Additive Manufacturing

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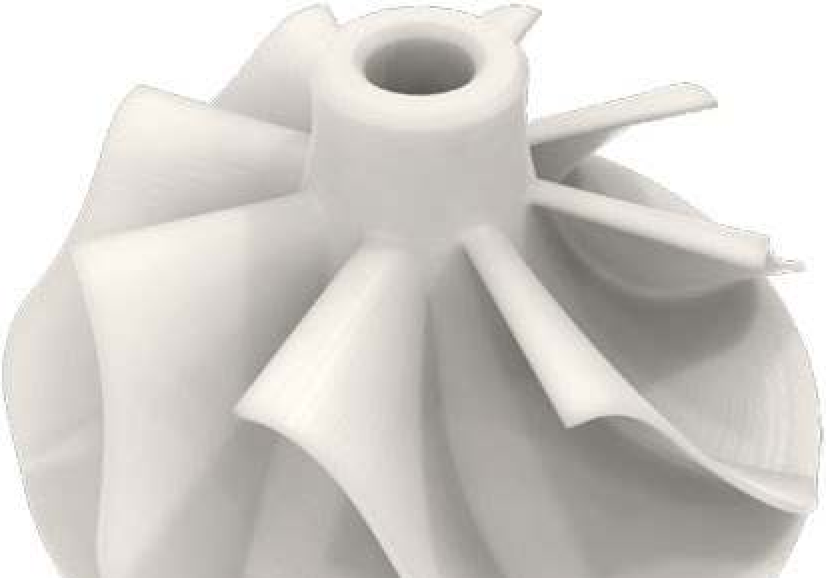
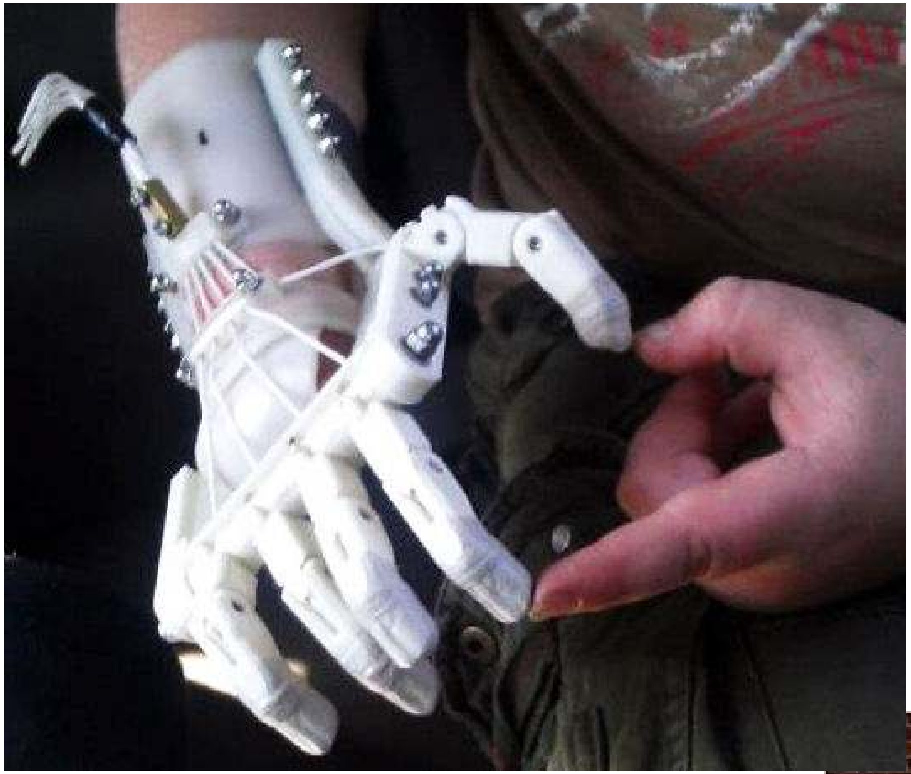




Definition

Additive Manufacturing (AM) refers to a process by which digital 3D design data is used to build up a component in layers by depositing material.

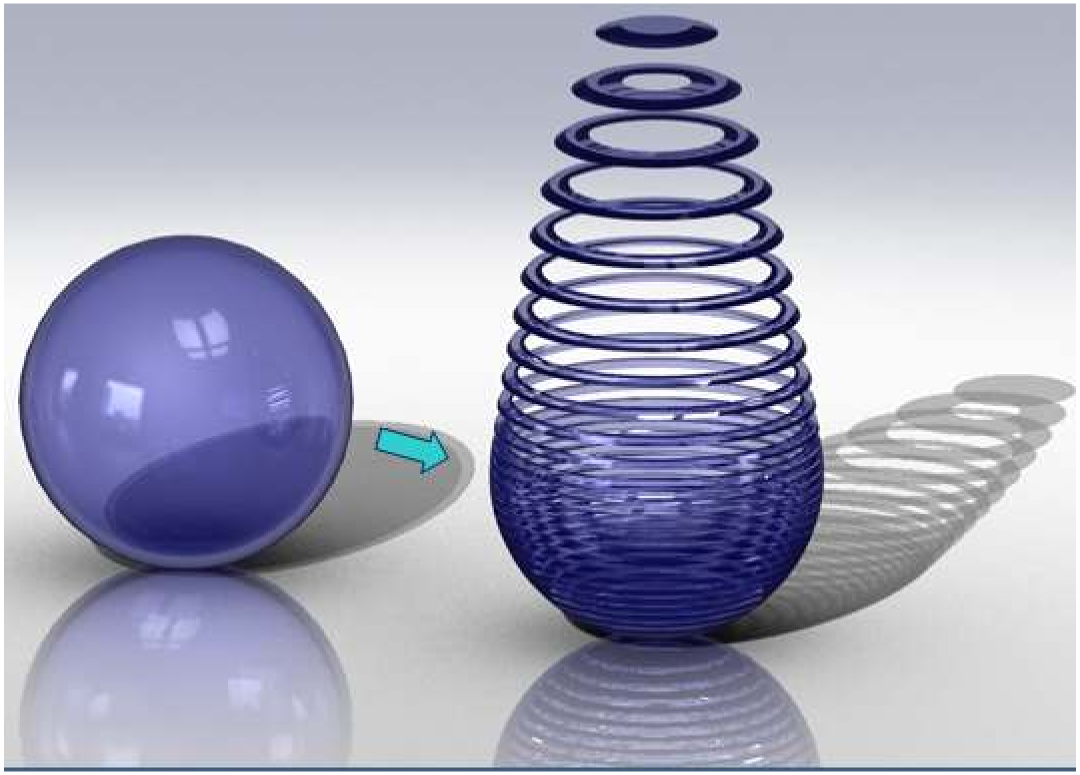
(from the International Committee F42 for Additive Manufacturing Technologies, ASTM)..

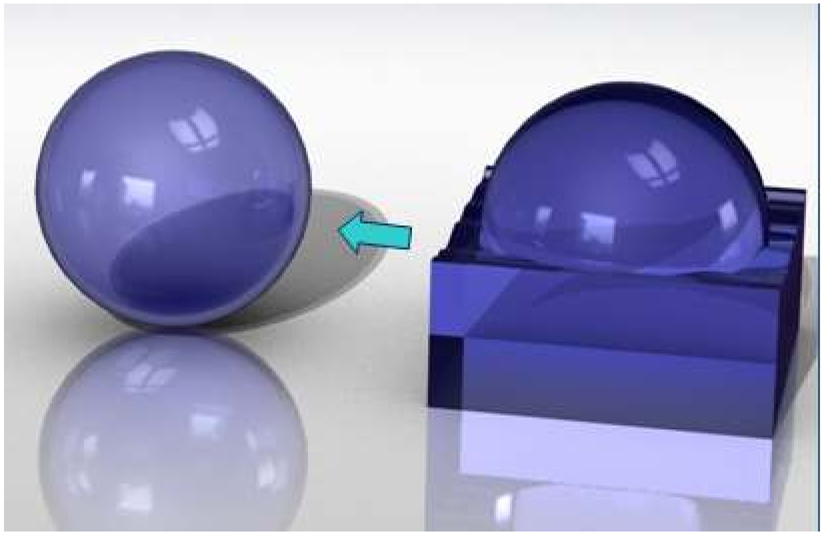
What You See Is What You Build (WYSIWYB) Process

Difference between Rapid Prototyping and Additive Manufacturing?

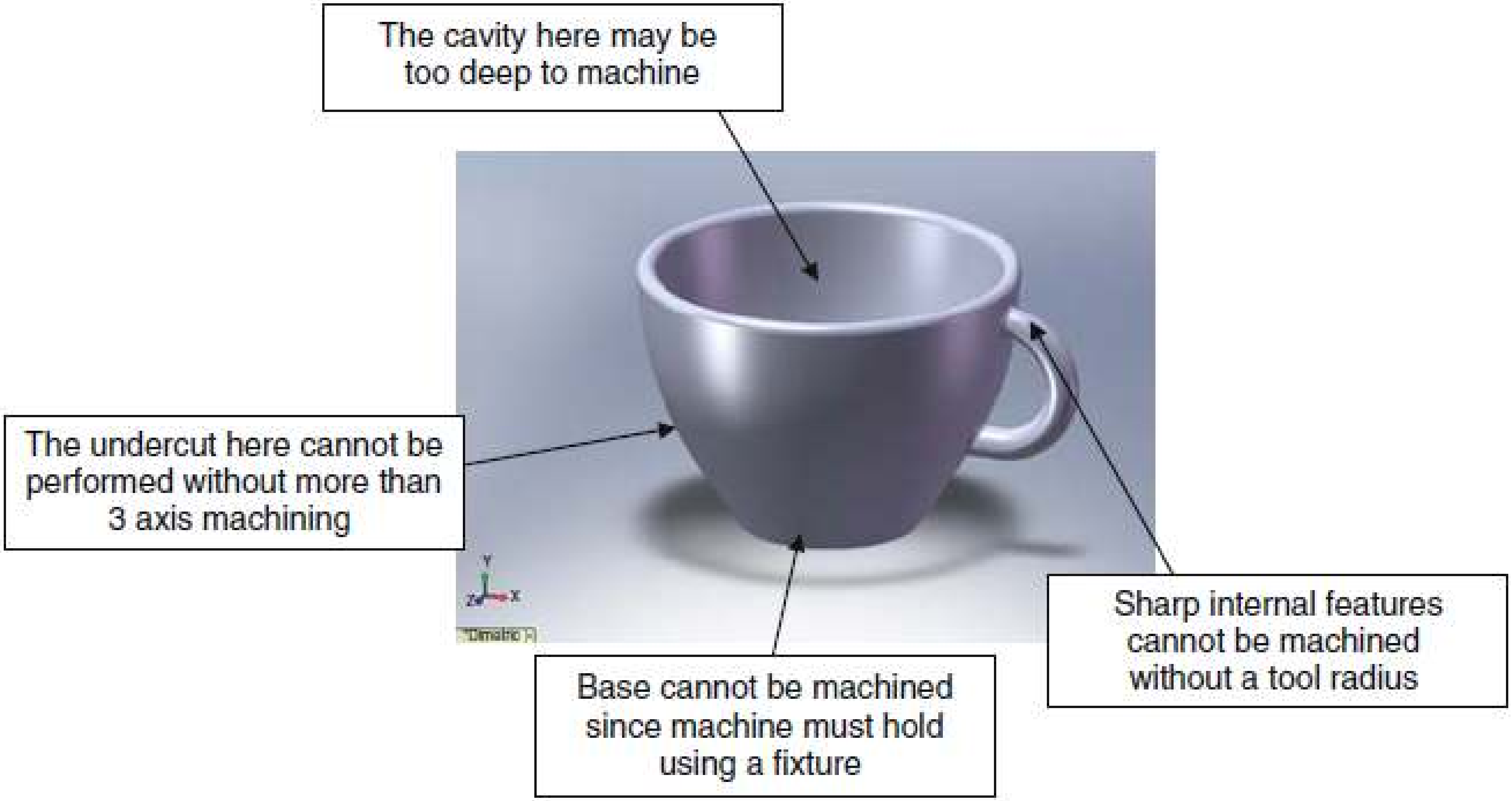
Additive vs Subtractive Manufacturing

- Part Complexity;
- Material;
- Speed;
- Part Quantity;
- Cost.





