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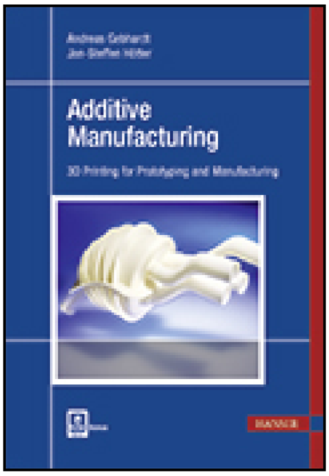

Sample Pages

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Additive Manufacturing

3D Printing for Prototyping and Manufacturing

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Foreword

Since the late 1980s, in fact, for more than 25 years, Additive Manufacturing (AM) has been penetrating the world of manufacturing. When the layer-based technology emerged, it was called Rapid Prototyping (RP). This was the best name for a technology that could not fabricate anything but sticky and brittle parts, which could only be used as prototypes. The process was not even "rapid," although it allowed the making of time- and money-consuming tools to be avoided. With the creation of the first prototype by RP, a significant amount of time and money could be saved.

The initial process was called *stereolithography* and it was based on photo-polymerization, which first processed acrylates and then epoxies later on. In the following years, new layer-based processes were developed and an extended range of materials became qualified for AM applications, and all of them were plastics.

Around the turn of the millennium, processes for making metal parts were introduced to the market. With this development, the focus of manufacturers as well as of the users changed from just prototyping to manufacturing because of improved processes, materials, software, and control. The challenge was then to make final parts.

Today all classes of engineering materials, such as plastics, metals, ceramics, and even nontraditional materials, such as food, drugs, human tissue, and bones, can be processed using 3D printers.

There is still a long way to go, but due to vibrant activities concerning all aspects of 3D printing worldwide, this high-speed development is incomparable to the expansion of any fabrication technology in the past.

There are two main reasons for intense interesting in this technology for somebody active in the field of product development and production:

First, to stay competitive, one should be able to judge the capabilities of existing, new, and emerging AM processes in comparison to traditional manufacturing processes and process chains. The task is not just a matter of speeding up the process but to improve the way we do engineering design towards "designing for AM." This makes completely new products possible and shifts the competition of traditional manufacturing towards a new level of lightweight design, as well as resource-saving and environmentally friendly mass production of individual parts.

Second, people begin to understand that AM is not just capable of revolutionizing our way of designing and producing parts, but able to affect many aspects of our daily lives.

AM touches upon legal aspects, such as product reliability and intellectual property rights, as compared to the digital entertainment market. AM also brings even more challenges as parts can cause significant problems like physical injuries or even death, which music and videos do not do.

Digital data, including not only technical data such as a blue print, but the exact information for creating the product, can easily be sent all over the world and encounter every imaginable hurdle, such as frontiers, embargos, custom fees, export regulations, and many more. This requires us to rethink the well-functioning world of today.

Many of the questions raised, if not the majority, need to be decided by people who are not technicians. The better that those involved understand the technical part and the more thorough their information, the better decisions they will be qualified to make.

Consequently, this book was written to support the product developers and people who are responsible for the production, as well as others who are involved in the process of realizing the enormous challenges of this technology.

Aachen in March 2016 *Andreas Gebhardt*

1 Basics, Definitions, and Application Levels

To understand the characteristics and the capabilities of additive manufacturing (AM), it is very helpful to take a look at the systematics of manufacturing technologies in general first.

1.1 Systematics of Manufacturing Technologies

Orientated on the geometry only, manufacturing technology in general is divided into three fundamental clusters [Burns, 93, AMT, 14]:[1]

1. subtractive manufacturing technology,
2. formative manufacturing technology, and
3. additive manufacturing technology.

With subtractive manufacturing technology, the desired geometry is obtained by the defined removal of material, for example, by milling or turning.

Formative manufacturing means to alter the geometry in a defined way by applying external forces or heat, for example, by bending, forging, or casting. Formative manufacturing does not change the volume of the part.

Additive manufacturing creates the desired shape by adding material, preferably by staggering contoured layers on top of each other. Therefore it is also called layer (or layered) technology.

The principle of layer technology is based on the fact that any object, at least theoretically, can be sliced into layers and rebuilt using these layers, regardless of the complexity of its geometry.

[1] In Germany, manufacturing technology is divided into six main categories, and each of them is subdivided into various subcategories [DIN 8580], [Witt, 06].

Figure 1.1 underlines this principle. It shows the so-called sculpture puzzle, in which a three-dimensional (3D) object has to be assembled from more than 100 slices. Therefore the layers have to be arranged vertically in the right sequence using a supporting stick.

Figure 1.1 Principle of layer technology, example: sculpture puzzle
(Source: HASBRO/MB Puzzle)

Additive manufacturing (AM) is an automated fabrication process based on layer technology. AM integrates two main subprocesses: the physical making of each single layer and the joining of subsequent layers in sequence to form the part. Both processes are done simultaneously. The AM build process just requires the 3D data of the part, commonly called the virtual product model.

It is a characteristic of AM that not only the geometry but the material properties of the part as well are generated during the build process.

■ 1.2 Systematics of Layer Technology

In this section the commonly used terms in AM are addressed. The related characteristics as well as their interdependency and the hierarchical structure are discussed.

In this book the generally accepted so-called generic terms are used, and alternatively used names are mentioned.

Generic terms and brand names have to be distinguished from each other. If they are mixed, which happens quite often, this frequently leads to confusion. As brand names are important in practice, they are addressed, explained, and linked to the generic terms in Chapter 3, where the AM machines are presented.

1.2.1 Application of Layer Technology: Additive Manufacturing and 3D Printing

Additive manufacturing is the generic term for all manufacturing technologies that automatically produce parts by physically making and joining volume elements, commonly called voxels. The volume elements are generally layers of even thickness.

Additive manufacturing is standardized in the US (ASTM F2792) and in Germany (VDI 3405), and is commonly used worldwide.

As alternative terms, additive manufacturing (technology) and additive layer manufacturing (ALM) have minor acceptance.

3D printing is about to replace all other names, including additive manufacturing, and to become the generally accepted generic term for layer technology in the near future. This is mainly because it is very easy to understand. Everyone who can operate a text editor (a word processor) and a 2D office printer easily understands that he or she will be able to print a 3D object using a 3D design program (a part processor) and a 3D printing machine, regardless of how it works.

NOTE: Additive manufacturing and 3D printing are used as equal generic terms in this book. While in Chapter 1 this is expressed by always writing additive manufacturing/3D printing (or AM/3DP). In the following chapters only additive manufacturing or AM is used in order to shorten the text volume.

Beginners should realize that 3D Printing is also the brand name of a family of powder binder processes (see Section 3.6), originally developed by MIT and licensed to Z-Corporation (now 3D Systems), Voxeljet, and others.

1.2.2 Characteristics of Additive Manufacturing

Layer technologies in general and additive manufacturing in particular show special characteristics:

- The geometry of each layer is obtained solely and directly from the 3D computer-aided design (CAD) data of the part (commonly called a virtual product model).
- There are no product-related tools necessary and consequently no tool change.
- The material properties of the part are generated during the build process.

- The parts can be built in any imaginable orientation. There is no need for clamping, thus eliminating the clamping problem of subtractive manufacturing technologies. Nevertheless, some processes need support structures, and the orientation of the part influences the parts' properties.
- Today, all AM processes can be run using the same so-called STL (or AMF) data structure, thus eliminating data exchange problems with preprocessors as used in subtractive manufacturing.

Additive manufacturing/3D printing therefore ensures the direct conversion of the 3D CAD data (the virtual product model) into a physical or real part.

As scaling can be done simply in the CAD file, parts of different sizes and made from different materials can be obtained from the same data set. As an example, the towers of a chess set shown in Fig. 1.2 are based on the same data set but made with different AM machines and from different materials. The range of materials includes foundry sand, acrylic resin, starch powder, metals, and epoxy resin.

Figure 1.2 Additive manufacturing. Scaled towers of a chess set, based on the same data set but made with different AM machines and from different materials.
Small towers, from left to right: PMMA (powder-binder process, Voxeljet), metal (laser sintering, EOS), acrylate, transparent (stereolithography, Envisiontec; height approx. 3 cm).
Big towers, from left to right: foundry sand (powder-binder process, Voxeljet), starch powder (powder-binder process, 3D Systems; height approx. 20 cm) (Source: machine manufacturers)

One of the biggest AM parts of all is the tower shown in Fig. 1.3 with a height of approximately 2.5 m, which is higher than the general manager of the Voxeljet Company, Mr. I. Ederer.

Figure 1.3 Chess tower made from foundry sand, height approx. 2.5 m, powder-binder process (Source: Voxeljet)

By contrast, Fig. 1.4 shows a tower made by micro laser sintering. It is approximately 5 mm high.

Figure 1.4 Tower made from metal, height approx. 5 mm, micro laser sintering (Source: EOS/3D Micromac)

AM/3DP allows manufacturing of geometric details that cannot be made using subtractive or formative technologies. As an example, the towers on Fig. 1.2 contain spiral staircases and centered double-helix hand rails. The details can be seen on a cutaway model displayed in Fig. 1.5.

Figure 1.5
Internal details of the rear right tower on Fig. 1.2 (Source: 3D Systems)

Another example of geometries that cannot be manufactured using subtractive or formative technologies is shown in Fig. 2.5.

All AM/3DP processes mentioned here will be explained in detail in Chapter 3.

■ 1.3 Hierarchical Structure of Additive Manufacturing Processes

For a proper definition of the terms used, it is very helpful to distinguish the technology and its application from each other. Subtractive manufacturing, for example, marks the technology level, and drilling, grinding, milling, and so on are the names for its application (or the application level).

The technology of additive manufacturing/3D printing is divided in two main application levels: *rapid prototyping* and *rapid manufacturing*. Rapid prototyping is the application of AM/3DP to make prototypes and models or mock-ups, and rapid manufacturing is the application to make final parts and products.

The manufacturing of tools, tool inserts, gauges, and so on usually is called *rapid tooling*. The term often is regarded as an independent hierarchical element or application level, but effectively it is not. Depending on how a tool is made, it represents a prototype or a product (Fig. 1.6).

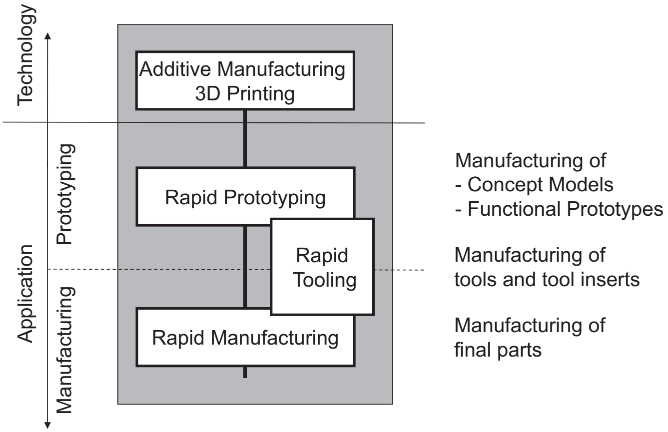


Figure 1.6 Basic structure of additive manufacturing/3D printing technology and its subcategories rapid prototyping, rapid manufacturing, and rapid tooling

1.3.1 Rapid Prototyping

Rapid prototyping (RP) is the application of AM/3DP technology to make prototypes, models, and mock-ups, all of them being physical parts but not products. They only mimic isolated properties of the latter product in order to verify the engineering design and to allow the testing of selected product capabilities and thus to improve and speed up the product development process. The goal is to preplan a part to make it as simple as possible in order to get it quickly and cheaply. Therefore, rapid prototyping parts generally cannot be used as final products.

As prototypes differ from products, serial identical prototypes (which are not products but prototypes) do not exist, although the term is used to underline a strategy.

Rapid prototyping again is subdivided into *solid imaging* or *concept modeling*, and *functional prototyping*.

Solid imaging or *concept modeling*: If a rapid prototyping part is made mainly for 3D visualization, it is called a solid image, a concept model, a mock-up, or even a rapid mock-up. The idea behind it is to generate a 3D picture or a statue (Fig. 1.7). To highlight this aspect, the parts are also called *show-and-tell models*.

If a part has a single or some of the functionalities of the latter product, it can be used to verify this aspect of the engineering design. Consequently it is called a functional prototype (and the process *functional prototyping* accordingly).

