Additive manufacturing

General principles

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Since the early 1980s, the digital revolution has had a direct impact on our daily lives: increased globalisation of markets, fiercer competition requiring optimal reactivity from businesses, and an ability to adapt constantly to changing products and services.

This means that companies, if they are to hold onto and/or acquire new shares of the market, given the increasing rate of product replacement, must:

- *control their costs;*
- *constantly improve the quality of their products/services;*
- *drastically reduce development and release to market times.*

Companies, to meet these essential criteria for success, are constantly adapting to new external environments, and must include technologies fostered by the digital revolution into their design process (and organisation).

The first patent associated with ***Additive Manufacturing*** *(AM) was applied for by Jean-Claude André's team and triggered a revolution in the field of manufacturing processes and by extension in the field of production. Starting from a single manufacturer in 1986 (3D Systems), by 2015 there were around fifty machine manufacturers. Recently, there is a merge of companies coanting to develop leading groups on the additive manufacturing market place.*

AM currently affects all fields of industry, particularly the automotive, aerospace and medical industries.

Over the first years of AM (1990 to 2000), applications basically covered the earlier phases of product design: visual appearance models, breadboard models, technological prototypes, and also the exploration of so-call rapid tooling. It was only from the early 2010s that the processes were considered to have reached sufficient maturity to allow serial production of manufactured parts.

Having introduced the principles of AM, this article goes on to present the different stages from idea to product, then analyses the material/process/machinery triangle from the AM point of view. Finally, it provides a description of the changes required in association with this new technology, in terms of both design processes and the ecosystem into which AM is deployed.

1. The principle of additive manufacturing

1.1 Definition of additive manufacturing

Standard NF E 67-001 [1] defines additive manufacturing as « the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies ».

However, while the term « additive manufacturing » (AM) is widely accepted today, it is not unusual to hear other terms being used to describe the same manufacturing technology. The most frequently used, although sometimes being seen as oversimplifications, are:

- additive layer manufacturing;
- 3D printing;
- digital manufacturing;
- rapid prototyping;
- rapid manufacturing.

The physical principle underlying AM has been in use since the end of the 19th century in the fields of photo-sculpture and topography [2]. It consists in making a product by building up successive strata. A digital model is prepared, defining the cross-sections of the 3D object you want to produce by slicing it into successive parallel planes. The distance between each plane corresponds to a thickness of one layer. To reconstitute the object, the cross-sections are built up in sequence, one after another (figure **1**).

AM is therefore the result of a generative manufacturing which can be boiled down into two steps which repeat until the finished product is obtained:

1. Production of one layer of material following a set outline and thickness. The material is deposited only where it is needed;

2. New layer created by the addition of material on top of the previous layer. Production can be summarised as step production (figure **1**).

Thus, due to the principle whereby material is added, AM turns the so-called traditional manufacturing processes on their head:

– processes subtractive (such as machining) where the product is made from a blank, from which material is progressively removed to give it its final form;
– forming processes (such as casting or hot forging), where the material is brought to a liquid or viscous state, then shaped by pouring it into a mould or by bringing two dies together.

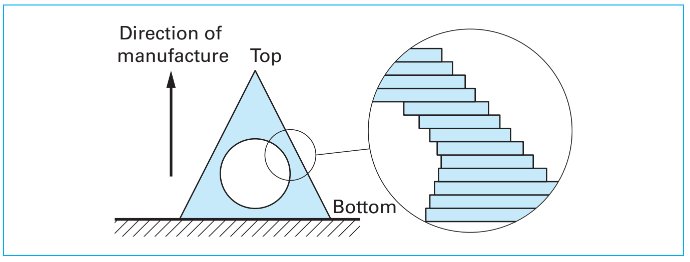


Figure 1 – The principle of additive manufacturing

1.2 Advantages of additive manufacturing

With AM, the dedicated tooling and blanks inherent in traditional processes are no longer needed, and the constraints associated with their production are thus removed (gains in time and money). AM's unique possibilities offer new prospects for the achievement of complex shapes (inclusions, cavities etc.) which could not be made by processes such as machining.

There are four types of complexity [3]:

- geometric;
- hierarchical;
- material;
- functional.

1.2.1 Geometric complexity

This is the first advantage of AM on product manufacture. Indeed, it enables to produce any geometry in a single operation, pushing back the boundaries of traditional techniques.

On the one hand, the ability to produce complex geometries without any additional constraint can be explained by break down of geometric problem, handled in 3D with traditional manufacturing, are here turned into a series of 2D problems which are much easier to deal with. Thus, although the product is made layer by layer, it is possible to obtain hollow shapes without resorting to coring or tapering, and without having to consider tool access when making shaped internal channels. In addition, complex shapes do not require splitting into multiple components for subsequent assembly; this leads to a reduction in the number of parts and a reduction (or even elimination) of assembly operations.

Moreover, using AM to produce complex internal or external geometries does not generate any additional cost. This observation appears all the more paradoxical when it is the exact opposite which occurs in traditional processes, because complex geometries require numerous operations which can prove prohibitive in terms of time and cost, or in some cases can be impossible to achieve.

1.2.2 Hierarchical complexity

With AM, it is now possible to make products with complex structures such as net, honeycomb or bionic structures (figure **2** and [4]) without requiring assembly of the various elements (bolting, welding, riveting, etc.). In addition, the recurring pattern of a structure can be produced at different scales, from the microscopic to the macroscopic, in the manner of fractals.

The main value of this hierarchical complexity is the reduction in product weight: solid structures can be replaced by much lighter structures, but with equivalent mechanical properties.

1.2.3 Material complexity

A part is a multi-material part when it comprises at least two materials whose distribution varies with width. Figure **3** provides a schematic representation of these two principles, applying it to a sports shoe sole prototype.

In the case of continuous distribution, the materials obtained are called Functionally Graded Materials (FGM) [5]. These are composite materials whose composition and microstructure evolve progressively across the part, thus leading to a variation in mechanical properties. The overall performance of the material is then greater than that of the components taken separately.

Discontinuous distribution allows the production of parts which consist of stacked single-material zones. The material complexity obtained in this case is more basic, because the performance obtained is less than that of functionally graded materials.

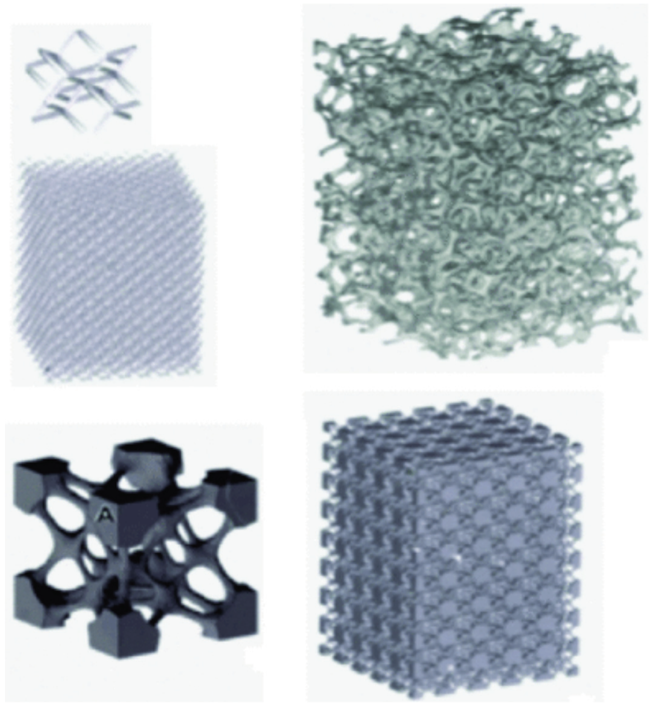


Figure 2 – Examples of complex structures which can be produced with AM (credit Murr et al. [4])

This is where the full potential of AM in producing multi-material parts becomes self-evident: within a single layer, with the material being deposited one point at a time or simultaneously, any composition at all can be achieved, giving the product unique mechanical, thermal or chemical properties.