Additive vs Subtractive Manufacturing



The cavity here may be too deep to machine

The undercut here cannot be performed without more than 3 axis machining

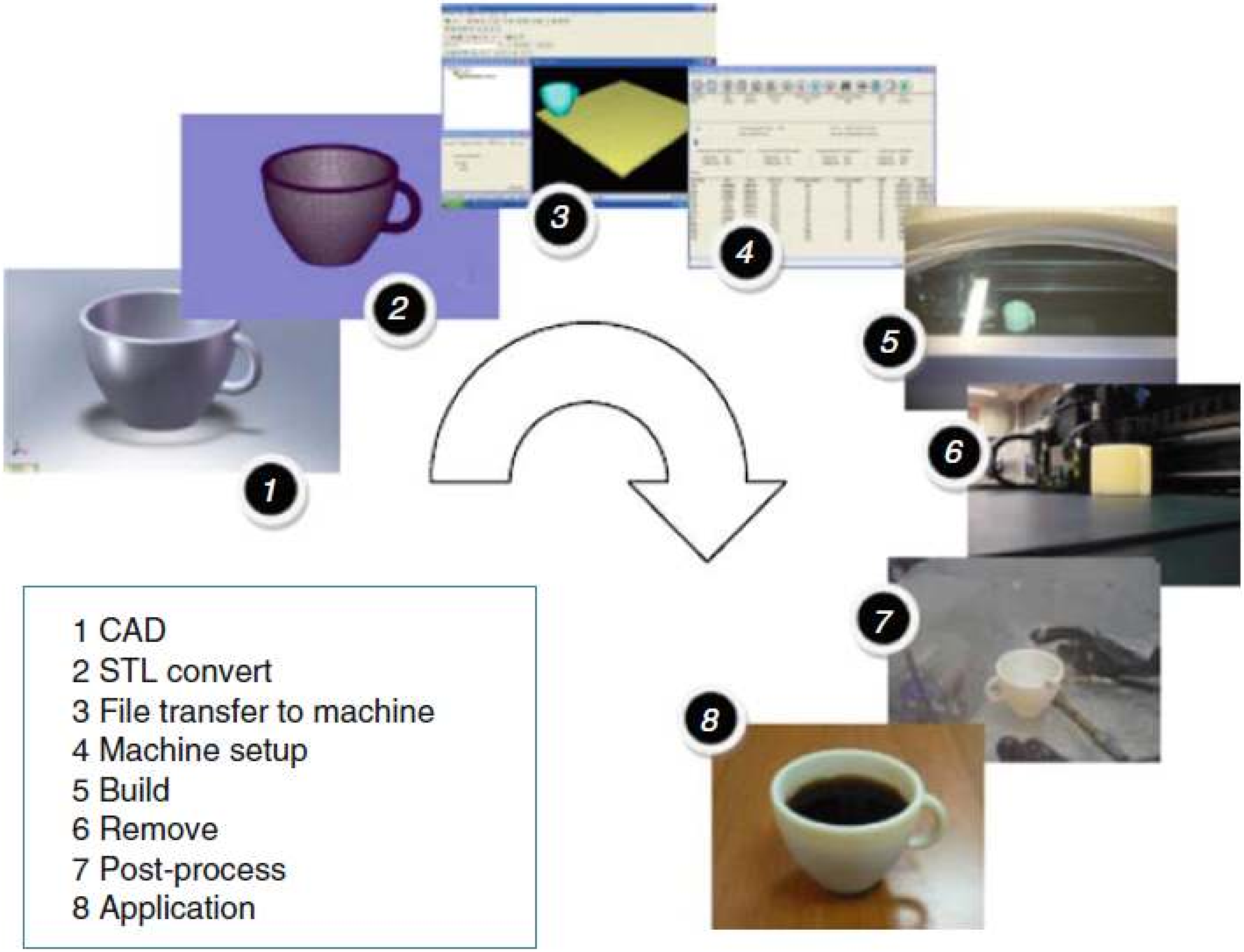
Base cannot be machined since machine must hold using a fixture

Sharp internal features cannot be machined without a tool radius

Figure: Features that represent problems using CNC machining.

Source: Gibson, Additive Manufacturing

Generic AM Process



1 CAD
2 STL convert
3 File transfer to machine
4 Machine setup
5 Build
6 Remove
7 Post-process
8 Application

Source: Gibson, Additive Manufacturing

CAD Model into STL Format

STL uses triangles to describe the surfaces to be built. Each triangle is described as three points and a facet normal vector indicating the outward side of the triangle, in a manner similar to the following:

```
facet normal 4.470293E02 7.003503E01 7.123981E-01
outer loop
vertex 2.812284E+00 2.298693E+01 0.000000E+00
vertex 2.812284E+00 2.296699E+01 1.960784E02
vertex 3.124760E+00 2.296699E+01 0.000000E+00
endloop
endfacet
```

Source: Gibson, Additive Manufacturing

Generic AM Process

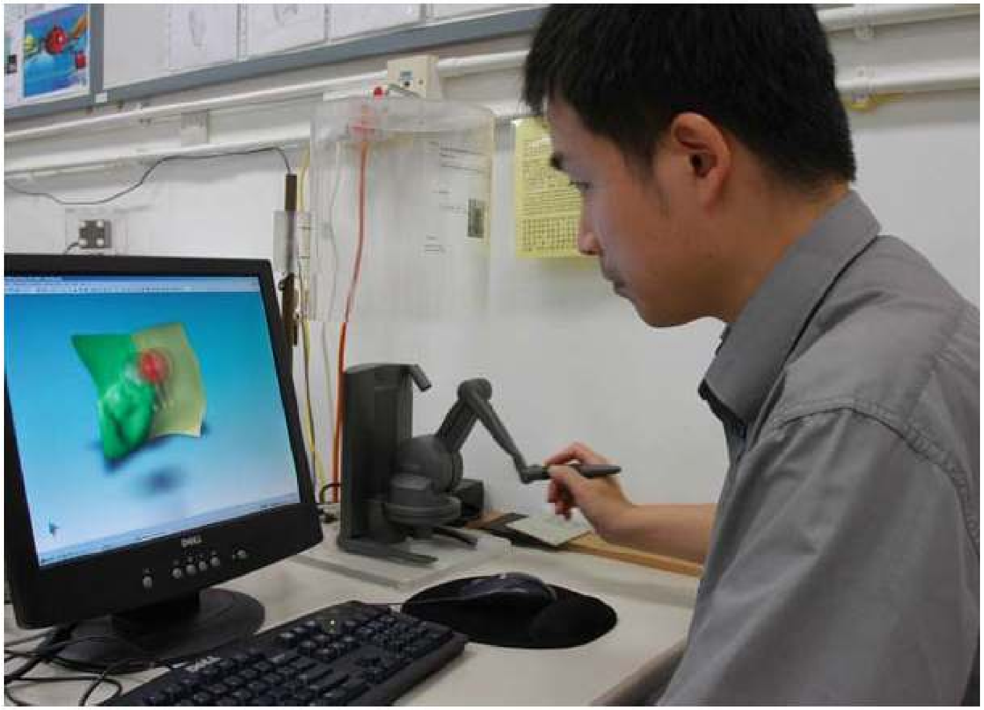
Effects of building using different layer thicknesses

Source: Gibson, Additive Manufacturing

Other Related Technologies

1. Reverse engineering technology
2. Computer aided engineering (CAE):

   3D CAD model + Engineering analysis software packages
3. Haptic-based CAD

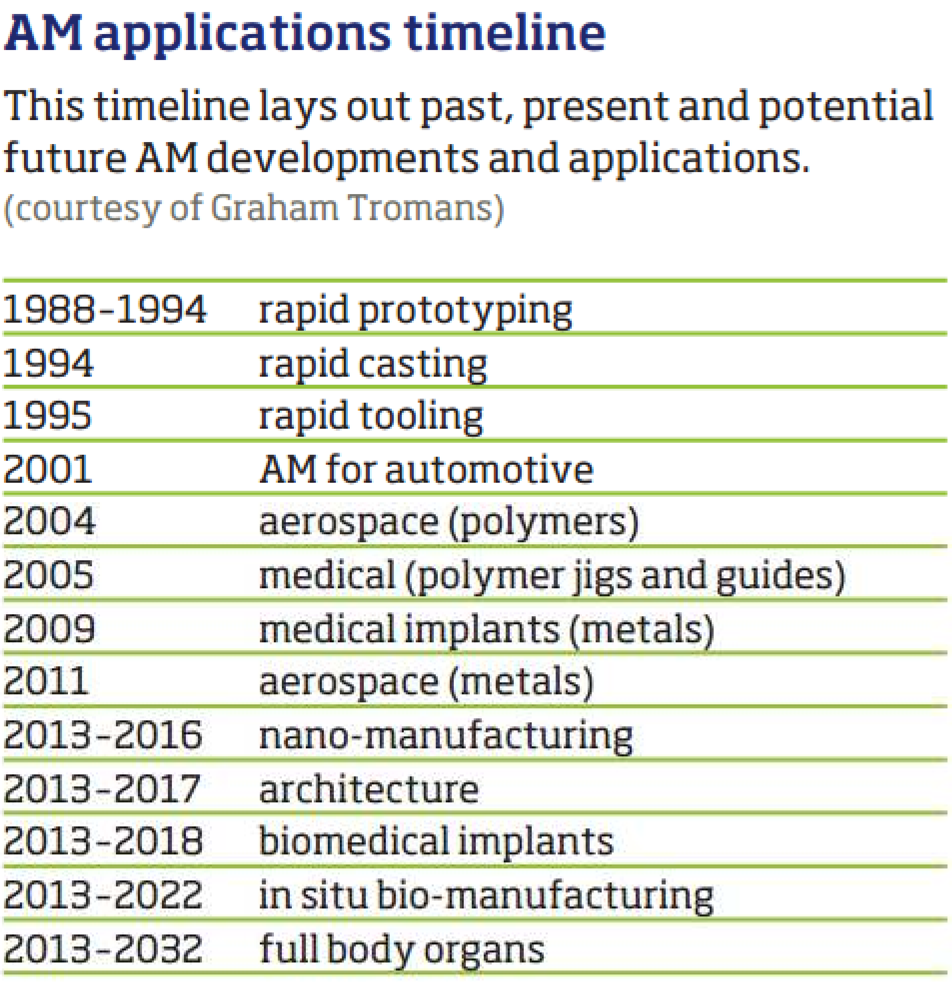


Source: Gibson, Additive Manufacturing

Difference between various AM techniques?

- ✓ Techniques used for creating layers;
- ✓ Techniques of bonding the layers together;
- ✓ Speed;
- ✓ Layer thickness;
- ✓ Range of materials;
- ✓ Accuracy;
- ✓ Cost.

