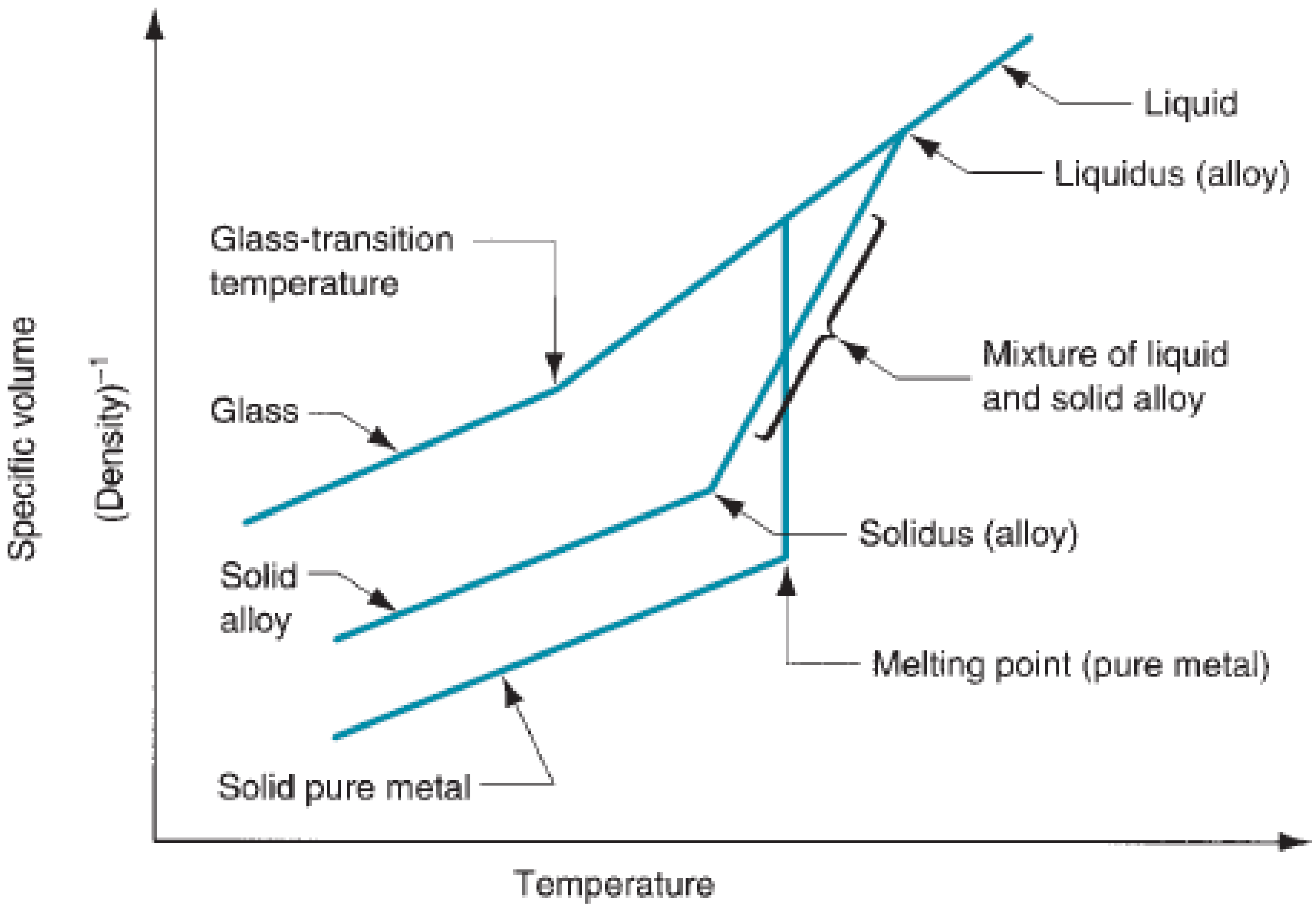
Material Classification

1. Polymers
2. Metals
3. Ceramics
4. Composites

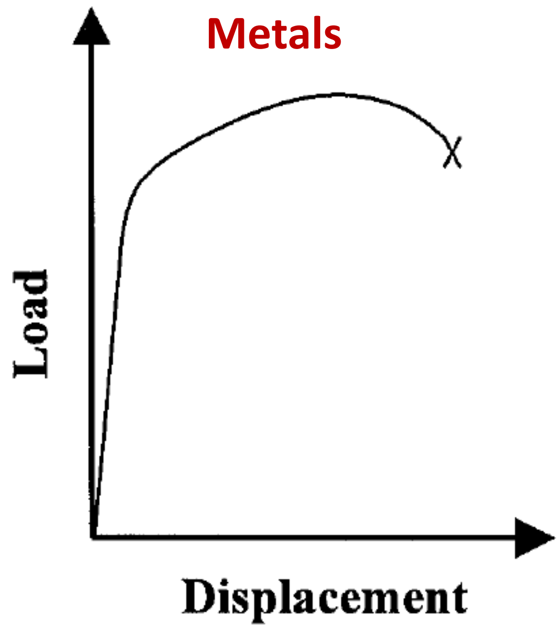
Polymers

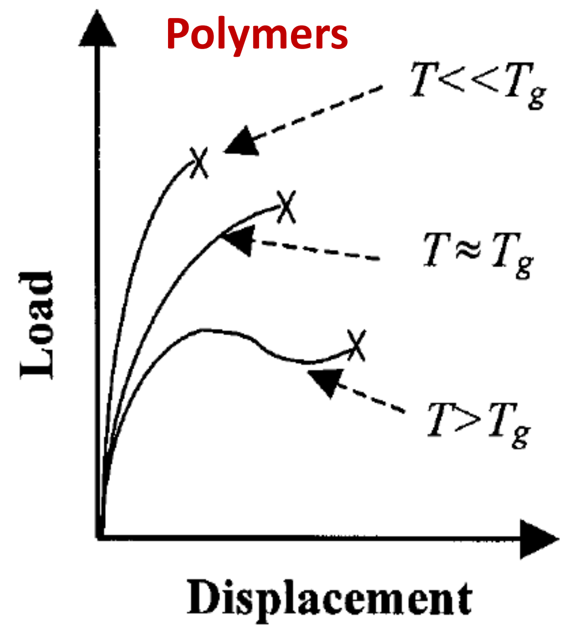
a) ABS polymer
b) Acrylics
c) Cellulose
d) Nylon
e) Polycarbonate
f) Thermoplastic polyester
g) Polyethylene
h) Polypropylene
i) Polyvinylchloride