1.2.4 Functional complexity

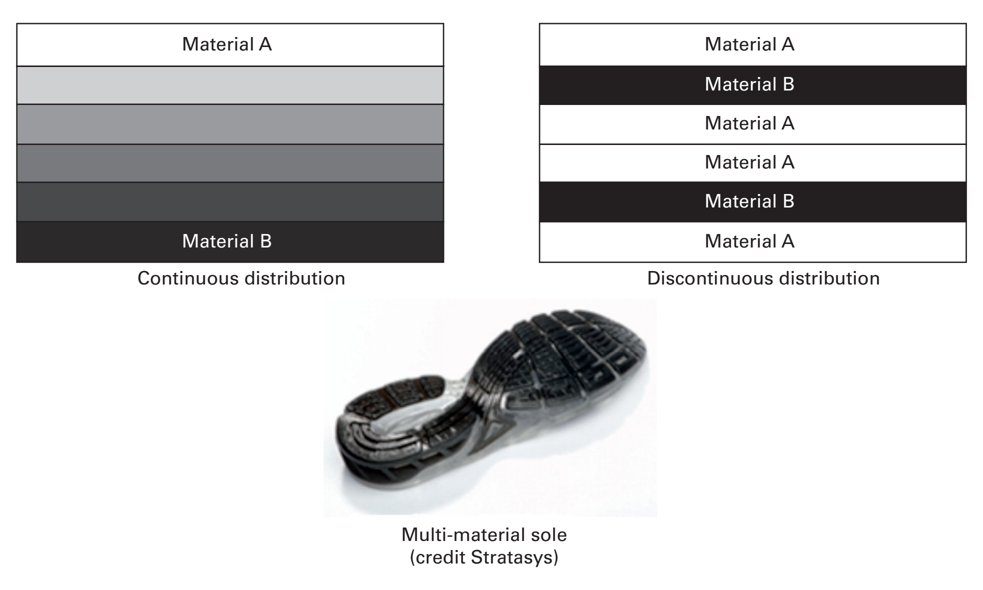
With AM, full ready-for-use assemblies of pre-assembled components can be made. Foreign bodies can also be incorporated during the manufacturing process, bringing increased functionality for products being manufactured. For example, cavities can be designed into the product, ready to accommodate items such as nuts, optical fibre or electronic or electrical components during manufacture. That inclusion allows a reduction in the number of processes required to manufacture a part, with the elimination of post-assembly and easier management of gradient materials.

1.3 Uses associated with additive manufacturing

AM experienced a huge industrial boom from 1988 onwards, with the market release of a machine developed by Hull [6]. It has not stopped developing then with successive technical and technological improvements [7], allowing a greater range of possible uses: rapid prototyping and rapid manufacturing. Figure **4** shows different uses of AM, discussed in detail in the rest of this article.

1.3.1 Rapid prototyping

From the industrial point of view, **Rapid Prototyping** (RP) has been the main driver of AM development. Indeed, the creation of prototypes was considered to be a complex, time-consuming and costly stage [3] slowing down the design process. AM technology



Continuous distribution

Discontinuous distribution

Multi-material sole
(credit Stratasys)

Figure 3 – Illustration of material complexity enabled by AM

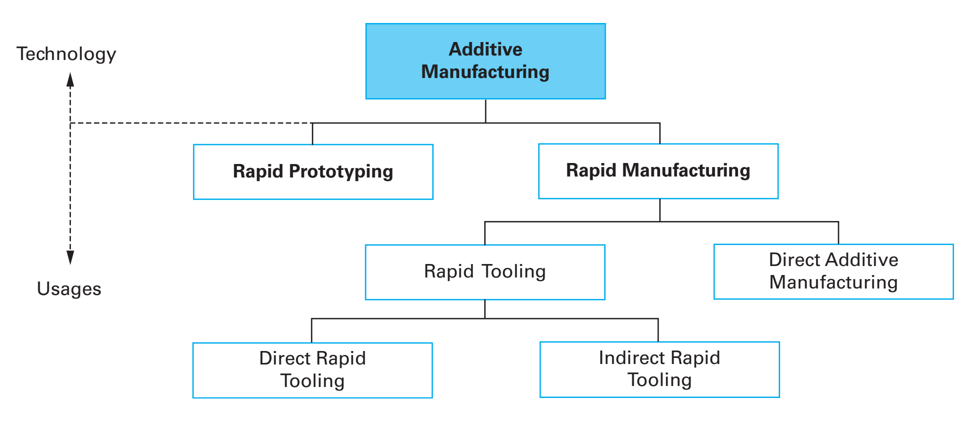


Figure 4 – Uses of additive manufacturing

has reduced the release to market time, because it makes it possible to obtain intermediate physical representations of objects quickly, which can then be used in the validation stages of product design and development (shape, appearance, ergonomics, etc.), all before the final version is made and released onto the market. There are two distinct approaches to RP: the modelling of concepts and the achievement of functional prototypes.

Concept modelling is used to obtain a 3D representation of a basic concept to assess its general appearance and/or proportions. With RP, the models obtained cannot withstand forces, but it is possible to introduce colour without requiring painting at a later stage.

Functional prototypes, meanwhile, are used to validate a specific function of the product (mechanical behaviour, thermal properties, etc.), or a design objective (manufacture, maintenance, safety, etc.), or even the use or function of a concept. This means they are a decision-making tool, even though the intermediate representation made cannot be used as a constituent element of the final product. From the mid-1990s, the application of AM to RP exclusively took a new turn: **Rapid Manufacturing**.

1.3.2 Rapid Manufacturing

Growing interest in Rapid Manufacturing (RM) from industry is due in particular to the maturity of particular processes, such as powder bed fusion, which are now well understood and where machine precision has increased, the range of available materials has broadened and the mechanical properties of the parts has become comparable with those produced using other manufacturing techniques [BM 7 900]. These things have therefore enabled the RM production of products able to provide all the characteristics and functions set in the specifications. However, within the RM approach, we need to distinguish between Rapid Tooling and Direct Additive Manufacturing.

1.3.2.1 Rapid Tooling

The basic idea of **Rapid Tooling** (RT) appeared in the 1990s. Originally, RT was used only to obtain die cavity to be used to validated production ranges in tests prior to their industrial roll-out. Its use was subsequently extended to the manufacture of functional tools with complex forms (dies, injection moulds, etc.) intended for

Indirect Rapid Tooling
Left: turbocompressor pattern produced in PMMA by material jetting
Right: final part obtained by lost pattern casting

Direct Rapid Tooling
Steel mould produced by powder bed fusion

Figure 5 – Indirect or direct tooling: examples (credits Voxeljet and EOS)

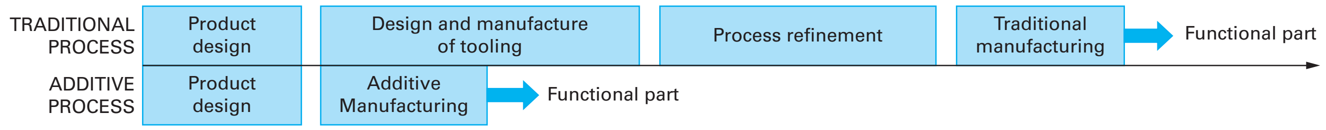


Figure 6 – Impact of chosen process on time and on development and production stages of a functional part

mass production. RT is therefore an indirect use of AM, because only the tools, and not the finished products, are produced in an additive way.

RT has thus enabled a reduction in development and production times because modifications to tools can be made quickly without recourse to expensive manufacturing processes, such as machining or electro-erosion.