Evolution



AM applications timeline

This timeline lays out past, present and potential future AM developments and applications.
(courtesy of Graham Tromans)

1988-1994	rapid prototyping
1994	rapid casting
1995	rapid tooling
2001	AM for automotive
2004	aerospace (polymers)
2005	medical (polymer jigs and guides)
2009	medical implants (metals)
2011	aerospace (metals)
2013-2016	nano-manufacturing
2013-2017	architecture
2013-2018	biomedical implants
2013-2022	in situ bio-manufacturing
2013-2032	full body organs

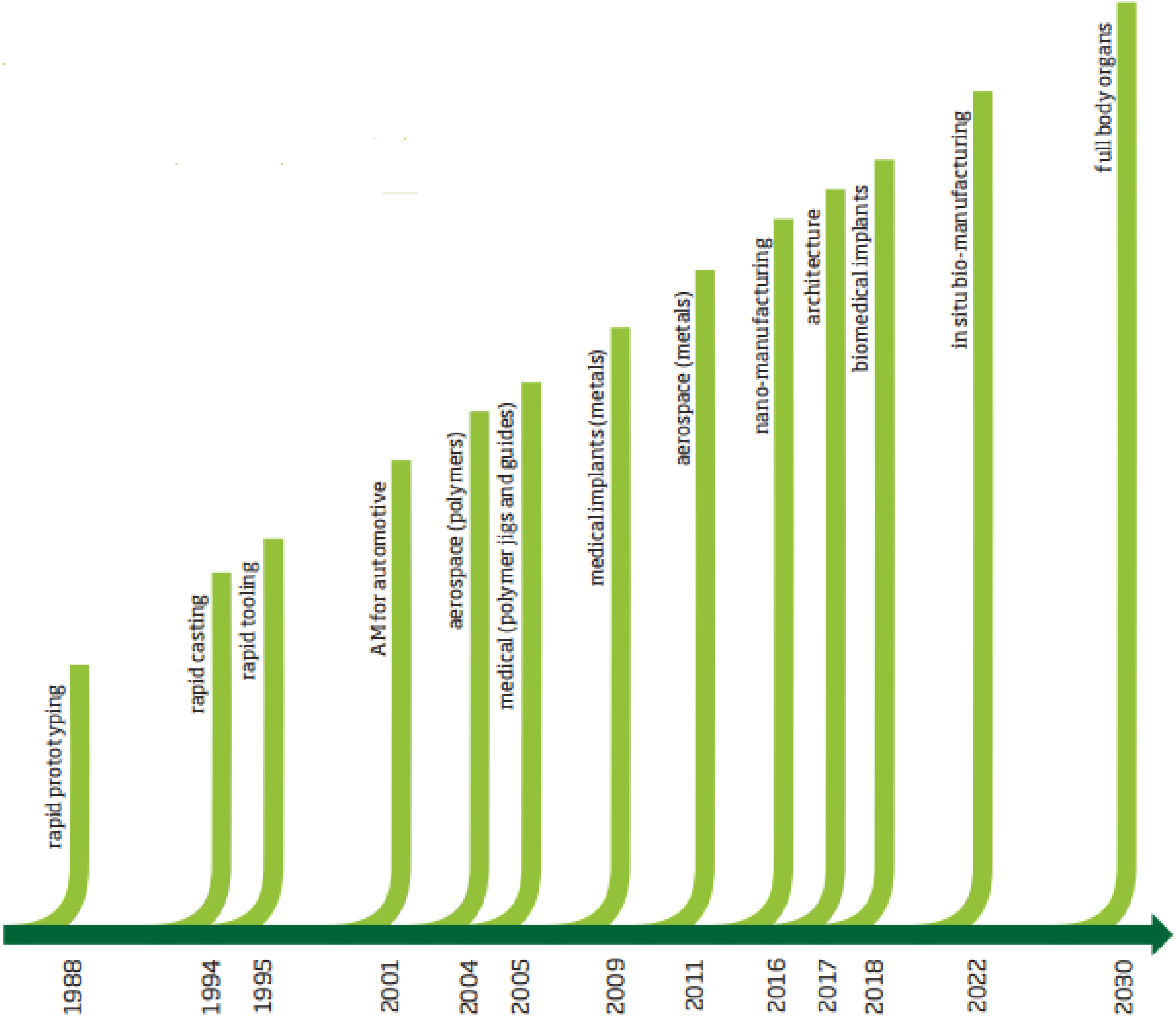
CASE STUDY

GE AND MORRIS TECHNOLOGY
Graham Tromans

The automotive and aerospace industries are two of the main beneficiaries of AM. In 2012, GE Aviation bought AM Morris Technologies, one of the biggest metal additive manufacturers in the world. GE is ramping up AM manufacturing of aero engine fuel nozzles. The conventional method of making fuel nozzles requires making 20 separate parts and welding them together, "which is extremely labour-intensive and has a high scrap rate," said Graham Tromans, Principal and President of AM consultancy GP Tromans Associates. AM allows the creation of pre-assembled nozzles. GE predicts that, by late 2015/16, it will make 10-20 fuel nozzles for each engine using AM, or 25,000 a year. The company also envisages that 50% of a jet engine will be additive manufactured within current lifetimes.

Source: Royal Academy of Engineering

Evolution



Source: Royal Academy of Engineering

Source
Google images

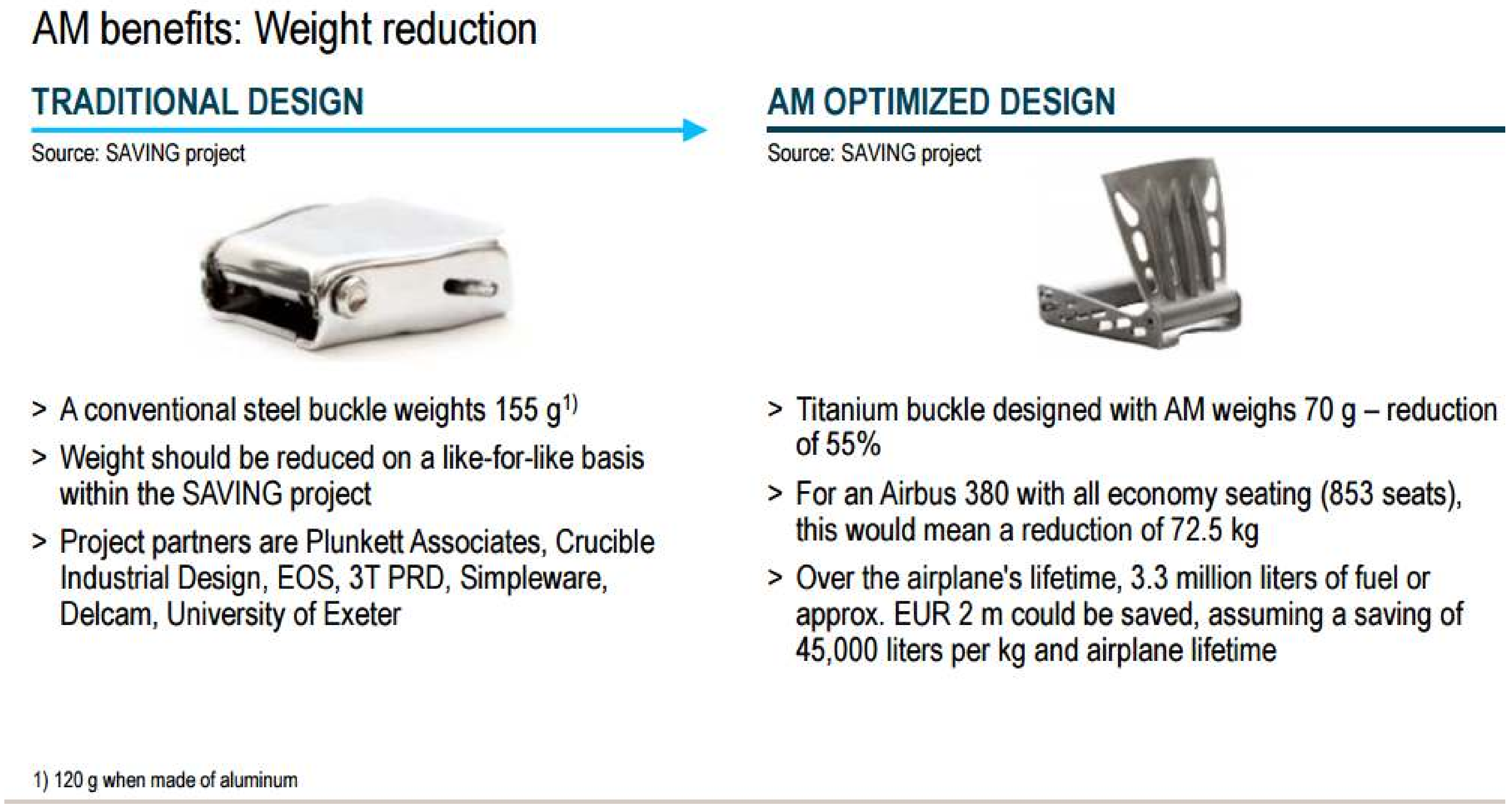
Current and Potential industries for Additive Manufacturing

Pros and Cons

Pros
Freedom to design and innovate without penalties
Rapid iteration through design permutations
Excellent for mass customization
Elimination of tooling
Green manufacturing
Minimal material waste
Energy efficient
Enables personalized manufacturing

Cons
Unexpected pre- and post-processing requirements
High process cost
Lack of industry standards
Low speed, not suitable for mass production
Inconsistent Materials
Limited number of materials
High equipment cost for high-end manufacturing

Benefits



AM benefits: Weight reduction

TRADITIONAL DESIGN

Source: SAVING project

- > A conventional steel buckle weights 155 g1)
- > Weight should be reduced on a like-for-like basis within the SAVING project
- > Project partners are Plunkett Associates, Crucible Industrial Design, EOS, 3T PRD, Simpleware, Delcam, University of Exeter

AM OPTIMIZED DESIGN

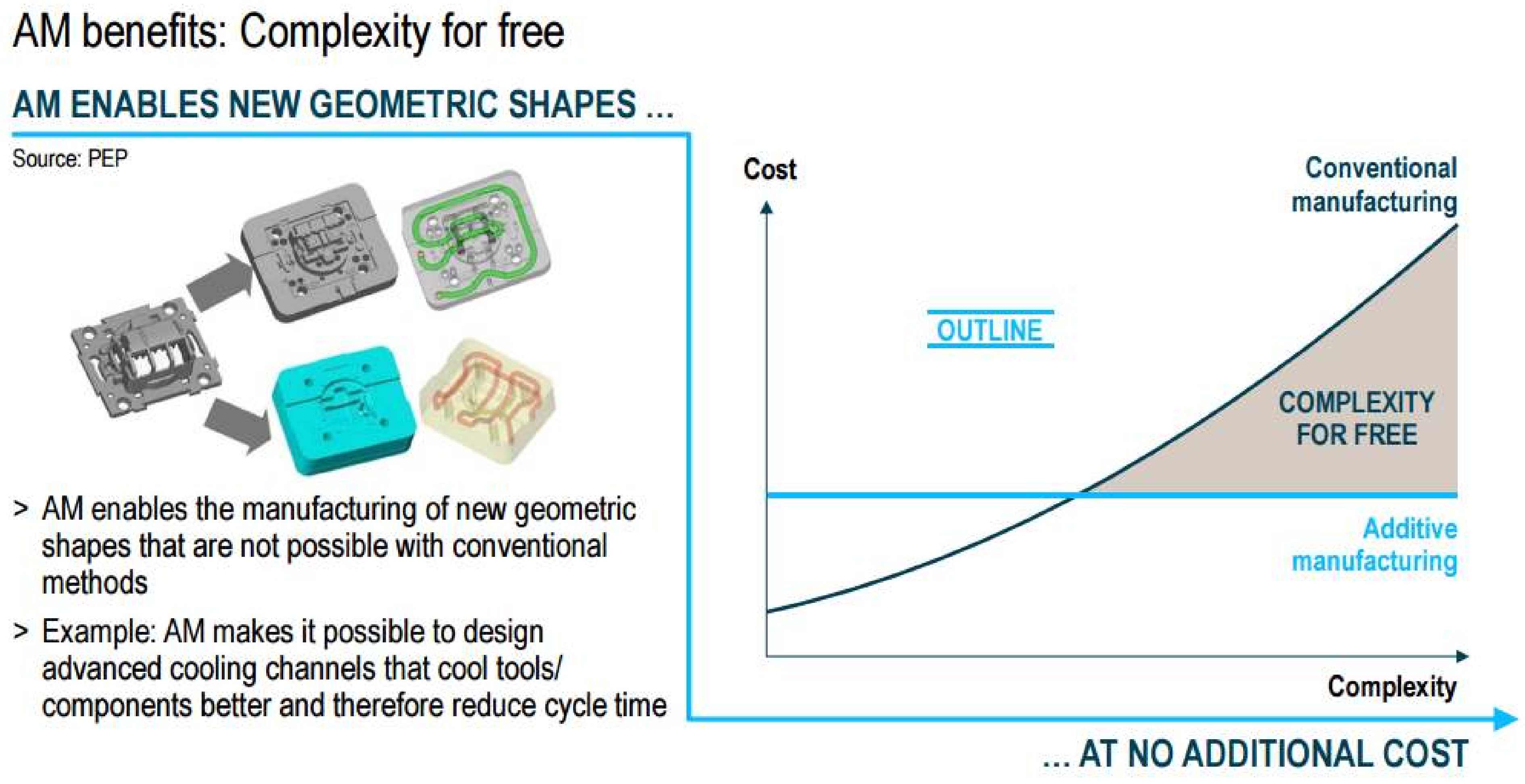
Source: SAVING project

- > Titanium buckle designed with AM weighs 70 g – reduction of 55%
- > For an Airbus 380 with all economy seating (853 seats), this would mean a reduction of 72.5 kg
- > Over the airplane's lifetime, 3.3 million liters of fuel or approx. EUR 2 m could be saved, assuming a saving of 45,000 liters per kg and airplane lifetime

1) 120 g when made of aluminum

Source: SAVING project/Crucible Industrial Design Ltd.; Roland Berger

Benefits



AM benefits: Complexity for free

AM ENABLES NEW GEOMETRIC SHAPES ...