Thermal Expansion Characteristics



Load-Displacement Characteristics



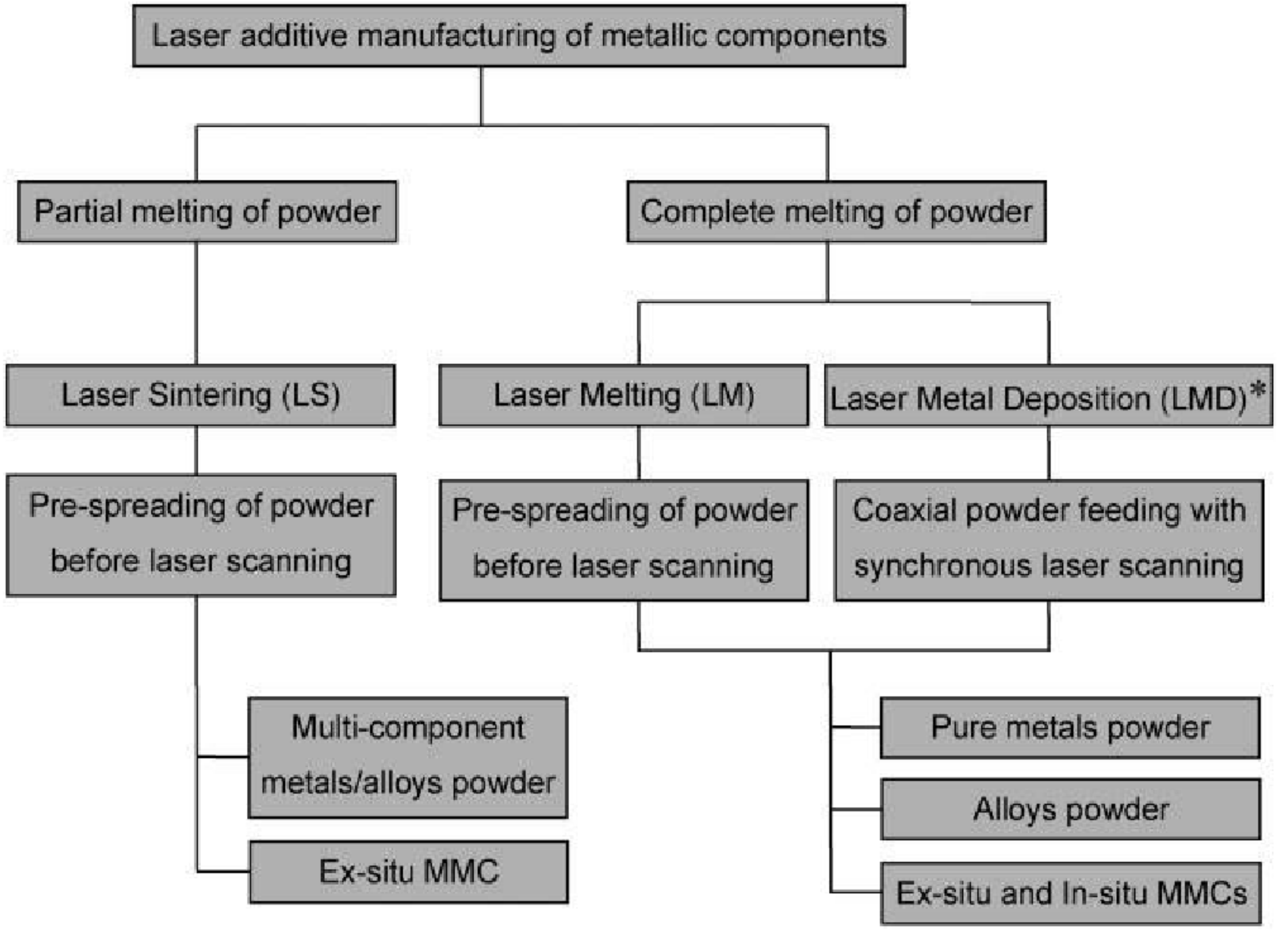


Metals: Characterized by a linear elastic region followed by a non-linear plastic region.

Polymers:

- Generally brittle at temperatures much lower than T_g, but their ductility increases as temperature rises.
- As the temperature increases to levels above T_g, a peak load is reached and a neck begins to form.
- As the specimen approaches its fracture point, the load rises due to the stretching of molecules.

Material Classification



Metals

a) Pure metals: Ti, Ta, Cu, Au, Ag
b) Alloys: Ti-based, Ni-based, Fe-based, Al-based, Co-based, Cu-based

Material/process considerations and control methods

Absorptance

Processes of AM generally involve a direct interaction of powders with laser beam. The determination of absorptance of powders is particularly important to thermal development, because it allows one to determine a suitable processing window free of a non-response of powder due to an insufficient laser energy input or a pronounced material evaporation due to an excessive energy input.

The absorptance is defined as the ratio of the absorbed radiation to the incident radiation. The absorptance of powders has a direct influence on the optical penetration depth δ of the radiation, which is defined as the depth at which the intensity of the radiation inside the material falls to 1/e (~37%) of the original value. Owing to the multiple reflection effect, the δ measured in powders is larger than in bulk materials.

Surface tension and wettability

The liquid–solid wetting characteristics are crucial for a successful AM process. The wetting behaviour of a partially melted LS system involves the wetting between structural metal and liquid binder as well as the wetting between the molten system and the solidified preprocessed layer. For the completely melted LM/LMD systems, the second kind of wetting behaviour prevails.

The wetting of a solid by a liquid is related to the surface tension of solid–liquid γ_{sl}, solid–vapour γ_{sv} and liquid–vapour γ_{lv} interfaces. Wettability can be defined by the contact angle θ

$$\cos\theta = \frac{\gamma_{sv} - \gamma_{sl}}{\gamma_{lv}}$$

The liquid wets the solid as cosθ ->1. A spreading coefficient has been defined in literature

$$S = \gamma_{sv} - \gamma_{sl} - \gamma_{lv}$$

to describe the wetting behaviour and, normally, a large positive S favours spreading of the liquid.

Viscosity

Besides the favourable wettability, it is required that the viscosity of the melt is low enough such that it successfully spreads on the previously processed layer and, in the case of LS, surrounds the solid structural particles. For a LS system consisting of a solid–liquid mixture, the viscosity of the molten material μ is expressed as

$$\mu = \mu_0 \left(1 - \frac{1-\phi_l}{\phi_m}\right)^{-2}$$

where μ_0 is the base viscosity that includes temperature terms, Φ_l is the volume fraction of liquid phase and Φ_m is a critical volume fraction of solids above which the mixture has essentially infinite viscosity. As to an LM or LMD system with a complete liquid formation, the dynamic viscosity of the liquid is defined by

$$\mu = \frac{16}{15}\left(\frac{m}{kT}\right)^{1/2} \gamma$$

where m is the atomic mass, k the Boltzmann constant, T the temperature and γ the surface tension of the liquid.

Ceramics

AM technology has been successfully demonstrated its advantages in producing ceramic parts through both “direct” and “indirect” methods.

Indirect Methods

❖ These processes typically create a ceramic green body with a high content of organic or inorganic binders.

❖ Then, binder burnout and densification of the green body are conducted in a conventional sintering step.

Example: A ZrB_2 part (fuel injector strut for aircraft engine), alumina and silica cores and shells for investment casting, graphite bipolar plates for fuel cells, and bio-ceramic bone scaffolds were fabricated using SLS by laser scanning the mixture of ceramic powder and binder and then removing the binder and sintering the parts in a furnace.

Ceramics

Direct Methods

Direct fabrication of ceramic parts using AM processes is much more challenging due to the high melting temperatures of ceramics such as Al_2O_3 (> 2000°C) and SiO_2 (> 1700°C), and also the large thermal gradients, thermal stresses and residual stresses associated with melting/resolidifying in the laser based AM processes.

