Gebhardt
**Understanding Additive Manufacturing**

Andreas Gebhardt

# Understanding Additive Manufacturing

Rapid Prototyping • Rapid Tooling • Rapid Manufacturing

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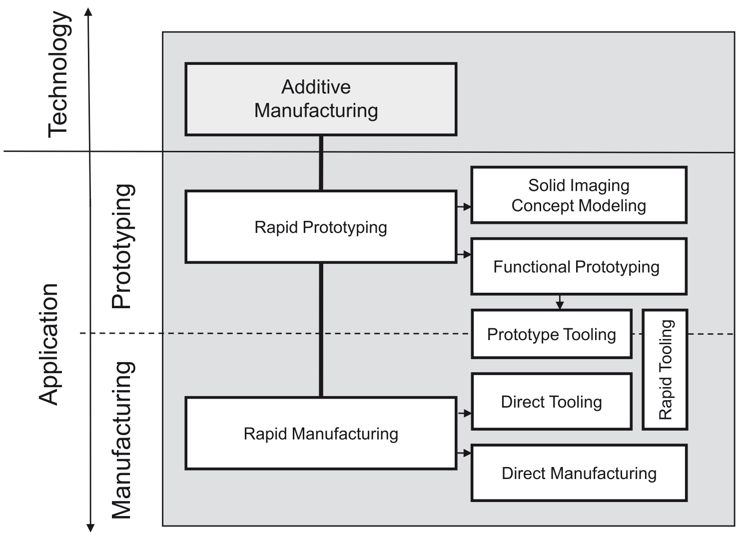
# 1 Basics, Definitions, and Application Levels

Chapter 1 will provide a brief overview of what is called Additive Manufacturing (AM) and the principle of layer-based technology including the main definitions. Throughout this book we will approach the topic from the viewpoint of the applicator and will focus on the industrial applications of AM. Process details will be discussed in Chapter 2.

All definitions are linked to a step-by-step elaboration of the "AM Application Sheet" which summarizes the definitions and interdependencies of the various applications, all of which will be illustrated by typical examples. The final version of the "AM Application Sheet" (identical with Fig. 1.19) is shown below.




Additive Manufacturing (AM) Application Sheet: Technology – and Application Level Definitions

## 1.1 Basics and Definitions

### 1.1.1 Additive Manufacturing – Layer Manufacturing

"Additive Manufacturing" (AM) is a layer-based automated fabrication process for making scaled 3-dimensional physical objects directly from 3D-CAD data without using part-depending tools. It was originally called "3D Printing" and is still frequently called that.

Together with the well established "Subtractive Manufacturing", such as milling or turning, and the "Formative Manufacturing", such as casting or forging, Additive Manufacturing provides the third supporting pillar of the entire manufacturing technology /Bur93/.

When the first approaches to "Additive Manufacturing" entered the market in 1987, it was called "Rapid Prototyping" or "Generative Manufacturing". Both terms are still in use and in the past years many different names have been presented and frequently more are added. Although each of the names is perfect from the special viewpoint of its creator, many of them cause confusion. Often, this is one reason why newcomers to the industry in particular sometimes feel lost in the field of AM.

To obtain a brief overview, a small selection of the mostly used terms are structured according to a few families of key words. Often used terms include:

- "additive" Additive Manufacturing (AM)
  Additive Layer Manufacturing (ALM)
  Additive Digital Manufacturing (DM)
- "layer" Layer Based Manufacturing
  Layer Oriented Manufacturing
  Layer Manufacturing
- "rapid" Rapid Technology
  Rapid Prototyping, Rapid Tooling, Rapid Manufacturing
- "digital" Digital Fabrication
  Digital Mock-Up
- "direct" Direct Manufacturing, Direct Tooling
- "3D" 3D Printing, 3D Modeling

Any and all imaginable (and even not imaginable) combinations of these keywords are existing too.

**Attention: Some of these terms are under copyright protection!**

There are additional terms in use that are created according to new and innovative manufacturing technologies, they include:

- Desktop Manufacturing
- On-Demand Manufacturing
- Freeform Manufacturing

As *Additive Manufacturing* (AM) is a comparably young technology, there were almost no efforts for standardization for many years other than some preliminary work in Germany in the early 1990s. In 2007, a special recommendation dedicated to *Rapid Prototyping* /VDI3404/ was created under the supervision of the German Society of Mechanical Engineers, VDI. It was published in autumn of 2008. As of 2009, the American Society of Mechanical Engineers (ASME) in cooperation with the American Society for Testing and Materials (ASTM) started the development of their own standardization procedures. In autumn 2009, the committee F42 on Additive Manufacturing (subcommittee F42.91 on Terminology) issued F2792-09e1 /F2792/, also called *Standard Terminology for Additive Manufacturing Technologies*. Among other definitions, the name *"Additive Manufacturing"* was defined by this committee.

As it always takes time until newly defined terms are generally accepted, a great varity of different terms, increased by brand names and company driven terms, are still in use, sometimes even in competition to each other.

### 1.1.2 The Principle of Layer-Based Technology

The term additive manufacturing, like "Generative Manufacturing", covers any imaginable way of adding material in order to create a 3-dimensional physical part. The technical realization of AM is based solely on layers and therefore it is called "layer-based technology", "layer-oriented technology", or even "layered technology". Consequently, today the terms, additive manufacturing, generative manufacturing, and layer-based technology are used synonymously. In the future, as new additive technologies may become available they will need to be classified within the current structure of AM definitions. As an example, a process called "Ballistic Particle Manufacturing, BPM" was introduced already in the early 1990s, but vanished soon after. It added material from all spatial directions by jetting discrete volumes (voxels) on the emerging object. This technology was additive but not layer-based.

The principle of layer-based technology is to compose a 3-dimensional physical object called "part" from many layers of (mostly) equal thickness. Each layer is contoured according to the corresponding 3-dimensional data set (see Fig. 1.1) and put on the top of the preceding one.

As a consequence of the even layer thickness, the resulting part shows a stair-stepping effect as shown in Fig. 1.1, (right).

**FIGURE 1.1** Principle of layer manufacturing. Contoured layers (left), 3D object made from staggered layers (right) (Source: HASBRO/MB Puzzle)

### Additive Manufacturing (AM)

Additive manufacturing (AM) is an automated and revolving process developed from the principle of layer-based technology. It is characterized by a process chain illustrated in Fig. 1.2. It starts with a (virtual) 3-dimensional CAD data set (solid) that represents the part to be produced. In engineering, the data set is typically obtained by 3D CAD design or by scanning or other imaging technologies such as computerized tomography scanning (CT-Scanning).

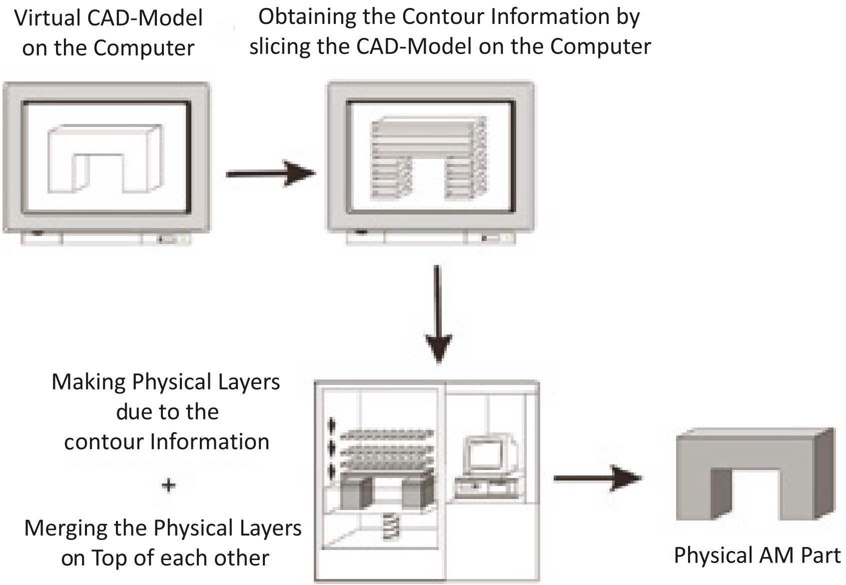



**FIGURE 1.2** Additive manufacturing (AM) process chain

Independently of how it was obtained, the 3D data set is first sliced into layers, using a computer and special software. As a result, a set of contoured virtual slices with even thickness is obtained.

The data set, consisting of the contour data (x-y), the layer thickness (dz) and the layer number (or z-coordinate) of each layer, is submitted to a machine that executes two elementary process steps per layer in order to create the part.

First, each layer is processed according to the given contour and layer thickness data. This can be done in many ways using different physical phenomena. The most simple method is to cut the contour from a prefabricated sheet or foil. In the second step, each layer is bonded to the preceding layer, now forming the top layer of the partly finished model. Again, the simplest method is to use a contoured foil and glue it on top of the preceding layer. Layer by layer, the physical model is growing from the bottom to the top until the final part is obtained.

These basic steps, called a process chain, are the same for all of the approximately more then 100 different AM machines available today. The machines differ only by the way each layer is processed and by the way adjacent layers are joined to form the part. Consequently, all machines discussed later (Chapter 2) are characterized according to some common characteristics.

As a first conclusion, additive manufacturing (AM) is a manufacturing process:

- based just on a 3D data set, a 3-dimensional virtual object, called a digital product model
- using layers of even thickness contoured according to corresponding cross sections of the product model. AM therefore basically is a 2-1/2 D process.
- that does not interfere with the design process and therefore can be done at any stage of product development.
- that mostly uses proprietary material thus forming a strong linkage between machine, process, and build material. This effect will diminish with the increasing number of machines in the market and the rising attraction for third party material suppliers to enter the market.

## 1.2 Application Levels

Most of the people interested in AM preferably want to know how they can use this new technology and what kind of new and different products they can develop using it. In addition, it is advantageous to use the right terms during discussions in the product development team.

Many think that each of the different AM processes, which will be described in detail in Chapter 2, is exclusively linked to a certain application in the sense that a certain AM process can only be used for one or a small range of applications while another process is solely suitable for another application. This opinion encourages people to study all different processes first and to care about suitable applications afterwards.

In practice, the identification of the best applicable AM process starts with the respective application. Then, special requirements, such as dimensions, resolution surface quality, tolerable mechanical forces, temperatures, etc. lead to a suitable material and finally to a machine capable of handling all these requirements properly. In general, different AM processes can be used alternatively to solve the same problem.

Therefore, before researching the different additive manufacturing (AM) processes (Chapter 2), a structured discussion of the broad field of applications should be done. In order to facilitate this discussion, different application levels will be defined.

To define such a structure, first the meaning of the term "technology" has to be distinguished from "application". Technology is defined as the science of the technical process and describes the scientific approach. Application means how to use the technology to benefit from it, which is also called the practical approach.

To obtain a better overview, different classes of applications, so called "application levels" are defined. The definitions are widely accepted but not standardized yet and despite all standardization efforts, sometimes there are different terms in use. As can be seen in Fig. 1.3, AM technology is characterized by two main application levels, "Rapid Prototyping" and "Rapid Manufacturing".

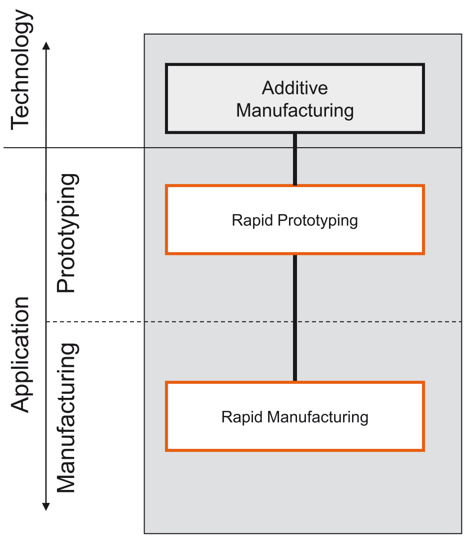



**FIGURE 1.3** AM: technology level and the two application levels rapid prototyping and rapid manufacturing

Rapid prototyping describes all applications that lead to prototypes, samples, models or mock-ups, while rapid manufacturing is used when final parts or even products are made.[1]

## 1.2.1 Direct Processes

All AM processes are called "direct processes" in order to indicate that the digital process model is directly converted into a physical object, called the part, by means of a generative machine. In contrast to this, some procedures are called "indirect processes" or also "indirect rapid prototyping processes". They do not apply the principle of layer manufacturing and consequently they are not AM processes. Actually indirect processes are copying techniques mostly based on silicon rubber casting such RTV (see Sections 1.3.1 and 2.2). Since AM parts are used as masters, the term "Indirect Rapid Prototyping Processes", was established because it sounds more innovative. The procedure is described in Section 1.3.

### 1.2.1.1 Rapid Prototyping

Regarding the application level "rapid prototyping", two sub-levels can be distinguished: "Solid Imaging" and "Concept Modeling" on the one hand and "Functional Prototyping" on the other hand (Fig. 1.4 and Fig. 1.7).

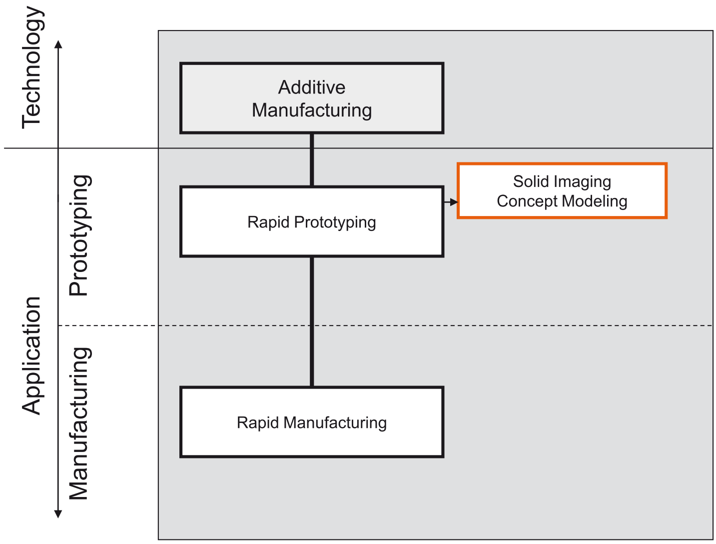



**FIGURE 1.4** AM: application level *rapid prototyping*; sub-level solid imaging and concept modeling

[1] The parts are named prototypes or models if they show just one or a few isolated properties or functions of the final series part, while they are named (final) parts or products if they show all functionalities of the series product.

Solid imaging or concept modeling defines a family of parts that are applied to verify a basic concept. The parts resemble a three dimensional picture or a statue. In most cases, they cannot be loaded. They are used just to get a spatial impression in order to judge the general appearance and the proportions. Because of this the parts are also called "show-and-tell models".

Scaled concept models are often used to verify complex CAD drawings. Here, they are called "data control models" as well (Fig. 1.5). Data control does not only mean verifying the CAD data, but to provide a basis for interdisciplinary discussions as they occur, e.g. in packaging problems. In the case of the convertible roof assembly model shown in Fig. 1.5, it helped to balance the ideas from divisions specialized on different aspects of the soft-top, the electric mechanism, and the kinematics.

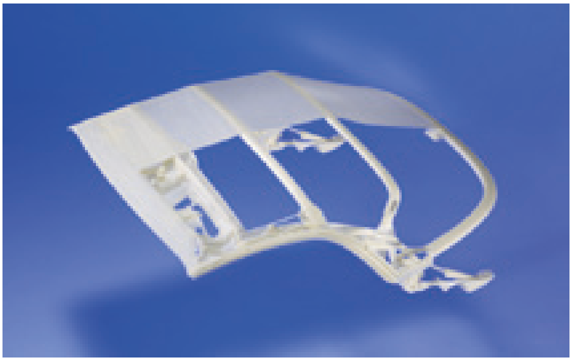


**FIGURE 1.5** Solid image or concept model; scaled assembly of a roof construction of a convertible passenger car; laser sintering, polyamide[2] (Source: CP GmbH)

Colored models made by the powder-binder process of 3D printing (see Section 2.1.4) are valuable tools for concept evaluation. The coloring helps to indicate the problematic areas of a product and to structure the discussion. Figure 1.6 shows a solid image of a cut-away model of a combustion engine unit. In reality the part is not colored, the different colors of the model can be linked to the topics of the agenda for example.

*Functional Prototyping*, Fig. 1.7, is applied to allow checking and verifying one or more isolated functions of the later product or to make the production decision, even though the model cannot be used as a final part /Geb07/.

As can be seen in Fig. 1.8, the adjustable air outlet grill for the climate adjustment nozzle of a passenger car can be used to verify the air distribution in a very early stage of product development. It was made in one piece using laser stereolithography.

[2] This part and the other ones in this chapter are just examples to illustrate the AM-application level. The processes and the materials used are added to provide full information. Detailed descriptions see Chapter 2, further applications see Chapter 3.

**FIGURE 1.6** Solid image or concept model. Cut-away demonstrating part of a combustion engine unit; 3D-printing (Source: Z-Corporation)

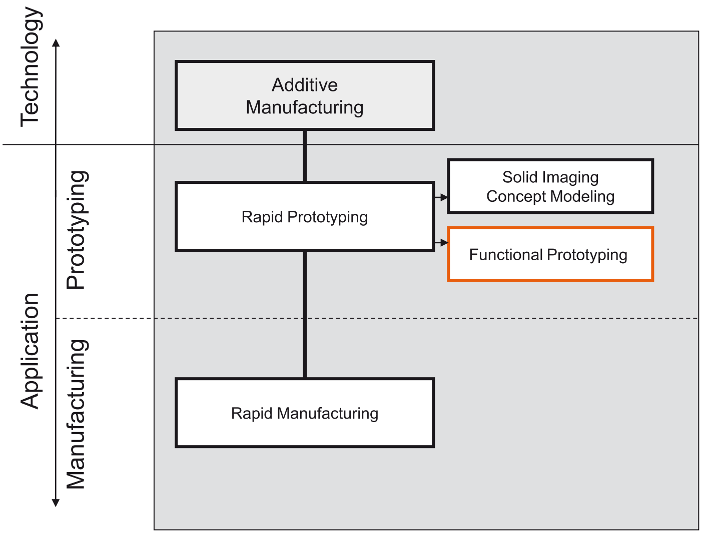



**FIGURE 1.7** AM: application level *rapid prototyping*; sub-level functional prototyping

This process results in a smooth surface that mimics the later series quality: however, due to its mechanical and especially its thermal properties as well as its color and its high price it is not acceptable as a series part. The moving parts were made leaving one connecting layer within the hinges uncured (see Section 5.2.4). In a final step the finished part was cleaned and in particular the uncured material was removed by hand. After that, the desired articulator was ready for testing.

**FIGURE 1.8** Functional prototyping: adjustable air outlet grill for a passenger car; laser stereolithography (Source: 3D Systems)

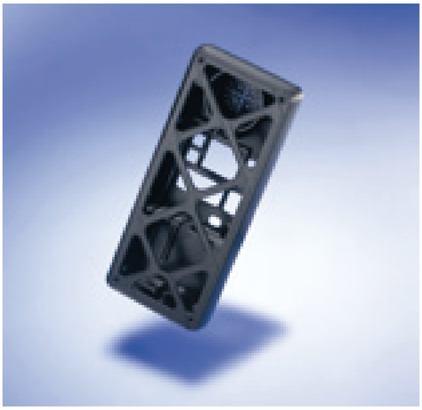


**FIGURE 1.9** Housing for a re-designed mobile phone. Extrusion-fused deposition modeling (Source: RP Lab, Aachen University of Applied Sciences)

Figure 1.9 shows the housing of a mobile phone designed to establish a local communication network for poor communities. The mobile is a re-designed, low cost walkie-talkie. To use it as a mobile, speaker and microphone must be re-arranged to allow simultaneous speaking and hearing as well as appropriate ergonomic handling. The two-piece test housing is made from ABS plastics by fused deposition modeling, FDM (see Section 2.3.1.). The lower element is designed to hold the electronics, while the upper element covers the housing. Both elements need to fit perfectly for evaluation.

The prototype housing was used to prove the perfect fit and to test the handling. But due to the clearly visible extrusion structure and the cost, which are too high for series manufacturing, it cannot be used as a product.

### 1.2.1.2 Rapid Manufacturing

The application level “Rapid Manufacturing” summarizes all processes that deliver final products or final parts that need to be assembled to become a product. An AM part is called a product or final part, if it shows all characteristics and functions that are allocated to it during the product development process. If the resulting part is a positive, the process is called “Direct Manufacturing”, if it is a negative, which means a die, a mold or a gauge, it is named “Direct Tooling”.

Direct Manufacturing leads to final parts that directly come from the AM process (Fig. 1.10). Today, a broad variety of materials from all material classes (plastics, metals, and ceramics) are available to be processed directly using an AM process, see Section 5.1.2). Here, it is not important that the available materials show exactly the same physical properties as the materials used within traditional fabrication processes. However, it must be assured that the properties on which the engineering design was based can be realized with the chosen AM process and material.

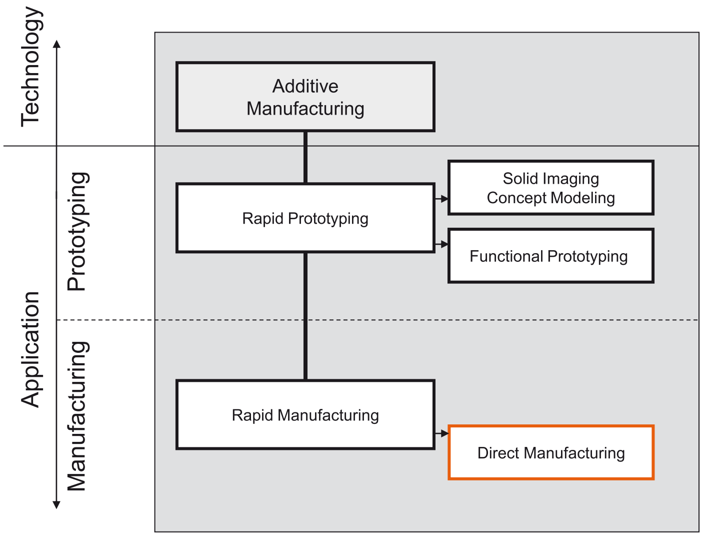



**FIGURE 1.10** AM: application level *rapid manufacturing*; sub-level direct manufacturing.

Figure 1.11 shows a three-unit dental bridge made from CoCr-alloy by selective laser sintering (SLM). The data was obtained from the patient by a dental imprint and then digitized. With the use of a professional dental software (3shape) the dental bridge was designed and directly manufactured using SLM. After finishing and geometric testing, the bridge was ready to be placed in the patient’s mouth. Regarding traditional processes, the directly manufactured bridge was made quicker, with a perfect fit, and at comparable cost.

**FIGURE 1.11** Direct manufacturing. Three-unit dental bridge (left), cross section (without removal of the supports, right), selective laser melting (SLM); CoCr-alloy (Source: RP Lab, Aachen University of Applied Sciences)

**FIGURE 1.12** Direct manufacturing. Aircraft engine cover hinge (bottom) in contrast to the conventionally made one (top). Selective laser melting, SLM, stainless steel (Source: EADS)

A hinge for an aircraft engine cover (Fig. 1.12 top) was re-designed, made by direct manufacturing, and tested. A bionic-type design was made resulting in weight reduction of 50%, but now it could no longer be manufactured by milling. The part is shown on Fig. 1.12, bottom. It was made using the AM metal process of selected laser melting (SLM) and passed the conventional tests and worked perfectly.

### 1.2.2.3 Rapid Tooling

Rapid Tooling involves all AM procedures that lead to final parts used as cores, cavities, or inserts for tools, dies and molds. Two sub-levels must be distinguished: direct tooling and prototype tooling.

*Direct Tooling* is technically equivalent to *Direct Manufacturing* but leads to tool inserts, dies and molds (Fig. 1.13) in series quality. Although tooling is based simply on the inversion of the product data set (positive to negative) there are reasons to attribute it

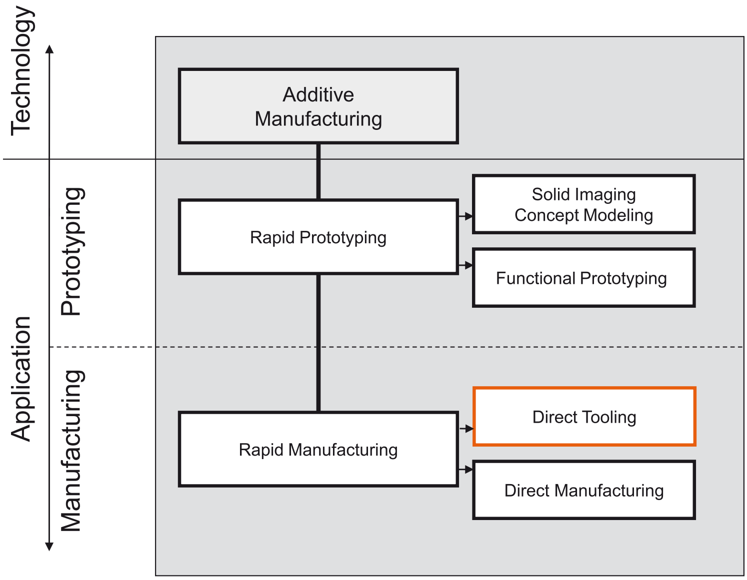



**FIGURE 1.13** AM: application level *rapid manufacturing*; sub-level direct tooling

with a separate application sub-level. In addition, for data inversion, a tool construction is needed, including scaling to compensate shrinking, parting line definitions, draft angles, ejectors, sliders, and so on. Tooling mostly requires a metal process and machines that are designed to run it.

It is important to understand that "Direct Tooling" does not mean that the entire tool is made, in fact only tool components, such as cavities or sliders, are generated. The entire tool is made using these cavities and standard components or inserts within a traditional tool making process.

The layer-based technology of all AM processes allows the fabrication of interior hollow structures. As an example, mold inserts can be built with internal cooling channels that follow the contour of the cavity beneath the surface (Fig. 1.14, left). Because the shaping of the cooling channels follows the contour of the mold, the method is called *conformal cooling*. Due to the increased heat extraction, the productivity of a plastic injection mold can be increased significantly. In addition, cooling and heating channels can be designed to obtain an integrated heat management system and thus much more effective tools.

To produce a steel blow mold for the manufacturing of golf balls, high precision is required. Using the direct metal laser sintering process, a near net shape mold was made by AM (see Fig. 1.15). It is not a final part, but an excellent example of how AM and subsequent high precision machining, such as high speed milling, die sinking EDM, and wire EDM provide an effective process.

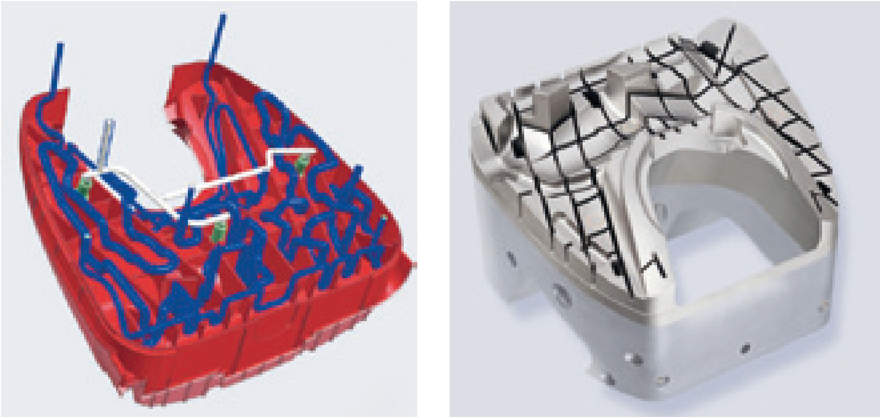


**FIGURE 1.14** Direct tooling. Mold insert with conformal cooling channels (blue) and pneumatic ejectors (white). Laser sintering/laser melting (laser cusing); tool steel (Source: Concept Laser)

**FIGURE 1.15** Steel mold for blow molding. Direct metal laser sintering (Source: EOS/Agie Chamilles)

**Prototype Tooling.** A mold in series quality often is too time and money consuming for small series manufacturing. If just a few parts are needed or details are changed frequently, a temporary mold made from substitute material is typically sufficient. This kind of mold shows the quality of functional prototypes but meets, at least partially, the direct tooling application level. The corresponding application level is some kind of an intermediate level between rapid prototyping and rapid manufacturing. This sub-level is called “Prototype Tooling” (Fig. 1.16). Some call it “Bridge Tooling”, although this name is also used for secondary rapid prototyping processes (see Section 1.3.2).

A prototype tool made from polyamide can bee seen as an example in Fig. 1.17. It is used to fabricate a small series of a new design for a grip sole for rubber boots. The soles are necessary to make the entire boot by applying it to a prefabricated bootleg without

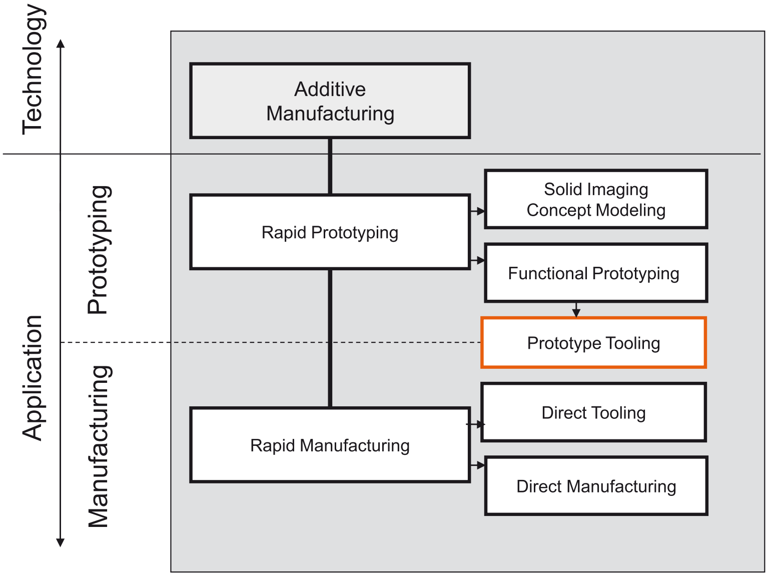



**FIGURE 1.16** AM: Intermediate application level *rapid prototyping/rapid manufacturing*; sub-level prototype tooling

**FIGURE 1.17** Prototype tooling; rubber boot sole mold; laser sintering, polyamide (PA) (Source: EOS GmbH)

making a series-like metal tool in advance. Different sole structures and materials can be evaluated very quickly by casting, even on a small budget.

A prototype tool that can be used on a plastic injection molding machine is shown in Fig. 1.18. It is made by a special stereolithography (see Section 2.1.1) process called AIM (ACES Injection Molding, where ACES is a proprietary built style of 3D Systems

Inc. /Geb07/). Both mold halves are made simultaneously by AM stereolithography, preferably with thin-walled contours and backed by thermally conductive material such as aluminum filled epoxy. AIM is suitable for low volume injection molding of simply shaped parts.

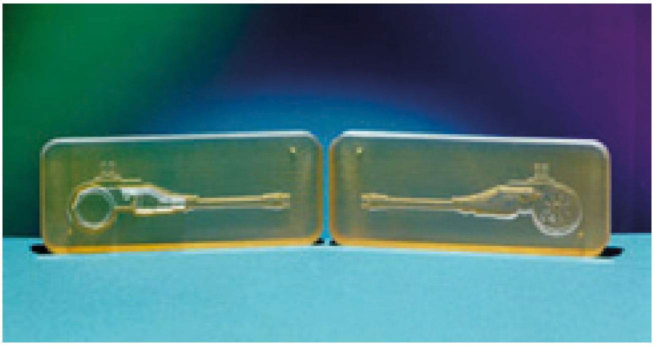


**FIGURE 1.18** Prototype tooling. AIM injection molding; mold insert; stereolithography (Source: 3D Systems)

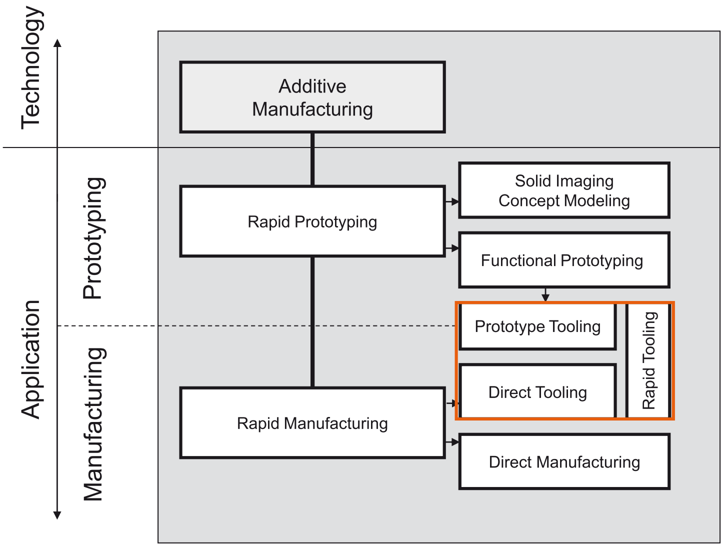



**FIGURE 1.19** AM: rapid tooling, defined as a subcategory that integrates prototype tooling and direct tooling

Summing up the different kinds of tooling, one can see that "Rapid Tooling" does not represent an autonomous application level (Fig. 1.19). Rapid tooling integrates all AM applications that can manufacture dies and molds or corresponding inserts.

## 1.3 Application Levels – Indirect Processes

The AM process directly delivers a geometrically exact and scaled physical facsimile of the virtual data set. But this process also comes with disadvantages (at least with regard to most of today's AM processes, see Chapter 2 for details).

AM processes

- work with process- and consequently with machine-depending materials and restrictions in terms of color, transparency, and flexibility.
- show almost no cost reduction with an increasing production volume.
- are rather expensive when used to make many copies and especially for series applications.

To overcome these problems, AM parts can be regarded as master models and then used for subsequent copying or reproduction processes. The principle behind this is often called "the splitting of capabilities": The geometrical exact part is quickly obtained from the AM process, while the desired quantity, and properties such as color and so on, come from a subsequent copying process.

A copying- or follow-up process is not a layer-based process and therefore it is not an AM process. It is called an "Indirect Process". Because of marketing reasons and in order to indicate the manufacturing speed, some call it "Indirect Rapid Prototyping Process" as well. For the same reason, in literature sometimes the term "Secondary Rapid Prototyping Process" is used.

### 1.3.1 Indirect Prototyping

Indirect prototyping is applied to improve the AM part's properties in order to fulfill the applicator's requirements, if the AM part is not capable to do so. If, for example, a flexible part is needed but due to material restrictions it cannot be built directly by an AM process. Then a geometrical exact but rigid AM part is built (and maybe scaled according to a possibly shrinkage during casting) and used as a master model for a subsequent or follow-up casting process (Fig. 1.20). As a detailed surface is required and the parts are mechanically loaded during the copying procedure, mainly functional prototypes, preferably made by stereolithography or polymer jetting are used as masters. They have to be manually finished before copying.

The majority of parts made by indirect processes are functional prototypes and consequently have to fulfill the same requirements. Solid images or concept models are rarely made by indirect processes because the higher effort in terms of time and costs can typically not justified.

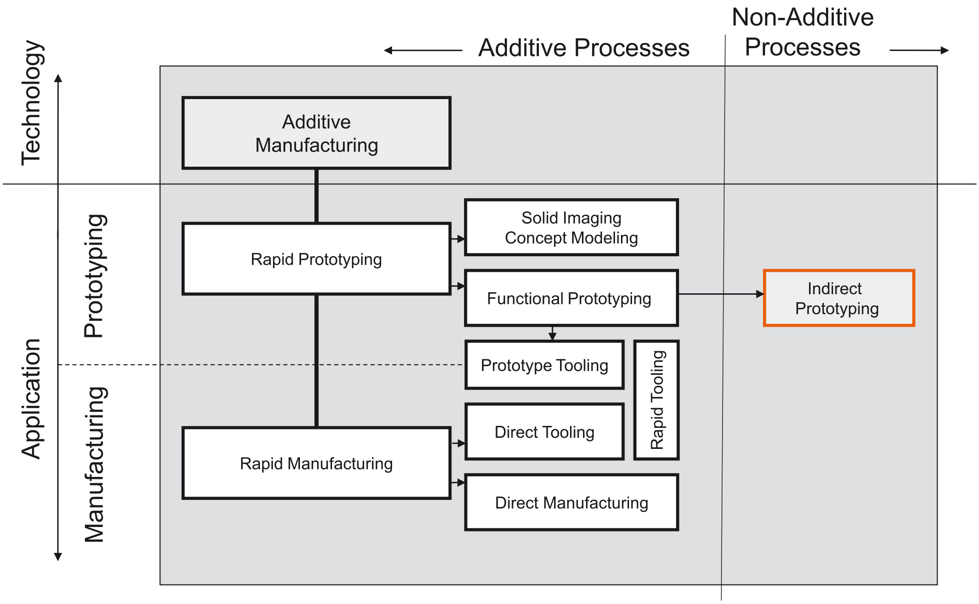



**FIGURE 1.20** AM: indirect processes; indirect prototyping

Many different "secondary processes" (details see Section 2.2 and /Geb07/) can be used. The most prominent one is the so called "Room Temperature Vulcanization", RTV, also known as "Vacuum Casting" or "Silicon Rubber Molding". Like silicon rubber molding, most of the secondary processes are completely or partially manual processes with long cycle times and therefore only useful for small series or one-of-a-kind production.

The plug system (Fig. 1.21) requires plug housings of different colors and transparency. Based on a two-parts AM master of the housing, a silicon rubber mold was made. Using this mold, approximately 15 different copies were obtained from the RTV process.

The different parts were used to present the new product and its capabilities to a perspective series manufacturer. As they are prototypes made from prototype material, the system elements are no series products, even if they function well.

The internal evaluation of the table lighter "Bruce" designed by Stefano Giovannio in 1998 was very important. As the lighter was operated after inserting a disposable lighter into the bottom while the flame exits through the mouth, easy and safe handling was required. As steel tooling was too expensive at this stage of product development, the test samples were made by RTV based on an AM stereolithography master. Figure 1.22 shows the stereolithography master (in the front) and some color variations with and without mechanism.