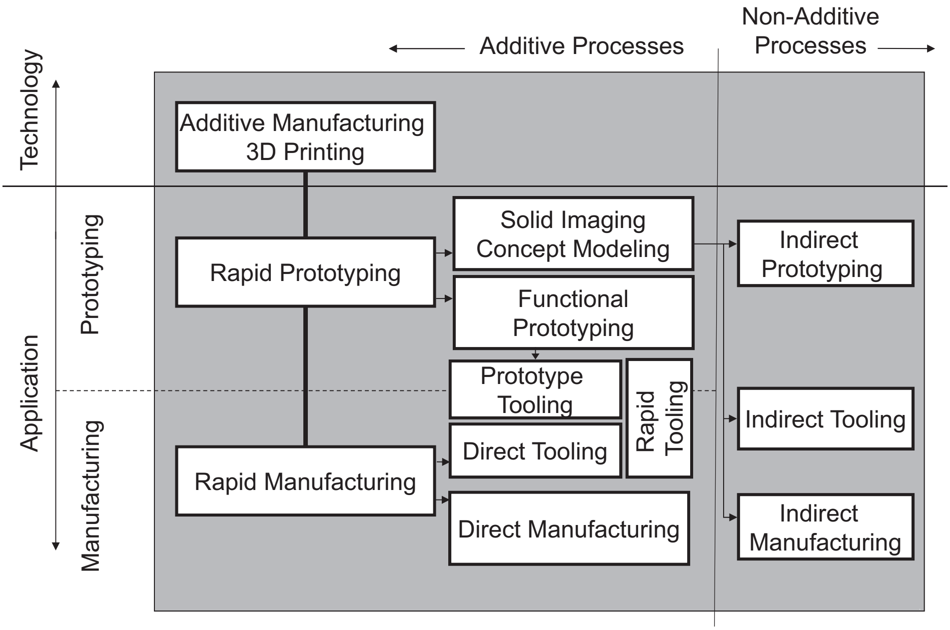


Figure 1.7 Basic structure of the AM/3D printing technology: application levels rapid prototyping, rapid manufacturing, and rapid tooling and its subcategories

A sample of each category is displayed in Fig. 1.8. The scaled data control model of a convertible roof system (made from polyamide by laser sintering) can be regarded as a typical concept model. The air-outlet nozzle of a passenger car (made by laser stereolithography from epoxy resin) is a functional prototype that supports the testing of the car's climate control.

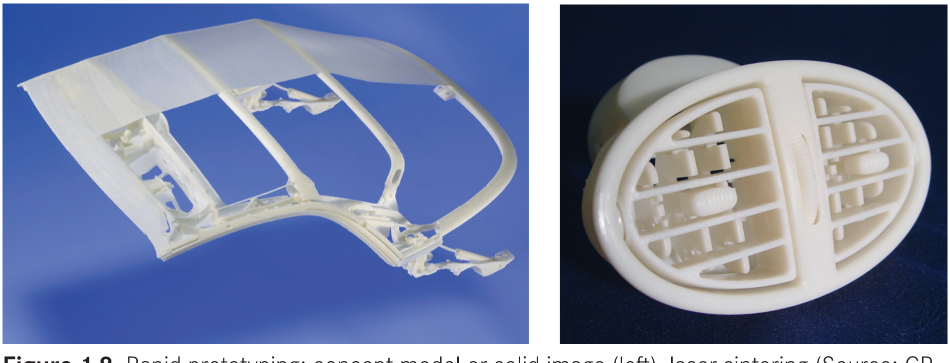


Figure 1.8 Rapid prototyping: concept model or solid image (left), laser sintering (Source: CP GmbH); functional prototype (right), laser stereolithography (Source: 3D Systems)

The corresponding AM processes are presented in detail in Chapter 3.

1.3.2 Rapid Manufacturing

Rapid manufacturing (RM) names the application of the AM/3D printing technology to make final parts or products, often called series products, even if they are one-offs. (A deeper discussion can be found in Chapter 6.) The parts can be positives like connectors as well as negatives like cavities. Making positives or parts is called *direct manufacturing*, and the additive manufacturing of negatives or cavities, such as tools and tool inserts, is called *direct tooling*; see Fig. 1.7.

1.3.2.1 Rapid Manufacturing—Direct Manufacturing

Additive manufacturing or 3D printing of final parts or products is called *direct manufacturing (DM)*. Frequently and for historical reasons it is also called r*apid manufacturing (RM)* and complies directly with the main term. Often the terms *e-manufacturing, digital manufacturing, tool-less fabrication,* and others are used.

Direct manufacturing is based on the same technology as rapid prototyping and, at least until today, uses the same machines. The goal is to make final products. Whether the goal can be reached or not depends on the degree of accomplishment of the required mechanical and technological properties. This again depends on the machines, processes, and materials available. Further, whether the needed accuracy can be reached and if a competitive price can be achieved are essential.

As an example of direct manufacturing, Fig. 1.9 shows a three-element dental bridge (left). The associated process chain will be shown in Chapter 3, and applications will be discussed in Chapter 6.

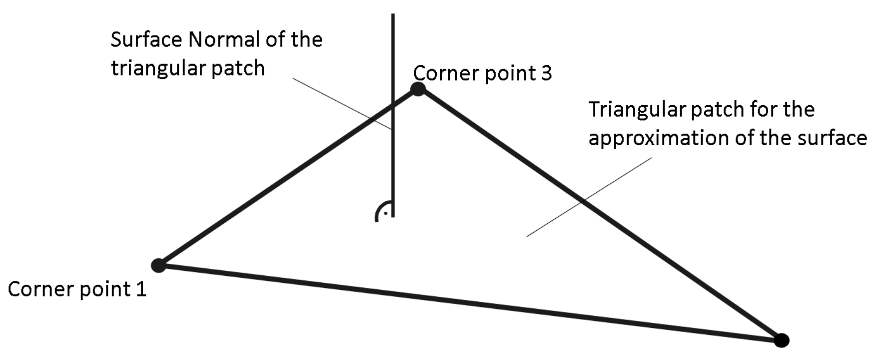
Figure 1.9 Rapid manufacturing: direct manufacturing of a three-element dental bridge (left) (Source: GoetheLab FH Aachen/Sokalla); direct tooling for making golf balls (right) (Source: EOS GmbH)

2.2.2.1 STL Format

In order to obtain an STL data set of the part, the surfaces of the part are approximated by triangles. Volume elements exhibit at least two surfaces, the inner and outer surfaces. Both of them differ only by the normal vectors. The definition of the surface by triangles is called triangulation or tessellation. This leads to the so-called STL data. It is regarded as a de facto industry standard for AM processes, but it is actually nowhere standardized.

This contributed to the fact that this process, long before it was discovered for additive manufacturing, was used for shading and thus for the visualization of three-dimensional CAD lattice models. Decisive for the establishment of the STL format as an interface for additive manufacturing was the early publication of the interface formulation. The STL interface, which has been known since then as the stereolithography interface, could be used by both machine manufacturers and free software businesses. This was especially beneficial to the development of special software that is offered by independent developers and made a lasting contribution to the user-friendliness of additive manufacturing systems.

The STL data contains the normal vector (positive direction outward, away from the volume) and the coordinates of the three vertices of each triangle (Fig. 2.9). An ASCII or binary file can be created. The amount of data is much lower for binary files, but ASCII files are comparatively easy to read and control in the source code. Figure 2.9 shows such a triangle patch and the corresponding ASCII data set per triangle enclosed by the commands FACET and ENDFACET.



FACET NORMAL 0.000000e+00 0.000000e+00 -	**Surface Normal of the triangular patch 1**
OUTER LOOP	Start of the point data
VERTEX 9.999990e+00 9.999990e+00	Triangular facet 1; corner point 1
VERTEX 9.999990e+00 1.100001e+01	Triangular facet 1; corner point 1
VERTEX 1.100001e+01 9.999990e+00	Triangular facet 1; corner point 1
ENDLOOP	End of the point data
ENDFACET	End of facet description for facet 1

Figure 2.9 Definition of triangle patches in STL format and the associated ASCII data set [Hoffmann, 95] [BRITE/EuRAM, 94]

Figure 2.10 shows the triangular patches coated on a real component, called the triangulated surface.

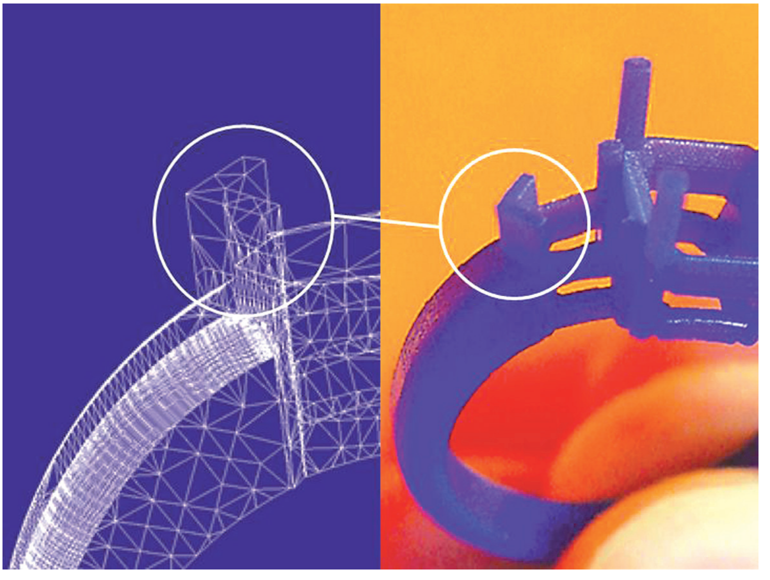


Figure 2.10 Triangulated surface and associated manufactured component (Source: 3D Systems)

The STL formulation, however, possesses practical advantages:

Given that the surface is based on triangles, it is possible to cut the model at any desired z coordinate. Also, when the CAD model is not available, STL models permit any desired scale at random without reversing into the CAD.

Because the intersection contains only data elements of a type that can be described by relatively simple means, syntax errors of the ASCII version in the programming of the interface are very easy to recognize and eliminate, and therefore they pose practically no problem.

In contrast to contour-oriented intersections, smaller errors may be repaired relatively easily. It is also an advantage that a triangle provides a higher quality of geometric information than does the contour vector.

The STL formulation also has disadvantages:

- It generates a large volume of data, especially when the surface quality is improved by refining the net of triangles.
- STL files contain only geometrical information. Information about color, texture, material, or other characteristics of the physical model are missing.

2.2.2.1.1 Errors in STL Files

During the transformation of the CAD internal geometry data into STL files, different errors can occur that affect the quality of the physical component. The errors are categorized by Hoffmann [Hoffmann, 95] as

- construction errors,
- transforming errors, and
- description errors.

Construction errors are based on unnecessary data inside the component that are the result of combining the single elements incorrectly in the CAD system (Fig. 2.11). These errors are problematic for the AM process. For example, LLM processes include unnecessary cuts because of these errors. The consequences range from additional expenses during the building process to the total loss of the part. Construction errors do not affect components that are produced by polymerization and sintering processes.

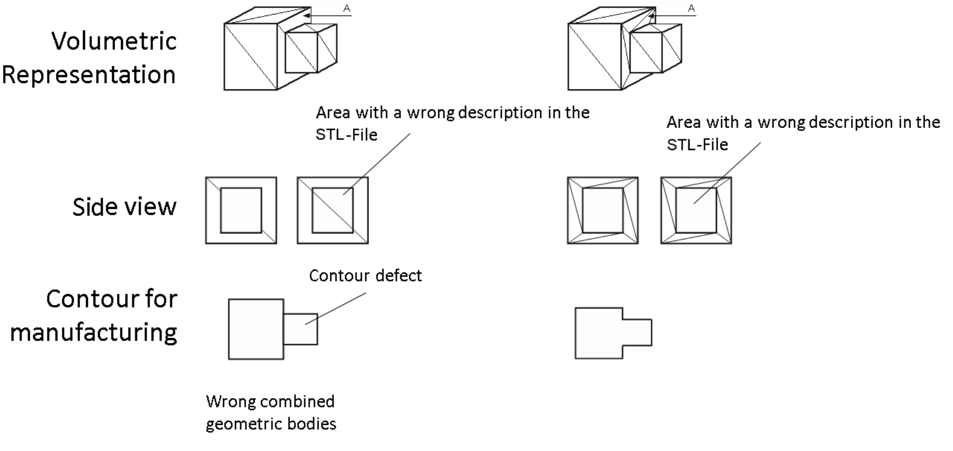


Figure 2.11 Effects of merged faulty geometric bodies [Hoffmann, 95]

Transforming errors exist when the convergence of the mathematically exact contour (as provided by the CAD) by triangles is inaccurate and the number of transforming errors is larger the lower the number of triangles chosen. In Fig. 2.12(a), this fundamental secant error is demonstrated in the example of errors appearing in the convergence of a circle by (f/4), eight (f/8), and twelve (f/12) secants. Figure 2.12(b) shows the consequences on the modeling of a globe surface.