Source: PEP

> AM enables the manufacturing of new geometric shapes that are not possible with conventional methods

> Example: AM makes it possible to design advanced cooling channels that cool tools/ components better and therefore reduce cycle time

... AT NO ADDITIONAL COST

Source: Roland Berger

Benefits

AM for customized medical products

DENTAL CROWNS/BRIDGES

Source: EOS

- > **AM holds a large share of the dental crowns and bridges market –** Geometry is scanned and processed via CAD/CAM. More than 30 million crowns, copings and bridges have already been made on AM machines over the last 6 years
- > **Increasing market share –** Experts estimate that more than 10,000 copings are produced every day using AM
- > **Faster production –** One AM machine produces up to 450 crowns per day, while a dental technician can make around 40

IMPLANTS

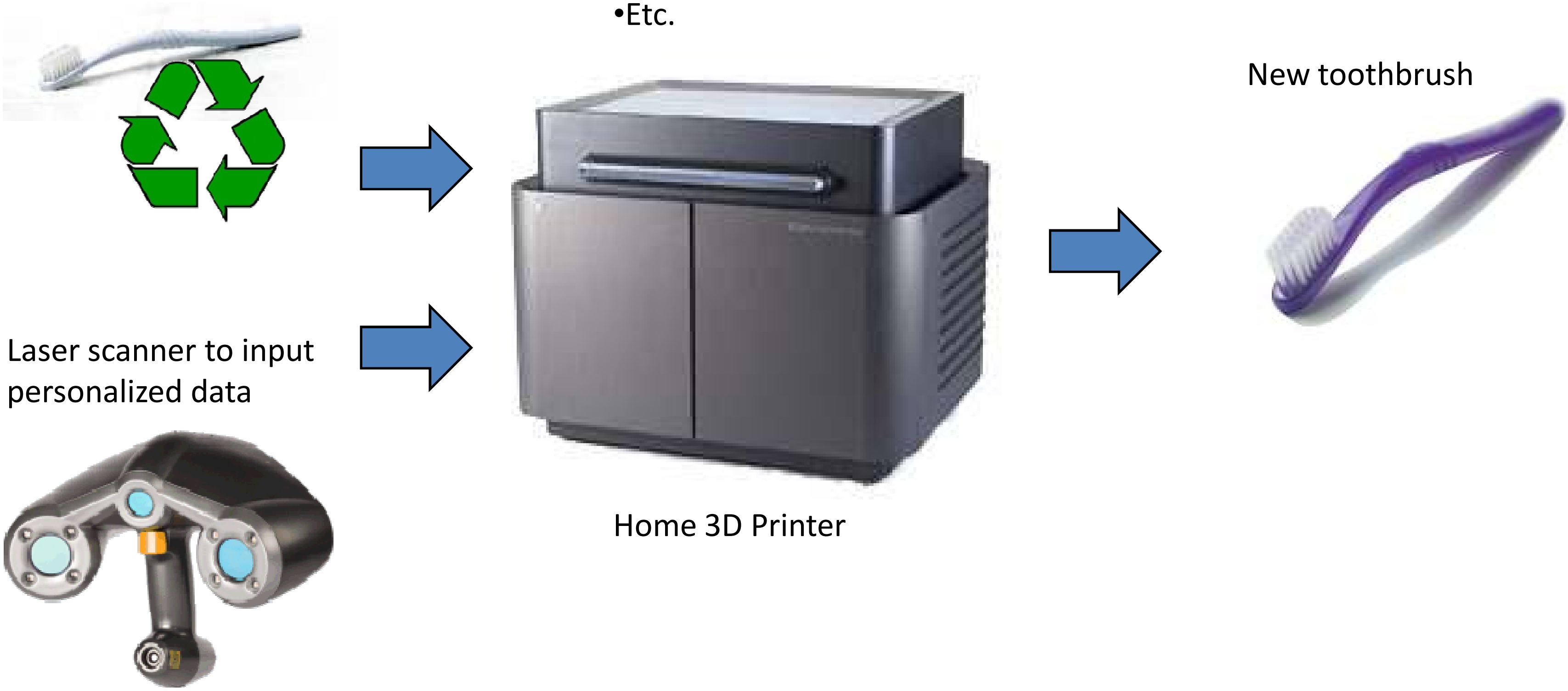
Source: EOS

- > **AM offers advantages with regard to manufacturing time, geometric fit and materials –** Example of a skull implant with modified surface structure
- > **Improved fit via AM –** Based on 3D scans of the skull, the resulting implant fits perfectly into the skull cap, leads to faster recovery and reduces operation time

Additive manufacturing will replace conventional manufacturing methods for customized products

Source: Roland Berger

Future: Home Manufacturing



Customization:
- Bristle hardness
- Colour
- Handle Style and shape
- Etc.

Old toothbrush

Laser scanner to input personalized data

Home 3D Printer

New toothbrush

Case Studies

CASE STUDY

ROLLS-ROYCE

Rolls-Royce is considering embarking on the additive manufacture of entire components because of the benefits of faster production and reduced costs that it offers. Says Rolls-Royce's Neil Mantle: "At the launch of an engine programme we start to consider forgings, and AM gives us a great opportunity here because conventional methods of manufacture can take 40, 50 or even 60 weeks, while a component using AM will take one month." Likewise, he praised the improved buy-to-fly ratio on materials: "Sometimes we machine away 90% of the materials to create the final component, but with AM that figure is much reduced." Neil Mantle added that while AM offers distinct advantages, investing in AM machines will require Rolls-Royce to feel confident of their economic viability and that the processes will be as robust and reliable as traditional methods.

CASE STUDY

VIRGIN UPPER CLASS MONITOR ARM

In a Technology Strategy Board (TSB) funded project for Virgin Atlantic, the arm holding the TV monitor in the airline's Upper Class seats was redesigned for AM. Latticing reduced the arm's weight by 50%, saving 0.5 kilograms for every unit, in turn saving $45,000 worth of fuel across the 30-year lifetime of the aircraft. "You can make an economic case for AM on that one component," said Dr Chris Tuck, Associate Professor of Additive Manufacturing and 3D Printing Research Group at the University of Nottingham.

Source: Royal Academy of Engineering

Introduction to Reverse Engineering

The primary input for AM is CAD file/model.

Suppose that for a part (to be copied, modified or repaired)

- ✓ CAD was not used in the original design;
- ✓ there is inadequate documentation on the original design;
- ✓ the original CAD model is not sufficient to support modification or manufacturing using modern methods;
- ✓ the original supplier is unable or unwilling to provide additional parts.

Introduction to Reverse Engineering

“Examining competitive or similar or prior products in great detail by dissecting them or literally taking them apart.”

- Dym & Little

Technological principles of a device through analysis of its structure, function and operation.

“What does this do?”

“How does it do that?”

“Why would you want to do that?”

Introduction to Reverse Engineering

Purposes solved

✓ Dissection and analysis

✓ Experience and knowledge for an individual's personal database

✓ Competitive benchmarking

Introduction to Reverse Engineering

Reverse Engineering Process

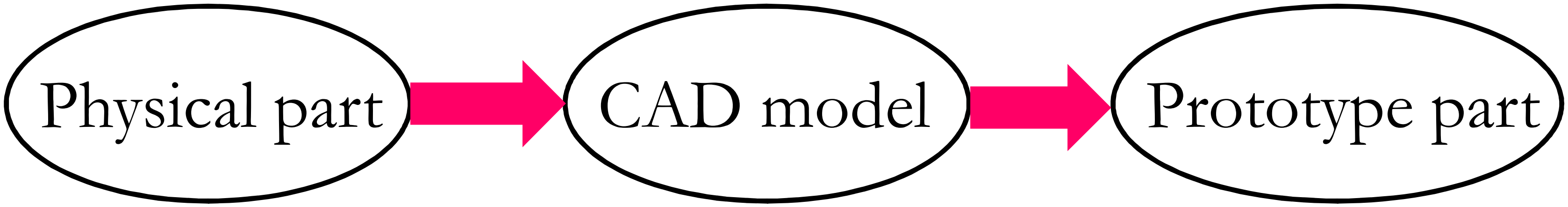
1. Digitizing the parts

This step uses a reverse engineering device to collect raw geometry of the object.

The data is usually in the form of coordinate points of the object relative to a local coordinate system.

2. Building CAD models

This step converts the raw point data obtained from step 1 into a usable format.



Physical part

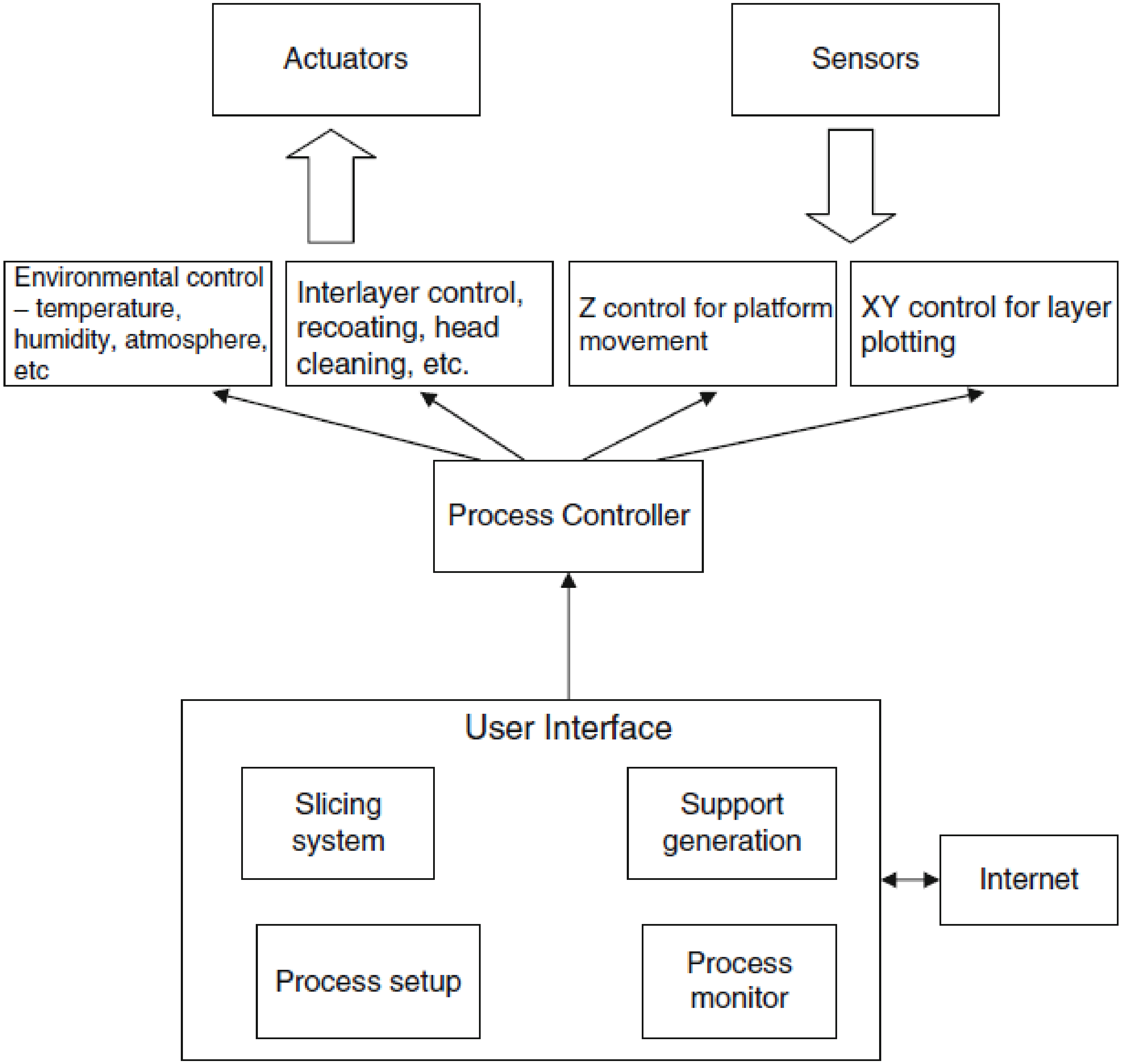
CAD model

Prototype part

Example


H
RATAN MRI & CT CENTER
Emotion 16
2/1
2/5
2/9
2/13
2/17
2/21
2/25
2/29
2/33
2/37
2/41
2/45
2/49
2/53
2/57
2/63
10cm
10cm

General Integration of an AM Machine



Actuators

Sensors

Environmental control – temperature, humidity, atmosphere, etc

Interlayer control, recoating, head cleaning, etc.

