Course Title	3D PRINTERS & APPLICATIONS	Credits	L T P C
Course Code			3 0 0 3
Course Category			

OBJECTIVES
• To develop CAD models for 3D printing.
• To import and export CAD data and generate. STL file.
• To select a specific material for the given application.
• To select a 3D printing process for an application.
• To produce a product using 3D printing or Additive Manufacturing (AM).

UNIT – I: 3D PRINTING (ADDITIVE MANUFACTURING)	9
Introduction, Process, Classification, Advantages, Additive V/s Conventional Manufacturing processes, Applications.	
UNIT – II: CAD FOR ADDITIVE MANUFACTURING	**9**
CAD Data formats, Data translation, Data loss, STL format.	
UNIT – III: ADDITIVE MANUFACTURING TECHNIQUES	**9**
Stereo- Lithography, LOM, FDM, SLS, SLM, Binder Jet technology. Process, Process parameter, Process Selection for various applications. Additive Manufacturing Application Domains: Aerospace, Electronics, HealthCare, Defence, Automotive, Construction, Food Processing, Machine Tools.	
UNIT – IV: MATERIALS	**9**
Polymers, Metals, Non-Metals, Ceramics. Various forms of raw material – Liquid, Solid, Wire, Powder; Powder Preparation and their desired properties, Polymers and their properties. Support Materials	
UNIT – V: ADDITIVE MANUFACTURING EQUIPMENT AND POST PROCESSING	**9**
Process equipment- design and process parameters Governing bonding mechanism Common faults and troubleshooting Process design Post processing: requirement and techniques Product quality Inspection and testing Defects and their causes	

CO	COURSE OUTCOMES	PO
Upon completion of this course, Students should be able to		
1.	Develop CAD models for 3D printing.	**PO3, PO5**
2.	Import and Export CAD data and generate . STL file.	**PO3, PO5**
3.	Select a specific material for the given application.	**PO3, PO5**
4.	Select a 3D printing process for an application.	**PO3, PO5**
5.	Produce a product using 3D Printing or Additive Manufacturing (AM).	**PO3, PO5**

TEXT BOOK	
1.	Andreas Gebhardt and Jan-Steffen Hötter "Additive Manufacturing: 3D Printing for Prototyping and Manufacturing", Hanser publications, United States, 2015, ISBN: 978-1-56990-582-1.
2.	Ian Gibson, David W. Rosen and Brent Stucker "Additive Manufacturing Technologies: Rapid

	Prototyping to Direct Digital Manufacturing", 2nd edition, Springer., United States, 2015, ISBN-13: 978-1493921126.
REFERENCES	
1.	Khanna Editorial, "3D Printing and Design", Khanna Publishing House, Delhi.
2.	CK Chua, Kah Fai Leong, "3D Printing and Rapid Prototyping- Principles and Applications", World Scientific, 2017.
3.	J.D. Majumdar and I. Manna, "Laser-Assisted Fabrication of Materials", Springer Series inMaterial Science, 2013.
4.	L. Lu, J. Fuh and Y.S. Wong, "Laser-Induced Materials and Processes for Rapid Prototyping", Kulwer Academic Press, 2001.
5.	Zhiqiang Fan And Frank Liou, "Numerical Modelling of the Additive Manufacturing (AM)Processes of Titanium Alloy", InTech, 2012.

Unit – I : Introduction - Additive Manufacturing – Layer Manufacturing

Contents..

- Introduction
- Process
- Classification,
- Advantages,
- Additive V/s Conventional Manufacturing processes
- Applications.

Introduction - Additive Manufacturing – Layer Manufacturing

- "Additive Manufacturing" (AM) is a **layer-based automated fabrication process** for making scaled 3-dimensional physical objects directly from 3D-CAD data without using part-depending tools. It was originally called **"3D Printing"** and is still frequently called that.
- Together with the well established "Subtractive Manufacturing", such as milling or turning, and the "Formative Manufacturing", such as casting or forging, Additive Manufacturing provides the third supporting pillar of the entire manufacturing technology.

- When the first approaches to "Additive Manufacturing" entered the market in 1987, it was called "Rapid Prototyping" or "Generative Manufacturing".
- Both terms are still in use and in the past years many different names have been presented and frequently more are added.
- Although each of the names is perfect from the special viewpoint of its creator, many of them cause confusion.
- Often, this is one reason why newcomers to the industry in particular sometimes feel lost in the field of AM.
- To obtain a brief overview, a small selection of the mostly used terms are structured according to a few families of key words. Often used terms include:

"additive" Additive Manufacturing (AM)

Additive Layer Manufacturing (ALM)

Additive Digital Manufacturing (DM)

"layer" Layer Based Manufacturing

Layer Oriented Manufacturing

Layer Manufacturing

"digital" Digital Fabrication

Digital Mock-Up

"direct" Direct Manufacturing, Direct Tooling

"3D" 3D Printing, 3D Modeling

The Principle of Layer-Based Technology

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

Principle of layer manufacturing. Contoured layers (left), 3D object made from staggered layers (right)

- Each layer is contoured according to the corresponding 3-dimensional data set and put on the top of the preceding one.

Fundamental manufacturing methodologies

Three fundamental manufacturing methodologies

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

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.

Product development cycle

- Rapid prototyping (RP), one of the earlier additive manufacturing processes, allows for the creation of printed parts, not just models. A few of the noticeable advances this process offered to product development and production include the following:

  (1) reductions in both time and costs,

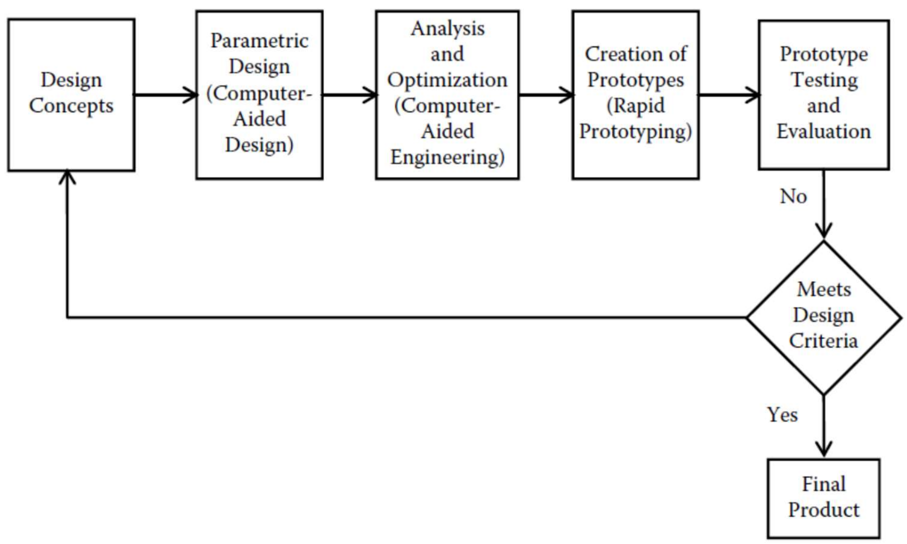
  (2) enhanced human interaction,

  (3) the possibility of creating almost any shape that would otherwise be very difficult to machine, and

  (4) a shortened product development cycle

- As there are no tool setting, workpiece fixture, and tool wear compensation requirements, the process was categorized as being the most flexible and direct form of digital manufacturing.
- In industry circles, the process began to be referred to as *additive digital manufacturing* (ADM) rather than rapid prototyping.

- In the mid-1990s, the rapid prototyping processes became firmly established as indispensable components for the rapid development of a product.
- With the emergence and use of rapid prototyping, both scientists and students have been able to build and analyze models for the purpose of theoretical analysis, comprehension, and study.
- Medical doctors can build models of a diseased or injured human body for the purpose of analysis and determining the various test procedures to be used.



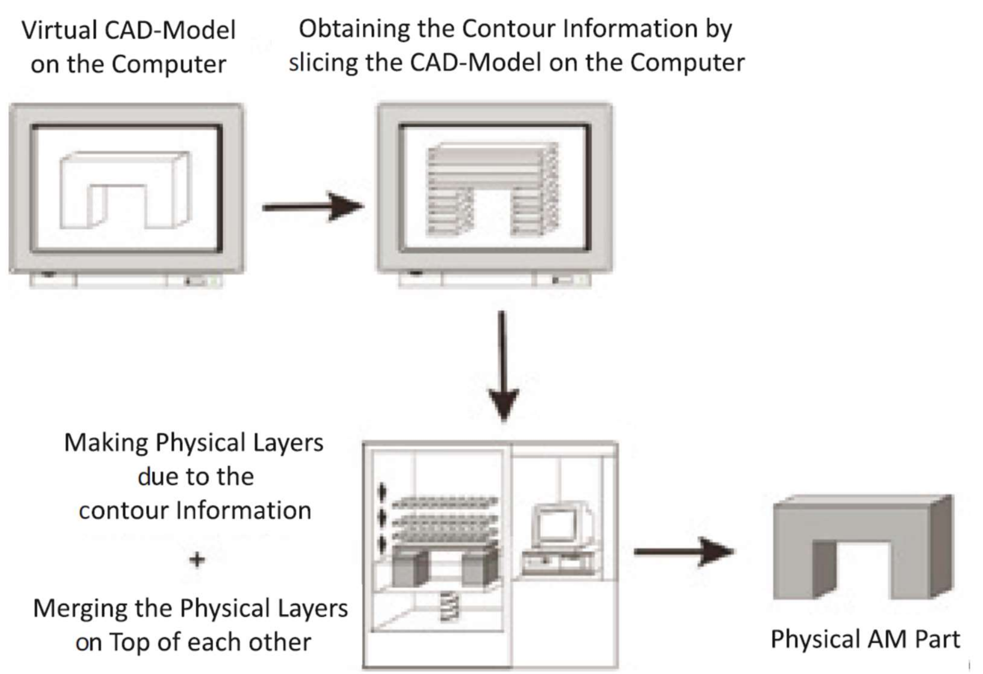
Flow chart - Product life cycle

- With the aid of rapid prototyping, market researchers can receive quick feedback on what the ultimate end users think of a new product.

- The key steps involved in product development using rapid prototyping are shown in Figure.
- It is apparent in this figure that creating models more quickly can save a lot of time, and there are advantages to be gained by being able to test a number of models to eliminate flaws in their design and make any changes required for improved performance.
- The technology of rapid prototyping has been used not just for the creation of models but also for the creation of finished products constructed of plastic materials.
- Subsequently, this technology has come to be termed 3D printing (3DP), although in reality it originated as rapid prototyping.
- The advent of rapid prototyping and the concurrent emergence and use of the technologies of computer-aided design (CAD), computer numerical control (CNC), and computer-aided manufacturing (CAM) resulted in the evolution of rapid manufacturing (RM).
- The CAD, CNC, and CAM technologies, when combined together, made possible the printing of three-dimensional objects.
- Rapid prototyping was found not to be the best solution in all cases, especially when dimensions of the part are larger than the available additive manufacturing printers.
- This raised the need for the use of CNC machining processes.
- The materials often chosen and used for rapid prototyping are still very limited.

- It became clear following years of trials that it is possible to print parts made from both metals and ceramics but not from all of the available and commonly used manufacturing materials.

Additive manufacturing process

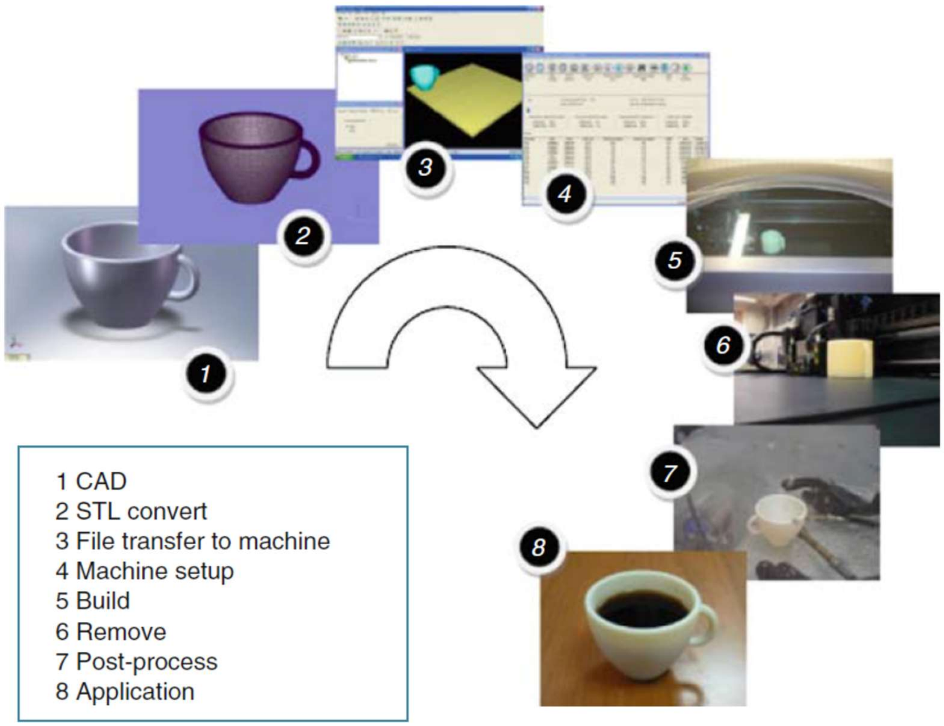


- Additive manufacturing (AM) is an automated and revolving process developed from the principle of **layer-based technology**.
- It is characterized by a **process chain.**
- It starts with a (virtual) 3-dimensional CAD data set (solid) that represents
- the part to be produced.

- 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).
- 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 simplest 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.
- 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.

Generic process of CAD to part, showing all 8 stages



Step 1: CAD - All AM parts must start from a software model that fully describes the external geometry. This can involve the use of almost any professional CAD solid modeling software, but the output must be a 3D solid or surface representation. Reverse engineering equipment (e.g., laser scanning) can also be used to create this representation.

Step 2: Conversion to STL

Nearly every AM machine accepts the STL file format, which has become a defacto standard, and nearly every CAD system can output such a file format. This file describes the external closed surfaces of the original CAD model and forms the basis for calculation of the slices.

Step 3: Transfer to AM Machine and STL File Manipulation

The STL file describing the part must be transferred to the AM machine. Here, there may be some general manipulation of the file so that it is the correct size, position, and orientation for building.

Step 4: Machine Setup

The AM machine must be properly set up prior to the build process. Such settings would relate to the build parameters like the material constraints, energy source, layer thickness, timings, etc.

Step 5: Build

Building the part is mainly an automated process and the machine can largely carry on without supervision. Only superficial monitoring of the machine needs to take place at this time to ensure no errors have taken place like running out of material, power or software glitches, etc.

Step 6: Removal

Once the AM machine has completed the build, the parts must be removed. This may require interaction with the machine, which may have safety interlocks to ensure for example that the operating temperatures are sufficiently low or that there are no actively moving parts.

Step 7: Postprocessing

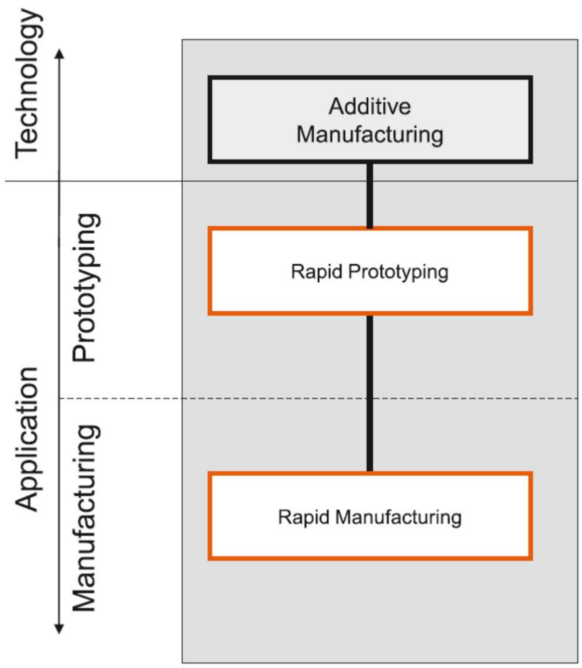
Once removed from the machine, parts may require an amount of additional cleaning up before they are ready for use. Parts may be weak at this stage or they may have supporting features that must be removed. This therefore often requires time and careful, experienced manual manipulation.

Step 8: Application

Parts may now be ready to be used. However, they may also require additional treatment before they are acceptable for use. For example, they may require priming and painting to give an acceptable surface texture and finish. Treatments may be laborious and lengthy if the finishing requirements are very demanding.

Understanding additive manufacturing process

- To define 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.
- AM technology is characterized by two main application levels, "**Rapid Prototyping" and "Rapid Manufacturing".**



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

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

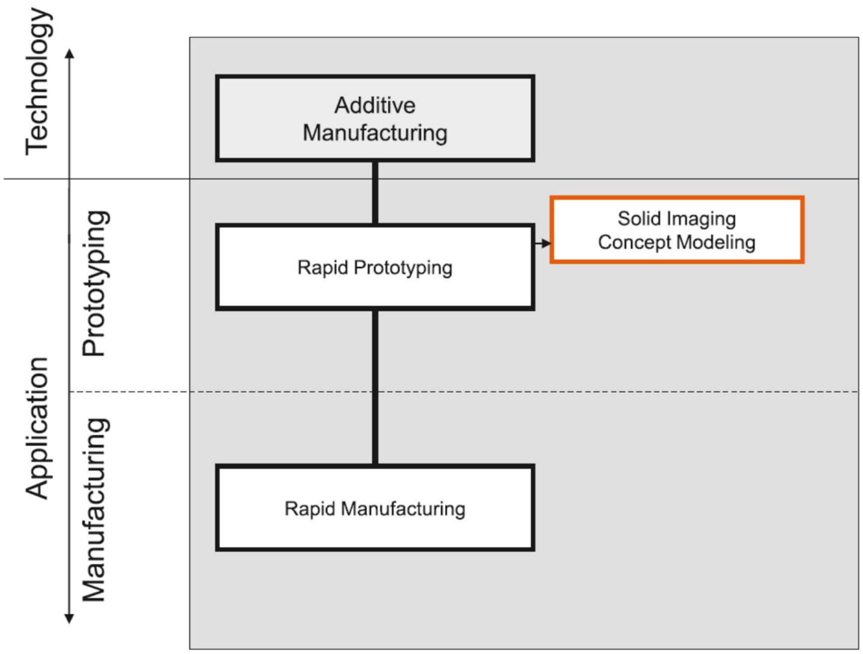
Direct Processes

- All AM processes are called **"direct processes"** in order to indicate that the digital process model is directly converted into a physical object, called the part, by means of a generative machine.
- In contrast to this, some procedures are called **"indirect processes"** or also **"indirect rapid prototyping processes".**
- They do not apply the principle of layer manufacturing and consequently they are not AM processes.
- Actually, indirect processes are copying techniques mostly based on silicon rubber casting such "room temperature visualization moulding (RTV)".

Rapid Prototyping

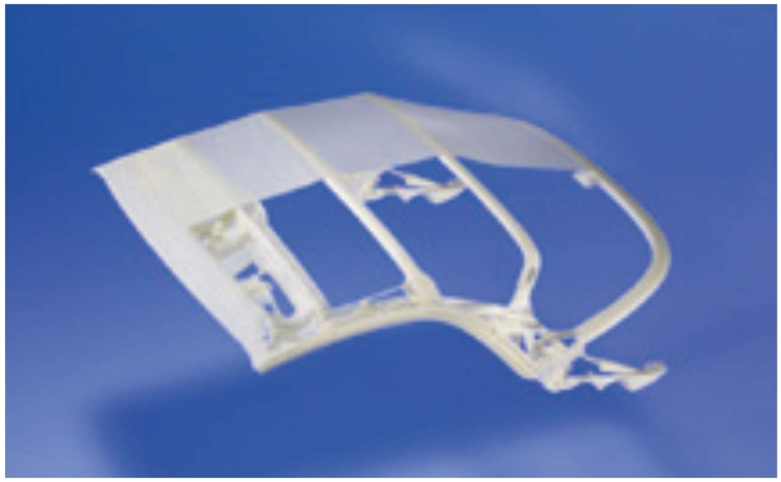
- The application level "rapid prototyping", two sub-levels can be distinguished: **"Solid Imaging" and "Concept Modelling"** on the one hand and **"Functional Prototyping"** on the other hand.
- Solid imaging or concept modeling defines a family of parts that are applied to verify a basic concept.
- The parts resemble a **three dimensional picture or a statue**.
- In most cases, they cannot be loaded. They are used just to get a spatial impression in order to judge the general appearance and the proportions.
- Because of this the parts are also called **"show-and-tell models".**

- Scaled concept models are often used to verify complex CAD drawings.