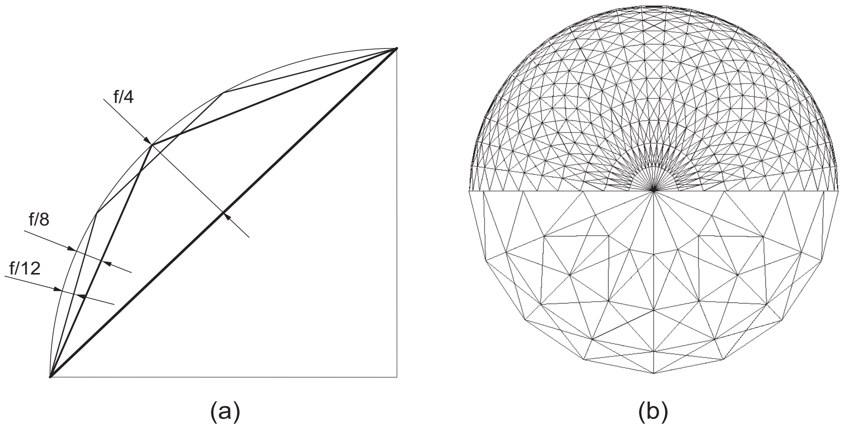


Figure 2.12 (a) Secant error at the approach of a circle by 4 (f/4), 8 (f/8), or 12 (f/12) line segments; (b) Influence of the number of triangles in the modeling of the surface of a sphere (STL)

With the increased accuracy in defining the surface made possible by increasing the number of triangles, the amount of data increases enormously. In one published example the growth factor was 22 [Donahue, 91]. Critics continually cite this as one of the disadvantages of the STL formulation. Although this is correct in principle, it should be remembered that if alternative processes are used, for example the contour-oriented formulation, the closed curves must also be displayed as polygonal drawings and the amount of data resulting from this kind of representation also grows enormously with the growing demand for accuracy.

In practical terms, the fineness of the triangulation is not problematic if approved settings are used.

Description errors are primarily attributable to three causes:

1. gaps between triangle patches (boundary error),
2. double triangle patches (overlap), and
3. incorrect orientation of individual patches (disorientation).

Figure 2.13 shows this error schematically.

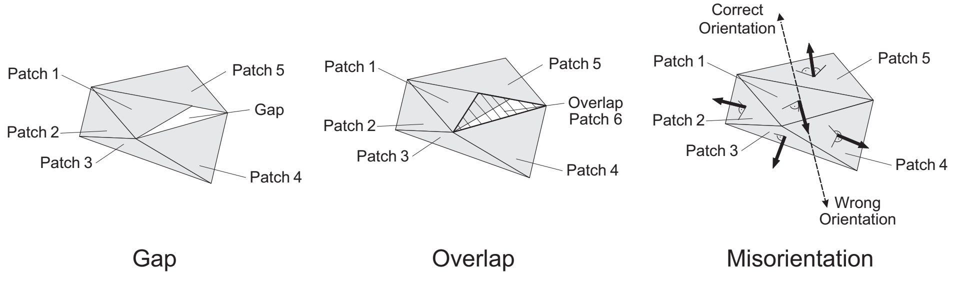


Figure 2.13 Description error: gap, overlap, and incorrect orientation

Gaps (and double triangle patches as a special form of gaps) are the result of inaccurate boundaries that border on each other. The existence of differing resolution densities of geometries can cause boundary errors on the edge on the opposite side. These are called “naked edges.”

Such defects are irrelevant for visualization and also for processing with cutter diameters in the range of millimeters. In applications with lasers that exhibit a beam diameter of 0.1 mm, such defects have a negative effect. Description errors make the production process difficult or in some cases impossible.

When the surface is oriented incorrectly, the normal vector points to the inside of the model. In general, the human eye can assign such surfaces correctly, but for generating machine data these results are problematic. The result is that the inner and outer sides cannot be separated (Fig. 2.13).

When the machine-specific layer information is generated, all gaps have to be closed. This process is called the repair of the data set. Normally, special modules of front-end software do this automatically. While repairing semiautomatically, manual intervention leads to faster and better results.

Repairing data are limited. The sample shown in Fig. 2.14(a) still allows for an easy repair. On the other hand, Fig. 2.14(b) shows a sample that is likely not fixable. The best solution for such errors is to avoid mistakes during the construction phase of the CAD model.

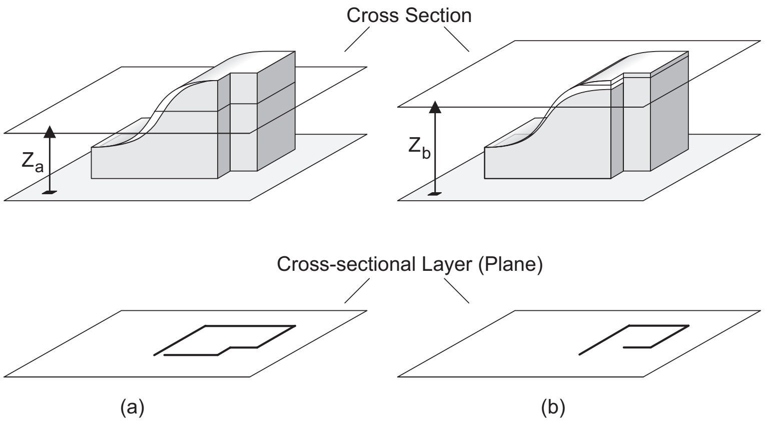


Figure 2.14 Influence of imperfectly bordered deterministic surface models on the production of layer models

2.2.2.2 CLI/SLC Format

The CLI (SLI, SLC) interface, also called the contour-oriented interface, assumes the geometry data for each individual layer of the component that is to be produced. In this case the CLI (common layer interface) interface is a cross-system, this process would bring the great advantage that the UV radiation necessary for polymerization would not need to penetrate a material layer of a certain thickness and thereby reducing its strength; it could instead be generated directly at the required point of polymerization. Spatial structures could be constructed by such sound fields and their interferences.

2.3.4.2 Electroviscosity

Electroviscosity is the ability of certain materials to alter their viscosity within broad limits while under the influence of powerful electromagnetic fields. This can go so far that liquids completely solidify. The process is not yet in use in commercial industry, primarily because the increase in viscosity cannot be produced technically and economically over a longer period of time. However, this method opens new perspectives for additive manufacturing processes. Electroviscosity enables liquids to be solidified along a defined 3D curve that can be calculated using potential equations. They form thereby a continuous contour that can be filled in with photosensitive or other rapidly solidifying materials. This can be done within a relatively short time. After solidification, the contour is removed by liquefaction and, on the basis of the new contour calculated from theoretical potential equations, another part of the model can be generated. Such a process opens the possibility of working entirely in 3D, but it depends, at least according to current knowledge, on theoretically calculated three-dimensional potential curves.

■ 2.4 Elements for Generating the Physical Layer

2.4.1 Moving Elements

The moving element defines the geometry of the component. Therefore it has to generate the inner and outer contours of each layer and if necessary, the intervening space. It demands high movement speeds and also a high path accuracy and repeatability. A (galvo) scanner or (*x*-*y*) plotter and sometimes combinations of both are used.

2.4.1.1 Plotter

Plotters are essentially *x*-*y*-positioning systems with separate axes. Timing belts and racks are used as drivers. Plotters are available in different sizes having characteristic dimensions in a range of a few millimeters to several meters. The variety is too large to be treated here in detail. The building platforms of most additive manufacturing machines have characteristic dimensions of several hundreds of millimeters. Plotters used in the cutting operation nowadays have the following technical data: cutting speeds between 10 and 100 mm/s (tangential plotters in the diagonal area to 1500 mm/s) and more; repeat accuracies of ± 0.1 mm; and pressing forces from about 0 to 600 grams.

2.4.1.2 Scanner

Scanners or galvos are freely programmable deflection systems that move the laser beam on the building plane. The term galvo merely refers to a motor-driven mirror unit rotating around its longitudinal axis according to the galvanometer principle, and is only one element of a scanner unit. Two galvos are aligned orthogonal to one another (one each for the *x* and *y* directions) to reach every point on the build platform. In this arrangement, the focus describes in fact a spherical shell. The projection is therefore in the center of the building plane, and with increasing distance it becomes increasingly blurred, especially so in the corners of the building space.

The answer to the blurriness is a so-called F-theta or flat-field lens that provides the focus outside the optical axis. The focus therefore remains for any deflection in one building plane.

Figure 2.33 shows the scanning optics, consisting of the beam expander, two motorized galvo mirrors, and the F-theta lens. The arrangement of the galvo in front of the flat-field lens is also called preobjective scanning.

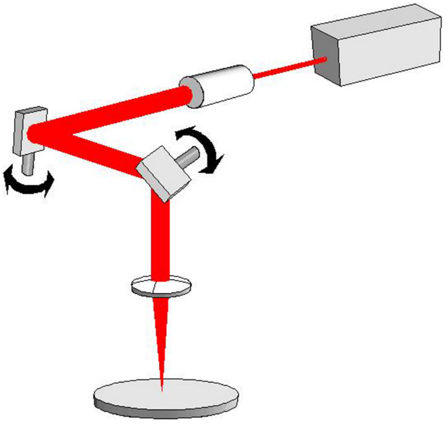


Figure 2.33
Scanning optics for imaging of the layer information on the building plane, consisting of the beam, two galvo mirrors, and an F-theta lens

The mirrors shall be lightweight to allow fast scanning speeds. To achieve fast scanning speeds, their mass inertia can be reduced by cutting off the corners, which gives them their characteristic shape. Mirrors are advantageously made of single-crystal silicon as a substrate material and a coating with the lowest possible absorption losses. The coating must be matched to the laser wavelengths used.

The trend is to use laser scanners with digital servo electronics. This is possible due to an improved encoder with a significantly improved dynamic response and increased accuracy. The electronics also allows communication between the system controller and the scanner and thereby enables online diagnostic procedures.

2.4.1.3 Simultaneous Robots (Delta Robots)

Delta robots are a variant of the parallel robots. There are three universal joints fixed to the frame-mounted rotary axes. The result is a spatial parallelogram guiding the moving element and the contouring element (the effector). This new design has only been used in the Delta Rostock fabber (Fig. 2.34). There the contouring element is an extrusion nozzle. Delta robots are relatively simple in construction, light, and fast. Their accuracy is sufficient for fabber applications.

Figure 2.34 Delta Rostock fabber with parallel kinematics

2.4.2 Generating and Contouring Elements

Generating elements generate the layer. Depending on the process, the elements also do the contouring.

The elements differ in that there may or may not be a mechanical interaction with the layer. Laser and nozzles are among the noncontact processes (nonimpact). The cutting blades, milling cutter, and to a lesser extent, the extruder, place mechanical forces on the component. These are called impact processes.

2.4.2.1 Laser

The laser is of special importance in prototyping because of its ability to focus a high energy density onto an extremely small operating diameter. Especially in connection with the scanners for the polymerization, melting, or vaporizing (cutting) of materials, it can be necessary to introduce energy with high positioning and tracking accuracy and repeatability that can produce pinpoint accuracy.

Depending on the absorption behavior of the materials, lasers with different wavelengths are used.

For the cutting of paper or plastics or the sintering or melting of plastics, a CO_2 laser (wavelength 10,600 nm) is preferred.

Polymerization requires a laser at wavelengths below 500 nm. For the processing of metals, even shorter wavelengths are advantageous.

Ar^{++} ion and HeCd lasers were the first lasers used in machines because of their favorable wavelengths despite their poor efficiency, and were used until the late 1990s. Today only solid-state lasers are installed in machines. Thus, the efficiency and the service life are significantly improved and the age-related gradual decline in performance largely eliminated.

The latest designs, such as diode-pumped solid-state lasers or disk or fiber lasers, have significantly contributed to improving the beam quality and dynamics. Today with fiber lasers, beam diameters in the range of 20 to 50 microns are realized. In addition, the beam cross section can be varied quickly with adjustable optical elements and thus reduced for boundaries and enlarged for filling areas. An elaboration of the laser principle, which due to the few types of lasers that were preferred for use in additive manufacturing production in 2000, was located in the appendix to the German second edition of this book. Given the numerous types that are used today, this has been omitted. A comprehensive current representation with a focus on production with lasers can be found for example in Poprawe [Poprawe, 04].

We differentiate between three processes when projecting the geometrical layer information onto the layer: vector, raster, and mask processes. The basic principles of these methods are also found in other contouring processes; for example, the vector process is used in cutting plotters when knives are in action. Masks can also be used in the process of using lamps or projectors for polymerization. The vector process uses either a (mirror) scanner or *x-y* plotters. In the vector process, the single contour elements are generated continuously from basic geometric elements such as straight lines, circular arcs, and so forth on the basis of the standardized plotter software. It can be assumed, therefore, that a circular contour parallel to the layer will appear as a polygonal curve in the STL formulation and as a continuous circle in the SLC formulation. The laser beam can be pulsed, as in most polymerization and sintering processes (the processes are discussed in Section 2.3), or work continuously (continuous wave, CW), as in layer laminate processes. The vector process is the most accurate process, but also the slowest. The duration of the generation of a layer depends in particular on the complexity of the layer.