Z control for platform movement

XY control for layer plotting

Process Controller

User Interface

Slicing system

Support generation

Process setup

Process monitor

Internet

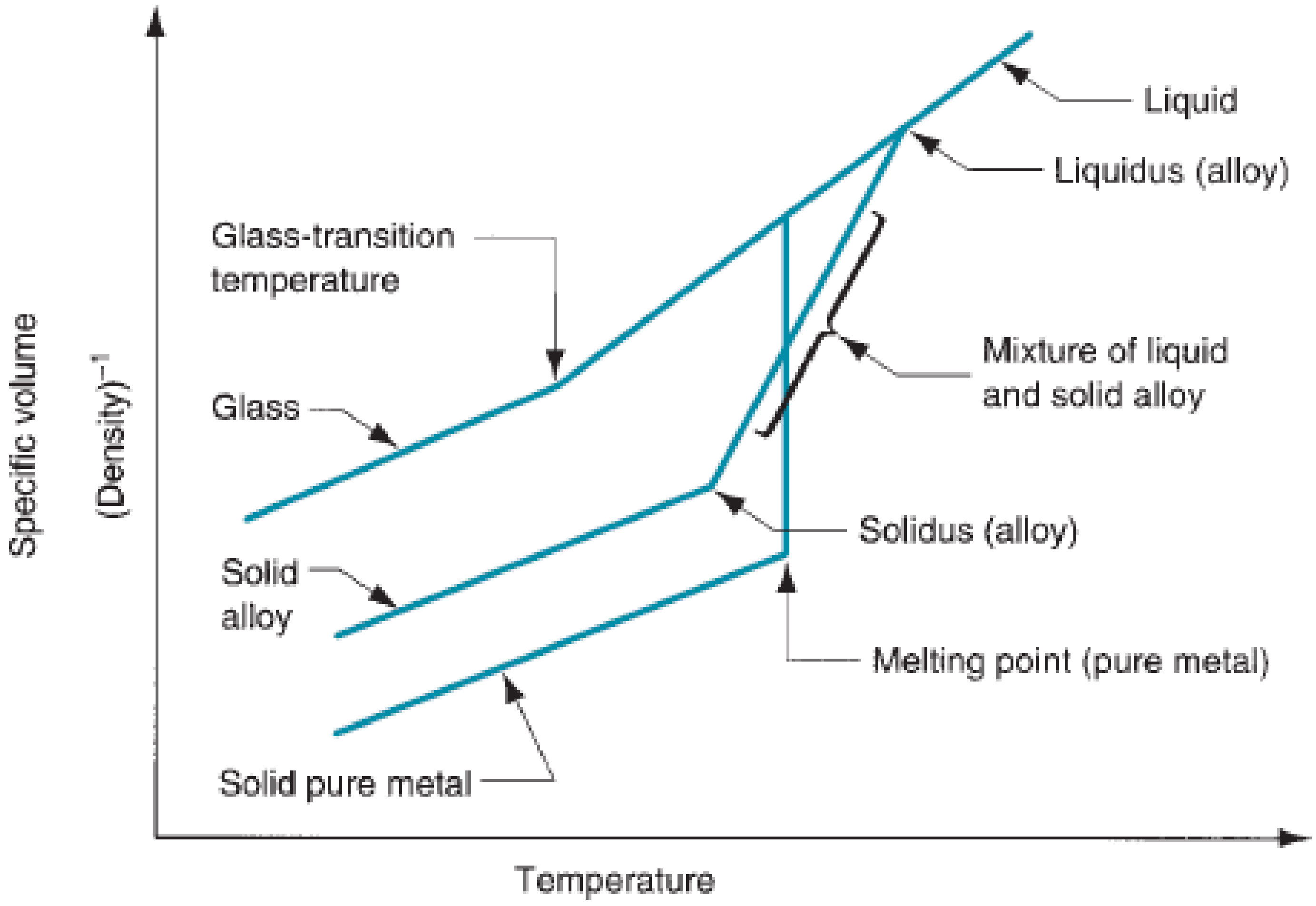
Material Classification

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

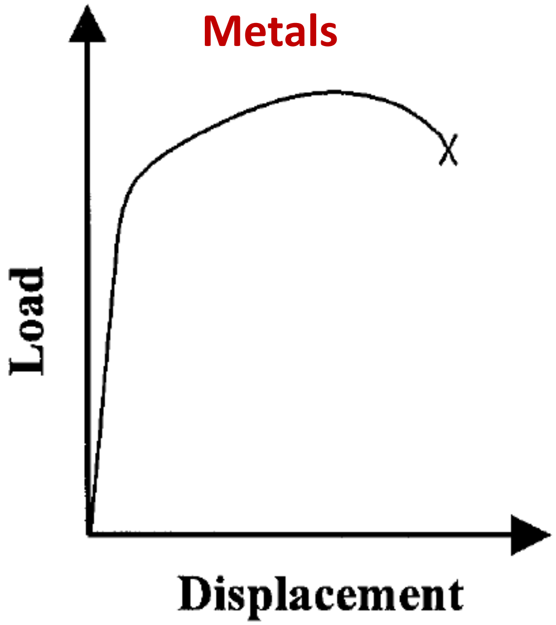
Polymers

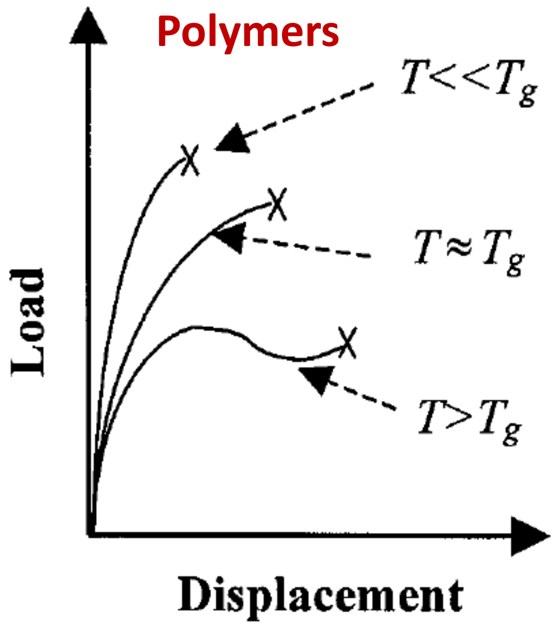
- a) ABS polymer
- b) Acrylics
- c) Cellulose
- d) Nylon
- e) Polycarbonate
- f) Thermoplastic polyester
- g) Polyethylene
- h) Polypropylene
- i) Polyvinylchloride

Thermal Expansion Characteristics



Load-Displacement Characteristics



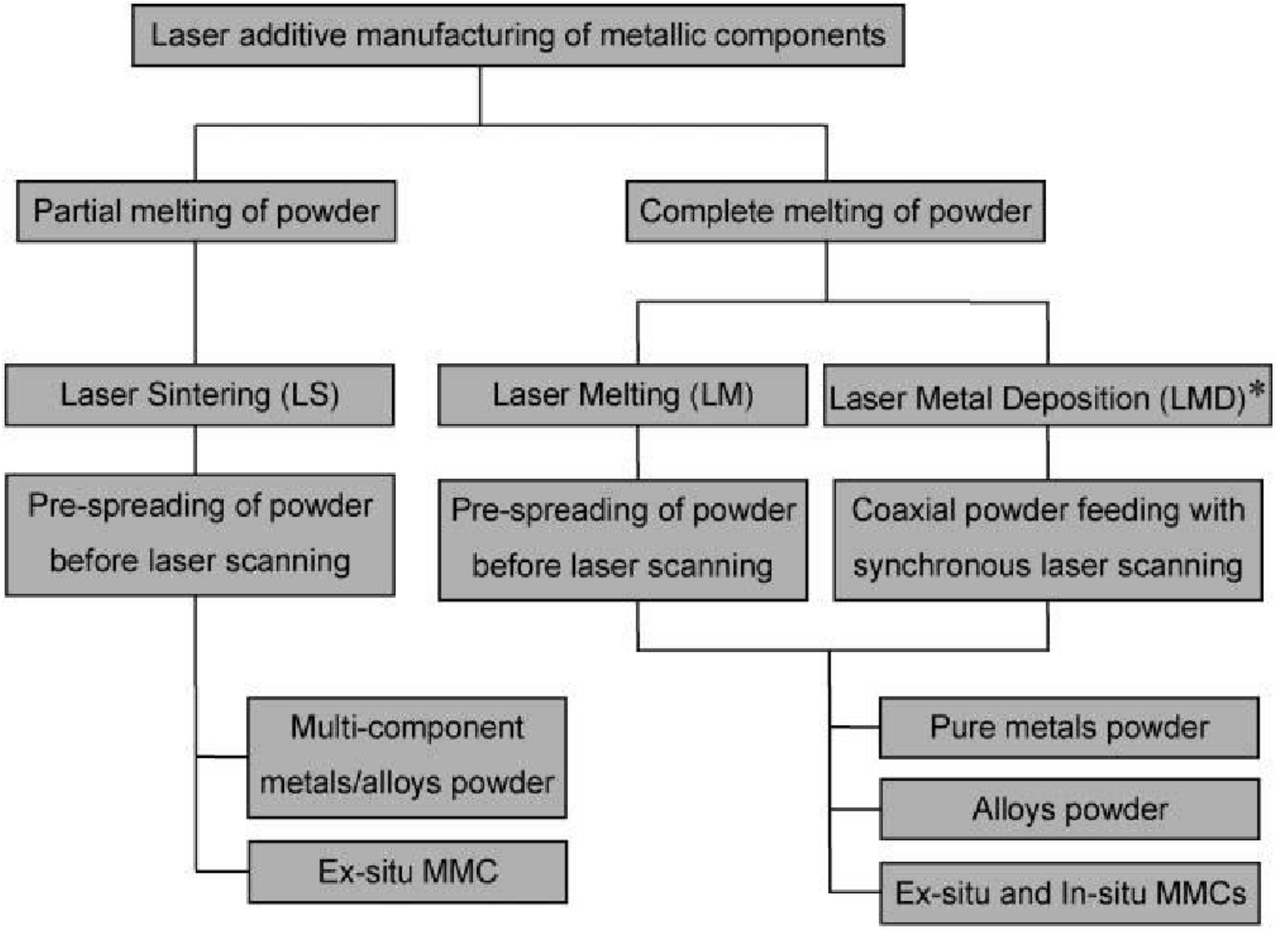


Metals: Characterized by a linear elastic region followed by a non-linear plastic region.

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


Laser additive manufacturing of metallic components

Partial melting of powder

Complete melting of powder

Laser Sintering (LS)

Laser Melting (LM)

Laser Metal Deposition (LMD)*

Pre-spreading of powder before laser scanning

Pre-spreading of powder before laser scanning

Coaxial powder feeding with synchronous laser scanning

Multi-component metals/alloys powder

Ex-situ MMC

Pure metals powder

Alloys powder

Ex-situ and In-situ MMCs

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

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

The liquid wets the solid as $\cos\theta \to 1$. A spreading coefficient has been defined in literature

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

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.