AM: application level *rapid prototyping*; sub-level solid imaging and concept modelling

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

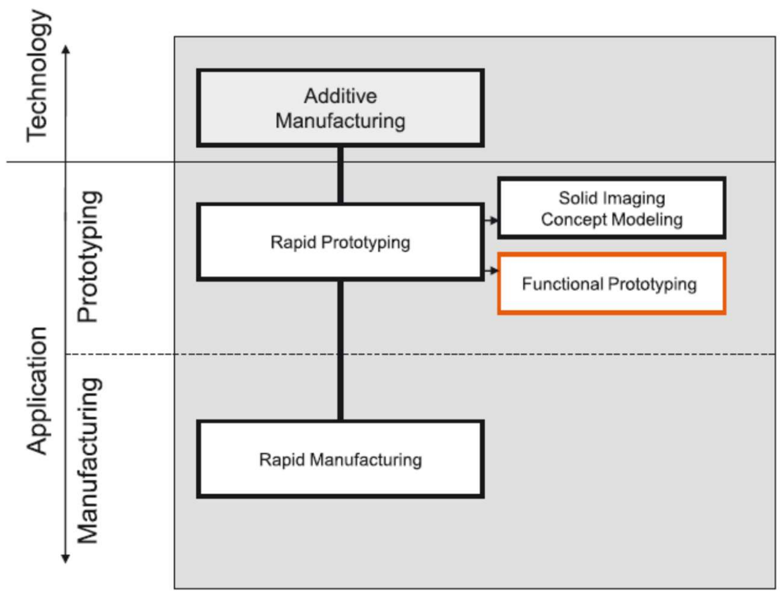


Solid image or concept model; scaled assembly of a roof construction of a convertible passenger car; laser sintering, polyamide

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

Solid image or concept model. Cut-away demonstrating part of a combustion engine unit; 3D-printing

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



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

- Figure show, the adjustable air outlet grill for the climate adjustment nozzle of a passenger car can be used to verify the air distribution in a very early stage of product development.
- It was made in one piece using laser stereolithography.
- Figure shows the housing of a mobile phone designed to establish a local communication network for poor communities.

- The mobile is a re-designed, low cost walkietalkie.
- To use it as a mobile, speaker and microphone must be re-arranged to allow simultaneous speaking and hearing as well as appropriate ergonomic handling.

Functional prototyping: adjustable air outlet grill for a passenger car; laser stereolithography

- The two-piece test housing is made from ABS plastics by fused deposition modeling, FDM.
- The lower element is designed to hold the electronics, while the upper element covers the housing.
- Both elements need to fit perfectly for evaluation.
- The prototype housing was used to prove the perfect fit and to test the handling.
- But due to the clearly visible extrusion structure and the cost, which are too high for series manufacturing, it cannot be used as a product.
- This process results in a smooth surface that mimics the later series quality: however, due to its mechanical and especially its thermal

properties as well as its color and its high price it is not acceptable as a series part.

- The moving parts were made leaving one connecting layer within the hinges uncured.
- In a final step the finished part was cleaned and in particular the uncured material was removed by hand.
- After that, the desired articulator was ready for testing.

Housing for a re-designed mobile phone. Extrusion-fused deposition modelling

- Figure shows the housing of a mobile phone designed to establish a local communication network for poor communities.
- The mobile is a re-designed, low cost walkietalkie.
- To use it as a mobile, speaker and microphone must be re-arranged to allow simultaneous speaking and hearing as well as appropriate ergonomic handling.
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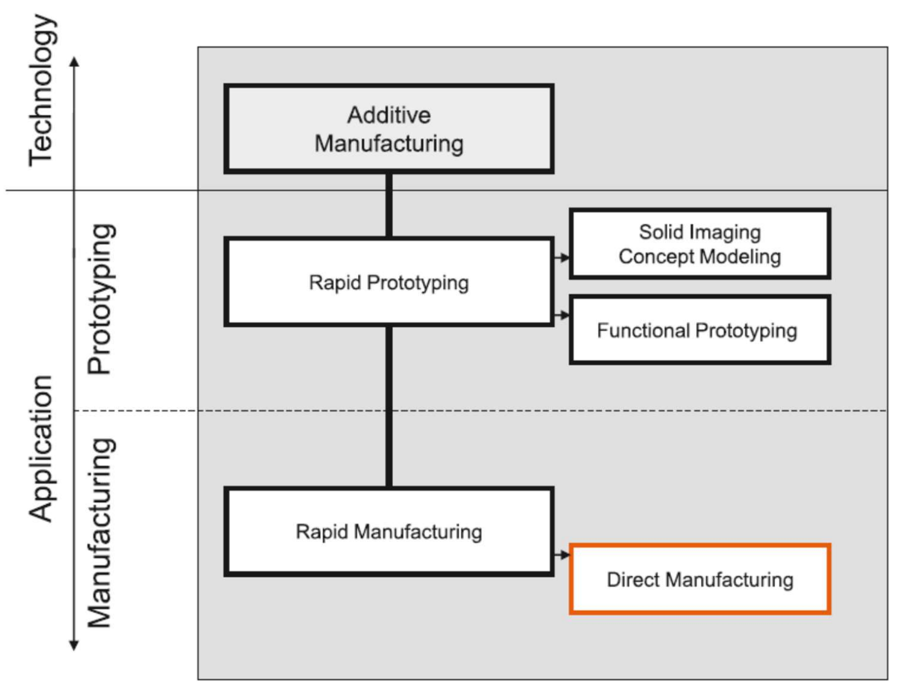
Rapid Manufacturing



AM: application level *rapid manufacturing*; sub-level direct manufacturing

- The application level "Rapid Manufacturing" summarizes all processes that deliver **final products or final parts that need to be assembled to become a product.**
- An AM part is called a **product or final part**, if it shows all characteristics and functions that are allocated to it during the product development process.
- If the resulting part is a **positive**, the process is called **"Direct Manufacturing",** if it is a **negative**, which means a die, a mold or a gauge, it is named **"Direct Tooling".**
- Direct Manufacturing leads to final parts that directly come from the AM process.
- Today, a broad variety of materials from all material classes **(plastics, metals, and ceramics)** are available to be processed directly using an AM process.
- Here, ***it is not important that the available materials show exactly the same physical properties as the materials used within traditional fabrication processes.***
- However, it must be assured that the properties on which the engineering design was based can be realized with the chosen AM process and material.
- Figure shows a three-unit dental bridge made from CoCr-alloy by selective laser sintering (SLM).
- The data was obtained from the patient by a dental imprint and then digitized.

Direct manufacturing. Three-unit dental bridge (left), cross section (without removal of the supports, right), selective laser melting (SLM); CoCr-alloy

- With the use of a **professional dental software (3shape)** the dental bridge was designed and directly manufactured using SLM.
- After finishing and geometric testing, the bridge was ready to be placed in the patient's mouth.
- Regarding traditional processes, the directly manufactured bridge was made quicker, with a perfect fit, and at comparable cost.

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

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

Rapid Tooling

- Rapid Tooling involves all AM procedures that lead to final parts used as **cores, cavities, or inserts for tools, dies and molds.**
- Two sub-levels must be distinguished: **direct tooling and prototype tooling.**
- ***Direct Tooling*** is technically equivalent to *Direct Manufacturing* but leads to **tool inserts, dies and molds** in series quality.
- Although tooling is based simply on the inversion of the product data set (positive to negative) there are reasons to attribute it with a separate application sub-level.
- In addition, for data inversion, **a tool construction is needed**, including scaling to compensate shrinking, parting line definitions, draft angles, ejectors, sliders, and so on. Tooling mostly requires a metal process and machines that are designed to run it.

- It is important to understand that "Direct Tooling" does not mean that the entire tool is made, in fact only tool components, such as cavities or sliders, are generated.
- The entire tool is made using these cavities and standard components or inserts within a traditional tool making process.
- The layer-based technology of all AM processes allows the fabrication of interior hollow structures.
- As an example, mold inserts can be built with internal cooling channels that follow the contour of the cavity beneath the surface.

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

- Because the shaping of the cooling channels follows the contour of the mold, the method is called ***conformal cooling.***
- Due to the increased heat extraction, the productivity of a plastic injection mold can be increased significantly.

- In addition, cooling and heating channels can be designed to obtain an integrated heat management system and thus much more effective tools.

Steel mold for blow molding. Direct metal laser sintering

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

Prototype Tooling.

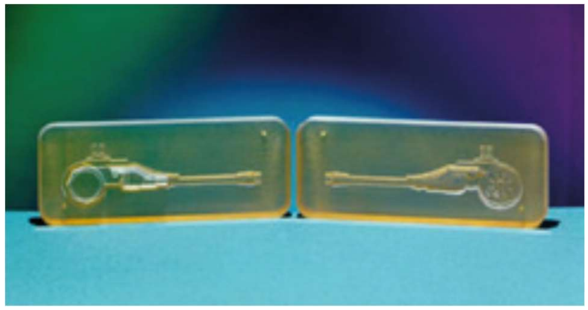
- A mold in series quality often is too time and money consuming for small series manufacturing.
- If just a few parts are needed or details are changed frequently, a temporary mold made from substitute material is typically sufficient.

- This kind of mold shows the quality of functional prototypes but meets, at least partially, the direct tooling application level.
- The corresponding application level is some kind of an intermediate level between rapid prototyping and rapid manufacturing. This sub-level is called **"Prototype Tooling".** Some call it **"Bridge Tooling",**
- A prototype tool made from polyamide can bee seen as an example in Figure.

Prototype tooling; rubber boot sole mold; laser sintering, polyamide (PA)

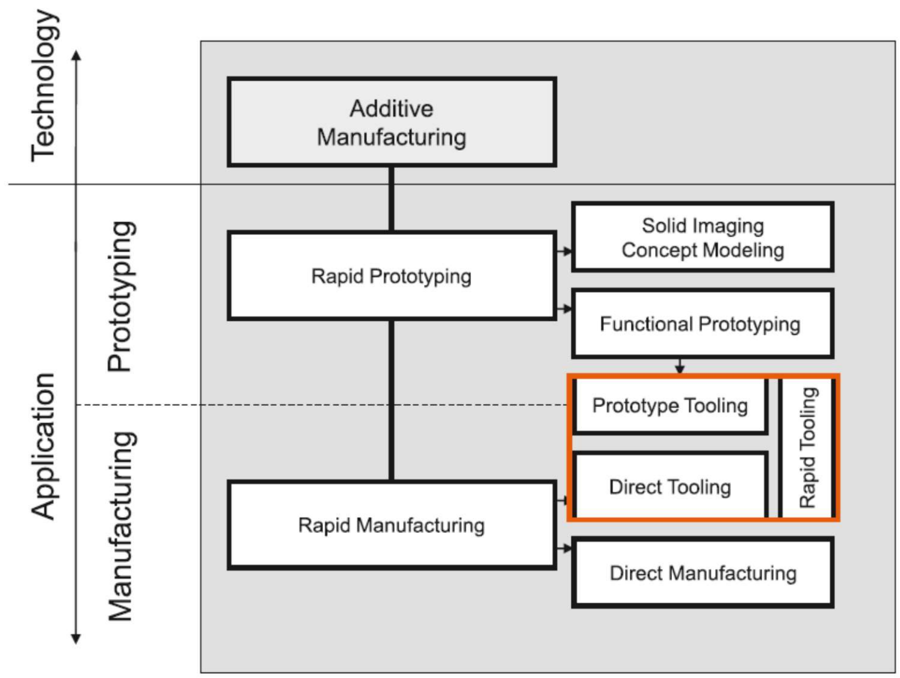
- It is used to fabricate a small series of a new design for a grip sole for rubber boots.
- The soles are necessary to make the entire boot by applying it to a prefabricated bootleg without making a series-like metal tool in advance.
- Different sole structures and materials can be evaluated very quickly by casting, even on a small budget.

- A prototype tool that can be used on a plastic injection molding machine is shown in Figure.



Prototype tooling. AIM injection molding; mold insert; stereolithography

- It is made by a special stereolithography process called **AIM (ACES Injection Molding, where ACES is a proprietary built style of 3D Systems Inc. /Geb07/).**
- Both mold halves are made simultaneously by AM stereolithography, preferably with thin-walled contours and backed by thermally conductive material such as aluminum filled epoxy.
- AIM is suitable for low volume injection molding of simply shaped parts. Summing up the different kinds of tooling, one can see that "Rapid Tooling" does not represent an autonomous application level.
- Rapid tooling integrates all AM applications that can manufacture dies and molds or corresponding inserts.



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

Application Levels – Indirect Processes

- The AM process directly delivers a geometrically exact and scaled physical facsimile of the virtual data set.
- But this process also comes with disadvantages
- AM processes
  - work with process- and consequently with machine-depending materials and restrictions in terms of **color, transparency, and flexibility.**
  - show almost **no cost reduction** with an increasing production volume.

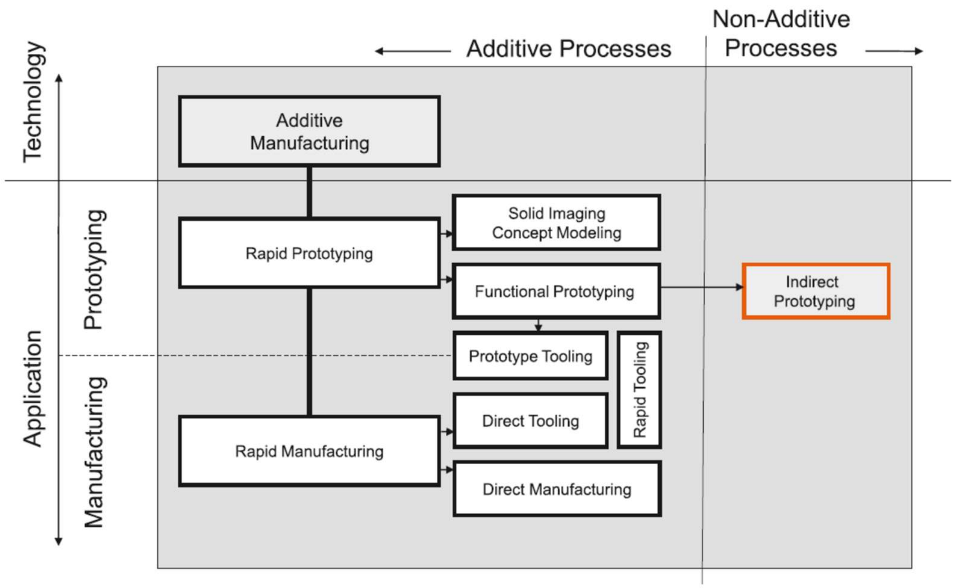
- are rather **expensive** when used to make many copies and especially for series applications.

- To overcome these problems, AM parts can be regarded as master models and then used for subsequent copying or reproduction processes. The principle behind this is often called **"the splitting of capabilities"**.
- The geometrical exact part is quickly obtained from the AM process, while the desired quantity, and properties such as color and so on, come from a subsequent copying process.
- A copying- or follow-up process is not a layer-based process and therefore it is not an AM process. It is called an **"Indirect Process".**
- Because of marketing reasons and in order to indicate the manufacturing speed, some call it **"Indirect Rapid Prototyping Process"** as well sometimes the term **"Secondary Rapid Prototyping Process"** is used.

Indirect Prototyping

- Indirect prototyping is applied **to improve the AM part's properties** in order **to fulfil the applicator's requirements**, if the AM part is not capable to do so.
- If, for example, a flexible part is needed but due to material restrictions it cannot be built directly by an AM process. Then a geometrical exact but rigid AM part is built (and maybe scaled

according to a possibly shrinkage during casting) and used as a master model for a subsequent or follow-up casting process.



AM: indirect processes; indirect prototyping

- As a detailed surface is required and the parts are mechanically loaded during the copying procedure, mainly functional prototypes, preferably made by stereolithography or polymer jetting are used as masters.
- They have to be manually finished before copying.
- The majority of parts made by indirect processes are functional prototypes and consequently have to fulfill the same requirements.
- Solid images or concept models are rarely made by indirect processes because the higher effort in terms of time and costs can typically not justified.

- Many different "secondary processes" can be used. The most prominent one is the so called **"Room Temperature Vulcanization", (RTV)**, also known as **"Vacuum Casting" or "Silicon Rubber Molding".**

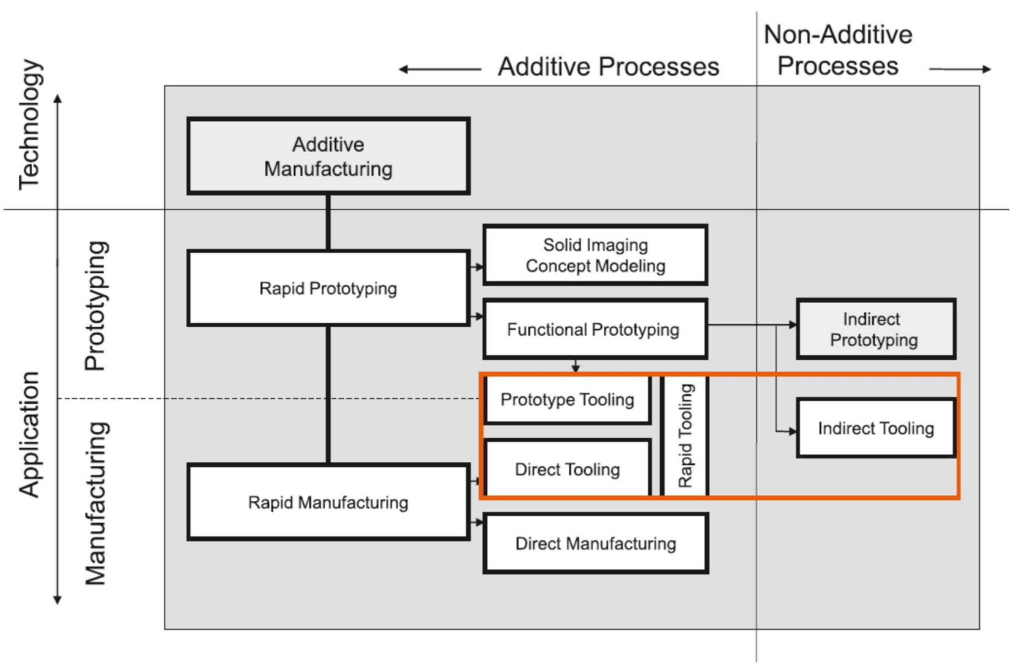
Indirect prototyping; silicon rubber molding; plug system; master made by stereolithography; mold with upper part of plug housing (left), mounted plugs (right)

Indirect prototyping; silicon rubber molding; lighter "Bruce"; AM master, stereolithography; working RTV copies

- Like silicon rubber molding, most of the secondary processes are completely or partially manual processes with long cycle times and therefore only useful for small series or one-of-a-kind production.

Indirect Tooling

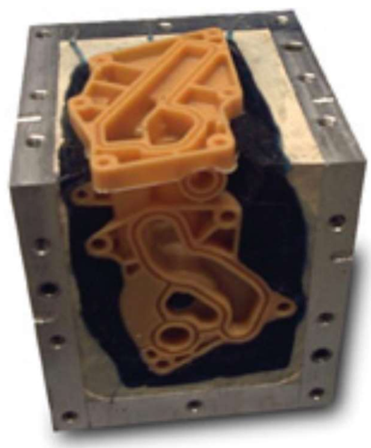
- Indirect tooling is based on the same copying procedures as all indirect processes. It is not the goal to obtain a final part, but a tool that provides the basis for a **small or medium size batch production** of final (or series) parts or products. In contrast to series tools made from tool steel, it can be made quickly and inexpensively.



AM: indirect processes; indirect tooling

- Like indirect prototyping, indirect tooling uses AM masters, thus avoiding milling, grinding, and EDM-processes. In contrast to silicon rubber molding, it must be usable for a larger number of parts made not only from plastics but from metals as well.

- Seen from this perspective, indirect tooling can be regarded as an element of rapid tooling, although it is not a layer oriented process.



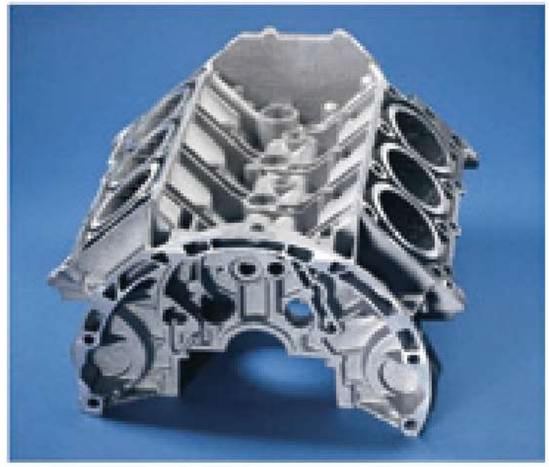
Indirect tooling. PUR mold obtained from an AM master, partly open. Separated mold half with cast wax pattern for lost wax casting.

- As an example, the above figure shows a mold for making wax patterns for lost wax casting.
- The **mold is obtained from an AM master by counter-casting** it in polyurethane, PUR, backed by an aluminum box.
- After the AM master is removed, the mold is used to process the required amount of wax pattern.
- The higher rigidity of the PUR material in combination with the backed up walls leads to a mold that delivers much more precise wax patterns than could be made by a soft silicon mold.