In the raster process, the contour is still generated using the same geometric information, but—as with an older television picture—line by line. As a result, a stair-stepping effect appears from line to line similar to that in the *z* direction. The height of the steps is determined by the width of the effective track, and in the case of a laser, by the width of the laser beam. As the effective width of the laser beam may be up to 0.3 mm. Such raster processes will, for nonrectangular geometries, have a much higher tendency to generate a stair-stepping effect in the layer surface than that of the design-dependent layers in the *z* surface. The vector process enables the contour to be moved by half a beam diameter (beam width compensation), resulting in very accurate contourings; the raster process cannot do this. The duration of the generation of a layer in the raster process does not depend on the complexity of the layer. The process is faster than the vector process, but slower than the mask process.

The third possibility is the mask process. Here a mask is produced to be geometrically similar but on a smaller scale and is then screened by an energy source. As with a diapositive, an authentic-scale contour is reproduced on the layer surface. The accuracy is limited by the precision with which the mask can be made. Mask processes operate with transparent, electrostatically or sequentially coated masks for LCD (liquid crystal display) technology monitors or directly with DLP (digital light processing) projectors, but also with mechanical masks. The exposure of an entire layer occurs all at once. The exposure time is therefore not dependent on the complexity of the layer, and the process operates quickly.

Figure 2.35 shows the three principal processes for the reproduction of the geometric layer information onto the layer.

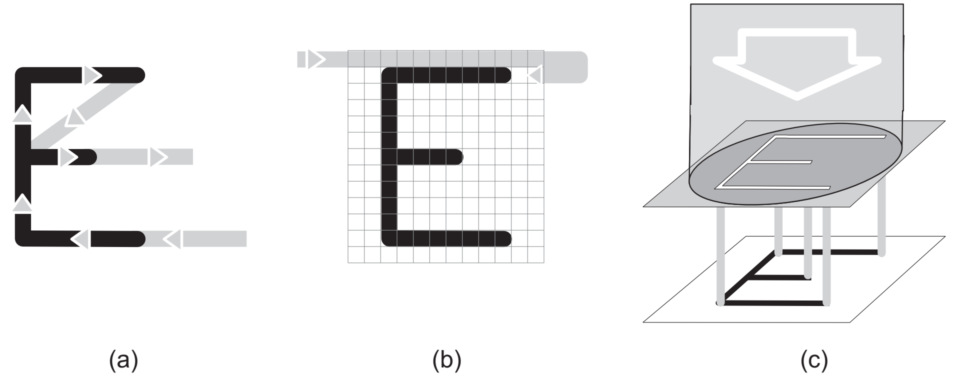


Figure 2.35 (a) Vector, (b) raster, and (c) mask processes to image the geometric information onto the layer

2.4.2.2 Nozzles

Bubble-Jet or Thermal Nozzles

A bubble-jet print head is composed of an ink reservoir that is connected through a capillary with the actual nozzle (Fig. 2.36). The ink channel is electrically heated shortly before the nozzle. As a result, the ink vaporizes locally. The resulting vapor bubble abruptly displaces a defined volume of ink that is fed due to the pressure conditions through the nozzle onto the print destination. In the case of additive manufacturing it is sprayed on the powder bed.

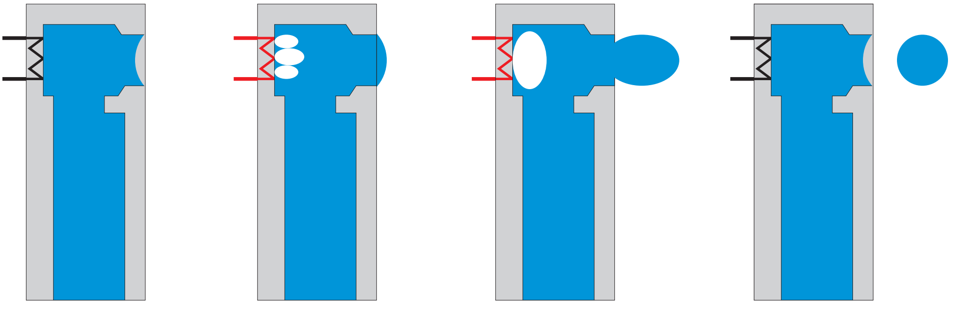


Figure 2.36 Principle of bubble-jet nozzles. (Source: Tecchannel (www.tecchannel.de))

In a print head, up to several hundred nozzles can be accommodated per print head, with the nozzle having diameters of about 20 to 50 microns. The drop volume is approximately 4 to 30 picoliters, and the temperature at the heating element is 300 °C. The thermal system is comparatively slow. A frequency of about 4 kHz is standard, with about 10 kHz as the upper limit. The Photo-Ret-III process of Hewlett-Packard reaches a frequency of approximately 18 kHz. From 408 nozzles, approximately 7.3 million droplets per second are applied with a volume of 5 picoliters. However, the process prints 29 points, one above the other, and has been optimized for 2D printing on paper or foil.

It is often considered a disadvantage of thermal print heads that the drop size cannot be varied. That is not true. By sequential heating, preferably by two downstream heaters connected in series, two different-sized vaporization zones can be created with appropriate tuning, which joins into one and thus carries away a significant amount of liquid. However, it is very difficult to form very different large drops. In addition, the drop rate is quite low. Thermal print heads for 2D printing are usually replaced together with the ink reservoir so that the wear of the nozzle does not affect the print result in practice. Each color (cyan, magenta, yellow, and black) may have its own reservoir and head, or an integrated head may be used for all colors, depending on the manufacturer and the use of the device. There are also systems with separate nozzles and reservoirs.

In the integration of printing systems in additive manufacturing machines, larger amounts of fluid have to be used, and the controllers are modified accordingly. Therefore, the standard ink reservoirs are replaced with binder tanks that are connected via tubing systems. The commercial print heads of 2D printers are usually used as nozzles.

Piezo Nozzle

A pure (electro)mechanical process can be more precise and especially faster than a thermal controlled one. The deformation occurs in approximately 5 microseconds, the reverse deformation as well, so frequencies up to 30 kHz can be achieved. The droplet size can be adjusted by the applied voltage and quickly varied. The ink channels and hence the drop volume are smaller (2 pl (pL)) than in thermal systems, so a point diameter of 0.035 microns can be achieved on the paper, which corresponds to a resolution of 800 dpi. Currently, the mechanical positioning systems set the limits more than the print heads.

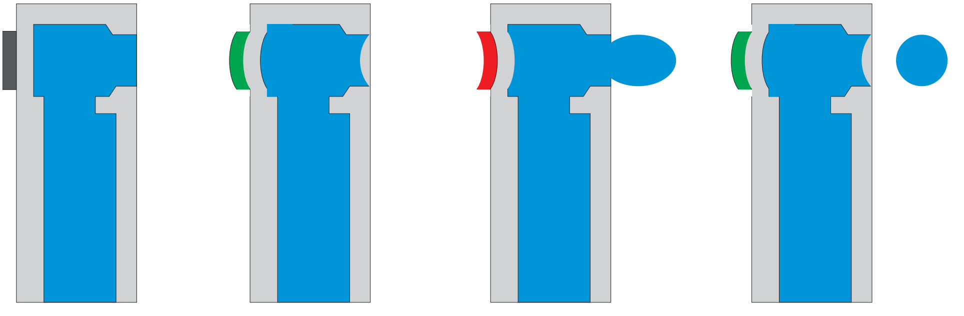


Figure 2.37 Principle of a piezo nozzle. (Source: Tecchannel (www.tecchannel.de))

With a piezo nozzle, highly viscous liquids and binders that are thermally sensitive can also be processed. Moreover, an independent preheating of the fluid is possible. Thus is created the optimal conditions for additive manufacturing machines that can print photopolymers or other high-viscosity fluids. Coinciding with the “firing” of a droplet, a negative pressure can be generated by applying a negative voltage to the piezo quartz in the ink channel. The result is that the ink is pulled back slightly at the nozzle. This “meniscus” effect (drastic pull ejection meniscus control) also causes a bias of the droplet surface, which favors the “firing” of the next droplet and at the same time suppresses the formation of secondary droplets.

Piezo heads are especially sensitive to air or gas inclusions, because due to its compressibility, the impulse needed for ejection can be resorbed (or absorbed). The problem corresponds to the case of the venting of water pipes. Piezo elements and their control usually require more space than thermal jets. Therefore a typical piezo print head has fewer nozzles (50 to 100, maximum 200) than does a thermal print head.

Piezo heads are robust but also more expensive than thermal print heads. They are not usually exchanged in printers, but are static and therefore also optimally adjusted. When refilling the ink there is no risk of maladjustment. Today's systems usually still have replaceable print heads because of the higher wear in additive manufacturing machines. Particularly maintenance-friendly designs offer replaceable single nozzles or nozzle groups.

Accuracy

The minimum droplet size can define the accuracy of a printing process in combination with the positioning in the *y* direction (row direction) and in the *x* direction (line spacing). High-quality printing requires a correspondingly high repeatability. The system also includes very high mechanical requirements.

Powder-binder systems are also limited in their accuracy by the size of the powder particles. Common are particle sizes of 50 microns (up to 100 µm). The lower limit is approximately 20 microns. When colored components are produced by such systems and their texture is defined by the binder, the surface shows after a possible grinding operation for finishing large areas of colored powder. At preferably white powder the component accordingly appears in pastel colors.

Materials

The different inks should not be discussed at this point because this happens later in the description of the individual machines. However, the development of a 2D printing technique that has primarily UV-stable colors as a goal should be pointed out. In this context, RCP colors (radiation curable pigmented inks) are developed whose coloring constituents polymerize by UV radiation to stable pigments. This allows one to print almost all weather-resistant materials. In view of today's additive manufacturing processes that print photopolymers, there arise interesting perspectives for the production of colored components.

2.4.2.3 Extruder

Extruders used in additive manufacturing operate according to the system of constant volume. A geometrically defined material, mostly as a wire but also in the form of blocks, is placed in an electrically heated chamber. There it is converted by the heat into the viscous state. The chamber is also called a "liquifier," although liquefaction must be avoided in order to achieve a defined material application. A supplied volume of the same amount is extruded through a nozzle and coated as a layer onto the component. Nowadays, machines have only one nozzle for the building material. Because the material is available colored, differently colored components can be manufactured. However, the color cannot be changed within one component, so textures cannot be achieved. Because all commercialized extrusion processes work with supports, a second nozzle for the support material is usually installed in the machine. The use of multiple, parallel operating extrusion nozzles is generally possible but currently only applied by fabbers. There are also constructions that apply differently colored material. For industrial machines this has not been realized yet. Unlike printing systems, extruders operate quasi-continuously; in other words, they apply the material in one go, but interrupt the extruding during the positioning phase. The distance between the outlet of the nozzle and the surface of the component must always be lower than the extruded material cross section so that the viscous material can be “crimped” on the partially completed structure. The cross section will become oval. Extruder systems work with little force, but not entirely without contact. Extrusion systems are very sensitive to air and gas pockets. Another problem is the water consumption of the building material, which is expressed as vapor bubbles with splashes.

2.4.2.4 Cutting Blade

Contouring with blades draws on the technique of 2D cutting plotters for paper and film. For this, *x-y* plotters are used. Cutting speeds of up to 300 mm/s can be reached. Processes with cutting blades are not nonimpact processes. The blades reach a pressing force of about 30 to 300 g.

Films made of paper, plastic, and ceramic are preferably contoured with blades. A cutting resolution of 0.025 mm per step and an accuracy of 0.1 mm (Roland SP 300) can be achieved.

All systems for contouring have in common that not only the characteristics of the contouring element, for example, the nozzle diameter, the laser beam diameter, or the width of the blade, but equally also the precision of the *x-y* (*z*) handling system used determine the quality of the component.

2.4.2.5 Milling Cutter

If cutters are used in additive manufacturing, the optionally modified milling machines and processing are not any different from conventional milling. Therefore, and in view of the large number of possible machine concepts, machining with milling cutters will not be discussed further. A very extensive and also hands-on book was written by Degner [Degner, 02]. Schulz [Schulz, 96] describes the aspects of high-speed machining in his book. Wirth [Wirth, 02] describes the model milling process and practical implementation from the CAD program.

2.4.3 Layer-Generating Element

An additive manufacturing machine is equipped with moving elements and generating elements that are geared to each other. Together they form the layer-generating element and thus constitute the additive manufacturing heart of the machine. Just a few combinations have been proven in practice. Table 2.1 shows the most common combinations. Any other special solutions are discussed with the corresponding machine in Chapter 3.