Example: SLM process was investigated to fabricate ceramic parts from a mixture of zirconia and alumina by completely melting the ceramic powder. The ceramic powder bed was preheated to a temperature higher than 1600°C to reduce thermal stresses, and nearly fully dense, crack-free parts were obtained without any post-processing. Fully dense, net-shaped, alumina parts were produced using LENS by direct laser melting of the ceramic powder.

Composites

- Composites are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties that remain separate and distinct at the macroscopic or microscopic scale within the finished structure but exhibit properties that cannot be achieved by any of the materials acting alone.

- The materials in a composite can be mixed uniformly, resulting in a homogeneous compound (uniform composite), or non-uniformly, resulting in an inhomogeneous compound (e.g., functionally graded materials) in which the composition varies gradually over volume, leading to corresponding changes in the properties of the composite material.

Composites

Uniform Composites

- Uniform composites fabricated using AM processes are usually done by employing a pre-prepared mixture of proper materials, such as a mixed powder bed for SLS, SLM and 3DP, a filament in mixed materials for FDM, a composite laminate for LOM, or a mixture of liquid photocurable resin with particulates for SLA.

- The composite materials that can be produced with AM technology include a polymer matrix, ceramic matrix, metal matrix, and fiber and particulate reinforced composites.

- Metal-metal composites (e.g., Fe-Cu and stainless steelCu), metal-ceramic composites (e.g., WC-Cu, WC-Co, WC-CuFeCo, TiC-Ni/Co/Mo, ZeB2-Cu, and TiB2-Ni), and ceramic-ceramic composites (e.g., Si-SiC) have been processed by SLS/SLM.

- These processed composites can be classified into two categories: those that aim to facilitate the process using a liquid-phase sintering mechanism, and those that combine various materials to achieve properties not possible with a single material.

Composites

Uniform Composites

- Examples of composites in the first category include Fe-Cu and stainless steel-Cu used in SLS, in which Cu acts as a binder to bond Fe or stainless steel particles rather than a reinforcement phase to enhance the mechanical or other properties of the final product.

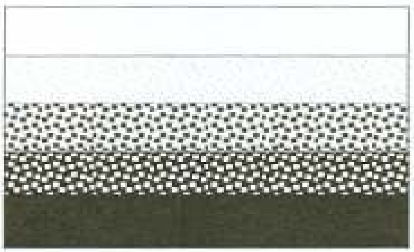
- An example of the second category is the bio-composite poly-epsilon-caprolactone and hydroxyapatite (PCL/HA) bone scaffold fabricated using SLS, with the addition of HA to enhance the strength and biocompatibility of PCL.

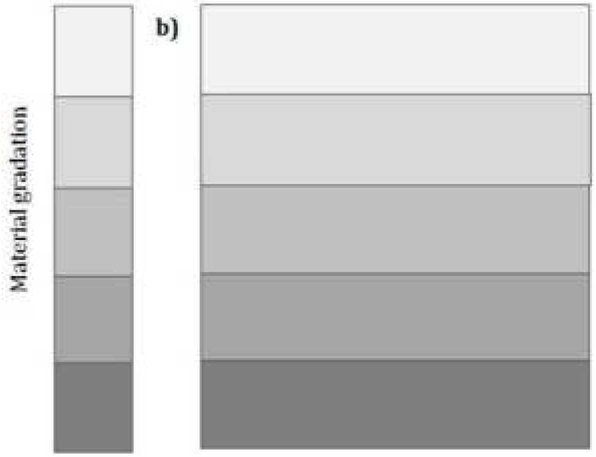
- By developing a feedstock filament with the proper composite, polymer-metal and polymer-ceramic composites could be produced with FDM. ABS-Iron composites have been made using FDM with a single-screw extruder by appropriately producing an iron particulate-filled polymeric filament. Fibers, such as short glass fibers and nanofibers (vapor-grown carbon fibers), have been added into ABS filaments to improve the mechanical properties of the parts built using FDM.

Composites: Functionally Graded Materials

Stepwise Graded Structures

An example is a spark plug which gradient is formed by changing its composition from a refractory ceramic to a metal

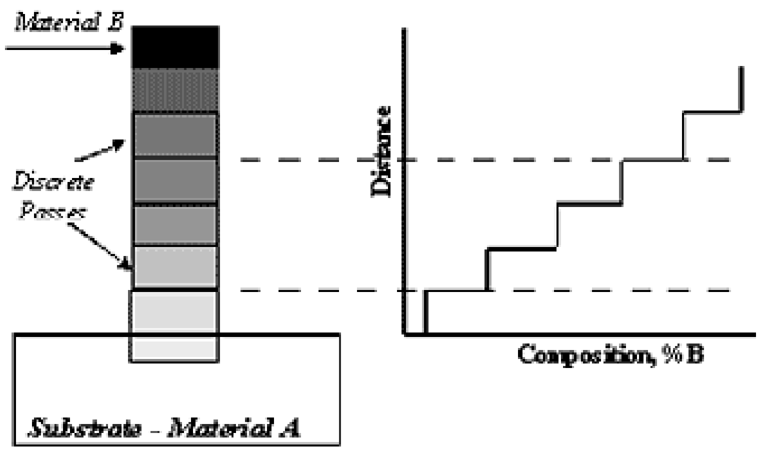


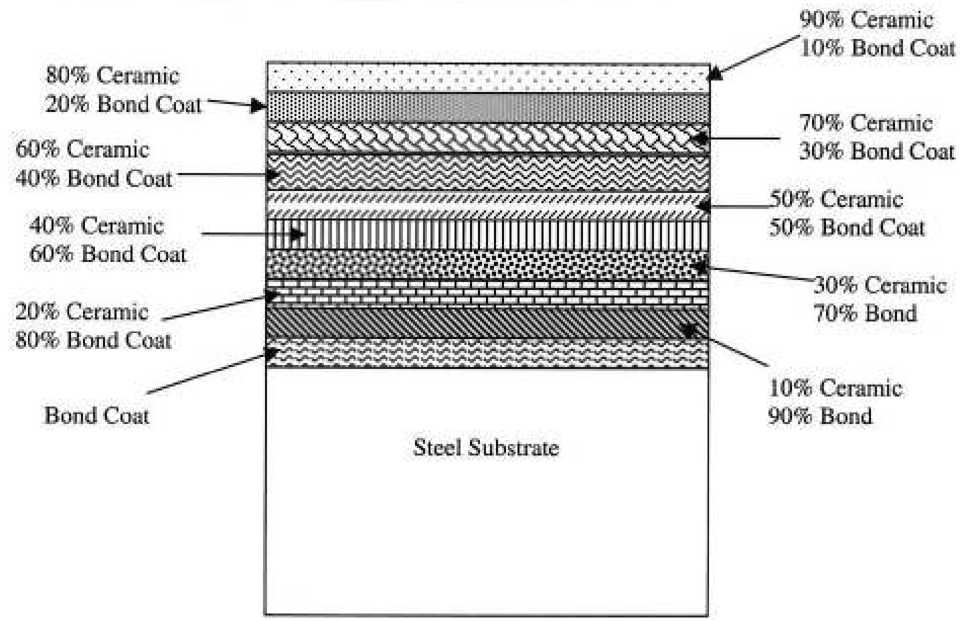


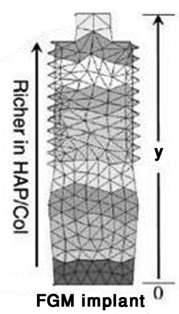
Continuous Graded Structures

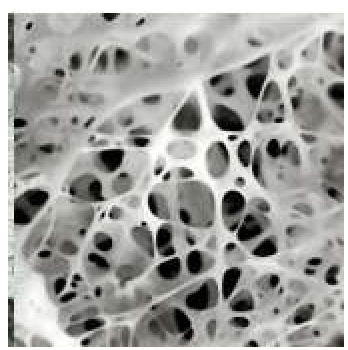
- An example is the human bone which gradient is formed by its change in porosity and composition;
- Change in porosity happens across the bone because of miniature blood vessels inside the bone.