- In comparison to milled all aluminum tools it is cheaper and has a much shorter lead time.
- **This kind of mold can be used for a small series production of complex precision cast parts.**
- There are parts that cannot be evaluated as samples made by manual casting from thermoset prototyping material, but need to be made by plastic injection molding machines and from the final series material.
- **Examples are plastic parts made of flame retarded materials.**
- Therefore, rigid molds are needed. To avoid traditional tooling, a suitable rigid mold can be cast from aluminum-filled epoxy using a stereolithography or polymer jetted master.
- Despite the material, the process resembles the RTV process.

Indirect Manufacturing

- The goal is to obtain final (or series) parts with properties equal to traditionally manufactured (non-AM) products.
- Consequently, indirect manufacturing belongs to the application level "Manufacturing".
- A six-cylinder combustion engine housing. It was produced as a one-of-a-kind part based on an AM master made from polystyrene by laser sintering.

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

The scaled master was transformed into an aluminum part by evaporative pattern casting (also called full-mold casting), which is a process closely related to the lost-wax-casting process.

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

- As a result, a series of identical engine housings is obtained. It can be used to optimize and verify the engine design, including fired test runs long before series molds are available, but also as a small series product, e.g., for racing. Whether this is an appropriate manufacturing method or not is not a technical but an economical question.
- The same process was used to make the air intake manifold of a combustion engine displayed in Figure above.
- It was made from aluminum by lost-wax casting.
- The left part shows the subsequent surface treatment with wax, while the cast part is displayed on the right side.

Unit – II

CAD for additive manufacturing

Contents

Basic Principles of Additive Manufacturing Process

- All additive manufacturing (AM) models are built by joining single layers of equal thickness.
- The layer is shaped (contoured) in an *x*-*y* plane two-dimensionally. The third dimension results from single layers being stacked up on top of each other, but not as a continuous *z* coordinate. In the strictest sense, additive manufacturing processes are therefore 2½D processes.
- The models are therefore three-dimensional forms that are very exact on the building plane (*x*-*y* direction) and owing to the described procedure are then stepped in the *z* direction, whereby the smaller the *z* step is, the more the model looks like the original. Figure 2.1 shows an

example of a three-dimensional model of a plastic and the resulting shift model, which is marked by the stair-step effect.

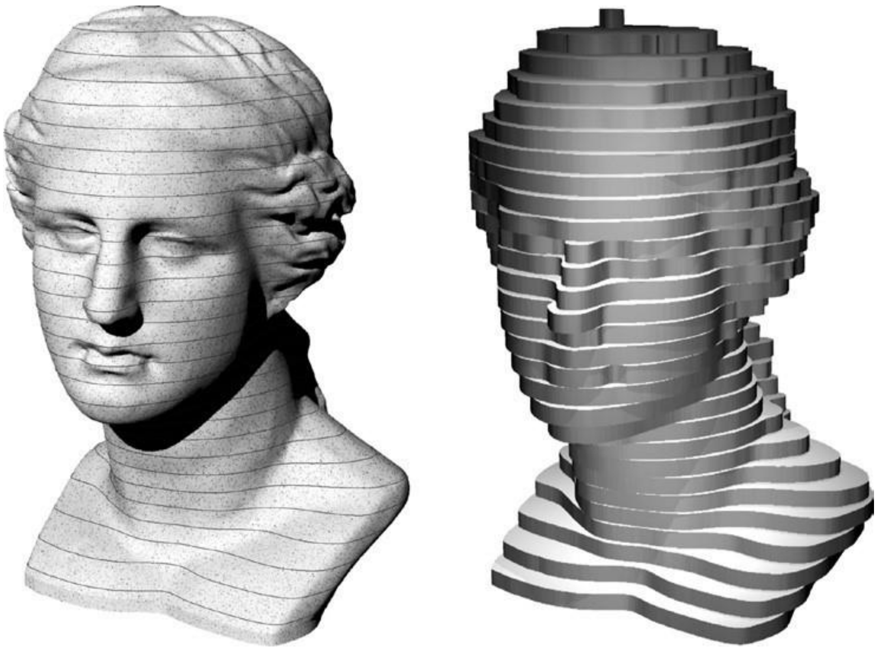


Figure 2.1 Stepped surface as a result of the layering process. Three-dimensional solid model (left) with marked equidistant layers and the created layer model (right)

- The stair-step effect is a typical characteristic of the additive manufacturing process that can never be entirely eliminated but can be reduced by decreasing the layer thickness. Figure 2.2 shows the proportions of a real model with a layer thickness of 0.125 mm.

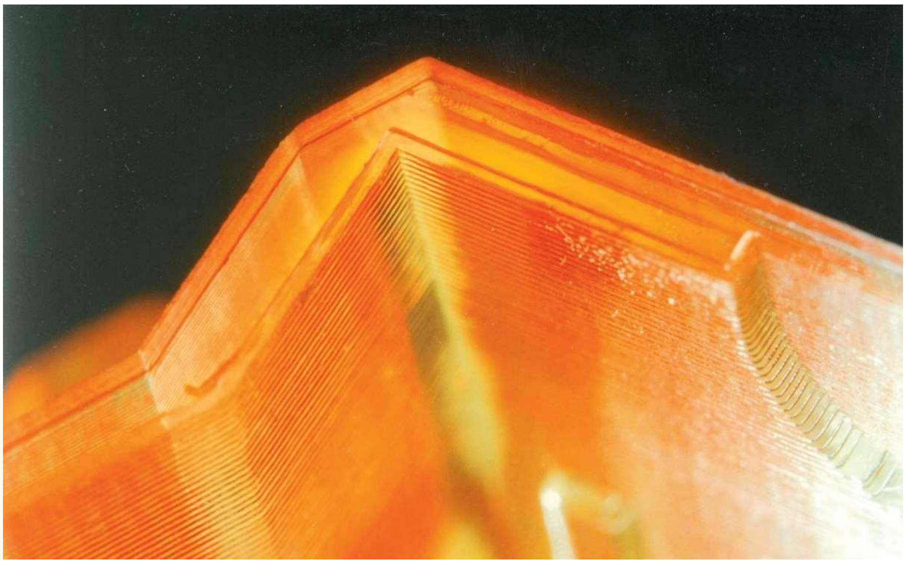


Figure 2.2 Stair-step effect in a stereolithography component (layer thickness 0.125 mm)

- Machines that are used for macroscopic components (characteristic dimensions of several to 100 mm) have a minimum thickness of 0.016 mm, and micro components have layer thicknesses up into the 5 nm range.
- A larger layer thickness, up to around 0.2 mm, is most often used for fabbers or for reducing the building time on other additive manufacturing machines.
- The consequence of a large layer thickness is low precision. Layer milling processes use plates with a thickness up to 40 mm.
- Depending on the type of contouring (scanning, plotting, and so on) and the chosen AM process, the object is contoured continuously in the building plane (*x*-*y* plane).

- If it is not, the secant effect or the stair-step effect occurs on the boundary, which develops lower in *x*-*y* direction than in the *z* direction.
- Therefore, models built by an AM process have different precisions in the *x*-*y* direction than in the *z* direction. As can be seen theoretically in Fig. 2.3, a drilling holeis built parallel to the *x*-*y* plane and another one perpendicular to the *x*-*y* plane. It is assumed that the circular contours in the layers are generated continuously.

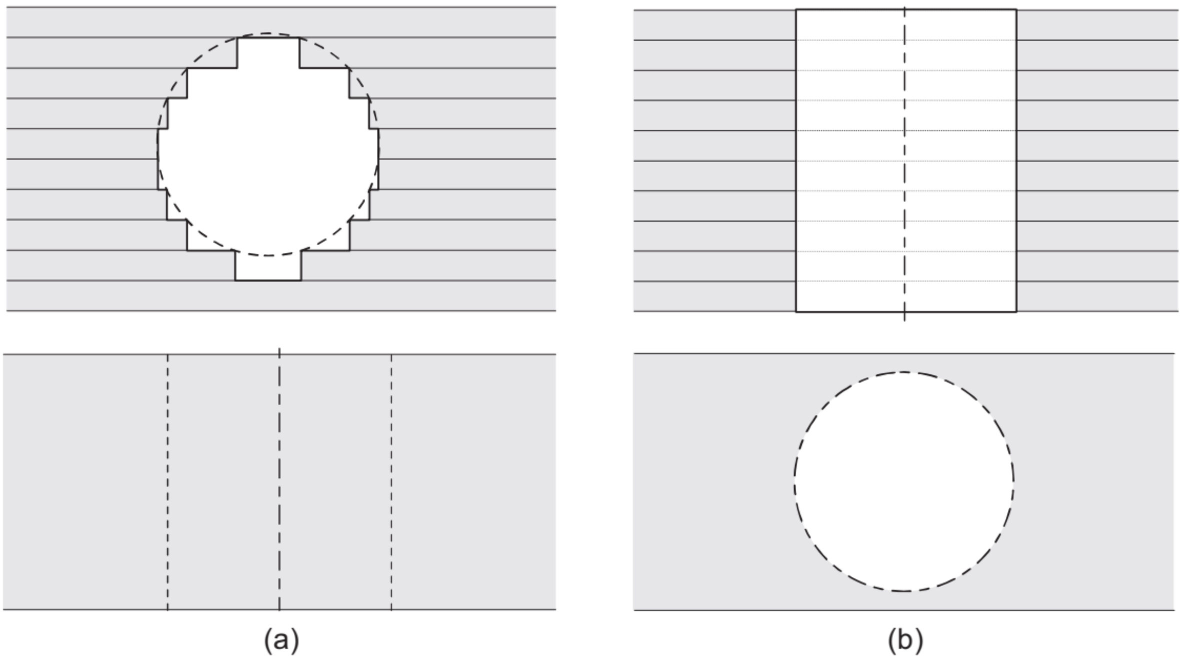


Figure 2.3 Stair-step effect at a hole contingent on layer processes: (a) on layer panel; (b) perpendicular to the layer panel

- Although all AM processes known today work in this way as 2½D processes, some processes (e. g., extrusion processes) are in principle 3D processes, which means they can add incremental volume elements at any chosen point of the model. Thismethod has not been implemented to date.

- The layer milling process is the only one that can be contoured continuously in the *z* direction.
- The characteristic feature of additive manufacturing processes is that the physical models are produced directly from computer data.
- In principle, it is therefore un-important from where the data are provided as long as they describe a 3D volumecompletely.
- Data from CAD construction, from the process of measuring and reverse engineering, or from other measurements (such as computer tomography (CT), magnetic resonance tomography (MRT), and 3D tracking systems) may beused equally as well if the relevant evaluation programs enable the preparation of the measured values in the 3D data models.
- In this way, model making has become an integral part of the computer-integrated product development. From the product development aspect, additive manufacturing models can, therefore, be regarded as three-dimensional plots or facsimiles of the corresponding CAD data.
- The decisive advantage, in contrast to the classic manual or semiautomatic model-making processes, lies in the fact that the data remain unaltered (with the exception of the generated

supports) by the model making. As a result, no data need to be taken from the model.

- Because the making of AM models does not alter the common database, additive manufacturing processes have become the most important elements of modern product development strategies such as simultaneous engineering.
- The 3D data model is used as a product model and as a basis for production at the same time.
- The advantage of AM processes over nonadditive manufacturing computer-controlled processes is that the AM machines are using the same data type, the so- called STL data.
- Nonadditive manufacturing numerically controlled processes, such as computer numeric control (CNC) milling, usually use a system-specific data set.
- The generation of layer information is based on a purely computer-oriented CAD model (Fig. 2.4). The CAD model is cut into layers with equal thickness by mathematical methods.
- This layer information is used to generate the physical single layers in an AM machine; the total sum of the single layers forms the physical model.
- The merging of the physical layers happens during the generation of the next layer or after completing the layer. This depends on the AM process.

- The finished physical model can be a prototype or the final product.

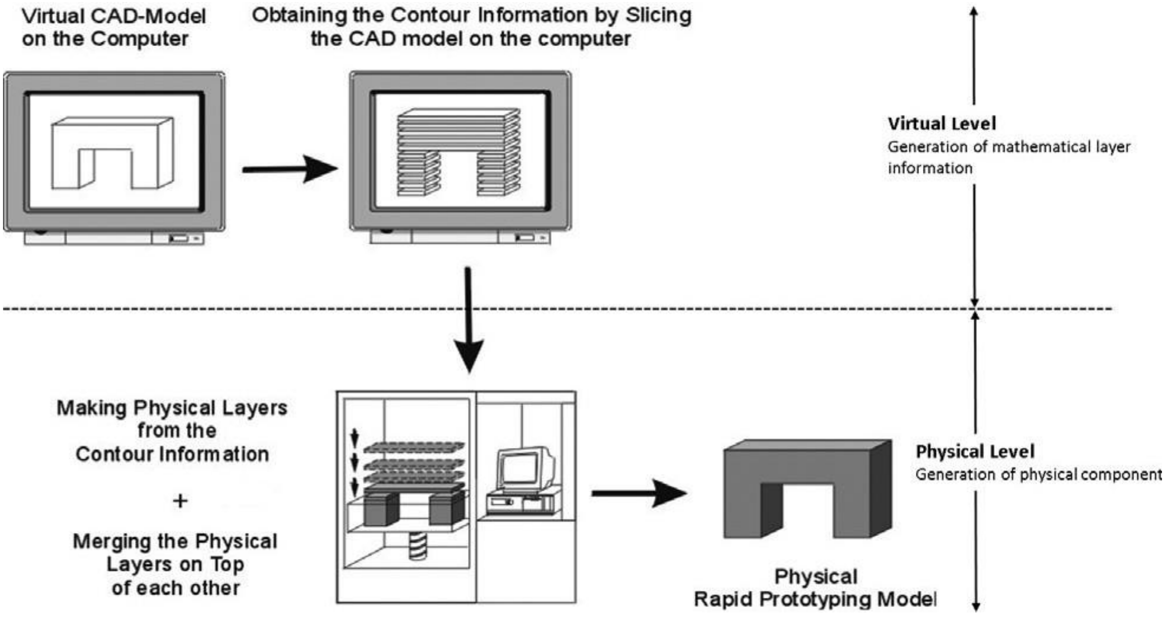


Figure 2.4 Concept of additive manufacturing

- With the method of layer generating it is possible to realize geometrically complex structures that are impossible or expensive to produce by conventional methods.
- As a result, new designs can be realized, like the mathematical compositions by George Hart.
- In Fig. 2.5 a (mathematical) 4D object can be seen that consists of 120 flattened dodecahedra and 600 tetrahedra.

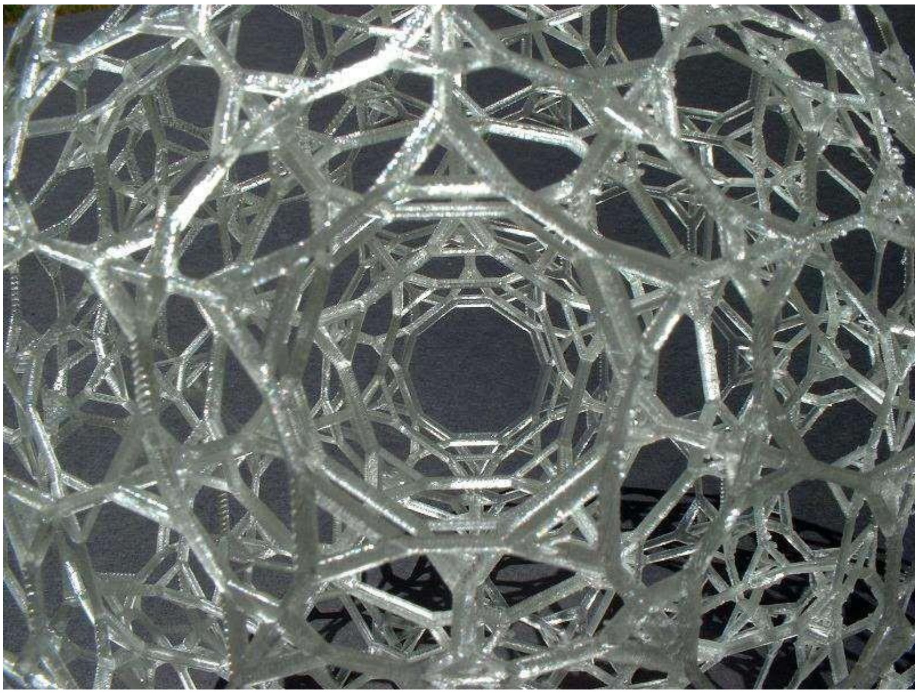


Figure 2.5 Complex structure of polymer printing, only additive manufacturing geometry

- “Rapid prototyping” or “additive manufacturing processes” are classified into twofundamental process steps:
- Generation of the mathematical layer information
- Generation of the physical layer model

Generation of layer formation

- The additive manufacturing process copies the virtual CAD data into a physicalmodel, so the generation of the mathematical slice information for the production of the single layers is most important in order to produce an accurate part. It is divided into three steps:

i. Description of the geometry by a 3D data record
ii. Generation of the geometrical information of each layer
iii. Illustration of the geometrical layer information on each layer

Description of the Geometry by a 3D Data Record

Data Flow and Interfaces

- The production of models and prototypes by means of additive manufacturing processes requires that the geometry of the component is available as a 3D data record.
- This is achieved in most industrial applications by construction on a 3D CAD system or by other measurements.
- The data are produced independently of the production and need to be prepared and transferred via an interface to the machines.
- The data are called the digital or virtual product model.
- To build the components further, process and installation specific calculations are necessary in addition to geometrical data and material parameters.
- The data are set with the help of programs called front-end software or additive manufacturing software.
- Front-end software is a part of AM machines and is supplied by the manufacturer. AM software is offered by a third party. The software types interface with each other (Fig. 2.6).

- The STL format has been established as an industry standard, but other formats are also used.
- Before starting production of an AM model, the 3D model first has to be placed on the building platform in the optimal direction by the front-end or additive manufacturing software.
- It is also necessary to add the process-specific data like the supports. To achieve the best use of the machine, several components are built simultaneously on the platform. In some AM processes the components are placed into and one above each other.

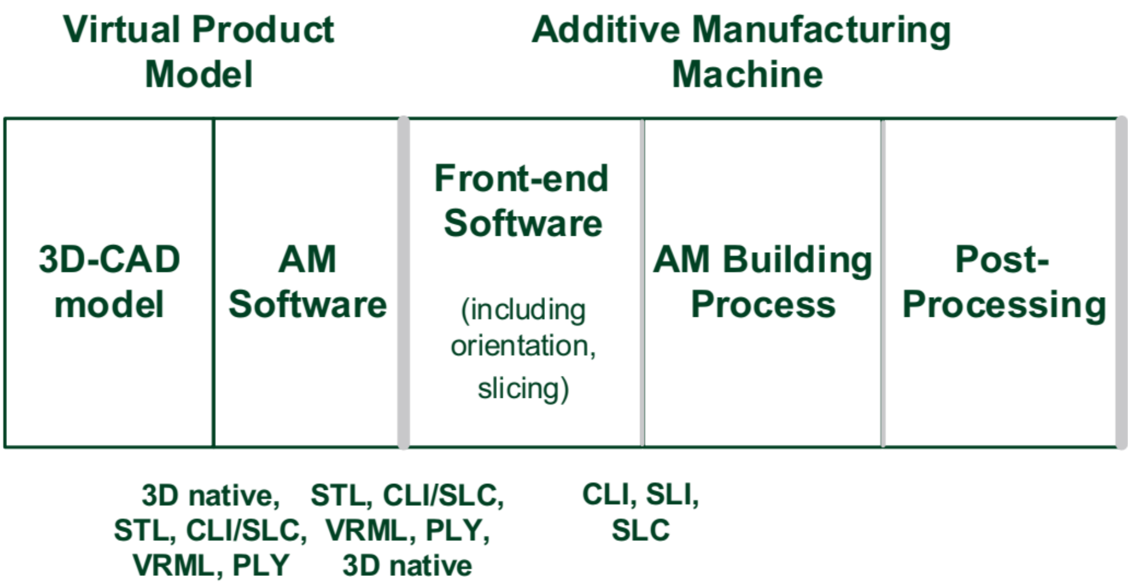


Figure 2.6 Data flow during additive manufacturing

- Third-party software contains optional features that allow, for example, the derivation of 3D data from 2D sketches.

- Some of this software is just used to display the 3D model. This kind of software is trimmed of the needed features of CAD software and can transform the model into the STL format.
- When the model is included with the geometrical and directional information, it is necessary to establish the machine and material parameters required for the control of the rapid prototyping process in order to proceed with the building process.
- In any case, the geometrical information of the entire body, like the layer thickness and the contour data for every layer, must exist to produce the 3D model.
- The generation of equal layer thicknesses with mathematical methods is called slicing. Most machines slice the whole 3D model and use the layer information in the batch mode.
- Depending on the capacity (speed and memory) of the computers the machines generate each layer shortly before the physical generation of each previous layer. Today, the so-called adaptive slice method ("slicing on the fly") is installed on the machines.
- This method allows measurement of the current geometrical height and generates the next layer depending on that value.

