TA 202A

Lecture 9

Additive Manufacturing

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RAPID PROTOTYPING AND ADDITIVE MANUFACTURING

1. Rapid Prototyping vs. Additive Manufacturing
2. Additive Manufacturing Processes

Rapid Prototyping (RP) and Additive Manufacturing (AM)

- Family of fabrication processes to make engineering prototypes or production parts in minimum lead time based on a CAD model of the item
  - Traditional manufacturing can require significant lead-times, weeks, depending on part complexity and difficulty in ordering materials
  - RP/AM allows a part to be made in hours or days, given that a computer model of the part has been generated on a CAD system
- One might say that RP is a subset of AM when the purpose is to make a prototype

Why is Rapid Prototyping Important?

- Product designers want to have a physical model of a new part or product design rather than just a computer model or line drawing
  - Creating a prototype is an integral step in design
  - A **virtual prototype** (a CAD model of the part) may not be sufficient for the designer to visualize the part adequately
  - Using RP to make the prototype, the designer can see and feel the part and assess its merits and shortcomings
  - Prototypes make excellent visual aids for communicating ideas with co-workers or customers
  - Prototypes can be used for **design testing**
  - RP technique can also be used for making tooling (known as **Rapid Tooling**)

Most prototypes require from 3 to 72 hours to build depending on the size and complexity of the object

Available Rapid Prototyping Technologies

1. Material removal RP - machining, using a dedicated CNC machine that is available to the design department on short notice. Top to bottom approach (subtractive)
   – Starting material is often wax
   – The CNC machines are often small - called desktop machines
2. Material addition RP - adds layers of material one at a time to build the solid part from bottom to top approach (additive)

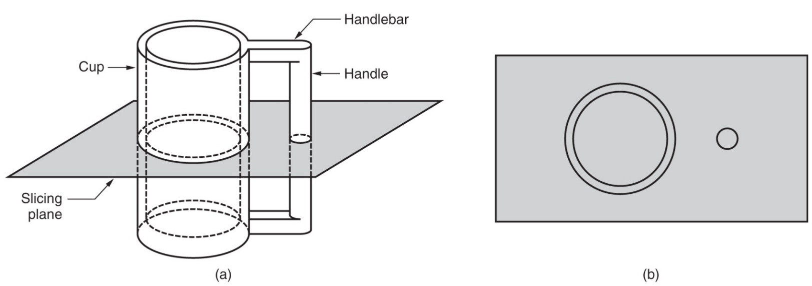
Advantages of Material Addition RP Technologies

- Speed of part delivery
- Avoidance of the CNC part programming task, because the CAD model is the part program in material addition RP
- Complexity of part geometry is not an issue in material addition RP

Steps to Prepare Control Instructions

1. Geometric modeling - design the component on a CAD system to define its enclosed volume
2. Tessellation of the geometric model - CAD model is converted into a computerized format that approximates its surfaces by facets (triangles or polygons)
3. Slicing of the model into layers - computerized model is sliced into closely-spaced parallel horizontal layers

Solid Model to Layers



(a) Conversion of a solid model of an object into layers
(b) Only one layer is shown

What is Additive Manufacturing (AM)

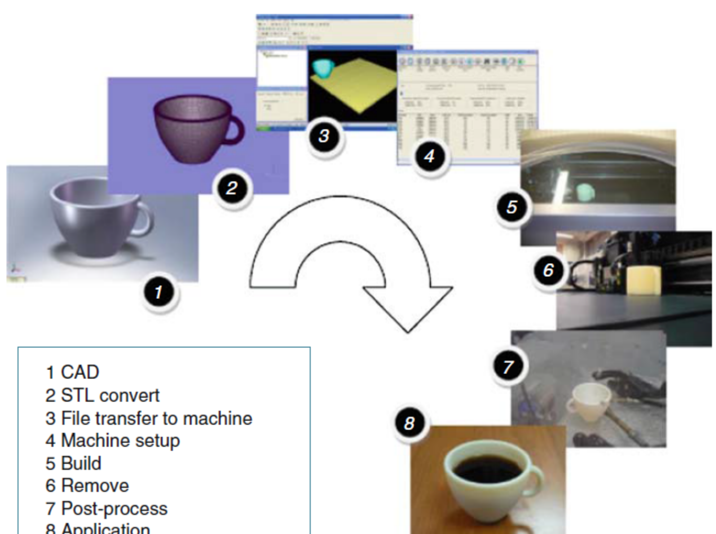
Additive Manufacturing (AM) refers to a process by which digital 3D design data is used to build up a component in layers by depositing material.

