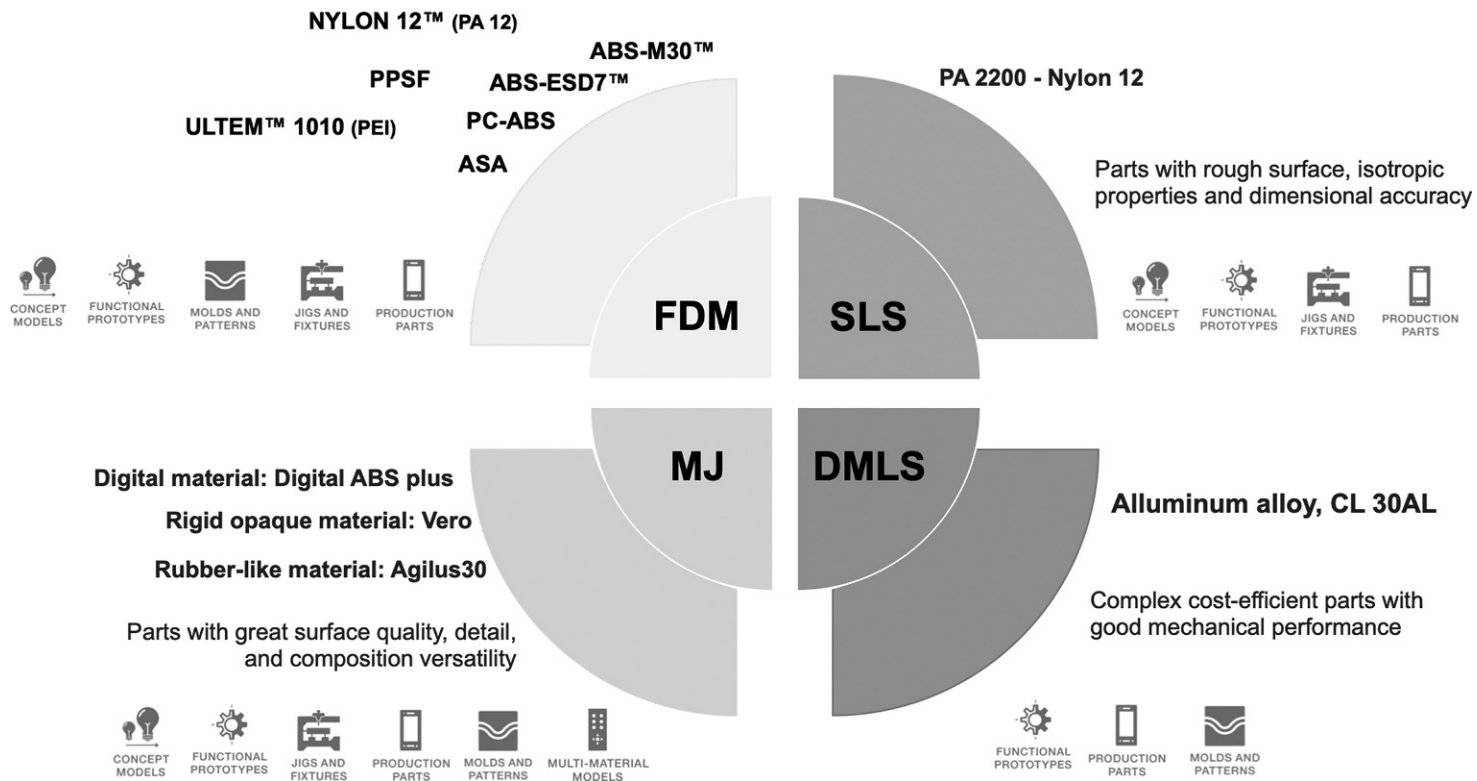


FIG. 7.41 Main AM processes, materials, and applications.

Thus, choosing the correct AM technology is vital to the prototyping success.

In conclusion, the steps of the rapid prototyping selection process, includes:

- Definition of the purpose of the prototype.
- Establishment of the level of approximation (quality and complexity).
- Outlining of the evaluation method and plan to identify quantities.
- Confirmation that the cost is kept within the prototype budget.

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