There are two categories within RT (figure **5**):

– Direct Rapid Tooling, where AM is used to obtain the mould or die cavity directly from a CAD model;
– Indirect Rapid Tooling, where AM is used to create a pattern which will then be used to make the mould from which the product will be made (as with lost wax casting).

1.3.2.2 Direct Additive Manufacturing

Direct Additive Manufacturing (DAM) means the production of dense products or components (density close to 1) which are mechanically strong, in other words finished and functional.

Over recent years, DAM has accounted for a growing proportion of AM, rising from 4% in 2001 to 28.3% of parts produced in 2013 [8].

For short series production (approximately 10,000 plastic parts or 1,000 metal parts), but also for complex or high added value parts, DAM achieves very competitive production costs compared with traditional technologies, which have to cope with high initial budgets associated with the purchase of tools or machines and the fine-tuning of their production process (figure **6**). DAM also allows a subsequent reduction in losses of material: only 3% losses for certain aerospace components made using AM compared with 80 to 90% swarf for those made by machining.

1.4 Areas of application

AM is not intended to supplant traditional manufacturing processes, but rather to bring a technological response at their limits. Thanks to the advantages of AM cited in paragraph 1.2, new prospects for product innovation are emerging, particularly in DAM. Today, three major areas are being impacted by these possibilities:

– made-to-order manufacture and customisation;
– short series or high added value items;
– made-to-measure manufacture.

Made-to-order manufacture or customisation is the longest-established area for AM, and the most widespread. It is basically the use of AM for the general public.

The aeronautical, defence and space sectors were the pioneers in the field of short series or high added value manufacturing; but today other sectors such as motorsport are also interested in it (figure **7**).

The main goal is to benefit from the weight reductions made possible by the use of complex shapes, to simplify assembly, and even to do away with the difficulties arising from the machining of certain metals such as Inconel. DAM produced parts are already on the market.

For example, following General Electric with the Leap engine, Turbomeca has taken the leap into additive manufacturing for its « Ligne du Futur » programme. Thus a powder bed fusion machine (Selective Laser Melting) is now qualified for the series production of swirl generators for combustion chambers in Ardiden 3 engines (approximately 1,000 engines a year) and fuel injectors for Arrano engines fitted to 4 to 6 t class helicopters. The use of AM for injectors in this way has reduced the fitting together of 12 parts to a single-piece system with internal shapes which have until now been impossible to make (figure **8**).

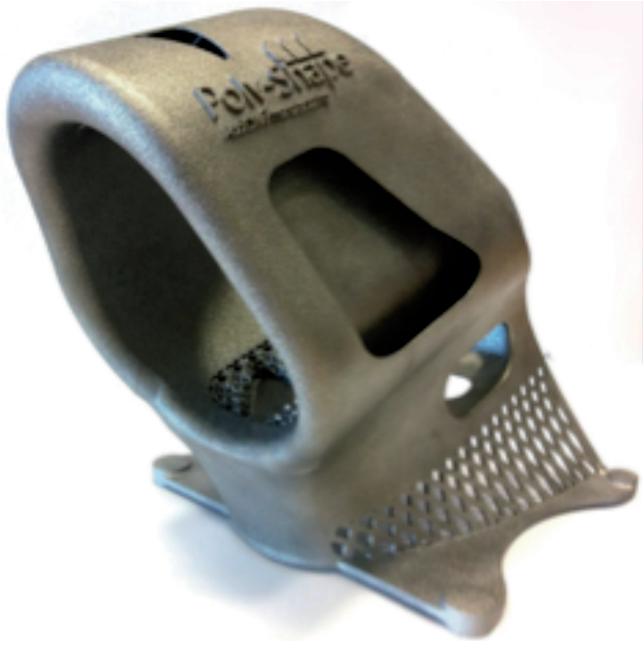


Figure 7 – Formula 1 roll-loop (credit Poly-Shape)

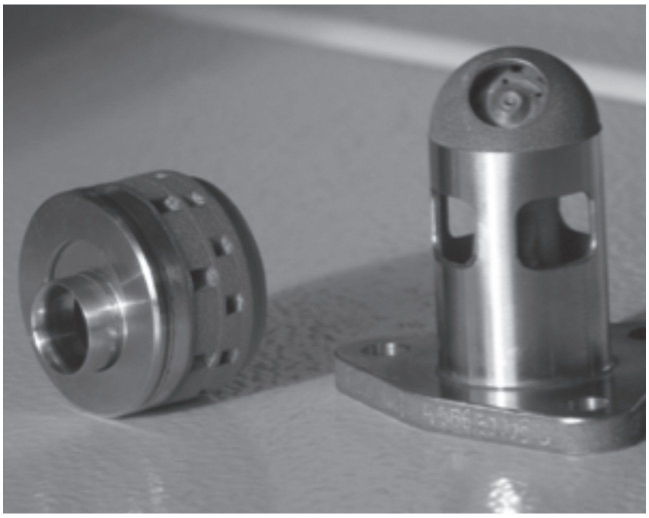


Figure 8 – Fuel injector and combustion chamber swirl generator (credit Turbomeca – R. Bertrand)

However, despite all the advantages of AM in these sectors, the time needed for approval and qualification of parts, whether for first use of the product or for maintenance, remains the major obstacle. Given the speed of technological developments, that delay can sometimes lead to a process being qualified when it has already become obsolete in the meantime.

The made-to-measure manufacturing market has also been widely adopted in the medical sector and in 2014 made up 13.7% of the DAM market according to the Wohlers report. AM offers the possibility of creating auditive prostheses, skull flaps (figure **9** and [4]) and dental or orthopaedic implants perfectly matched to patient morphology and made from biocompatible materials (Titanium type ti6Al4V alloys or Chrome Cobalt alloy). According to the McKinsey consultancy, 40,000 hip prostheses were produced using AM in 2012. The possibility of manufacturing implants from net structures, which would be impossible to make previously, was the second trigger for AM's wide adoption. Indeed, net structures have demonstrated their usefulness because they encourage the growth of organic tissues and are lighter while offering the same properties. Finally, the possibilities offered by AM in the medical field are such that research work is now looking at the additive manufacturing of organs from cells which will be implanted into live patients. Although the medical sector is the best example of AM's use in made-to-measure manufacturing, others sectors such as jewellery or art have also seen AM's possibilities for the development over a very short period of products which are each specific to their clients.

2. The additive manufacturing digital chain: from model to product

The meteoric rise of AM was mainly facilitated by increasing computer processing capabilities. Indeed, it is thanks to their high calculating power that computer aided design (CAD) developed,

Figure 9 – Ti6Al4V skull flap obtained through a powder bed fusion process (credit Murr et al. [4])

allowing the 3D representation of digital objects and stirring a desire to make them [3].

As with traditional processes, AM also relies on a succession of operations to move from the digital object to the real object. This is referred to as the **digital chain**. It can be broken down into a sequence of 4 stages, as summarised in figure **10**:

- 1. creation of a 3D digital model of the product to be made;
- 2. conversion and checking of data;
- 3. preparation for manufacture and manufacture;
- 4. completion of the product.

2.1 Creation of a 3D digital model of the product

Every part destined for AM must have a digital model which perfectly describes its geometry. That digital model may be obtained in various ways, the simplest being the use of CAD software. As we shall see, *reverse engineering* can also be used.

2.1.1 Direct CAD

The development of a product requires attention to be paid to the design process so that it is possible to move from a preconceived idea of the product to its detailed description and on to its manufacture. After the conceptualisation phase, which may take a number of forms (sketch, plan, pattern or template), it is necessary to produce a description of the product in digital form. This is called a digital model and can be shared across a number of different design personnel through collaborative engineering.

