HANSER

Sample Pages

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Understanding Additive Manufacturing

Rapid Prototyping - Rapid Tooling - Rapid Manufacturing

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Table of Contents

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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).

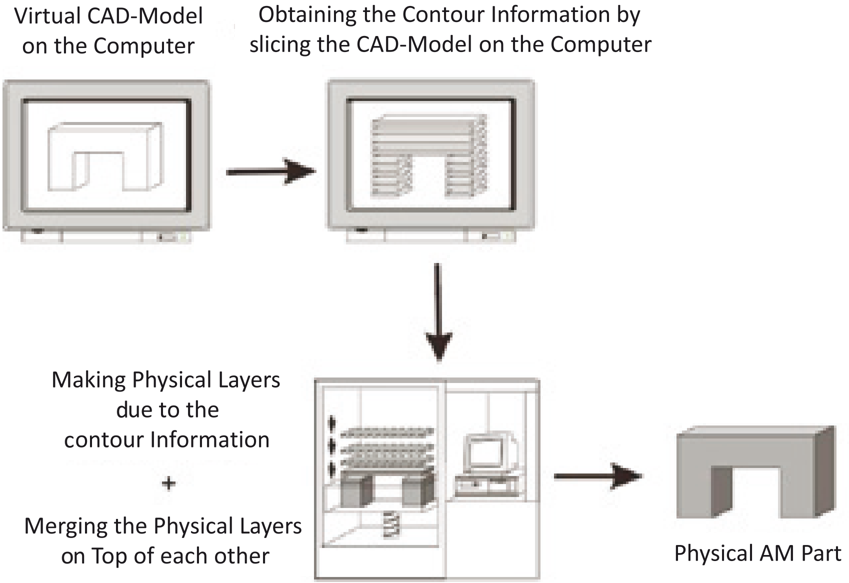

FIGURE 1.2 Additive manufacturing (AM) process chain

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".

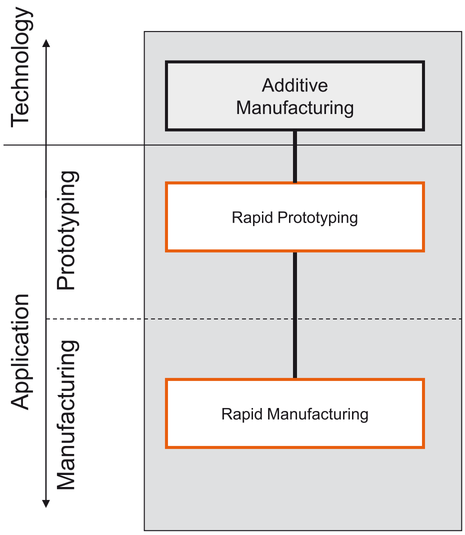

FIGURE 1.3 AM: technology level and the two application levels rapid prototyping and rapid manufacturing

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.

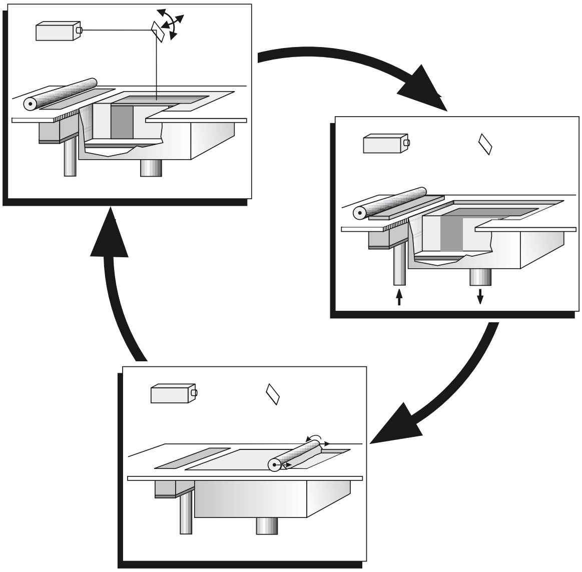

FIGURE 2.10 Laser sintering and laser melting, scheme; melting and solidification of a single layer, lowering of the platform, recoating (clockwise from top left)

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).

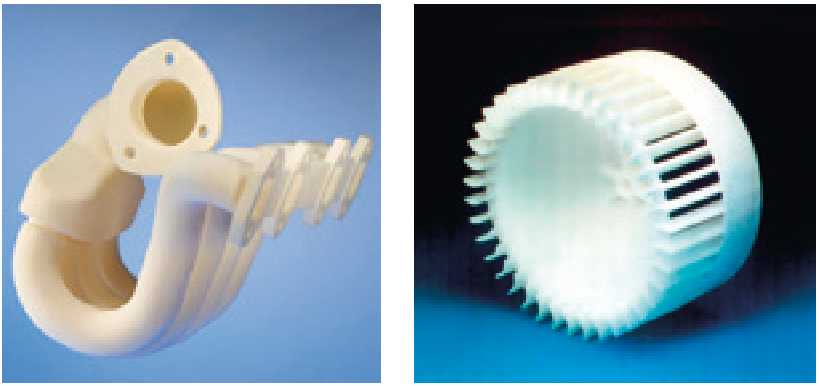

FIGURE 2.11 Selective laser sintering, SLS (3D Systems), polyamide; exhaust gas device, prototype (left); fan, final product (right) (Source: CP-GmbH)

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

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].

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

Index