- In that way, geometrical errors in the z direction that depend on propagation errors will be reduced or avoided completely.
- The data is the basis for manufacturing the AM model, and after postprocessingthe model is ready for use.
- In addition to this direct path, there are also alternatives in the design and production. It is possible to deliver the geometrical data in SLI/SLC, PLY, or AMF format instead of STL format.
- Neutral interfaces are also used to transfer data. The reason is in the advantages when the construction is finished and the model has to be modified during the production process.
- Modification of an STL model is possible but not as straight forward as in a full-fledged CAD system.
- The most important neutral interfaces that are integrated into 3D CAD systems are listed below:
    - IGES Initial graphic exchange specification
    - VDAIS Association of Automotive Manufacturers – IGES interface
    - VDAFS Association of Automotive Manufacturers – Surface interface
    - DXF Drawing exchange format
    - HPGL Hewlett-Packard graphics language
    - SET Standard Exchange and Transfer

○ STEP - Standard for the Exchange of Product Model Data.

- IGES is one of the worldwide standards for geometrical interfaces. This format exhibits a lot of varieties that should be described in detail.
- VDAIS is an IGES interface from the Association of Automotive Manufacturers. This interface also includes a lot of varieties, so in each particular case one must examine carefully which interface formulation the data exchange is based on.
- VDAFS is specialized for freeform surfaces and therefore has importance in the automotive industry.
- HPGL is a contour-oriented plotter format that is especially used in the context of direct contouring in CAD for AM processes
- STEP is an interface that is becoming increasingly established after a long test phase. In addition to the geometrical information, other information can be ex- changed with the STEP format. The STEP format represents an approach to ex- changing the original CAD model and not only the geometry information.

Modeling 3D Bodies in a Computer by Means of 3D CAD

- The creation of a 3D body is the indispensable prerequisite for the production of an additive manufacturing model. Therefore, the application of AM processes is linkedespecially close with CAD processes.
- For this reason, 3D CAD processes will belooked into only as

far as is absolutely necessary to understand the fundamental relationships in the production of rapid prototyping models.

- Every CAD system uses certain data elements and data structures to describe a component in detail.
- The data record includes not only the component geometry but also the materials, the quality of the surface, the production process, and much more.
- The component geometry therefore comprises only one part of the informa- tion. The complete information registered in the database of a CAD system for a component is called a CAD model (the product to be made).
- If the geometric de scription of a component is 3D, then it is called a 3D CAD model or digital productmodel.
- By choosing a certain CAD system the user commits himself to its database. The structure and the data elements decide to a high degree the quality of a CAD system and its compatibility with other systems via an interface.
- The CAD system alsodefines the type, extent, and quality of the AM process.

CAD Model Types

- CAD models are defined by model types regardless of the kind of CAD system.
- As shown in Fig. 2.7, not all types that display a 3D model are

suitable for an AM process; some types do not have sufficient information.

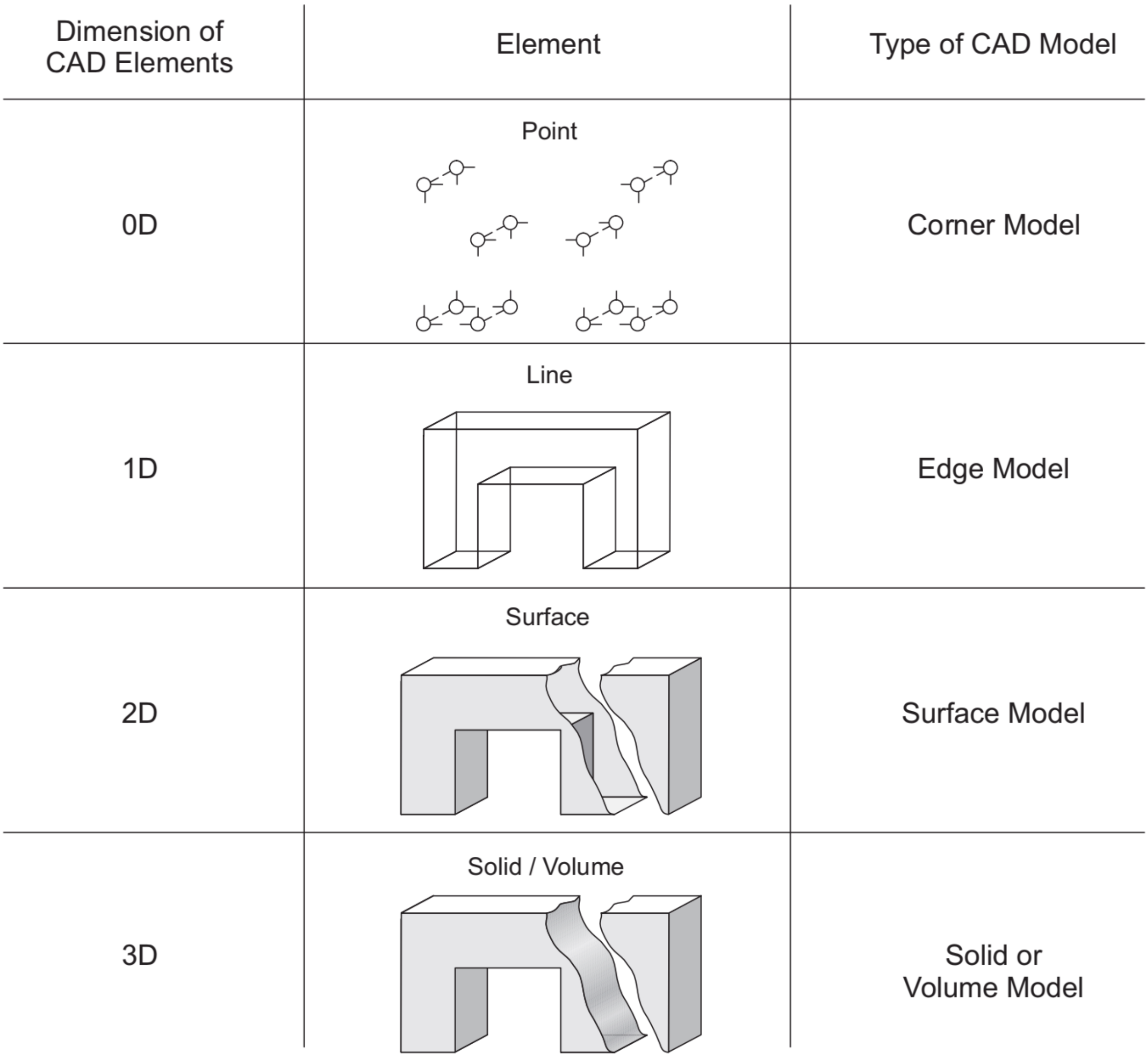


Figure 2.7 CAD models and element types

- The corner model defined by points is of less practical importance and not usablefor AM processes.

- It is used, for example, as an intermediate model for the semi-automatic transformation of grid data or 2D CAD models into 3D CAD models.
- Owing to its small amount of data, the edge model enables a fast graphic representation of 3D elements even with low-performance computers.
- Its importance is therefore growing again in connection with virtual reality (VR) applications and digital mock-ups (DMU).
- The most important disadvantage of the edge model is themissing information about the exact position of the surfaces and the volumes. For this reason it cannot be recommended as a basis for the production of AM models.
- All CAD systems that process components as surface models in their geometricaldatabases are in principle suitable for issuing data via an additive manufacturinginterface.
- When a component is defined by its external surface, the user is usually able to calculate the exact component volume as well.
- This is usually achieved byassigning and storing an additional normal vector for each surface pointing awayfrom the inside of the component.
- For the complete description of a component, therefore, it is absolutely necessary that the orientation of the component volumeis known.
- Solids are optimal for the modeling of CAD models that (among

other things) are also used for additive manufacturing. The orientation of the volume is preset exactly and need not be explicitly defined by the user.

- Solids are differentiated into
  - basic solids,
  - surface determining models, and
  - hybrid models.
- For basic solids, the component is reproduced in the CAD system by combining basic bodies (so-called geometric primitives) such as cuboids, globes, and cylinders by means of Boolean operations.
- The CSG (constructive solid geometry) tree ispart of the database and reflects the component's history of origin.
- The basic solid includes the CSG tree, but it does not contain any information about the single surfaces. If a basic solid is issued as an STL file, the contours of the basic body are calculated as a first step.
- Mistakes caused by inexactitudes in fitting neighboringsurfaces are therefore impossible.
- With surface determination models in the extreme case, only the details concerning single surfaces and the position of the volume are stored.
- The position of the volume, also defined by a normal vector standing on each surface and pointing tothe outside, does not

need to be defined by the user. This model type also enables bodies with extremely complex outlines to be described, which is otherwise possible only with the aid of surface models.

- CAD systems do not usually work on the sole basis of one of the two described solids but rather in a combination of both model types.
- The advantages of both model types are combined in so-called hybrid models, which include elements of the basic solid as well as those of the surface model.
- CAD systems that work with hybrid models usually generate faultless STL data, as the edges of the surfaces used forthe issuing are exactly fitted by the system itself when the resulting hybrid modelis generated.

Demands on CAD Systems

- When judging CAD systems as the basis for additive manufacturing processes, many of the properties discussed in the preceding as possible should be taken into consideration.
- The basic requirements for the systems are to develop a 3D model and the possibility to transfer this model for additive manufacturing via the inter-face.
- The transformation via neutral interfaces into an- other CAD system and from there via an STL interface to the AM machine

should always be regarded as a detour.

- The following features have been established as advantageous for the selection ofCAD systems:
    - *Parametric 3D designs*

  Instead of using fixed measurements, parameters are agreed on that can be correlated with each other by mathematical functions.

    - *Hybrid models*

  Hybrid models combine the advantages of both solids and surface models and are therefore very well suited for rapid prototyping applications.

    - *Continuous database*

  The CAD system and all associated modules must always refer to a common, compulsory database.

    - *Redundancy avoidance*

  A continuous database will avoid redundancies; that the database will be free of data unnecessarily stored more than once. Such multiple storages are to be avoided in view of the storage capacity, speed, and clarity of the program.

    - *Open system*

  It needs to be guaranteed that the systems can be linked with specialized modules from independent producers (reverse engineering, CT modeling, and additive manufacturing software).

- *Associativity*

  The internal architecture of the CAD systems must ensure that any alterations cause all dependencies to be checked and modified where necessary.

- Further, when choosing a CAD system, one should, for example, assess how easy itis to learn to work with it and its level of support in performing certain tasks, which may be specific for special branches.
- The market offers a vast number of CAD systems that often differ only in specialties typical for specific fields of activity.
- It is increasingly probable that all important CAD systems either possess an STL interface already or will obtain one in the near future. Usually other complementary rapid prototyping interfaces areavailable, for example, SLC, PLY, VRML, or HPGL.

Generating 3D Models from Measurements

- Normally it doesn't matter how the 3D data will be generated.
- Figure 2.8 shows several other alternative possibilities for obtaining a 3D model.

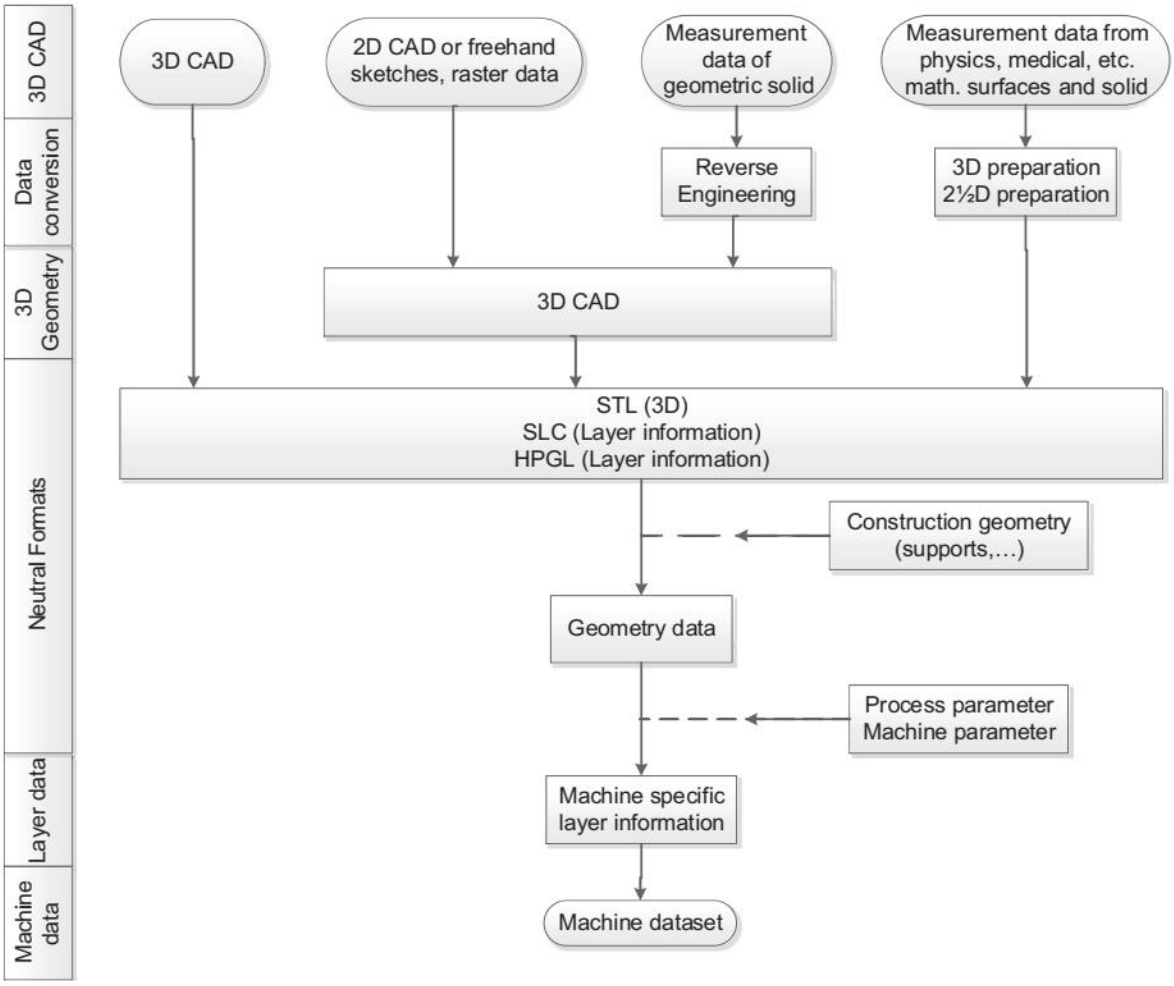


Figure 2.8 - Generalized representation of the data paths for additive manufacturing

- In addition to 3D CAD designs, 2D CAD sketches, manual sketches, and anything similar can in general be used as input data.
- To transform them into AM models, they will require a final conversion into 3D volume information via various inter- mediate operations. If a body is described only by means of 2D elements, then they require conversion into a 3D format by preparing them with a 3D CAD.
- In most cases this is done using a manual 3D CAD drawing that is no

less time-consuming than a new design. When the layer thickness is known, some systems can process the required contour data directly. For example, the 2D data in the HPGL format are used for transmitting.

- If, on the other hand, 3D measurement data exist, for example from a coordinate-measuring device, then the measured data can be converted into a 3D CAD model with the aid of special program systems.
- In the field of mechanical engineering, this conversion of point data (considered geometrically inferior) to surface data (geometrically higher quality) is called "re- verse engineering."
- Even point clouds can be used for additive manufacturing when the format is exchanged in a neutral data format for the model description. Use of them is made in particular when only the physical model is required and no CAD drawing, such as for body scanning for producing sculpture.
- Furthermore, 3D measurement data are obtained from computer tomography (CT) scanners, which are more and more established in the technical industry; for ex- ample, they are used for nondestructive testing and also to generate 3D data.
- The CT data can be converted into 3D volume data that can be used for the AM process.
- Application fields include the individual repair of defective parts, for which the defective geometries have to be gathered.

- Another application is the production of spare parts that have no existing production documents, for example spare parts for a vintage car.
- In particular for private use of fabber also libraries are used that allows to down- load the data directly from the Internet. Depending on the provider the data can be modified.

STL Format

- In order to obtain an STL data set of the part, the surfaces of the part are approximated by triangles.

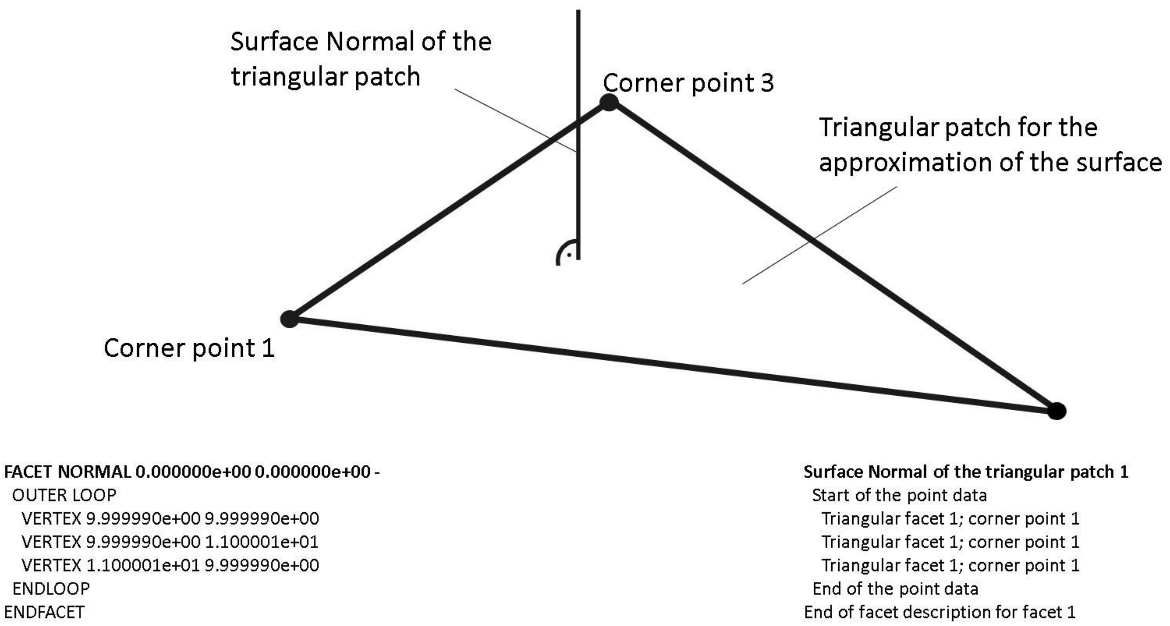


Figure 2.9 - Definition of triangle patches in STL format and the associated ASCII data set

- 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 as shown in Figure 2.9 (positive direction outward, away from the volume) and the coordinates of the three vertices of each triangle. 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 2.10 shows the triangular patches coated on a real component, called thetriangulated surface.

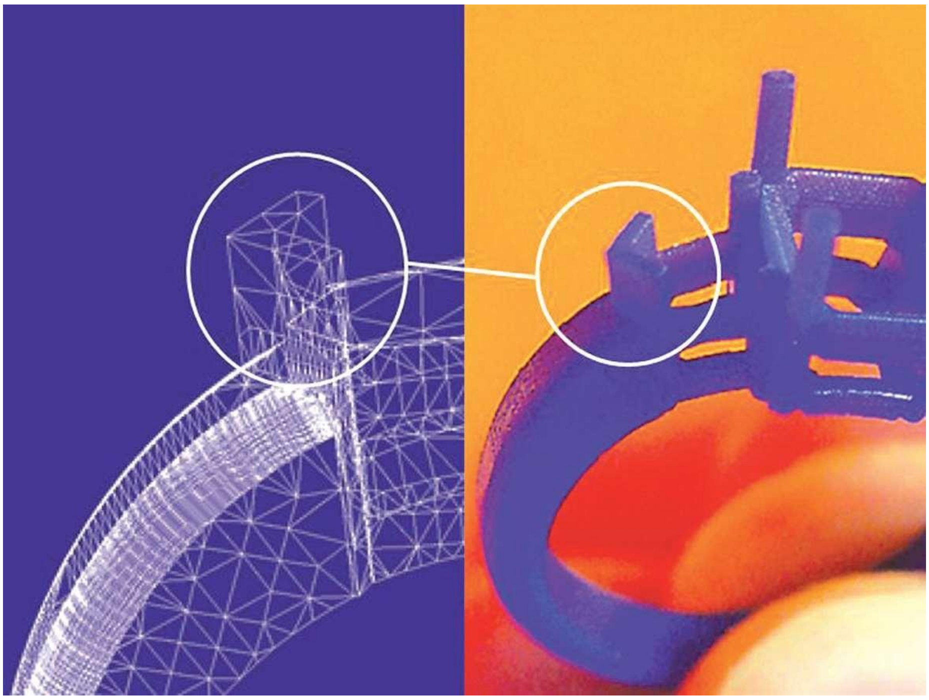


Figure 2.10 - Triangulated surface and associated manufactured component

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 thereforethey 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.