Prototype parts from soft materials, for example gaskets, often have a very complex shape. This is especially true for gaskets for car mirror fixation that must fulfill many

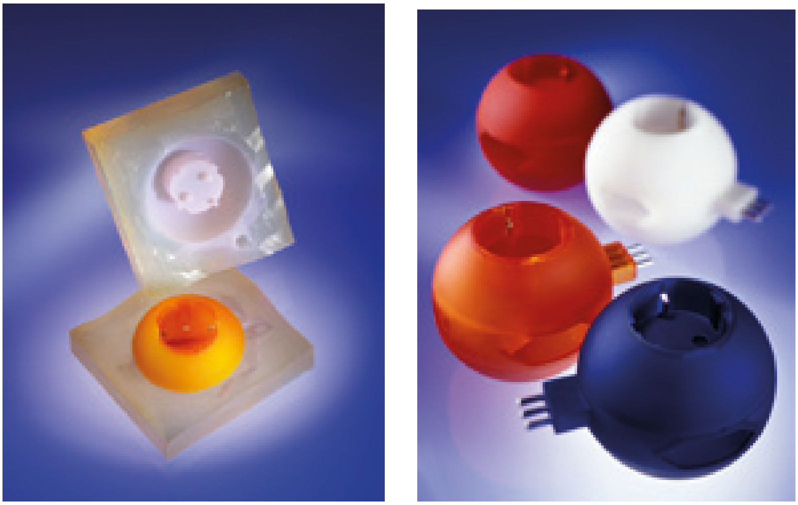


**FIGURE 1.21** Indirect prototyping; silicon rubber molding; plug system; master made by stereolithography; mold with upper part of plug housing (left), mounted plugs (right)
(Source: mais van schoen DESIGN,CP-GmbH)

**FIGURE 1.22** Indirect prototyping; silicon rubber molding; lighter "Bruce"; AM master, stereolithography; working RTV copies (Source: Alessi/Forum Omegna)

functions such as sealing against water, fixation of the mirror and parts of the window, placement of cables, attractive optical appearance, and integration of adjacent extruded sealings. Figure 1.23 shows such a triangle-shaped gasket that was made by RTV based on an AM stereolithography master.

**FIGURE 1.23** Indirect prototyping; silicon rubber molding; triangle-shaped gasket for car mirror fixation (Source: CP GmbH)

### 1.3.2 Indirect Tooling

Indirect tooling is based on the same copying procedures as all indirect processes (Fig. 1.24). It is not the goal to obtain a final part, but a tool that provides the basis for a small or medium size batch production of final (or series) parts or products.

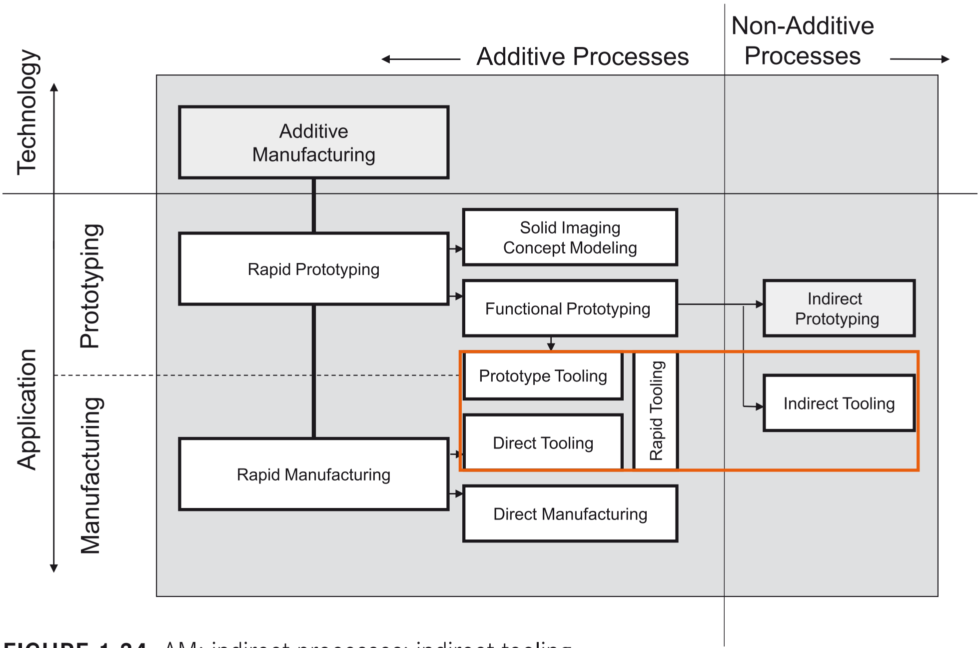



**FIGURE 1.24** AM: indirect processes; indirect tooling

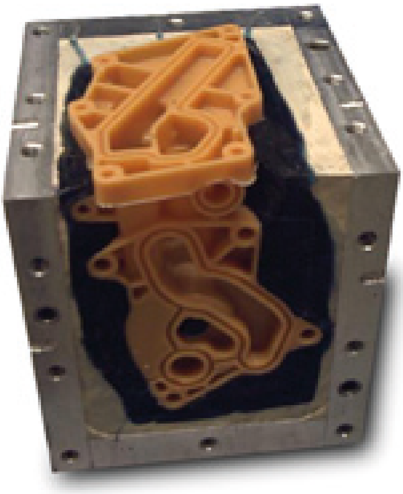


**FIGURE 1.25** Indirect tooling. PUR mold obtained from an AM master, partly open.
Separated mold half with cast wax pattern for lost wax casting.
PUR cavity (black) obtained from AM master.
Back up system by aluminum walls (Source: BeNe)

In contrast to series tools made from tool steel, it can be made quickly and inexpensively. Like indirect prototyping, indirect tooling uses AM masters, thus avoiding milling, grinding, and EDM-processes. In contrast to silicon rubber molding, it must be usable for a larger number of parts made not only from plastics but from metals as well. Seen from this perspective, indirect tooling can be regarded as an element of rapid tooling, although it is not a layer oriented process.

As an example, Fig. 1.25 shows a mold for making wax patterns for lost wax casting. The mold is obtained from an AM master by counter-casting it in polyurethane, PUR, backed by an aluminum box. After the AM master is removed, the mold is used to process the required amount of wax pattern. The higher rigidity of the PUR material in combination with the backed up walls leads to a mold that delivers much more precise wax patterns than could be made by a soft silicon mold. In comparison to milled all-aluminum tools it is cheaper and has a much shorter lead time. This kind of mold can be used for a small series production of complex precision cast parts.

There are parts that cannot be evaluated as samples made by manual casting from thermoset prototyping material, but need to be made by plastic injection molding machines and from the final series material. Examples are plastic parts made of flame retarded materials. Therefore rigid molds are needed. To avoid traditional tooling, a suitable rigid mold can be cast from aluminum-filled epoxy using a stereolithography or polymer jetted master. Despite the material, the process resembles the RTV process.

**FIGURE 1.26** Indirect tooling. Rigid mold made from aluminum filled epoxy for injection molding of a set of series identical parts (black) based on stereolithography masters (light brown) (Source: Elprotec)

For improvement of sharp edged details, milled inserts can be used. This kind of tool is typically not cooled and shows just a few manually operated inserts that substitute the sliders. As a disadvantage, long cycle times have to be taken in consideration. In Fig. 1.26 both cast resin mold-halves can be seen before being inserted in the mold frames. The stereolithography master (light brown) as well as a set of molded parts (black) can be seen. A small series of parts has been made from HD-PE to be tested in the engine compartment of a passenger car.

### 1.3.3 Indirect Manufacturing

Indirect manufacturing is based on AM masters as well. The goal is to obtain final (or series) parts with properties equal to traditionally manufactured (non-AM) products. Consequently, indirect manufacturing belongs to the application level "Manufacturing" (Fig. 1.27).

As an example for indirect manufacturing, Fig. 1.28 shows a six-cylinder combustion engine housing. It was produced as a one-of-a-kind part based on an AM master made from polystyrene by laser sintering. The scaled master was transformed into an aluminum part by evaporative pattern casting (also called full-mold casting), which is a process closely related to the lost-wax-casting process.

As a result, a series of identical engine housings is obtained. It can be used to optimize and verify the engine design, including fired test runs long before series molds are available, but also as a small series product, e.g., for racing. Whether this is an appropriate manufacturing method or not is not a technical but an economical question.

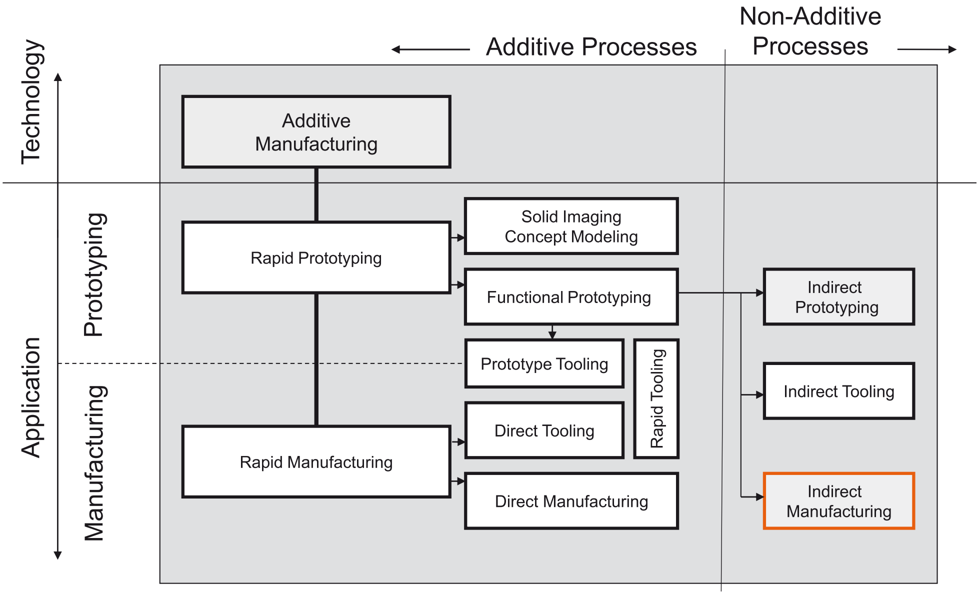



**FIGURE 1.27** AM: application level: rapid manufacturing; sub-level: indirect manufacturing

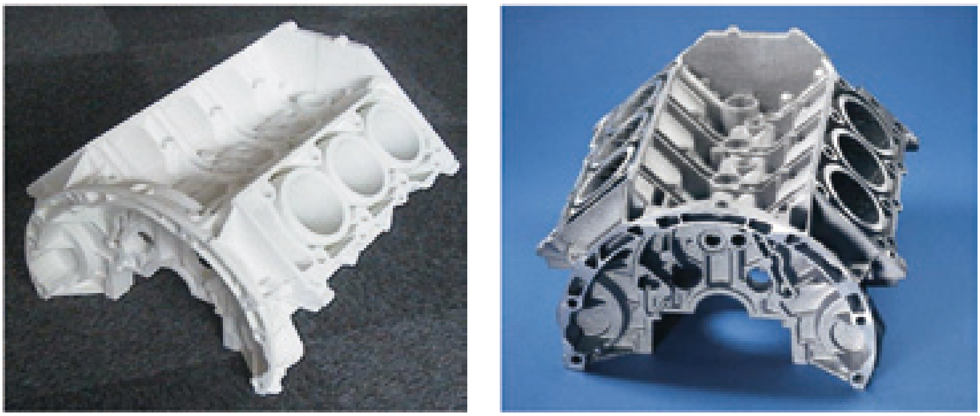


**FIGURE 1.28** Indirect manufacturing; combustion engine housing; AM master (left), laser sintering, polystyrene; aluminum casting, one-of-a-kind part (right) (Source: Grunewald)

The same process was used to make the air intake manifold of a combustion engine displayed in Fig. 1.29. It was made from aluminum by lost-wax casting. Like in Fig. 1.28, the master was obtained from laser sintering of polystyrene. The left part shows the subsequent surface treatment with wax, while the cast part is displayed on the right side.

**FIGURE 1.29** Indirect Manufacturing. Air intake manifold; AM master made from polystyrene by laser sintering after surface treatment (left), aluminum casting, one-of-a-kind part (right) (Source: CP-GmbH)

**FIGURE 1.30** Indirect manufacturing: Gear box for a racing car; AM master made from PMMA by 3D printing (left), aluminum casting, one-of-a-kind part (right) (Source: Voxeljet)

Another variation of this process is displayed in Fig. 1.30, showing that the 3D printing process of PMMA-type plastics provides precise castings as well. In the picture, a gear box for a racing car is displayed as a lost form along with the cast part.

## 1.4 Classes of Machines for Additive Manufacturing

There is a wide variety of machines for additive manufacturing available on the market. They are loosely linked to the application levels but more or less independent from the AM process used.

### 1.4.1 Fabricators and Others

In general, a machine used for layer oriented AM is called a “fabricator”, especially if it can make (fabricate) final parts. If it is only capable of making prototypes, some call it a “prototyper”. The trend is to call all types of layer oriented additive manufacturing machines “printers” or “3D printers”, often with a prefix like “personal”, “professional” or similar terms.

### 1.4.2 Nomenclature of AM Machines

Actually a nomenclature is developing that roughly assigns all AM machines on the market to three categories or classes: fabbers, office machines, and shop floor machines (see Table 1.1 and Fig. 1.31).

As a common abbreviation “fabber” is used in particular to address a small, simple, and cheap machine. If a fabber is used by a private person or a group of private individuals and operated from home or a co-working space, it is increasingly called “personal fabber” (PF).

An “office machine” can be operated in an office environment. That means it emits minimum noise, smell, and particles. The build material can be refilled by office staff and is typically delivered in cartridges. Operation is easy and part handling is simple, including post processing. The waste is disposable as normal office- or household waste.

A “shop floor” machine requires an industrial environment, including trained personnel and logistics. It is designed for high output and productivity, which means it can handle large amounts of material. Sometimes solvents and machines, e.g., for sand blasting, are needed for cleaning. Here, economic production is more important than simple operation.

While this three categories are more or less agreed upon, the terms used are varying depending on company strategies and tend to incorporate at least the word “printer”. In Table 1.1 this nomenclature is structured and dedicated to the application levels.

**TABLE 1.1** Nomenclature for AM Machines and its Relationship to Application Levels

| **Names** | | |
|---|---|---|
| Fabbers | Office machines | Shop floor machines |
| Also called: | | |
| Personal fabricators | Office printers | Production machines |
| Personal fabbers | Professional printers | Production printers |
| Personal printers | Professional 3D printers | Production 3D printers |
| Personal 3D printers | | |
| **Application** | | |
| Semi professional or private use at home office | Professional use in the office or in a workshop | Professional use in production or professional job-shop |
| **Application Level** | | |
| Rapid prototyping | Rapid prototyping | Rapid manufacturing |
| Solid imaging | Functional prototyping | Direct prototyping |
| Concept modeling | Masters for secondary rapid prototyping processes | Direct tooling |


**FIGURE 1.31** Nomenclature for AM machines and its relation to the application levels; examples

This categorization does not directly depend on the AM processes the machines are based on and which are discussed in Chapter 2.

Nevertheless there is a loose interdependency between AM process and the application level. A typical machine for each category is displayed on Fig. 1.31. The machines

**TABLE 1.2** Categorization of AM Machines According to the Required Infrastructure, Professional Skills for Operation, and Average Prizing

| Class of Machine | Operator | Infrastructure | Prizing |
|---|---|---|---|
| Fabbers | Everyone with basic skills to operate a personal computer | Despite a kitchen table no infrastructure is required | From under €/$ 1.000 to €/$ 20.000 |
| Office Printers | People who professionally work with different types of 3D CAD | No special infrastructure is indispensable. A separate office room helps to handle the material and the parts and keeps away the (not really bothering) noise. | From €/$ 15.000 to €/$ 140.000 |
| Shop Floor Machines | Technicians of the fabrication department | A shop floor environment is needed. | From €/$ 120.000 to €/$ 800.000 and up |

displayed show the typical appearance of machines belonging to one of the three categories fabbers, office machines, and shop floor machines. Of course, the machines shown here are just examples. Many others are discussed in Chapter 2 and are displayed in Figs. 2-26 to 2-28, once the basic principles are discussed.

Seen from the operator's point of view, AM machines can be categorized according to the professional skills needed for operation as well as according to their prizing. This is done in Table 1.2 which is linked to the definitions above and the environment needed

## 1.5 Conclusion

The discussion of the applications of additive manufacturing proves that today all levels of applications and all branches already benefit from the capabilities of AM. The definitions support a professional discussion. In practice it is particularly important to distinguish between the different application levels. Disappointments often result because the users do not properly define their expectations.

The examples underline that various AM processes can be used, sometimes even alternatively, to meet the user's needs. To take advantage of this fact, the different AM processes that are commercially available are presented and discussed in Chapter 2.

Today's restrictions, such as a limited variety of materials, poor surface quality, or a far too slow performance of AM production processes will be overcome quickly.

As worldwide hundreds of scientists and industrial product developers work on all facets of this new technology, tremendous improvements as well as completely new processes will be available soon. Composite multi-material products will be realized. They will open up new fields of applications for all kinds of industrial products, mainly for electronic parts and medical applications (see Chapter 4).

## 1.6 Questions

### 1. Why there are no AM processes named and discussed in Chapter 1?

Chapter 1 discusses the application areas and provides a structure of AM process applications. This basic structure does not depend on certain processes.

### 2. What is the main characteristic of additive manufactured parts?

Almost any geometry can be made.

Due to the layer oriented process, all AM parts show stair-stepping.

### 3. Why do technology level and application level have to be distinguished from each other?

The technology level provides the theoretical and scientific background, while the application level defines the use and the benefit expected from AM.

### 4. What is the difference between *Generative Manufacturing* and *Additive Manufacturing*?

None, they are just two different names for the same thing. Parts are generated by adding incremental volumes (voxels, layers) to a semi-finished part.

### 5. What is the relationship between *Generative Manufacturing*, *Additive Manufacturing*, and *Layer-based Manufacturing*?

Additive manufacturing and generative manufacturing are generic terms that indicate that the parts are built by adding material or by generating it from volumes. Today, the technical realization of AM is solely based on layers and therefore it is called “Layer-based Technology”, “Layer-oriented Technology ”, or even “Layered Technology”.

All three terms define identical processes.

### 6. What are the applications of *Solid Images*?

Solid images are used to evaluate the general appearance, the shape, and the haptic properties of a part during product development. It is valuable as well for product data control.

### 7. How do *Solid Images* and *Functional Prototypes* differ from each other?

Solid images are just 3-dimensional pictures or statues, while functional prototypes show one or a limited number of the functionalities of the later product.

### 8. Why do *Follow-Up* or *Secondary Rapid Prototyping* processes not belong to the family of AM processes?

Because the parts are not made layer by layer but cast using a tool (the mold).

### 9. Why are indirect processes often called *Indirect Rapid Prototyping* processes or just *Rapid Prototyping* processes?

Because the prefix *rapid* is fashionable and an the users expect an improvement of the economic success.

### 10. Why does the term *Rapid Tooling* not define its own application level?

Making tools and tool components is technically identical with making final metal parts. The machines, the process, and the materials are identical. Therefore, both applications belong to the level *Rapid Manufacturing*. Only the CAD design differs depending on whether a part (positive) or a mold for its production (negative) is made. Consequently, there is no indication for a specific application level but for a family of similar applications.

### 11. What is the difference between *Functional Prototyping* and *Direct Manufacturing*?

Functional prototyping leads to prototypes that show just a few selected functionalities of the final product while direct manufacturing generates parts that are completely identical with the final product.

### 12. Why is *Prototype Tooling* an application, positioned between the application levels *Manufacturing* and *Prototyping*?

Because the tool is made using prototype parts and methods and therefore it is considered a prototype, while the resulting parts made from it show series quality, at least under special circumstances.

# 2 Layer Manufacturing Processes

The technical realization of additive manufacturing is done by layer manufacturing processes (also called direct layer manufacturing processes). Based on different methods to generate a solid layer and to file and bond adjacent layers to form a part, five families of layer manufacturing processes used in additive manufacturing are commercially available. All of them directly follow the principle of AM as discussed in Chapter 1. All five processes, including some derivations, are described in detail. Corresponding commercially available machines are presented together with typical parts.

If prototypes and parts are not made directly by AM but based on AM processes, they are called *"Secondary Rapid Prototyping Processes"*. The principle and the most frequently used variations have been discussed briefly in Section 1.3. The most prominent one, *room temperature vulcanization (RTV)*, is explained in more detail in Section 2.2.

## 2.1 Direct Layer Manufacturing Processes

The principle of additive manufacturing (AM) is as simple as sketched in Chapter 1, Fig. 1.2. It is based only on (virtual) 3D CAD data (solids). The data set is sliced according to a given layer thickness, thus approximating the freeform surface by a sequence of contoured layers of even thickness (Fig. 2.1).

The (physical) manufacturing process (the AM process) is focused on the revolving production of a single layer and its bonding to the preceding one. The process consists of only two steps that are repeated until the part is finished:

1. Generation of a single layer with a shape according to the contour and with a given layer thickness both based on the slice data.
2. Joining each new layer on top of the preceding one.

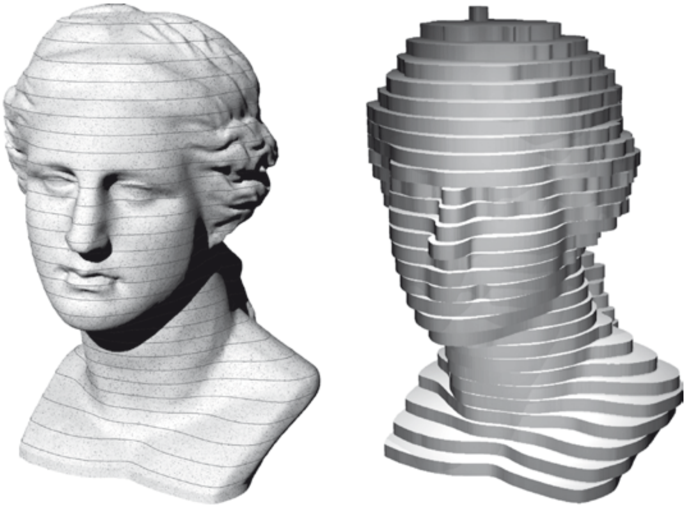


**FIGURE 2.1** Slicing of a 3D freeform surface into contoured layers of even thickness showing the characteristic stair-stepping effect (layer thickness exaggerated for clarity)

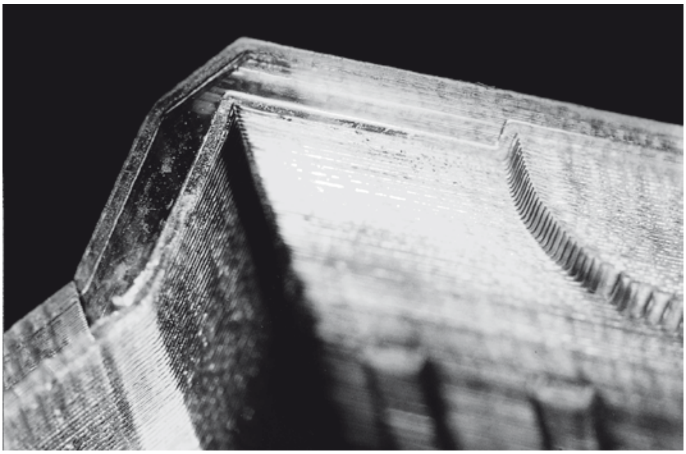


**FIGURE 2.2** Stair stepping. Layer thickness 0.1 mm; stereolithography

As can be seen theoretically in the scheme (Fig. 2.1), the resulting parts also show stair-steps, which are characteristic for AM processes (Fig. 2.2).

The standard layer thickness is about 0.1 mm but it can be reduced to 0.016 mm, thus increasing not only the precision of the part but the amount of layers and the build time as well. It also depends on the processed material, because the resulting stair steps require much more effort, if the material is hard, e.g., with metal and ceramics.

Today, there are considerably more than 100 different machines commercially available. All of them show the two basic manufacturing steps mentioned earlier. They only differ in the way, each layer is made, how successive layers are merged, and what material is processed.

The generation of the physical layer can be done using various materials, such as plastics, metals, or ceramics, supplied as powders, fluids, solids, foils, or sheets. Different physical effects are used, such as photo-polymerization, selective fusing, melting, or sintering, cutting, particle bonding, or extrusion (for details see /Geb07/ and Chapter 5).

The contouring of each layer requires an energy source that generates the chosen physical effect and a handling device that controls the x-y coordinates. Commonly used are

- lasers with galvo-type scanning devices, optical switches, or gantry-type handling systems
- electron beams,
- single- or multi-nozzle print heads,
- knifes, extruders, or infrared heaters with plotters or DLP projectors.

All imaginable processes can be assigned to five basic families of AM processes (Table 2.1). The names listed in Table 2.1 are the so-called generic names that act as a descriptive for all members of a genus. Generic names have to be distinguished from the brand names given to the processes or machines by a specific manufacturer. Both, including the common abbreviations, are listed in Table 2.2.

**TABLE 2.1** Physical Principles of Layer Generation and Contouring and the Resulting Five Basic Families of AM Processes (Generic Names)

| Generating a solid layer by | Contouring the layer by | Subsequent ALM-Process |
|---|---|---|
| Polymerization | Laser, Printhead | Stereolithography<br>Polymer jetting |
| Selective melting or<br>selective sintering and resolidification | Laser, IR-source<br>electron beam | Laser sintering<br>Laser melting |
| Contour cutting and bonding | Laser, Knife, Milling | Layer-Laminate manufacturing |
| Selective bonding or gluing by binder | Multi-Nozzle printhead | 3D Printing |
| Selective application of thermally activated phases | Single-nozzle extruder | Fused layer manufacturing |

**TABLE 2.2** AM Processes: Generic Names, Brand Names and Their Abbreviations

| Generic Name | Abbr. | Brand Name | Abbr. |
|---|---|---|---|
| Polymerisation<br>Stereolithography | | Laser-stereolithography<br>Polymer jetting | SL |
| Laser sintering<br>Laser melting | LS | Selective laser sintering<br>Selective laser melting<br>Electron beam melting | SLS<br>SLM<br>EBM |
| Layer-laminate manufacturing | LLM | Laminated object manufacturing | LOM |
| 3D Printing | 3DP | Three dimensional printing | 3DP |
| Fused laser manufacturing | FLM | Fused deposition modeling | FDM |

### 2.1.1 Polymerization

The selective solidification of liquid monomeric resin (of the epoxy-, acrylate, or vinyl ether type) by ultraviolet radiation is called (photo)-polymerization. There are various processes that differ only in the way the UV-radiation is generated and by the way the contouring is done. Some polymerization processes provide just a partially solidification. Consequently, a ”green part” is made that requires additional curing to become a completely cured part. The additional curing is done after the build process using a special device called post-curing oven. It is equipped with UV emitting lamps to provide a complete and even solidification of the entire part.

During the build, polymerization processes need so-called supports. They are necessary to stabilize the entire part including overhangs, to match temporarily unconnected elements, to fix it on the platform, and to thwart distortion and warping. The supports are added to the 3D CAD model using automated software and have to be removed manually after the build. Some can be washed out automatically, using a special cleaning device.

#### 2.1.1.1 Laser-Stereolithography (SL)

Stereolithography is not only the oldest but also still the most detailed AM process. It was invented and first commercialized by 3D Systems, Rock Hill, SC, USA. Laser stereolithography delivers parts with very good surfaces and fine details. The parts are created by local polymerization of the initially liquid monomers. Initiated by a UV-laser beam, the polymerization turns the liquid into a solid, leaving a scaled solid layer. The laser beam is directed by a galvo-type scanning device that is controlled according to the contour of each layer. A typical machine can be seen in Fig. 2.3, left.

**FIGURE 2.3** AM machines. Laser stereolithography, 3D systems, left (Source: 3D Systems). Laser sintering, right (see Section 2.1.2) (Source: EOS GmbH)

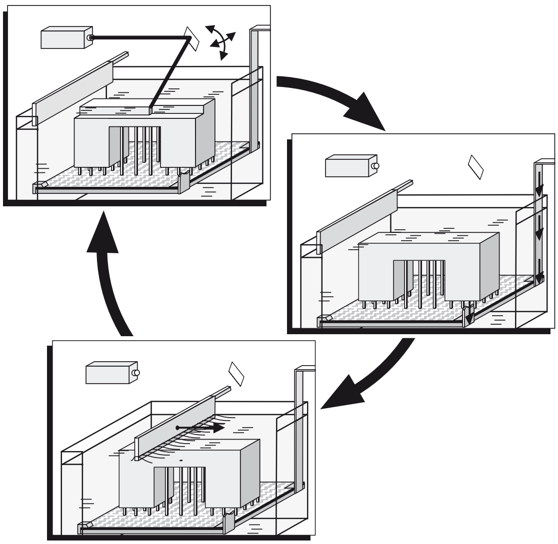


**FIGURE 2.4** Polymerization, laser-stereolithography; scheme; solidification of a single layer, lowering of the platform, recoating (clockwise starting from top left)

A laser stereolithography machine consists of a build chamber filled with the liquid build material and a laser scanner unit mounted on top of it which generates the x-y contour. The build chamber is equipped with a build platform fixed on an elevator-like device that can be moved in the build (z-)direction (Fig. 2.4). On this platform the part is built. The laser beam simultaneously does the contouring and the solidification of each layer as well as the bonding to the preceding layer. The motion of the beam is controlled by the slice data of each layer and directed by the scanner.

As the beam penetrates the surface of the resin, an instantaneous solidification takes place. Depending on the reactivity and transparency of the resin, the layer thickness can be adjusted by the laser power and by its traveling speed.

After solidification of one layer, the build platform, including the partially finished part, is lowered by the amount of one layer thickness. A new layer of resin is applied. This is called recoating. Because of the low resin viscosity, the recoating procedure needs to be supported by vipers and vacuum depositing devices. The new layer is then solidified according to its contour. The process continues from the bottom to the top until the part is finished.

The process requires supports (Fig. 2.5, right), which limits the possible orientation of the part in the build chamber, because after removal the supports leave tiny spots on the surface. For this reason the orientation should be chosen carefully. Because of the supports the parts cannot be nested to increase the packing density and the productivity accordingly.

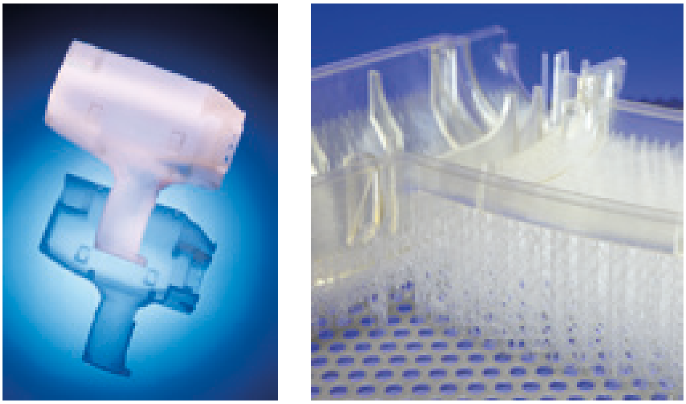


**FIGURE 2.5** Laser stereolithography; thin-walled shell type parts (left), part with supports on the build platform (right) (Source: CP-GmbH)

After the build, the part is cleaned and finally fully post-cured in a UV chamber (post-curing oven). This process step is an integral part of the AM process and called "post processing".

The parts can be sanded, polished, and varnished if necessary. These process steps are called "finishing". Finishing is a process-independent step and not a part of the AM process. It depends only on the user requirements for the parts and possible restrictions regarding its application.

The available materials are unfilled and filled epoxy and acrylic resins. Unfilled materials show a comparably poor stability and heat deflection temperature. This can be improved by adding micro spheres or rice-grain shaped geometric objects made from glass, carbon, or aluminum. Today, these filled materials contain nano-particles made from carbon or ceramics.

Typical parts are concept models as can be seen in Fig. 3.13 (left) or thin walled shell-type geometries such as drill housings or hair dryers (Fig. 2.5, left).

### 2.1.1.2 Polymer Printing and –Jetting

If the curable build material is applied by print heads, the process is called polymer printing or polymer jetting. The process is commercialized by Objet, Rehovot, Israel. It can be regarded as a 3D printing process; however, due to the part building by UV curing of liquid monomers it is a polymerization or stereolithography process.

The machine design very much resembles a 2D office printer (Fig. 2.6, left). The build material is directly applied to the build platform through a multi-nozzle piezo-electric print head. The solidification is done simultaneously by a twin light curtain. It is created by two synchronously traveling high performance UV lamps. The layer thickness is only 0.016 mm, which creates very smooth surfaces. Adjacent layers are processed by moving the platform in the z-direction. The process continues layer by layer until the part is finished.

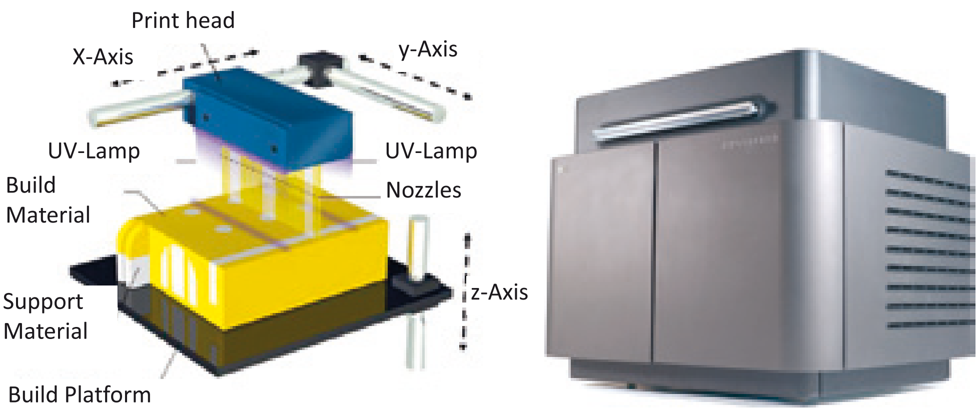



**FIGURE 2.6** Polymer jetting (PolyJet, Objet), scheme (left), two material machine Connex 500 (right) (Source: Objet Geometries)

The parts need supports during the build process. The supports are generated automatically and build simultaneously by a second set of nozzles so that each layer consists either of build or of support material. Consequently, the supports are solid and consume a large amount of material. The support material can be washed out without leaving marks in a mostly automated post process. A typical part can be seen in Fig. 2.7, left.

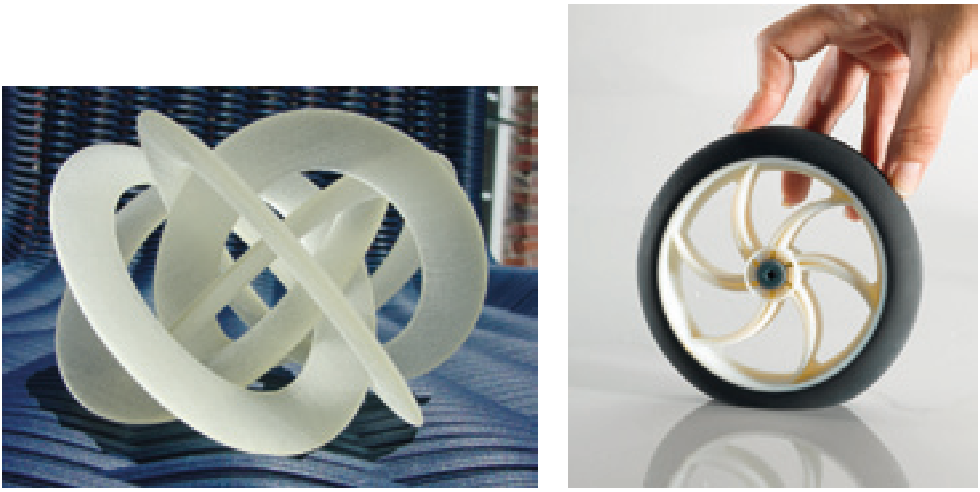


**FIGURE 2.7** Polymer jetting (PolyJet, Objet); structure (left); two-material wheel with elastic tire (right) (Source: RP Lab, Aachen University of Applied Sciences, Objet Geometries)

The process uses photosensitive monomers to create plastic parts. Materials are available in different colors and shore hardness. Using a proprietary technology called "Poly-Jet Matrix" together with a family of fabricators called "Connex", parts can be made from two different materials that resemble two component injection molded parts (Fig. 2.7, right). This opens up the future possibility of composing multi-material parts. Typical parts are thin walled and detailed and show interior hollow structures.

#### 2.1.1.3 Digital Light Processing

This variation of the photo polymerization process works with a commercial DLP projector as UV light source. It projects the complete contour of a cross-section of the actual layer and initiates the solidification simultaneously. The process is commercialized under the name "Perfectory" by Envisiontec, Gladbeck, Germany.

The projector is mounted into the lower part of the machine body. The resin is kept in a reservoir made from glass sitting on the top of the projection unit. The actual cross section is projected from below on the lower surface of the resin. An upside-down arranged build platform (Fig. 2.8) dips into the resin from the top, leaving the space of one layer thickness between the transparent bottom and itself. After solidification of the layer, the platform is raised by the amount of one layer thickness, making space for the material of the subsequent layer. Due to the small reservoir, the process is designed for small parts. It allows quick material changes and the build needs supports.

A wide variety of photosensitive plastic materials are available, including biocompatible grades that can be used to make hearing aid housings or masters for dental prostheses.