(International Committee F42 for Additive Manufacturing Technologies, ASTM)

What You See Is What You Build (WYSIWYB) Process

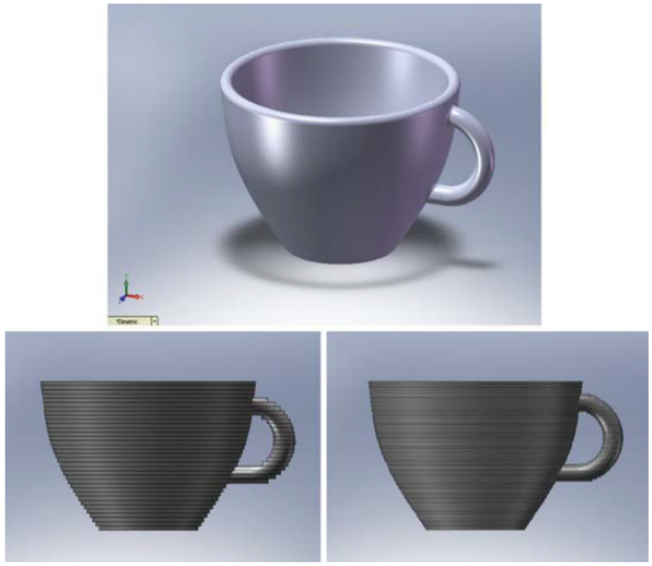
Difference between Rapid Prototyping and Additive Manufacturing?

Generic AM Process



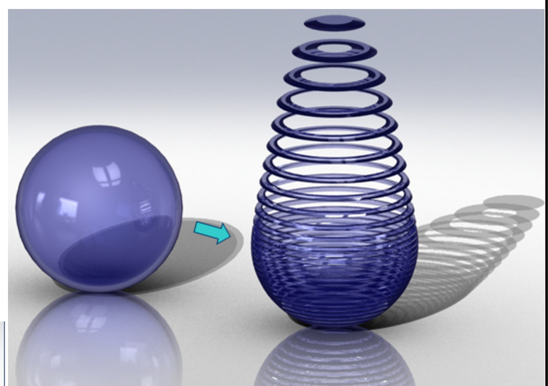
1 CAD
2 STL convert
3 File transfer to machine
4 Machine setup
5 Build
6 Remove
7 Post-process
8 Application