Table 2.1 Most Common Combinations of Layer-Generating Elements

Physical principle		Additive manufacturing family	Moving element	Generating/contouring element
Photopolymerization	2.3.1.1	Stereolithography	Scanner	Laser
		Polymer printing	Plotter	Printing head
Melting and solidification of powders and pellets	2.3.2.1	Sintering Melting	Scanner	Laser
Cutting from foils/films and joining	2.3.2.2	LLM	Plotter	Laser, knife, milling tool
Melting and solidification out of the solid phase	2.3.2.3	FLM	Plotter	Extruder, nozzle
Conglutination of granules with binders	2.3.2.4	3D Printing	Plotter	Printing head
Generation from the gas phase	2.3.3.1	Aerosol printing	Plotter	Nozzle

The layer-generating element is actually the tool of the additive manufacturing machine. It firmly belongs to the machine and would not change depending on the component, which is why it is said that additive manufacturing works without tools. Strictly speaking, they do not need a tool that is individually adapted to the production task. It is not necessary to change the tool when a skull model and a radio panel are produced one after the other, just as with a 2D printer: if a notice is to be printed instead of a commendation, it is not necessary to change the machine settings.

Because the layer-generating element has the function of the tool, it is important to determine and control the parameters that define the operational capability of the tool and also develop strategies to operate in the allowed parameter fields.

For all elements, the designers make use of additive manufacturing systems that have preferably been proven on large-series technology. Around 26 million installed inkjet and laser printers form an economically solid basis for the development of applications adapted accordingly. Only through the use of components, whose development had been financed through sales from other markets, was the development of additive manufacturing equipment possible. It is also the only way to finance it in the future. In about 15 years (1988–2003), additive manufacturing machines increased to 10,000 systems worldwide.

■ 2.5 Classification of Additive Manufacturing Processes

The professional literature contains a number of different representations concerning the systematics of additive manufacturing processes. Many are oriented only to the currently available methods or to isolated properties of such processes. They agree, for the moment, but that quickly reaches the limits when new processes need to be integrated. All additive manufacturing processes (including all additive manufacturing processes) are in the end manufacturing processes. Therefore their nomenclature should be based on the standardization of the manufacturing processes (DIN 8580).

Additive manufacturing processes are not always unique to a main group due to their variety. Basically they are in the main group 1, creating cohesion or archetypes (DIN 8581).

As constituent manufacturing processes, they would fall under the aspect "cohesion increasing" assigned to the main group 5 "Coating," and because of many variants of the process, assigned to other groups and subgroups. After weighing the pros and cons, a classification is possible based on the standardization of archetypes (DIN 8581). The additive manufacturing methods are classified in the first outline level according to the state of aggregation of their original material, and in the following level, by the appearance in the sense of a semifinished product. In the third level, the mechanism of layer formation is shown, and the fourth level contains the generic description of the process.

In Fig. 2.38, the current processes can be clearly classified to date while maintaining the proven structure.

The industrial processes and their manufacturers or brand names allocated to the generic designations are discussed in Chapter 3. There the classification found in Fig. 2.38 continues, including the industrial processes and their product names.

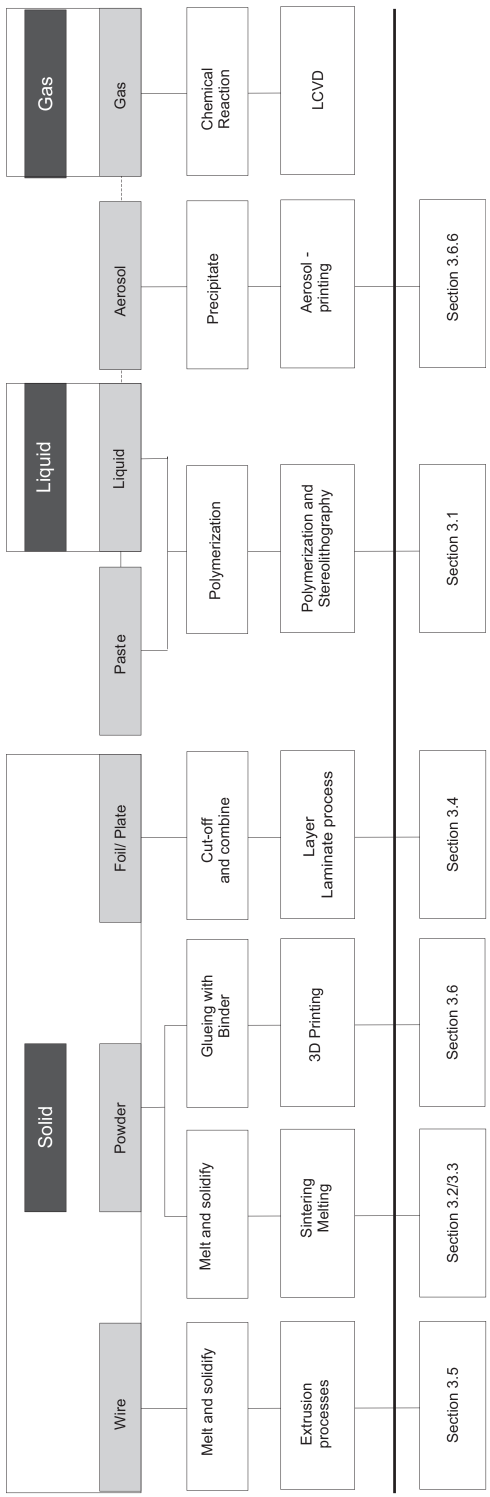
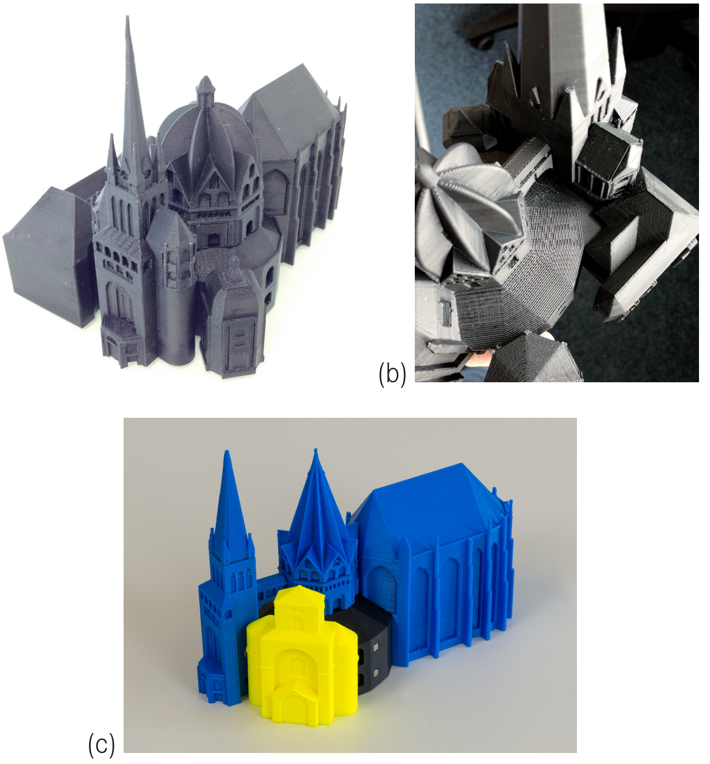


Figure 2.38 Classification of additive manufacturing processes depending on aggregate state of the basic material referring to DIN 8580



(a) (b) (c)

Figure 4.50 Model of the Aachen cathedral, fused deposition modeling. The CAD data were reconstructed from images and processed for model building: (a) full model, scale around 1 : 468, (b) detail of the roof, with deliberate extrusion structure, (c) important parts of the building history produced as single parts (Source: FH Aachen/Einhard Gymnasium Aachen)

4.3.6 Rapid Prototyping for the Evaluation of Calculation Methods

4.3.6.1 Photoelastic and Thermoelastic Stress Analysis

Mathematical-physical calculation models allow the simulation of product properties, like stability, vibration behavior, and temperature resistance, and of manufacturing technologies, for example, casting simulations that are based only on theoretical approaches directly at the computer. The use of such methods, which are also the basis for virtual reality, is the fastest route to new products.

One disadvantage of the calculation models is that they are more or less simplified, so their results cannot be fully applied on the repetition part and there are more or less uncertainties. Therefore, the variables of the models have to be changed or corrected constantly by the results of evaluations, which were carried out on repetition parts. A fast and efficient way to get such correction values is to carry out the experimental evaluations on rapid prototyping parts instead of repetition parts.

A longer-used method is the so-called photoelastic stress analysis on specially developed acrylic glass parts. Polished rapid prototyping models could also be used here and can enhance the geometric possibilities.

A newer, but also significantly more complex, approach is the detection of the stress level by a systematic analysis of analogies between the optical and the thermal properties of the part. This method is called thermoelastic stress analysis.

4.3.6.1.1 Photoelastic Stress Analysis

The approach is to use the refraction properties of stereolithography models for photoelastic analyses and thereby verify the predictions of computer calculations by testing at an early stage of product development.

Epoxy resins, especially those used for stereolithography, have the property of displaying optical double refractions, which is the basis for a stress analysis aided by photoelasticity. An interference pattern in the transparent stereolithography component is obtained that is proportional to the stress within the component and that can be interpreted manually or automatically.

This process adopts the concept of photoelasticity, which has been known since the beginning of this century. With the aid of stereolithography models, today's greatest problem can now also be solved—that of making 3D models from conventional photoelastic materials.

Epoxy resins are exceedingly well suited for the generation of models for photoelasticity because of their high transparency. They hardly differ from the standard materials (Araldit B, Ciba Geigy) used for photoelasticity. Acrylates are less well suited because of their lower degree of transparency. If used for stereolithography models, care should be taken that the model is cured as evenly as possible, so as few air bubbles as possible are created, and that the surface is flawless. Some kinds of construction and exposure methods, for example, those generating hollows intentionally to increase the quality and dimensional stability of SL components, are therefore unsuitable for photoelastic checks. It also has to be taken into account that semipolymerizing processes (whereby complete polymerization occurs later in a postcuring oven) thus create optically effective parting planes. From the aspect of photoelasticity, components made of epoxy resins SL5170 and SL5180 that use the build style ACES (3D Systems) are especially suitable.

The basic setup for photoelastic checks (Fig. 4.51) consists of a pole filter, a light source, and two $\lambda/4$-wave plates, which facilitate the separation of the isochromatics (lines of the same principal stress difference) from the isoclines (lines of the same principal stress) so that then only the isochromatics and the transparent model, which is placed between the two $\lambda/4$-plates, can be viewed.

Regardless of the type of resin used, the necessary material parameters must first be defined before the photoelastic test can be carried out and evaluated. The most important value is the photoelastic constant, which is determined from a calibration test and which denotes the relationship between stress and isochromatic order. The photoelastic material parameters of the most important stereolithography resins are listed in Appendix A3.15, “RP Materials and Casting Resins” [Steinchen, 94]. Should other resins or other kinds of constructions (scan strategies) be used, these calibration tests ought to be repeated.

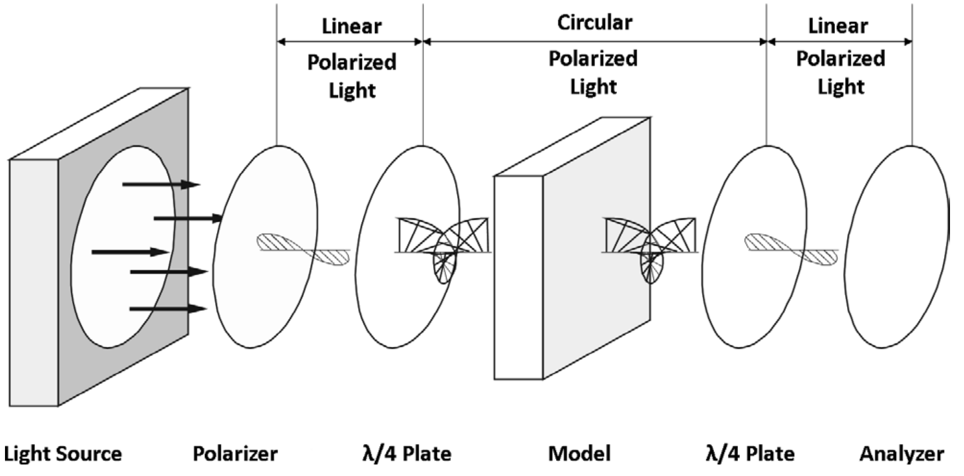


Figure 4.51 Setup for a photoelastic stress analysis (Drawing: Steinchen)

4.3.6.1.2 Thermoelastic Stress Analysis

The development of safety-relevant devices such as, for example, steering assembly parts in automobile manufacturing, still relies on tests made on series identical models. Rapid prototyping processes change little here because the plastic parts and also modern metal parts can either not be tested under series conditions or, if tested, they do not allow any applicable conclusions to be drawn.