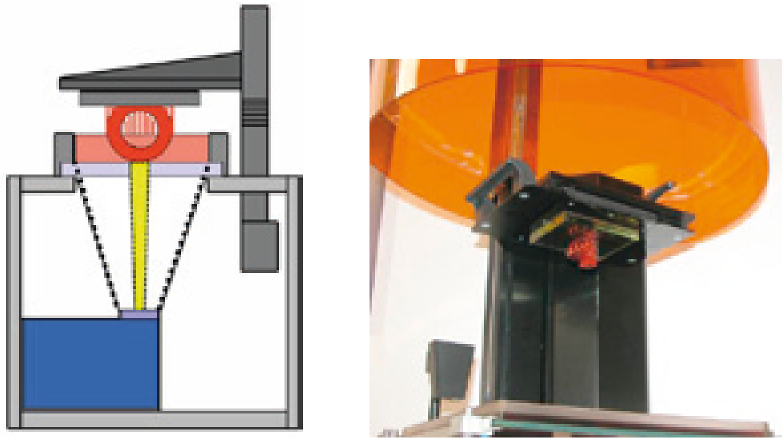
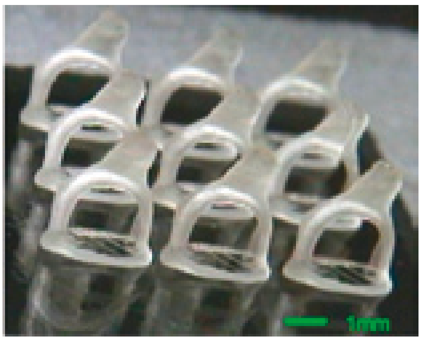
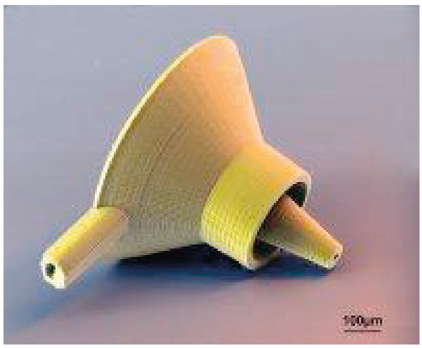


**FIGURE 2.8** Digital light processing, Perfectory, Envisiontec. Scheme, cross-section and reservoir with glass bottom that represents the projection area (left), upside-down arranged build platform (with part) (Source: Gebhardt, Envisiontec)

### 2.1.1.4 Micro Stereolithography

There is a wide variety of processes to make parts in the micro-millimeter and even in the sub-micro-millimeter range (Fig. 2.9). Many of them are still under scientific



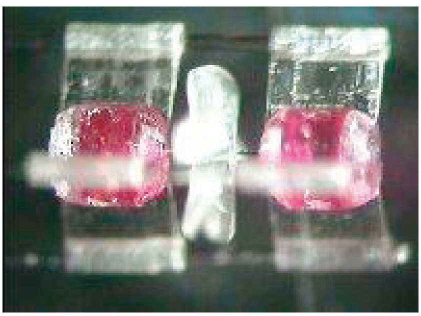



**FIGURE 2.9** Micro-stereolithography, parts and MEMS (Source: microTEC)

development. Industrially applicable processes use laser stereolithography and mask-based systems, preferably for mass production of final micro parts. Especially if the build is offered as a service, proprietary materials are available. A commercial company that is specialized on customized materials and applications even in large series and which does not sell the machine is microTEC of Duisburg, Germany.

## 2.1.2 Sintering and Melting

The selective melting and re-solidification of thermoplastic powders is called *laser sintering* (also, depending on the manufacturer: *selective laser sintering*), *laser fusing* or *laser melting*. If an electron beam is used instead of a laser the process is called *electron beam melting* (EBM), and if the energy is provided by a radiator through a mask, it is called *selective mask sintering*.

Sintering processes in general do require neither bases to build the parts on nor supports to link the parts to the bases, because the loose powder surrounds and stabilizes the part during the build. While this is true for plastic processes, metal parts are an exception. They use bases and consequently supports as well, mainly to prevent the parts from warping during the build process.

### 2.1.2.1 Laser Sintering – Selective Laser Sintering (LS – SLS)

The term laser sintering or selective laser sintering is used preferably for machines that process plastics. They are commercialized by 3D Systems, Rock Hill, SC, USA and EOS GmbH, Munich, Germany.

The machines of both manufacturers, as well as the machine that processes metals are very similar. They consist of a build chamber to be filled with powder with a grain size of up to 50 μm and a laser scanner unit on top that generates the x-y contour. The bottom of the build chamber is designed as a movable piston that can be adjusted at any z-level (Fig. 2.10). The top of the powder bed defines the build area in which the actual layer is built. The whole build chamber is preheated to minimize laser power and completely flooded by shielding gas to prevent oxidation (a laser sintering machine can be seen in Fig. 2.3, right).

The laser beam contours each layer. The contour data are obtained from the slice data of each layer and directed by the scanner. Where the beam touches the surface, the powder particles are locally molten. The geometry of the melting spot is defined by the laser beam diameter and the traveling speed. While the beam travels further, the molten material solidifies by thermal conductivity into the surrounding powder. Finally, a solid layer is achieved.

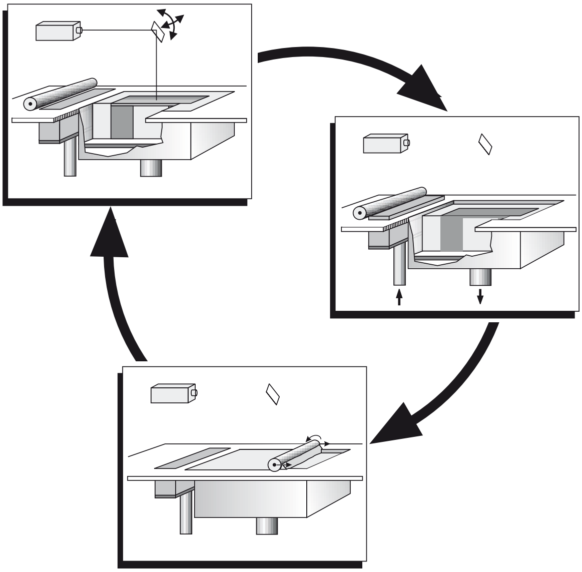


**FIGURE 2.10** Laser sintering and laser melting, scheme; melting and solidification of a single layer, lowering of the platform, recoating (clockwise from top left)

After solidification of one layer, the piston at the bottom is lowered by the amount of one layer thickness, thus lowering the whole powder cake including the semi-finished part. The emerging space on the top of the powder is filled with new powder taken from the adjacent powder feed chamber using a roller. The roller rotates counter-clock wise to its linear movement in order to spread the powder uniformly. This procedure is called recoating.

After recoating, the build process starts again and processes the next layer. The whole process continues layer by layer until the part is completed. In most cases, the top layer is made using a different scan strategy in order to improve its solidity.

After the build is finished and the top layer is processed, the whole part, including the surrounding powder, is covered by some layers of powder. This so-called powder cake has to be cooled down before the part can be taken off by removing the part from the surrounding powder. The cool-down can be done in the machine; however cooling down in a separate chamber allows immediate beginning of a new build job.

Sintering allows the processing of all classes of materials: plastics, metals, and ceramics. The machines are basically very similar. They are either adapted to the different materials by software (and maybe minor hardware changes) or special versions of a basic machine design are adapted to process a specific class of materials. In this case, the recoating systems are specially designed for the materials to be processed; e.g., roller-based systems for plastic powders and hopper-type systems for plastic coated foundry sand. For metal processes wiper-type systems are used as well.

While the standard plastic material is a polyamide of the PA11 or PA12 type, today's cutting edge materials mimic the properties of PC, ABS, PA (6.6) plastics and deliver parts that show engineering design elements, such as film-hinges and snap-fits. Although the high temperature system EOS 395 (2011) is currently the only commercial system that processes even high performance plastics (PEEK,) it marks a future trend.

Materials for laser sintering are available unfilled or filled with spherical or egg-shaped glass, aluminum, or carbon particles in order to improve the stability and heat deflection temperature. Even flame-retarding materials are available.

The extraction of the part from the powder (the so called "break out") is typically done manually by brushing and low pressure sand blasting. Semi automatic, so-called "break out" stations facilitate the work and mark the trend to automated cleaning. Metal parts require the mechanical removal from the base and of the supports from the part which is time consuming and requires manual skills.

Plastic parts are often porous and need to be infiltrated. If required, they can be varnished and surface treated. Typically, metal parts are dense. They can be processed depending on the material, e.g., by cutting or welding.

Sintered parts made from plastic show properties close to plastic injection molded parts. They are either used as prototypes (Fig. 2.11, left) or as (direct manufactured) final parts (Fig. 2.11, right).

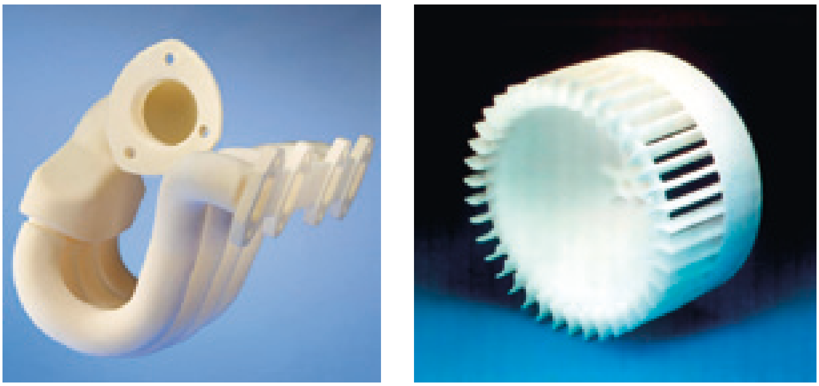


**FIGURE 2.11** Selective laser sintering, SLS (3D Systems), polyamide; exhaust gas device, prototype (left); fan, final product (right) (Source: CP-GmbH)

### 2.1.2.2 Laser Melting – Selective Laser Melting (SLM)

Laser melting basically is a laser sintering process as described earlier. It was developed in particular to process metal parts that need to be very (> 99%) dense. The laser melts the material completely. Therefore, it produces a local (selective) melt pool that results in a fully dense part after re-solidification. The process is generally called selective laser melting, SLM. There are some proprietary names as well such as "CUSING", which is an acronym of "cladding" and "fusing".

Today, most of the machines come from Germany: EOS-GmbH of Munich, Realizer-GmbH of Borchen, Concept Laser GmbH of Lichtenfels, and SLM-Solutions of Lübeck. In addition, 3D Systems, Rock Hill, SC, USA offers a re-branded system based on MTT machines, the predecessor of SLM Solutions. MTT, UK, now separated from its German branch, continues to design its own machine.

For almost all metal machines a wide variety of metals, including carbon steel, stainless steel, CoCr, titanium, aluminum, gold and proprietary alloys are available. Typically, metal parts are final parts and used as (direct manufactured) products or components of such products. Typical examples are the internally cooled cooling pin inserts for injection molds made from tooling steel in Fig. 2.12, left, and the micro cooler made from AlSi10Mg in Fig. 2.12, right.

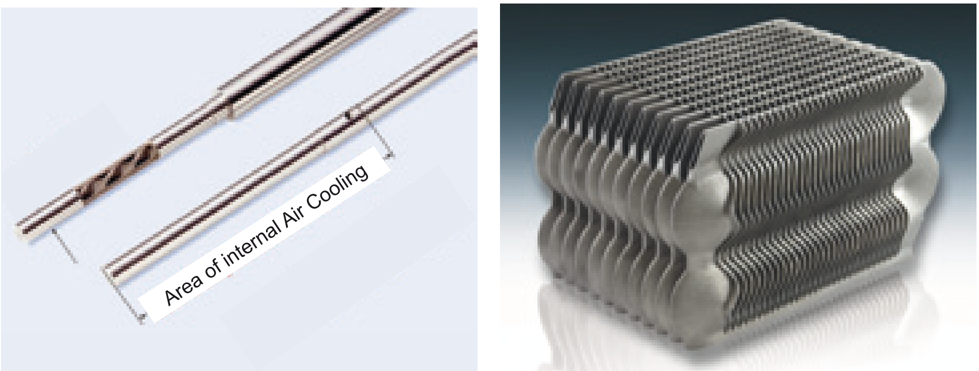



**FIGURE 2.12** Selective laser melting, SLM.
*Internally cooled* pin for injection molds, left (Source: Concept Laser GmbH); micro cooler made from AlSi10Mg (Source: EOS GmbH)

The machine designs are very similar to the plastic laser sintering machines. They use fiber lasers with a very good beam quality as well as sealed build chambers that can be evacuated or fed with shielding gas in order to handle inflammable materials such as titanium or magnesium. Build-in auxiliary heating devices help to prevent warping and distortion of the part.

Metal and ceramic micro sintering machines are close to market entry but still under development. Commercialization has been announced by EOS based on the machine development of 3D Micromac, Chemnitz, Germany. The typical layer thickness is in the range of 1–5 µm and the smallest wall thickness is > 30 µm. A fiber laser with a focus diameter < 20 µm is used. As an example, a chess set is shown on Fig. 2.13. The tower's height is about 5.5 mm.

**FIGURE 2.13** Micro laser sintering (EOS), demonstrator chess set (Source: EOS GmbH)

### 2.1.2.3 Electron Beam Melting

The local melting of the material can be achieved by an electron beam that replaces the laser. The procedure is then called *electron beam melting*, EBM. Because electron beam material processing requires a vacuum, a completely sealed construction is needed.

Arcam AB of Mölndal, Sweden presents a family of EBM machines dedicated to special applications, such as aerospace, medical, or tooling (Fig. 2.14).

The electron beam penetrates very deep and the set up allows a very high scan speed that can be used for preheating as well, therefore the process is very fast and works at elevated temperatures. As a result, stress and distortion are reduced and very good material properties can be achieved, according to the company.

As an example, Fig. 3.35, right, shows an individual scull implant made from titanium by EDM.

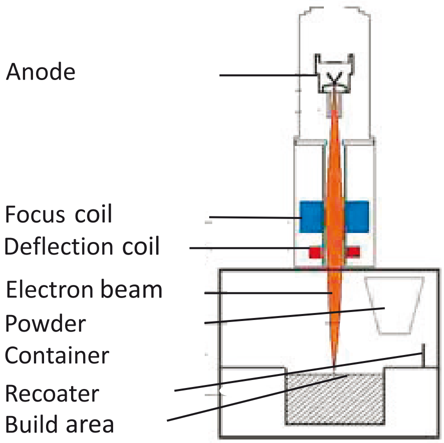



**FIGURE 2.14** Electron beam melting, EBM. ARCAM.
EBM System A2, left; EBM scheme, right (Source: ARCAM)

### 2.1.3 Extrusion – Fused Layer Modeling

The layer-by-layer deposition of pasty strings is called *fused layer modeling*. The process works with prefabricated thermoplastic material. Colored parts are obtained when colored material is used. Technically, FLM is an extrusion process, see Fig. 2.15. The parts need support during the build.

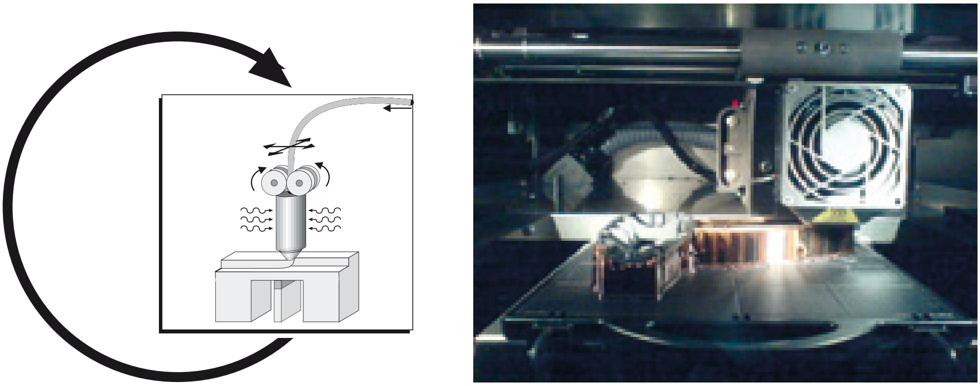


**FIGURE 2.15** Fused layer modeling extrusion process, scheme (left); build chamber with build platform, part in progress, print head (right)

Many of the so-called fabbers (Section 1.4) work with a simplified extrusion process, some of them even without the possibility of using supports. The most popular ones are the BFB 3000, Fabber 1, RapMan, and RapRaP. This section of the industry is growing rapidly.

#### Fused Deposition Modeling (FDM)

FDM is a registered, protected trade name for a fused layer process offered by Stratasys Company, Eden Prairie, MN, USA. Because it was the first commercialized FLM process worldwide, the name FDM is often used synonymously with FLM even as a generic name.

A FDM machine consists of a heated (app. 80 °C for ABS plastic processing) build chamber equipped with an extrusion head and a build platform. Consequently, the machine does not use a laser. The extrusion head provides the material deposition in the x-y area according to the contour of the actual layer. It is a plotter-type device.

The build material is a prefabricated filament that is wound up and stored in a cartridge from which it is continuously fed to the extrusion head. The cartridge has a build-in sensor that communicates with the material management system of the machine. In the head, the material it is partly molten by an electric heating system and extruded through a nozzle that defines the string diameter that nearly equals the layer thickness.

Usually, string diameters range from 0.1 mm to 0.25 mm. The platform moves in z-direction and defines the layer thickness, as the material is squeezed on the top of the partly finished part. The process needs supports. They are made by a second nozzle that extrudes another plastic support material simultaneously with the build material.

The simultaneous processing of two materials indicates that the FLM process is basically capable of handling multi-material print heads. Therefore, the manufacture of multi-material parts can be expected in the future.

After deposition, the pasty string (of the build material as well as of the support material) solidifies by heat transfer into the preceding layer and forms a solid layer. Then the platform is lowered by the amount of one layer thickness and the next layer is deposited. The process repeats until the part is completed.

There are a wide variety of machines that follow the principle of the FDM process. The machines range from the personal printer µPrint (starting at € 11,900; status 2011) and the almost double priced Dimension office printers to the high-end Fortus Production Systems brand, including the Fortus 900mc that offers the largest build space (914 × 610 × 914 mm) currently available.

There are many plastic materials available for FDM processes, including engineering materials such as ABS, PC-ABS, and specialty grades for medical modeling. Some machines are restricted to only a limited number of different materials. There is a big variety of colors available, amongst it even translucent, black, and white qualities. Because the color is linked to the filament, it cannot be changed during the build process (Fig. 2.16, left).

The Fortus 400 and 900 machines process the high temperature thermoplastic material polyphenylsulfone (PPSF/PPSU). They were the first machines on the market to handle these high performance plastics.

**FIGURE 2.16** Fused deposition modeling. Epicyclic gear set assembled from monochromatic FDM parts, made from ABS plastic (left); part with support as manufactured (center); part after removal of the supports and manual polishing (right) (Source: RP-Lab, FH Aachen University of Applied Science (2), Stratasys (1 left))

Typical part properties resemble those of plastic injection molded parts; however, they tend to show anisotropic behavior that can be reduced by properly adjusted build parameters. The parts are either used as concept models, functional prototypes, or as (direct manufactured) final parts.

FDM parts show typical surface textures that result from the extrusion process (Fig. 2.16, center). According to the layer thickness and the orientation of the part in the build chamber, these textures are more or less visible. Therefore, the positioning (orientation) in the build chamber has a big influence on the appearance of the part.

Post processing requires the removal of the supports, which can be done manually, or using a special washing device. Finishing requires manual skills and time; but together with artisan capabilities leads to perfect surface qualities and astonishing results (Fig. 2.16, right). It is needless to say that intensive finishing affects the part's accuracy.

### 2.1.4 Powder-Binder Bonding – Three Dimensional Printing (Drop on Powder Processes)

The layer-by-layer bonding of powder particles in the range of 50 µm by selectively injecting a liquid binder into the top area of a powder bed is called "Three Dimensional Printing – 3DP". The process family is also called "Drop on Powder Processes". The process was developed and registered by MIT[1] in the early 1990s and licensed to Z-Corporation and others who commercialized it. Today, variations processing plastics, metals, or ceramics are commercially available. Most of them are two-step processes, requiring infiltration after the build. Some, especially metal processes, deliver a sort of green part that has to undergo thermal de-binding and sintering to achieve their final properties. As there are binders imaginable for any powder, the range of materials is almost infinite, including food and drug applications; however, only a small fraction is currently commercialized.

"Three Dimensional Printing" or more frequently "3D Printing" became a synonym for all AM processes in general, thus being used as a generic term, because 3D printing resembles two-dimensional printing and therefore provides a very simple way to explain what AM is about. But the use of two identical terms with different meanings sometimes causes confusion. Therefore, especially beginners should avoid to mix the two meanings of this term.

[1] Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

#### 2.1.4.1 Three Dimensional Printing – Z-Corporation

The commercialized machines made by Z-Corporation, Burlington, MA, USA, work exactly according to the basic process. The process delivers a kind of green part that is dimensionally stable but needs infiltration to achieve solidity. The part remains in the powder bed until the build process is finished. It is stabilized by the surrounding powder and therefore does not require supports. As the binder can be colored, the parts can be colored as well. The company offers a family of 3D printers, most of which are capable of producing colored parts.

The lower part of the machine contains the build chamber and carries the powder. It is designed very much alike a laser sintering machine with a movable piston to adjust the layer and a roller for recoating. A plotter device with a commercial print head, as known from a 2-D office printer, is mounted on top of it. It travels over the build area and prints the binder onto the powder according to the actual contour. The particles forming the layer are bound, while the loose powder supports the part. In contrast to sintering, the process requires neither preheating nor shielding gas.

After solidification of one layer, the bottom piston is lowered by the amount of one layer thickness, thus lowering the whole powder cake including the semi-finished part. The emerging space on the top of the powder is filled with new powder taken from the adjacent powder feed chamber using a blade or a roller (recoating).

Today, starch-like powder and plaster-ceramic qualities are available to make parts and even shells for investment casting. As the binder can be colored, continuously colored parts can be made in the same way colored pictures are printed in 2D. The coloring even of texture-like designs is a unique selling point of this process.

After the top layer is processed the build is finished. Because this process works at room temperature, the powder cake shows room temperature and can be directly taken from the machine. The loose powder is removed by gently brushing and low pressure air blasting.

Finally, the part needs infiltration to obtain durability. For this, wax or epoxy resin is used. As a result, the durability of the parts depends not only on the material but on the quality of the infiltration as well. Therefore, 3DP parts should not be used for structural testing.

Typical parts are concept models. They can be monochromatic or continuously colored (Fig. 2.17, top left and right). Z-printers are office friendly and easy to handle (Fig. 2.17, bottom).

The surface quality is rough compared to polymerization processes (Fig. 2.18, left) but can be improved significantly by manual post processing (Fig. 2.18, right).

**FIGURE 2.17** 3D printing. Powder-binder-process; colored parts (top left and right) (Source: RP-Lab, FH Aachen University of Applied Sciences); machine ZPrinter 450 (bottom) (Source: Z-Corporation)

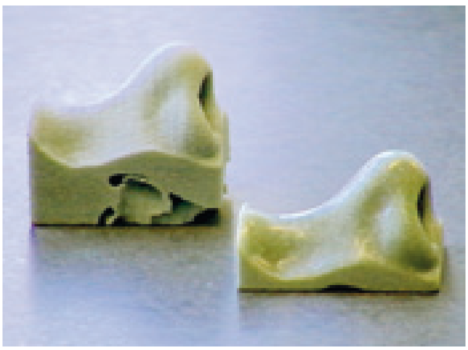


**FIGURE 2.18** 3D printing. Powder-binder-process; improved surface quality by manual finishing; part as from the machine (left) and after finishing (right) (Source: RP-Lab, FH Aachen University of Applied Sciences)

### 2.1.4.2 Three Dimensional Printing – Prometal

A variation of the basic process was licensed to the Ex-One LLC's Prometal Division, Irwin, PA, USA, that commercialized a metal printing and a sand-printing machine based on this principle.

The metal printing process makes metal and metal-ceramic parts by binding the powders via micro droplets. The process, run on a machine called R1, resembles the basic process, but uses a different recoating and leveling system and an additional heater to assure an even consistency of the powder bed and the part. A subsequent thermal process provides the part's strength and durability. Using this process, metal parts are made to customer requirements, amongst others by the 3dmetaltec company and by the artist Bathsheba. The California based artist uses the process to manufacture her 3D objects that cannot be machined (see Fig. 3.23). Their special appearance is created by a proprietary surface treatment. Figure 3.23 displays the surface quality before (left) and after (right) finishing and post processing. An example for industrial parts can bee seen in Fig. 3.11.

The sand-printing machine, commercialized as S-print by Prometal RTC, is part of a family of machines designed to produce complex cores from foundry sand. The reproducible manufacturing of complex cores increases the productivity of sand casting not just for prototype and test casting but also for production. The big machine is capable to feed a production line and must be regarded as a foundry machine. In Fig. 2.19, left, the S-print is displayed and Fig. 2.19, right, shows the actual top layer of the part during printing. The gantry that covers the print head can be seen partially on the very left.

**FIGURE 2.19** 3D printing. Prometal foundry sand printer S-print (left); build chamber with print head-gantry at the very left and build area (right) (Source: Ex-One LLC)

### 2.1.4.3 Three Dimensional Printing – Voxeljet

A plastic printing process based on the 3D printing principle was developed by Voxeljet technology GmbH, Friedberg, Germany. The company offers a family of printers, including the VX500 (build volume 500 × 400 × 300 mm) and VX800 (build volume 850 × 450 × 500 mm, Fig. 2.20, left). The standard layer thickness is 0.150 mm and ranges down to 0.080 mm /VX500/. The main element is the high performance multi-nozzle print head with 768 nozzles mounted in six simultaneously operating print modules.

A concept machine (VX4000) covers a very big build space (4 × 2 × 1 m), allowing to either make a big part or a series of small parts in one build. Almost all exceeding powder can be re-used after the build. The machine, working with PMMA plastics and a suitable solvent-type binder, directly makes plastic parts. They can be used as functional prototypes but also provide very good lost masters for precision casting because of a low amount of residual ashes (Fig. 2.20, right).

**FIGURE 2.20** 3D printing.
Voxeljet VX800 plastic printer (left), art object "knot" by Josh Harker, finished casting based on a printed master
(Source: Voxeljet, www.joshharker.com)

## 2.1.5 Layer Laminate Manufacturing (LLM)

The cutting of contours out of prefabricated foils or sheets of even layer thickness according to the sliced 3D CAD file and the subsequent bonding on the top of the preceding layer is called *layer laminate manufacturing*, LLM.

The foils or sheets can be made of paper, plastics, metal, or ceramics. A laser, a knife, or a milling machine can be used as a cutting device. The bonding of adjacent layers is done by glue, ultrasonic, soldering, or diffusion welding. Most of the processes just need one production step; a few require a post treatment such as sintering in a furnace.

The overall advantage of LLM processes is the fast build when massive parts are requested. The disadvantage is a huge amount of waste, depending on the geometry of the part.

### 2.1.5.1 Layer Laminate Manufacturing, Laminated Object Manufacturing (LOM)

The oldest and widely known AM LLM-process is the *laminated object manufacturing* (LOM). It was originally developed by Helisys, USA, which is now Cubic Technologies, Torrance, CA. This machine as well as a similar one, which was developed later by Kinergy, Singapore, is no longer produced. But there are a lot of these machines in the market and the company provides service, maintenance, and contract manufacturing. The build material is coiled paper of approximately 0.2 mm thickness. On its down face it is coated with glue which is activated by heat during the recoating process.

The machine consists of a build table that can be moved in z-direction and a mechanism to uncoil the paper, position it on the build table, and wind up the remaining paper on the opposite side. A laser does the cutting of the contour.

To build a part, the paper is positioned on the build table and fixed by a heated roller that activates the glue. The contour is cut by a plotter-type laser device that allows adjusting the cutting depth according to the paper thickness. Another frame-like laser cut defines the boundaries of the part. It leaves two paper stripes on each side of the part that enables the exceeding paper to be lifted and wound up by the second coil (Fig. 2.21). The material that fills the space between the contour and the frame remains within the part and supports it. It is cut into squares for easy removal of the waste material.

After the build process is finished, the block of paper, including the part and the support material is removed from the build platform. The frame and the squares that result in small blocks are removed and finally the part is obtained. The parts need varnishing to prevent de-lamination of the layers. Gear housings, which are typical parts, can be seen in Fig. 2.22.

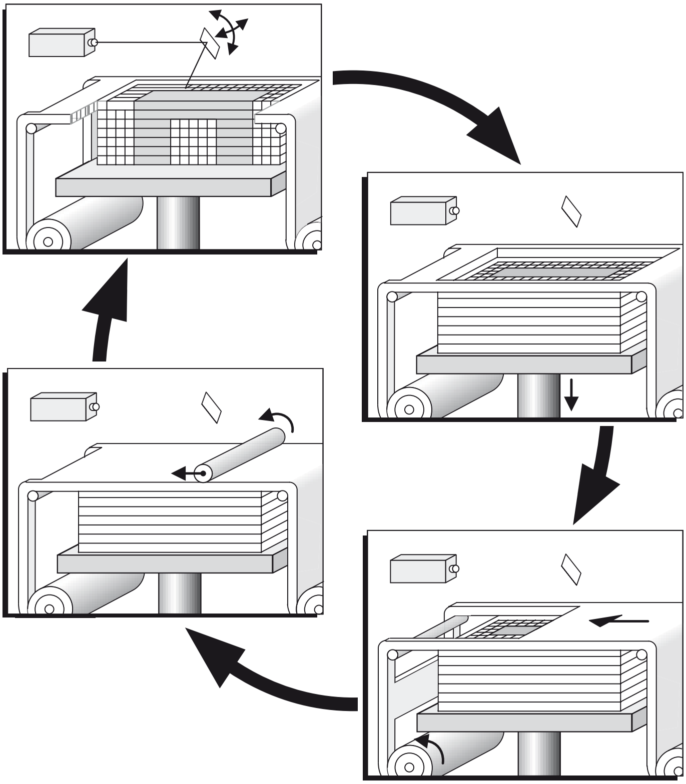


FIGURE 2.21 Layer laminate manufacturing, laminated object manufacturing (LOM); scheme

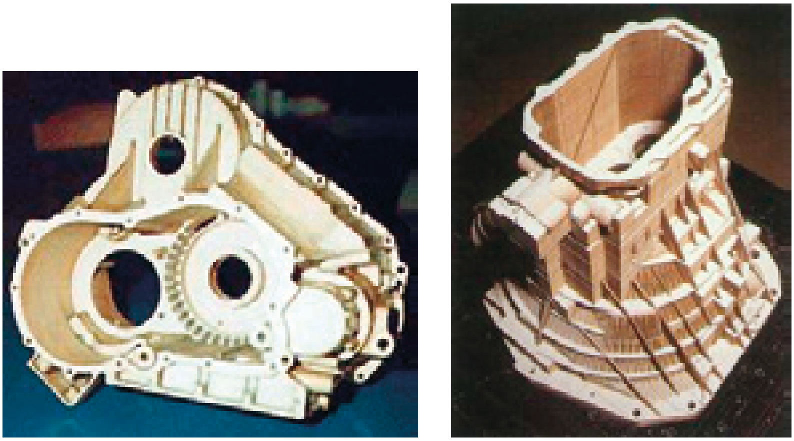


FIGURE 2.22 Layer laminate manufacturing, paper lamination, gear housings (LOM)

### 2.1.5.2 Layer Laminate Manufacturing, Paper Lamination, MCOR Matrix

A variation of the paper lamination process was commercialized by Mcor Technologies, Ardee, Ireland. The contour is cut with a tungsten carbide drag blade instead of a laser. The process is based on loose sheets of office paper (A4, 80 gsm) that is glued using standard white polyvinyl acetate (PVA) glue. As this glue tends to blister the paper, a special coating system based on micro drops was designed to overcome this problem. The drop density is lower in the area that does not belong to the part, which enables easy cleaning. The machine, called Matrix 300, works fast and delivers cheap models with a layer thickness of approx. 0.1 mm (Fig. 2.23, left). The parts can be colored if colored paper is used. To obtain the colored structure of the part, the paper must be filed manually in the right sequence (Fig. 2.23, right).

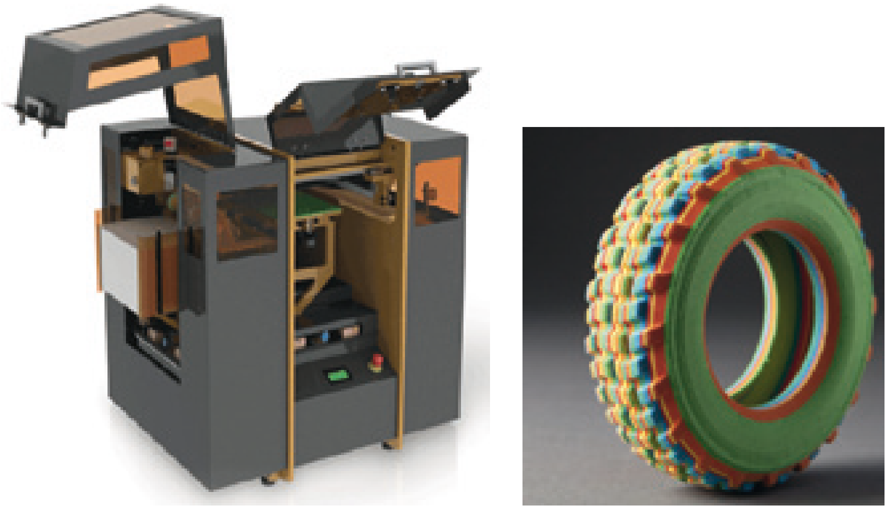


**FIGURE 2.23** Layer laminate manufacturing; paper lamination; MCOR Matrix 300 machine (left), colored part made from paper, right (Source: MCOR Technologies)

### 2.1.5.3 Layer Laminate Manufacturing, Plastic Laminate Printers

Although the term "laminate" is not dedicated to a special material, AM machines that work with PVC based plastic foils are called *laminate printers*. Originally developed and produced by Solidimension and shipped as SD300, identical machines as well as upgraded machines entered the market as Graphtec XD700 and Solido SD 300pro.

During the build, the contour of each layer is defined by a masking fluid and glue. Then the next layer is applied and fixed by the glue and the contour is cut using a build-in cutting plotter, see Fig. 2.24, left. Finally, a rigid plastic part surrounded by frame-like waste is obtained. The frames of each layer are alternating linked to the opposite edges of the preceding ones by glue as well. This allows easy peeling off of the resulting

**FIGURE 2.24** Layer laminate manufacturing; plastic laminate printers; machine (left); fan wheel made by the laminate Printer Solido SD 300 pro, PVC (right) (Source: Solido)

accordion-like waste structure. The rigid plastic parts perform very well, if their geometry meets the process requirements. As a typical part, a fan wheel can be seen in Fig. 2.24, right. Complex parts with interior hollow elements may cause problems.

### 2.1.5.4 LLM Machines for Metal Parts

Most of the approaches to make metal parts use cutting and joining of sheet metals. The contours are either obtained from laser cutting or from milling. The sheets are joined by diffusion welding, powder welding, soldering, or mechanically by bolts. This kind of a semi-automated multi-step process is not a real AM process, although they are additive and layer oriented

#### 2.1.5.4.1 Ultrasonic Consolidation – Solidica

One of the rare real AM LLM machines is made by Solidica, MI, USA. The process is called *ultrasonic consolidation*. It is based on a traditional milling machine with an integrated ultrasonic (US) welding device that joins thin aluminum strips on top of the semi-finished part. After one layer is applied, its contour is milled and the next layer is joined, again by US. The process delivers completely dense aluminum parts that may contain integrated sensors that are placed into cavities made and sealed during the process. Further development enables the process not only to manufacture different materials including titanium, steel, copper, and nickel but also to realize combinations such as the Ti-Al structure shown in Fig. 2.25. As a result, Gradient-Modulus[2] Energy Absorbing Material (GMEAM) can be manufactured, that shows a tremendous improvement in impact resistance.

[2] Generally called „Graded Materials" (from: gradient modulus), this material shows a defined variation of its properties within the parts made from it.

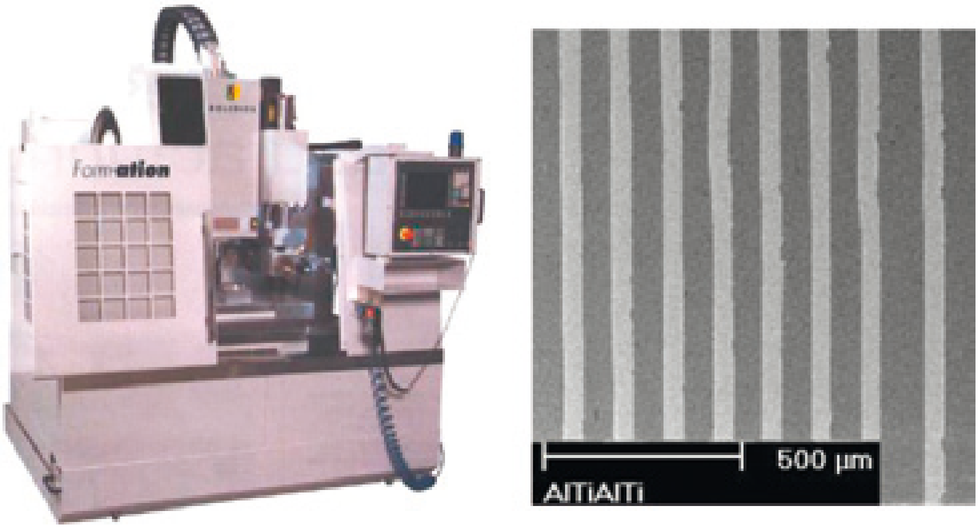



**FIGURE 2.25** Ultrasonic consolidation. UC-machine formation, left; Ti-Al high energy absorbing structure, right (Source: Solidica)

## 2.1.6 Other Processes: Aerosolprinting and Bioplotter

### 2.1.6.1 Aerosolprinting

A very interesting process with a high potential is called *aerosolprinting*. It was developed and launched as Maskles Mesoscale Materials Deposition (M3D) by Optomec, NM, USA.

A stream of very fine droplets (aerolsols) is generated, loaded with ultra fine particles with diameters in the nm range, and guided to the surface of a substrate (Fig. 2.26). Here, the aerosols are deposited according to a CAD designed pattern. The liquid phase is vaporized, leaving the particles in place. The particles may consist of any kind of functional inks, metals, ceramics, plastics, or even living cells. Depending on the kind of material, a post treatment by laser may be needed. Aerosolprinting is a very promising process for electronic devices as well as for tissue engineering.

As it is currently suitable only for 2½ D surface texturing and objects (at least now) and not for real 3D parts, some do not regard it a real AM process.

### 2.1.6.2 Bioplotter

As already indicated during the introduction of the Objet polymer jetting machine (Section 2.1.1.2.) and the Optomec M3D machine (Fig. 2.26), one of the most unique selling points of AM will be multi-material processing. The 3D Bioplotter, which is a registered trademark of Envisiontec, Marl, Germany, allows to process a wide variety of materials from plastics, such as polyurethane or silicone, to bone materials such as hydroxyapatite, and drugs such as PCL (polycaprolactone[3]) or materials such as collagen or fibrin for organ printing or soft tissue fabrication. Up to five materials can be processed using either a heated or a cooled dispenser unit that is operated by a 3-axis plotter. Depending on the material, the system uses different hardening processes such as precipitation, phase transition (liquid to solid), or two-component reaction. Some materials need post processing such as sintering.