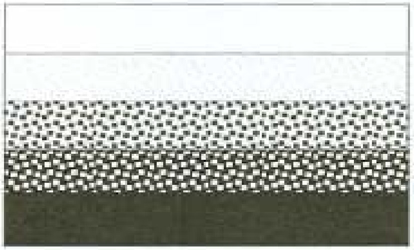
- An example of the second category is the bio-composite poly-epsilon-caprolactone and hydroxyapatite (PCL/HA) bone scaffold fabricated using SLS, with the addition of HA to enhance the strength and biocompatibility of PCL.

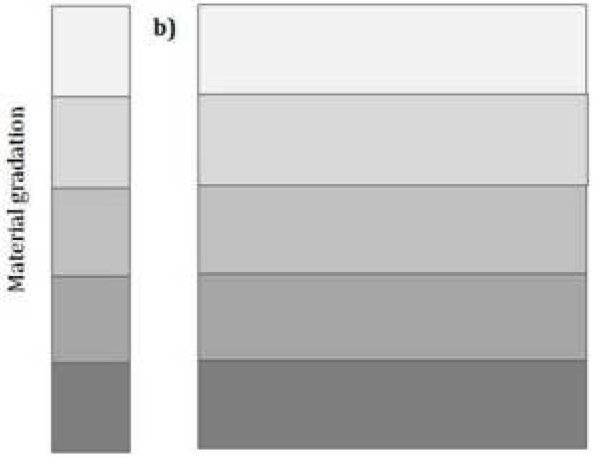
- By developing a feedstock filament with the proper composite, polymer-metal and polymer-ceramic composites could be produced with FDM. ABS-Iron composites have been made using FDM with a single-screw extruder by appropriately producing an iron particulate-filled polymeric filament. Fibers, such as 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

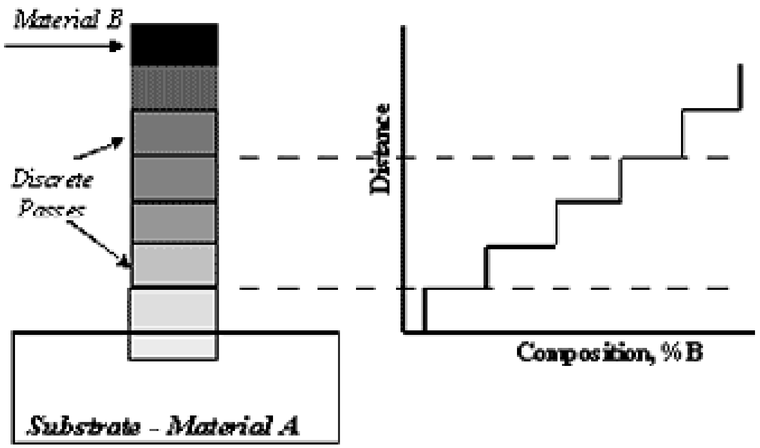


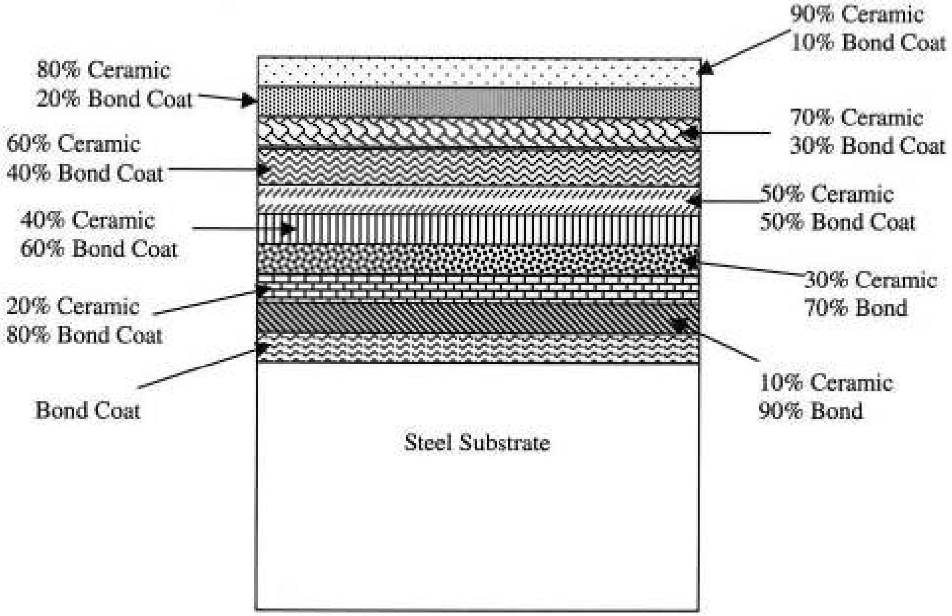


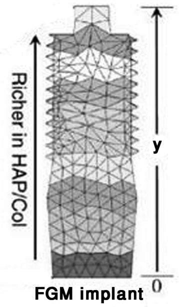
Continuous Graded Structures

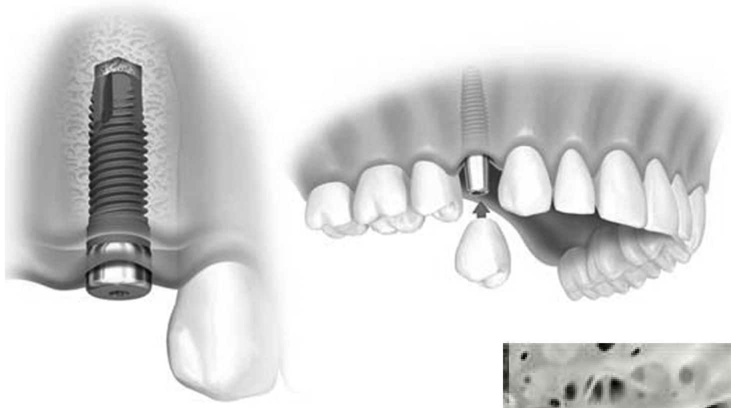
- An example is the human bone which gradient is formed by its change in porosity and composition;
- Change in porosity happens across the bone because of miniature blood vessels inside the bone.

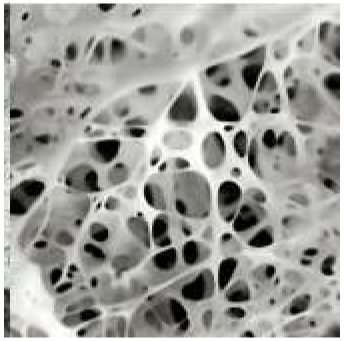
Functionally Graded Materials (FGMs)









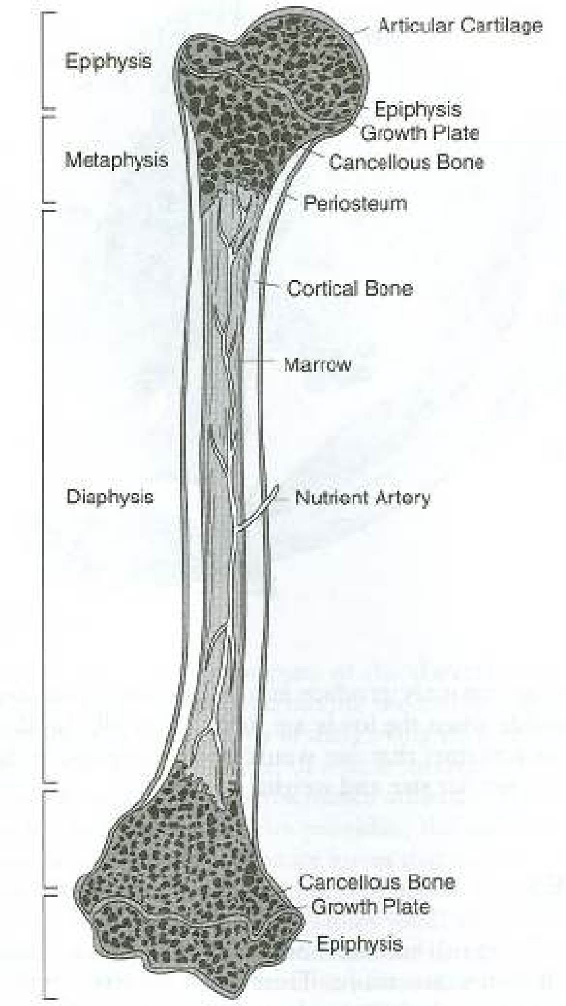


FGMs can be obtained by layered mixing of two materials of different thermo-mechanical properties with different volume ratio by gradual changing from layer to layer.

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

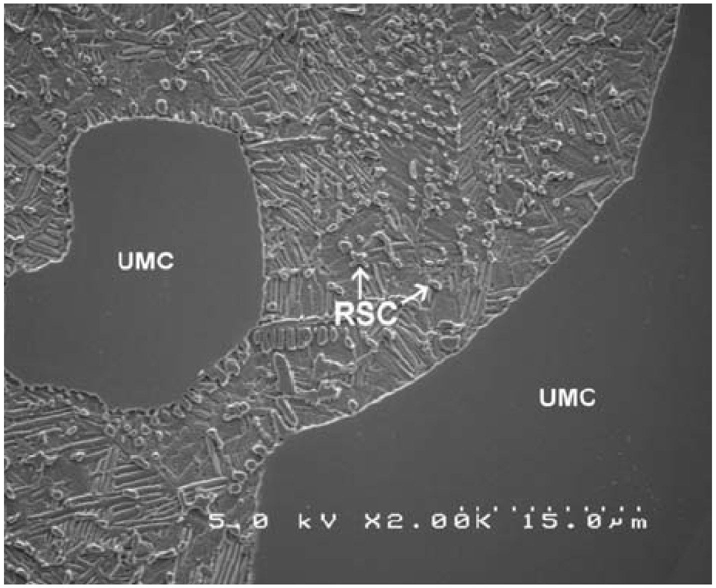
Current applications of FGMs include:

- 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;

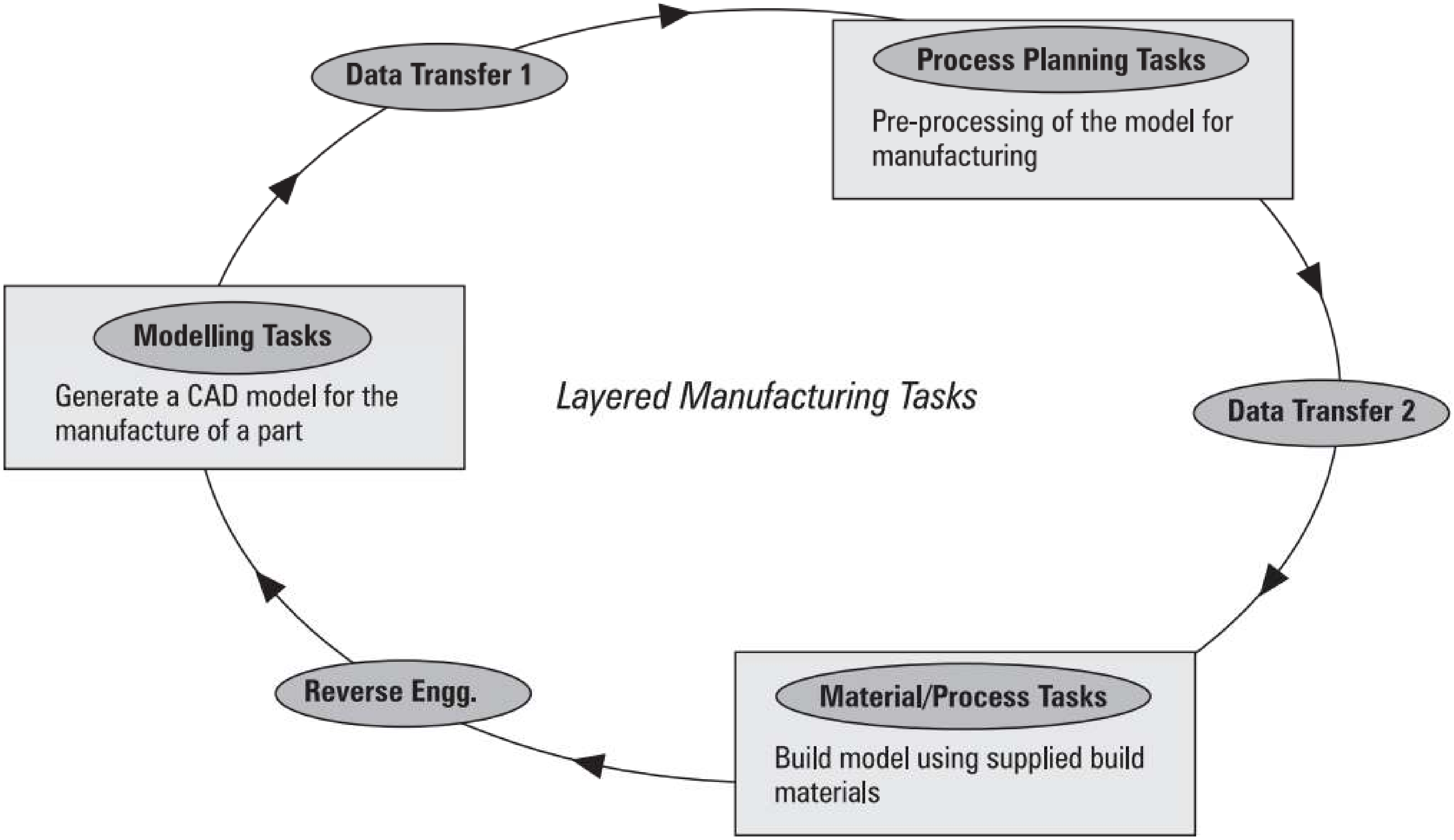
III. Blade interiors must have high heat conductivity so that the blades can be cooled.