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 as
  - construction errors,
  - transforming errors, and
  - description errors.
- Construction errors are based on unnecessary data inside the component that arethe result of combining the single elements

incorrectly in the CAD system as shown in Figure 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 thepart.
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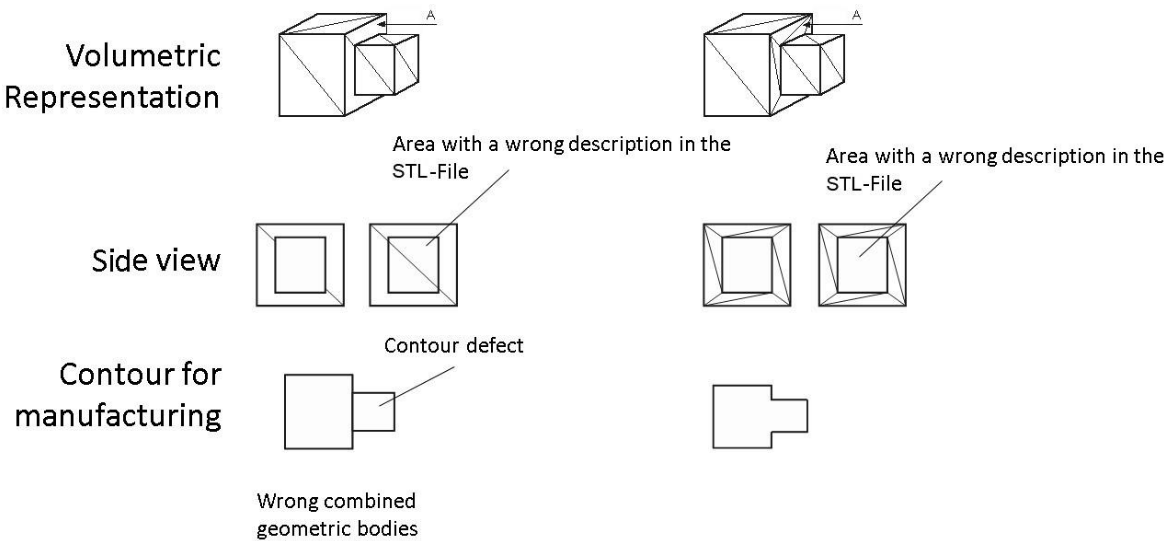

Figure 2.11 - Effects of merged faulty geometric bodies

- Transforming errors exist when the convergence of the mathematically exact con- tour (as provided by the CAD) by triangles is inaccurate and the number of trans-forming errors is larger the lower the number of triangles chosen.
- In Figure 2.12, this fundamental secant error is demonstrated in the example of errors appearingin the convergence of a circle by (f/4), eight (f/8), and twelve (f/12) secants.

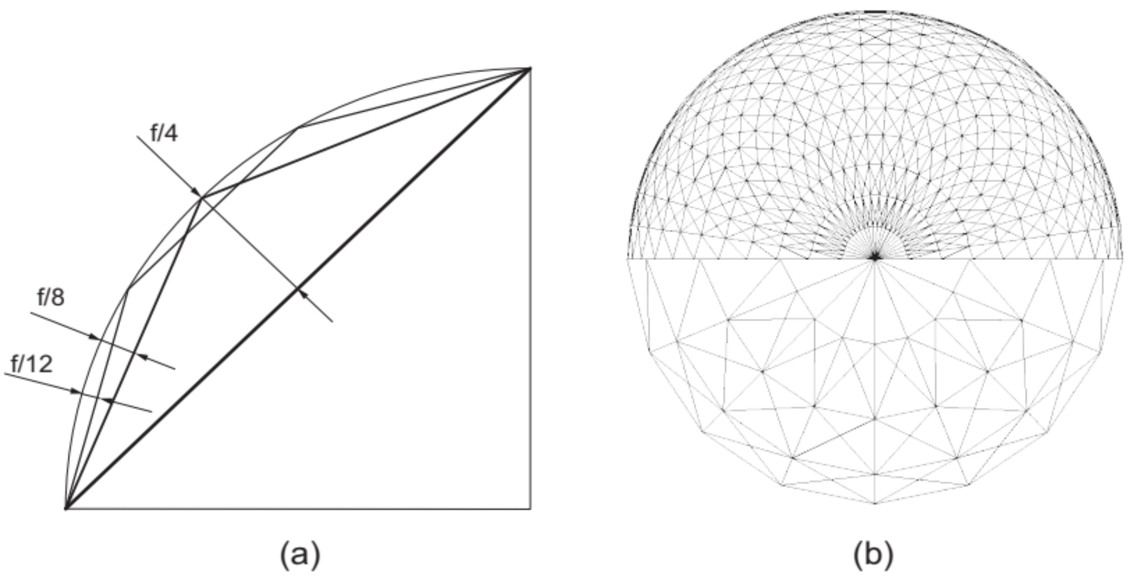

Figure 2.12 (a) Secant error at the approach of a circle by 4 (f/4), 8 (f/8), or 12 (f/12) line seg- ments; (b) Influence of the number of triangles in the modeling of the surface of a sphere (STL)

- With the increased accuracy in defining the surface made possible by increasing the number of triangles, the amount of data increases enormously.

- In practical terms, the fineness of the triangulation is not problematic if approvedsettings are used.
- Description errors are primarily attributable to three causes:
    - gaps between triangle patches (boundary error),
    - double triangle patches (overlap), and
    - incorrect orientation of individual patches (disorientation).
- Figure 2.13 shows this error schematically.

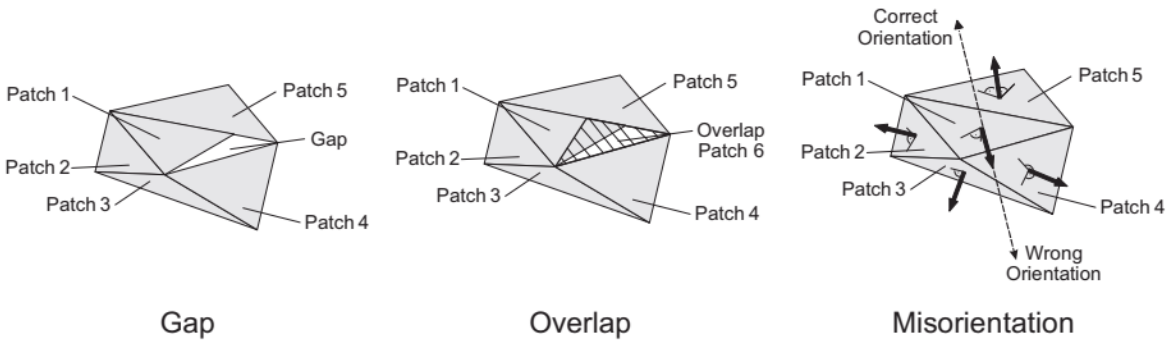

Figure 2.13 - Description error: gap, overlap, and incorrect orientation

- 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 resolutiondensities 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.

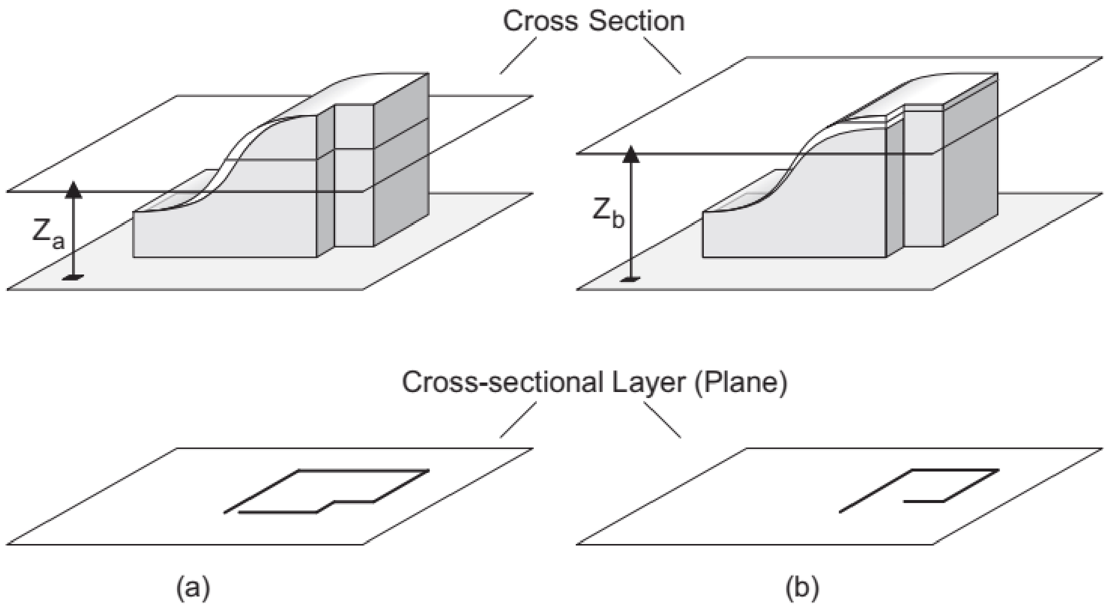

Figure 2.14 Influence of imperfectly bordered deterministic surface models on the production of layer models

- 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.
- 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 semi automatically, manual

intervention leads to faster and better results.

- Repairing data are limited. The sample shown in Figure 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.

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Unit – III

Additive Manufacturing Techniques

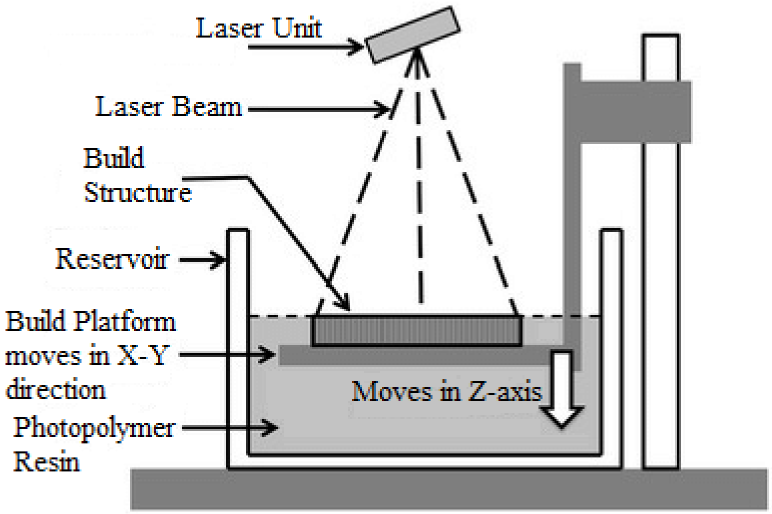
Syllabus

- Stereo- Lithography, LOM, FDM, SLS, SLM, Binder Jet technology.
- Process, Process parameter, Process Selection for various applications.
- Additive Manufacturing Application Domains: Aerospace, Electronics,
- HealthCare, Defence, Automotive, Construction, Food Processing, Machine Tools.

Laser-Stereolithography (SL)

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

A typical machine can be seen in Figure. 3.1, left



Schematic representation of Stereolithography (SLA) process

- A laser stereolithography machine consists of a build chamber filled with the liquid build material and a laser scanner unit mounted on top of it which generates the x-y contour.
- The build chamber is equipped with a build platform fixed on an elevator-like device that can be moved in the build (z-) direction (Figure. 3.2). On this platform the part is built.

- The laser beam simultaneously does the contouring and the solidification of each layer as well as the bonding to the preceding layer. The motion of the beam is controlled by the slice data of each layer and directed by the scanner.
- As the beam penetrates the surface of the resin, an instantaneous solidification takes place.
- Depending on the reactivity and transparency of the resin, the layer thickness can be adjusted by the laser power and by its traveling speed. After solidification of one layer, the build platform, including the partially finished part, is lowered by the amount of one layer thickness.

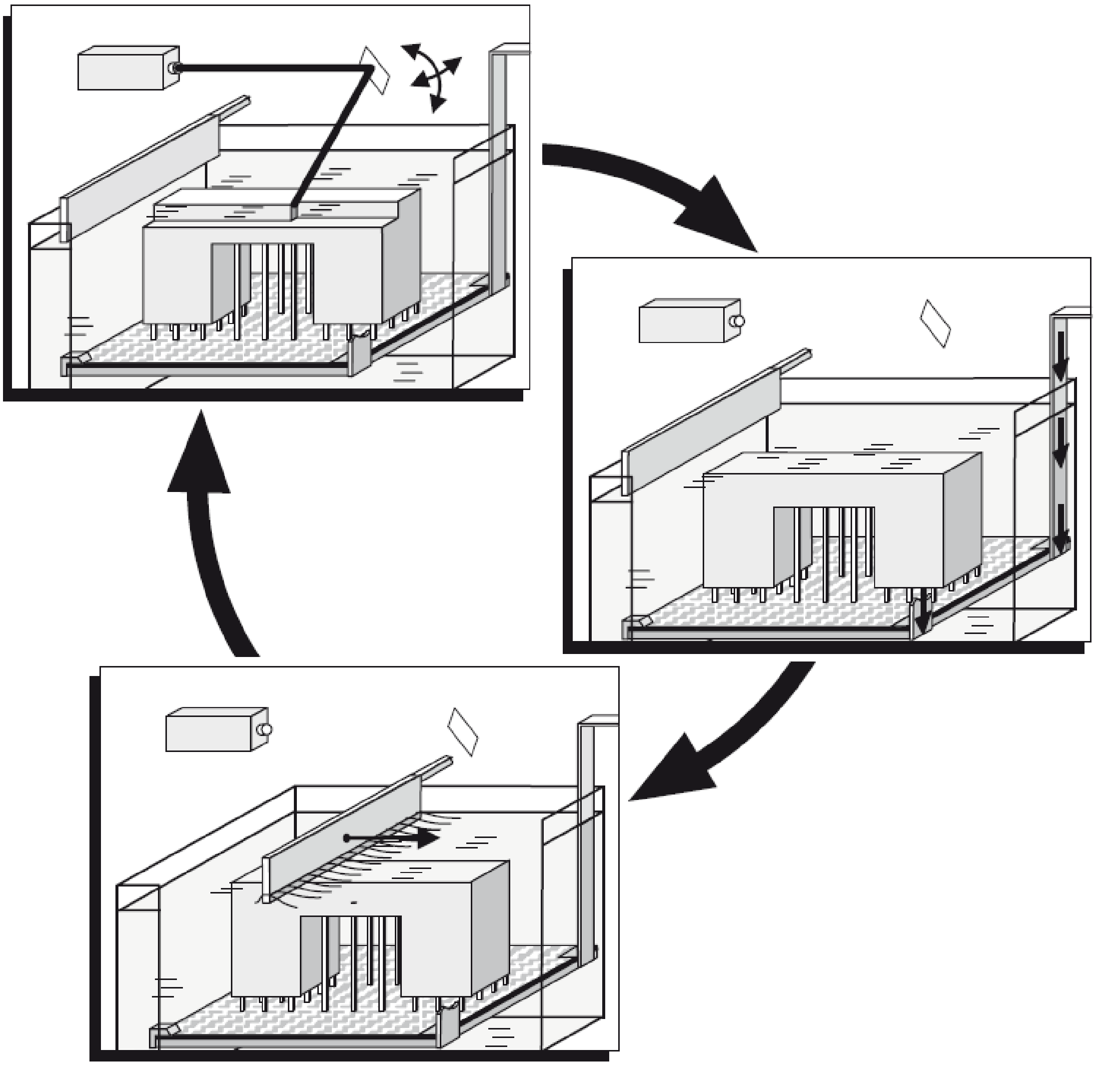


Figure 3.2 Polymerization, laser-stereolithography; scheme; solidification of a single layer, lowering of the platform, recoating (clockwise starting from top left)

- A new layer of resin is applied. This is called recoating. Because of the low resin viscosity, the recoating procedure needs to be supported by vipers and vacuum depositing devices. The new layer is then solidified according to its contour. The process continues from the bottom to the top until the part is finished.

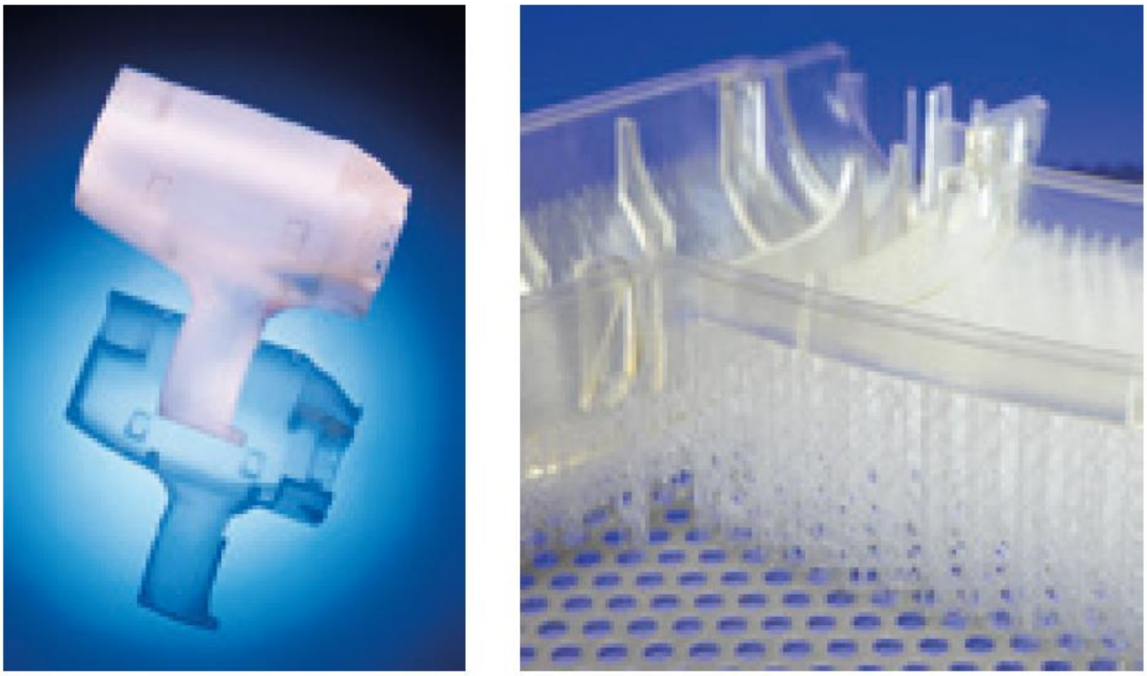


Figure 3.3 - Laser stereolithography; thin-walled shell type parts (left), part with supports on the build platform (right)

- The process requires supports (Figure. 3.3, right), which limits the possible orientation of the part in the build chamber, because after removal the supports leave tiny spots on the surface.
- For this reason the orientation should be chosen carefully. Because of the supports the parts cannot be nested to increase the packing density and the productivity accordingly.
- After the build, the part is cleaned and finally fully post-cured in a UV chamber (post curing oven).
- This process step is an integral part of the AM process and called “post processing”. The parts can be sanded, polished, and varnished if necessary.

- These process steps are called “finishing”. Finishing is a process-independent step and not a part of the AM process. It depends only on the user requirements for the parts and possible restrictions regarding its application.
- The available materials are unfilled and filled epoxy and acrylic resins. Unfilled materials show a comparably poor stability and heat deflection temperature.
- This can be improved by adding micro spheres or rice-grain shaped geometric objects made from glass, carbon, or aluminum. Today, these filled materials contain nano-particles made from carbon or ceramics.