Functionally Graded Materials (FGMs)







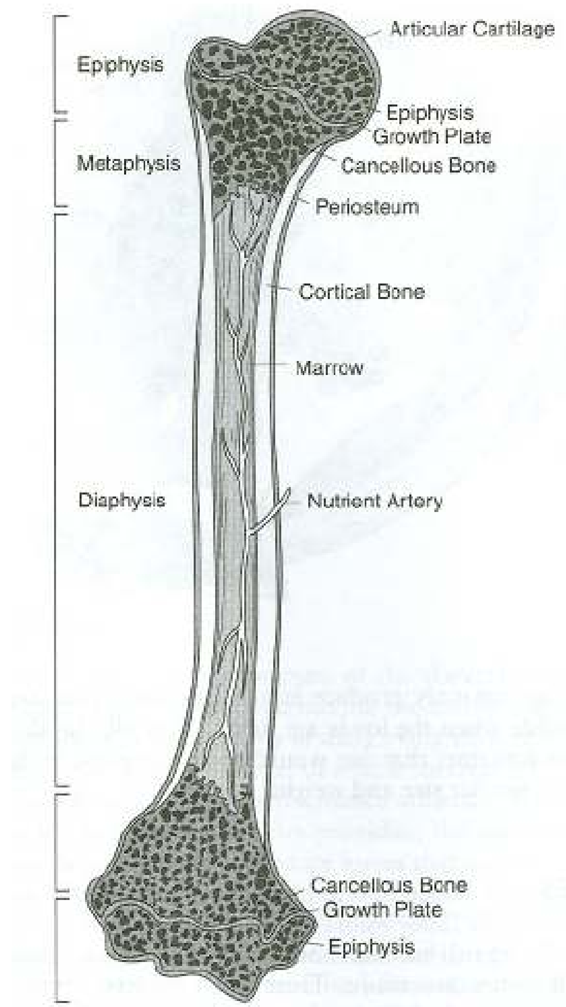


FGMs can be obtained by layered mixing of two materials of different thermo-mechanical properties with different volume ratio by gradual changing from layer to layer.

Composites: Functionally Graded Materials

The human bone is a an example of a FGM. It is a mix of collagen (ductile protein polymer) and hydroxyapatite (brittle calcium phospate ceramic).

A gradual increase in the pore distribution from the interior to the surface can pass on properties such as shock resistance, thermal insulation, catalytic efficiency, and the relaxation of the thermal stress. The distribution of the porosity affects the tensile strength and the Young's modulus.



Composites: Functionally Graded Materials

Current applications of FGMs include:

- Structural walls that combine two or more functions including thermal and sound insulation;

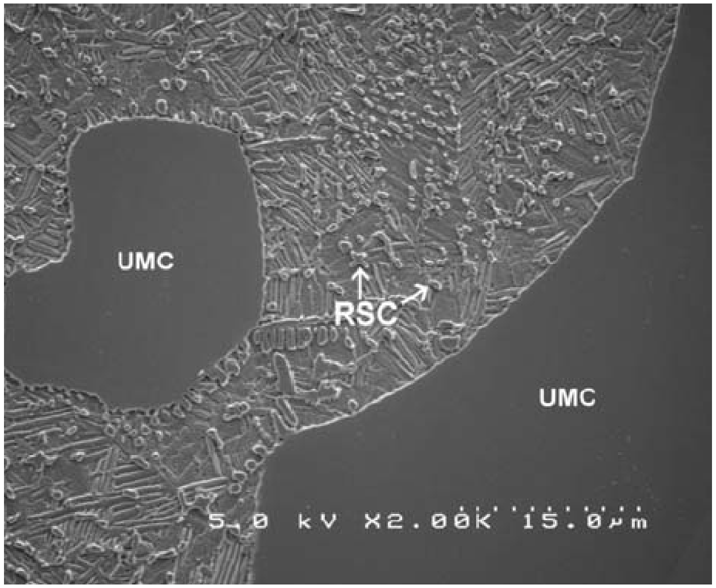
- Enhanced sports equipment such as golf clubs, tennis rackets, and skis with added graded combinations of flexibility, elasticity, or rigidity;

- Enhanced body coatings for cars including graded coatings with particles such as dioxide/mica.

AM Unique Capabilities

- Shape complexity: it is possible to build virtually any shape
- Hierarchical complexity: features can be designed with shape complexity across multiple size scales

Various types of nano/microstructures can be achieved by careful control of the process parameters (e.g. laser power, scan rate) for a particular material, and can vary from point to point within a structure.



The ability to simultaneously control a part's nano/microstructure, mesostructure, and macrostructure simply by changing process parameters and CAD data is a capablity of AM which is unparalleled using conventional manufacturing.

AM Unique Capabilities

- Functional complexity: functional devices (not just individual piece-parts) can be produced in one build
- Material complexity: material can be processed one point, or one layer, at a time as a single material or as a combination of materials

- When building parts in an additive manner, one always has access to the inside of the part.
- Component can be inserted and it is possible to fabricate operational mechanisms in some AM processes.

Pulley-driven snake-like robot
Source: Gibson.

AM Unique Capabilities

The concept of functionally graded materials, or heterogeneous materials, has received considerable attention.

However, manufacturing useful parts from these materials often has been problematic.