Thermoelastic stress analysis (THESA) is successfully employed in testing such components without extensive field trials. It allows single parts to be simulated on the test bench instead of monitoring the module or doing a driving test. THESA is based on the fact that metal components under stress show temperature changes that are proportional to the given stress, provided the load stays within the elastic sector. These temperature fields and their fluctuations can be recorded using appropriate high-resolution thermal cameras; tensions can be related to the temperature fields and correlated with the strains. This process was modified in cooperation with an automobile manufacturer, so it is now possible to use this process, initially meant for metal components, for plastic components also [Gartzen, 98]. In principle, this has paved the way for the optimization of highly stressed components with the aid of plastic rapid prototyping models.

4.3.6.2 Example: Photoelastic Stress Analysis for a Cam Rod in the Engine of a Truck

The starting point is a 3D CAD model of the component to be tested. This is produced as a stereolithography component. Care should be taken that the value of the photoelastic constant is kept as low as possible. The most important parameter here is the aftercure under UV light [Steinchen, 94].

Further action depends on whether a 2D test at room temperature is to be run, or a 3D photoelastic test. If a 3D test is required, the stereolithography component must first be “frozen.” Using an oven with a programmable cooling curve, the model is heated up to approximately the glass transition temperature, loaded, and then cooled down to room temperature at 2 to 3 °C per hour. Afterward, the elongations, and thereby also the tensions, are “frozen.”

The photoelastic test itself is now run on 2D models. In the case of a 3D photoelastic test, this involves the cutting out of a cross section at the test-relevant area for use as a 2D model. A normal band saw can be used for this purpose.

When placing such a 2D (Fig. 4.52, top) or 3D (Fig. 4.52, middle) model of the valve lifter (Fig. 4.52, bottom) between two polarizers or quarter-wave plates (Fig. 4.51), a usable isochromatic pattern is recognizable in the 2D model. For the 3D model of the valve lifter, the isochromatic images of the single layers are superimposed so that a clear definition is not readily possible. In general, it can be observed that the stress concentration is higher the more isochromatics appear at a particular point and the closer they are together. If the quarter-wave plates are removed, the isoclines are recognizable. Whether an interpretation of the isocline picture is necessary depends on the method of analysis used. An automatic analysis using an electronic image processing system is also possible. The aim of the analysis is to define the main extensions and the main tensions to allow a conclusion to be drawn concerning the number of tensions.

After the interpretation of the isochromatic picture is complete, the results of the test can be used for dimensioning prototypes with the aid of similarity laws. The similarity law for the static case is, for example:

$$\frac{\sigma_P}{\sigma_M} = \frac{F_P}{F_M} \cdot \left(\frac{l_M}{l_P} \right)^2 \tag{4.1}$$

As Equation 4.1 shows, the results are transferable without great effort. To summarize, it can be stated that photoelasticity together with stereolithography is a reliable and economical method of implementing an experimental optimization of the subsequent product already in the design phase [Jacobs, 95], [Kramer, 92], [Susebach, 93], [Steinchen, 94].

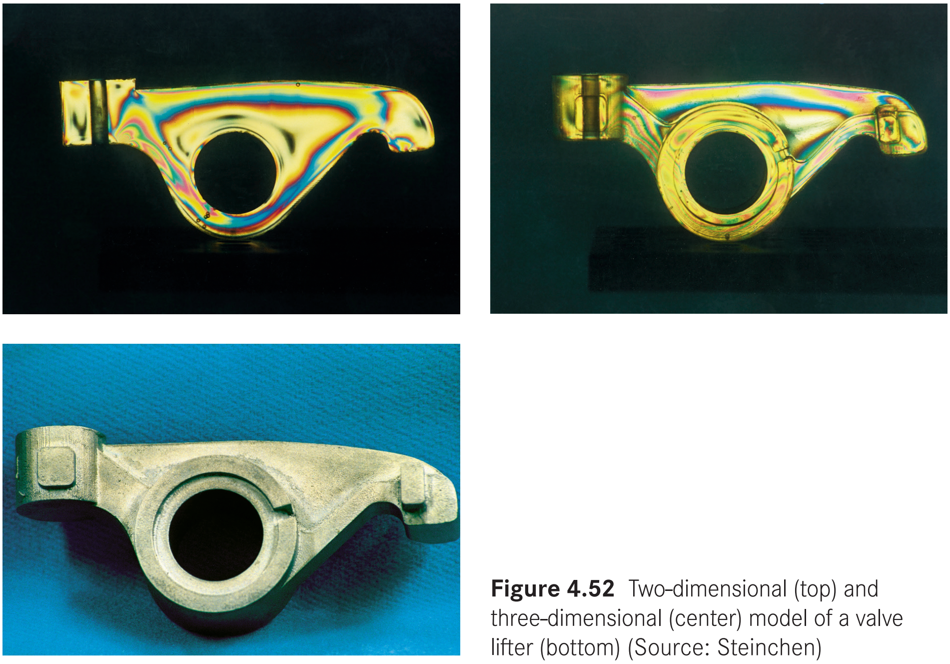


Figure 4.52 Two-dimensional (top) and three-dimensional (center) model of a valve lifter (bottom) (Source: Steinchen)

4.3.6.3 Example: Thermoelastic Stress Analysis for Verifying the Stability of a Car Wheel Rim

The wheel rims of sports cars are highly stressed safety components that are increasingly required to be lightweight and attractive while the dynamic stress on them increases continuously. A hollow rim promises to fulfill these requirements. The development is difficult, however, because the prototypes of hollow rim segments cannot be produced by milling as in solid constructions. For optimization purposes, therefore, the components must be cast as in series processes. One set of molds is necessary for each casting and has to be made as custom-built models from wood in a model workshop.

The development until now has been correspondingly complicated (Fig. 4.53, left string). From the CAD data, which are checked and optimized by FEM processes (for reasons of clarity, the optimization loop is not shown in the graph), a second cast in aluminum is obtained by conventional mold making. This cast is finished, mounted, and tested. Depending on the results, this loop is performed several times and the results iteratively improved.

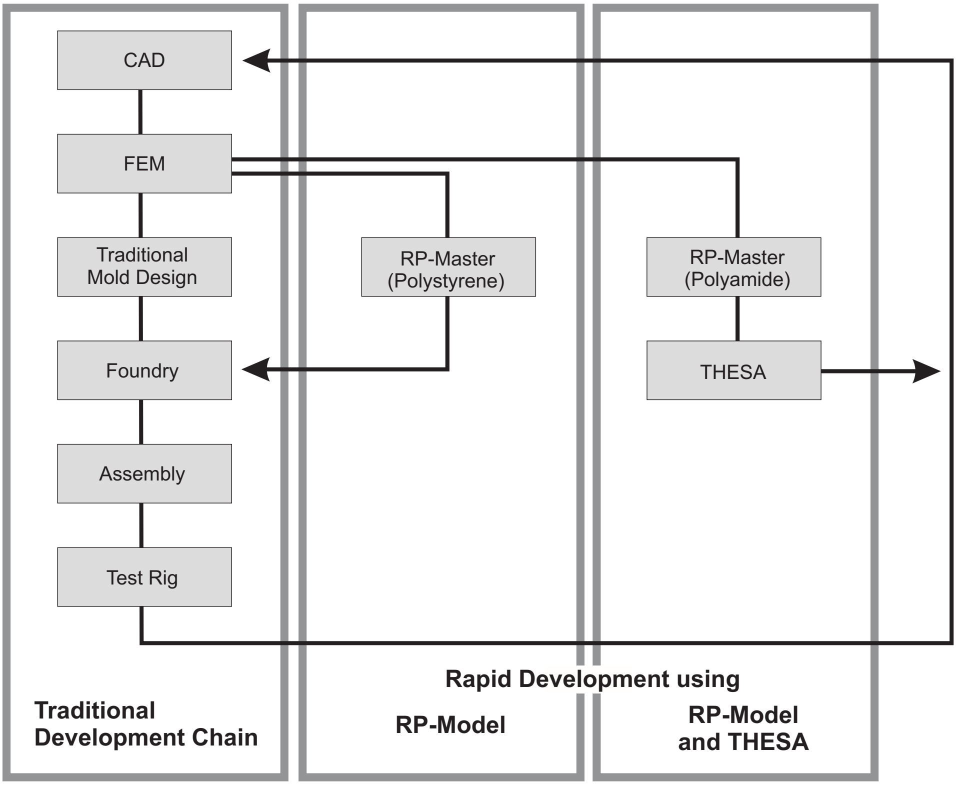


Figure 4.53 THESA, schematic steps in the process chain and the shortening thereof by the use of rapid prototyping (Source: Schwarz/CP)

When THESA is employed, this process is shortened because assembly and driving tests are omitted.

When using rapid prototyping processes, the process can be further shortened insofar as the mold making is substituted by a rapid prototyping model that is cast directly in a precision casting process.

The decisively shorter development process is achieved by being able to test the sintered polyamide rapid prototyping component directly by means of THESA, thereby eliminating the necessity of the entire casting process. Figure 4.54 shows an exemplary thermographic image with a defined stress and, in comparison, the same situation with a molded aluminum wheel rim. The conformities are excellent, as documented by the totals of the main tensions given in the example over the radius at the center of the component (Fig. 4.55).

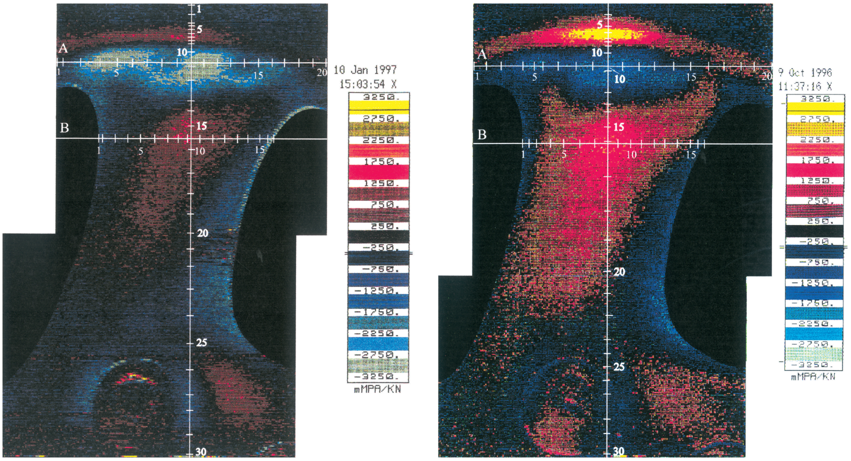


Figure 4.54 THESA, thermographic reproduction of a rapid prototyping component (polyamide) (left) and of an aluminum series part (right) (Source: Schwarz/CP)

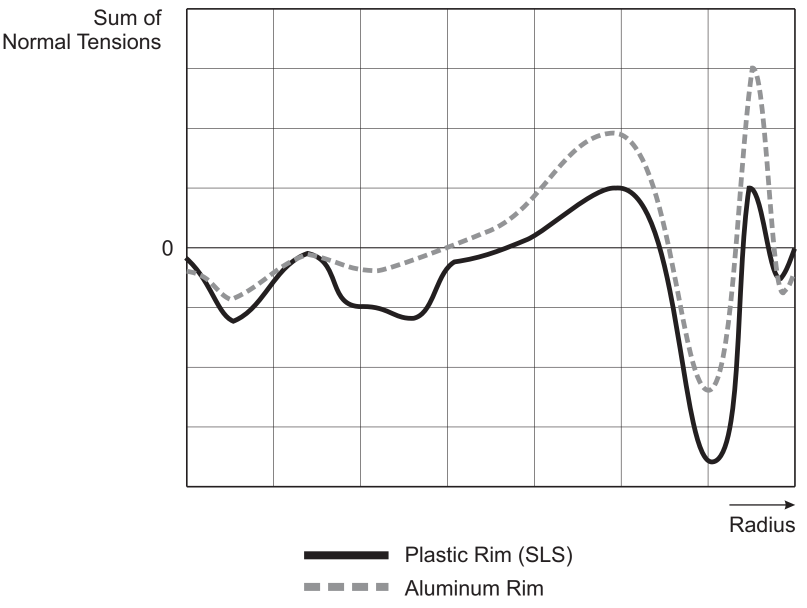


Figure 4.55 THESA, total of the main tensions over the radius in the center of the component (Source: Schwarz/CP)

When THESA is used for sintered plastic components generated by rapid prototyping, the time needed for the iteration loop is reduced to 20% of the time previously needed. The greatest single effect is the reduction of production time from 18 days for a cast component to three days for a polyamide component. By applying this modified THESA process, the entire development process can be reduced dramatically, although not down to 20 % of the previous time because the final test for a safety component still needs to be run with a component made of the original material.

■ 4.4 Outlook

For solid images and concept models, the trend is toward cheap and easy-to-use personal printers that can be used at home or in the office. The production of models requires less or no data preparation and also no or less manual postprocessing. The price limit for the mass production is today at around 5,000 € (just over $5,000), and for self-made systems and kits the price is between 1,000 € and 4,000 €. The ProJet 1000/1500, which was presented as V-Flash in 2007, shows the way.