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



Data Transfer 1

Process Planning Tasks

Pre-processing of the model for manufacturing

Data Transfer 2

Material/Process Tasks

Build model using supplied build materials

Reverse Engg.

Modelling Tasks

Generate a CAD model for the manufacture of a part

Layered Manufacturing Tasks

Process Planning in Layered Manufacturing

There are four main planning tasks:

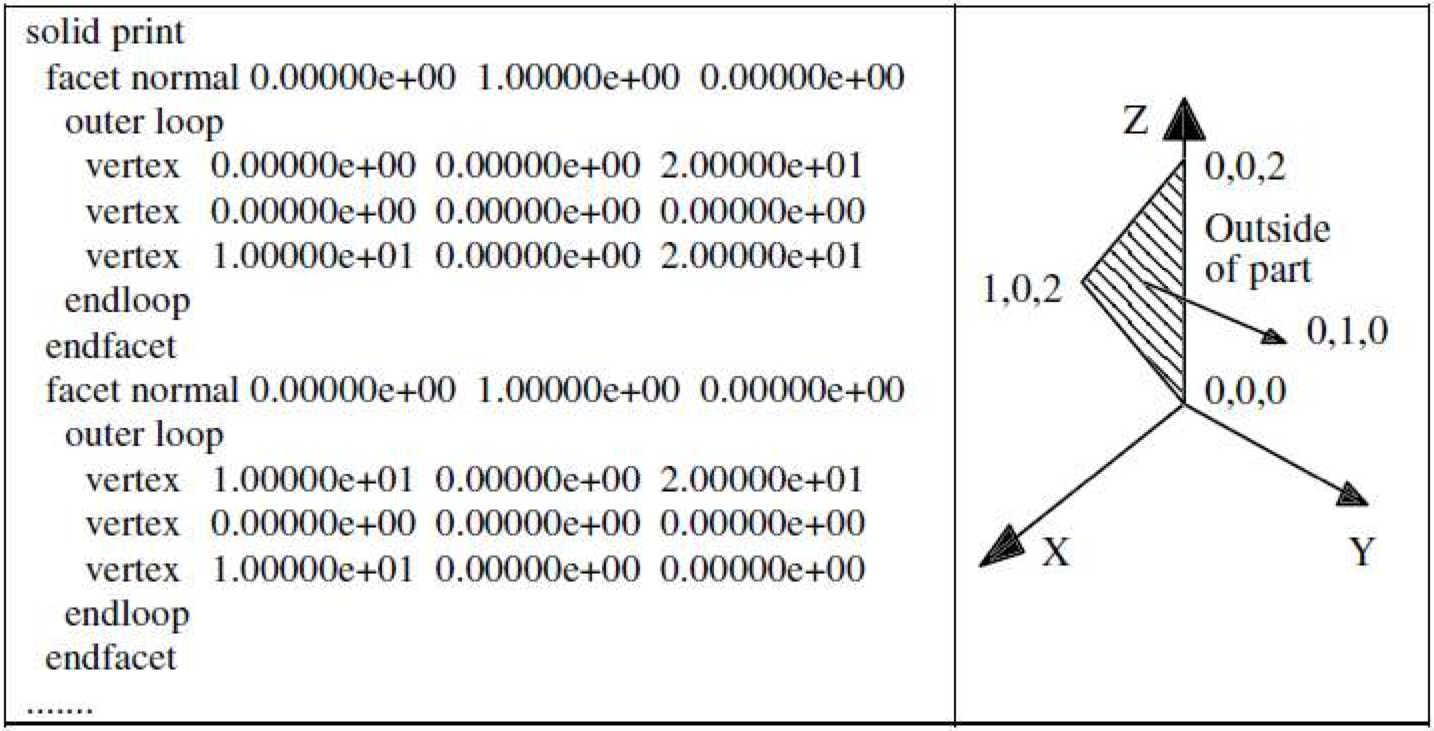
(i) orientation optimization,

(ii) support design,

(iii) slicing, and

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

Sample STL File



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  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

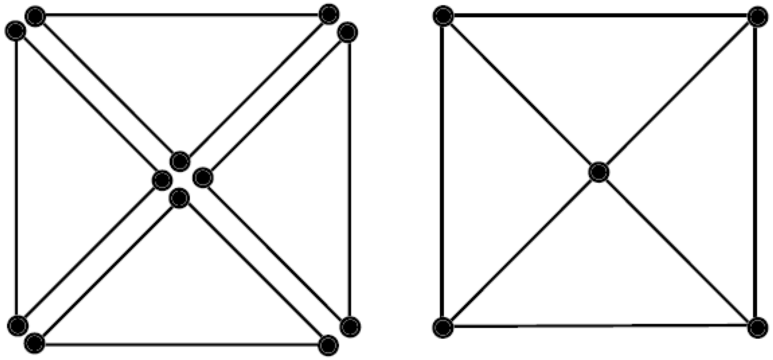
(iii) It can provide small and accurate files for data transfer for certain shapes

Disadvantages

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

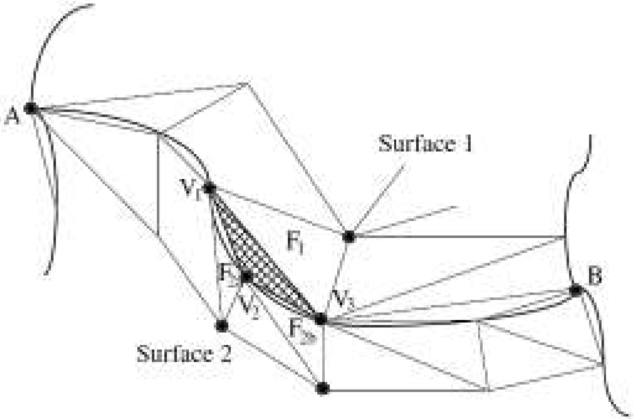
(ii) The geometry flaws exist in the STL file

(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.



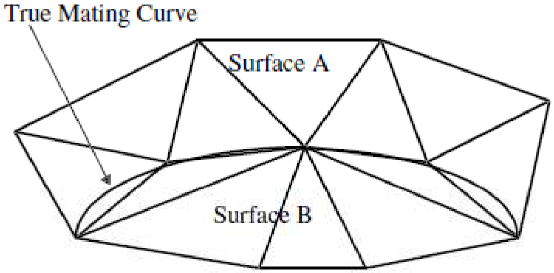


Figure 6.4(a): Shell punctures created by unequal tessellation of two adjacent surface patches along their common mating curve

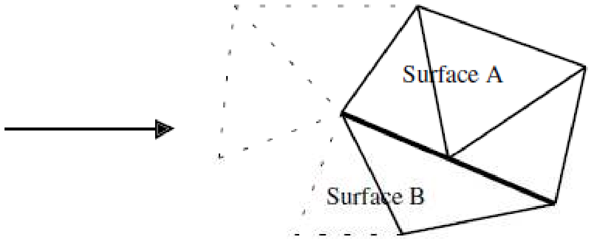
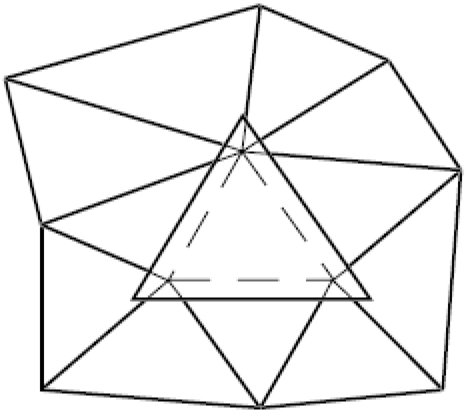
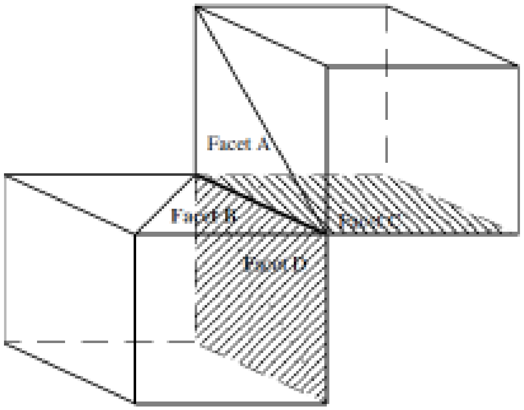


Figure 6.4(b): Shell punctures eliminated at the expense of adding degenerate facet