Example: Turbine blade for a jet engine

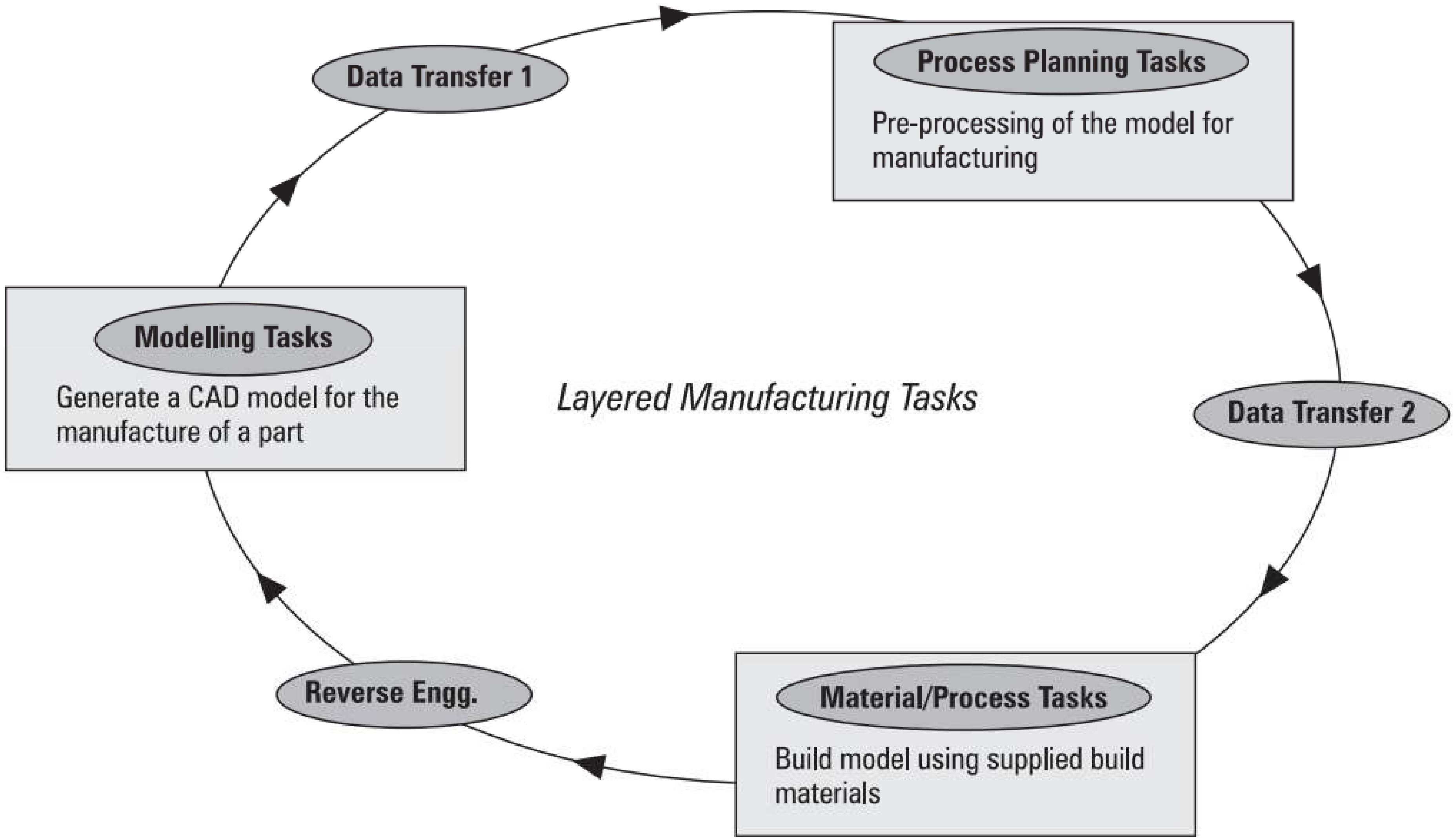
I. The outside of the blade must be resistant to high temperature and very stiff to prevent elongation;
II. The blade root must be ductile and has high fatigue life;
III. Blade interiors must have high heat conductivity so that the blades can be cooled.

A part with complex shape that requires different material properties in different regions.

No single material is ideal for this range of properties.

A significant issue hindering the adoption of AM's material complexity is the lack of design and CAD tools that enable representation and reasoning with multiple materials.

Process Planning in Layered Manufacturing



Process Planning in Layered Manufacturing

There are four main planning tasks:

(i) orientation optimization,

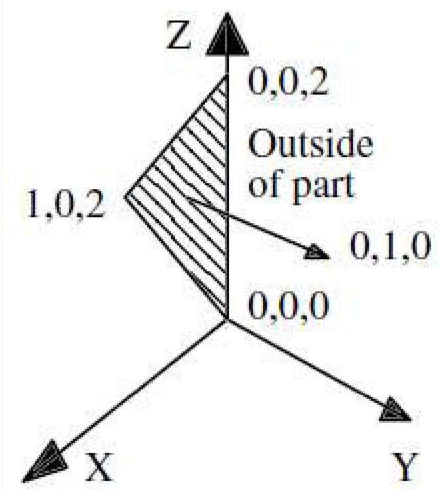
(ii) support design,

(iii) slicing, and

(iv) tool-path/scanning-path planning.

Sample STL File

```
solid print
 facet normal 0.00000e+00  1.00000e+00  0.00000e+00
  outer loop
   vertex  0.00000e+00  0.00000e+00  2.00000e+01
   vertex  0.00000e+00  0.00000e+00  0.00000e+00
   vertex  1.00000e+01  0.00000e+00  2.00000e+01
  endloop
 endfacet
 facet normal 0.00000e+00  1.00000e+00  0.00000e+00
  outer loop
   vertex  1.00000e+01  0.00000e+00  2.00000e+01
   vertex  0.00000e+00  0.00000e+00  0.00000e+00
   vertex  1.00000e+01  0.00000e+00  0.00000e+00
  endloop
 endfacet
.......
```



Advantages and Disadvantages?

STL File

Advantages

(i) Provides a simple method of representing 3D CAD data

(ii) A *de facto* standard and has been used by most CAD systems and RP systems

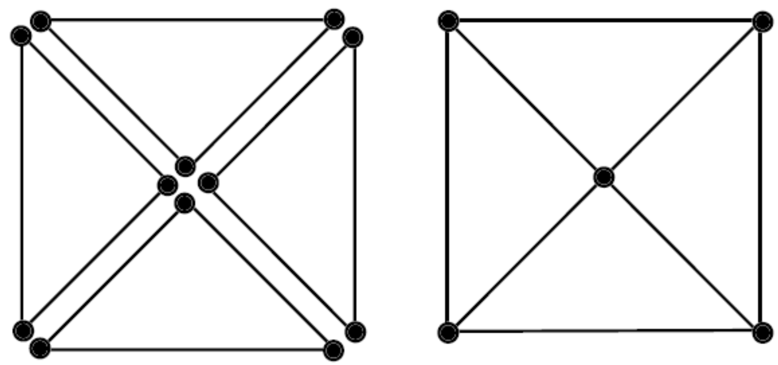
(iii) It can provide small and accurate files for data transfer for certain shapes

Disadvantages

(i) The STL file is many times larger than the original CAD data file

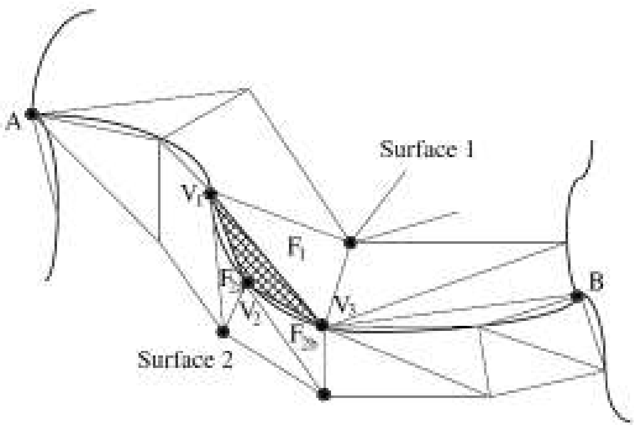
(ii) The geometry flaws exist in the STL file

(iii) The subsequent slicing of large STL files can take many hours



STL File Problems

(1) Gaps (cracks, holes, punctures) that is, missing facets.
(2) Degenerate facets (where all its edges are collinear).
(3) Overlapping facets.
(4) Non-manifold topology conditions.