The development of machines for the production of functional prototypes goes in another direction. The coupling of machines and materials today allows the given assignment of model requirements to the additive processes. In the future, development will concentrate on the materials, and from this there will be a bigger material range for every machine available. The models and prototypes will become more and more powerful, but the choice of a process is getting complicated. From today's optimization of two groups of process parameters, the model definition and the additive process, three groups of parameters will grow: the process, the model definition, and the material.

The development of machines will lead to a reduction of the necessary manual postprocessing and partially reduce costly finishing. Models and prototypes will then be easier to reproduce, and also be available quicker. Office-usable processes that produce hazardous waste and require the use of solvents, alkalis, and the like will be less accepted.

frequency identification (RFID) should be checked for their utility. The documentation must permit the production of a replacement part at any time.

6.3.3.6 Logistics

Logistically, the additive manufacturing process is therefore a "manufacturing on demand," or a *just-in-time* manufacturing of single parts. The difference from the logistics of current big series is not irrelevant, because due to the single part character, the parts are not delivered in containers or other bulk packaging for further assembly, but must be placed as individual items in the usage site.

Variant production by the automobile manufacturers is already an indication of this integrated logistics and production engineering task. In the Audi A6 (built in 2005), for example, 18,000 different door panels can be installed. A journal on automobile production headlines it accordingly: "Insanity with method" [Automobil Produktion, 05]. With these numbers, it is still a matter of parts that are in series, albeit small, and produced with current production methods.

Therefore, series products are combined with other series products to form individualized mass products with a unique image. But all part products relied on for individualization are part of series and logistically can be treated as anonymous series products charge-wise.

Additive manufactured individualized products are unique in manufacturing technology as well. In the future, "single part-uniques" are completed with other "single part-uniques" to complete "product-uniques." Logistically, consequently, all elements of the whole supply chain are to be treated as individual parts.

Logistically, the task also is to implement a suitable merger between the product with all of its parts and all necessary accessories, also individualized, such as manual, warranty certificate, and packing material. Finally, everything must be archived so that the individual access is ensured at all times and over a long period of time.

■ 6.4 Implementation of Rapid Manufacturing

In the application of the methods of additive manufacturing, different scenes are possible. AM machines are integrated as elements of a mostly nonadditive multicomponent fabricator in the manufacture process as well as decentralized for complete additive manufacturing. They are used in industry or privately as personal printers. Depending on the application case, different machine concepts will emerge. The developments conceivable today are introduced next with examples. The transition from current additive manufacturing in the concept of rapid prototyping to rapid manufacturing takes place smoothly. It had already begun some time ago.

Classifications are not reflected accurately in these following examples because, in practice, mixed forms tend to occur.

6.4.1 Additive Manufacturing Machines as Elements of a Process Chain

In industry, rapid manufacturing that has already been introduced by additive methods was integrated into a production network with nonadditive methods. Parts are manufactured that are additionally machined, finished, and assembled with other products in the course of the production chain. An example of a simple combined process is the production of a titanium structure for aviation (Titanium 6Al-4V); see Fig. 6.21. The structure is additively manufactured on a milled plate, heat treated, machined to size, separated from the stabilizing base plate by machining, and measured. The structures have characteristic dimensions up to 2500 mm. The additive method consists of an adapted LENS process (see Section 3.3.2) and machine finishing. It is marked by a high percentage of manual operations.

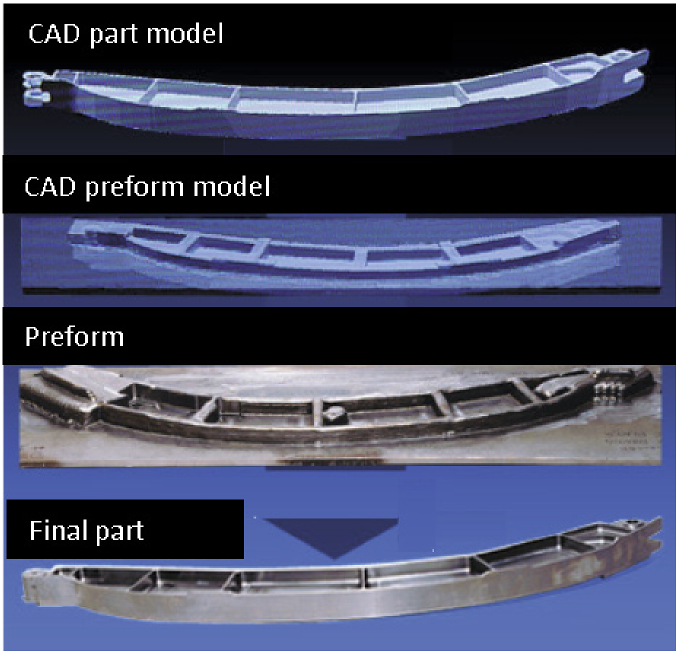


Figure 6.21 Combined additive and conventional manufacturing process for aviation components made of titanium (Source: Aeromet)

In the field of plastic molded parts, a combined conventional and additive manufacturing is also possible if plastic injection-molding machines do large quantities, while parallel to that, the additive machines provide the single parts.

For that, the additive machines must be free of manual work parts (according to Section 6.3.3, "Future Efforts in Additive Series Production") and be integrated into production lines.

6.4.2 Additive Machines for Complete Production of Products

Additive manufacturing methods have the potential to directly manufacture not only components, like plastic moldings, but also complex products (see Section 6.2, "Potential for Additive Manufacturing End Products"). Such approaches represent a paradigm shift from today's multipart single part and assembly-oriented production technology to an additive one-step manufacturing of complex products.

6.4.2.1 Industrial Complete Production

In the form of complete manufacturing machines, fabricators will enable the manufacturing of selected parts or complete products. One example is the 3D printing machine of Therics Theriform that can produce up to 40,000 pills per hour with complex inner structures and distributed active components. The pills leave the machine already packed (see Fig. 6.22).

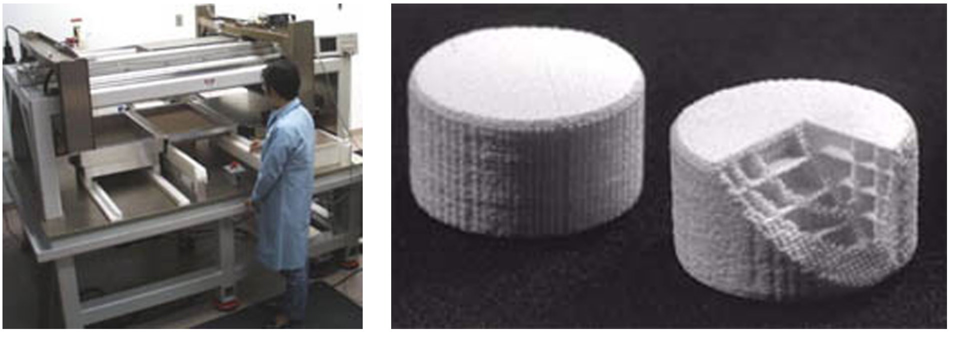


Figure 6.22 TheriForm 3100: manufacturing of pills by 3D printing machine (left), pill outer view and in section (right) (Source: Therics)

Because producing additive manufacturing machines do not have to be integrated into production lines, but constitute the lines themselves, and because any spatial separation of design and production is possible, their operation and installation can be decentralized. A central design with a decentralized manufacturing can be realized, and vice versa, as well as all conceivable combinations. Especially attractive would be the equipping of customer service centers for the direct production of the required accessories and spare parts or the adaptation of hull products with country specific, locally additive manufactured attachments.

The industrial fabricators for those applications must include all of the properties just discussed in future AM machines and in particular, to ensure a high productivity.

Examples of products are a one-piece additive manufactured cable clamp with two integrated hinges and cable guides with integrated clamps (Fig. 6.8) or the gripper in Fig. 6.5.

The nozzle plate produced by microTec (Fig. 6.23) is an example of the micromanufacturing of components. As part of a catheter, it drives the turbine wheel of the mill. Its diameter is 4 mm, and the outlet cross section of each nozzle is 20 μm. The plate consists of biocompatible material. It is an example of microparts that cannot or can only with much greater effort be manufactured with conventional methods.

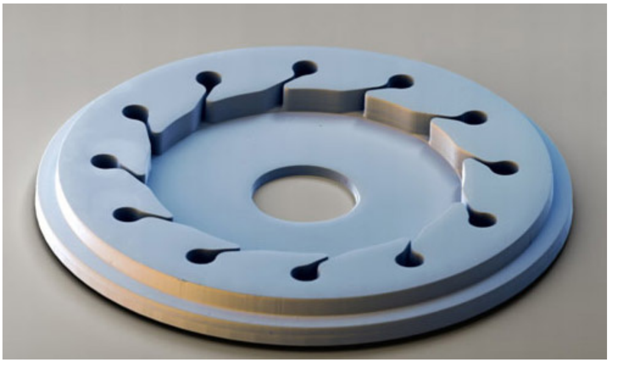


Figure 6.23 Nozzle plate (Source: microTec)

An example of an integrated product that, from the point of view of the manufacturer of mobile phones, represents one component, is a tapered helical mobile antenna manufactured with the M^3D Technology of Optomec. See Fig. 6.24.

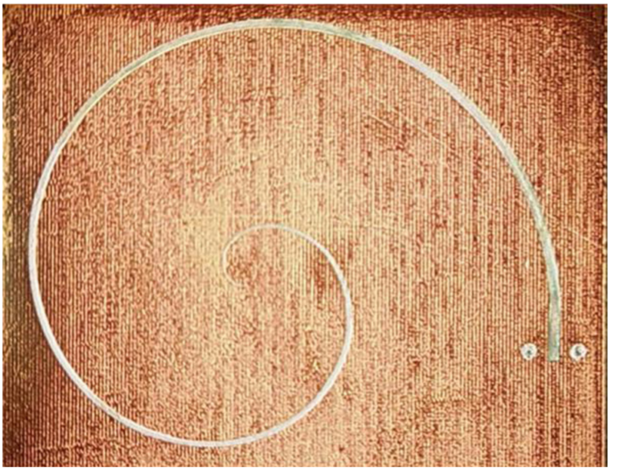


Figure 6.24 Mobile antenna, aerosol printing (Source: Optomec)

6.4.2.2 Individual Complete Production (Personal Fabrication)

With complete and in one step automated additive manufacturing machines, non-manufacturing technicians can also produce products. This is possible through personal printers or fabbers (Section 3.5.2). They are available as complete machines with good part properties (FDM Mojo, Polymerisation ProJet 1000/1500) or as fabbers with reduced component quality, but at very affordable prices, either as complete machines or as an assembly kit. The bottom price for a DIY fabber of the type Prusa Mendel is today (2013) at about 600 € (about $ 675).

In combination with a personal computer, those kinds of fabbers or personal 3D printers represent complete production systems for individual decentralized production. The implementation, especially in a private setting, has already begun.

The data come from a personal 3D design that can be created by anyone with programs like Google SketchUp or as a complete data set from Internet portals like 3D Warehouse or Shapeways.

With this, the over 10-year-old scenario is becoming realistic in which children design system construction kits and other toys on the computer on their own and directly manufacture them. The 3D printing blogs provide assistance and promote the exchange of experiences. Self-made spare and additional parts are therefore no longer ideal. The step from cybercommunication to cyberproduction has been taken.

The productivity for these applications mostly plays a subordinate role, and manual work parts are accepted.

An example of personal fabrication is the model of a camshaft wheel (Fig. 6.25). It was manufactured with the (up to 2006) easiest and cheapest machine, the LD3 Printer (Section 3.4.10). It is easy to imagine that in this way, system assembly kits, components of model toys, or spare parts can also be manufactured.

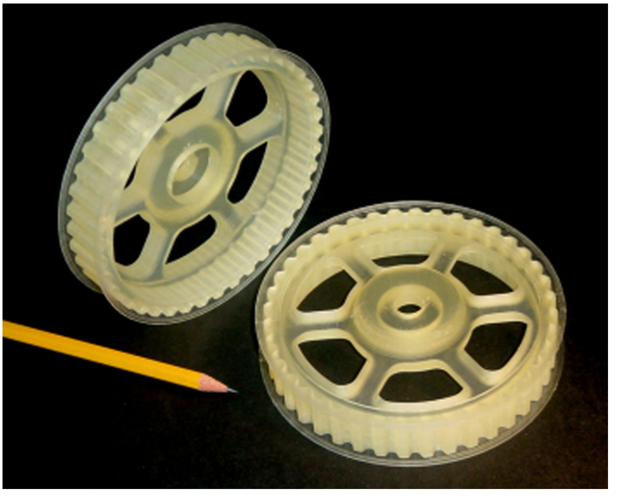


Figure 6.25 Camshaft wheel as example for system toys (Source: Solidimension)

6.5 Application Fields

During the discussion of additive manufacturing machines, it has already become clear that development is running in two directions. One of them leads to universal machines, the other one to specialized applications, also in the sense of branch solutions. Both trends will grow further in future.