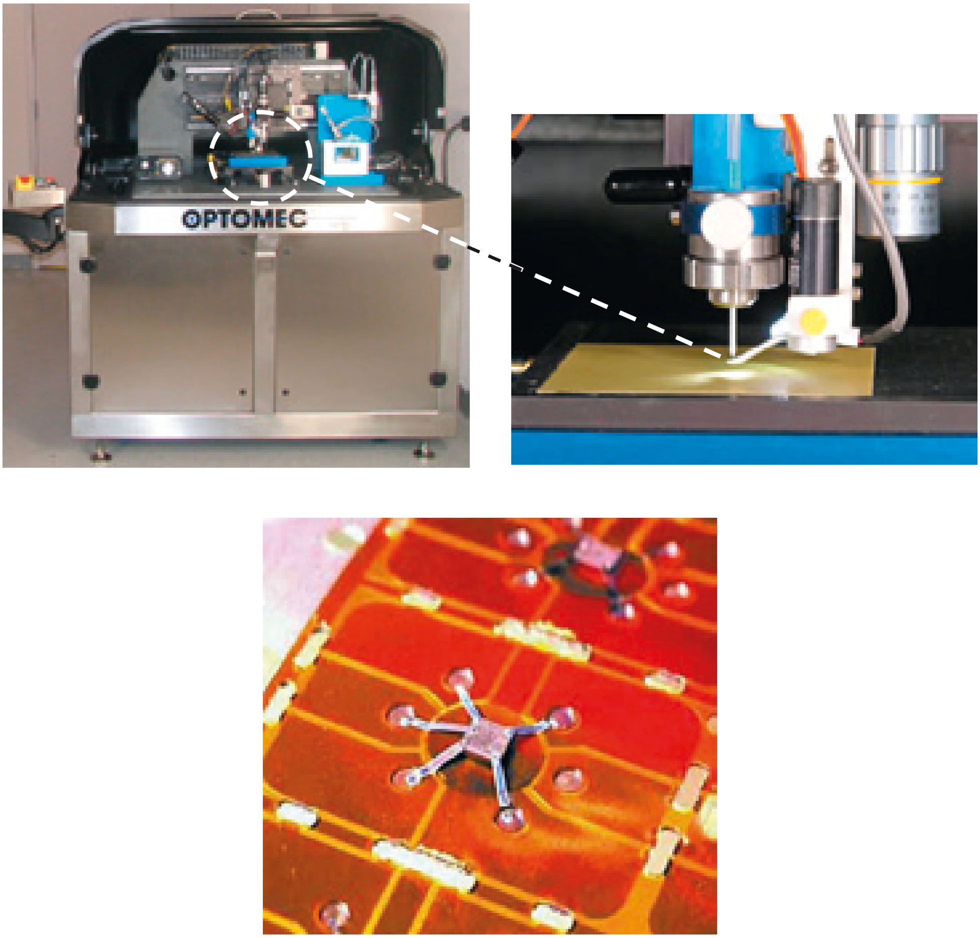



**FIGURE 2.26** Aerosolprinting, Maskles Mesoscale Materials Deposition (M3D); machine and deposition unit (top), surface structure for smart card (right) (Source: Optomec/eppic-faraday)

[3] which is a biodegradable polyester

## 2.2 Machines for Additive Manufacturing – Fabricators, Printers, and more

As already pointed out in Section 1.4, the wide and rapidly growing variety of different machines can be assigned to three classes of layer based or additive manufacturing machines. Details are displayed in Table 1.1, Table 1.2, and Fig. 1.31. Here, we will dedicate the machines already mentioned to the three classes and provide some additional examples of machines. They are assigned to the three categories of AM machines: “fabbers” in Fig. 2.27, “office machines” in Fig. 1.28, and “shop floor machines” in Fig. 2.29. Currently, there are definitely more than 150 machine commercialized, of which only a few were selected.

| | | | |
|---|---|---|---|
| Vflash<br>3D Systems | HP DesignJet<br>HP / Stratasys | SD 300 Pro<br>Solido | Thing-O-Matic 3D Printer<br>Makerbot |
| Plastic<br>Polymerization | Plastic<br>Extrusion | Plastic<br>Layer Lamination | Plastic<br>Extrusion |

**FIGURE 2.27** Layer manufacturing processes: category “fabbers”

| | | | |
|---|---|---|---|
| ProJet HD 3000<br>3D Systems | SST 1200<br>Dimension | Alaris 24<br>Objet | Z Printer 450<br>Z-Corporation |
| Plastic<br>Polymer Printing | Plastic<br>Extrusion | Plastic<br>PoliJet | Starch / Ceramics<br>3D Printing |

**FIGURE 2.28** Layer manufacturing processes: category “office machines”

| | | | |
|---|---|---|---|
| iPro 9000 SLA<br>3D Systems | VX 800<br>Voxeljet | M3 Linear<br>Concept Laser | P 780<br>EOS GmbH |
| Plastic<br>Stereolithography | Plastic<br>3D Printing | Metal<br>Laser Cusing /<br>Laser Melting | Plastic<br>Laser Sintering |

**FIGURE 2.29** Layer manufacturing processes: category "shop floor machines"

## 2.3 Secondary Rapid Prototyping Processes

As pointed out in Section 1.3, parts can be made using a quickly obtained and precise AM master and follow-up procedures such as copying- or secondary rapid prototyping processes in order to make a small series or improved quality parts. The most prominent copying process is vacuum casting, which is also called silicon rubber molding or room temperature vulcanization (RTV). The process is illustrated in Fig. 2.30.

Preparation of the master model, definition of the parting line and positioning within the casting box, casting of the silicon, reaction to solid, opening of the mold, removal of the master, preparation and closing of the mold, positioning of the mold and the material within the vacuum casting device, casting process, opening of the mold and removal of the part, part cleaning and quality control. Different final castings made from the same mold (Source: MTT Technologies)

In combination with AM processes, secondary processes such as RTV are a very valuable tool to quickly manufacture a small series of parts or even a one-of with defined properties.

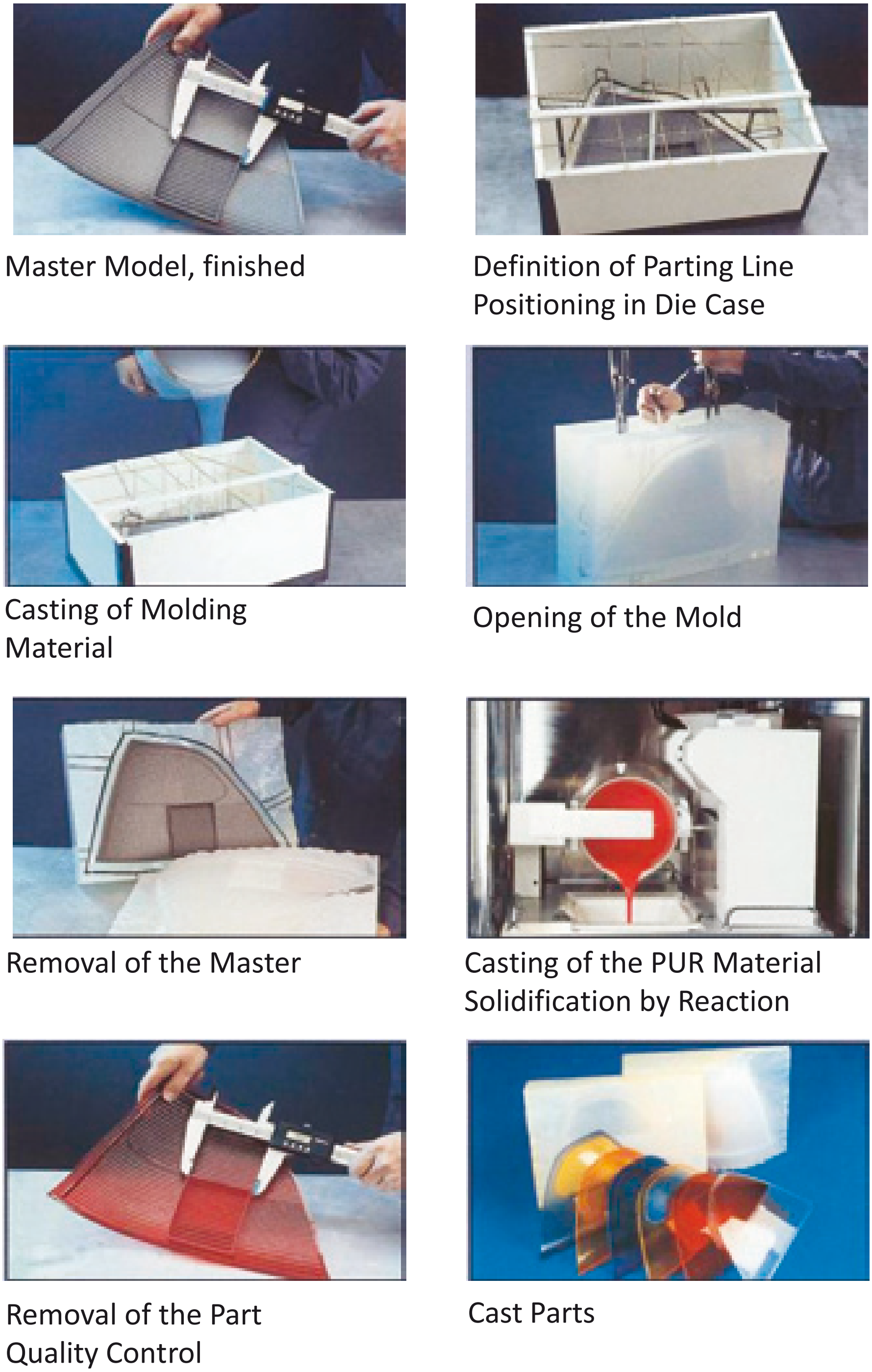



**FIGURE 2.30** Secondary rapid prototyping processes: room temperature vulcanization (RTV)

## 2.4 Conclusions and Perspective

AM is a new and outstanding fabrication technology with unique features. AM machines and machine related processes are capable to process a wide variety of materials. Besides plastics, metals, and ceramics which can also be processed using subtractive processes such as milling, medical and bio materials including living cells can be turned into products. Materials can be mixed within the process and enable the realization of different properties within the part (graded materials).

But even traditional engineering materials such as polyamides can be processes with almost no geometric limitations. This eliminates many of the restrictions engineering designers have to follow today. There are more than 100 machines currently on the market and the number of new machines, following either the established or emerging processes, is assumed to increase further.

The machines cover all kind of applications and are available as fabbers, office machines, or shop floor machines from various manufactures.

Especially the fabbers mark the beginning of a new AM era. Examples are the Thing-O-Matic 3D Printer by Makerbot (Fig. 2.27) and the BFB 3000 by 3D Systems shown in Fig. 1.31. The extrusion-fused layer modeling FDM µPrint machine mentioned in Section 2.1.3 can also be regarded a fabber. Hewlett-Packard's "HP DesignJet" version (Fig. 2.27) is about to be introduced to the mass-market.

This marks the beginning of a new AM era. In the future, different kinds of fabbers will enable everybody to fabricate solid parts and share it with a huge community worldwide. He or she will be able to create and fabricate his or her own products. The digital revolution has started to go three-dimensional.

## 2.5 Questions

### 1. What is the principle of AM?

The part to be produced has to be represented by a set of 3D CAD data. The data is virtually cut into layers of even layer thickness using a so-called slice algorithm. This provides the contour data and the layer thickness of each layer.

The AM machine transfers the virtual data into real layers and joins each layer with the preceding one. As the layer thickness is constant, the part shows a stair stepping effect on its surface.

### 2. Why do AM parts show stair-stepping effects?

Because the layer thickness is constant and there is only one contour per layer.

### 3. What are the two main steps of every AM process?

Step 1: Generating a single layer with a shape according to the contour and with a given layer thickness both based on the slice data.

Step 2: Joining each new layer on top of the preceding on.

### 4. What is the typical layer thickness of AM parts made of plastics?

Most of the machines process layers in the range of 0.1 mm but there are machines that deliver layers with a thickness of 0.016 mm and machines delivering layers with approximately 0.2 mm thickness.

### 5. Describe the AM process (to be selected)

**Stereolithography**

**Polymer-printing and -Jetting**

**Laser Sintering – Selective LS**

**Laser Melting – Selective LM**

**Laminated Object Manufacturing**

**Fused Deposition Modeling**

**Three Dimensional Printing**

Answer: see text.

### 6. There are two AM processes that deliver colored parts. Name both.

Extrusion, namely fused deposition modeling, FDM and 3D printing (powder-binder process)

7. **How do they differ from each other?**

FDM can process only one color at a time which is provided by the pre-fabricated filiament. 3D printing can process a continuously colored part as it is known from 2-office printers.

8. **Why should a 3D printing part (powder-binder-process) not be taken for structural tests?**

Because the properties of the part are defined by the quality of the infiltration rather than by the build process and the powder-binder material system used.

9. **How do the master models have to be prepared for RTV?**

They have to be polished. Ducts and vents need to be added. The parting line has to be defined.

10. **What processes can be used to join the metal sheets when using LLM for metal parts?**

Diffusion welding, soldering, powder welding, mechanical bolts

# 3 Applications

Chapter 3 will discuss what kind of parts can be obtained using AM and where they can be applied. First, the part's basic application characteristic will be discussed. Do we talk about *rapid prototyping* or *rapid manufacturing*? Is the part a prototype or a final part? Astonishingly it is neither the material nor the machine that determines whether the part is a prototype or a product, but the way in which the requirements of the customer are transformed in engineering design and how it is related to manufacturing. To understand the different approaches, the determining workflow is documented and analyzed.

In the following, the chapter is structured according to application areas or industry branches. The examples underline the fact that there is not a strict linkage between a specific industry branch and one particular AM process. In practice, there are typically a couple of alternatives of applicable AM processes competing with each other. Often, subsequent indirect or secondary AM processes need to be added in order to obtain the desired results.

The selection of examples is neither complete nor exclusive in the sense that it neither shows the optimal nor the only possible solution. As almost every industry is using AM processes, not all specific industries are mentioned. The discussion of the examples in this chapter can be regarded as a phenomenological approach to AM applications. A more systematic approach, regarding the strategies and the unique design aspects that come with AM, are discussed in Chapter 4.

Because the correct data and its proper handling are a precondition for successful application of AM technologies, the chapter starts with this topic.

## 3.1 Data Processing and Application Workflow

A complete and error-free 3D data set is the mandatory prerequisite for AM. Today, in most cases the data are obtained from professional 3D CAD systems. Alternatively, scanners and all kind of digital imaging systems – even for medical applications – are used as well. Most of these systems have to be operated by professionals, mostly by engineering designers. With the increasing use of AM by non-professionals such as private persons or professionals who use AM in addition to their core business as a presenting- or pre-production tool, easy to operate shareware CAD systems and even prefabricated 3D data libraries gain more importance.

Although data acquisition is a precondition for AM, it will remain a separate topic that cannot be discussed in detail in the context of this book. There are just two aspects that are closely related to AM workflow and therefore need to be addressed here: First, it is important to know the standard process chain and data-flow between CAD and AM. Second, knowledge of the application level of the final part and how it depends on the AM workflow and how it interferes with the CAD design.

### 3.1.1 AM Process Chain

According to Fig. 1.2, the precondition for the AM workflow is the creation or acquisition of an error-free 3D data set from the solid type that is also called a virtual product model.

Although the data acquisition is an element of a professional product development process and obtained from 3D CAD, basically it does not matter from which source it is obtained. As mentioned above, scan data or, generally, mesh data from various sources can be used as well.

The interface between the data acquisition and the so called AM front-end marks the entry point of the AM and the according process chain which is displayed in Fig. 3.1.

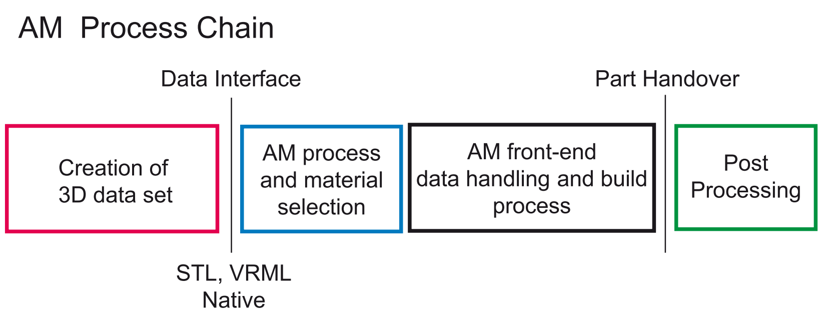



**FIGURE 3.1** AM process chain

Admissible data formats include the native format of the CAD system, some other 3D modeling data structure, such as VRML or the so called STL format which is close to an industry standard. Because this format plays a prominent role, it will be mentioned in detail in the following (Section 3.1.3).

Next, appropriate AM material and AM process have to be selected. Therefore, the customers needs and his AM capabilities have to be taken into consideration. The build parameter setting and machine handling details, such as refill of material, have to be determined for the selected AM process. Because the material influences the build parameters, the front-end data setting is linked to the material selection and database. The communication between operator and machine is supported by icon-based software and easy mouse actions, especially for office machines. The AM- or front end software, often still called *Rapid Prototyping Software* for historical reasons, is either an integrated package that comes with the machine or a third-party software (e.g., from Materialise) that in most cases has a broader range of functions and addresses professionals in particular. Prior to the build, the machine-depending parameters, such as recoating time, are added and the build is started. Once started, the build process runs automatically until the part is finished.

After the part is completed, it undergoes machine specific cool-down processes, if applicable, and then is taken from the machine. In most cases, the build process releases some kind of a green part. Depending on the process (described on Section 3.2 ff), the part needs cleaning, low pressure sand blasting, removal of the supports, post curing, or infiltration. These process steps are part of the entire AM process and are called "post processing". In addition, the parts can be treated by processes such as varnishing or machining. This separate process is called "finishing". It is not an element of the AM process chain.

## 3.1.2 Application Workflow

All AM processes basically follow the AM process chain discussed above and considered a common workflow. From one AM process to another it differs only in small detail. Today, the same machines and consequently the same processes and materials are used for both basic application levels – making prototypes (rapid prototyping) as well as final parts (rapid manufacturing). Prototype parts and products can even be built in the same build process.

Whether the part is a prototype or a product is determined by the details of the workflow.

#### 3.1.2.1 Workflow for Rapid Prototyping

Rapid prototyping parts are for design evaluation and testing of isolated properties such as fit and function (see Section 1.2.1). As pointed out in Section 3.1.1, the common workflow indicates no feedback between the AM process and the CAD design. The AM machine acts like a printer.

Therefore, in most cases there is no special design for prototyping and the data are obtained from the engineering design of the later series product. Consequently, the design rules and the material properties are dedicated to the final product and the way it will finally be mass-produced (Fig. 3.2). In this context, the AM prototype part is only a derivative of the engineering design process of the final series part. Regarded from a systematic point of view, the rapid prototyping workflow does not have any influence on the 3D CAD design and the AM process starts after the CAD design is finished.

The workflow underlines the different responsibilities. To make a prototype, a suitable AM material and a corresponding AM process are selected by the person responsible for the AM process. The criteria are that the material should match the later production material and the prototype part should show the main characteristics of the later series parts, such as geometry.

The data are transmitted to the fabricator. The positioning and the orientation of the part on the build platform are established and the build parameters are set with the help of the front-end software. This is done by the person responsible for the AM process and according to the requirements of the AM process. The part's technological properties are determined by the AM process. After the build the post processing is typically done manually.

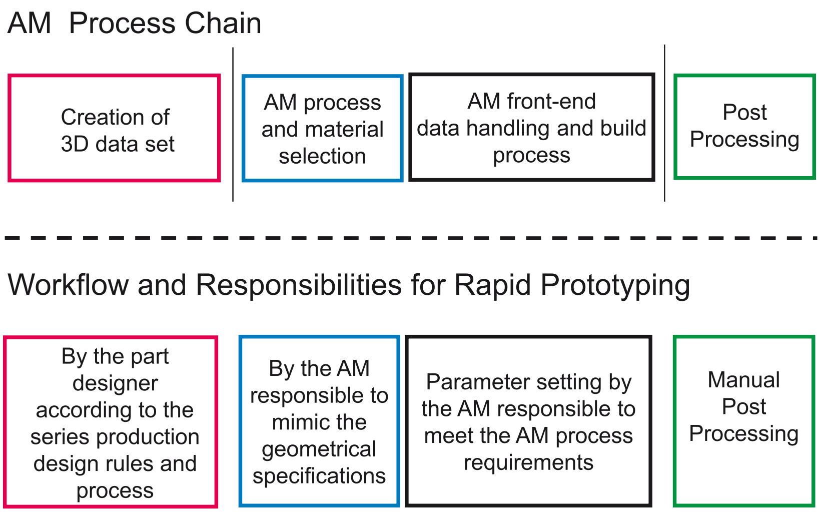



**FIGURE 3.2** Workflow for rapid prototyping

As a conclusion, an AM rapid prototyping part is created according to the design-rules of the later series parts and its material properties, but produced from a different material and based on a different production process, the AM process. Therefore, an AM prototype part can mimic a series product but can never be series-identical.

To underline this aspect, see the two scull models in Fig. 3.34. They are based on identical 3D data, but show completely different properties depending on the process selection (either a stereolithography or a 3D printing process).

#### 3.1.2.2 Workflow for Rapid Manufacturing

If the final series part is made using the AM application level "rapid manufacturing", it has to be designed according to the design rules, material properties, and the product characteristics of the selected AM process (Fig. 3.3). As a consequence, the responsibilities change.

Prior to the design the engineering designer has to select the build material and a matching AM process that in the case of rapid manufacturing is the final production process. Therefore, he has to define all parameters not only for the part but for the build process as well. As this includes the scaling, the position, and the orientation of the part as well, the operator of the AM machine is no longer responsible for these parameters but just for the proper run of the machine.

If produced according to this rapid manufacturing workflow, the AM part shows all properties assigned to it by the designer. That means it is a product. From a systematic point of view, the rapid manufacturing workflow intensively interferes with the 3D CAD design.

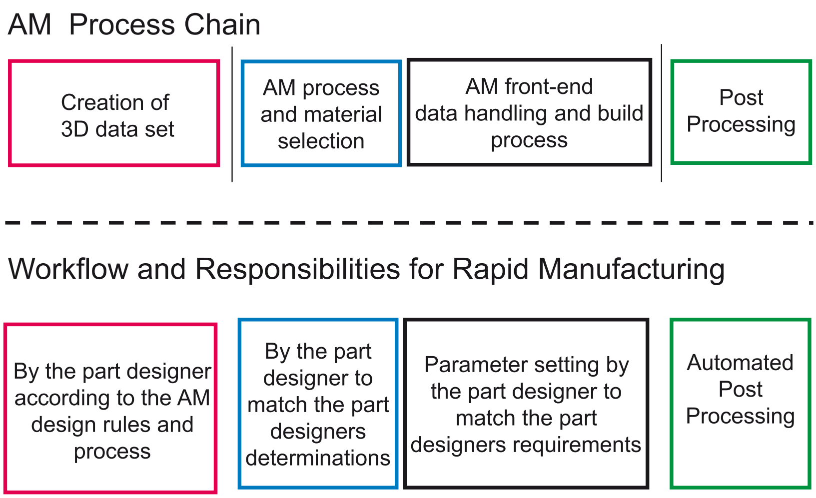



**FIGURE 3.3** Workflow for rapid manufacturing

According to the strategy of manufacturing, after the build all post processing procedures should be done automatically if at all possible.

### 3.1.3 STL Data Structure, Errors, and Repair

In order to obtain an STL data set of the part, the surfaces of the part, the inner surface as well as the outer one, is approximated by triangles. This is called triangulation or tessellation. For an optimal fit, the freeform surface of the part is approximated by triangles of different sizes, using big triangles for flat areas and small ones for curved areas.

STL is a very simple data format, because every triangle is defined by just four data elements, three corner points with three coordinates each, and one normal vector defining the inner and the outer surface. Because of the triangles, the data set can simply be sliced in any desired coordinate direction in order to receive the contours of each layer. STL was called "*standard transformation language*" in the beginning, but being closely linked to AM, today is addressed as "*stereolithography language*". The corresponding file type is .stl. The STL format can be exported from almost any 3D CAD system and from almost any scanner. STL data can be imported and processed by any given AM machine. It is regarded as a de-facto standard.

The STL data are either exported by the CAD system or are calculated by rapid prototyping software. In either case, the STL data are verified by means of a view function. The rapid prototyping software supports the orientation and the positioning of the part on the platform and the grouping of multiple parts for one build. It does the scaling and calculates bases and supports if needed. In addition, it adds the build parameters and in most cases it does the final slicing. As a service function, often the software estimates the build time as well and controls the entire build process, including material management and down cooling if needed.

One advantage of the STL formulation is that the triangles can be varied in size for any given geometry and the file can be adapted to the customer's accuracy requirements if needed. Accordingly, reducing the amount of triangles also reduces the file size, but the accuracy of the part will decrease and vice versa. The principle and the effect of different triangle sizes can be seen in Fig. 3.4 considering a geometrical object (a sphere) and a technical part (a ring) as examples.

The most prominent advantage of the STL formulation is that a triangle can easily be cut at any desired coordinate, which opens up the opportunity to slice the STL data according to the layer thickness that will be fabricated by the AM process. Some processes allow adaptive slicing, which is based on triangulation as well. Slicing based on triangles can be done interdependently from the native CAD data, which is regarded to be another advantage because the complete CAD model does not need to be transferred just because of AM.

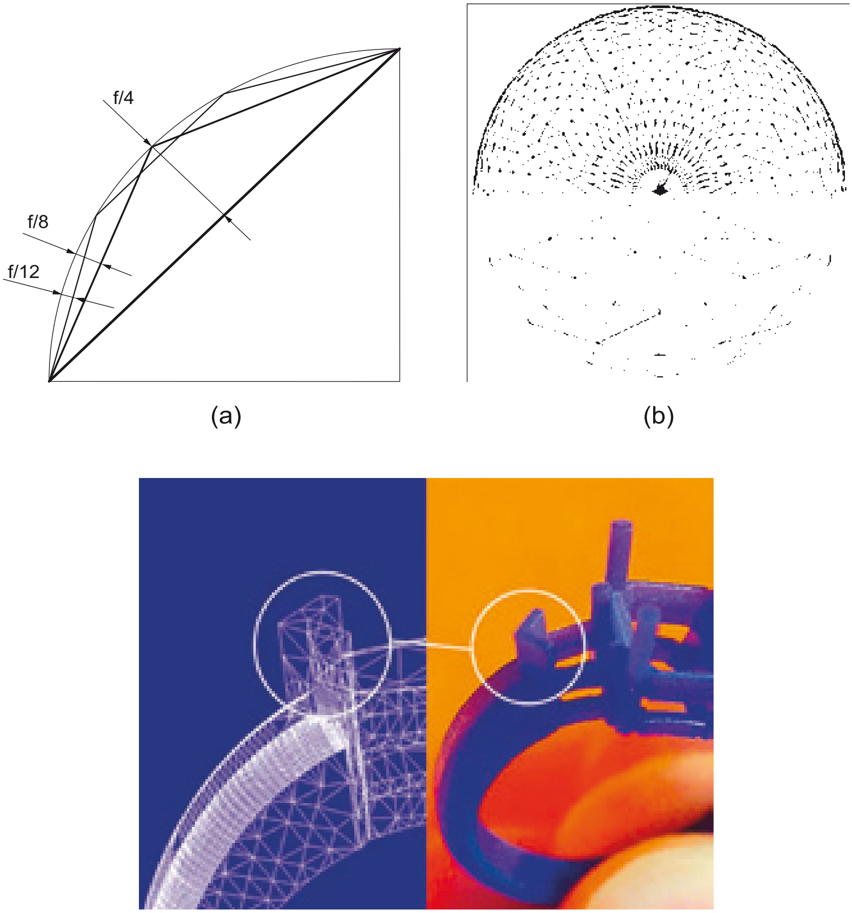



**FIGURE 3.4** Triangulation; principle (a) and effect of different triangle sizes (b) on a sphere (top) and on a technical part (bottom)

STL data retrieved from professionally operated CAD systems may include mistakes, which are not necessarily part of a sloppy job. If 3D data sets are frequently transferred between different CAD systems, mistakes are likely to occur. Because currently there is powerful repair software available, typically integrated in the software used for AM file preparation, this does no longer pose a problem. In order to give the user an idea of what the mistakes are about and what their consequences are, the most frequent errors in STL files are displayed in Fig. 3.5.

Due to an improper fit, adjacent triangles can show holes or gaps (Fig. 3.5 (a)) or twice defined or overlapping triangles or parts of triangles (Fig. 3.5 (b)). In both cases the tool path for the layer cannot be calculated properly, which causes errors or, in the worst case, the stop of the unfinished build. Similar problems occur at an intersection of triangles.

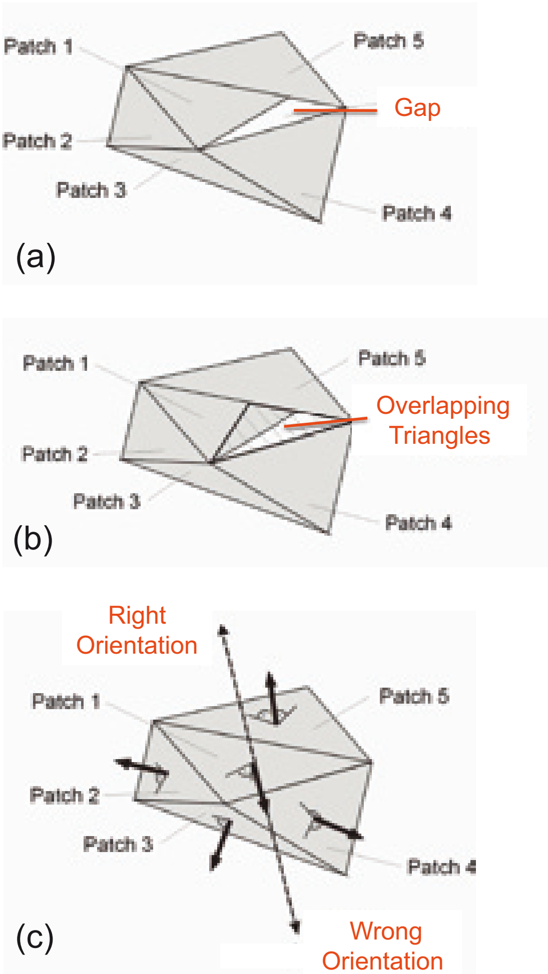



**FIGURE 3.5** Errors in STL files;
holes or gaps (a), overlapping triangles (b), wrong normal vector (c)

A part's volume is defined by the space between two boundary walls. The distinction between inner wall and outer wall is made by the normal vector. If it has the wrong orientation the parts show either a hole, double wall thickness, or some unpredictable geometrical details (as can be seen in Fig. 3.5 (c)). All these errors can be discovered easily on the sample graphs or on a simple part, respectively. But real parts are never simple, and consequently mistakes are not obvious and hard to discover. Therefore, the correct data should be verified prior to the build.

Besides STL data, different formulations such as VRML or contour oriented directly sliced data such as SLC are used as well. Other common file types are .WRL, .PLY, .MAX, and .SLDPRT. More details can be found in the literature, for example in /Geb07/.

# 3.2 Applications of AM

When talking about applications of AM, industrial applications are in the focus. Besides this professional approach, there are more and more users and consequently branches of industry that chose AM as a tool to strengthen their business and to bring new ideas to reality. They mostly show fascinating applications and parts and are the real drivers for new solutions and inspirations for others. This section tries to document both the industrial efforts as well as new aspects in order to support the spreading of the AM technology. Because today almost every branch of industry uses AM, the examples presented display just a small selection of what is possible.

## 3.2.1 Automotive Industries and Suppliers

Car manufacturers and suppliers have been amongst the first users of AM when it emerged in the late 1980s because they do a lot of design and re-design and they have been operating 3D CAD systems professionally for a long time. Therefore, the delivery of perfect data sets is not a problem for automotive OEMs and suppliers. Nowadays the amount of prototypes increases because diversification makes to the development of product variations much more important. Prototype parts are used for in-house evaluation as well as to support negotiations with suppliers. The increasing importance of customization raises the question of direct AM of parts in order to avoid tooling with its associated cost in time and money.

### 3.2.1.1 Car Components: Interior

Interior design very much contributes to the character of the car, thus often leading to and influencing the final buying decision. In contrast to the exterior design, it mostly consists of a large number of parts originating from many suppliers. The majority of the parts are finally produced by plastic injection molding. Therefore, the AM parts are mainly used for testing and presentation of car concepts. Nevertheless, as series are becoming smaller and the number of variations increases, more and more AM parts are directly used in the final car.

Although all AM processes can be used to make interior automotive parts, laser sintering and polymerization are the favorites. Laser sintering typically leads to directly usable parts while stereolithography or polymer jetted parts are typically used as master parts for secondary processes.

Figure 3.6, left shows a 1 : 1 scale dashboard insert for radio or air conditioning control installations. Because the geometry depends on how the car is equipped, which means

**FIGURE 3.6** Dashboard insert; laser sintering, polyamide (left); fuel tank. laser sintering polyamide (right). both: 1 : 1 scale (Source: EOS)

it depends on the buyers taste and budget, many variations and many different parts are needed accordingly to verify the final design variations.

The fuel tank in Fig. 3.6 is a non-visible interior technical part and a very complex one too. Often, the fuel tank has to fit in the space that is left after the preliminary packaging. Additional fuel level sensors have to be integrated. As it is a very big AM part, not very many machines, such as the EOS P 760, are able to build it in one build process. Alternatively, laser sintered parts can be cut by the rapid prototyping software, built in parts and assembled by gluing. Sometimes this procedure can be even advantageous in terms of build space economy. The tank can be sealed and used for tests. Laser sintering using polyamides leads to a loadable part such as the dashboard insert or the fuel tank, but shows limited surface quality.

In contrast, the speaker housing in Fig. 3.7 (right) shows a very good surface quality and is ready to be used as a series part. It is made as a RTV copy from a finished stereolithography master. The AM master delivers the detailed geometry and surface quality, while the RTV process adds the colored and loadable material and the desired number of parts (Fig. 3.7 (left)).

Interior lamps, as well as head and rear lamps, are subjects to design changes and face-lifts. They can be produced in high quality using AM not only for prototyping but for exposition as well. As shown on Fig. 3.8, design variations can be evaluated easily. Transparent parts, which are important elements of lighting modules, can be made by RTV and even the diffusion texture can be applied by special inserts in the silicon mold. Movable parts such as switches or lens-frames are made separately by the same procedure and are assembled into the final part (Fig. 3.8, left).

Lamp sockets and covers are products available as old-timer spare parts.

**FIGURE 3.7** Speakers, stereolithography master and silicon mold (left), cast part (RTV, right) (Source: CP-GmbH)

**FIGURE 3.8** Interior lighting; design variations; stereolithography and RTV with inserts (Source: CP-GmbH)

#### 3.2.1.2 Car Components: Exterior

Special editions of high volume production cars often do not only have more powerful engines but also demonstrate their performance optically by exterior parts such as front and rear spoilers or side skirts.

The example in Fig. 3.9 shows that a series may be very small and due to economic reasons, mass production techniques, such as steel tools, are not applicable. The front spoiler in Fig. 3.9 is made by AM using laser stereolithography. It was made in three


**FIGURE 3.9** Modified front spoiler for a special edition car;
laser stereolithography, RTV and finishing, spray-painting (Source: CP-GmbH)

**FIGURE 3.10** Exhaust gas manifold of a racing car (Source: Concept Laser/TU Fast e. V.)

separate sections (left, center, and right), finished, and joined using a gauge in order to perform as a master. After a subsequent secondary RTV-process, a small series of spoilers was made from PUR, spray-painted in the car's original color, and finalized using the OEM's original decorative parts.

Metal parts for power train or engine components can be made in final quality using the AM metal process of selective laser melting (SLM). They can be used as hot test parts or for small series such as in competition cars. As an example, Fig. 3.10 shows an exhaust gas manifold of a racing car which is used in a student's race competition (Formula Student).

### 3.2.2 Aerospace Industry

Because of the small series and frequent special design requirements of their customers, the aerospace industry tries to avoid tools and preferably employs the tool-less AM

**FIGURE 3.11** Hot air duct for an aero engine, 3D metal printing, post processing (Source: FhG-IFAM, Airbus)

processes. A milestone for the direct production of aerospace interior parts was the introduction of a flame retardant material for laser sintering, which now is available for polymerization and extrusion processes as well. Many of the interior parts of airplanes do not differ very much from parts made for cars. Therefore, sample parts for automotive applications can be taken as samples for aerospace applications. Developing metal and ceramic processes enable the direct fabrication of technical parts both for the cell and for the engine. Figure 3.11 shows a hot-air duct made by metal 3D printing and subsequent additional heat treatment.

Figure 3.12 shows a combustion chamber element made by metal sintering (selective laser melting, SLM). It proves that complex engine parts can be made using AM technologies today.

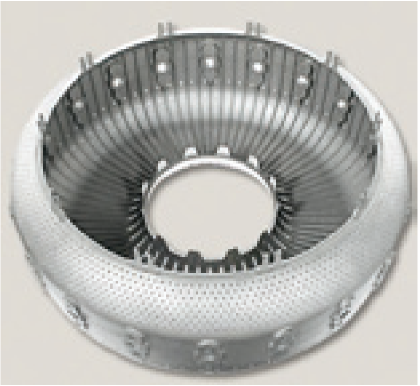


**FIGURE 3.12** Combustion chamber element, selective laser melting, SLM (Source: Concept Laser)

### 3.2.3 Consumer Goods

Today, consumer goods do not only have to perform their expected functions but they also have to follow a certain trend. They have to be focused on the needs of a special consumer group, including their favorite design orientation.

As a very important section, electronic consumer products, such as mobile phones, dominate the scene. Figure 3.13 shows a mobile phone housing study, consisting of many detailed parts with very good surface quality (left), which are ready for a secondary RTV process. To accomplish this, stereolithography is still the favorite process, regardless whether laser stereolithography or polymer jetting is used. The required quantity as well as the colored material is delivered by the RTV process.