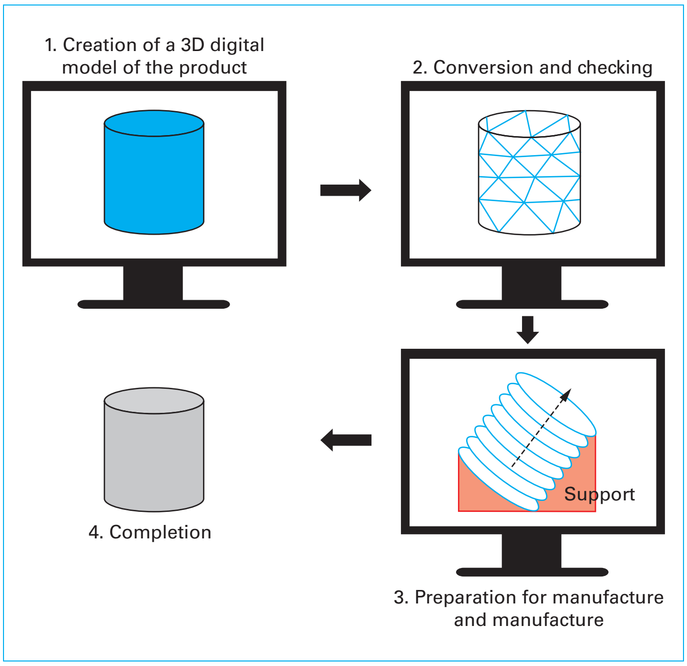


Figure 10 – Digital chain associated with AM

3D CAD software, which enables these digital models to be made, is based on surface modelling or solid/volume modelling.

In surface modelling, the object is defined in terms of its envelope, its boundary surfaces. The surfaces are described using parametric polynomial equations such as those for *B Splines* or NURBS (*Non Uniform Rational B-Spline*). The accent is placed on style/form considerations rather than technological considerations. This includes modelling software intended essentially for the aerospace, automotive and industrial design trades (e.g.: Catia© *Generative Shape Design*, Alias©, Rhino©).

Volume/solid modelling is more widely used than surface modelling. It incorporates the notion of materials and is based ion B-Rep (*Boundary Representation*) and CSG (*Constructive Solid Geometry*) construction techniques.

B-Rep construction uses primitives (generally 2D sketches) to create volumes through various operations (extrusion, revolution etc.). Those volumes can be combined with one another to make the final solid.

One approach, CSG, is created through a succession of Boolean operations (union, intersection, subtraction) on generic solids (sphere, cylinder, parallelepiped).

At present, solid modellers (PTC Creo©, SolidWorks©, TopSolid©, etc.) can be used to apply a material to a part and incorporate parametric design and construction logs.

2.1.2 Reverse engineering

Geometric modelling also implies knowing how to reconstruct objects from the digitisation of existing objects when a digital model is unavailable or does not exist. This is referred to as ***reverse engineering***. This technique is used in a high variety of fields such as art (for the reproduction of statues, for example) or medicine (such as the creation of made-to-measure prostheses).

Reverse engineering, the process of which is illustrated in figure **11**, is built on the acquisition of a point cloud representing the enveloping surfaces of the digitised item. These sets of points are then processed with surface reconstruction software to define the skin of the object using mathematical entities, then exported to a CAD application. The 3D model is then modified, adapted to its environment and internal architecture. It is also possible to create an STL (*Stereolithography*) mesh from a point cloud; after checking for any errors (section 2.2) a file can be obtained for direct application in AM.

The quality of the digital model created by this method depends on the quality of the three-dimensional shape acquisition system and the competence of the operator in reconstructing the surface. There are two main families of processes in reverse engineering:

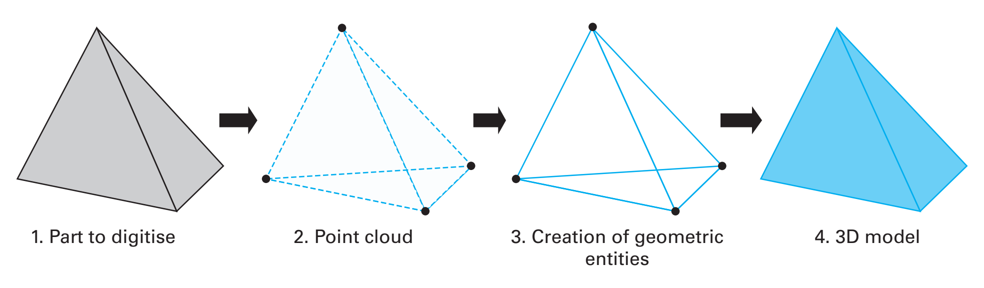


Figure 11 – Illustration of the reverse engineering process

contact based and non-contact based. When choosing, it is necessary to consider important parameters, which include:

– the resolution obtained by the spacing of points measured in a given direction;
– precision, in other words the maximum error between the position measured for a point and its exact position;
– repeatability through measuring the dispersion in positions for a point for a given measurement protocol;
– measurement speed or the capacity to measure all the characteristics of a point in a given time period;
– acquisition speed, which is the time needed to obtain usable information. The subtle distinction between measurement speed and acquisition speed comes from the time needed to process information, particularly in the case of multi-pass acquisition;
– the number of degrees of freedom or the minimum number of axes or relative movement between the sensor and the object required for point acquisition;
– the sensor's working volume, which is the maximum allowable size of the object to be digitised.

At the end of the CAD or reverse engineering work, the resulting file must be converted and checked before it can be used for manufacturing.

2.2 Conversion and checking of data

The STL (*STereoLithography*) file is the standard for transferring CAD data to AM machinery. It is independent of the CAD software used and serves as a very simple describer of the geometry of parts through the approximation of enveloping surfaces using a set of triangles (or facets) and their normals. These elements are obtained by a facetisation operation known as **tessellation**.

Creation of the STL file requires surface modelling to be as good as possible. Surfaces must be perfectly closed and orientated. If these two conditions are not met, the STL file will be of poor quality, or even unusable subsequently by the machine. This problem must be overcome by checking the files with suitable software such as Magics©, NetFabb© or Meshlab.

The errors most frequently encountered and requiring corrections to the file are as follows (figure **12**):

a. inadequate facetisation. This is generally due to the mesh parameter being too large (use of the CAD software's default setting, or choice of an inappropriate setting). It results in a large initial surface approximation characterised by cord error « d » representing the maximum distance separating the facet from the surface element it represents. This error can be minimised by increasing the number of facets. However, caution must be exercised, because finer triangulation can also be a nuisance, as the STL files then generated will impose high calculation times;

b. normal inversion. The direction of the normal to the triangle shows the position of the material; when it is inverted, this causes confusion over the direction of the material;

c. missing facets. This is a hole in the mesh;

d. non-*manifold* items present. These are overwritten or superimposed triangles.

The main limitation on an STL file is the poverty of information contained in it: the construction log and description data (colour, material, etc.) of the CAD model are not retained. That is why new file formats have been developed, to deal with these limitations:

– the .VRML (or .WRL) format is used for AM technologies with colour printing capabilities;
– the .AMF (Additive Manufacturing file Format), introduced in 2013 as part of the NF ISO/ASTM 52915 [9] standard is expected to replace SLT in time, due to the generous amount of information it contains: geometry is handled, along with materials, textures, colours, functional details and realisation processes. Some CAD software applications currently offer this file format type (Catia©, Solidworks©, SpaceClaim©).

2.3 Preparation for production and manufacture

Once the STL file has been checked, the manufacturing strategy adopted to produce the part has to be defined. The strategy needs to address the following parameters:

– the orientation of the part, in other words, defining the direction of manufacture. This operation is very important, because parts produced using AM often exhibit anisotropy in the direction of manufacture;
– the placement of parts on the build plate;
– the positioning of supports, if applicable. Supports act as scaffolding, and are manufactured at the same time as the part.