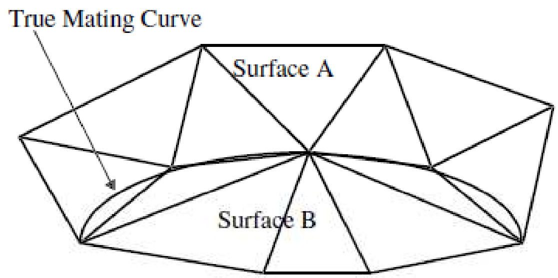


Figure 6.4(a): Shell punctures created by unequal tessellation of two adjacent surface patches along their common mating curve

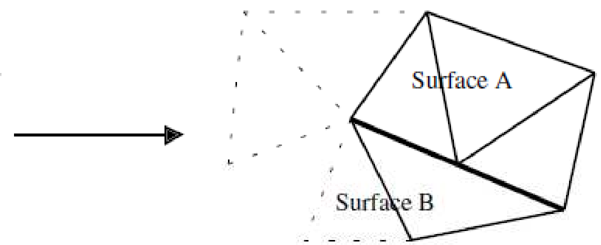
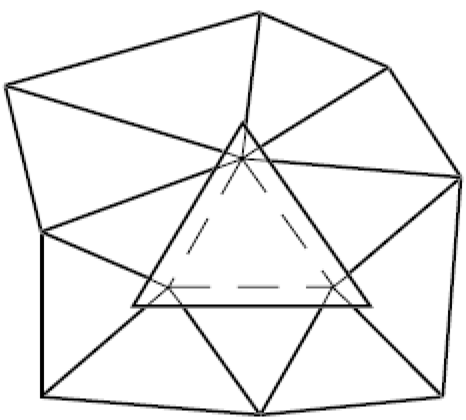
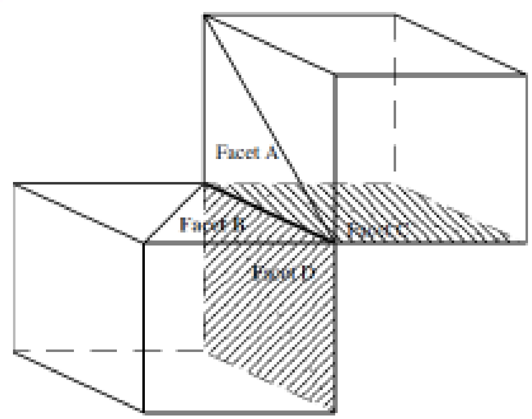


Figure 6.4(b): Shell punctures eliminated at the expense of adding degenerate facet





Valid vs. Invalid Tessellated Models

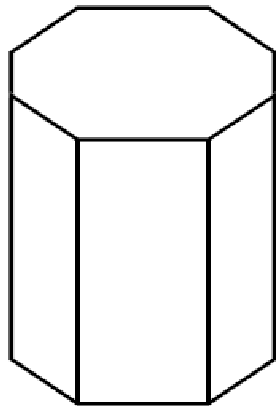


Figure 6.7(a): A valid 3D model

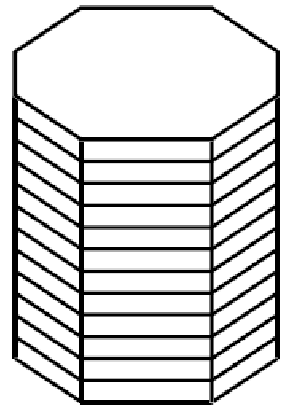


Figure 6.7(b): A 3D model sliced into 2D planar layers

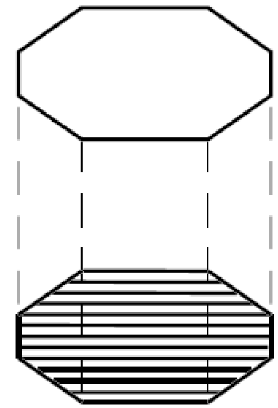


Figure 6.7(c): Conversion of 2D layers into 1D scan lines

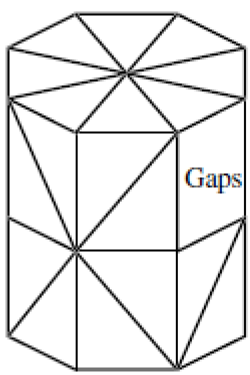


Figure 6.8(a): An invalid tessellated model

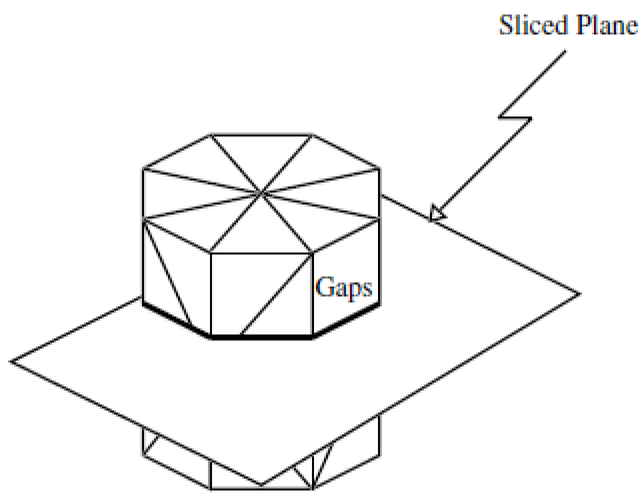


Figure 6.8(b): An invalid model being sliced

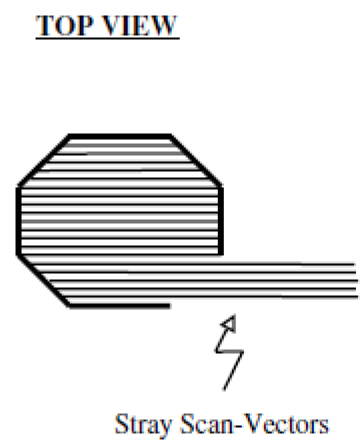
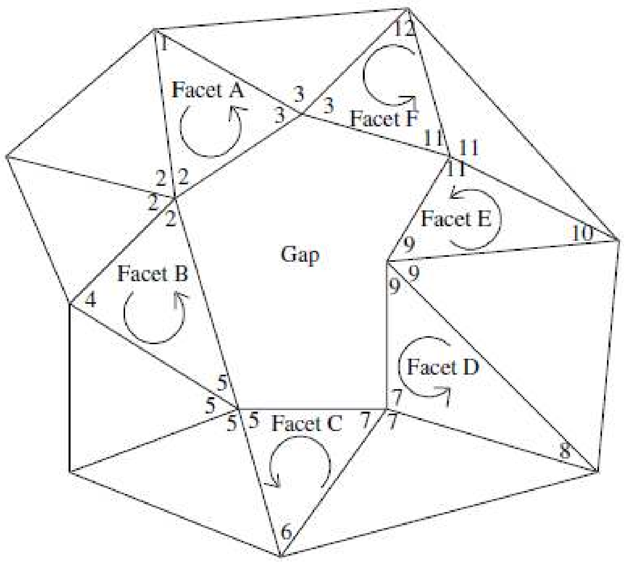
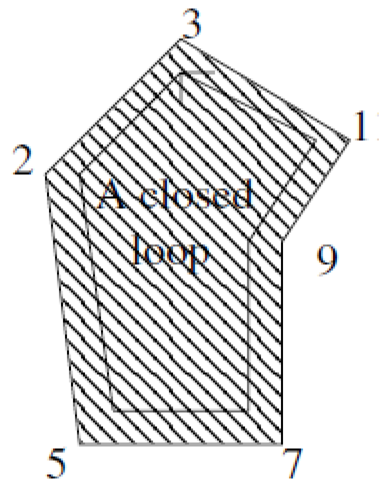