**FIGURE 3.13** Mobile phone housing, laser stereolithography masters (left), colored copies by RTV (right) (Source: CP-GmbH)

Life-style products define another upcoming market. As life style changes rapidly, it is recommended to investigate trends and to test the market before production. Therefore, prototypes are needed. As an example, the cocktail cup shown in Fig. 3.14 was made by laser stereolithography to obtain fine details such as the decorations. The cup itself was regarded as a master and transferred in highly transparent material using RTV, while the socket was just sprayed and the electric equipment was installed.

Bowls, vases, lamps, and other more decorative items are favored objects for designers who use the new freedom of design provided by AM to overcome geometrical restrictions. Durable parts are preferably produced by plastic laser sintering (Fig. 3.15), while complex filigree and transparent or translucent compositions (Fig. 3.16) are typically made using laser stereolithography or polymer jetting.

**FIGURE 3.14** Cocktail cup, laser stereolithography, RTV and finishing (Source: Pfefferkorn/Toorank/CP-GmbH)

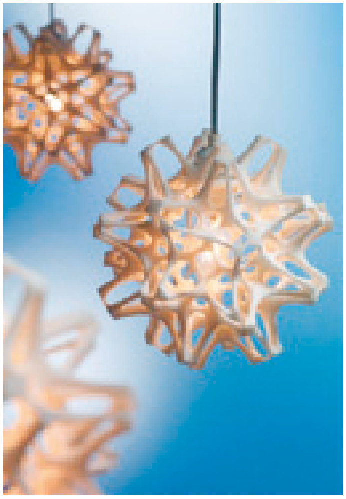


**FIGURE 3.15** Lamp, laser sintering, polyamide (Source: CP-GmbH)

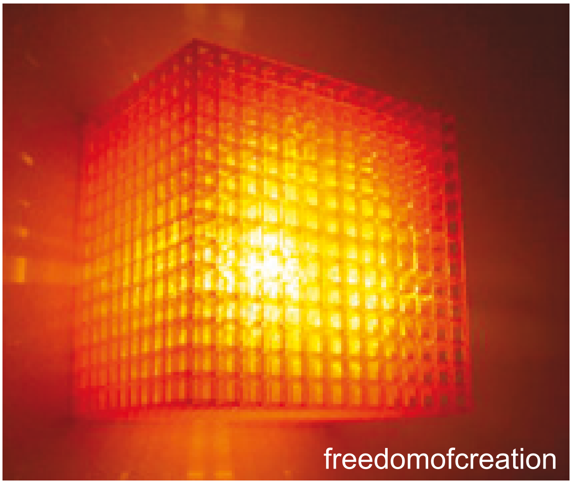



**FIGURE 3.16** Lamp, laser-stereolithography, epoxy (Source: Freedomofcreation, FOC)

Based on AM, the 3-dimensional visualization of geodesic data is about to form an emerging niche-market. For this kind of models, the 3D printing process by Z-Corporation is very useful, because the parts can be continuously colored thus avoiding manual work. Examples see Section 3.2.9: Architecture and Landscaping.


**FIGURE 3.17** Relief globe; mountain heights (left) and ocean floors (right), exaggeration 250 times; laser stereolithography and post-processing (Source: 1worldglobes)

Based on AM, new ways of geodesic displays can be made. Figure 3.17 shows two models of a globe displaying the land portion and the sea portion of the earth with an exaggerated scaling of the topographic lines of the mountains and of the ocean floor in order to point out the details. In order to make the fine spike-shaped details on the surface, stereolithography was chosen. Consequently, manual coloring must be applied. AM allows the customer to order his preferred scaling.

Depending to the application, other AM processes can be used too, such as polymer jetting or laser sintering for durable thin structures such as the roof construction of a stadium as displayed in Fig. 3.18.

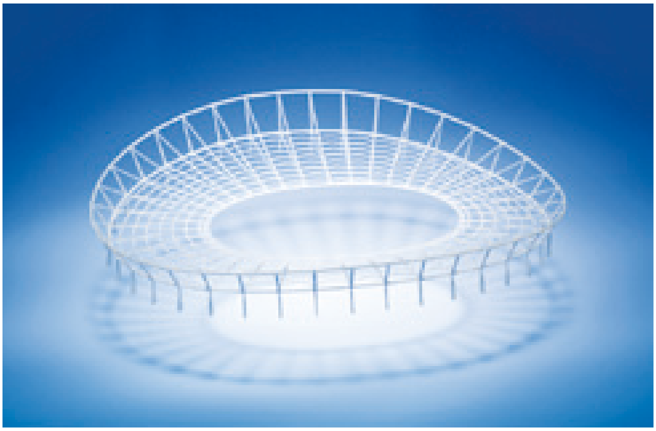


**FIGURE 3.18** Roof construction of a stadium; laser sintering (Source: CP-GmbH)

**FIGURE 3.19** Customized sunglasses; laser sintering; finishing by water transfer printing (Source: EOS)

The closer a product approaches the human individual, the more intensive becomes the interaction between both and the more individual features are required. To make the parts needed, mold- and die-bound manufacturing is not longer applicable. This opens up advantages for AM processes, which can manufacture large quantities of different parts in one build, even if all of them are different in terms of individual features. Examples are individually designed sunglasses (Fig. 3.19) that are finished by water transfer printing.

The fancy sandals in Fig. 3.20 can be regarded as an archetype of individually designed trendy shoes and they can also be made by request in any size and any height. As these parts are directly usable, they can be regarded as products and we are talking here about rapid manufacturing. Although these examples were made by laser sintering from polyamide, today's extrusion and polymerization processes and materials could also be employed here.

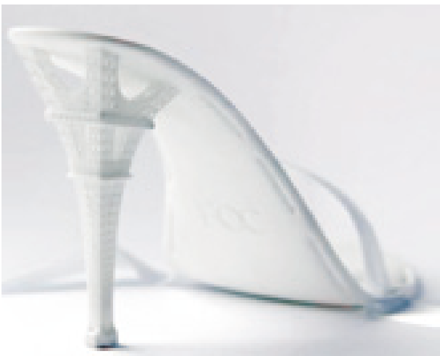


**FIGURE 3.20** "Paris Sandals", high heels; laser sintering; polyamide (Source: Freedomofcreation, FOC)

### 3.2.4 Toy Industry

Although toys are also "consumables", the toy industry usually is addressed separately. It deals with the various plastic parts for children's toys but also with more and more customized models of cars, planes, and trains, even for adults. These models require fine details and a sensitive scaling, handling small details differently from larger ones. Depending on the scale, different AM processes are more suitable than others. Figure 3.21 shows a G-Scale (1 : 22.5) model of a toy steam train engine, which, including the tender, is almost 1.5 m long. For the production of this part layer laminate manufacturing is a good alternative because the material is cheap and the details are not too small. For this kind of model, physical properties are not as important as geometrical accuracy.

Reduced scaling, for example the most popular HO toy train standard (1 : 87), requires models with finer details. Even for a sample, stereolithography is required. Figure 3.22 shows the toy train engine from Fig. 3.21 as it emerges after the process but after cleaning (rear) and after post-processing by grinding and coloring (front).

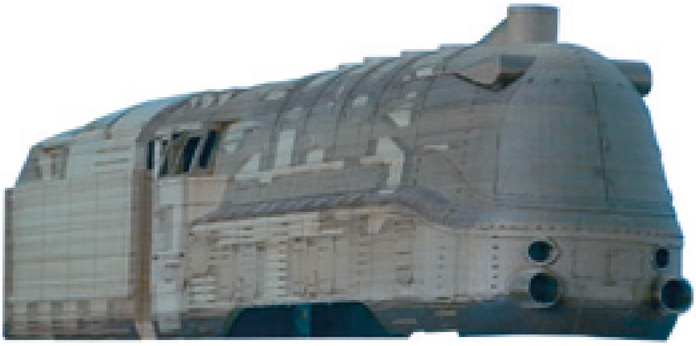


**FIGURE 3.21** G-Scale (1 : 22.5) model of a toy train steam engine; laminated object manufacturing (LOM); paper, post-processing by varnishing (Source: CP-GmbH)

**FIGURE 3.22** HO scale (1 : 87) toy train steam engine; stereolithography part after processing (rear); part after post-processing by grinding, decorating, and coloring (front) (Source: CP-GmbH)

### 3.2.5 Art and History of Art

Artists were amongst the first to use the freedom of unlimited geometries offered by AM processes. The Californian artist Bathsheba makes individual objects by metal 3D printing and post-processing to obtain special proprietary surface effects. Her objects are final products and are sold as pieces of art via the internet.

Metal was chosen because it is regarded more valuable than plastic due to its weight. In Fig. 3.23 left, the part can be seen as processed by 3D printing. Figure 3.23, right underlines that the unique appearance is obtained by the finishing operations.

**FIGURE 3.23** Art objects; metal 3D printing (Prometal); part after AM production (left) and after post-processing and finishing by surface treatment (Source: Prometal, Bathsheba)

The 3D data needed for the reproduction of human sculptures can be obtained very easily by 3D body scanning. This was done at an exhibition designed by the artist Karin Sander at the "Staatsgalerie Stuttgart". The exhibits were generated by body scanning and 3D printing of the visitors. At show opening there were only empty shelves. At the 'finissage', all shelves were covered by a large number of 1 : 7 scale sculptures of the visitors. For this, monochromatic 3D printing is a suitable process, because it is quick, cheap, and the details are sufficient. Figure 3.24 shows a group of the sculptures.

Even the creative work of artists can be supported successfully by AM. To work out a sculpture, a first hand-made model can be scanned and transformed into an AM part made of polyamide (by sintering) or a material close to plaster (by 3D printing). This master can be worked out manually to express the intention of the artist and then be transferred via a wax pattern into a small series made from brass. As an example, the sculpture of Alexander Pushkin, made by the NY-based artist Alysa Minyukovan is shown in Fig. 3.25.

**FIGURE 3.24** Body scanning and 3D printing (Z-Corp); plaster-ceramics (Source: Karin Sander/FH-Aachen University of Applied Sciences)

**FIGURE 3.25** Sculpture of Alexander Pushkin, made by Alysa Minyukova, NY, using AM and traditional process steps; Laser sintering (left), wax master obtained from RTV (center), final sculpture (right) (Source: Alysa Minyukova, CP-GmbH)

The portrait head of Teje, the mother-in-law of Nefertiti, is one of the secret-keeping exhibits of the Egyptian museum in Berlin (Fig. 3.26, background left).

It is made of wood and covered with a silver bonnet that is hidden under another bonnet made of papier mâché. The actual bonnet was already added in antique days and indicates the change of her social status when her husband, king Anophenes III, died. In the 1920s, scientists investigated it by X-rays but still did not get a complete impression of the 3D situation, especially under the bonnet. As the bonnet could not be destroyed for this investigation, a CT scan, a 3D reconstruction and an AM stereolithography part based on the CT data led to a multi-piece model that answered the open question and was placed close to the original in the museum (Fig. 3.26, front, right).

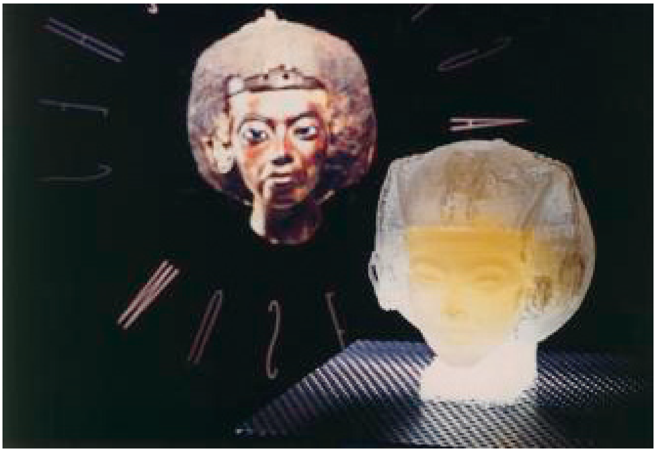


**FIGURE 3.26** Bust of Teje. Original covered by a papier mâché bonnet (background, left), stereolithography part, showing the invisible silver bonnet beneath it (Source: Egyptian Museum Berlin, CP-GmbH)

### 3.2.6 Foundry and Casting Technology

Foundries use AM processes to receive prototypes and samples of the later product (3D imaging) or to make cores and cavities for production. If just a demonstrator part is required, all AM technologies can be applied. 3D printing is preferred, if the part is not mechanically loaded and a cheap and quickly available sample is needed. The application level is rapid prototyping/solid imaging.

AM offers new impulses mainly for sand casting and investment casting, because the needed lost cores and cavities can be made quickly and easily. The improved complexity of the AM parts allows realizing geometries that cannot be made manually or by special tools. Due to the simple scaling of AM parts, the lost cores and cavities can be optimized easily. For sand casting applications, laser sintering or 3D printing of foundry sand is used, while lost cores for investment casting are made by polymerization of resolvable or meltable thermoplastic waxes or resins. Lost patterns are made form polystyrene by laser sintering. If infiltrated with wax, 3D printing parts can be used as well. As the cores and cavities are used for production, the application level is rapid manufacturing/direct tooling.

Lost cores and patterns can also be made by injection of wax into silicon molds obtained from AM masters. If finished properly, all AM technologies can be applied.

### 3.2.6.1 Sand Casting

For sand casting processes, AM provides support to two trends, the digitalization of the entire process and the raising complexity of cast parts that requires precise and filigree cores, and cavities.

As shown in Fig. 3.27, today's foundry process chain is completely CAD based and all data can be obtained directly from the CAD model. With AM processes the cores and cavities that produce high precision parts can be made in any desired quantity directly from the digital data.

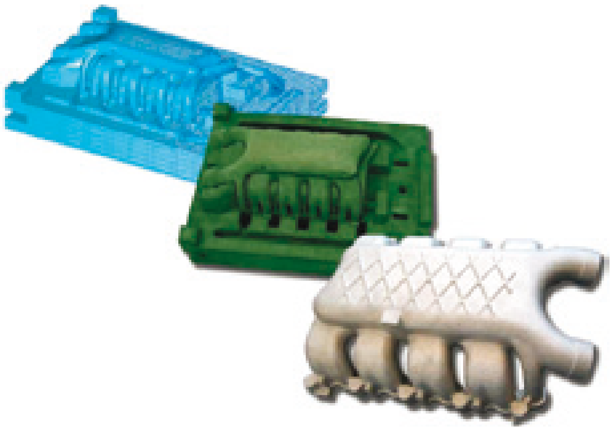


**FIGURE 3.27** CAD based foundry process chain. 3D CAD model (top left), AM based sand core and cavity (center), cast part (bottom right) (Source: Prometal)

Reduced wall thickness of cast parts, filigree, and freeform shaped cores define the second trend in casting. As the partially manual manufacturing and assembly of these elements reach their limits, AM cores and cavities fulfill the new requirements. Besides the geometrical complexity, cores must be rigid and durable during mold assembly and casting process; however, they need to be easily removed (destroyed) after the solidification of the part, which can be optimized by a proper setting of the AM parameters.

AM processes, optimized for sand casting applications are laser sintering and 3D printing of foundry sands.

Sintering is done using a modified laser sintering machine and polymer-coated sand. The polymer acts as thermally activated binder. Various silica and zircon sand qualities are available. Figure 3.28 shows a core made by laser sintering (left). A sand core for the cooling jacket of a cylinder head can be seen in Fig. 3.28 (right, background) together with the cast part. The pictures display very complex, but filigree AM cores which resemble pieces of art. As the handling is rather delicate, transportation should be avoided and AM sand processes should be installed directly in the foundry.


**FIGURE 3.28** Sand core made by laser sintering of foundry sand (left), sand core for the water jacket of a cylinder head (right, background), cast part (right, front) (Source: EOS)

Sand sintering machines made by EOS look very much like the metal sintering machine displayed in Fig. 2.3.

The 3D printing process for making parts from foundry sand works similar to the powder binder process described in Section 2.1.4. The binder is sequentially applied by multi-nozzle print heads. The process is very fast and allows local parameter optimization. A machine based on 3D printing made by Prometal can be seen in Fig. 3.29.

As with laser sintering, each sand grain is coated with polymer binder, the amount of binder per volume is fixed and dependent on the part geometry. With 3D printing, the polymer binder is injected according to the part geometry and can be handled more sensitively.

**FIGURE 3.29** 3D printing machine for sintering of foundry sands (Source: Prometal)

If a classical box based sand casting process with a permanent model is used, the LOM process described in Section 2.1.5.1 can be used. As the filed paper behaves like wood, the resulting model can be handled like the classical wooden ones. The process is slow but the material is cheap.

### 3.2.6.2 Investment Casting

Investment casting is traditionally linked to a lost wax process, while today "wax" means any thermoplastic material that behaves similar to wax. "Wax" printers, such as 3D Systems ProJet family or envisionTEC's perfectory, that actually are based on polymerization processes, provide wax-like structures that can be resolved by heat. Figure 3.30 shows a filigree part for jewelry applications. A manually assembled tree-like assembly of an AM wax pattern consisting of sprue, gating, and runners, all made from wax, can be seen as well as the entire casting before cleaning.

**FIGURE 3.30** Investment casting; casting tree made from AM-pattern using wax runners, sprue and gating (left), casting before cleaning (right) (Source: 3D Systems)

As an alternative, lost patterns are made using laser sintering with amorphous materials such as polystyrene (EOS, 3D Systems), or 3D printing processes using PMMA (Voxeljet) that can be removed by firing the shell (Fig. 3.31 and Fig. 1.28) with very little residual ashes.

AM masters can also be transformed to wax patterns and cast traditionally as it was done with the sculpture of Alexander Pushkin displayed in Fig. 3.25.

**FIGURE 3.31** Lost pattern process; AM master part of a gear box housing made by laser sintering of polystyrene, left; casting, background right (Source: EOS)

### 3.2.7 Mold and Die Making for Plastic Injection Molding and Metal Die Casting

The term “mold” will be used here to address molds for series production and consequently does not include prototype tooling and soft tooling such as RTV (see Sections 1.3.2 and 2.2). Making molds and dies basically means to invert the product-data. Molds (negatives) can be done using the same AM processes as for making parts (positives). Mainly due to marketing reasons the technology was given a separate label: *rapid tooling* (see Section 1.2.3). It is important to note that AM does not deliver complete molds but rather mold inserts, sliders, or similar mold elements. As in traditional mold making, a mold made by direct tooling is a composition of AM-based cavity elements and mold inserts completed by standard parts.

The great advantage of AM series tools and tool inserts is to reduce the cycle time by so-called conformal cooling channels. With layer technology, arbitrarily shaped channels can be designed and manufactured close to the surface. The geometry needs to be neither straight nor round, as it is demanded to facilitate drilling. Figure 3.32 shows the improvement of a production tool. The drilled straight channels, which additionally require a sealing plug, were replaced by conformal cooling channels adapted to the freeform surface and the amount of heat expected. The part was made from tool steel by SLM and tested in the production run. As can be seen from the simulation of this production run (Fig. 3.32) that was proven in practice, conformal cooling channels considerably influence the heat management, leading to a reduction in cycle time by approximately 30% in this particular example.

Another complex conformal cooled tool element was shown in Fig. 1.14. Here, one half of a mold-insert for the production of a hood for a vacuum cleaner was displayed.

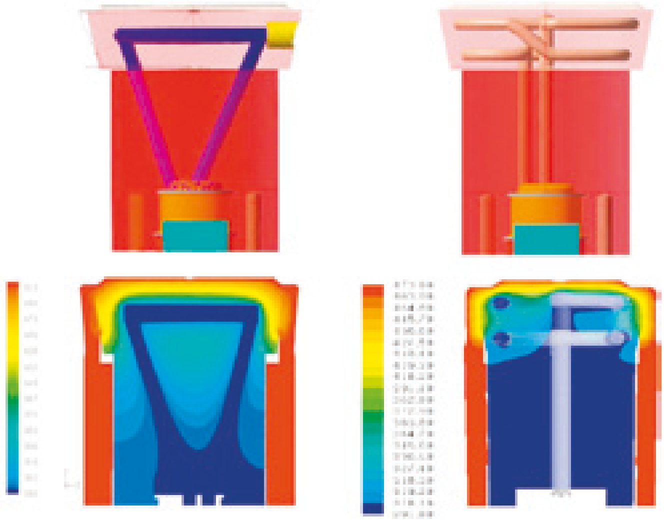


**FIGURE 3.32** Conformal cooling; conventional approach by drilling straight cooling channels, top left; conformal channels made by AM, top right; CFD-simulation bottom. Note that the temperature scales differ (Source and details see /Geb09/)

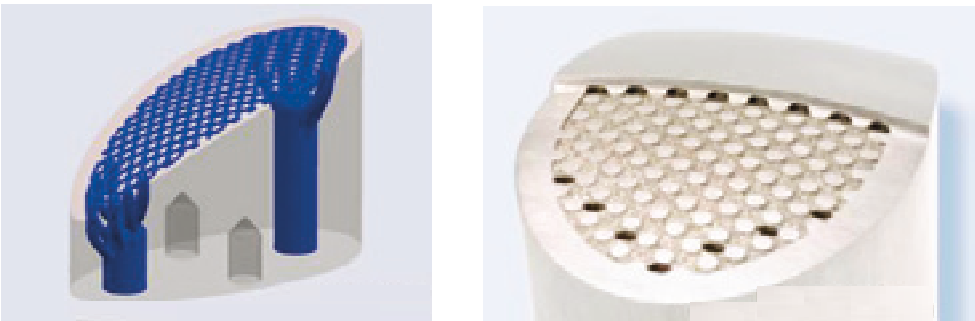


**FIGURE 3.33** Internal grid of channels for conformal cooling application; CAD design, left and cut-away view of the generated part, right; selective laser melting (Source: Concept Laser)

The deep narrow grooves need to be cooled in order to perform a quick and safe part release. After designing the conformal cooling channels (blue), there is almost no space to drill the holes of the ejecting pins. Consequently, air ducts were designed to allow the operation of pneumatic ejecting pins (white). The AM part made by selective laser melting is shown on the right side of Fig. 1.14.

The further development of the idea of conformal cooling will result in complex systems of channels as shown on Fig. 3.33. The CAD design is illustrated in Fig. 3.33, left and a cut-away view of the AM part can be seen in Fig. 3.33, right. To make parts like this, laser melting is the favorite process. If designed properly, hollow structures can be built without supports and cleaned easily because of the loose powder. The materials needed for tooling, especially tooling steel and aluminum if required, can be processed by AM.

### 3.2.8 Medical

Humans are still individuals, who need individual treatment including, customized aids such as implants, episthesis, orthosis (leg braces), and others. For a proper fit, the 3D data need to be acquired by medical imaging processes such as computed tomography (CT) or ultrasonics (US). A common format for medical images is DICOM. Special software allows a suitable threshold selection and a 3D reconstruction that provides the basis for a set of STL data that can be processed in any AM machine.

Because of the good surface quality and the detailed reproduction, laser stereolithography (Fig. 3.34, left) and polymer jetting are used preferably to make medical models such as sculls and other human bone structures. Interior hollow structures such as the frontal sinus or the filigree sub cranial bone structure can be reproduced best by these processes.

But laser sintering, 3D printing, fused layer manufacturing (extrusion, FDM), or layer laminate manufacturing (LLM) deliver medical models as well and are frequently used for this purpose. For sintering and FDM there are special, approved materials for medical use available that can be sterilized.

Figure 3.34, right shows a scull made by 3D printing based on the identical data set as the stereolithography scull in Fig. 3.34, left. The differences can be seen clearly. 3D printing delivers slightly less details and a rough surface. It is not transparent. Whether this is a disadvantage or not depends on the intended use; however, this technology definitely it is fast and cheap.

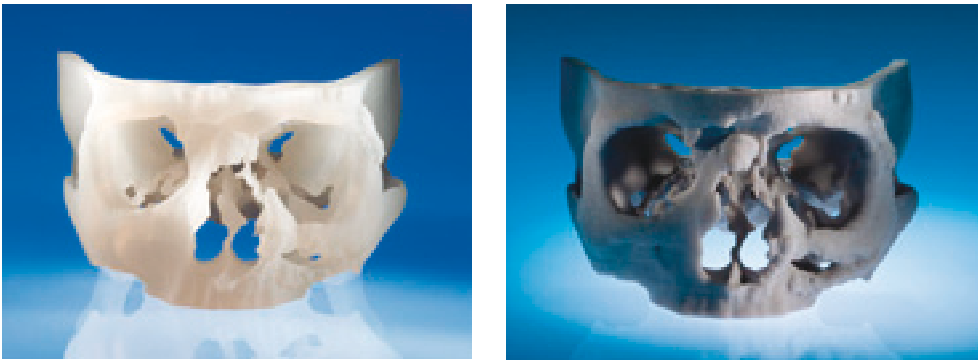


**FIGURE 3.34** Facsimile of a human scull based on CT data, stereolithography, left; 3D printing, right (Source: CP-GmbH)

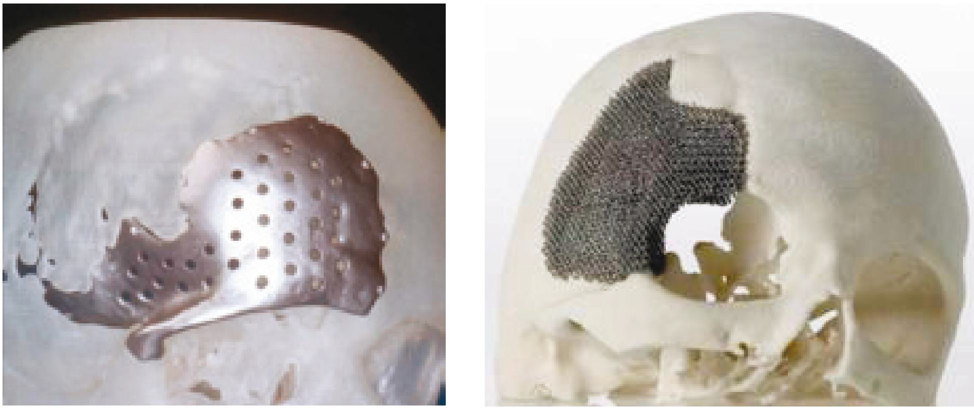


**FIGURE 3.35** Medical modeling and customized implants. Facsimile of a human scull with customized implant made from an AM wax pattern by investment casting of titanium (left) and made directly by EBM (right) (Source: CP-GmbH/ARCAM)

The decision which process to use depends mainly on whether the part must be transparent, what surface quality is requested, whether it needs to be sterilized, how to address sustainability, do medical doctors need models for training, and how big is the budget?

Figure 3.35 (left) shows an example of a medical application: a model of a human scull made by laser stereolithography which is used for surgery planning. A customized implant made from titanium is fit into the scull. The implant (Taylored Implant™) is obtained from investment casting based on an AM master. Here again, a stereolithography scull model is used to guarantee appropriate fit of the implant.

Alternatively the implant can be designed by special software such as Mimics offered by Materialise and made directly from titanium or CoCr using laser melting technology, such as SLM or EBM, as shown on Fig. 3.35 (right).

Using an intermediate wax pattern and then casting the implant (Fig. 3.35, left) bears the advantage that the wax pattern can be quality-checked and easily adjusted prior to surgery even by the medical doctors, while the directly sintered AM part made from titanium is a final part.

3D printing opens up interesting opportunities for anaplastologists and other professionals who make individually shaped parts for final casting. The data of missing organs or parts of organs is received from medical imaging, 3D reconstruction and subsequent 3D modeling by software such as Sensable. These data are preferably based on mirroring. The desired artificial organ must be adapted individually to each patient's situation. To shorten this procedure and to allow the anaplastiologist to concentrate on his or her core skills, the designed part is made by 3D printing and regarded a green part.

**FIGURE 3.36** Ear epithesis, "raw ear" after 3D printing and wax infiltration (left); final ear made from silicon by counter casting of the wax master (Source: CP-GmbH; Bier, Charitée, Berlin)

After the part is infiltrated by wax, it can be easily modified manually by adding or removal of wax. Figure 3.36 (left) shows a so-called "raw ear" after 3D printing and wax infiltration and the final ear epithesis (Fig. 3.36, right) after individual wax modeling, counter casting from medical silicon material, and final decoration.

The same procedure is used by sculptors in order to receive a worked-out wax master for the final casting.

### 3.2.9 Architecture and Landscaping

Architects usually present their creative ideas by scaled models. Since they are working with 3D design programs, the 3D data needed for AM are directly available and the model making can be significantly improved by the use of AM models or model elements.

Figure 3.37 shows a model of a mosque. The very complex, thin walled freeform-shaped structure could hardly be made by traditional model making but needs to be built using AM. Laser sintering was chosen to create a detailed model as well as to ensure a practical level of solidity that prevents it from being damaged by touching. Although the cube-shaped elements were sintered, they could also be made traditionally by milling thus making it a so-called hybrid model. The model was primarily used for a public presentation of the project.

Another example is the display model of a planned touristic center made by laser sintering in Fig. 3.38. It is part of a concept presentation that included the project description and 3D renderings. The scaled model was made by laser sintering for the same reason as the mosque. Stereolithography or FDM could be used, if the supports

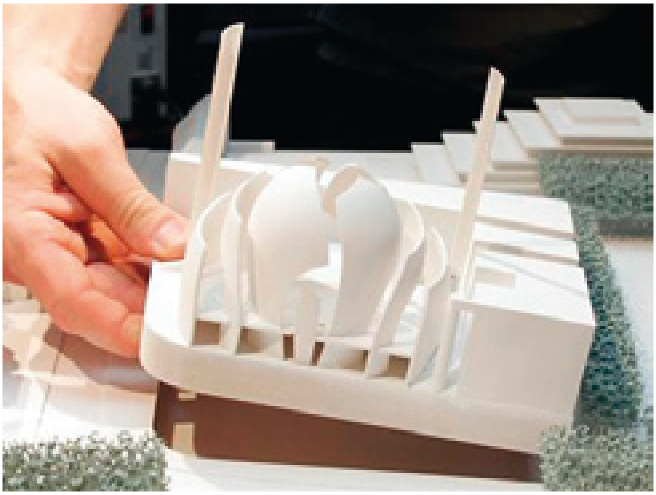


**FIGURE 3.37** Architectural model, mosque, laser sintering
(Source: Deutschlandwoche, 10/2007)

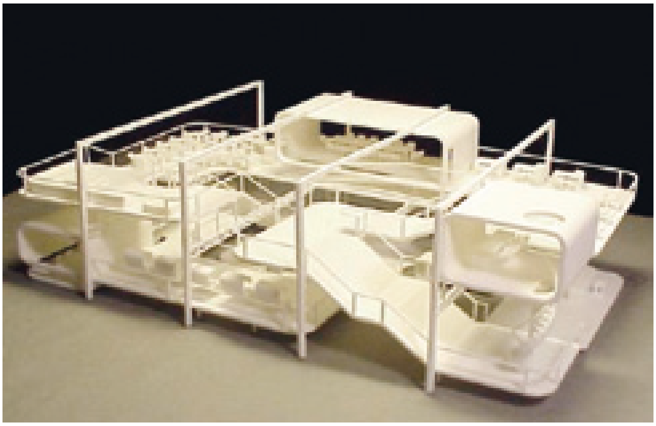


**FIGURE 3.38** 3D display of a concept for a touristic center, laser sintering of polyamides
(Source: Bernhard Bader)

are set accordingly. 3D printing would cause problems because of the filigree details such as handrails. Polymer jetting would also deliver good parts, however a large amount of support material would be needed.

Besides the modeling of single buildings or parts of buildings, a growing application is the making of models of ensembles of houses, villages, and landscapes. Many of these require color, either to point out the benefits of the construction or to indicate landmarks. If no filigree geometric details have to be displayed, colored 3D printing often is the best choice (Fig. 3.40).

**FIGURE 3.39** Architecture, two houses in their rural environment (Source: Z-Corporation)

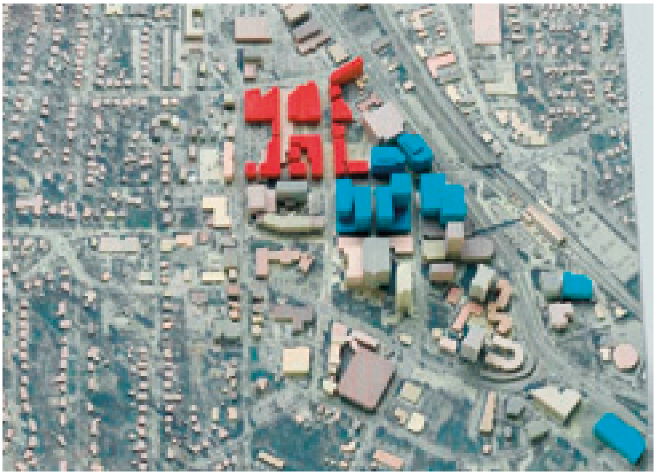


**FIGURE 3.40** Urban landscape, landmarks highlighted by individual coloring (Source: Z-Corporation)

The data can be obtained from any type of GIS or it can be extracted from the Internet, e.g., from Google Earth or 3D warehouse, and displayed in 3D using various AM processes. Among others, AM is able to deliver 3D displays of anybody's house, home town, or friend's site, prominent buildings, bridges and more. They can be individually colored by software in order to create special highlights (Fig. 3.39).

## 3.10 Miscellaneous

Since the only precondition for making parts by AM processes is to have processable 3D data, any source of valid data can support a 3D object. Therefore, almost every branch of industry uses this opportunity. To underline this, a few special applications are mentioned in the following.

#### Mathematical Functions and 3D Graphs

Even mathematical functions may become very attractive when displayed as a 3-dimensional physical object. Figure 3.41 shows the AM model of a minimal-surface function made by laser stereolithography. All AM processes that deliver good surface qualities and preferably do not use supports can also be used for this purpose.

**FIGURE 3.41** 3D model of a minimal surface function, CAD rendering, left; stereolithography model (right) (Source: David Hoffman and Stewart Dickson)

#### 3D Decoration and Ornaments

With the Z-Corp's 3D printing process there is an AM process available that does not only allow to make nearly every geometrical shape, to be continuously color it. So it is possible to make colored decorative parts or ornaments, such as the "serpent knot" in Fig. 3.42. Textures like this quickly reach the limits of the STL data capabilities that can hardly transmit bitmaps. Therefore typically .ply- or VRML formats are used.

**FIGURE 3.42** Decorative element “serpent knot”; colored 3D printing (Source: Z-Corporation)

### Aerodynamic and Freeform Elements

One of the greatest advantages of AM is the possibility to turn any freeform surfaces, used to improve the aerodynamics or to create a fancy design, into a physical part. Some final applications can be seen in Figs. 3-15, 3-20, and 3-23.

Today, the conception of a new airplane is based on 3D CAD- and simulation tools from the first sketch. Besides the computer graphics and renderings, which provide a good impression of the basic idea, a scaled model is used to communicate the concept and to improve the feeling for proportions. In Fig. 3.43 (left) the concept of a single engine airliner can be seen as a rendering and as a corresponding AM part (right). The part was laser sintered thus showing the freeform surface without post processing.

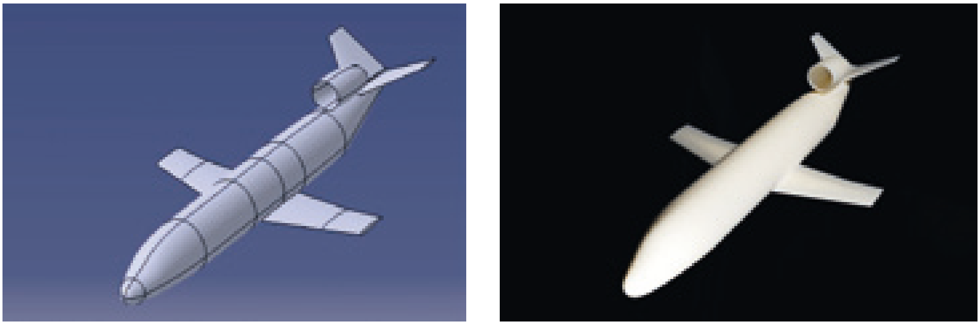


**FIGURE 3.43** Single engine airliner concept; rendering (left); AM part, laser sintering of polyimide (right) (Source: Philipp Gebhardt, University of Stuttgart)

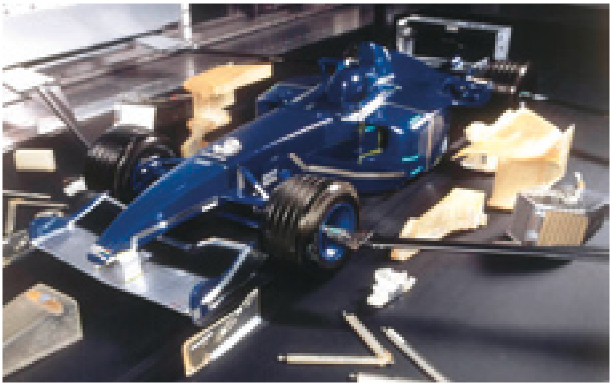


**FIGURE 3.44** Freeform shaped parts for the aerodynamic improvement of racing cars; test bed in a wind tunnel; parts: stereolithography (Source: 3D Systems)

Figure 3.44 shows a set of scaled parts for the aerodynamic improvement of a racing car to be tested in a wind tunnel. The scaled test provides a quick and cheap first impression and helps to focus on the greatest effects in order to reduce testing time and money. Stereolithography was chosen because of the good surface quality of the parts and because the parts experience only moderate mechanical loads.

## 3.11 Conclusion

As every branch of industry already uses or shortly will use computers and work on the basis of 3D data, the most important pre-requisition for the use of AM processes is about to be fulfilled. Consequently, every branch of industry is a potential user of AM and sooner or later will take advantage of this technology.

The examples provided here underline that there is not a fixed link between industry branches and AM processes. What kind of process will be the most suitable must be decided case by case. Sometimes it is even more complicated because although in certain applications the same result can be obtained by different AM processes, yet in other cases there is just one applicable process. Consequently, the AM process has to be chosen according to the part and not to the industry branch.

## 3.12 Questions

1. **Why can AM prototypes be made on the same machine, utilizing the same process, and the same material that are used to make AM products?**

Whether a part is a prototype or a product does not depend on the machine or the material used, but on the part design. The part will be a product, if it is designed to meet the AM design rules and the AM material data. If it is designed according to the subsequent series manufacturing method and the series material, but made by AM and from AM material, it will be a prototype independently from the AM machine and material.