Layer Laminate Manufacturing, Laminated Object Manufacturing (LOM)

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

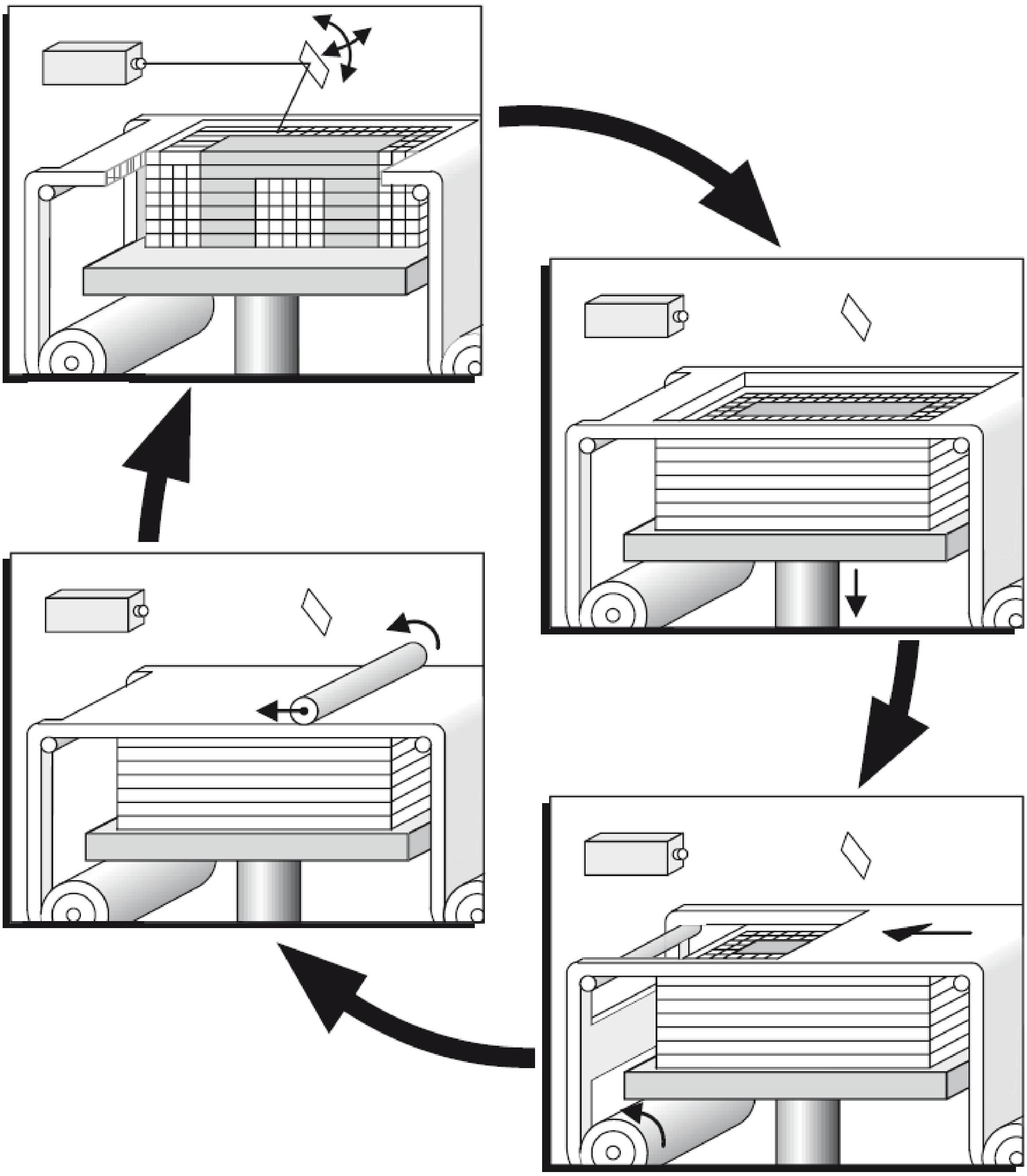


Figure 3.4 Layer laminate manufacturing, laminated object manufacturing (LOM); scheme

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

- To build a part, the paper is positioned on the build table and fixed by a heated roller that activates the glue. The contour is cut by a plotter-type laser device that allows adjusting the cutting depth according to the paper thickness.
- Another frame-like laser cut defines the boundaries of the part. It leaves two paper stripes on each side of the part that enables the exceeding paper to be lifted and wound up by the second coil (Figure. 3.4).

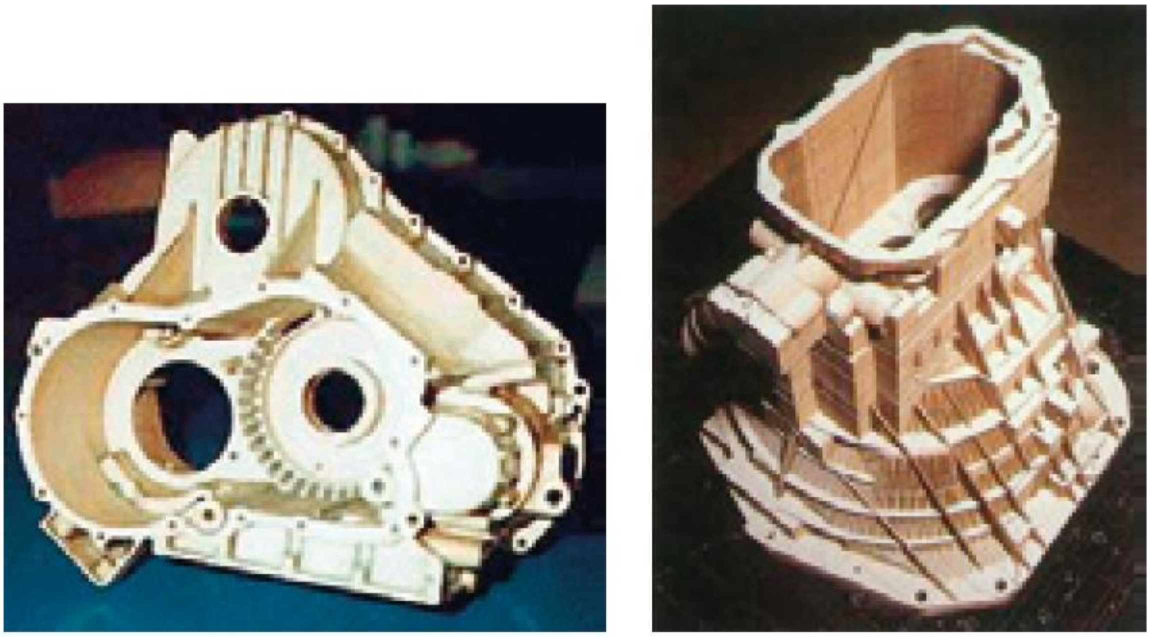


Figure 3.5 - Layer laminate manufacturing, paper lamination, gear housings (LOM)

- The material that fills the space between the contour and the frame remains within the part and supports it. It is cut into squares for easy removal of the waste material.
- After the build process is finished, the block of paper, including the part and the support material is removed from the build platform.

- The frame and the squares that result in small blocks are removed and finally the part is obtained.
- The parts need varnishing to prevent de-lamination of the layers. Gear housings, which are typical parts, can be seen in Figure 3.5.

Fused Deposition Modelling (FDM)

- FDM is a registered, protected trade name for a fused layer process offered by Stratasys Company, Eden Prairie, MN, USA. Because it was the first commercialized FLM process worldwide, the name FDM is often used synonymously with FLM even as a generic name.
- A FDM machine consists of a heated (app. 80 °C for ABS plastic processing) build chamber equipped with an extrusion head and a build platform. Consequently, the machine does not use a laser.
- The extrusion head provides the material deposition in the x-y area according to the contour of the actual layer. It is a plotter-type device.
- The build material is a prefabricated filament that is wound up and stored in a cartridge from which it is continuously fed to the extrusion head. The cartridge has a build-in sensor that communicates with the material management system of the machine.
- In the head, the material it is partly molten by an electric heating system and extruded through a nozzle that defines the string diameter that nearly equals the layer thickness.

- Usually, string diameters range from 0.1 mm to 0.25 mm. The platform moves in z-direction and defines the layer thickness, as the material is squeezed on the top of the partly finished part.
- The process needs supports. They are made by a second nozzle that extrudes another plastic support material simultaneously with the build material.
- The simultaneous processing of two materials indicates that the FLM process is basically capable of handling multi-material print heads. Therefore, the manufacture of multi material parts can be expected in the future.
- After deposition, the pasty string (of the build material as well as of the support material) solidifies by heat transfer into the preceding layer and forms a solid layer.
- Then the platform is lowered by the amount of one-layer thickness and the next layer is deposited. The process repeats until the part is completed.
- There are a wide variety of machines that follow the principle of the FDM process.
- There are many plastic materials available for FDM processes, including engineering materials such as ABS, PC-ABS, and specialty grades for medical modeling.
- Some machines are restricted to only a limited number of different materials. There is a big variety of colors available, amongst it even translucent, black, and white qualities.

Figure 3.6 - Fused deposition modeling. Epicyclic gear set assembled from monochromatic FDM parts, made from ABS plastic (left); part with support as manufactured (center); part after removal of the supports and manual polishing (right)

- Because the color is linked to the filament, it cannot be changed during the build process (Figure. 3.6, left). The Fortus 400 and 900 machines process the high temperature thermoplastic material polyphenylsulfone (PPSF/PPSU). They were the first machines on the market to handle these high performance plastics.
- Typical part properties resemble those of plastic injection molded parts; however, they tend to show anisotropic behaviour that can be reduced by properly adjusted build parameters.
- The parts are either used as concept models, functional prototypes, or as (direct manufactured) final parts. FDM parts show typical surface textures that result from the extrusion process (Figure. 3.6).
- According to the layer thickness and the orientation of the part in the build chamber, these textures are more or less visible.

- Therefore, the positioning (orientation) in the build chamber has a big influence on the appearance of the part.
- Post processing requires the removal of the supports, which can be done manually, or using a special washing device. Finishing requires manual skills and time; but together with artisan capabilities leads to perfect surface qualities and astonishing results (Figure. 3.6.) It is needless to say that intensive finishing affects the part's accuracy.

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 (Figure. 3.7).
- 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.

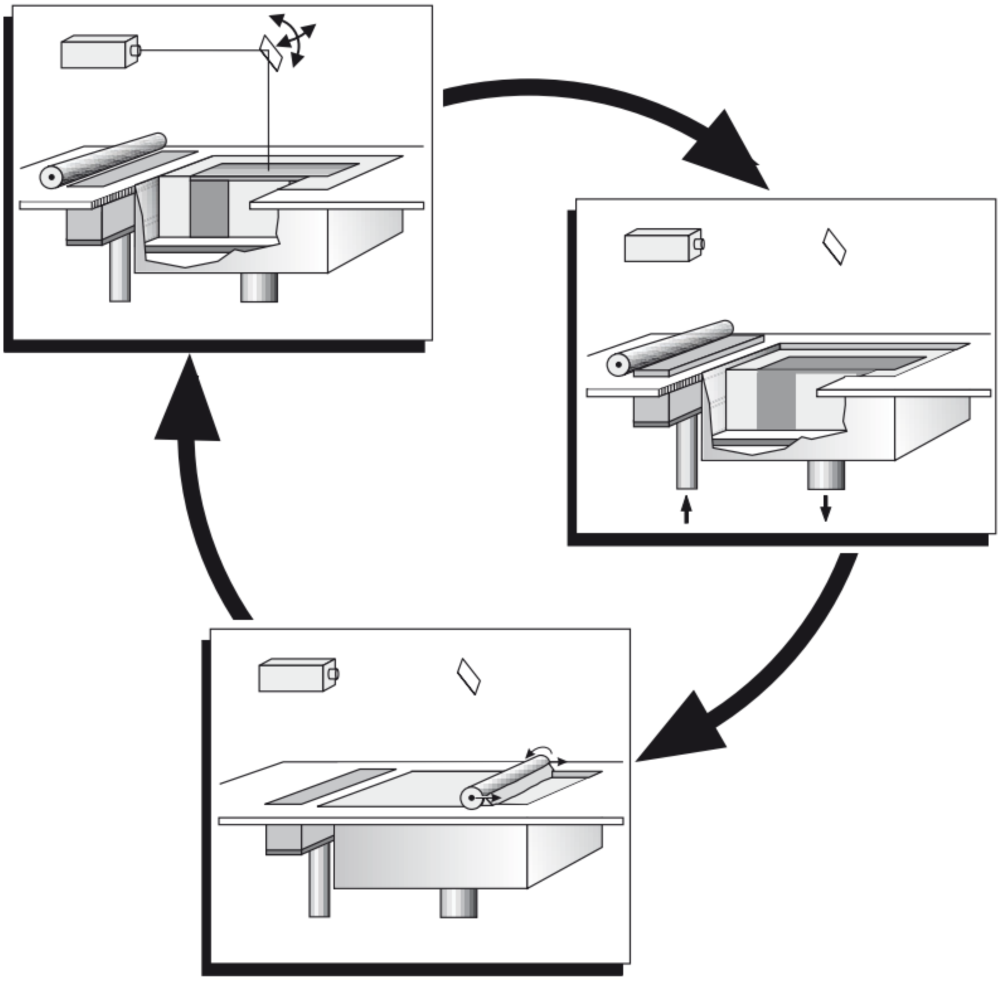


Figure 3.7 - Laser sintering and laser melting, scheme; melting and solidification of a single layer, lowering of the platform, recoating

- 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.
- 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 (Figure. 3.8, left) or as (direct manufactured) final parts (Figure. 3.8, right).

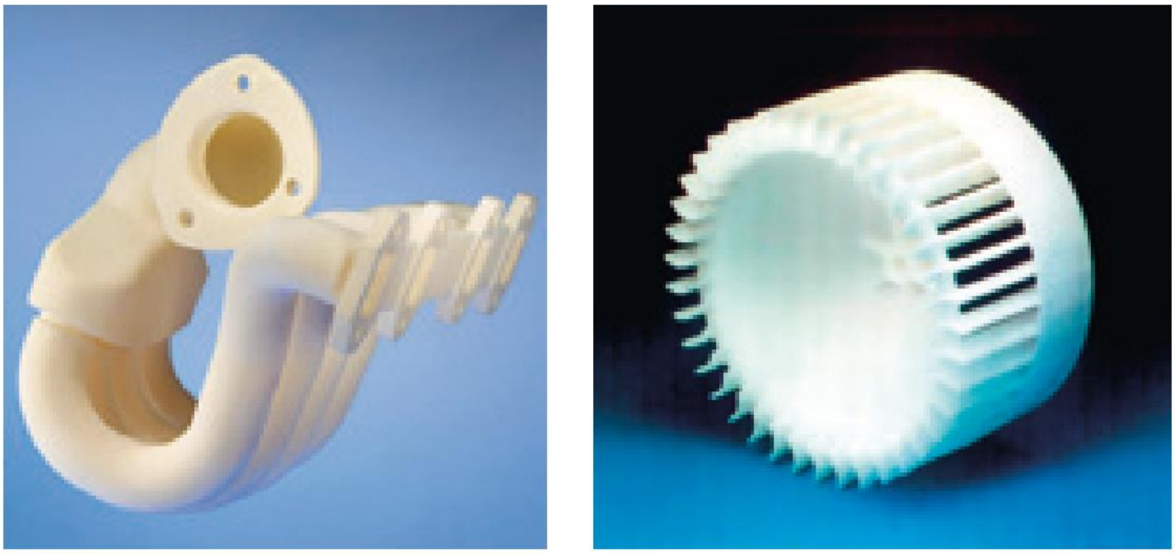


Figure 3.8 - Selective laser sintering, SLS (3D Systems), polyamide; exhaust gas device, prototype (left); fan, final product (right)

Laser Melting – Selective Laser Melting (SLM)

- Laser melting basically is a laser sintering process as described earlier. It was developed in particular to process metal parts that need to be very (> 99%) dense.
- The laser melts the material completely. Therefore, it produces a local (selective) melt pool that results in a fully dense part after re-solidification. The process is generally called selective laser melting, SLM.
- There are some proprietary names as well such as "CUSING", which is an acronym of "cladding" and "fusing".
- Today, most of the machines come from Germany: EOS-GmbH of Munich, RealizerGmbH of Borchen, Concept Laser GmbH of Lichtenfels, and SLM-Solutions of Lübeck.
- In addition, 3D Systems, Rock Hill, SC, USA offers a re-branded system based on MTT machines, the predecessor of SLM Solutions. MTT, UK, now separated from its German branch, continues to design its own machine.
- For almost all metal machines a wide variety of metals, including carbon steel, stainless steel, CoCr, titanium, aluminum, gold and proprietary alloys are available.
- Typically, metal parts are final parts and used as (direct manufactured) products or components of such products.

- Typical examples are the internally cooled cooling pin inserts for injection molds made from tooling steel in Fig. 3.9, left, and the micro cooler made from AlSi10Mg in Fig. 3.9, right.

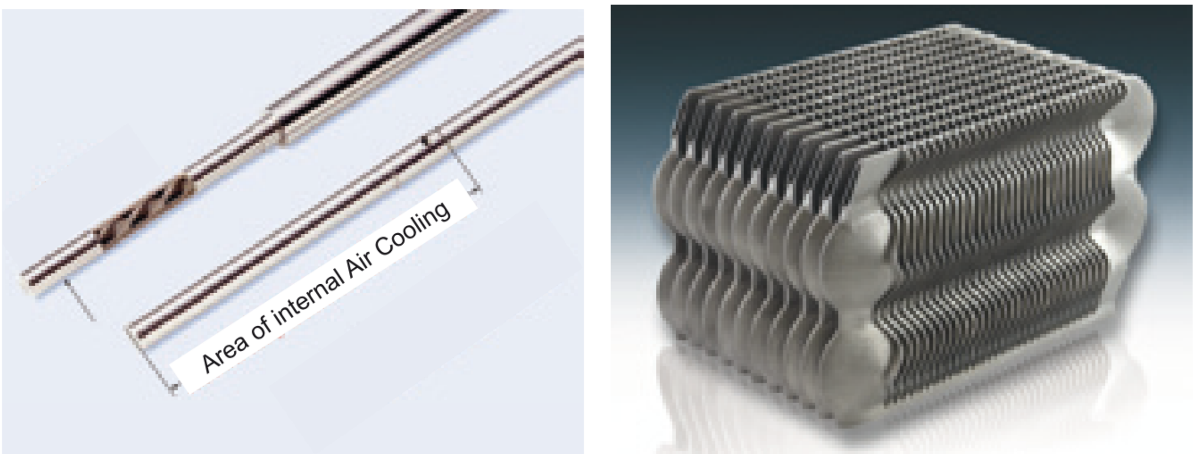


Figure 3.9 Selective laser melting, SLM. *Internally cooled* pin for injection molds, left (Source: Concept Laser GmbH); micro cooler made from AlSi10Mg (Source: EOS GmbH)

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

- Metal and ceramic micro sintering machines are close to market entry but still under development.
- Commercialization has been announced by EOS based on the machine development of 3D Micromac, Chemnitz, Germany.

Figure 3.10 - Micro laser sintering (EOS), demonstrator chess set (Source: EOS GmbH)

- The typical layer thickness is in the range of 1–5 μm and the smallest wall thickness is > 30 μm. A fiber laser with a focus diameter < 20 μm is used. As an example, a chess set is shown on Figure. 3.10. The tower's height is about 5.5 mm.

Binder Jetting Technology

- Binder Jetting is a family of additive manufacturing processes.

- In Binder Jetting, a binder is selectively deposited onto the powder bed as shown in Figure 3.11, bonding these areas together to form a solid part one layer at a time.
- The materials commonly used in Binder Jetting are metals, sand, and ceramics that come in a granular form.
- Binder Jetting is used in various applications, including the fabrication of full-color prototypes (such as figurines), the production of large sand casting cores and molds and the manufacture of low-cost 3D printed metal parts.

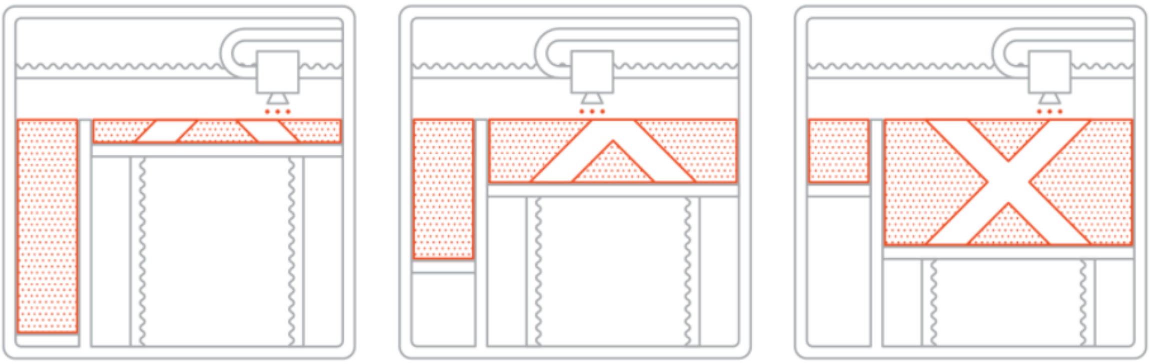


Figure 3.11 – Binder Jetting Processes

- With such diverse applications, it is essential for a designer who wants to use the capabilities of Binder Jetting to the fullest, to understand the basic mechanics of the process and how these connect to its key benefits and limitations.
- Schematic diagram represents the binder jetting process as shown in Figure 3.12. The Binder Jetting process works:

- First, a recoating blade spreads a thin layer of powder over the build platform.