More specifically, for the so-called universal machines there are also two lines of development. One leads to simple office-suitable or also privately usable machines that are summarily described as personal 3D printers.

The other one leads to complex additive manufacturing machines that require a manufacturing infrastructure and are suitable for developers, for in-house or independent service providers, or for research laboratories. With them, depending on the application, end products (production 3D printer) or also prototypes (professional 3D printer) can be manufactured.

The specialized machines aim at the processing of special, often also branch-specific materials or material families. But they contain also more often packaged solutions, consisting of the additive machine, a branch-specific software solution, and materials matched to the process. Both the total packages as well as the pure service are offered. In each case only finished products or their components are manufactured.

Therefore, from the point of view of additive manufacturing technology, application fields have been developed that it can be usefully structured by materials or by branch. Of course the areas have strong interactions with each other.

6.5.1 Application Fields for Materials

This chapter gives an overview of selected, particularly heavily developed areas of application. It does not claim to be complete.

The processes and the mechanical-technological properties of the materials will not be discussed in detail. These are described in Chapter 3 and compiled in Appendix A3.1/A3.12.

6.5.1.1 Metallic Materials and Alloys

The development of metallic materials is oriented preferably in niches that contain attractive boundary conditions for additive manufacturing. Niches with respect to the application are flow-conducting, thermally loaded parts, such as the turbine housing of a turbocharger in Fig. 6.26.

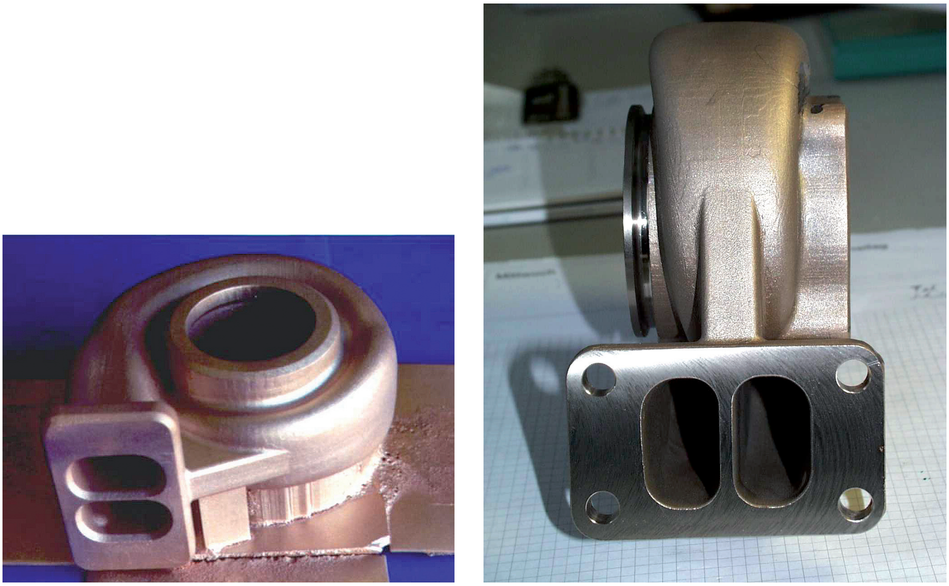


Figure 6.26 Casing of the turbine of an exhaust turbocharger. Selective laser sintering, after the building process (to the left) and after finishing (right) (Source: 3D-Systems)

Industry niches include aerospace and medical technology. The applications are characterized by small numbers or single parts. These industries are used to materials that are specially prepared and sensitively monitored, and to extensive testing of each part. Also, one is more willing to tolerate an appropriate price level for this effort.

Titanium and CoCr alloys are the keys to these branches. All suppliers of metal processes (Sections 3.2 and 3.3) have multiple relevant approved materials. The parts are all end products.

The niches also include the tooling, although altogether it is a very large industry. The basic requirement to offer tool steels was first fulfilled a few years ago. The tendency, compared to nonadditive processed steels, to higher strength and lower elasticities is increasingly overcome. The range is still small and often includes only a few materials per supplier, but it is growing very dynamically.

6.5.1.2 High-Performance Ceramics

Unnoticed by many and hidden by the efforts in the processing of metallic materials, applications have been developed in ceramic materials for all additive process families [Gebhardt, 07]. Used are 3D printing and extrusion processes, polymerization and layer laminate processes with subsequent sintering processes, and also direct applications of the additive sintering technique. Figure 6.27 shows a filter element made with the Ceraprint 3D printing process, which has been modified by Specific Surface based on the MIT license.

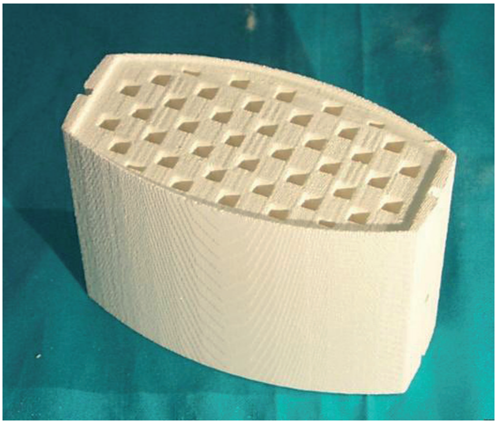


Figure 6.27
Ceramic filter element
(Source: Specific Surface)

Direct sintering in the high-temperature chamber was developed by Phenix and implemented industrially. The process is described in Section 3.2.12. Figure 6.28 shows a ceramic heat exchanger with an intricate internal structure.

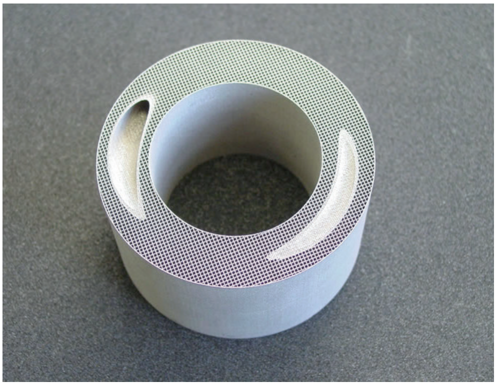


Figure 6.28
Ceramic heat exchanger
(Source: Phenix)

The range of ceramic materials covers almost the entire spectrum: shapes and parts made of Al_2O_3, SiO_2, ZrO_2, and SiC, fully sintered Si_3N_4, and so-called *graded materials*, such as zirconia-reinforced aluminum (ZTA) formed by coating ZrO_2 on an Al_2O_3 layer or a corresponding substrate.

Monolithic ceramics are manufactured, but flowed mainly through or with high temperatures impinged structures. Defined macroporosities are the basis for implants of resorbable bioceramics. Microporosities are used in reactors, but especially in tribological systems.

6.5.1.3 Plastics

Many critics focus primarily on devaluing additive processable plastics when parts do not have properties equal to those of nonadditive plastic parts, especially when processed in a thermoplastic injection mold. This is mainly a question of the design (compare Section 6.3.3.4, "Design"), but consequently this criticism causes intensive work on the improvement of existing materials systems, and the qualification of new ones.

Certain specific additively processed materials, such as polyamides, can come quite close to the properties of their nonadditively processed counterparts, but overall this is still some way away from a technically important range, especially for the high-performance materials (see Fig. 6.18). The qualification of PEEK has already been achieved, and the important PA 6 is scheduled to launch.

An important application of plastics is in the casings (shells) for in-ear hearing aids. If the relevant data were available, hearing aid shells could have been additive manufactured since 1991. In addition to the development of appropriate software packages for the design of the shells, the development of materials provided the breakthrough that means that worldwide an estimated 85% of all hearing aid shells are manufactured with (different) additive processes today (see Section 6.5.2.3, "Medical Equipment and Aids, Medical Technology"). The breakthrough came with the development of a material that can directly and permanently be worn in the ear (see the next Section 6.5.1.4, “New Materials”).

Alternative plastic materials are pigmented polyamide for the sintering process and colored resins based on (meth)acrylate for polymerization processes.

6.5.1.4 New Materials

According to the previous section, the development of hearing aid shells required new materials. Radiation-curable resins from the SLA technology are not usually biocompatible. The reasons are often the use of a combination of radical and cationic curing (hybrid system), and the selection of highly reactive unsaturated epoxy compounds. Therefore, new biocompatible materials have been developed for the otoplastics that are permanently in contact with the patient. By means of an anaerobic inhibitor, 2,2,6,6-tetramethylpiperidin-1-yloxy (TEMPO, free radical), the resins were stabilized, and the photosensitivity was adjusted so that a low radiation energy results in the greatest possible depth of cure with a high degree of polymerization, good green strength, and sufficient stability (material: Fototec, [Klare, 05]). The final products obtained by complete curing not only have good mechanical characteristics, but also exhibit excellent biocompatibility, are hard-elastic, and show a very low water absorption. The material is opaque or transparent.

In microtechnology, the material is often the deciding factor for a successful application, and frequently this material must be developed or modified. In this context, the use of a service provider is often the better choice. This is the business model of the company microTec (Section 3.1.6), which also undertakes individual material development.

New materials created through the composition of different layers of, among others, plastic, metal, ceramic, or even living cells, are produced by the M^3D method of Optomec (Section 3.6.6).

6.5.2 Application Fields by Industry

This section provides an overview of selected applications that have been strongly developed. It does not claim to be complete.

The processes and the mechanical-technological properties of the materials will not be discussed in detail. These are described in Chapter 3 and listed in the appendix.

6.5.2.1 Tooling

In addition to the basic requirement to offer tool steels that match the properties of nonadditive processed materials, the additive systems must be integrated in particular into the production flow in the tooling. Some systems are tailored to the tooling in this sense. They build up for example on a system holder or integrate pallet or clamping systems, which can be aligned with little effort for the subsequent steps in nonadditive machines. Examples were discussed in Section 5.4.3.

In tooling, it is essential to optimally match additive and nonadditive elements together. One example is the ecoMold project [Hennings, 04] that touches upon the DMLS processes (Section 3.2.4) but, in principle, is possible to implement with each sintered metal or fusion process. The starting point is a modularization in the sense of dividing additive and nonadditive manufacturable elements.

The nonadditive finishing work is enabled by clamping elements. Figure 6.29 shows an element after additive processing, a compilation of all of the elements and the clamping plate and the fully assembled mold half.

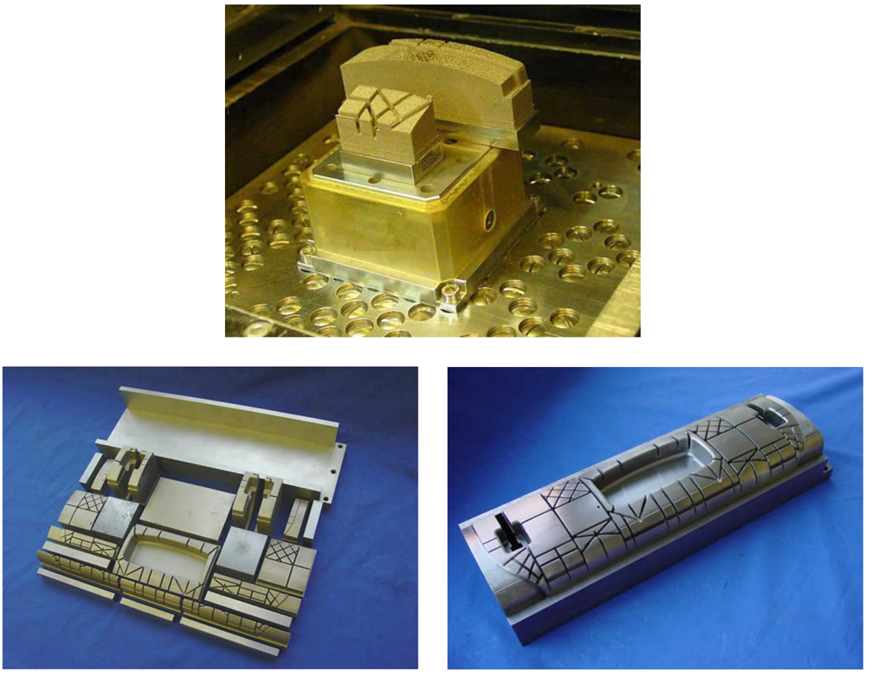


Figure 6.29 Ecomold: additive construction process (above), additive and nonadditive manufactured tool components (bottom left), and assembled tool half (bottom right) (Source: IFAM)

The application tooling is particularly discernible by design enhancements that are only additively implementable. Of special significance is conformal cooling. It was presented and discussed in Chapter 5.

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