2. **What kind of AM processes is preferably used to make cores for sand-casting? Why?**

Laser sintering and 3D printing of foundry sands and polymer-based binder.

It is very much the same material used in conventional sand casting.

3. **What industry branch preferably uses stereolithography?**

The application of an AM process, for instance stereolithography, is not a question of industry branch but of the characteristics of the part. If fine details have to be processed, good surface qualities are required, and only low temperatures are applied to the part, stereolithography is the preferred AM process. This is valid for any branch of industry.

4. **What materials can be processed with metal laser sintering or laser melting processes?**

Laser melting delivers dense metal parts. The processes are developed to process commercially available metal powders. A wide variety of blends that lead to alloys can be used if the powder has been validated. The powders offered by the manufacturers of AM machines can be regarded as validated. Materials are mild steel, tool steel, stainless steel, CoCr-Alloy, titanium, aluminum, and others. Copper is supposed to enter the market.

5. **Where do the 3D data needed for processing come from?**

In the field of engineering the data mostly come from 3D CAD design and can be directly derived from the CAD data by a STL post processor. In the medical field most of the data come from CT scans of living individuals. In industry there is a growing tendency to use specialized CT scanners as well, because this allows for non destructive overall data verification.

### 6. What AM processes can be used to make colored parts?

If just one color is needed, the AM materials of most processes can be colored. This is very easy with extrusion (FDM-) processes, because colored material is available and can be changed quickly. If stereolithography or sintering is required, the whole build chamber has to be filled with the desired material.

Two colors, due to two materials, can be processed by the Objet Connex machine. Multi-colored parts can be made by the Z-Corp 3D printing process. It even allows to process bitmap-based textures. On the downside, the color is placed just on the surface.

### 7. Architects have been using scaled models for many years and developed high non-AM modeling skills. How can AM improve architecture modeling?

All parts of architecture models that can be processed by non-AM technologies such as cutting and milling, should be made by these methods. AM is preferably useful when freeform surfaces or very detailed parts are requested. In practice, models will be composed from AM and non-AM parts. If color is needed and manual painting should be avoided, 3D printing is very helpful.

### 8. AM processes often are not very suitable for making a small series of parts or parts with defined properties such as transparency or elasticity. How can AM be used in such cases?

AM delivers a very good geometrical model in a short time. If it is not directly applicable it could be used as a master model for secondary rapid prototyping processes.

### 9. How do toys for children and for adults differ and how is AM affected by this?

Toys for adults are mainly for display and require very good details and filigree structures even in the prototype phase. That is why polymerization is often used for these applications. Toys for children have to be more robust. Often this has to be proved during the prototype phase. In such cases, sintering or extrusion of plastics are typically used.

### 10. What are the two AM-based approaches for making medical implants for head surgery?

Based on the data of the defect, either a wax-type master for precision casting can be made by polymerization or sintering of amorphous plastics or waxes and then turned into titanium parts by casting.

Alternatively the implant can be made directly by laser melting. The direct AM production is faster, the lost wax casting is cheaper. If major changes are needed, the part made by casting can be modified and redone very quickly and at low cost.

### 11. How are AM and conformal cooling linked?

Conformal cooling requires 3-dimensional channels following the surface of the mold cavity as close as possible. Shaped channels like this cannot be drilled or cast, although there are exceptions. Layer oriented AM is the only way to manufacture such channels. It requires metal laser melting processes.

# 4 Additive Manufacturing Design and Strategies

This chapter will discuss new strategies for product design, development, and production that are enabled or supported by AM processes. In addition to Chapter 3, it can be regarded as a systematic approach to AM application.

Based on the potentials of AM, strategies for making new products with alternative or new design features are shown. The aim is to motivate the reader to assign the examples to his own part of industry. Doing so, it will help him to apply AM in the optimal way in order to design better products with outstanding functionalities in a shorter time. The different and new approach of manufacturing additionally bears the potential to establish a radically different customer-manufacturer relationship. Emerging strategies are also discussed.

The chapter is based on the knowledge of the five basic families of AM, and the AM process chain as discussed in Chapter 2.

## 4.1 About the Potential of AM

As seen in Chapter 1, AM directly transfers 3D CAD files into real (that means physical) 3D objects[1] that can be used as prototypes or final parts (products). Prototypes can be just "3D-pictures" or "statue-like objects" but may have selected functionalities as well. Final parts or products must show all functionalities assigned to them during the engineering design process. Parts can be positives (parts) or negatives (molds and dies).

The wide variety of possible applications of AM already has been addressed within Chapter 3 (applications). The examples provided there are dedicated to selected branches of industry in order to allow for easy identification for special groups of users.

[1] under the boundary conditions mentioned in Chapter 1

But AM offers more – it offers the potential of initiating another Industrial Revolution[2]. AM enables everybody to create parts or products of any imaginable shape, to produce them from any desired material and quantity, and to do all this in any place and possibly even simultaneously in different places. This defines the beginning of an era of customized mass production, thus revolutionizing today's industrial world and society.

This potential of AM to initiate an industrial revolution is based on three of its basic properties:

- First, AM processes deliver very complex geometries, which cannot be fabricated by most of the non-AM processes.
- Second, at least in the near future, the materials can be varied to a great extent during the manufacturing process, leading to completely different part properties and products, respectively (graded materials, composite materials).
- Finally, the direct digital manufacturing process that does not require product-depending tools enables the manufacturing of different products simultaneously in one production-run wherever the fabricator is located. This opens up the chance of mass-production of individualized small series and even one-of-a-kind products at a variety of different locations.

Needless to say that the success of AM, to a great extent, is based on the fast development of 3D data acquiring and handling systems, including CAD systems as well as scanners, internet based 3D data sources, and 3D libraries. In the following, the main strategies will be addressed and underlined by examples. The examples are neither complete nor do they reflect any kind of ranking. The goal is to inspire the reader to look for similar applications in his business environment.

## 4.2 Potentials and Resulting Perspectives

### 4.2.1 Complex Geometries

Here, complex parts are those made directly and in one piece, if AM processes are utilized, while its production with non-AM processes requires multi-step processing or complicated tools with sliders and assembly operations.

[2] While the first Industrial Revolution, dated to the begin of the 18th century, is defined as the change of an agricultural to an industrial society, further important changes are judged different. The use of electricity and mass production in the beginning 20th century is called the Second Industrial Revolution (G. Friedman), while the computer-based additive manufacturing is frequently called the third industrial revolution. The upcoming microelectronics industry has a similar potential. The definitions are not final.

As discussed earlier in Section 3.8 and demonstrated in Figs. 3-34 and 3-35, a human skull, which is one of the most complex parts imaginable, can be made directly and in one piece using AM processes. Most non-AM processes would not be able to manufacture such an elaborate part or would require time and money consuming tools or intermediate process steps with subsequent assembly. The figures underline that different AM processes can be used, depending on the customers needs. Comparable complex engineering parts are tools or tool inserts with contour adapted, so-called conformal cooling channels /Geb09/. The idea of "close to surface" cavity cooling is not new, but until recently it was limited to straight drilled geometries with round cross-sections that could not follow the cavity contour close to the surface. AM allows to make user-defined cooling channels or even 3D shaped grids, thus improving the tools' productivity enormously. Figure 3.32 showed an AM conformal cooling channel in contrast to a drilled straight one.

An even more complex interconnected cooling grid was shown on Fig. 3.33 as a CAD drawing and as a cut-away view after AM processing. The mold insert was made using selective laser melting of steel powder.

Another example for a very complex geometry, again from the medical field, is the model of the bronchial tubes shown in Fig. 4.1. The part was needed as a lost core for the production of a transparent test duct for flow investigations of the human respiratory ducts /Bru03/. The data can only be acquired from living individuals and must be obtained from a CT (computerized tomography) scan followed by a 3D reconstruction. The core was built by a powder-binder 3D printing process. In order to obtain a clean duct, the core's complete decomposition after casting was necessary. Therefore it was built using the minimum possible amount of binder. This resulted in a very fragile part that required an extremely sensitive handling and cleaning.

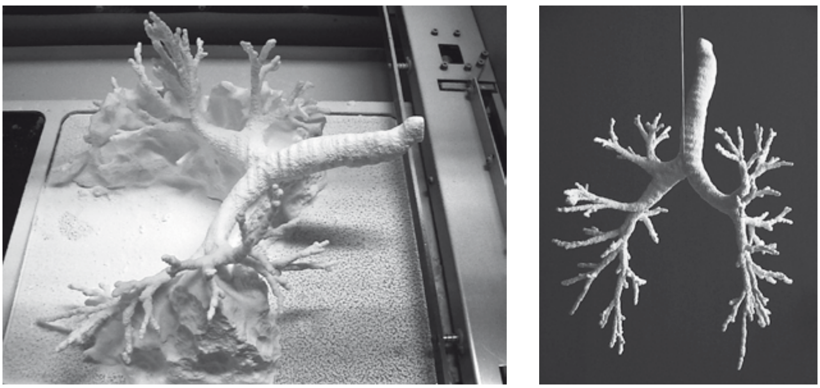


**FIGURE 4.1** 1 : 1 scale model of human bronchial tubes; 3D printing (powder-binder); final part (left); part during removal from the machine (Source: RP-Lab, Aachen University of Applied Sciences)

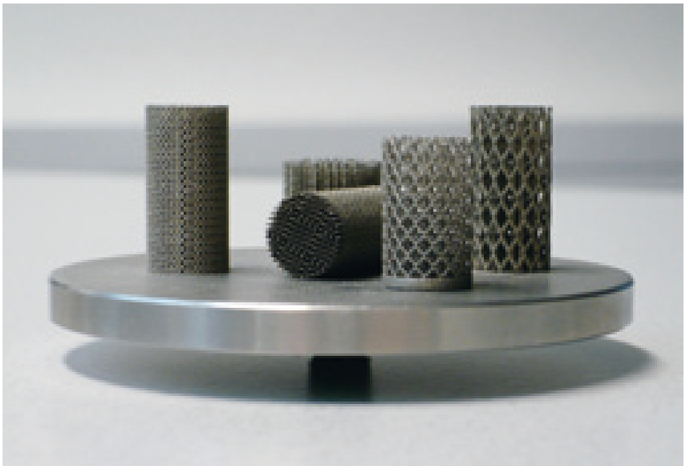


**FIGURE 4.2** 3D grid, selective laser melting; CoCr alloy; parts as removed from the machine (Source: RP-Lab, Aachen University of Applied Sciences)

Another example for the almost unlimited range of part geometries that can be manufactured by AM is the 3D grid displayed in Fig. 4.2. It also proves that the manufacturing is capable to deliver filigree and complex parts not only using plastic but also using metal.

The spaced grid in Fig. 4.2 is not a product but it demonstrates the capabilities of AM to make implants, heat exchanger elements, stiff lightweight structures, and others. AM even allows the manufacture of non-even spacing, varying diameters, and non-round cross-sections – if necessary on the same platform.

### 4.2.2 Integrated Geometry

In today's non-AM (or traditional) manufacturing, the complex geometry of a product has to be simplified to allow its fabrication. Typically, the part is divided into elements that can be manufactured according to the restrictions of the chosen fabrication process. In most cases final assembly procedures are needed to form the product. Alternatively, complex tools are required to facilitate manufacturing in a one-step non-AM process such as die casting.

Here, we refer to integrated geometry as merging different elements into one part that can be directly manufactured by AM processes. Seen from the production point of view, integrated geometry and complex geometry are the same after the merger/assembly. From a strategic point of view it means to assemble the product virtually rather than doing it physically, thus avoiding the amount of tools needed, eliminating production bottle necks due to parallel production, skipping assembly, and reducing storage space and administration.

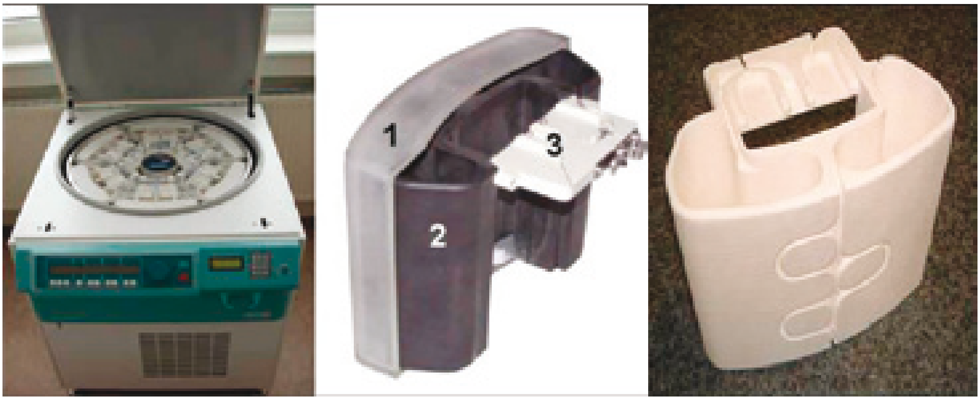



**FIGURE 4.3** Blood centrifuge, overall view, left; blood container made from three plastic injection molded parts, center; AM blood container, one part, right; laser sintering, PA. (Source: Hettich/EOS)

Non-AM production by plastic injection molding provides a very good example.

Plastic injection molding requires making a relevant number of tools, molding each part, finishing it, and assembling of all parts to obtain the final product.

Using AM, the different parts can be integrated into one geometry that can be fabricated in one piece. As an example, Fig. 4.3 (left) shows a blood centrifuge for blood test preparation. While the machine body is standardized, the containers typically belong to the hospital equipment and vary due to company policy and local or state standards. The container consists of three parts to allow the undercut-free manufacturing by injection molding and the adaptation to the centrifuge. Figure 4.3, center, shows one of the blood containers as it was made traditionally and assembled from three parts.

Unfortunately, in many cases the number of containers needed is too small to justify the tool costs, thus excluding the SME-type company from these markets. Using AM solved the problems. The container was re-designed in one piece by integrating the individual adapting geometry (Fig. 4.3, right). Because no tools were needed, even small series could be made on request, using the AM process of sintering of polyamides. The costs per container are higher using AM than injection molding, but far beyond the break-even price including tool costs and thus very economical.

Another example for complex and integrated geometry was shown in Fig. 3.28. Here, very complex kernels for sand casting are displayed which are made from foundry sand by laser sintering. Using non-AM technology, complex kernels for casting were assembled from a number of different parts. This was a mainly manual work and therefore costly and time consuming. In addition, it implied the risk of misalignment which can lead to core displacement and cause holes in the cast parts.

**FIGURE 4.4** Guide wheel for an Aero Engine Airplane combustion chamber element (left) Source: EOS/Morris Techn.; hot work steel; base plate (right), aluminum, dimensions 30 × 100 × 50 mm (Source: Concept Laser)

Examples for complex parts can be seen in Fig. 4.4. The guide wheel element of an airplane engine, left, is made from stainless hot-work steel by laser melting. It is quite a big part with dimension of 298 × 120 mm and ready for installation as a final part.

The base plate of the mirror shown in Fig. 4.4, right, is made from aluminum (AlSi12) and has the dimensions 30 × 100 × 50 mm.

The traditional manufacturing alternative for both parts is a sequence of casting, welding, and milling, including heat treatment.

The capability of AM to integrate geometric elements traditionally manufactured separately due to manufacturing restrictions, offers a great potential in terms of flexible production, reduced amount of parts and assembly costs, including related quality assurance and spare part management. The principle can be transferred to all types of parts and all branches of industry.

### 4.2.3 Integrated Functionalities

Here, integrated functionalities are mainly geometry based kinematic functions that can be made in one build when AM is used, but require tooling of several parts, assembly and adjustment when made by non-AM manufacturing.

Using plastic materials, the elasticity of the material is used to obtain functions such as film hinges or snap-fits. While this can also be achieved by plastic injection molding, AM additionally allows to make parts with articulators such as mechanically linked hinges and similar constructions in one build and from any processable material.

As an example, the adjustable air outlet grill of a passenger car, displayed in Fig. 1.8, was manufactured as a single piece in one build using laser stereolithography. The gaps needed for the movement of the hinges are created by leaving one or two uncured layers of resin between the adjacent parts (see Chapter 5). After cleaning by moving the parts, the hinges are ready for use.

This approach to the manufacture of linked but articulated parts can be regarded as an engineering design principle of AM. It is preferably used for plastic sintering processes, but can also be employed with polymer jetting, 3D printing, and extrusion (FDM). While the powder based processes work as discussed earlier, the processes that require supports have to use support material to define the gaps. Consequently, the supports have to be removed after the build. From this perspective, soluble supports offer advantages. The scaled wrenches made from plastic material displayed in Fig. 4.5 are very good examples for movable elements such as guides, gears, and in this case especially worm gears. They also show that different AM processes, in this case polymer jetting and FDM, can lead to reasonable results.


**FIGURE 4.5** Scaled wrenches, demonstrators; polymer jetting, acrylate (top); extrusion, FDM, ABS (bottom)
(Source: Objet (top), Dimension/Stratasys (bottom))

Based on the same principle, "bullhead type" rivets can be designed to make articulated arms, hinges, and related parts in one AM build. The Articu-Light Lamp by the Brooklyn-based designer Paul Gower (Fig. 4.6) provides an interesting example. It was made in one AM build.

The articulated cable clamp in Fig. 4.7 is another very good example of how traditionally manufactured multi-part products can be made faster, better, cheaper, and in one piece by integrating geometrical functions using AM.

**FIGURE 4.6** Articu-Light lamp, extrusion, FDM (Source: Paul Gower)

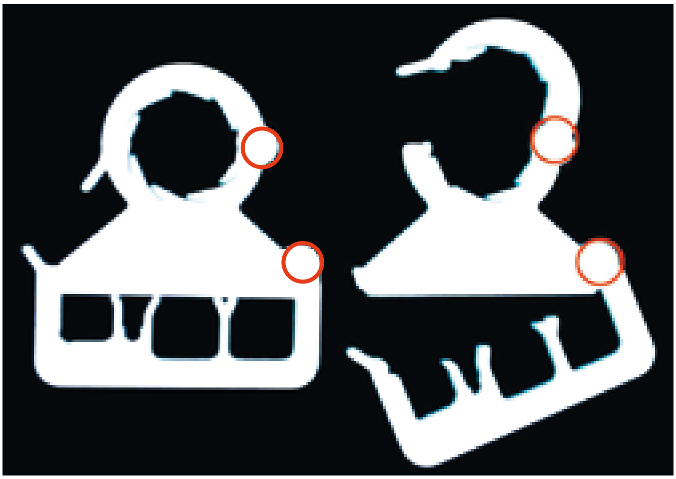


**FIGURE 4.7** Articulated cable clamp made in one piece using polyamide sintering; closed (left) and open (right) (Source: EOS)

Traditionally, a comparable cable clamp consists of various metal parts, screws, and rubber inlets to fix and protect the plastic cables /Len05/. An AM compatible cable clamp was designed from a single plastic (PA) piece with two movable closures, one for the supporting tube and one for the cables. Each of the closures can be operated and closed by a snap-fit mechanism. Even the elastic fixture, traditionally is made by rubber inlays, was integrated. As a replacement of the rubber inlet, the solid plastic material was shaped like a saw tooth to bridge the emerging gap and to obtain the desired elasticity to fix the cable. The basic design shown in Fig. 4.7 can be varied in

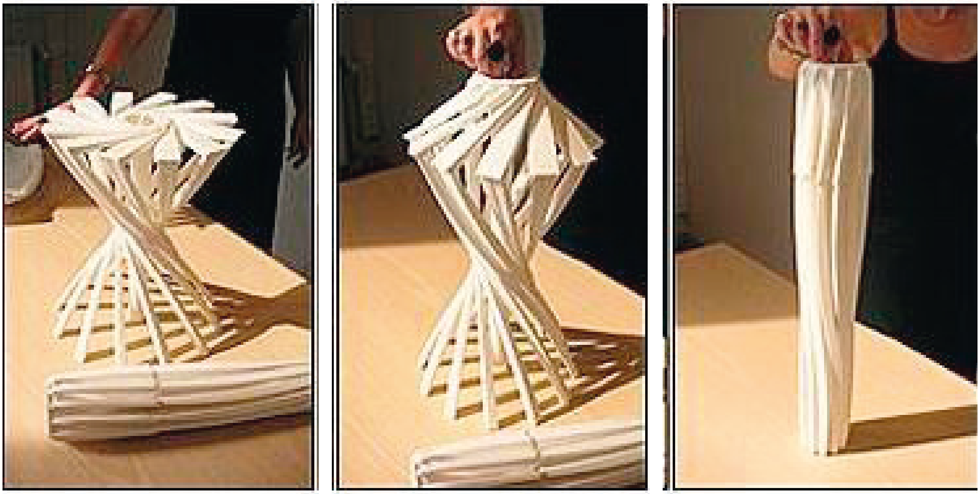


**FIGURE 4.8** One shot stool, laser sintering, polyamide (Source: Patrick Jouin)

terms of basic shape, diameter, number of fixing paths, and so on. Different designs can be made in one AM built. After the built and smooth sandblasting, the parts are ready for use.

The "one shot stool" by Patric Jouin (2006), Fig. 4.8, uses the same principle. It consists of a structure of articulated elements that can be manufactured only by AM. The lack of any type of rivets, bolts, or screws leads to the elegant appearance and the surprising application. The "one-shot-stool" demonstrates that the invisible integrated connection of articulated elements is a dedicated element of AM technology that would cause significant manufacturing efforts if made traditionally.

Another variation of this principle is a fin-type actuator presented by FESTO. It represents another type of engineering design element, the flexure hinge. Flexure hinges are solid elements that are bent by exterior forces. This movement is used for micropositioning systems that are typically operated by piezo elements.

As can be seen in Fig. 4.9, the construction consists of a closed, thin-walled, acute-angled triangle with two long thin-walled arms and a rigid base. Because of 5 movable connectors parallel to the base which link the long arms, the element can be continuously adjusted to a wide variety of defined fin-shaped contours after a momentum is applied on the base. As shown in Fig. 4.10, right, the actuator can be used as a very sensitive element of a bionic handling system that resembles an elephant's trunk and will be shown later.

The actuator is made in one piece from aluminum-filled sintering powder that provides a technical appearance of the surface. With the different wall thickness of the triangle and the moving elements and the integrated connectors, the part can only be made

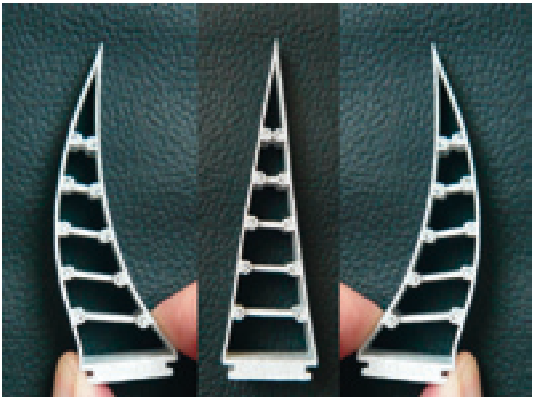


**FIGURE 4.9** Fin-shaped actuator (left), shape variations due to the applied momentum on the base plate; filled polyamide (Source: FESTO)

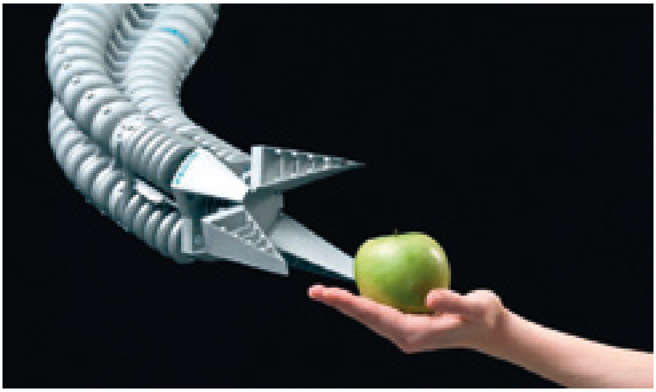


**FIGURE 4.10** Bionic handling system resembling an elephant's trunk. Assembled from sintered elements as shown in Fig. 4.9; laser sintering, polyamide (Source: FESTO)

by AM. Regarded from a systematical point of view, the actuator is a combination of a flexure hinge (triangle walls) and a classical two-piece hinge sintered in one piece.

The company is specialized on pneumatic systems and introduced sintered bellow-type elements operated by compressed air. AM allows variations in wall thickness according to the requested motion. A complete bionic handling system that resembles an elephant trunk was introduced at the Hannover Fair in 2011. It integrates the actuator and pneumatic elements and is operated by a Bowden cable and compressed air (Fig. 4.10).

Using a combination of some of the principles mentioned earlier together with solid joints or flexure hinges led to the "easy push". The mobile phone extension cover "easy push" shown in Fig 4.11 (left) enables older, handicapped, or people wearing gloves to use a commercial mobile phone without having to buy an expensive special model.

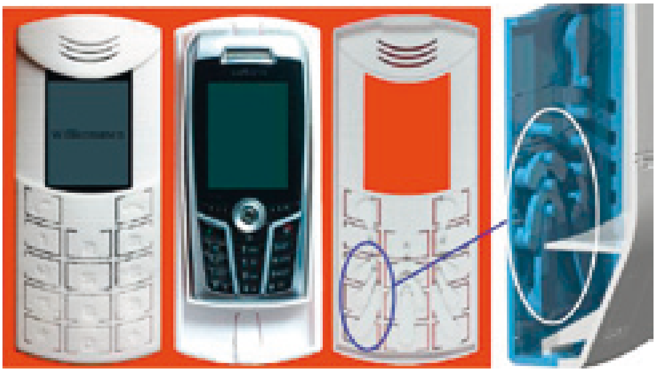


**FIGURE 4.11** Mobile phone extension cover “easy push”; laser sintering, Polyamide (Source: Tobias Fink, Aachen University of Applied Sciences)

The cover consists of two parts, one with a frame-like housing for the phone (Fig. 4.11, middle, left) and another that bears the key operation adapter mechanism (Fig. 4.11, middle, right and detail right). Both parts, especially the top one that bears the key operation mechanism, are made in one piece each and they are ready for use as they come from the machine. This is very important, because the key operation mechanism does not allow post-processing or finishing except for low pressure sand blasting. The polyamide material used is strong enough to guarantee long service life but flexible enough to assure the proper function of the key operation adapter mechanism. The surface of the keyboard can be finished by water transfer printing as shown on Fig. 3.19.

The basic design can be easily adapted to other commercial mobile phones and directly fabricated as a one-off.

Another example for an elaborated version of flexure hinges that cannot be made by any other fabrication technology is the mirror positioning system displayed in Fig. 4.12.

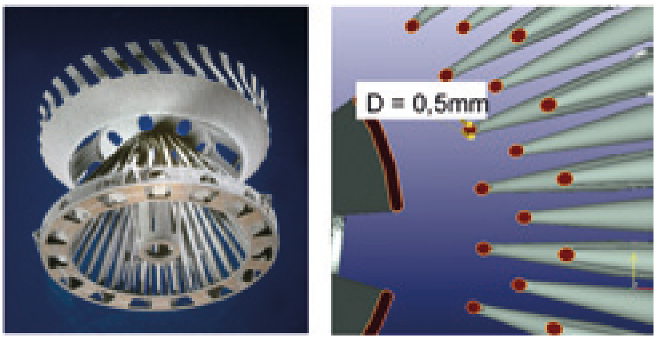



**FIGURE 4.12** Fastener and positioning system for a laser mirror designed as a flexure hinge made from titanium; the tubes are hollow with cooling channels for temperature control; selective laser melting (SLM), titanium (Source: Over, BESSY)

The mirror is part of a scientific laboratory for the investigation of electron acceleration. For proper adjustment it must not only be precise but also needs an integrated temperature compensation mechanism to avoid thermal induced misalignment. Following the flexure hinge principle, the positioning is done by deformation of the whole structure. The deformable flexure hinges are hollow tubes with a diameter of approx. 0.5 mm, into which water channels are integrated to assure the cooling. The whole part is made in one piece from titanium. The flexible fasteners of the mirror are also integrated.

Making fabric-type flexible products such as hand bags or clothes by AM was first presented by FOC several years ago. Although the use of hard materials to form a soft product was interesting, the design resembled chain armor rather than modern cloth. In 2011, a couple of young ladies from “Continuum Fashion” rejuvenated the idea and presented the world’s first AM bikini. The structure consists of small circles linked by tiny strings that act as flexible connectors. This esthetic design also met the structural requirements such as durability and flexibility and most of all: fit. Continuum Fashion calls it a completely new material. Because of the rough surface of sintered polyamide, the product is designed to be worn only temporarily at the beach. The hydrophilic behavior of the material does not affect this use because the small geometric changes caused by the water do neither affect the fit nor the elastic function. The part has to be protected from UV radiation by special coatings. Although the tiny connecting strings can break when loaded, there is no repair solution yet.

Despite these drawbacks, the project is another step towards using AM for making clothes. This kind of product opens up another field for customized products (see Section 4.3).


**FIGURE 4.13** AM of clothes; “World’s first 3D printed bikini”; laser sintering, polyamide (Source: Continuum Fashion/ Shapeways)

### 4.2.4 Multi-Material Parts and Graded Materials

The majority of the parts discussed and shown in this book consist of one (almost) isotropic material. This is considered to be a requirement, because most non-AM processes, such as milling or casting, deliver isotropic parts with uniform properties and engineering designers are used to handle isotropic materials. However, AM has an even broader perspective. AM is capable to handle multi-material processes. The discussion begins with today's applications but includes new and emerging processes as well, because they will enter the market in the near future.

Already commercialized, the polymer jetting (PolyJet, Objet) process (Chapter 2, Fig. 2.6) is capable of simultaneously processing two materials with defined proportions, thus simulating a two-component plastic injection molding part. As an example, Fig. 2.7 (right) showed a wheel consisting of a rigid hub and an elastic hoop which was processed in one piece. Another example is the razor handle in Fig. 4.14 (left), also made in one piece from a combination of a flexible and a rigid material. Figure 4.14 (right) shows a working prototype of a paper trimmer with built-in laser cutting guide. It was made using PolyJet parts from a soft (light grey)/ hard (dark) material combination.

Considering the support material that is printed simultaneously with the actual part, one can easily imagine not just a two-, but a multi-material AM process. The same is valid for FDM processes. Today, two simultaneously working extrusion heads apply the build- and the support materials. There is no technical reason why the machine should not be able to operate three or more materials.

Figures 3-39, 3-40, and 3-42 represented parts that are colored during the AM process. Seen from a material point of view, different colors mean different properties and a process that delivers infinite numbers of properties in one part is imaginable.

**FIGURE 4.14** Razor handle (left), X-ACTO laser paper trimmer (right), polymerization (PolyJet) (Source: Objet Geometries)

The 3D printing process and all AM processes that add the build material voxel by voxel to the part are basically capable to build each voxel with different properties. In the near future we will be able to design and build products with properties such as tensile strength, elasticity (Fig. 2.7, right), transparency, electrical and thermal conductivity, and others varying across their cross section,thus adapting the material locally to the designed values.

An emerging application of AM that deals with multi-material processing of organic materials is food processing. The first attempts go back to the Fab-at-Home cold extrusion process that applied liquid or pasty prefabricated food that got dimensionally stable after extrusion, forming an eatable arbitrary shaped geometric object. Today, "The Cornucopia", a MIT-backed 3-D printer concept that claims to be "a personal food factory that fuses the digital world with the realm of cooking by storing, precisely mixing, depositing, and cooking layers of ingredients with no waste" brings dynamic into the discussion (Fig. 4.15).

**FIGURE 4.15** AM of food; MIT 3D food printer concept "The Cornucopia"; the printer set-up, left; details of the print head, right (Source: Diane Pham/Inhabitat.com)

The food printer works with food canisters that define the cook's offerings. The clients make their decisions on site and watch the selection, the mixing, and the real time preparation of their food. The deposition of the various food components is done via extruders. The extruders are equipped with heating or cooling tubes that prepare the final meal. Food printers work very exactly in terms of reproducibility and composition. They also provide a precise management of ingredients, such as fat, lactose, calories, carbohydrates, and others. Whether they really reduce waste must be decided by future investigations, including the preparation of the raw food and the cleaning of the printer.

These developments add a new dimension to manufacturing as well as to the engineering design systematic. Machines such as the Optomec's M3D™ or Envisiontec's 3D-Bioplotter™ will be able to process electronic circuits, drugs, and human tissue. In early 2010, scientists from Organovo used the NovoGen MMX Bioprinter to make the first printed vein. A future option of printing even organs is coming into sight.

## 4.3 AM-Based New Strategies – Customization

For several years customers increasingly demanded individualized products. The buyers reject mass produced parts and long for a unique, individual, and distinctive product – the customized product.

It is very hard to meet these requirements under the law of mass production. Because the economical success of a production is closely linked to the number of products made per time unit, tools are necessary. Tools are producing identical parts. Tool production is costly and time consuming and the tool's service life must be long to achieve the high volume output that is needed to make a return on investment. Product changes and sometimes even smaller design updates are avoided if possible, because of the costs and time needed to modify tools or tool inserts and to update the production machines.

AM has the potential to initiate a real change. AM is a manufacturing technology that does not require tools and for this reason it perfectly meets the requirements of individualized production. AM can make different parts in one build process. Each part can be either "one-of-a-kind", or belong to a small, medium size, or even big series.

"AM changes production from mass production of identical parts to mass production of different or individual parts" – this is the revolutionary aspect of AM that can be regarded as a paradigm shift in production technology. There are different approaches to customization by AM. AM can be performed under the roof and in the responsibility of the manufacturer, but it can also involve the customer or even be done by the customer, thus changing today's product development and production structure completely.

Although from a manufacturing point of view customized design is independent from customized production, customization always involves the customer as a designer, at least up to a certain point. Any serious discussion therefore has to take into account both, design and manufacturing. If the manufacturer is in charge and runs the production on his site, the approach is called *Customized Mass Production*. If the customer himself does the production at home or under private responsibility, it is called *Personal Fabrication*. The design can be done in the responsibility of the manufacturer, or the customer, or anything in between.

Finally, personal fabrication by an increasing number of private customers provides the basis for internet linked, locally based production networks that form a totally new production strategy (*Distributed Customized Production – Coproducing*).

Regardless of which strategy is preferred, AM machines as well as any other type of production machines require investment and consequently have to make a return on that very investment by producing as many parts per time unit as possible. Whether the process is an economic one or not is determined to a lesser extent by the engineering design of the parts but rather by the organization of the AM-based individual mass production /Zae06/.

### 4.3.1 Customized Mass Production

Customization is the adaption of a product to the needs of a particular customer or a specific group of customers. Customization can be done in terms of quantity or of quality, which means making either one-offs or small batches or changing the part's appearance, geometry, or function. The part design can be changed according to the taste of groups of individuals, which is called *individualization*. If the part is made to meet the requirements of one special customer, it is called *personalization*. Personalization again can be done in two ways. If the customer provides just his biometric data, it is called *passive personalization*. If the customer uses his creativity to interfere with the design, it is called *active personalization*.

Customization is closely linked to part design, while AM is a manufacturing technology. As discussed in Section 3.1, AM is an integrated design and manufacturing process. Consequently, its main influences cannot be regarded separately.

#### 4.3.1.1 One-Offs and Small Batch Production

One-of-a-kind products or small batches are the quantity approach to customized production. The customization effect is the production on demand, while the product remains unchanged. AM allows to manufacture of any quantity that fits the customer's needs – just one piece in total, one part per time unit, or a small quantity of parts several times per year. If such a kind of production were done with tools, it means running the process several times or producing a much bigger quantity than needed at one point and then stocking the over-production.

As an example, a leak detector is displayed in Fig. 4.16. The customer orders a small batch of equal products every couple of months. The total production number is too small to justify a tool and subsequent plastic injection molding. The product's housing is made from polyamides by plastic laser sintering. It is finished in black and assembled using the electronics, a printed display, sensors, and the handgrip.

**FIGURE 4.16** Leak detector; laser sintering, finishing and assembly (Source: CP-GmbH)

#### 4.3.1.2 Individualization

Individualization and personalization (see Section 4.3.1.3) are quality approaches to customized products. With AM, the number of different variations of a product made at once can be increased in order to meet the requirements of different groups of clients. The strategy is called individualization, when the part is designed by the manufacturer. As an example, Figs. 4-17 and 4-18 show different AM masters for making jewelry rings, representing two AM-based ways to produce the final part: wax printing of scaled masters for casting with the lost wax process (Figure 4.17) and direct manufacturing of jewelry by selective laser melting of precious metals (Fig. 4.18).


**FIGURE 4.17** Customized production; individualization, jewelry masters for investment casting processed in one build (Source: Envisiontec)

**FIGURE 4.18** Customized production; individualization, jewelry direct manufacturing by selected laser melting of gold (Source: Realizer GmbH)

The customers are not personally involved in the design, which was made by professional designers, based on interviews of the representatives of targeted customer groups and other related marketing methods. The different parts of each variation are made on one platform and by the same build.

Alternatively, there are various AM processes available that support the two approaches.

High quality investment casting procedures were discussed in Section 3.2.6.2. A complete casting tree made by 3D's ProJet printer and assembled manually is displayed in Fig. 3.30. The direct manufacturing of jewelry can be done using all-metal sintering and metal 3D printing processes.

Each AM process needs finishing just like the results of traditional processes need finishing procedures. This can be regarded as a disadvantage and as a reason to develop automated finishing devices – which are already emerging. But from a craftsman point of view this fact is regarded an advantage. AM does not take traditional jobs, but delivers perfect raw (or green) parts that need a master's skill and experience to turn it into perfect (jewelry) products. So, AM supports the competitiveness and further development of small and medium enterprises (SMEs).

Individualized products appear in almost any branch of industry. Examples were already shown in Chapter 3, Figures 3-15 to 3-26.

Today, even furniture is made by AM. An impressive example is the chair made by the French designer Patric Jouin (Fig. 4.19). The structure exposes the mechanical design. It could not be made by traditional manufacturing processes. Further examples are the individual art objects made by Bathsheba that were already mentioned in Chapter 3 (Fig. 3.23).

All examples given in Section 4.2.3 can also be regarded under the perspective of individualization. The mobile phone cover fits any imaginable mass produced mobile phone (Fig. 4.11) and the One-Shot Stool (Fig. 4.8) can be taken as a working principle.