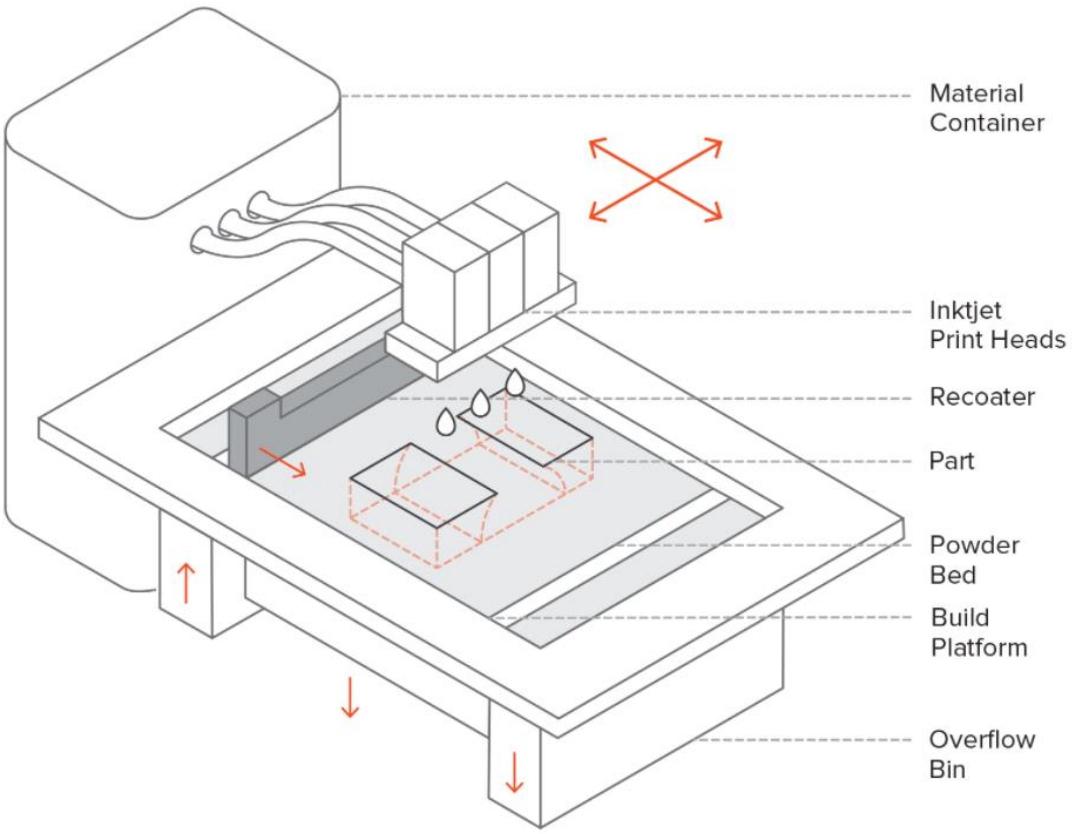


Figure 3.12 - Schematic of a Binder Jetting 3D printer

- Then, a carriage with inkjet nozzles (which are similar to the nozzles used in desktop 2D printers) passes over the bed, selectively depositing droplets of a binding agent (glue) that bond the powder particles together.
- In full-color Binder Jetting, the colored ink is also deposited during this step. The size of each drop is approximately 80 μm in diameter, so good resolution can be achieved.

- When the layer is complete, the build platform moves downwards and the blade re-coats the surface. The process then repeats until the whole part is complete.
- After printing, the part is encapsulated in the powder and is left to cure and gain strength. Then the part is removed from the powder bin and the unbound, excess powder is cleaned via pressurized air.
- Depending on the material, a post-processing step is usually required. For example, metal Binder Jetting parts need to be **sintered** (or otherwise heat treated) or **infiltrated** with a low-melting-temperature metal (typically bronze).
- Full-color prototypes are also infiltrated with acrylic and coated to improve the vibrancy of colors. Sand casting cores and molds are typically ready to use after 3D printing.
- This is because the parts are in a "green" state when they leave the printer. Binder Jetting parts in the **green state** have poor mechanical properties (they are very brittle) and high porosity.

Characteristics of Binder Jetting

Printer Parameters

- In Binder Jetting, almost all process parameters are preset by the machine manufacturer.

- The typical **layer height** depends on the material: for full color models the typical layer height is 100 microns, for metal parts 50 microns and for sand casting mold materials 200-400 microns.
- A key advantage of Binder Jetting over other 3D printing processes is that bonding occurs at **room temperature**. This means that dimensional distortions connected to thermal effects (such as warping in FDM, SLS, DMSL/SLM or curling in SLA/DLP) are not a problem in Binder Jetting.
- As a result, the **build volume** of Binder Jetting machines are amongst the largest compared to all 3D printing technologies (up to 2200 x 1200 x 600 mm).
- These large machines are generally used to produce sand casting molds. Metal Binder Jetting systems typically have larger build volumes than DMSL/SLM systems (up to 800 x 500 x 400 mm), which allows the parallel manufacturing of multiple parts at a time.
- The maximum part size though is restricted to a recommended length of up to 50 mm, due to the post-processing step involved.
- Moreover, Binder Jetting requires **no support structures**: the surrounding powder provides to the part all the necessary support.
- This is a key difference between metal Binder Jetting and other metal 3D printing processes, which usually require extensive use of support structures, and allows for the creation of freeform metal structures with very few geometric restrictions.

- Since the parts in Binder Jetting do not need to be attached to the build platform, the whole build volume can be utilized.
- Thus, Binder Jetting is suitable for **low-to-medium batch production.**

Benefits & Limitations of Binder Jetting

The key advantages and disadvantages of the technology are summarised below:

- Binder Jetting produces metal parts and full-color prototypes at a **fraction of the cost** compared to DMLS/SLM and Material Jetting respectively.
- Binder Jetting can manufacture **very large parts** and **complex metal geometries**, as it is not limited by any thermal effects (e.g. warping).
- The manufacturing capabilities of Binder Jetting are excellent for low to medium **batch production**.
- Metal Binder Jetting parts have **lower mechanical properties** than DMSL/SLM parts, due to their higher porosity.
- Only **rough details** can be printed with Binder Jetting, as the parts are very brittle in their green state and may fracture during post processing.
- Compared to other 3D printing process, Binder Jetting offers a **limited material selection**.

Unit – IV

Materials

Contents:

- ✓ Polymers, Metals, Non-Metals, Ceramics.
- ✓ Various forms of raw material – Liquid, Solid, Wire, Powder
- ✓ Powder Preparation and their desired properties
- ✓ Polymers and their properties. Support Materials

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Anisotropic Properties

- Isentropic means constant characteristic properties in any direction and identical values at any point of the part's volume.
- Isentropic material behavior therefore is a requirement for traditional tool-based production and consequently provides the basis for engineering design calculations.
- When a part is manufactured in layers it is not surprising that the part will exhibit recognizable property differences.
- In this case, the part is said to have anisotropic properties, which means that its properties vary in different directions and within the part.
- Layer-oriented manufacturing by AM processes in fact produce anisotropicparts. The degree of anisotropy may vary: from barely

recognizable to a degree that has significant impact on the part's stability.

- Although the degree of anisotropy depends mainly on the AM process, the orientation of the part in the build volume and its engineering design also play a role.
- Because of the layer manufacturing, the part's properties parallel to the build area and those perpendicular to it differ from each other.
- This effect can be theoretically compensated by simply changing the orientation of the part in the build chamber.
- As a design rule, the area of the highest load should be parallel to the build area.
- In practice, the change of the orientation in one area of a part changes the orientation of all other areas as well. Therefore, any change of the part's orientation within the build chamber has to be decided very carefully.

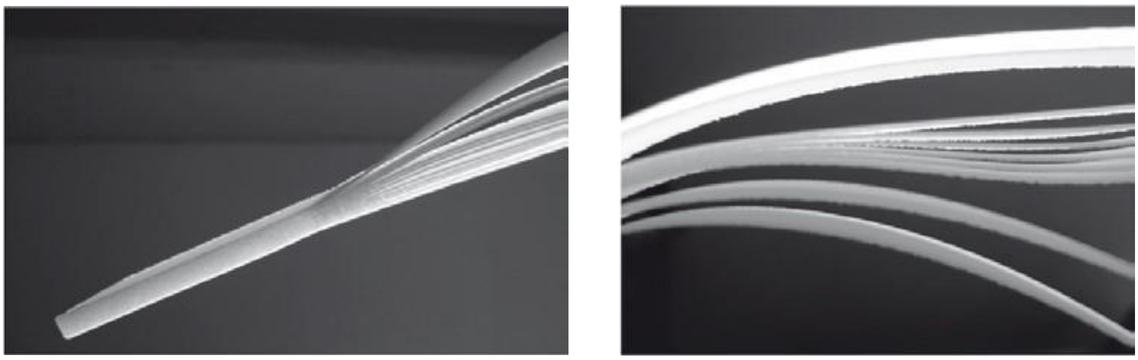

Figure 4.1 shows delamination in a laser sintered part that was made using inaccurate build parameters on purpose.

- The anisotropic effect is also closely linked to the way adjacent layers are bonded. The worst imaginable case is a delamination of layers.
- It is obvious that this might happen with FLM processes but delamination may occur with all AM processes.
- The anisotropic effect depends on the AM process used. Laser stereolithography works with liquid resin and simultaneously solidifies the voxels within the layer by the same process as the bonding between two adjacent layers.
- Therefore, anisotropic effects are less pronounced. Polymer printing or PolyJet processes, in which a new layer is polymerized on top of an already hardened one, show a slightly more pronounced anisotropic behavior, which is true for laser sintering of plastics as well because an already solidified layer is partially molten for a second time in order to apply the next layer.
- Similar, but again more pronounced, anisotropic effects result from 3D-printing processes (powder-binder-processes).
- However, here the porosity of the part has a bigger effect on the part's properties than the layer-induced anisotropy. Infiltration reduces this effect, but does not eliminate it.
- Compared to stereolithography, the extrusion processes (fused deposition modeling) show higher anisotropic effects.

- The process requires a pasty state while extruding the material, but does not allow the total melting in order to guarantee the geometrical stability of the partially finished build.
- This effect can be reduced by improved machine technology, especially by proper heat treatment and by using thin layers.
- Professional- and shop floor machines consequently produce reasonably reduced anisotropic behavior of the parts compared to personal printers and fabbers that work on the same principle.
- For these processes, the maximum endurable strength in vertical direction should be reduced to one half of the strength in the build plane (horizontal).
- From the process point of view, layer laminate processes show the most pronounced anisotropic behavior because the prefabricated and therefore isotropic layers are bonded by some type of glue with completely different properties.
- Unfortunately, these rules do not hold for all variations of processes and materials.
- While they are typically valid for plastic processes, laser sintering of metals causes different material behavior.
- The powder material is molten completely, resulting in fully dense parts that show just minor anisotropic effects.
- This is also indicated by the name *selective laser melting* (SLM) that labels the metal variant of the sintering process; however, the layers are still visible in the micrograph.

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

Basic Isentropic Materials

- AM allows to process materials of all material classes, namely plastics, metals, and ceramics. This is also valid for each of the five AM families, although in practice the intensity of use varies considerably.
- Sintering of plastics and metals can be regarded as widely used standard processes, while for the extrusion of metal- or -ceramic-filled materials processes are still under development.
- The number of different materials within each material class is still quite limited, although this number has increased significantly over the last years and grows continually due to international research activities.

- The reason for the limited number of materials is that in most cases a simultaneous material and process development is required.
- Material for plastic laser sintering, for example, must not only be locally meltable, but easy to recoat which requires rounded edges.
- Additives and process details, such as shielding gas and preheating, suppress local evaporation, oxidation, and other inter-process effects and interactions with the environment.
- This is one reason why powder materials for laser sintering are different from powders for sinter coating, although they are quite similar in terms of their chemical composition.
- As a consequence, AM materials are usually developed by or under the responsibility of the machine manufacturer who treats the material as a proprietary product and exclusively sells it to his machine customers.
- Some users are skeptical, mainly because of economical reasons; but on the other hand, this approach guarantees a proper build.
- The continuous increase of overall material consumption forces the activities of so called third party suppliers that already entered the AM business.
- Mainly for materials for plastic laser sintering and stereolithography independent markets are developing.

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

Plastics

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

creates confidence in this material, they also cause problems because the AM-polyamides and the ones used for plastic injection molding differ significantly from each other.

- Even if the material would be chemically identical, the resulting parts would differ a lot, because a material that is completely molten and injected into a tool under high pressure shows different properties compared to the same one that is locally molten under atmospheric pressure, deposited layer by layer, and solidified by heat conduction.
- Industrial products are typically made from polyamide 6 or 6.6, while laser sintering mainly utilizes polyamide 11 or 12.
- Polyamide 12 is used because it is barely hydrophilic and, even more importantly, offers a sufficiently big process window for reproducible manufacturing. The powder particles have a primary particle size of 20 to 50 μm.
- Warping and distortion were severe problems in the early days of AM, however, are today reduced to a minimum due to preheating and improved scanning strategies.
- There is a broad and successively increasing variety of polyamide-based powder materials for laser sintering on the market. This includes flame retardant, aluminum filled, and qualities that can be sterilized.
- Improved mechanical properties are provided by glass-filled powders, although this term is confusing, because spheres and

rice-grainshaped particles are used instead of fibers in order to allow recoating.

- They provide higher stiffness compared to unfilled qualities, but do not reach the properties that canbe expected from fiber filled injection molded materials.
- As the number of installed systems worldwide increases, an independent (third party) market for powder materials develops and influences the economic situation as well as the qualification of new andapplication-driven qualities.
- Different formulations, such as polyamide 6.6, have been investigated but did not reach the market yet.
- Although the development and production of new products urgently asks for high performance plastic materials, currently there are only a few are available.
- A PPSU material is released for FDM extrusion processes and in late 2010 the high temperature material PEEK (polyetheretherketones) was introduced as EOS PEEK HP3.
- PEEK has excellent heat- and corrosion-resistant properties. It is flame and temperature resistant, chemical resistant, has high tensile strength, is lightweight, biocompatible, and can be sterilized. It has a melt point of 334 °C and requires a process window between 350 °C and 380 °C.

- This is far beyond the temperature ranges of today's plastic laser sintering machines and triggered the development of a completely new high temperature machine, the EOS 800/900.
- Another group of materials for laser sintering are polyamide-coated particles made fromalmost any arbitrary material.
- It can be used in the plastic laser sintering machines. The most prominent applications are coated foundry sands for sintering of cores and forms for sand casting. Particle sizes of the uncoated material range around 50 μm.
- Similar materials are available as coated metals. Here, the coating acts as a binder, making AM a two-step process; however, it is not widely used because one-step processesare available.

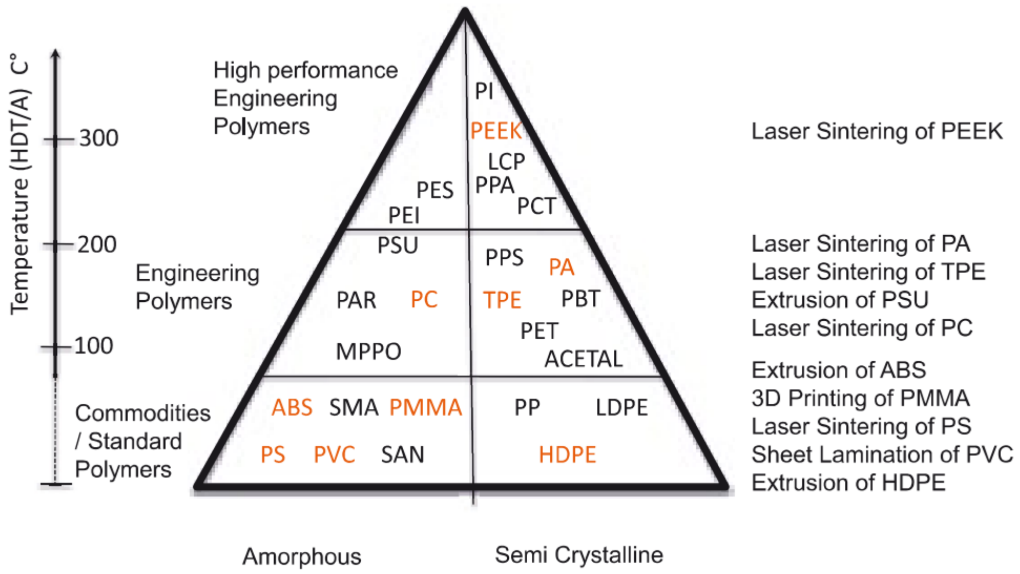

Figure 4.2 Plastic triangle with plotted AM processes and related materials

- But it opens up the possibilities for new materials such as coated filled spheres that act like granules.

- The amorphous structured polystyrene is also used as a material for laser sintering, preferably to make lost cores and cavities for the lost foam process.
- For FDM, the basic material is an ABS plastic grade. Because ABS is frequently used as a material for plastic injection molding, it is often regarded as a "series material".
- The user should keep in mind that ABS is a standard polymer able to resist significantly lower temperatures than polyamides.
- For all AM processes that apply the build material from a separate storage (PolyJet,FDM) rather than keeping it in the build chamber (laser sintering, laser stereolithography), the material and consequently the parts can be colored.
- Although laser sintered or parts made by stereolithography can also be colored, however, this requires the coloring of all material stored in the machine and the fabrication of parts from just this color.

Metals

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

Figure 4.3 Top layer of a laser sintered metal part (SLM)

- The materials are very similar to the materials used for laser coating or welding with filler material.
- Therefore, a wide variety of qualities is available from different suppliers and a high level of expert-knowledge has already been gathered.

- Although various commercialized powders can be used, it needs to be taken in consideration that the qualification of the material must be made or at least evaluated in-house.
- On the other hand, powders delivered by the AM machine manufacturers come with material datasheets based on proven parameters that incorporate optimized scan strategies as well.
- For AM of metals, stainless steel, tool steel, CoCr-alloys, titanium, magnesium, aluminum as well as precious metals, such as gold and silver are available.
- Recently, the first parts made from copper were presented /Pho11/, however, the process has not been commercialized yet. Proprietary variations, especially for dental applications, were developed and are frequently marketed in a package with specialized software and modified machines.
- Figure 4.4 provides a short overview over the different kinds of AM metals processable using metal laser sintering (melting). The data come from the service bureau 3 T RPD Ltd and is based on EOS materials (full bullets). In addition, some values obtained from other manufacturers are added, mainly from /CAS05/ (unfilled bullets).

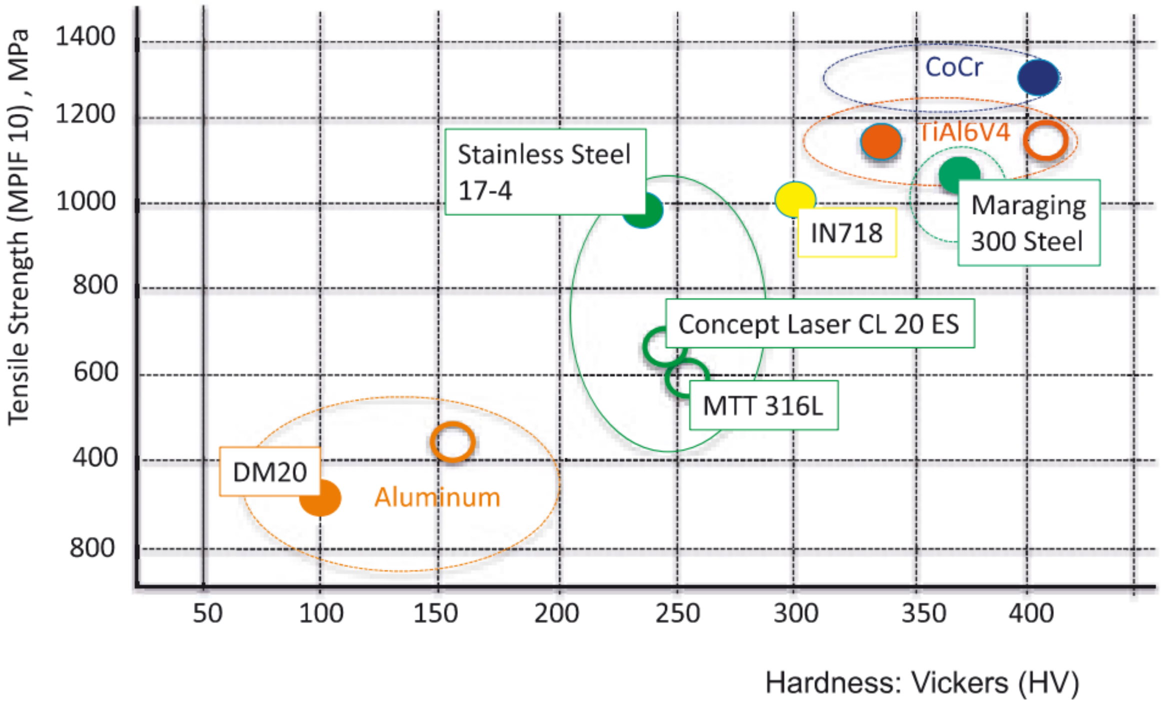

Figure 4.4 Selection of materials for AM metal processes based on EOS, 3 T RPD and /Cas05/

- Layer laminate manufacturing is preferably linked to plastic and paper sheets and foils.
- If metal parts are required, only the ultrasonic consolidation (Solidica) process is available, which works with aluminum straps that come wound up and are bonded by ultrasonic welding on the top of the partially finished build.
- The machine also contains a 3-axis milling device that contours the layer in the same clamping position. The process manufactures completely dense aluminum parts.
- Because the process is cold, even sensitive electronic parts can be put in the milled pockets and sealed with the subsequent layers.

- The parts are preferably used as integrated sensor housings for aeronautical and deep sea applications.

Composites

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

FIGURE 4.5 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. 4.5.
- 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.