Figure 6.8(c): A layer of an invalid model being scanned

STL File Repair





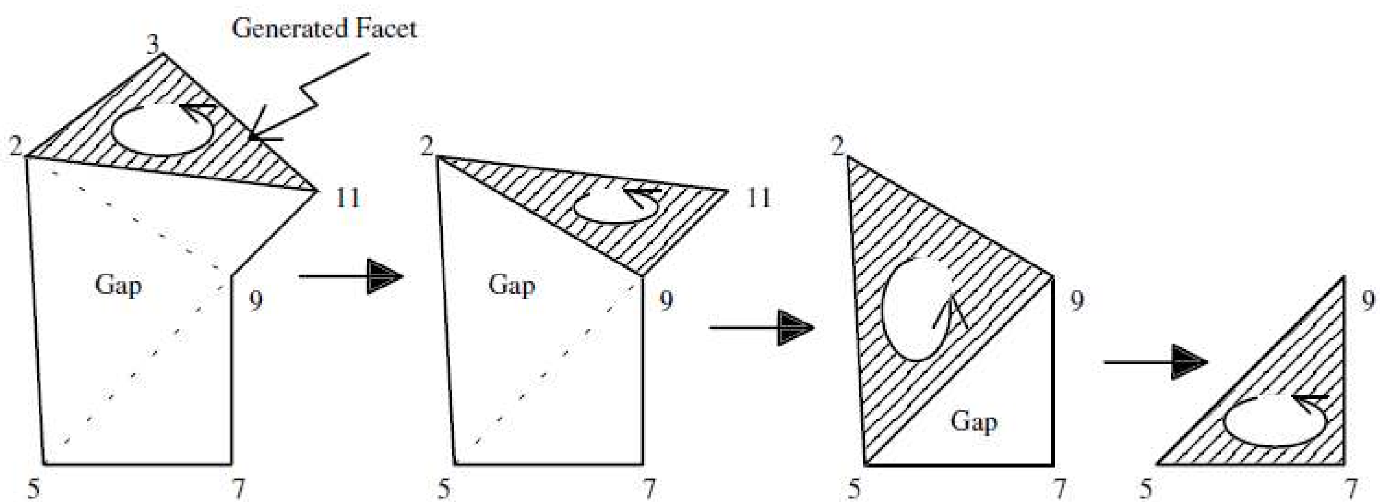
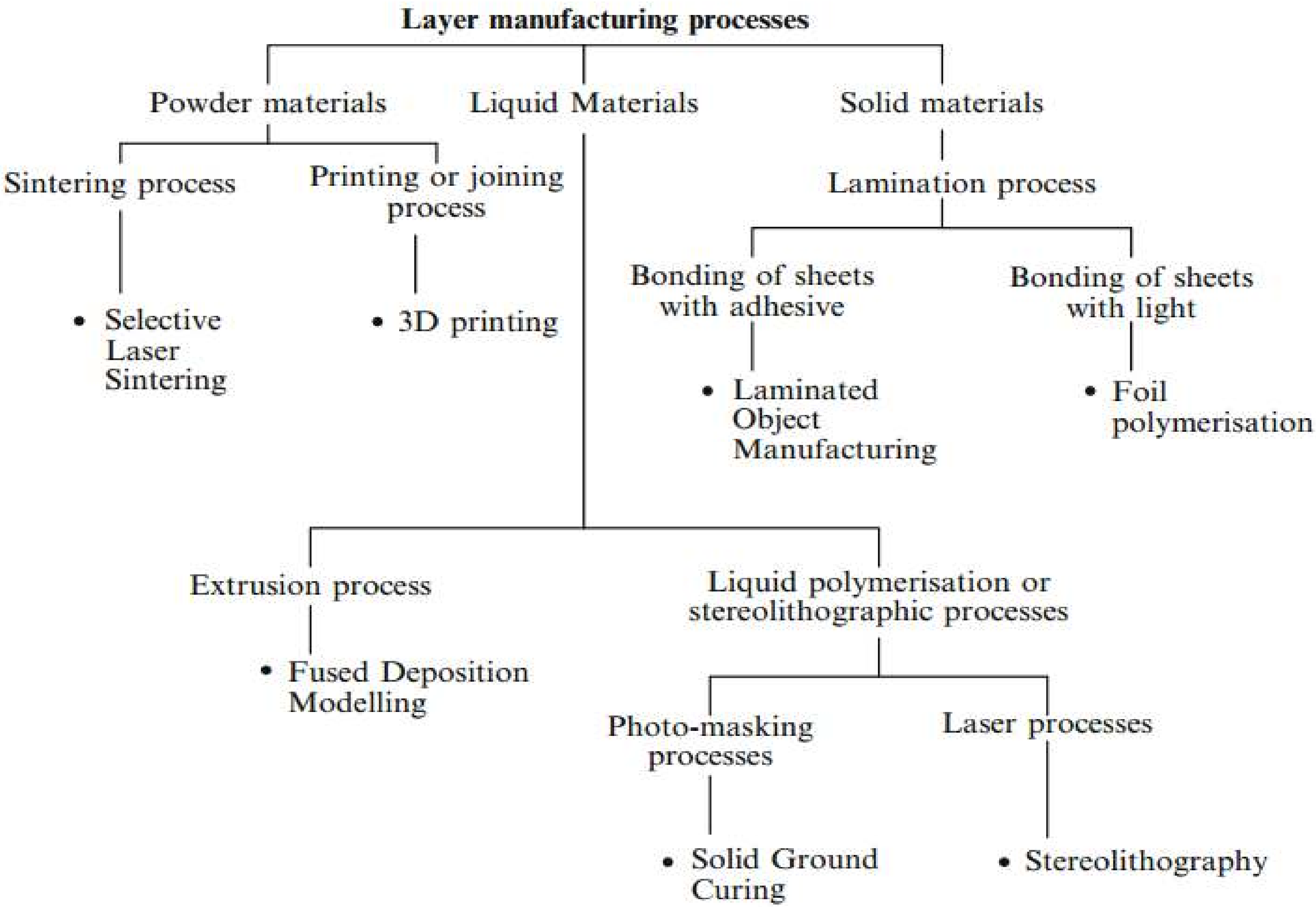