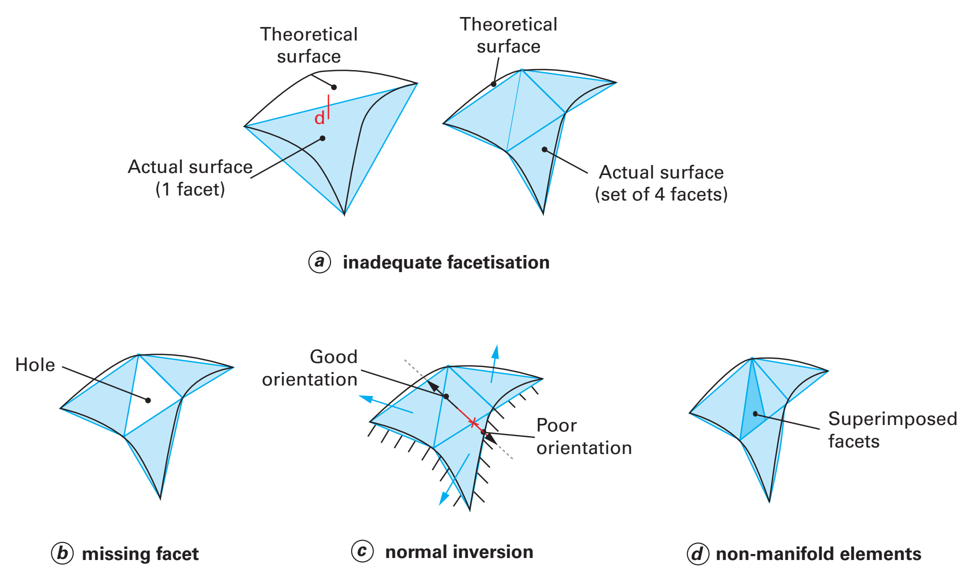


Figure 12 – Common errors in STL files

They prevent it from collapsing or deforming under its own weight if it is too unstable.

When these various parameters have been set, the STL files can be sliced. Slicing needs to consider the thickness of the layer and the resolution of the machine. These are the layers which will be used to generate the machine paths.

Once all these parameters have been set, part production can be started, followed by post processing.

2.4 Post processing

Decisions taken during the previous three stages (creation of a digital 3D model, data conversion and checking, production preparation and manufacturing) will have significant consequences in the post processing cycle for AM produced parts (number of operations and duration of operations). Operations which may take place during post processing include:

– the removal of supports, if applicable;
– impregnation of porous parts;
– thermal stress relief to remove any residual stress in metal parts;
– densification processes (such as Hot Isostatic Pressing (HIP)) used to increase the density of parts;
– surface treatments and superfinishing, either manual or automatic, associated with the stair-stepping effect inherent in the layer-by-layer manufacturing process.

3. The material/process/ machinery triangle in additive manufacturing

3.1 Materials

Before even looking at the processes, it is important to consider the materials dimension in AM. At present, four families of materials are represented: metals, polymers, ceramics and composites. However, the two most widely used families are polymers (thermoplastics, thermosetting resins, etc.) at 80% of volume sold and metals (aluminium, steel, nickel, titanium, etc.). These figures are liable to change over the coming years due to the growing interest in industry towards DAM, particularly for metal parts.

However, even though the available range continues to grow constantly, it remains limited compared with the choice of materials accessible for traditional processes. In addition, these materials must be available in liquid, powdered or solid state (in filament form) depending on the type of process for which they are intended.

The cost of purchasing materials is a significant factor in the return price for a part manufactured using AM. Parameters which have a bearing are the purity of the material, its granulometry and the grade of material required.

> Take, for example, a kilo of PLA filament intended for 3D printers for the general public, which costs a few euros, compared with 200 to 600 euros for powdered titanium alloys.

However, although competition is starting to emerge, it is not unusual for materials which can be used on a machine to be sold only by the manufacturer of that machine. Finally, certain materials imply particular precautions for use:

– limited exposure to air to prevent the oxidation of titanium or aluminium alloys (work in a vacuum or neutral atmosphere);
– limited or no recycling possible (photopolymer resins);
– powders certified for a specific use (biomedical, food, etc.) with the associated cost multipliers.

One final point to highlight is making machine operators aware of the risks to health when handling powders with very small particle sizes (a few tens of micrometres).

3.2 Processes

Historically, different classes of process have been developed. They offered just one view of the material, even though the range of materials available continues to increase. So, in order to clarify the nomenclature used, a classification system was set up as part of the NF ISO 17262-2 [10] standard. It is based on the grouping within a single category of processes which use an identical machine architecture and for which the physical transformation processes of the materials are similar. That classification also makes it possible to « talk about a category of machines rather than looking at commercial variations in technologies ». This classification includes seven AM process categories.

3.2.1 VAT photopolymerisation

For this process, a liquid photosensitive resin contained in a vat is hardened by polymerisation through the action of a light source (figure **13** and [12]). When a layer of resin is polymerised, the build plate is moved vertically (Z axis) by a distance which is set in the production parameters so that the cycle can be repeated.

Variants of this process originate from the nature of the light source, which could be a laser or a UV light, and from the direction of movement of the plate.

Polymerisation by means of a laser is the first patent applied for in respect of AM [11] and the first process to be commercialised. It is better known by the name **stereolithography**. The light source in this case is from one single point, and a layer is created as it sweeps the surface.

The second variant is based on the use of visible radiation using UV lights. In this case, polymerisation occurs simultaneously across the whole exposed surface.

The last variant, which has recently emerged, is called **CLIP** (*Continuous Liquid Interface Production*). This is based on the combined action of a UV light to generate polymerisation and oxygen to protect those areas of the layer which must not be cured. Unlike the two previous technologies, the plate in this case is moved upwards, thus allowing continuous manufacture.

The main drawback of this process, despite good precision (a few tens of microns) and the quality of surfaces obtained, resides in the raw material used: limited varieties of resin, resin properties less

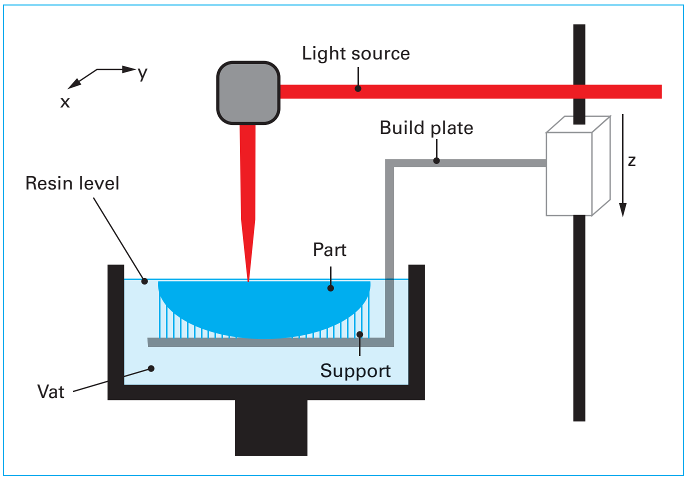


Figure 13 – Illustration of the VAT photopolymerisation process, adapted from Rias [12]

than those of technical polymers (which are not suitable for functional prototypes) and ageing which can cause such parts to become brittle over time.

3.2.2 Material jetting

This process works on the same principle as inkjet printers. It uses print heads which deposit drops of material on the surface of the manufacturing area. Two types of material can be used:

– photosensitive resins which, once deposited, are polymerised by the light source built into the print head (figure **14** and [12]);

– waxes deposited in liquid form which, when they cool, will make up the part.

The main advantage of this process is the possibility of making multi-material parts and introducing colour. Added to which, its wide range of materials (about 60) means that prototypes can be obtained to simulate the behaviour of parts made from technical or standard polymers by injection in functional tests.