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 encountered 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.

Unit – V

Additive manufacturing equipment & post processing

Content:

- Process equipment- design and process parameters
  - Governing bonding mechanism
  - Common faults and troubleshooting
  - Process design
- Post processing: requirement and techniques
  - Product quality
  - Inspection and testing
  - Defects and their causes

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Post processing

- Most AM processes require post-processing after part building to prepare the partfor its intended use.
- Depending upon the AM technique, the reason for post-processing varies. For purposes of simplicity, this chapter will focus on post- processing techniques which are used to enhance components or overcome AM limitations.
- These include:

1. Support Material Removal
2. Surface Texture Improvements

3. Accuracy Improvements
4. Aesthetic Improvements
5. Preparation for use as a Pattern
6. Property Enhancements using Non-Thermal Techniques
7. Property Enhancements using Thermal Techniques

- The skill with which various AM practitioners perform post-processing is one of the most distinguishing characteristics between competing service providers.
- Companies which can efficiently and accurately post-process parts to a customer's expectations can often charge a premium for their services; whereas, companies which compete primarily on price may sacrifice post-processing quality in order toreduce costs.

Support Material Removal

- The most common type of post-processing in AM is support removal.
- Support material can be broadly classified into two categories:
- (a) material which surrounds the part as a naturally-occurring by-product of the build process (natural supports), and
- (b) rigid structures which are designed and built to support,

restrain or attach the part being built to a build platform (synthetic supports).

Natural Support Post-Processing

- In processes where the part being built is fully encapsulated in the build material, the part must be removed from the surrounding material prior to its use.
- Processes which provide natural supports are primarily powder-based and sheet-based processes.
- Specifically, all powder bed fusion (PBF) and binder printing processes require removal of the part from the loose powder surrounding the part; and bond-then-form sheet metal lamination processes require removal of the encapsulating sheet material.
- In PBF processes, after the part is built it is typically necessary to allow the partto go through a cool-down stage.
- The part should remain embedded inside the powder to minimize part distortion due to non-uniform cooling.
- The cool-down time is dependent on the build material and the size of the part(s). Once cool-down is complete, there are several methods used to remove the part(s) from the surrounding loose powder.

- Typically, the entire build (made up of loose powder and fused parts) is removed from the machine as a block and transported to a “breakout” station where the parts are removed manually from the surrounding powdered material.
- Brushes, compressed air, and light bead blasting are commonly used to remove loosely adhered powder; whereas, wood-working tools and dental cleaning tools are commonly used to remove powders which have sintered to the surface or powder entrapped in small channels or features.
- Internal cavities and hollow spaces can be difficult to clean and may require significant post-processingtime.
- With the exception of an extended cool-down time, natural support removal techniques for binder printing processes are identical to those used for PBF. In most cases, parts made using binder printing are brittle out of the machine.
- Thus, until the parts have been strengthened by infiltration the parts must be handled with care. This is also true for PBF materials that require post-infiltration, such as some elastomeric materials, polystyrene materials for investment casting, and metal and ceramic green parts.
- More recently, automated loose powder removal processes have been developed. These can be stand-alone apparatuses or integrated into the build chamber. Newer Z Corp binder printing

machines (*see* Fig. 5.1) and MTT SLM machines have integrated powder removal into their machines.

Fig. 5.1 Automated powder removal using vibratory and vacuum assist in a ZCorp 450 machine.

- Bond-then-form sheet lamination processes, such as laminated object manufacturing, also require natural support material removal prior to use.
- If complex geometries with overhanging features, internal cavities, channels or fine features are used, the support removal may be tedious and time-consuming.
- If cavities or channels are created, it is often necessary to delaminate the model at a specific *z*-height in order to gain access to de-cube the internal feature; and then re-glue itafter removing excess support materials.

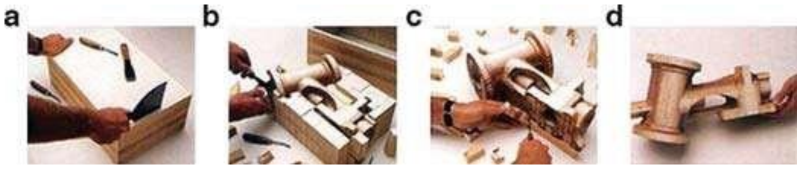

Fig. 5.2 LOM support removal process (de-cubing) process, showing: (a) the finished block of material; (b) removal of cubes far from the part; (c) removal of cubes directly adjacent to the part; (d) the finished product

- An example de-cubing operation for LOM is shown in Fig.5.2.

Synthetic Support Removal

- Processes which do not naturally support parts require synthetic supports for over-hanging features.
- In some cases, such as when using PBF techniques for metals, synthetic supports are also required to resist distortion. Synthetic supports can be made from the build material or from a secondary material.
- The development of secondary support materials was a key step in simplifying the removal of synthetic supports as these materials are either weaker, soluble in a liquid solution, or melt at a lower temperature than the build material.

- The orientation of a part with respect to the primary build axis significantly affects support generation and removal. If a thin part is laid flat, for instance, the amount of support material consumed may significantly exceed the amount of build material (*see* Fig. 5.3).

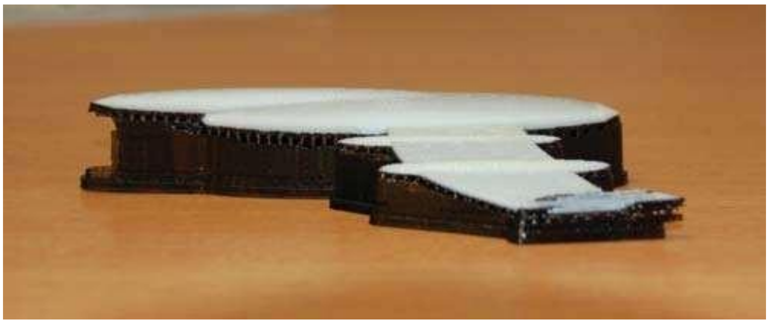

Figure 5.3 Flat FDM-produced aerospace part. White build material is ABS plastic and black material is the water-soluble Water Works support material.

- The orientation of supports also affects the surface finish of the part, as support removal typically leaves “witness marks” (small bumps or divots) where the supports were attached.
- Additionally, the use of supports in regions of small features may lead to these features being broken when the supports are removed. Thus, orientation and location of supports is a key factor for many processes to achieve desirable finished part characteristics.

Supports Made from the Build Material

- All extrusion, direct printing and photopolymer processes require supports for overhanging structures and to connect the part to the build platform.
- Since these processes are used primarily for polymer parts, the low strength of the supports allows them to be removed manually.
- These types of supports are also commonly referred to as breakaway supports.
- The removal of supports from downward-facing features leaves witness marks where the supports were attached. As a result, these surfaces may require subsequent sanding and polishing.

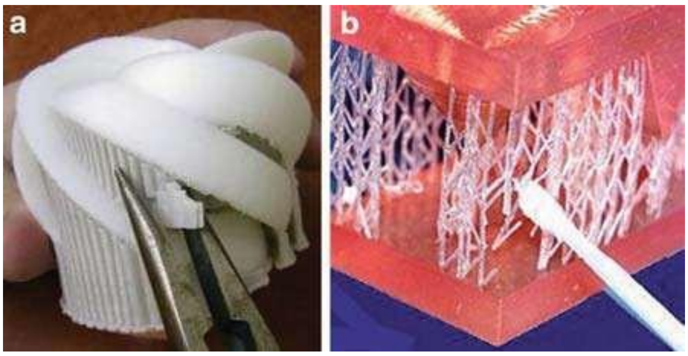

Fig. 5.4 Breakaway support removal for (a) an FDM part (courtesy of Jim Flowers) and (b) an SLA part.

- Figure 5.4 shows break- away support removal techniques for FDM and SLA. PBF and beam deposition processes for metals and ceramics also typically require support materials.

Fig. 5.5 SLM dental framework

- An example dental framework, oriented so that support removal does not mar the critical surfaces, is shown in Fig. 5.5.
- For these processes the metal supports are often too strong to be removed by hand; and thus the use of milling, band-saws, cut-off blades, wire-EDM and other metal cutting techniques are widely employed.

Supports Made from Secondary Materials

- A number of secondary support materials have been developed over the years in order to alleviate the tedious, time-consuming, labor-intensive, error-prone manual removal of support materials.

- Two of the first technologies to use secondary support materials were the Cubital layer-wise photopolymerization process and the Solids-cape direct printing process.
- Their use of wax support materials enabled the block of support/build material created during processing to be placed in a warm water bath; thus melting or dissolving the wax and leaving behind the final parts.
- Since that time, secondary supports have become common commercially in FDM and direct printing processes.
- Secondary supports have also been demonstrated for form-then-bond sheet metal lamination and beam deposition processes in research environments.
- For polymers, the most common secondary support materials are polymer materials which can be melted and/or dissolved in a water-based solvent.
- The water can be jetted or ultrasonically vibrated to accelerate the support removal process.
- For metals, the most common secondary support materials are lower- melting-temperature alloys or alloys which can be chemically dissolved in a solvent (in this case the solvent must not affect the build material).

Surface Texture Improvements

- AM parts have common surface-texture features that may need to be modified for aesthetic or performance reasons. Common surface textures are: stair-steps; powder adhesion; fill patterns from extrusion or beam-based systems; and witness marks from support material removal.
- Stair-stepping is a fundamental issue in layered manufacturing and is difficult to overcome, although one can choose a thin layer thickness to minimize error at the expense of build time.
- Powder adhesion is also afundamental characteristic of binder printing, PBF and powder-based beam depo-sition processes. The amount of powder adhesion can be controlled, to some degree, by changing part orientation, powder morphology and thermal control technique.
- The type of post-processing utilized for surface texture improvements is dependent upon the desired surface finish outcome.
- If a matte surface finish is desired, asimple bead blasting of the surface can help even the surface texture, remove sharp corners from stair-stepping and give an overall matte appearance.
- If a smooth or polished finish is desired, then wet or dry

sanding and hand-polishing are performed. In many cases, it is desirable to paint the surface (e.g., with cyanoacrylate, or a sealant) prior to sanding or polishing.

- Painting the surface has the dual benefit of sealing porosity and, by viscous forces, smoothing the stair-step effect; thus making sanding and polishing easier and more effective.
- Several automated techniques have been explored for surface texture improvements.
- Two of the most commonly utilized include tumbling for external features and abrasive flow machining for, primarily, internal features. These processes have been shown to smooth surface features nicely, but at the cost of small feature resolution, sharp corner retention and accuracy.

Accuracy Improvements

- There is a wide range of accuracy capabilities in AM. Some processes are capable of sub-micron tolerances, whereas others have accuracies around 1 mm.
- Typically, the larger the build volume and the faster the build speed the worse the accuracy for a particular process.
- This is particularly noticeable, for instance, in beam deposition processes where the slowest and most accurate beam deposition processes have accuracies approaching a few

microns; whereas, the larger bulk deposition machines have accuracies of several millimeters.

Error Sources

- Process-dependent errors affect the accuracy of the *X*–*Y* plane differently from the *Z*-axis accuracy.
- These errors come from positioning and indexing limitations of specific machine architectures, lack of closed-loop process monitoring and control strategies, and/or from issues fundamental to the volumetric rate of material addition (such as melt pool or droplet size).
- In addition, for many processes, accuracy is highly dependent upon operator skill.
- Future accuracy improvements in AM will require fully automatic real-time control strategies to monitor and control the process, rather than the need to rely on expert operators as a feedback mechanism.
- Integration of additive plus subtractive processing is another method for process accuracy improvement.
- Material-dependent phenomena also play a role in accuracy, including shrinkage and residual stress-induced distortion.
- Repeatable shrinkage and distortion can be compensated for by scaling the CAD model; however, predictive capabilities

at present are not accurate enough to fully understand and compensate for variations in shrinkage and residual stresses.

- Quantitative understanding of the effects of process parameters, build style, part orientation, support structures, and other factors on the magnitude of shrinkage, residual stress and distortion is necessary to enhance these predictive capabilities.
- In the meantime, for parts which require a high degree of accuracy; extra material must be added to critical features, which is then removed via milling or other subtractive means to achieve the desired accuracy.
- In order to meet the needs of applications where the benefits of AM are desired with the accuracy of a machined component, a comprehensive strategy for achieving this accuracy can be adopted.
- One such strategy involves pre-processing of the STL file to compensate for inaccuracies followed by finish machining of the final part. The following sections describe steps to consider when seeking to establish a comprehensive finish machining strategy.

Model Pre-processing

- For many AM processes, the position of the part within the build chamber and theorientation will influence part accuracy, surface finish and build time. Thus, translation and rotation operations are applied to the original model to optimize the partposition and orientation.
- Shrinkage often occurs during AM. Shrinkage also occurs during the post process furnace operations needed for indirect processing of metal or ceramic green parts.
- Pre-process manipulation of the STL model will allow a scale factor to be used to compensate for the average shrinkage of the process chain.
- However, when compensating for average shrinkage, there will always be some features which shrink slightly more or less than the average (shrinkage variation).
- In order to compensate for shrinkage variation, if the highest shrinkage value is used then ribs and similar features will always be at least as big as the desired geometry. However, channels and holes will be too large. Thus, simply using the largest shrinkage value is not an acceptable solution.
- In order to make sure that there is enough material left on the surface to be machined, adding “skin” to the original model is necessary. This skin addition, such that there is material left to

machine everywhere, can be referred to as making the part "steel-safe."

- Many studies have shown that shrinkage variations are geometry-dependent, even when using the same AM or furnace process parameter settings.
- Thus, compensating for shrinkage variation uncertainties requires offsetting of the original model to guarantee that even the features with the largest shrinkage levels and all channels and holes are steel-safe.
- There are two primary methods for adding a skin to the surface of a part. The first is to offset the surfaces and then re-calculate all of the surface intersections.

Hole Drilling

- Circular holes are common features in parts and tools. Using milling tools to create holes is inefficient and the circularity of the holes is poor.
- Therefore, a machining strategy of identifying and drilling holes is preferable. The most challenging aspect is to recognize holes in an STL file, as the 3D geometry is represented by a collection of unordered triangular planar facets (and thus all feature information is lost).

- The intersection curve between a hole and a surface is typically a closed loop.
- By using this information, a hole recognition algorithm begins by identifying all closed loops made up of sharp edges from the model.
- These closed loops may not necessarily be the intersection curves between holes and a surface, so a series of hole-checking rules are used to remove the loops that do not correspond to drilled holes.
- The remaining loops and their surface normal vectors are used to determine the diameter, axis orientation, and depth for drilling. From this information, tool paths can be automatically generated.
- Thus, by pre-processing an STL file using a shrinkage and surface offset value, and then post-processing the part using adaptive raster milling, contour machining and hole drilling, an accurate part can be made. In many cases, however, this type of comprehensive strategy is not necessary.
- For instance, for a complex part where only one or two features must be made accurately, the part could be pre-processed using the average shrinkage value as a scaling factor and a skin can be added only to the critical features.
- These critical features could then be manually machined after AM part creation, leaving the other features as-is. Thus, the finish machining strategy adopted will depend greatly upon the application and part-specific design requirements.

Aesthetic Improvements

- Many times AM is used to make parts, which will be displayed for aesthetic or artistic reasons or used as marketing tools. In these and similar instances, the aesthetics of the part is of critical importance for its end application.
- Often the desired aesthetic improvement is solely related to surface finish. In this case, the post-processing options discussed in 5.2 can be used.
- In some cases, a difference in surface texture between one region and another may be desired (this is often the case in jewelry). In this case, finishing of selected surfaces only is required.
- In cases where the color of the AM part is not of sufficient quality, several methods can be used to improve the part aesthetics.
- Some types of AM parts can be effectively colored by simply dipping the part into a dye of the appropriate color. This method is particularly effective for parts created from powder beds, as the inherent porosity in these parts leads to effective absorption.
- If painting is required the part may need to be sealed prior to painting. Common automotive paints are quite effective in these instances.
- Another aesthetic enhancement (which also strengthens the part and improves wear resistance) is chrome plating. Figure 5.10 shows a SLA part before and after chrome plating.

Fig. 5.10 SLA part (a) before and (b) after chrome plating. (Courtesy of Artcraft Plating)

- Several materials have been electroless coated to AM parts, including Ni, Cu and other coatings. In some cases, these coatings are thick enough that, in addition to aesthetic improvements, the parts are robust enough to use as tools for injection molding or as EDM electrodes.

Preparation for use as a Pattern

- Often parts made using AM are intended as patterns for investment casting, sand casting, room temperature vulcanization (RTV) molding, spray metal deposition or other pattern replication processes.

- The use of an AM pattern for metal part creation using a secondary molding or casting process is often the least expensive way to use AM to produce a metal part, as many of the metal-based AM processes are still expensive to own and operate.
- The accuracy and surface finish of an AM pattern will directly influence the final part accuracy and surface finish.
- As a result, special care must be taken to ensure the pattern has the accuracy and surface finished desired in the final part. In addition, the pattern must be scaled to compensate for any shrinkage that takes place in the pattern replication steps.

Investment Casting Patterns

- In the case of investment casting, the AM pattern will be consumed during processing. In this instance, residue left in the mold as the pattern is melted or burned out is undesirable. Any sealants used to smooth the surface during pattern preparation should be carefully chosen so as not to inadvertently create unwanted residue.
- AM parts can be printed on a casting tree or manually added to a casting tree after AM.
- Figure 5.11 shows rings made using an InVision HR printer. In the first picture, a collection of rings are shown on the build platform; each ring is supported by a secondary support material in white. In the

second picture, a close-up of the ring pattern is shown. The third picture shows metal rings still attached to a casting tree. In this instance, the rings were added to the tree after AM, but before casting.

- When using the SLA Quickcast build style, the hollow, truss-filled shell patterns must be drained of liquid prior to investment. The hole(s) used for draining must be covered to avoid investment entering the interior of the pattern. Since SLA materials are thermosets, they must be burned out of the investment rather than melted.
- When powdered materials are used as investment casting patterns, such as polystyrene in SLS or starch in a ZCorp process, the resulting part is porous and brittle. In order to seal the part and strengthen it for the investment process, the partis infiltrated with an investment casting wax prior to investment.

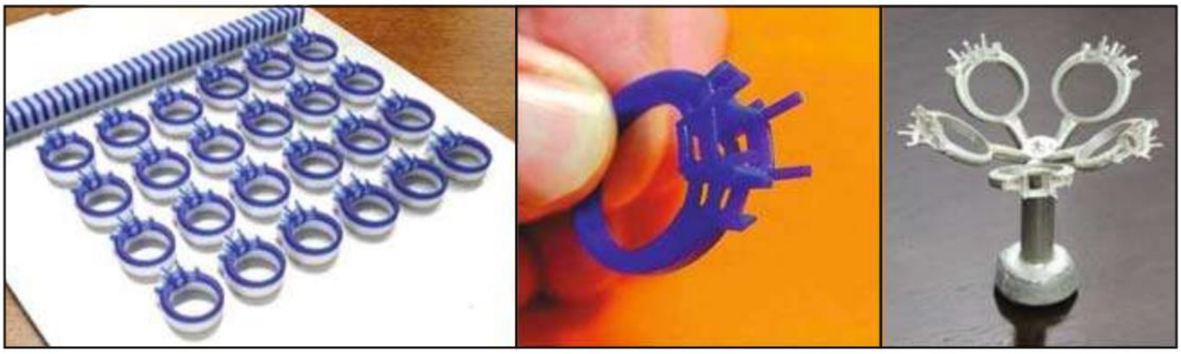

Fig. 16.11 Rings for investment casting, made using a ProJet 1 CPX 3D Printer

Sand Casting Patterns

- Both binder printing and PBF processes can be used to directly create sand mold cores and cavities by using a thermosetting binder to bind sand in the desired shape. One benefit of these direct approaches is that complex-geometry cores can be made that would be very difficult to fabricate using any other process, as illustrated in Fig. 5.12

Fig. 5.12 Sand casting pattern for a cylinder head of a V6, 24-valve car engine (*left*) during loose powder removal and (*right*) pattern prepared for casting alongside a finished casting.

- In order to prepare AM sand casting patterns for casting, loose powder is removed and the pattern is heated to complete cross-linking of the thermoset binder and to remove moisture and gaseous by-products.
- In some cases, additional binders are added to the pattern before heating, to increase the strength for handling. Once the pattern is

thermally treated, it is assembled with its corresponding core(s) and/or cavity, and hot metal is poured into the mold. After cooling, the sand pattern is removed using tools and bead blasting.

- In addition to directly producing sand casting cores and cavities, AM can be used to create parts which are used in place of the typical wooden or metal patterns.
- Inthis case, the AM part is built as one or more portions of the part to be cast, split along the parting line. The split part is placed in a box, sand mixed with binder is poured around the part, and the sand is compressed (pounded) so that the binder holds the sand together.
- The box is then disassembled, the sand mold is removed from the box, and the pattern is removed from the mold. The mold is then reassembled with its complementary mold half and core(s) and molten metal is poured into the mold.

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