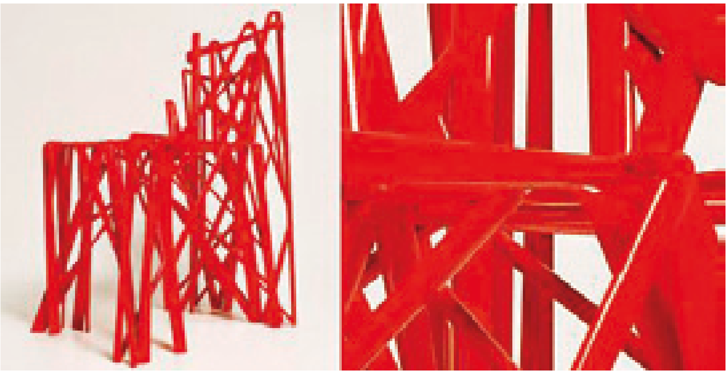


**FIGURE 4.19** Customized production; individualization; furniture: chair from the solid series by Patric Jouin (Source: R. Guidot /Gui06/)

Individualized products are not necessarily one-of-a-kind products and therefore can be made by non-AM as well as by AM. If, due to forced individualization and an increasing number of variations, the production volume decreases, the break-even point moves towards very small production numbers that can definitely be produced by AM alone.

#### 4.3.1.3 Personalization

Personalization is the development and manufacturing of a unique or one-of -a-kind product. Its details are dedicated to one special person who is the customer. The customer determines or mainly influences the design of the product either based on his biometric characteristics (passive personalization) or by his own creative potential (active personalization).

Personalization in general requires a basic design and a manufacturing chain that defines the product and the way it can be personalized. The final personalized product results from the adjustment of this chain and the software behind it, according to the needs of a special customer. The whole process, design as well as production, works under the responsibility of the manufacturer. Personalized products definitely require the production of a "one-of-a-kind" product. Therefore, AM is the preferred and in many cases is the only production method.

*Passive personalization* is closely linked to medical devices and products in the field of (not only medical) human-machine interaction. Medical products, for example, are implants, epitheses (extra-oral implants), orthoses, hearing aids, and related medical devices. They all have in common that the 3-D data of the part has to be obtained from the patient using medical imaging technologies, such as CT scans (computerized tomography) or US (ultrasonography or diagnostic sonography). Based on this and supported by special software, the data set of the personalized part is obtained and the AM part is built.

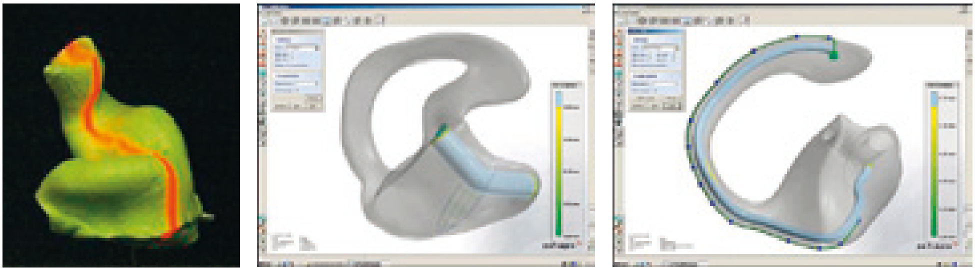


**FIGURE 4.20** Customized production; personalization; design of personalized hearing aid shells; manual imprint (during subsequent scanning), left;
design of the power vent canal (center), design of the resonance canal (right) (Source: Klare, M; /Kla05/)

A prominent example is the design and production of hearing aid shells. The process starts from a manually taken imprint of the auditory canal that is scanned to obtain its 3D contour (Fig. 4.20, left). In the future, the geometry will be directly scanned in the auditory canal and transmitted to the software.

Hearing aid shells need channels that guarantee ventilation and adjust the resonance chamber. The traditional manufacturing of hearing aid shells was limited to straight-drilled interior channels in order to enable manufacturing. With AM, arbitrary shaped channels are no longer a manufacturing problem. Special software, based on the results of an audiogram of the patient, optimizes the shell geometry and its interior structure. As an example, both the interior 3D resonance canal and the power vent canal can be seen in Fig. 4.20 (center and right).

The production can only be done by AM. Figure 4.21 shows the build platform with a couple of hearing aid shells after the build and while being removed from the machine.

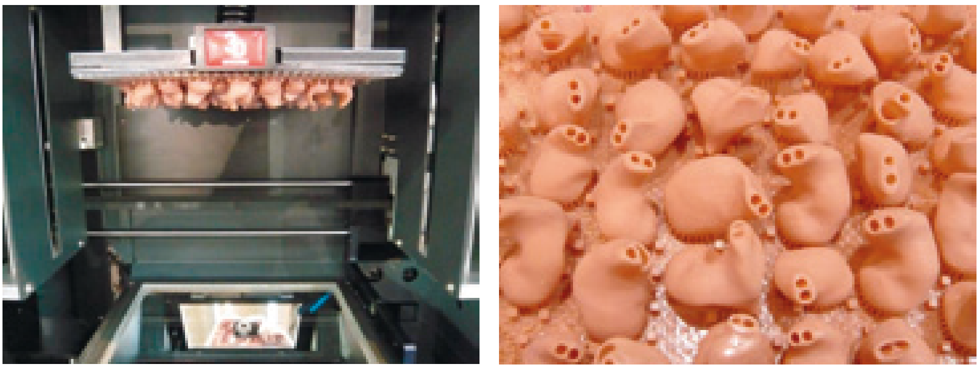


**FIGURE 4.21** Customized production; personalization; AM production of hearing aid shells, left; hearing aids shells, right (Source: 3D Systems)

The machine is a 3D Systems V-flash machine that works upside down (see also Fig. 2.27, left). Up to 50 pairs of hearing aid shells can be produced on one platform and they may all differ from each other (Fig. 4.21, right).

Another important personalized product is the dental bridge shown on Fig. 1.11, right. Generally, dental devices made by AM gain more and more economic interest. With the introduction of the fully digital process chain, the dentist can be an active part of the design and production process. In the future, the dentist will acquire the data using his intraoral scanner. Supported by special software, he will be able to complete the dental restoration directly on the computer or share it with the dental technician. The dental device will be produced directly by AM. In competition to this direct design and manufacturing chain, manual work done in low-wages countries will no longer be advantageous.

Figure 4.22 shows the digital design of another dental aid, a removable partial denture, also called: partial (left). It is a fixation for artificial teeth and needs to be detailed and strong, but must also endure high loads during operation as well as when put in place and removed. Casting is the method today, but comes with many problems, mainly because of pores and distortion. AM by selective laser melting promises to be a very good alternative production method. The finished product made from Co-Cr-alloy by SLM can be seen in Fig. 4.22, right.

*Active personalization* involves the customer and his creative potential. As most of the customers are not familiar with 3D CAD, the simplest way, but with limited design freedom, is to download the data from specialized Internet-based 3D part libraries such as Shapeways. Some of these libraries offer AM production as well or are linked to independent service offices. A step towards more personalized products is to use sites that support the individual change of prefabricated data. They also offer the exchange

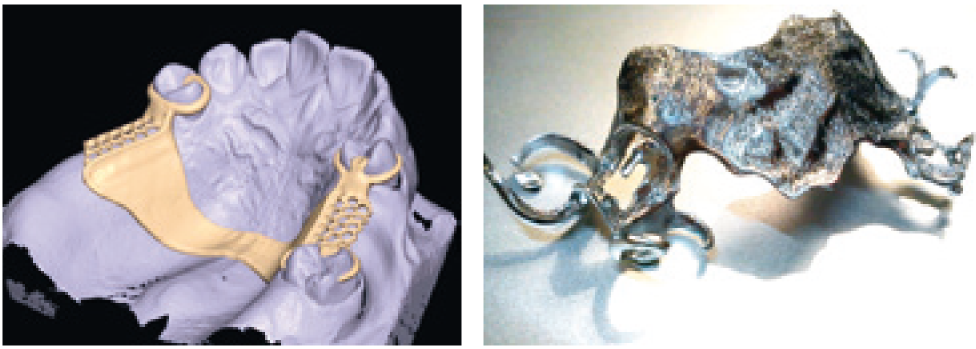


**FIGURE 4.22** Partial denture; digital design (left), finished part made by selective laser melting (right) (Source: SensAble Dental Lab System (left), RP Lab Aachen University of Applied Science (right))

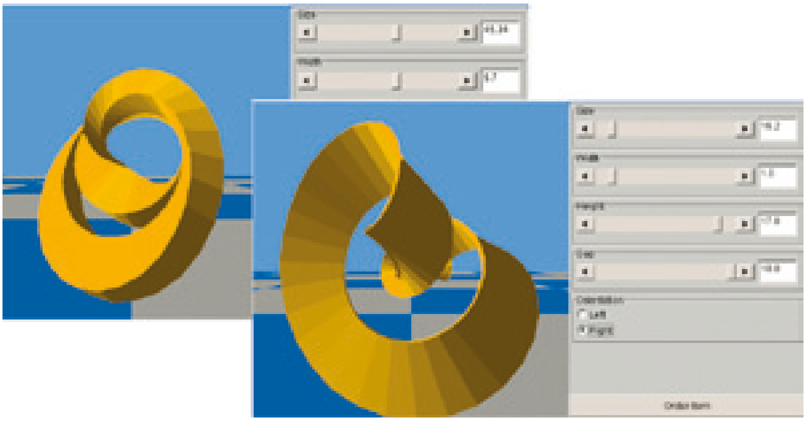


**FIGURE 4.23** Customized production; personalization; Meta Design, software-based personal design of jewelry (Source: University of Zurich)

of data sets or the guided operation of simplified 3D part processors such as Google SketchUP. Based on this, the customers can transform their ideas into a processable data set that can be produced by any AM machine.

A similar way towards a personalized product is to use Meta Designs. Meta Designs delivers a completely designed product but allows the customer to change some of the key-parameters in order to define a unique product.

As an example, Fig. 4.23 shows two screen shots of a jewelry ring during online personalization by manipulating the scroll bars in the navigation area. After conclusion of the internet-based design process, the jewelry will be produced as a one-of-a-kind product using a suitable AM process. Design and production are either under the responsibility of the manufacturer or split according to who delivers the design and who does the AM.

The applications discussed in Section 4.2.3, the articulated cable clamp (Fig. 4.7), the actuator (Fig. 4.9), the related bionic handling system (Fig. 4.10), the mobile phone extension cover "easy push" (Fig. 4.11), and the printed bikini (Fig. 4.13) are examples of individualized or personalized products as well.

### 4.3.2 Personal Fabrication, Self Customization

If the strategy of customization is realized under the responsibility of the customer alone, it is called self-customization. Typically, the design is made by the customer either using internet-based tools discussed in Section 4.3.1.3 (personalization) or, depending on his design capabilities, by 3D AD software. Self-customization implies manufacturing by AM, which until approximately 2005 was not economically viable.

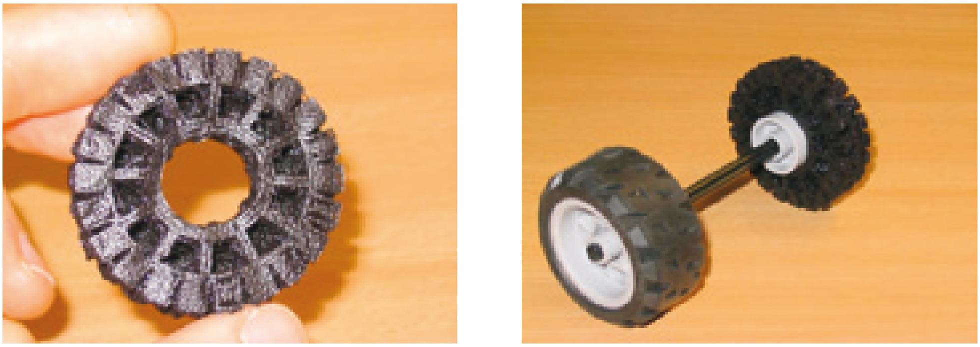


**FIGURE 4.24** Self customization; Toy car tire made by Fabber 1, left; mounted on a Lego hub and axis, right background (Source: Fab-at-Home (www.fabathome.com))

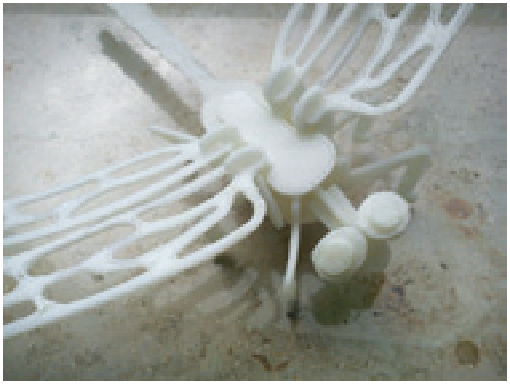


**FIGURE 4.25** Self customization: Sculpture of a dragonfly assembled from several parts made from polyamide using the Fabber 1 (source: RP Lab, Aachen University of Applied Sciences)

Since then, cheap and easy to operate machines called fabbers or personal fabricators (PF) entered the market (see Section 1.4).

With this development, a rapidly increasing number of PFs and an enormously growing community based on Internet blogs such as Fab-at-Home or manufacturer-linked user communities such as RepRap initiated and supported a fabbing movement comparable only to the development of the personal computer 40 years ago from simple platforms such as the ATARI. Examples are custom made car tires that fit the Lego hub and axis shown in Fig. 4.24 and the sculpture of a bee assembled from several parts made by the Fabber 1, Fig. 4.25.

Today's simple fabbers process only one material and consequently cannot make supports, which means that they are limited to simple-shaped parts. Advanced models such as the HP Designjet, the upgraded Makerbot, and others allow the use of two

(Makerbot allows even more, if integrated) nozzles with different materials and thus the application of supports.

### 4.3.3 Distributed Customized Production – Coproducing

In the near future, a huge number of fabbers will be available all over the world. Each fabber is owned by someone who is familiar with the machine itself, the net, and the computer. All fabbers can be easily linked via the World Wide Web (www). This opens up the unique chance to establish a worldwide production web that can be accessed, fed, or used by every web user who then can be regarded as an internet- or cyber manufacturer. Following the idea of the *Coworking* movement, this scenario is called *Coproducing*. Based on cloud computing systems, a cloud manufacturing system will be formed.

AM is the most capable technology to realize such kind of distributed world factory, because the different AM machines can be run independently at any time. In addition, all AM processes can be run by STL files that are similar in any place of the world. In contrast to the most CNC control programs, this allows easy processing of any STL file on any machine. As the total variety of AM machines can process almost any material and cover a wide variety of dimensions, a coproducing network can manufacture almost anything, any place, and anytime.

Because most everybody who owns a fabber also has some level of design capabilities (as mentioned earlier), a world wide design and production web is likely to develop in the near future. It's important to note that such a network is a self-organizing movement that will grow whether established structures want it or not.

## 4.4 Conclusion

AM provides the opportunity to manufacture products with new features. It does not only support the production of very complex geometries, which cannot be fabricated using traditional (non-AM) processes, but it also allows to produce these products from different materials and even to vary the material properties within the part.

In addition, AM puts the traditional rules of manufacturing upside down. AM supports making an arbitrary number of parts of any shape from (at least in future) any imaginable material at any place in the world. It does not use product-depending tools and is therefore the basis of individualized and personalized mass production. AM marks the change from mass production of identical parts to mass production of one-off's.

AM allows the customer to exclusively design and manufacture his own parts, thus altering the classical rules. AM supports the idea of coproducing in an internationally networked but locally executed production community as part of a cloud producing movement.

## 4.5 Questions

### 1. Why can AM deliver parts with almost unlimited complex geometries?

As any imaginable part can be sliced (at least virtually), any part can be composed by its slices, regardless of what geometry it shows.

### 2. What kind of AM processes are capable of processing materials that vary in their properties within the parts?

AM processes creating parts voxel by voxel can basically change the material properties of each voxel.

### 3. Give at least three examples for material properties that can be varied within a part.

Flexibility, color, or the composition of different materials.

### 4. Why can AM processes deliver arbitrary numbers of individual parts?

AM works layer by layer, regardless of whether the layers are identical or not.

### 5. What hinders traditional (non-AM) processes from making individual parts?

Non-AM processes need tools and tools require a comparably huge quantity of identical parts in order to realize a return of investment for the tools.

### 6. Why does individualization not depend on the selected AM process?

Individualization is a strategy to meet the customer's requirements. It basically is a design method that first of all defines the product. This product can be manufactured by several AM processes that might fit more or less. Whether it fits is not a question of the strategy but of its application.

### 7. Why is an AM-based, worldwide networked, local production more likely to be realized than a technology based on other digital controlled manufacturing techniques (such as CNC milling)?

Because all AM machines worldwide can be run with the same type of STL data files, while most CNC programs need machine dependent pre-processors

### 8. What are the characteristics of self customization?

Self customization is defined by the design and manufacturing of a personalized object by the customer's own AM device, preferably by a fabber.

### 9. By which criteria can individualized and personalized products be distinguished?

Individualized products are focused on target customer groups. They are produced in *small* series, but still in series. Depending on the break-even point, both non-AM and AM can be utilized. Personalized products are designed to meet the requirements of one only customer. This definitely requires a one-of-a-kind product made by AM.

### 10. How can hinges be made in one piece using AM?

The space needed to articulate the hinge is left as an unsintered layer of powder or an equivalent amount of support material. After the build, the powder is blown off or the supports are removed, leaving the space needed for the hinge movement.

# 5 Materials, Design, and Quality Aspects for Additive Manufacturing

This chapter discusses the materials available for AM, which design rules should be applied to obtain a good part, and how parameters have to be set for quality results. First, the influence of build processes on the parts properties are discussed for various AM processes and characteristics are presented. Second, the different types of materials that can be used for AM are discussed.

As for any other manufacturing method, AM requires that the user follows certain rules of engineering design. Some, particularly valid for AM, are presented. This field is quite young and still under development. Nevertheless, some basic design rules have been defined and help to make and use AM parts in an optimal way. Finally, the selection of a suitable AM process is addressed and aspects of quality assurance by *part property management* (PPM) are presented.

This chapter tries to identify and discuss the main influences on and characteristics of AM which differ the most from the traditional approach in terms of design, manufacturing, and material. It does not aim to be complete but rather tries to make the user aware of the possible problems in order to obtain quality parts. Some information has already been presented during the discussion of processes and machines in Chapter 2, but here they are regarded from a different point of view.

## 5.1 Materials for AM

This chapter addresses selected material-related topics that gained importance with the increasing use of AM. Because the part's material properties are determined only in part by the raw material, but result from the AM process as well, the overall part quality is influenced by a variety of parameters. Therefore, material, build process, and engineering design cannot be regarded separately but rather all of them need to be addressed.

**TABLE 5.1** Manufacturers and Distributors of AM Equipment

| Company | Headquarters | URL |
|---|---|---|
| ARCAM AB (publ.) | Mölndal, Sweden | www.arcam.com |
| 3D Systems, Inc. | Rock Hill, SC | www.3dsystems.com |
| Concept Laser GmbH | Lichtenfels, Germany | concept-laser.de |
| Cubic Technologies, Inc. | Carson, California | www.cubictechnologies.com |
| Envisiontec GmbH | Gladbeck, Germany | www.envisiontec.de |
| EOS GmbH<br>Electro Optical Systems | Munich, Germany | www.eos.info |
| Extrude Hone | Irwin, Pennsylvania | www.extrudehone.com |
| Mcor Technologies | Ardee, Co. Louth, Ireland | www.mcortechnologies.com |
| MTT-Group<br>Renishaw PLC | Stone, United Kingdom | www.renishaw.com/en/<br>selective-laser-melting–15240 |
| Objet Geometries Ltd | Billerica, MA | www.objet.com |
| Optomec, Inc | Albuquerque, NM | www.optomec.com |
| Prometal RCT GmbH<br>A Ex One Company, LLC | Augsburg, Germany | www.prometal-rct.com/en/home.html |
| Realizer GmbH | Paderborn, Germany | www.realizer.com |
| KIRA Corp. | Aichi, Japan | www.kiracorp.co.jp |
| SLM Solutions GmbH | Lübeck, Germany | www.slm-solutions.com |
| Solido | Manchster, New Hampshire | www.solido3d.com |
| Stratasys, Inc. | Eden Prairie, Minnesota | www.stratasys.com |
| Z Corp | Burlington, Massachusetts | www.zcorp.com |

As the materials itself and its selected properties are subject to continued improvements and rapid changes, brand names and properties are barely addressed. This kind of information can be obtained from the manufacturers' and distributors' customer service or internet platforms. This approach also makes sure that the upgraded last data version is obtained. A brief overview will be given on Table 5.1.

### 5.1.1 Anisotropic Properties

When materials properties are discussed in general, it is always assumed that the final parts will exhibit isentropic behavior. Isentropic means constant characteristic properties in any direction and identical values at any point of the part's volume. Isentropic material behavior therefore is a requirement for traditional tool-based production and consequently provides the basis for engineering design calculations.

When a part is manufactured in layers it is not surprising that the part will exhibit recognizable property differences. In this case, the part is said to have anisotropic properties, which means that its properties vary in different directions and within the part. Layer-oriented manufacturing by AM processes in fact produce anisotropic parts. The degree of anisotropy may vary: from barely recognizable to a degree that has significant impact on the part's stability. Although the degree of anisotropy depends mainly on the AM process, the orientation of the part in the build volume and its engineering design also play a role.

Because of the layer manufacturing, the part's properties parallel to the build area and those perpendicular to it differ from each other. This effect can be theoretically compensated by simply changing the orientation of the part in the build chamber. As a design rule, the area of the highest load should be parallel to the build area. In practice, the change of the orientation in one area of a part changes the orientation of all other areas as well. Therefore, any change of the part's orientation within the build chamber has to be decided very carefully.

The anisotropic effect is also closely linked to the way adjacent layers are bonded. The worst imaginable case is a delamination of layers. It is obvious that this might happen with FLM processes but delamination may occur with all AM processes. Figure 5.1 shows delamination in a laser sintered part that was made using inaccurate build parameters on purpose. As can be seen, the effect may vary within a part, resulting in local delamination.

The anisotropic effect depends on the AM process used. Laser stereolithography works with liquid resin and simultaneously solidifies the voxels within the layer by the same process as the bonding between two adjacent layers. Therefore, anisotropic effects are less pronounced. Polymer printing or PolyJet processes, in which a new layer is polymerized on top of an already hardened one, show a slightly more pronounced anisotropic behavior, which is true for laser sintering of plastics as well because an already solidified layer is partially molten for a second time in order to apply the next layer.

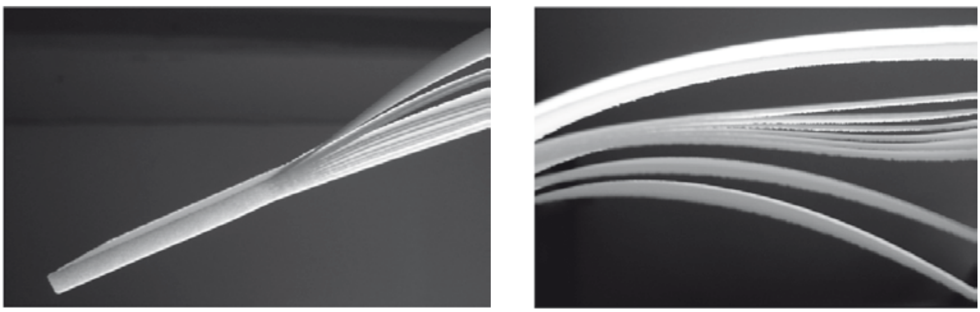


**FIGURE 5.1** Delaminating of layers due to inaccurate build parameters set on purpose; laser sintering, polyamide (Source: CP-GmbH)

Similar, but again more pronounced, anisotropic effects result from 3D-printing processes (powder-binder-processes). However, here the porosity of the part has a bigger effect on the part's properties than the layer-induced anisotropy. Infiltration reduces this effect, but does not eliminate it.

Compared to stereolithography, the extrusion processes (fused deposition modeling) show higher anisotropic effects. The process requires a pasty state while extruding the material, but does not allow the total melting in order to guarantee the geometrical stability of the partially finished build. This effect can be reduced by improved machine technology, especially by proper heat treatment and by using thin layers. Professional- and shop floor machines consequently produce reasonably reduced anisotropic behavior of the parts compared to personal printers and fabbers that work on the same principle. For these processes, the maximum endurable strength in vertical direction should be reduced to one half of the strength in the build plane (horizontal).

From the process point of view, layer laminate processes show the most pronounced anisotropic behavior because the prefabricated and therefore isotropic layers are bonded by some type of glue with completely different properties.

Unfortunately, these rules do not hold for all variations of processes and materials. While they are typically valid for plastic processes, laser sintering of metals causes different material behavior. The powder material is molten completely, resulting in fully dense parts that show just minor anisotropic effects. This is also indicated by the name *selective laser melting* (SLM) that labels the metal variant of the sintering process; however, the layers are still visible in the micrograph

Even the layer laminate manufacturing process, that basically shows the most elaborated anisotropic behavior, performs very heterogeneously. If paper is used and bonded by some kind of glue, the material is anisotropic. The anisotropic effect decreases, if plastic foils are used and are bonded by solvents. In contrast, the layers are completely invisible, even by micrographs, if metal foils are staggered to solid metal parts and bonded by diffusion welding or ultrasonic welding.

As a conclusion, the user may consider the above remarks for orientation but should double check with the machine manufacturer or the service bureau after the final process is defined.

With direct manufacturing processes, anisotropic part behavior must be compensated in the part design phase and also when the build parameters for AM are set. This requires information about the directional differences of the material properties. In many cases, this information is not readily available and the proper calculation of the part is subject to experience.

A systematic approach called *part property management* (PPM) (see Section 5.3) was developed by EOS /Mat10/. The system integrates special material databases, the so-called *part property profiles* (PPPs). Material properties are displayed for the build area (x-y) and vertically (z-direction) if needed, which unfortunately has not been common practice in the AM community in the past.

### 5.1.2 Basic Isentropic Materials

Today, AM allows to process materials of all material classes, namely plastics, metals, and ceramics. This is also valid for each of the five AM families (Chapter 2), although in practice the intensity of use varies considerably. Sintering of plastics and metals can be regarded as widely used standard processes, while for the extrusion of metal- or ceramic-filled materials processes are still under development.

The number of different materials within each material class is still quite limited, although this number has increased significantly over the last years and grows continually due to international research activities. The reason for the limited number of materials is that in most cases a simultaneous material- and process development is required. Material for plastic laser sintering, for example, must not only be locally meltable, but easy to recoat which requires rounded edges. Additives and process details, such as shielding gas and preheating, suppress local evaporation, oxidation, and other inter-process effects and interactions with the environment. This is one reason why powder materials for laser sintering are different from powders for sinter coating, although they are quite similar in terms of their chemical composition.

As a consequence, AM materials are usually developed by or under the responsibility of the machine manufacturer who treats the material as a proprietary product and exclusively sells it to his machine customers. Some users are skeptical, mainly because of economical reasons; but on the other hand, this approach guarantees a proper build.

The continuous increase of overall material consumption forces the activities of so called third party suppliers that already entered the AM business. Mainly for materials for plastic laser sintering and stereolithography independent markets are developing.

Metal powders are very similar to powders for laser coating and welding and therefore have been well known for many years. The user can chose among a wide variety but has to qualify the process, that means the development of the material data sheet, himself. Alternatively, the materials that are released by the machine manufacturer can be used, accepting the limited number of materials and the price level.

Some AM related problems are more elaborated and occur generally during manufacturing, because at this point there is no long-time experience with AM. The most important problems are aging and UV stability for plastics and corrosion, de-composition, sedimentation, and oxidation for metal powders, as well as pores and inclusions for all AM processes. The frame of this book will not allow to discuss all issues in detail.

#### 5.1.2.1 Plastics

Plastics were the first group of materials to be processed by AM and they still provide the biggest part of materials. Materials for stereolithography are acrylic or epoxy resins that must support photo polymerization. Today, the sticky and brittle materials of the early 1990s are replaced by materials that mimic materials for plastic injection molding. This was achieved by filling the resin with nano-particles to increase heat deflection temperature and mechanical stability. In addition, the variety of materials was increased and now includes transparent and non-transparent, elastic, stiff, and many more different materials.

For plastic laser sintering, polyamides are the preferred material. Although polyamides are one of the most popular thermoplastic material families for injection molding which creates confidence in this material, they also cause problems because the AM-polyamides and the ones used for plastic injection molding differ significantly from each other. First, even if the material would be chemically identical, the resulting parts would differ a lot, because a material that is completely molten and injected into a tool under high pressure shows different properties compared to the same one that is locally molten under atmospheric pressure, deposited layer by layer, and solidified by heat conduction. Second, polyamides are a big family with many special properties and consequently just the name polyamide is not sufficient to describe the material. Industrial products are typically made from polyamide 6 or 6.6, while laser sintering mainly utilizes polyamide 11 or 12. Polyamide 12 is used because it is barely hydrophilic and, even more importantly, offers a sufficiently big process window for reproducible manufacturing. The powder particles have a primary particle size of 20 to 50 μm.

Warping and distortion were severe problems in the early days of AM, however, are today reduced to a minimum due to preheating and improved scanning strategies.

There is a broad and successively increasing variety of polyamide-based powder materials for laser sintering on the market. This includes flame retardant, aluminum filled, and qualities that can be sterilized. Improved mechanical properties are provided by glass-filled powders, although this term is confusing, because spheres and rice-grain shaped particles are used instead of fibers in order to allow recoating. They provide higher stiffness compared to unfilled qualities, but do not reach the properties that can be expected from fiber filled injection molded materials. As the number of installed systems worldwide increases, an independent (third party) market for powder materials develops and influences the economic situation as well as the qualification of new and application-driven qualities. Different formulations, such as polyamide 6.6, have been investigated but did not reach the market yet.

Although the development and production of new products urgently asks for high performance plastic materials, currently there are only a few are available. A PPSU material is released for FDM extrusion processes and in late 2010 the high temperature material PEEK (polyetheretherketones) was introduced as EOS PEEK HP3. PEEK has excellent heat- and corrosion-resistant properties. It is flame and temperature resistant, chemical resistant, has high tensile strength, is lightweight, biocompatible, and can be sterilized. It has a melt point of 334 °C and requires a process window between 350 °C and 380 °C. This is far beyond the temperature ranges of today's plastic laser sintering machines and triggered the development of a completely new high temperature machine, the EOS 800/900.

Another group of materials for laser sintering are polyamide-coated particles made from almost any arbitrary material. It can be used in the plastic laser sintering machines. The most prominent applications are coated foundry sands for sintering of cores and forms for sand casting. Particle sizes of the uncoated material range around 50 µm.

Similar materials are available as coated metals. Here, the coating acts as a binder, making AM a two-step process; however, it is not widely used because one-step processes are available. But it opens up the possibilities for new materials such as coated filled spheres that act like granules.

The amorphous structured polystyrene is also used as a material for laser sintering, preferably to make lost cores and cavities for the lost foam process

For extrusion processes, mainly for FDM application but also for PolyJet processes, there are proprietary materials available and distributed by the manufacturers (see Chapter 2). For the latter, the user has to keep in mind that polymer-printing uses acrylates, while laser stereolithography prefers epoxy resins which exhibit better properties but require more energy for polymerization.

For FDM, the basic material is an ABS plastic grade. Because ABS is frequently used as a material for plastic injection molding, it is often regarded as a "series material". The user should keep in mind that ABS is a standard polymer able to resist significantly lower temperatures than polyamides.

For all AM processes that apply the build material from a separate storage (PolyJet, FDM) rather than keeping it in the build chamber (laser sintering, laser stereolithography), the material and consequently the parts can be colored. Although laser sintered or parts made by stereolithography can also be colored, however, this requires the coloring of all material stored in the machine and the fabrication of parts from just this color.

As a conclusion, an increasing variety of plastics can be fabricated using AM. This is valid for all five AM families introduced in Chapter 2. In Fig. 5.2 the plastic processes are plotted in the traditional "plastic triangle" that sums up the different plastics and distinguishes them from each other in terms of its basic structure (amorphous, crystalline) and their respective temperature resistance (HDT/A). Figure 5.2 should only be used for orientation. Temperatures in particular should not be obtained from it but double-checked with the supplier.

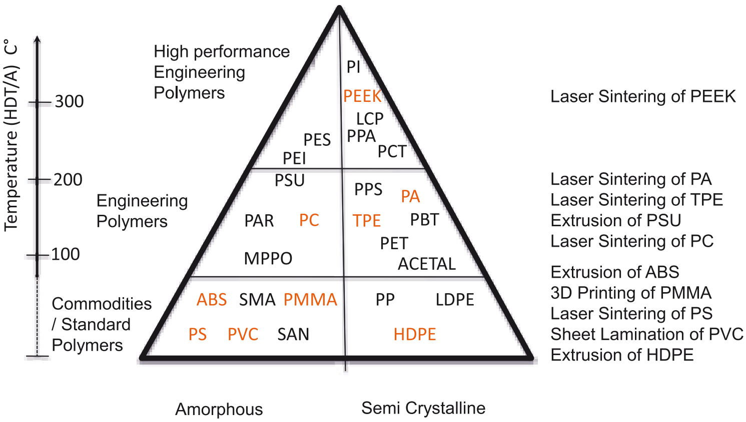



**FIGURE 5.2** Plastic triangle with plotted AM processes and related materials (based on /Kru07/)

Today, at least every level is represented by an AM material and process, except the level of imidized materials. Polyimides are a very interesting group of very strong and heat and chemical resistant polymers that would be very desirable to utilize as AM materials.

### 5.1.2.2 Metals

The most frequently used methods for AM of metals are sintering in the variation of selective laser melting and fusing (Chapter 2). The material comes as powders with a primary particle size of 20–30 µm. Because laser beam diameter, layer thickness, and width of the track are in the same size range, the scanning structure is clearly visible on the top (Fig. 5.3).

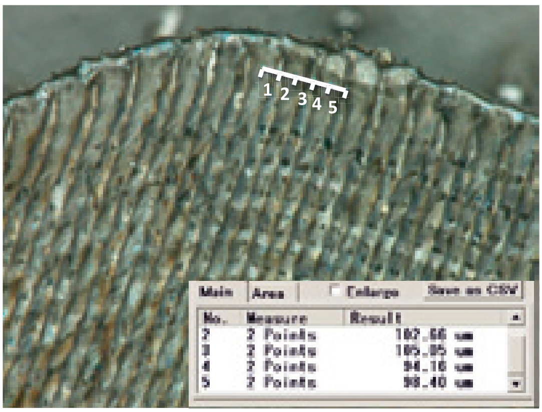



**FIGURE 5.3** Top layer of a laser sintered metal part (SLM)

The materials are very similar to the materials used for laser coating or welding with filler material. Therefore, a wide variety of qualities is available from different suppliers and a high level of expert-knowledge has already been gathered. Although various commercialized powders can be used, it needs to be taken in consideration that the qualification of the material must be made or at least evaluated in-house. On the other hand, powders delivered by the AM machine manufacturers come with material data sheets based on proven parameters that incorporate optimized scan strategies as well.

For AM of metals, stainless steel, tool steel, CoCr-alloys, titanium, magnesium, aluminum as well as precious metals, such as gold and silver are available. Recently, the first parts made from copper were presented /Pho11/, however, the process has not been commercialized yet. Proprietary variations, especially for dental applications, were developed and are frequently marketed in a package with specialized software and modified machines. Figure 5.4 provides a short overview over the different kinds of AM metals processable using metal laser sintering (melting). The data come from the service bureau 3 T RPD Ltd and is based on EOS materials (full bullets). In addition, some values obtained from other manufacturers are added, mainly from /CAS05/ (unfilled bullets).

It is important to take into account that other manufacturers offer a similar range of materials and that the properties displayed depend on many effects, as discussed in this chapter.

Layer laminate manufacturing is preferably linked to plastic and paper sheets and foils. If metal parts are required, only the ultrasonic consolidation (Solidica) process is available, which works with aluminum straps that come wound up and are bonded by ultrasonic welding on the top of the partially finished build. The machine also

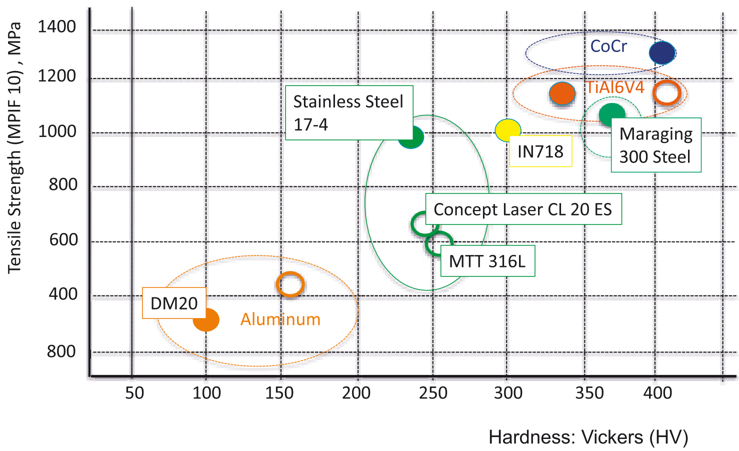



**FIGURE 5.4** Selection of materials for AM metal processes based on EOS, 3 T RPD and /Cas05/

contains a 3-axis milling device that contours the layer in the same clamping position. The process manufactures completely dense aluminum parts. Because the process is cold, even sensitive electronic parts can be put in the milled pockets and sealed with the subsequent layers. The parts are preferably used as integrated sensor housings for aeronautical and deep sea applications.

As a conclusion, the range of metal materials is even wider and their properties mimic the materials that are used for traditional manufacturing even better than plastics. A survey that discusses AM for metal micro parts including dental application and the deposition of various metals using the M3D process (Optomec) was published in /Geb09/.

#### 5.1.2.3 Ceramics

AM using ceramic materials is still subject to a specialized niche of layer manufacturing technologies. Although for each of the five families of AM processes (see Chapter 2) there exists at least one process, ceramic applications are still rare.

Here again laser sintering is the favorite process and the French manufacturer PHENIX Systems developed a high temperature machine for this technology. 3D printing is used as well, opening up the perspective of working with various powder-binder combinations, even proprietary ones. Doing so, a two-step process has to be accepted and the verification of the material has to be done in-house.

A laser stereolithography process working with a ceramic filled resin called Paste Polymerization was launched by 3D Systems/Optoform; however, it is not commercialized yet.

LLM is basically suitable to fabricate ceramic foils. The process resembles the traditional tape casting and is a two-step process with additional sintering.