3.2.3 Binder jetting

This process, which is very close to the material jetting process, emerged in 1993 at the Massachusetts Institute of Technology, under the name ***3D Printing*** **(3DP)**. Just like material jetting, it is based on the use of print heads, here to spray a liquid binder onto a powder bed making up the construction material (figure **15** and [12]). The unbound powder acts as a support for the part.

The range of basic compatible materials ranges from polymers to metals, including ceramics. The combination of drops of coloured binder makes it possible to produce coloured products.

However, its chief disadvantage lies in the fragility of the parts obtained, which generally require post processing (infiltration or sintering) and use in applications not subject to high mechanical strain.

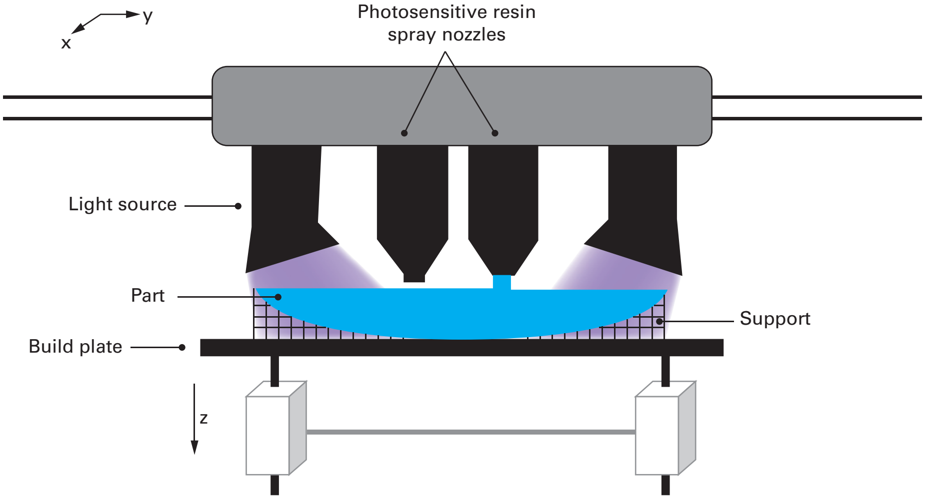


Figure 14 – Illustration of the material jetting process (Polyjet technology), adapted from Rias [12]

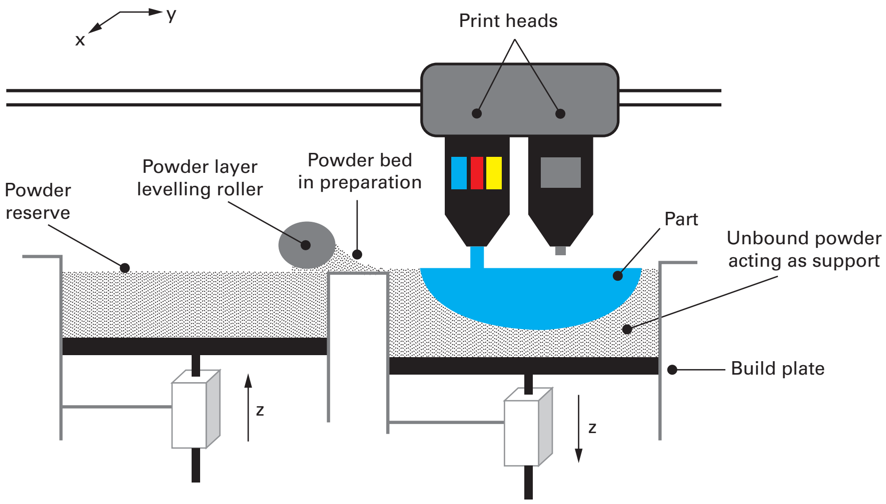


Figure 15 – Illustration of the binde jetting process (Polyjet technology), adapted from Rias [12]

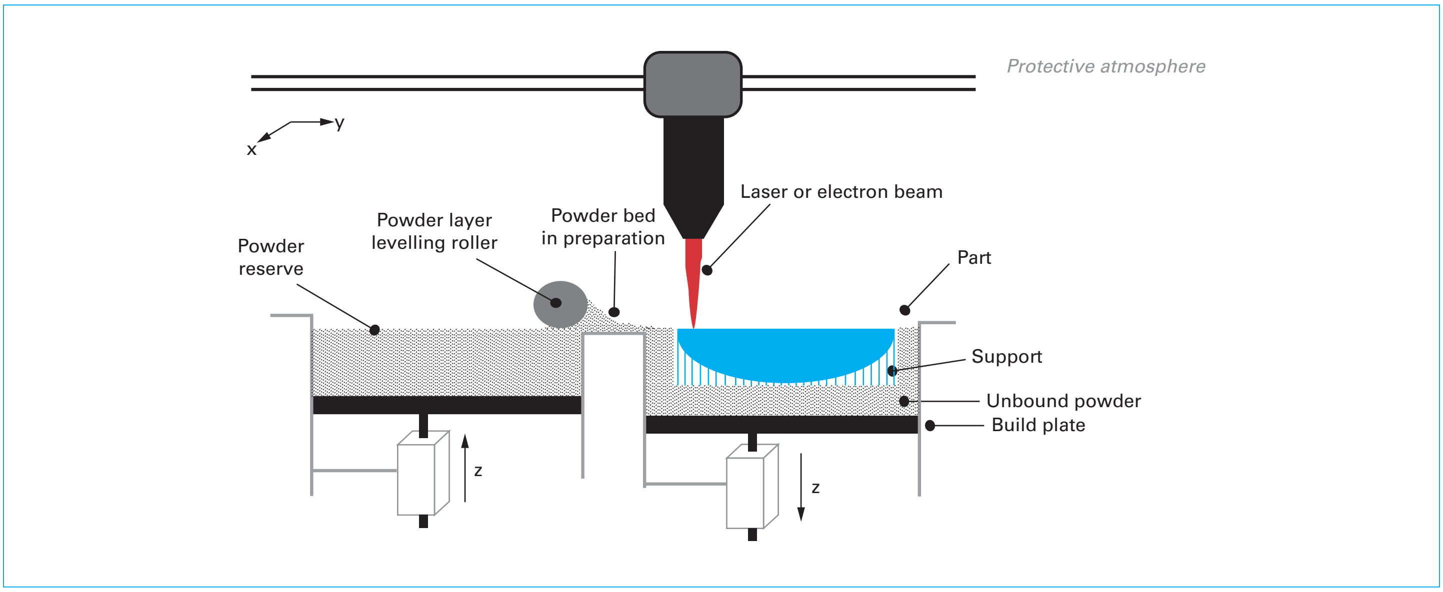


Figure 16 – Illustration of the powder bed fusion process, adapted from Rias [12]

3.2.4 Powder bed fusion

The principle of powder bed fusion is the use of heat energy to melt a fine layer of powder previously laid down by a roller on a build plate (figure **16** and [12]). It implies control of the protective atmosphere in the build chamber.

Nota: the distinction which exists between fusion and sintering is to do with the amount of energy supplied. In sintering, the powder is heated without reaching its melting point. The grains of powder then weld themselves to one another, which causes the layer to build.

There are accepted to be three main categories within this process:

– the sintering of powdered polymers (thermoplastics) by laser uses CO_2 lasers with a power of a few tens of Watts. The first patents to protect this technology entered into the public domain in February 2014;

– laser metal fusion uses YAG lasers of between 100 W and 1 kW. Layer thicknesses are in the order of a few tens of microns (20 to 100 µm depending on manufacturer);

– Electron Beam Melting (EBM) of metal powder, meanwhile, is restricted to conductive materials. In this case, it is necessary to preheat the powder bed to limit head gradients and thus any residual stresses. However, the surface condition of the resulting parts is less good because the electron beam is wider than a laser beam.

For these troolast categories, one main research concern is the health of the material during its manufacturing and the resulting mechanical behavior. Thus a post treatment of metal parts produced is stile essential.