Figure 6.12(a): First facet generated

Figure 6.12(b): Second facet generated

Figure 6.12(c): Third facet generated

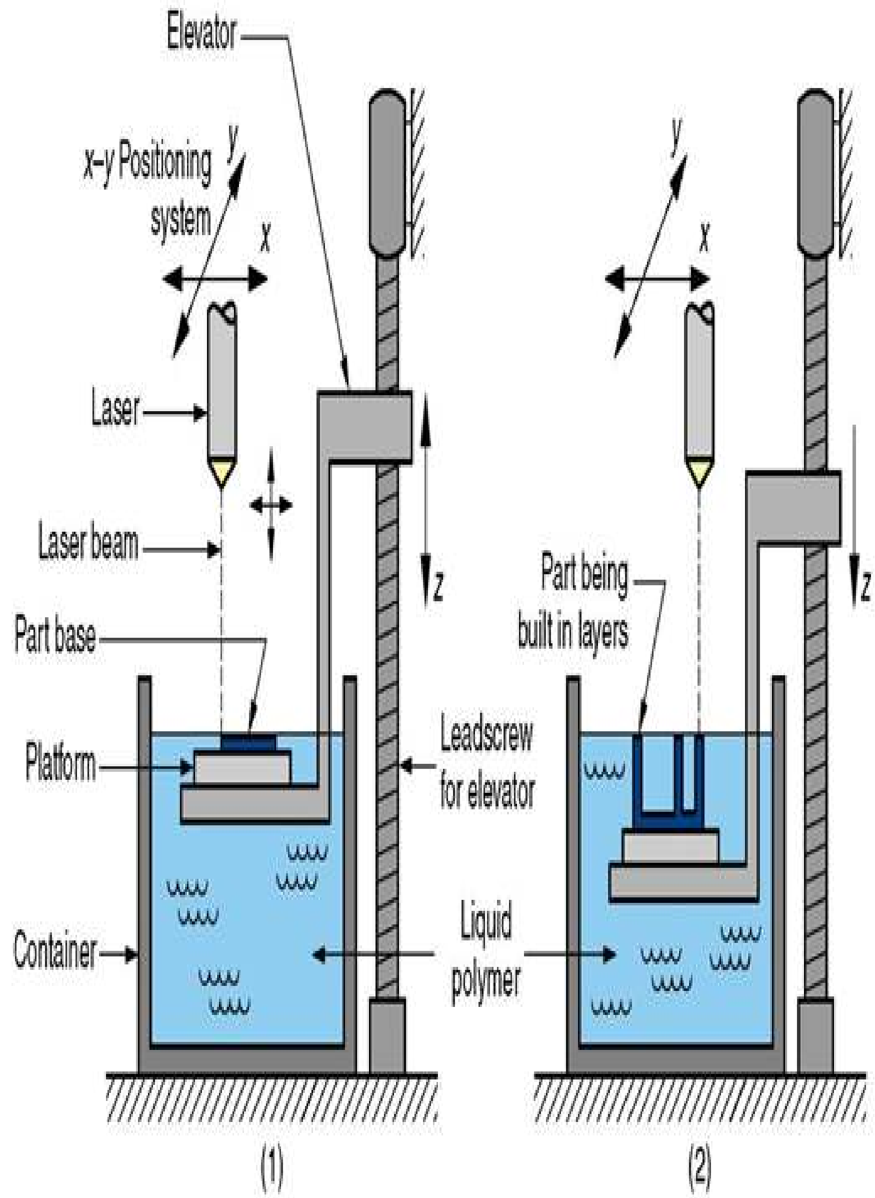
Figure 6.12(d): Fourth facet generated


Layer manufacturing processes
Powder materials
Liquid Materials
Solid materials
Sintering process
Printing or joining process
Lamination process
• Selective Laser Sintering
• 3D printing
Bonding of sheets with adhesive
Bonding of sheets with light
• Laminated Object Manufacturing
• Foil polymerisation
Extrusion process
Liquid polymerisation or stereolithographic processes
• Fused Deposition Modelling
Photo-masking processes
Laser processes
• Solid Ground Curing
• Stereolithography

Stereolithography

- One of the most important additive manufacturing technologies currently available.
- The first ever commercial RP systems were resin-based systems commonly called stereolithography or SLA.
- The resin is a liquid photosensitive polymer that cures or hardens when exposed to ultraviolet radiation.
- This technique involves the curing or solidification of a liquid photosensitive polymer through the use of the irradiation light source.
- The source supplies the energy that is needed to induce a chemical reaction (curing reaction), bonding large no of small molecules and forming a highly cross-linked polymer.

- The UV light comes from a laser, which is controlled to scan across the surface according to the cross-section of the part that corresponds to the layer.
- The laser penetrates into the resin for a short distance that corresponds to the layer thickness.
- The first layer is bonded to a platform, which is placed just below the surface of the resin container.
- The platform lowers by one layer thickness and the scanning is performed for the next layer. This process continues until the part has been completed.



A part produced by stereolithography (Source: 3D Systems, Inc.).

Facts About STL

- Each layer is 0.076 mm to 0.50 mm (0.003 in to 0.020 in.) thick
  - Thinner layers provide better resolution and more intricate shapes; but processing time is longer
- Starting materials are liquid monomers
- Polymerization occurs on exposure to UV light produced by laser scanning beam
  - Scanning speeds ~ 500 to 2500 mm/s

Part Build Time in STL

Time to complete a single layer :

$$T_i = \frac{A_i}{vD} + T_d$$

where T_i = time to complete layer i; A_i = area of layer i; v = average scanning speed of the laser beam at the surface; D = diameter of the "spot size," assumed circular; and T_d = delay time between layers to reposition the worktable

Part Build Time in STL - continued

Once the T_i values have been determined for all layers, then the build cycle time is:

$$T_c = \sum_{i=1}^{n_l} T_i$$

where T_c = STL build cycle time; and n_l = number of layers used to approximate the part

- Time to build a part ranges from one hour for small parts of simple geometry up to several dozen hours for complex parts

Numerical Problem

A prototype of a tube with a square cross-section is to be fabricated using stereolithography. The outside dimension of the square = 100 mm and the inside dimension = 90 mm (wall thickness = 5 mm except at corners). The height of the tube (z-direction) = 80 mm. Layer thickness = 0.10 mm. The diameter of the laser beam ("spot size") = 0.25 mm, and the beam is moved across the surface of the photopolymer at a velocity of 500 mm/s. Compute an estimate for the time required to build the part, if 10 s are lost each layer to lower the height of the platform that holds the part. Neglect the time for postcuring.

Numerical Problem: Solution

Layer area A_i is same for all layers.

$A_i = 100^2 - 90^2 = 1900\ mm^2$.

Time to complete one layer T_i is same for all layers.

$T_i = (1900\ mm^2)/(0.25\ mm)(500 mm/s) + 10\ s = 25.2\ s$

Number of layers

$n_l = (80\ mm)/(0.10\ mm/layer) = 800$ layers

$T_c = 800(25.2) = 20{,}160\ s = 336.0\ min = 5.6\ hr$