Materials are available from the whole spectrum of ceramics, such as aluminum oxide, $Al_2O_3$; silicon dioxide or silica, $SiO_2$; zirconium oxide or zirconia, $ZrO_2$; silicon carbide, SiC; silicon nitride, and $Si_3N_4$.

Products are monolithic ceramics, mainly with flow-through channels and high temperature loaded structures, such as heat exchangers. Defined macro-porosities that support incorporation of implants are a unique selling point of resorbable bio-ceramics. Micro-porosities facilitate the production of micro reactors. A detailed survey can be found in /Geb06/.

#### 5.1.2.4 Composites

Composites in the sense of lightweight reinforced structures are barely known in AM. They consist of more than one material and therefore can also be regarded as graded materials (see Section 5.1.3). Composites are typically used to create light-weight products that are uniform in structure and that are isotropic or at least isotropic under defined angles of load, therefore they are mentioned here.


**FIGURE 5.5** Layer laminate manufacturing (LLM);
reinforced curved parts with integrated SIC fibers /Klo99/

In general, LLM is capable to fabricate composite parts with integrated fibers or fabrics, if these reinforcements are available as prepregs or flat semi-finished materials that can be integrated in the process. A specially adapted process for making reinforced curved parts from ceramic fiber (SiC), which avoids cutting the fibers, is mentioned in /Klo99/, see Fig. 5.5. It is capable to put the layers under defined but different angles in order to adapt the structure to the expected load. In addition, the part can have a (slightly) curved surface in order to create structural elements and to avoid stair steps parallel to the area of the load.

### 5.1.3 Graded and Composite Materials

Isotropic material behavior seems to be the basis of engineering design assumptions. This may be the fact because the majority of today's products follow this rule and both, engineering design and production, are optimized accordingly. But AM enables the manufacturing of products from materials with non-uniform properties that can be locally adapted to the load encounterd in use. Parts from such materials cannot be made by traditional manufacturing methods, but they can be produced by AM technology, because the material characteristics are not determined by the raw material alone but by the local melt pool, thus by the process. AM allows to locally influence, even to compose, the material needed for a certain application.

As an example, the parameter "color", which also defines a material property, can be adjusted during 3D printing (powder-binder process) which results in continuously colored parts. In the future, the same process can be used to adjust the flexibility or other properties of the part.

The polymer jetting process (Objet) can process different materials in the same build and their respective proportion can even be changed during the process. Two-component parts, for example hard-soft combinations, can be made to mimic two-component injection molded parts.

These examples are the beginning of the production of anisotropic products, which marks a unique selling point of AM parts. These first steps prove the general principle and will be developed intensively in the future, thus leading to the manufacturing not only of industrial products but of food as well as of medical structures, drugs and artificial organs. Examples are already available, although still under research and development.

In principle, all processes that are fed with material coming from small storage units, such as containers or wound up filaments, are capable off running in multi-material mode by simply multiplying the depositioning devices. PolyJet as well as 3D printing processes have already started to utilize this technique and there is no reason, why FDM should not be capable to be run in a multi-material mode.

But graded and composite materials are not just a challenge for AM. To benefit from the emerging opportunities, the engineering designer must be aware of them. Construction rules need to be extended to calculate anisotropic materials with arbitrary material parameters.

## 5.2 Engineering Design Rules for AM

To take advantage of the possible benefits of AM, certain design rules must be obeyed. They are mainly obtained from the practical application of AM and only to a lesser amount a result of methodical design investigations. As this field is quite new, a closed design guide, such as those for casting or milling, is not available yet. But as a rudimental beginning, some rules can already be provided.

### 5.2.1 Tolerances – Digital to Object

Engineering designers have to keep in mind that AM parts are built according to a 3D CAD drawing and that the tool path is defined by the part contour. To achieve this in the process, the tool path is retracted by half of the tool width, which is the beam diameter of laser based processes, to make the designed outer contour identical with the manufactured one of the part. For laser based processes, this is called beam width compensation[1].

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[1] This is another reason, why each volume element must be labeled with the normal vector that indicates the inner and the outer surface.

For this reason, the part must be designed in the middle of the tolerance zone in order to place a symmetric tolerance field all across the part. A bore of 20 mm diameter, for example, with overall tolerances of 0.30 mm needs to be designed as ∅ 20 ± 15 mm. If designed as, for example, ∅ 20 + 20/ –10 mm, which would be all right from the designer's perspective, the outer contour will be built incorrectly. To address this kind of issues the term "digital-to-object"[2] was created recently.

### 5.2.2 Design Freedom

The freedom of AM to make almost any imaginable shape is an enormous advantage and opens up a number of opportunities. The most important ones are discussed with regard of the design limitations of injection molding and die-casting. Rules for other applications can simply be derived from this.

Using AM processes, the part can be designed in one piece without any mold joints, which means that there is no need to define a parting line. Undercuts can be realized and do not increase manufacturing cost. Small gaps and slots can be designed avoiding the cost of sinking EDM[3] machining. Release angles are not required and no flow simulation is necessary to optimize the injection molding process and the part's geometry, respectively. Cooling channels are no longer a manufacturing problem.

Although it is claimed that major changes in wall thickness are no problem for AM, the user should keep in mind that all AM processes are based on phase changes, therefore, the accumulation of volume should generally be avoided.

### 5.2.3 Relative Fit

AM often requires the exact absolute dimension of a part that may consists of at least two parts who's relative position does not matter. In this case, a proper relative fit is sufficient. To assure this, the parts are positioned face-to-face in the build chamber and as close as possible together, which means leaving a gap of 0.10 to 0.20 mm. This ensures that the adjacent parts will fit, regardless whether they show the perfect contour or not and how complex the boundary contours are. Even distortions caused by the process do not influence the fit.

This discussion touches the basic "spare parts" problem. All tool-bound manufacturing methods, that means, almost all of today's fabrication technologies, are based on the manufacturing of interchangeable parts which is a precondition of (distributed) mass

[2] Don't confuse with "Object-oriented design" which is a software strategy for systems design.
[3] electrical discharge machining

production. As AM competes with this established world, AM parts are interchangeable too, if series are made or if spare parts are needed. But basically AM parts are one-off's and do not need to adhere to this convention – which is another element of the industrial revolution mentioned in Chapter 4.

### 5.2.4 Flexures, Hinges, and Snap-Fits

The most important design elements of plastic parts are snap fits, film joints (or film hinges), and flexures, which provide the basis for integrating geometric functions into AM parts, thus avoiding multi-part products, many tools, assembly work, and calibration. Plastic AM allows making these elements directly in one process while providing the same functionality. Here they are also called "non-assembly mechanisms" /Mav01/. Polymerization and laser sintering are preferred processes; however, extrusion is also applicable. 3D printing (powder-binder) and lamination processes are not suitable for the production of such elements.

Snap-fits should follow the same design rules for plastic injection molded parts. They should never be loaded while in operation in order to avoid creeping. The wall thickness should not be smaller than 0.5 mm and the free moving space should be as large as possible in order not to overload the part. Film hinges should have a wall thickness of 0.5 mm. Variations from these general values are subject to experience.

For laser based processes, hinges can be treated similar to bores but due to the much larger diameter of typically 1 to 10 mm, different values result. Both sides of the hinges can be built in the assembled position in one process, thus avoiding assembly and calibration. Even top layers can be added to receive a bullhead rivet-type joint. Preferred processes are polymerization and plastic laser sintering. To assure the movability, sufficient space must be left between adjacent walls. Many sources claim it is sufficient to add just one or two unsintered (or not exposed) layers to obtain a functional hinge after cleaning. In practice it should be at least twice as many.

The dimensioning of the clearing between the parts of a hinge depends on its orientation. If it is situated in the x/y area, 0.3 to 0.5 mm are proven values, see "A" in Fig. 5.6 a, while in the z-area 0.5 to 0.6 mm are recommended, see "B" in Fig. 5.6 b /Pfe11/. This agrees with an older but very good research report about "non assembly mechanisms" that recommends to design a clearance of 0.3 mm, if the adjacent surfaces are planar and of 0.5 mm if they are spherical /Mav01/.

In addition, the absolute dimension and position of the hinge has to be taken into consideration, which means the diameters of the pin and the barrel, the total length of the hinge, see "C" in Fig. 5.6 a, and the wall thickness or the volume of the parts, respectively. Bigger volumes that store the heat and support the adhering of particles require larger clearings. The same effect occurs if the hinge in total is inclined.

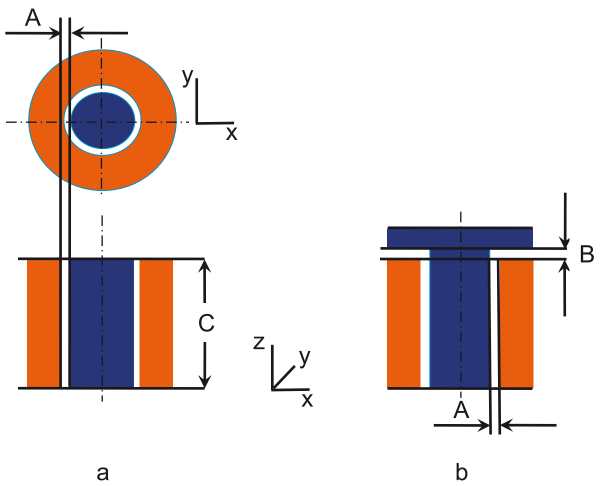


**FIGURE 5.6** Clearings for hinges and bores for laser based AM processes (according to /Pfe11/)

Flexural hinges, typically called flexures, are solid body hinges used in micromechanics to make ultra-precise positioning systems. They are used to avoid tolerances, backlash, and hysteresis problems. In AM, flexures are used as a design element. For plastic processes, film hinges can be regarded as flexures as well.

The precision mirror fixture and positioning system (Chapter 4) is a very good example for an extended flexure design that cannot be fabricated other than by AM.

### 5.2.5 Orientation and Clamping

AM processes do not require clamping. The "clamping" is either done by supports that are build with the part or by the material the part is embedded in during the build. Because of this and in contrast to most traditional fabrication processes, AM allows the positioning of the part under any imaginable angle onto the build platform. This can be used to reduce the effect of stair stepping in certain important regions of the part.

As discussed earlier, AM can process any 3D data, in particular data provided in STL formats. Fundamentally, the parts can be arranged on the build platform in any imaginable position. In practice, the orientation of the part is determined by the orientation of the layers, which should be parallel to the build area. Functional surfaces should be arranged facing up, while surfaces of minor interest and those linked to the supports are made in down-facing position. In general, the quality of down-facing surfaces is lower. This is true even for the PolyJet process even though it does not use supports.

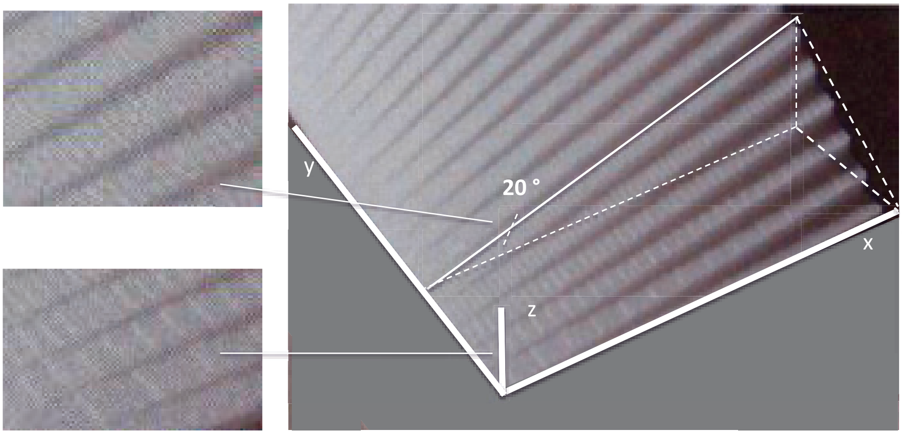


**FIGURE 5.7** Stair stepping effect depending on the inclination of x-y build area (according to /Pfe11/)

As mentioned in Chapter 2, stair stepping is a characteristic effect of AM processes. The visibility of the steps can be minimized, if the inclination between the z-area and the x-y build area exceeds an angle of 20°. Following this rule /Pfe11/, flat areas show stair stepping, while the effect is reduced when inclined walls are made, as can be seen in Fig. 5.7. It totally disappears on perpendicular walls.

If a layer pattern emerges on perpendicular walls, this is not caused by stair stepping but by improper joining of the layers.

As a consequence, areas parallel to the build plane that are not parallel but show a minor angle of a few degrees by mistake show a few stair steps that neither originate from the data set nor are they a build mistake. Figure 5.8 shows the down-facing area of the dental bridge shown on Fig. 1.11 as a false color picture. Due to a small misalignment between the machine coordinates and the data set, one (false) stair step of approximately one layer thickness (20 to 25 μm) was built and measured correctly.

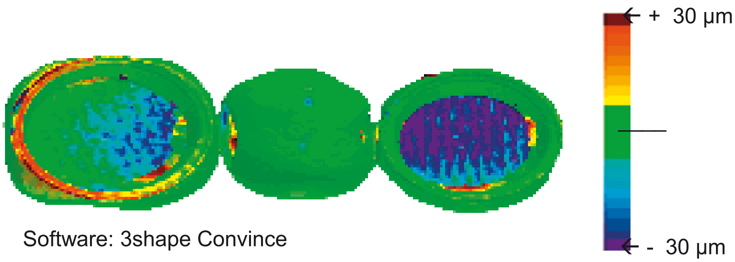


**FIGURE 5.8** Stair stepping of one layer thickness due to a misalignment of machine and data set (Source: Gebhardt, Sokalla /Geb10/)

### 5.2.6 Drillings (Bores), Gaps, Pins, and Walls

Drillings and other features, such as gaps and shaped grooves, cause some problems. First, due to the stair stepping, bores are not completely round and their shape also depends on their orientation in the build space. As a rule of thumb, for polyamide laser sintering, a bore diameter should not be smaller than 0.5 mm to be recognizable (but not of very good quality) if the wall thickness is 0.30 mm or less. For a wall thickness larger than 0.6 mm, the minimal recognizable diameter increases to 0.70 mm /Pfe11/.

Test cubes designed by the computer magazine CT /CT11/ and made by different job shops provide an idea of the capabilities and the limits of established AM processes when offered as an (Internet) service (Fig. 5.9).

| A | B | C | D | E |
|---|---|---|---|---|
| Extrusion | Polymerization | Laser Sintering | Polymerization | Laser Sintering |
| ABS | Epoxy | Polyamide | Epoxy | Polyamide |

**FIGURE 5.9** Geometric test cube for various AM geometries and processes /CT11/

The cubes have an outer wall thickness of 2 mm, a footprint of 3 $cm^2$ and the same height. The base part shows freestanding walls and pins of 5, 2, 1, 0.5, and 0.2 mm wall thickness and diameter, respectively. The cover is equipped with the fitting gabs and holes when put upside down on the base. A clearance of 0.1 mm enables the fit, if the parts are made correctly. The parts were produced by three different Internet-based companies. The AM processes and machines are not mentioned in detail, because the users were only interested in the result (see Chapter 1). They order the job based on Internet information on accuracy such as "standard" or "fine" and verbal material description. Figure 5.9 displays 5 test cubes made from ABS by extrusion (A), from epoxy resin by polymerization (B, D), and from polyamide by laser sintering (C, E). Figure 5.9 underlines that the quality of the parts is not just a result of the process but of the material and the sum of different influences along the process chain.

Bores and walls of 0.2 mm diameter and wall thickness, respectively cannot be produced at all and those of 0.5 mm have to be calibrated in advance to deliver reliable results. It is interesting to note that this result is valid for both polymerization processes and sintering processes. Even extrusion of ABS shows similar results, leading to too large diameters of the small pins (Fig. 5.9, A).

All AM processes have problems with the cleaning of very small holes. Sintering tends to leave partly molten particles in the hole or gap (Fig. 5.9, C and E) that can be removed by sand blasting but sometimes adheres permanently. Polymer processes tend to deliver better quality because of the liquid material; however, sometimes the melt solidifies and blocks the canal during or after the cleaning procedure (Fig. 5.9, B and D).

As AM bores show stair steps on the wall due to the locally decrease in material, wear is more pronounced and the diameter grows within a short time after the build. This has to be taken into account when precise bores are required.

Sometimes it is the best to mark the drillings in the AM process and drill them during finishing – like it is an old custom in the casting branch. Also, a gauge for drilling that is sintered in the same process may be a good solution. All remarks regarding bores are basically valid for gaps as well.

Free walls can be reproduced slightly better than pins. Walls with a thickness of 0.5 mm and even 0.2 mm pins can be made, if the process is calibrated and as long as they are properly finished.

All these data are subject to calibration and professional handling of the machines. A laser stereolithography machine that is calibrated properly can produce parts with through channels of 0.05 mm wall distance, if positioned in the very center of the build platform to minimize scanner problems. As an example, a precise microfluidic device is displayed in Fig. 5.10.

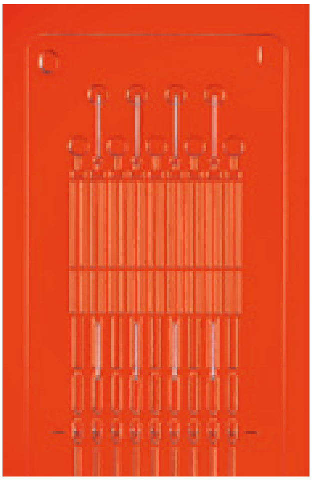

**FIGURE 5.10** Microfluidic device, laser stereolithography (Source: 3D Systems)

## 5.3 AM Properties, Selection, Build Management

The selection of a suitable AM process depends on the application level of the part (Chapter 1) and differs depending on whether a prototype or a part is needed.

To obtain a prototype, such as a solid image or a functional prototype, the selection begins "at the end". First, a material has to be selected that best represents the properties of the later series part. Second, an AM process has to be chosen which can process the selected material. Finally, the machine that matches material and process selection has to be identified. The part's 3D data have to be transmitted and the part is manufactured. Depending on the selected material and process, a solid image (e.g., using a 3D printing process) or a functional prototype (e.g., using laser sintering of polyamides) is obtained.

If a product is needed, again the material has to be selected but the engineering design of the part has to be based on the material properties of this particular AM material and the design rules for AM must be taken into consideration. Other parameters, such as the orientation in the build space, must be introduced during the construction. For the AM process, exactly the same parameters have to be set that were used during engineering design.

The operator of the AM machine is only responsible for the proper function of the machine and its professional operation (see Section 3.1). To do this in a reproducible way, perhaps even on different machines, the operator has to have a sort of management system that is typically based on experience. With an increasing number of builds, repeated builds of preceding jobs that must have the same quality, more available materials and more machines running, this "live from hand to mouth" way of management is no longer sufficient to ensure the production of quality parts.

EOS developed and published a part management system that provides on-line support for their customers /Mat10; Pfe11/. It is available for polyamide sintering and in a first approach for metal sintering as well.

An important element is the part property profile, a data bank closely linked not only to the material properties but to the quality management as well. The user defines the quality level by selecting the layer thickness in five stages (60 μm to 180 μm) and the material. Depending on this selection, the smallest details are set. The profile provides reliable information for dimensioning the laser-sintered part based on tensile strength, elongation at break, and moduli of elasticity. The properties are available separately for the x-y plane and for the z-axis, thus taking anisotropic effects into consideration.

The system includes design and construction rules and parameters as discussed in Section 5.2 In addition, it contains hints for labeling, design for proper cleaning, and economical optimization, e.g. by staggering or nesting of parts. Different versions are stored in order to be able to identify and recall data from previous builds. Special software allows the customers to create, store, and use their proprietary data. As a link to quality management, a protocol for every build is made and stored. Such supporting platforms will become a standard soon.

## 5.4 Conclusion

AM is a manufacturing technology and like any other technology relies on proper selection of the material, process, and engineering design. Therefore, characteristic design rules must be taken into consideration. The five AM families (Chapter 2) come with different advantages and disadvantages. All aspects are linked and need to be taken into consideration simultaneously. With the increasing number of machines and parts made from different materials, the management can no longer be made just by experience. As additional quality requirements ask for documentation, interlinked databases and management systems are needed.

## 5.5 Questions

### 1. Why is anisotropy an important problem for AM

Building a part layer-by-layer causes bonding problems between the layers that depend on the material and the way the bonding is done.

### 2. Which plastic AM processes show anisotropic effects to what extend?

The sequence from quasi-isotropic to anisotropic is: polymerization, laser sintering, FDM, 3D-printing and layer laminate manufacturing.

### 3. Why does metal laser sintering perform better in terms of isotropy than plastic laser sintering?

Because the material is molten completely, thus creating the name selective laser melting

### 4. What are the pros and cons of qualifying materials in-house?

Pro: Well known material, proprietary composition and build files, lower price

Contra: Higher price, dependent on supplier, lack of knowhow

### 5. How differ powders and processes for plastic laser sintering form those taken for sinter coating?

Additives and process details such as shielding gas and preheating suppress local evaporation, oxidation, and other inter-process effects and interactions with the environment.

### 6. What are typical grain sizes for polyamide sintering?

20 µm to 50 µm

### 7. What kinds of plastics can be processed by AM? Plot them in the plastic triangle.

See: Figure 5.2

### 8. How can hinges be made in one build? Which geometrical parameters (clearance) have to be take into account?

As film hinges or by leaving some unsintered layers for clearing; 0.3 µm to 0.8 µm

### 9. Why does AM not have clamping problems? How are the parts fixed?

Because they are supported by the powder bed or by supports

### 10. What does “relative fit” mean? Why is it only relevant for AM?

Parts fit although they are not geometrical correct, because they are put face to face and close together in one build.

# Glossary: Terms and Abbreviations

The list contains terms that are not only used in this book but also in the relevant literature, where they are often not even explained. Additional terms are listed for the same abbreviation that have a completely different meaning and may cause confusion. It also is a guide through the jungle of 2, 3 and 4 letter abbreviations. Abbreviations of company names are not listed (see: Table 5.1).

| Abbr. | Term | Explication |
|---|---|---|
| 3DP | Three Dimensional Printing | AM process. Layers made and bonded by selective injection of binder fluid onto a powder bed. Infiltration needed. Trademark of Massachusetts Institute of Technology (MIT). Licensed to several companies |
| 3DP, 3D-P | Three Dimensional Printing 3D Printing | Equivalent to → AM. Generic term. Frequently used term for all layer-based manufacturing processes. Not standardized |
| ACES | Accurate Clear Epoxy Solids | Stereolithography build style (3D Systems) |
| AF | Additive Fabrication | Manufacturing by adding volume-elements (Voxels) |
| AF | Anatomic Facsimile | Scaled anatomic model for surgery planning |
| AFM | Anatomic Facsimile Models | Scaled anatomic model for surgery planning |
| AIM | ACES Injection Molding | Plastic injection molding tool made using → ACES (3D Systems) |
|  | Anaplastologist | Orthotics specialist who creates realistic body prosthetics, usually of the face or upper body to fill in deep gaps or wounds produced by cancer therapy or other forms of nontherapeutic injury (www.medilexicon.com) |
| AM | Additive Manufacturing | Generic term. Manufacturing by adding volume-elements (voxels), especially layers. Standardized term for all layer-based manufacturing processes |

| Abbr. | Term | Explication |
|---|---|---|
| AM | Agile Manufacturing | Proprietary term used by 3D Systems to name AM processes to underline the agility of AM. Rarely used today |
| BASS | Break Away Support System | Support material and structure for post processing FDM parts by simply breaking off the material manually (Dimension/Stratasys) |
| BIS | Beam Interference Solidification | AM process. Solidification by polymerization in the intersection of two laser beams |
| BPM | Ballistic Particle Manufacturing | AM process. Part building by ballistic adding of voxels under any arbitrary angle. Real 3D process. No commercial use today |
| | Bridge Tooling | Tooling processes that quickly and inexpensively "bridges" the gap between soft tooling and production tooling. Used for small and pre-production series |
| | Build | The entire process in the AM machine to make an AM part is called a build |
| CAD | Computer Aided Design | Computer supported (engineering) design |
| CAE | Computer Aided Engineering | Computer supported (geometrical) construction |
| CAL | Computer Aided Logistic | Computer supported logistics |
| CAM | Computer Aided Manufacturing | Computer supported manufacturing |
| CAMOD | Computer Aided Modeling Devices | Computer supported soft- and hardware for making mock-ups and models |
| CAP | Computer Aided Production | Computer supported production |
| CAQ | Computer Aided Quality Assurance | Computer supported quality assurance |
| CAS | Chemical Abstract Service | Computer supported nomenclature and institution for the characterization of chemicals |
| CAS | Computer Aided Styling | Computer supported styling |
| CAT | Computer Aided Testing | Computer supported measuring and testing |
| CAx | Computer Aided …<br>Computer Assisted … Computer supported … | General abbreviation for any kind of computer supported process |
| | AutoFabs | Automated fabricator(s).<br>Equivalent to → Fabricator(s) |
| CD | Concurrent Design | Parallelized conception and design processes. Equivalent to simultaneous engineering → SE |
| CEM | Contract Electronics Manufacturing | Electronic manufacturing as a service |

| Abbr. | Term | Explication |
|---|---|---|
| CIM | Computer Integrated Manufacturing | Manufacturing based on a complete CAD-CAM workflow. Equivalent to ICAM |
| CMB | Controlled Metal Build Up | AM process. Laser generation and subsequent contour milling of metal parts (FhG-IPT) |
| CMC | Computer Mediated Communication | Computer supported communication. |
| CP | Centrum für Prototypenbau GmbH | Rapid Prototyping service bureau. Based at Erkelenz/Düsseldorf, Germany |
| CPDM | CIMATRON Product Data Management | PDM system of CIMATRON |
| CS … | Computer Supported … | General abbreviation for any kind of computer supported process |
| CSCW | Computer Supported Cooperative Work | Computer supported product development and communication |
| CSG | Constructive Solid Geometry | Characterization and specification of a complex solid based on geometric primitives using Boole's operations |
| CT | Computerized (or computed) tomography | X-ray based layer inspection system for non-destructive testing in medicine and industrial production |
| DCM | Direct Composite Manufacturing | AM process. Direct manufacturing of composite parts. Preferably used by Optoform for its M3D process |
| DICOM | Digital Imaging and Communications in Medicine | A standard that allows to link the input of most of the medical imaging systems to most of the outputs, including AM |
| DMLS | Direct Metal Laser Sintering | AM process. Direct sintering of metals. EOS |
| DMU | Digital Mock Up | Digital or virtual → mock up. Can be animated. Mainly used in Virtual Reality |
| $D_P$ | Cure Depth | Photopolymerization. Penetration depth of the curing radiation into curable resins of polymerization systems, mainly for stereolithography. Also called optical penetration depth |
| DSPC | Direct Shell Production Casting | AM process. Proprietary (Soligen) hard- and software process for making molds for casting of ceramics |
| DTM | Desktop Manufacturing | Synonym of AM. Underlines the capability of AM to manufacture parts on the desktop |
| DXF | Drawing Exchange Format | Data exchange format, preferably for CAD-drawings |

| Abbr. | Term | Explication |
|---|---|---|
| $E_C$ | Critical Energy | Photopolymerization. Threshold value of curing energy that causes solidification of curable resins |
| EDM | Electronic Data Management<br>Engineering Data Management | Software system for the management of huge amounts of data that simultaneously can be accessed by many users |
| EDM | Electric Discharge Machining | Machine tool for removing material by local melting caused by discharge. Also called eroding, spark machining, or spark eroding |
| EDM | Electronic Document Management | Electronic filing and management of documents |
| ERM | Enterprise Resource Management | System and software for planning and management logistic supply chains |
| ERP | Enterprise Resource Planning | System and software for planning and management logistic supply chains |
| | Fabber | Abridgment of → Fabricator |
| | Fabricator | Machine for the automated additive manufacturing of parts |
| FDM | Fused Deposition Modeling | AM process. Variation of the → FLM process. Stratasys |
| FFF | Fast Freeform Fabrication | Synonym of AM. Underlines the capability of AM to make complex parts quickly |
| FLM | Fused Layer Modeling | AM process. Generic term. Part building by extrusion of plasticized thermoplastic material and solidification by thermal conductivity |
| FM | Facsimile Models | Scaled model of an existing geometry.<br>Mainly obtained by scanning. No design changes |
| FRP | Foam Reaction Prototyping | AM process. Part building by layered extrusion of reaction foams. Herback (rtejournal 2004) |
| GIS | Geographic Information System | System for capturing, storing and manipulating geographical information on computer. (www.gis.com) |
| GMEAM | Gradient-Modulus Energy Absorbing Material. | Proprietary layer-structured material for improved impact resistance. Solidica. Ultrasonic Consolidation AM process |
| | Graded materials | Materials that show a defined variation of its properties, mainly the modulus (therefore: Graded = gradient modulus), to obtain load adapted performance of the parts |

| Abbr. | Term | Explication |
|---|---|---|
| | Grower | Synonym of AM. Underlines the capability of AM to grow parts. Solidscape. Preferrably used for the T66 machine |
| HIS | Holographic Interference Solidification | AM process. Part building by polymerization of spherical layers based on holographic images |
| HPGL | Hewlett Packard Graphic Language | Data exchange format. Mainly used for plotters |
| HSC | High Speed Cutting | Mainly used for high speed milling by machine tools |
| HSPC | High Speed Precision Cutting | Proprietary variation of → HSC. Kern Microtechnik |
| | Indirect Rapid Prototyping Processes | Non-AM processes that are based on AM masters in order to increase the quantity or the quality of the parts. Also called → Secondary Rapid Prototyping Processes |
| ICAM | Integrated Computer Aided Manufacturing | Equivalent to → CIM |
| IGES | Initial Graphics Exchange Specification | Data exchange format. Mainly used for 3D CAD data |
| LCVD | Laser Chemical Vapor Deposition | AM process. Chemical driven 3D deposition of metals out of the gaseous phase |
| LENS | Laser Engineered Net Shaping | AM process. Part building by laser assisted layered cladding of metals. OPTOMEC |
| LLM | Layer Laminate Manufacturing | AM process. Generic term. Part building by bonding staggered layers from sheet material made from paper, plastics, metal, or ceramics. Contouring by laser, knife, or milling |
| LM | Laminate Manufacturing | Synonym of AM. Underlines the layer-oriented principle. Mainly used for → LLM processes. |
| LMPM | Low Melting Point Metal | Metals with precise defined low melting points (under and around 100 °C) used for secondary AM processes |
| LMS | Laser Modell System (ger.) | AM process. Variant of stereolithography. F&S Fockele & Schwarze. Company inactive. Term no longer used today |
| LMT | Layer Manufacturing Technologies<br>Layer Manufacturing Techniques | Equivalent to → AM. Generic term |
| LOM | Laminated Object Manufacturing | → LLM process. Paper. Cubic Technologies (ex. Helisys) |

| Abbr. | Term | Explication |
|---|---|---|
| LS | Laser-Sintering | AM process. Generic term. Part building by locally melting of powders made from plastics, metals, or ceramics. Melting by laser. Radiators or electron beam. Solidification by thermal conductivity |
| LSM | Laser Surface Melting | AM process. Variant of laser sintering of metals. F&S Fockele & Schwarze. Company inactive. Term no longer used today |
| M3D, $M^3D$ | Maskless Mesoscale Material Deposition | Aerosol jet printing system by Optomec |
| MEMS | Micro Electromechanical Systems | Integrated mechanic and electronic micro- and mesoscale elements |
| | META design | A product design that covers an almost unlimited number of variants that can be derived from it, typically by sliders or mouse functions that can be operated by the customer |
| MIM | Metal Injection Molding | Injection molding process based on a plasticized metal-plastic feedstock |
| MIM/ MAM/ MDM/ | Material Incress Manufacturing/ Material Addition Manufacturing/ Material Deposition Manufacturing | Synonym of AM. Underlines the manufacturing by increasing the volume of a part by adding material |
| MJM | Multi-Jet Modeling | AM process. Variant of the → FLM process combined with polymerization. Older term. 3D Systems |
| MJS | Multiphase Jet Solidification | AM process. Variant of the → FLM process. ITP. Company inactive |
| | Model | A model is a physical AM part that is used as sample or a prototype. In the beginning, when only prototypes could be made, the terms model, part and prototype were identical |
| | Modding | Individualization of products mainly by end-users. Equivalent to: tuning, styling, pimp |
| Mock-Up, Mockup | | Scaled non-functional model of a future product. The term originated in the aviation industry to present new airplanes. Term is not exclusively linked to AM |
| MRT | Magnetic Resonance Tomographie | 3D medical imagine process mainly to investigate soft tissue |
| OEM | Original Equipment Manufacturer | Here: Manufacturer of AM machines and equipment |

| Abbr. | Term | Explication |
|---|---|---|
| | Part | The physical object that is made by the AM process is called a part. "Part" is the umbrella term and covers all more specific terms such as prototype, sample, model, mock up as well as products made by AM |
| | Pimp | Individualization of products mainly by end-users. Equivalent to → modding |
| PDM | Product Data Management<br>Produktdaten-Management | Software system for the management of huge amounts of product development data that can be simultaneously accessed by more than one user |
| PET | Positron Emission Tomography | Nuclear 3D medical imagine process mainly to investigate functional processes in the body |
| | Powder cake | The whole amount of compacted sintered and unsintered powder after the build. Sometimes for 3D printing the powder with the part in it also is called powder cake, although it is not compacted by heat |
| PPS | Production Planning System | Software system for production planning, management and control |
| | Prototype | A part that shows selected properties of a future product in order to allow an early product evaluation |
| | Prototype Tooling | Tools based on AM prototypes that are capable of making a small series of final parts |
| | Prototyper | Machine for the automated additive manufacturing of parts, mainly for making prototypes, samples, and mock-ups |
| | Rapid Mockup Machine | Machine for the automated additive manufacturing of parts, mainly for making mock ups. Kira. Preferably used for Katana paper laminating machine |
| RIM | Reaction Injection Molding | Injection molding process based on a plasticized metal-plastic feedstock. Solidification by chemical reaction |
| RM | Rapid Manufacturing | Application of → AM for making usable final parts |
| RM | Rapid Modeling | Application of → AM for making models such as prototypes, samples, and mock ups. Term rarely used |

| Abbr. | Term | Explication |
|---|---|---|
| RP | Rapid Prototyping | Application of → AM for making prototypes, samples, and mock ups |
| RP | Reinforced Plastics | Plastic material reinforced mainly by fibers. |
| RP&M | Rapid Prototyping & Manufacturing | Collective term for all applications of AM processes |
| RPD | Rapid Product Development | Collective term for all processes to speed up the development of products |
| RPro | Rapid Production | Collective term for all processes to speed up the production of products |
| RPT | Rapid Prototyping Techniques/ Technologies | Processes to verify → RP |
| RT | Rapid Tooling | Application of → AM for making tools, tool inserts, dies, molds, and gauges |
| SAHP | Selective Adhesive and Hot Press Process | AM process. Variation of → LLM. Paper. KIRA |
| | Sample | Part that is identical with the later mass produced part but comes from a pre-series or is made by pre-production tools |
| SDU | Shell Design Unit | Hard- and software process for designing the shape of ceramic cast forms. Soligen |
| SE | Simultaneous Engineering | Methodical approach to parallelized conception and design processes. Equivalent to Concurrent Design → CD or Concurrent Engineering |
| | Secondary Rapid Prototyping Processes | → Indirect Rapid Prototyping Processes |
| SET | Standard d'échange et de Transfer | Data exchange format. Mainly used for 3D CAD data |
| SFF | Solid Freeform Fabrication | Synonym of AM. Underlines the capability of AM to make complex geometries. → SFF |
| SFM | Solid Freeform Manufacturing | Synonym of AM. Underlines the capability of AM to make complex geometries. → SFF |
| SFP | Solid Foil Polymerization | AM process. Synonym of → FLM using plastic foils and bonding them by polymerization |
| SGC | Solid Ground Curing | AM process. Polymerization process supported by milling. Cubital. Company inactive |
| SL | Stereolithography | AM process. Solidification by local polymerization due to UV radiation (photopolymerization) obtained from lasers or lamps |

| Abbr. | Term | Explication |
|---|---|---|
| SLA | Stereolithography Apparatus | Proprietary term for stereolithography machines. 3D Systems |
| SLPR | Selective Laser Powder Remelting | AM process. Laser generation of metal parts (FhG-ILT) |
| SLS | Selective Laser Sintering<br>Selektives Laser Sintern | AM process. Proprietary term for laser sintering machines. 3D Systems |
| SOM | Stratified Object Manufacturing | Software based system for the undercut-free preparation of complex solids. Manufacturing by milling |
| SOUP | Solid Object Ultra-violet Laser Plotter | AM machine. Part building by polymerization (stereolithography). C-MET |
| SPECT | Single Photon Emission Computed Tomography | 3D medical imagine process mainly to investigate functional processes in the body |
| SPF | Super Plast Forming | Blowing up of welded elements. Non-AM process |
| STAR-Weave | Staggered Alternated Retracted Hatch | Stereolithography build style (3D Systems) |
| STEP | Standard of Exchange of Product Model Data | Data exchange format. Mainly used for 3D CAD data |
| STL | Stereolithography Language | Data exchange format between CAD-systems and AM machines.<br>Created as: “Standard Transformation Language” to shadow 3D-CAD files and simplify the recognition of details |
| TCT | Time Compressing Technologies | Collective term for all processes that speed up the development and manufacturing of products |
| THESA | Thermoelastische Spannungsanalyse (ger) | Thermal Elastic Tension Analysis. Experimental testing process based on the measurement of thermal effects caused by tension in loaded parts |
| TI | Tailored Implants | Individual implants, mainly for cranio facial surgery |
| TP | Thermal Polymerization | Polymerization caused by heat |
| UV | Ultraviolet | Wavelength in the range of 100 nm – 380 nm |
| VDAFS | Verband der Automobilhersteller – Flächenschnittstelle (ger) | Data exchange format. Mainly used for 3D CAD data of freeform surface data |
| VDAIS | Verband der Automobilhersteller – IGES-Schnittstelle (ger) | Data exchange format. Mainly used for 3D CAD data of IGES elements |

| Abbr. | Term | Explication |
|---|---|---|
| | Virtual Product Model | A complete data set that contains all (not just geometrical) data defining a product. It is the prerequisite for digital manufacturing |
| VR | Virtual Reality | Display and animation of virtual 3D models preferably in real-time |

# Index