Valid vs. Invalid Tessellated Models

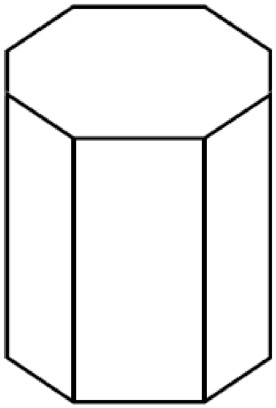


Figure 6.7(a): A valid 3D model

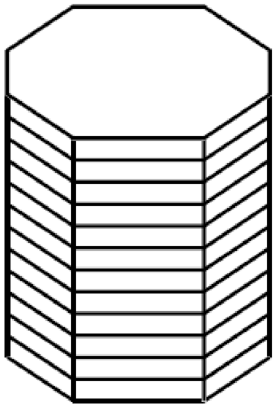


Figure 6.7(b): A 3D model sliced into 2D planar layers

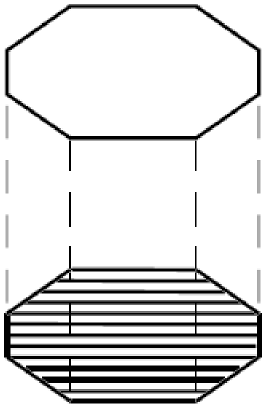


Figure 6.7(c): Conversion of 2D layers into 1D scan lines

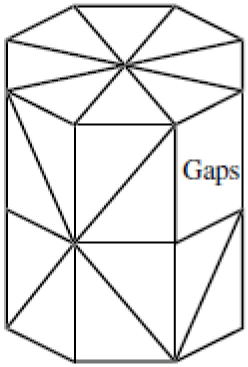


Figure 6.8(a): An invalid tessellated model

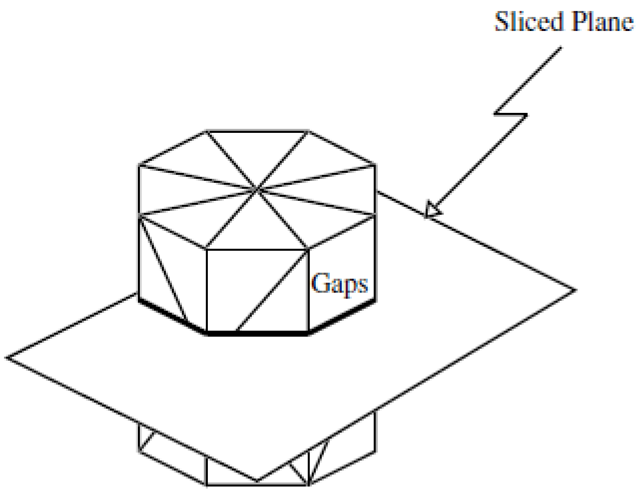


Figure 6.8(b): An invalid model being sliced

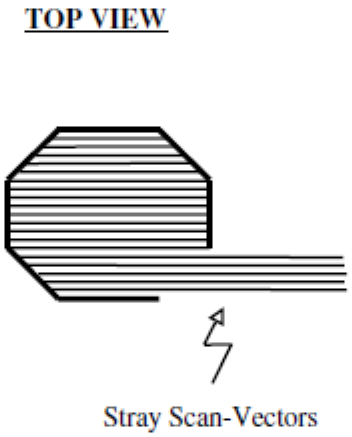
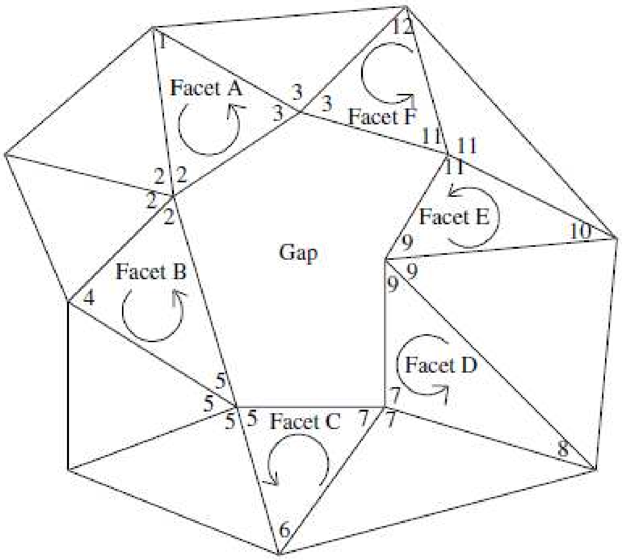
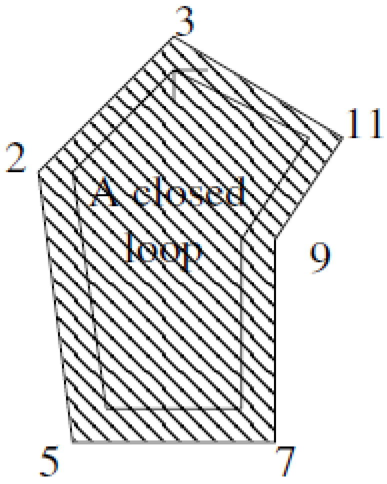


Figure 6.8(c): A layer of an invalid model being scanned

STL File Repair





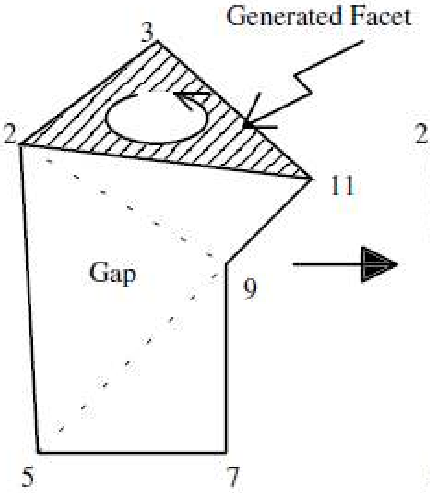


Figure 6.12(a):
First facet
generated

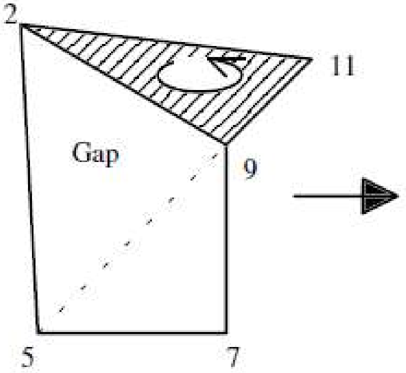


Figure 6.12(b):
Second facet
generated

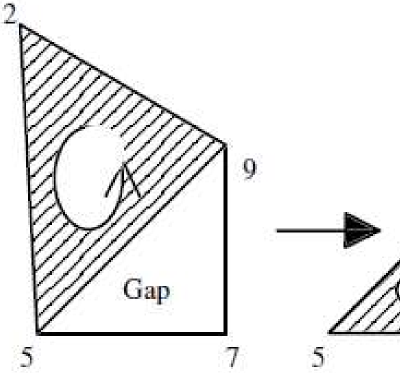


Figure 6.12(c):
Third facet
generated

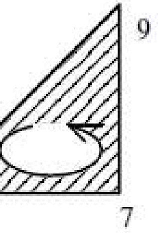
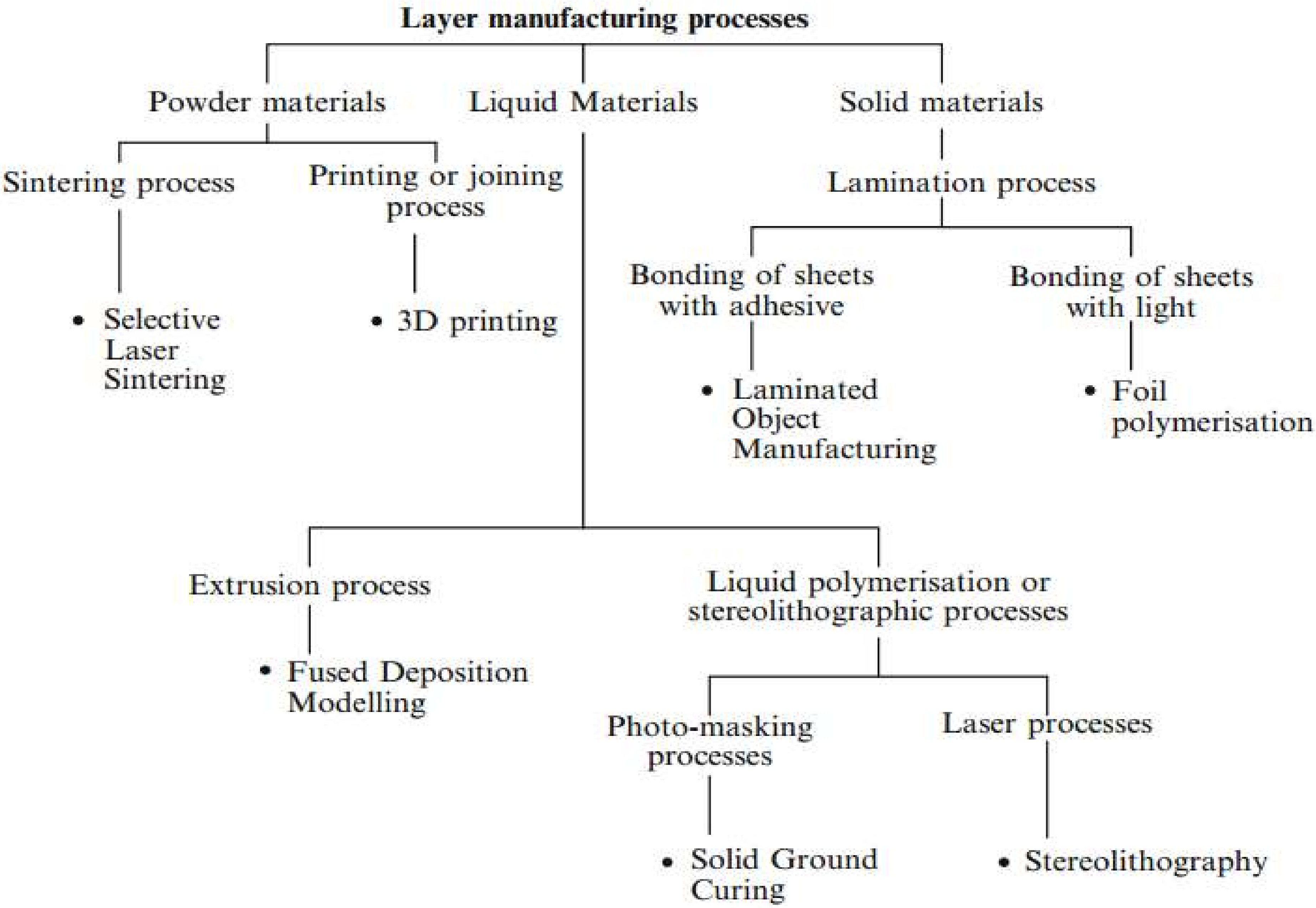


Figure 6.12(d):
Fourth facet
generated



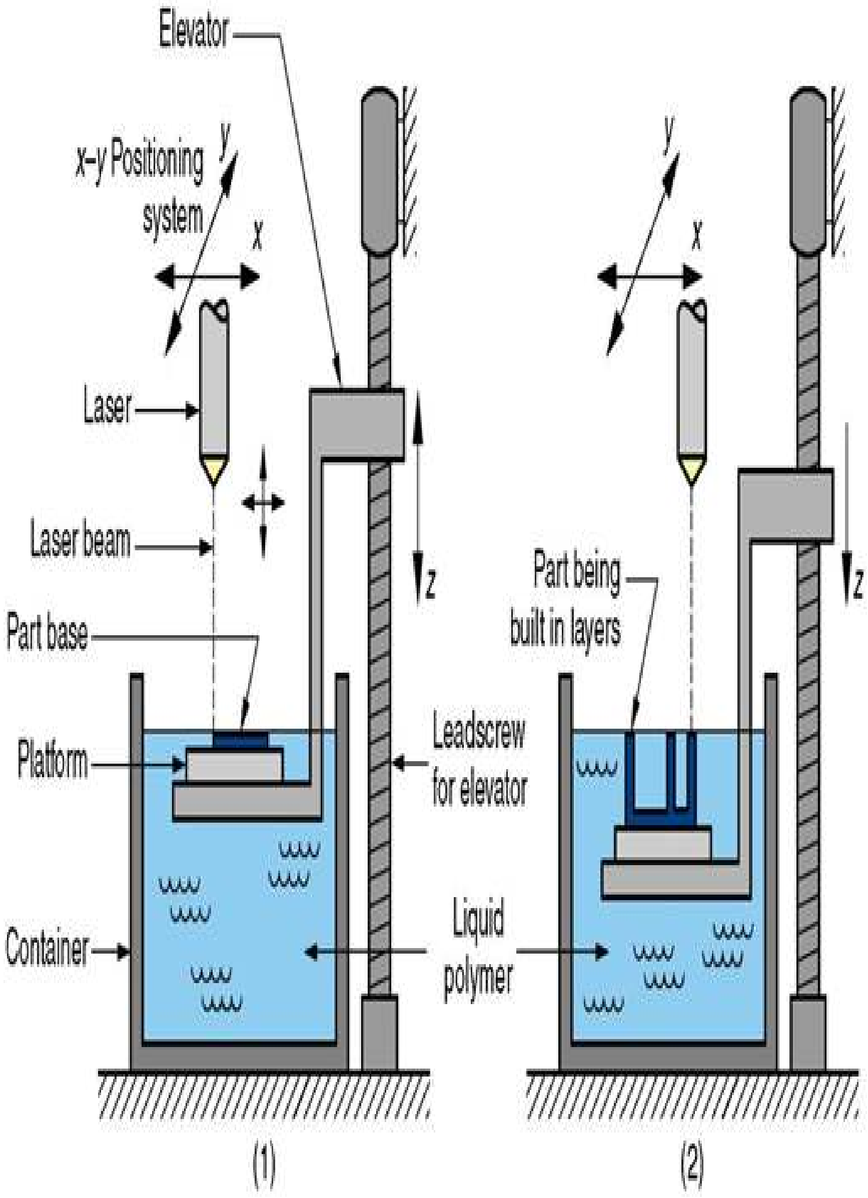
Layer manufacturing processes

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

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.

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

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

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

Number of layers

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

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

How layer by layer adhesion takes place in stereolithography?

The new layer adheres to the previous one because the depth of penetration of each pulse of laser is greater than the thickness of the layer and hence over cures the prior layer.

This process is repeated as many times as is necessary to recreate the entire object layer by layer. When completed, the platen is raised from the vat and the model is ready for removal of the support structure and postcuring.