3.2.5 Material extrusion

The principle of this process rests on the heating of a material above its melting point, then its extrusion through a spinneret (or nozzle) which moves in the horizontal plane. Solidification of the material on the previous layer is almost immediate. It is the main used AM process worldwide because of its purchase cost/ especially for polymer FDM).

Material extrusion was first applied to thermoplastic polymer materials (Fused Deposition Modelling (FDM) process) and led to the creation of Stratasys®, the leading company in the market. Many developments have taken place in recent years:

– the first patents protecting FDM have expired, encouraging the development of *open source* machines inspired by the RepRap project [13];

– broadening of the range of materials, leading in particular to the emergence of bioprinting (manufacture of a biological tissue from living cells) or use in the food industry;

– multiplication of nozzle numbers. In the case of two-nozzle machines, one can be used to deposit the base material whilst the other can be used for the support material, which is much cheaper and can be detached from the part without damaging its surface (figure **17** and [12]); or indeed to manufacture parts with two different materials and no support.

3.2.6 Directed energy deposition

This process has developed from laser coating techniques. Its principle relies on the melting of a surface using an energy source with the simultaneous supply of a jet of power or a filament of material to the molten area, all in the presence of a protective gas (figure **18** and [12]). Supports are not required because the build plate is moved in five axes, as can be found in machining centres. It can be used to obtain materials with graded properties. The accuracy of the parts obtained is less than with powder bed fusion techniques. The layer thickness is around 500 µm.

At present, this process has only been developed for metal powders.

3.2.7 Sheet lamination

Sheet lamination (figure **19** and [12]) is a process which combines the addition and subtraction of material: sheets or plates of material are cut up using a cutting system (laser, cutting tool, ultrasound, etc.), stacked and then bonded to one another (positioning, glueing, ultrasonic welding, or possibly the use of inserts, etc.) to form the product.

All materials which exist in sheet form can be used.

3.2.8 Summary

Figure **20** below shows current uses in industry of the seven processes defined by NF ISO 17296-2 during the product development

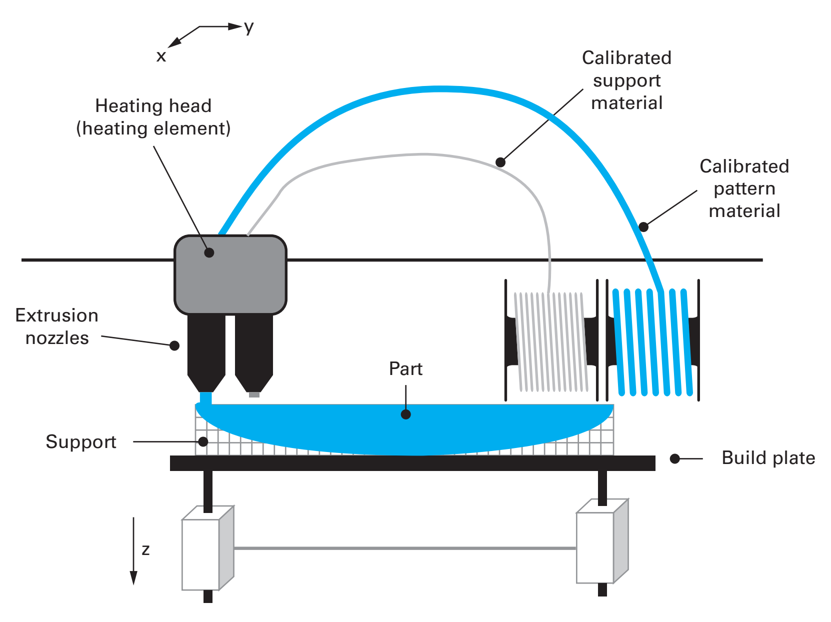


Figure 17 – Illustration of the material extrusion process – Case of a two-nozzle machine, adapted from Rias [12]

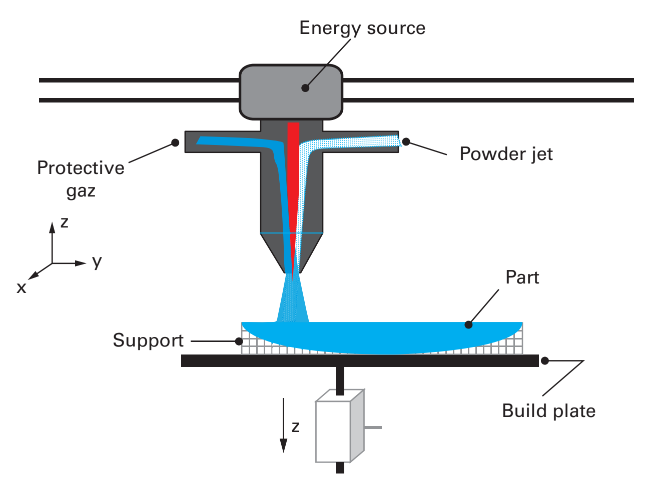


Figure 18 – Illustration of the directed energy deposition process, adapted from Rias [12]

process, along with prospects for their development over the coming years.

3.3 Machines for AM

The range of AM machines currently available on the market is growing rapidly. Figure **21** shows the distribution of machine sales turnover by user sector, across all categories, in 2014 [14].

However, only two separate categories of process exist: so-called office machines and industrial machines.

3.3.1 Office machines

According to the Wohlers consultancy, around 278,385 machines of this type were sold in 2015, the number doubling in a single year. There are two distinct types of use: office machines for the general public and professional office machines.

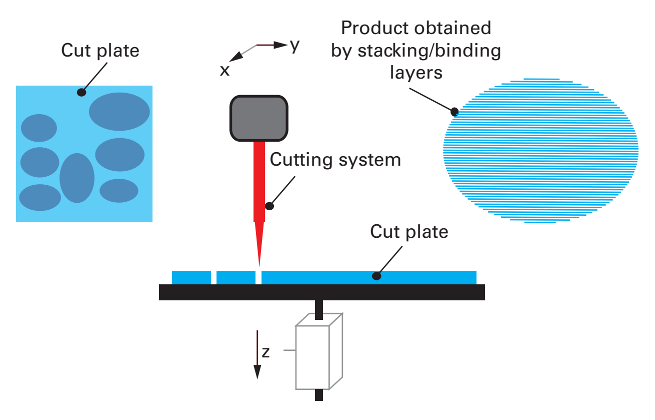


Figure 19 – Illustration of the sheet lamination process, adapted from Rias [12]

Office machines for the general public, with a purchase price of less than $5,000 (€4,600) have made it possible to introduce AM into private homes and the « makers » community as part of FabLab (collaborative workshops). A simple table is needed to set them up, and learning to use them requires no particular skills. This general public machines market has opened up a great deal in recent years with these open source machines. This appetite for the equipment has also favoured a rapid drop in prices, with some machines now selling for less than $300 (€250).

However, the range of materials available is limited to thermoplastics (essentially PLA and ABS), the quality of the parts obtained is mediocre, and production volumes are limited (approximately 200 x 200 x 200 mm^3), confining their use to the production of low-quality prototypes or concept modelling.

Professional office machines provide an alternative to machines for the general public. Their performance (speed, accuracy, etc.) and characteristics (production volume, noise pollution, etc.) are better, but their purchase price is higher as a result, at between 5 and 50 thousand euros. They are used by industrial users who want to make their prototypes internally without resorting to

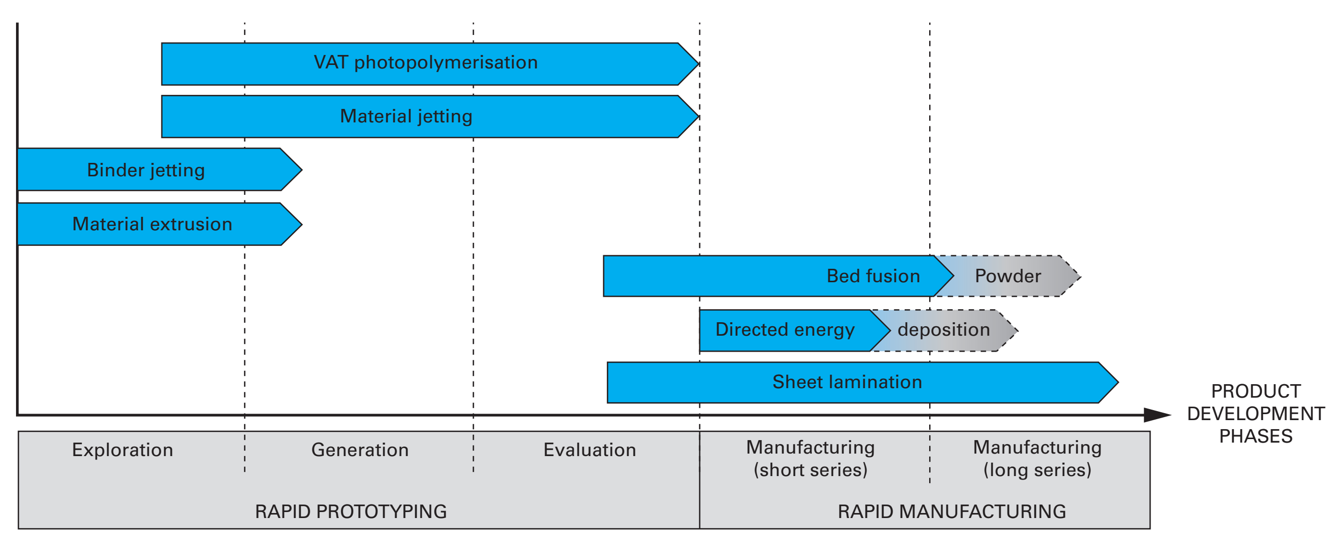


Figure 20 – Uses of AM processes

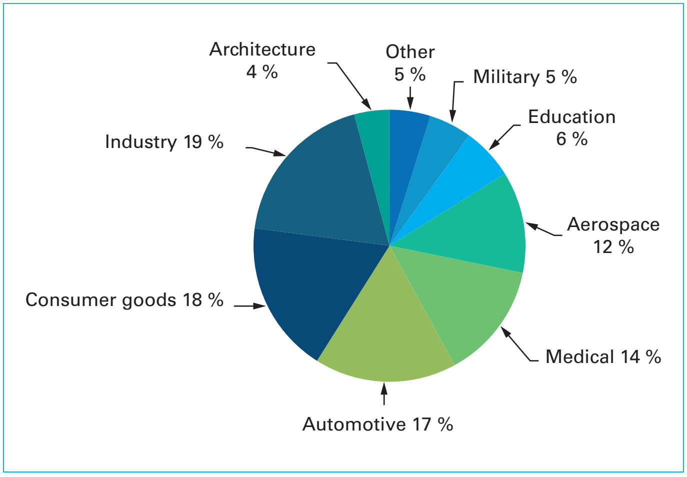


Figure 21 – AM machine user sectors

subcontracting, thus ensuring confidentiality for products currently in development, and enabling prototypes to be made available more quickly.

Given current developments, the boundary between machines for the general public and those for professional offices is starting to become less well-defined.

3.3.2 Industrial machines

In 2015, 12,558 industrial AM machines (priced at more than $5,000) were sold worldwide and metal AM systems represents only 1,768 of this amount, compared with 7,800 in 2012. They intended both for the production of functional prototypes, but also and most of all for DAM. Their use requires a specific environment based on qualified personnel who have been made aware of the particularities of the digital chain associated with AM. In addition, the production of parts using these machines involves the implementation within businesses of a quality assurance system designed in particular for the certification of the products.

The purchase price of industrial machines is high: between €5k and €200k for a polymer-specific machine, and €500k to €2bn for a machine intended to produce metal parts. This price difference can be explained by the need for a sturdy design ensuring industry can enjoy high usage rates, but also offering high production speeds and large production sizes. Finally, unlike for office machines, the range of available materials is much larger.

4. Developments associated with additive manufacturing

4.1 Design process

In the ever-changing field of AM, it is not unusual to notice that designers feel helpless. The emergence of AM has indeed overturned a design process which was hitherto founded solely on traditional processes.

It is easy therefore to understand the importance of promoting the potential of AM among designers so that they can derive full benefit from it during the design process, in broader terms than simply as a product innovation objective. That means providing them with tools and methods suited to the particularities of AM and allowing a change in current design habits: this is the challenge of **Design For Additive Manufacturing** (DFAM).

The DFAM approach is currently the subject of research and development work, and is based on the introduction of elements to facilitate the work of the designer, such as:

– multiple-criteria selection methods for AM processes;
– a reference base of rules and facts to help consider the limitations of processes (e.g. the minimum wall thickness achievable, the optimal orientation depending on strain, etc.);
– tools to facilitate form creation and to help disregard the forms automatically adopted in connection with traditional design methods. Tools built on mathematical methods and enabling topological optimisation have been developed by software publishers such as Inspire® from SolidThinking®;
– AM process simulation tools designed to optimise sweep paths;
– tools to predict the mechanical behaviour of parts;

– methodology to encourage the development of innovative products [15];
– deeper knowledge about material comportment and properties during the manufacturing process.

4.2 Emergence of a new ecosystem

A new ecosystem has appeared following the development of AM: **made-to-order manufacture**. These days, through the growth of open design, it is possible to select the CAD file from an online database, make the changes you want, and then manufacture it using your own machine or by subcontracting it out to service providers (such as Shapeways or Sculpteo®), who will take charge of the manufacturing. The Wohlers 2014 report [16] estimates there are more than 250 businesses currently operating in this market.

However, such changes raise the question of industrial ownership of products which could now be so easily reproduced or copied. For that reason, new regulations to define the shape of this ecosystem are currently being considered, but that will run counter to the principle of free data access which drives the industry. The INPI (French National Industrial Property Institute) has also provided recommendations on this issue [17].

The boom in AM has also helped with the development of FabLabs, a meeting place for personal activities connected with leisure, DIY and creative activities associated with start-ups. Here, again, the idea of mutualisation is important. This is where resources and skills are made available to a community, and this is not restricted simply to digital files. This is where AM takes on a more social role, and an important one in the development of those communities.

5. Conclusion

Recent developments in AM technologies serve to highlight the sector’s great dynamism. Such advances, both in materials and in the forms or complexity which can be achieved, provide a glimpse of the innovative uses to which the processes may be put. Thus, although current applications remain chiefly dedicated to made-to-measure production (implants, surgery, etc.), or high added value items (aerospace, defence, Formula 1, etc.), the democratisation of such technologies will, in the very near future, have an impact on many fields, both technologically and socially. While the main constraints on the massive roll-out of some of these processes remains the limited size of parts and the high costs of machines and/or materials (particularly for metal products), it is highly probable that, once these barriers have been lifted, the potential for innovation associated with these technologies could finally be seen with their widespread adoption.

6. Glossary

Rapid prototyping; *Prototypage rapide*

The use of additive manufacturing to obtain intermediate representations of the design of products such as concepts or functional prototypes.

Rapid manufacturing; *Fabrication rapide*

The use of additive manufacturing to produce finished working products or tools.

Acronyms, notation, symbols

Symbol	Description
ABS	Acrylonitrile-Butadiene-Styrene
DFAM	Design For Additive Manufacturing
AM	Additive Manufacturing
DAM	Direct Additive Manufacturing
RT	Rapid Tooling
RP	Rapid Prototyping
PLA	PolyLactic Acid
STL	Stereolithography