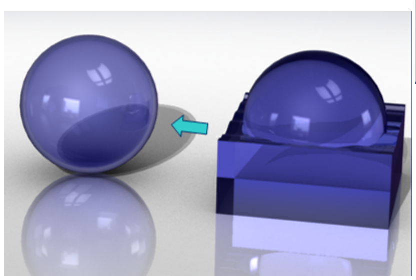
Generic AM Process



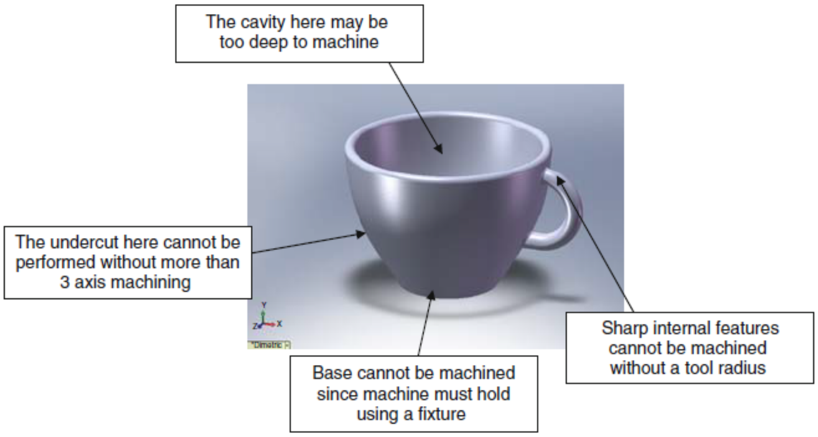
Additive vs Subtractive Manufacturing

- Part complexity
- Material
- Speed
- Part quantity
- Cost



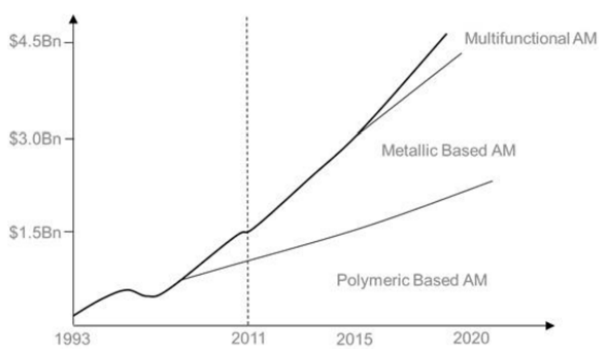


Additive vs Subtractive Manufacturing



Features that represent problems using CNC machining

Evolution



Growth of AM Technologies

Additive Manufacturing Applications

Applications of rapid prototyping can be classified into:

1. Design
2. Engineering analysis and planning
3. Tooling
4. Parts production

Design Applications

- Designers are able to confirm their design by building a real physical model in minimum time using RP
- Design benefits of RP:
  - Reduced lead times to produce prototypes
  - Improved ability to visualize part geometry
  - Early detection of design errors
  - Increased capability to compute mass properties

Engineering Analysis and Planning

- Existence of part allows certain engineering analysis and planning activities to be accomplished that would be more difficult without the physical entity
  - Comparison of different shapes and styles to determine aesthetic appeal
  - Stress analysis of physical model
  - Fabrication of pre-production parts for process planning and tool design

Parts Production

- Small batches of plastic parts that could not be economically molded by injection molding because of the high mold cost
- Parts with intricate internal geometries that could not be made using conventional technologies without assembly
- Spare parts (make as needed rather than inventory)
- One-of-a-kind parts such as biomedical implants that must be made to correct size for each user

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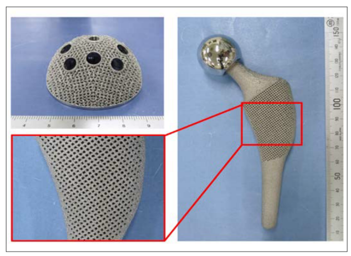
Tooling Applications

- Called *rapid tool making* (RTM) when RP is used to fabricate production tooling
- Two approaches for tool-making:
    1. Indirect RTM method
    2. Direct RTM method

Current and Potential Industries for Additive Manufacturing

Medical



Medical Implant / Coating

Benefits

AM benefits: Weight reduction

TRADITIONAL DESIGN

Source: SAVING project

- A conventional steel buckle weights 155 g[1)]
- 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

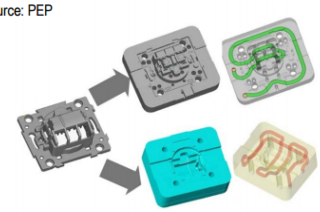
Source: SAVING project/Crucible Industrial Design Ltd.; Roland Berger

Benefits

AM benefits: Complexity for free

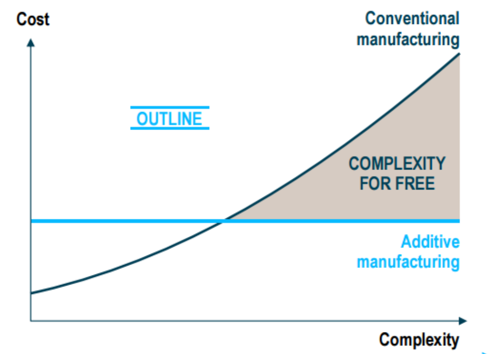
AM ENABLES NEW GEOMETRIC SHAPES ...

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/softness
- Color
- Handle, style and shape, etc.

Old toothbrush

Laser scanner to input personalized data

Home 3D Printer

New toothbrush

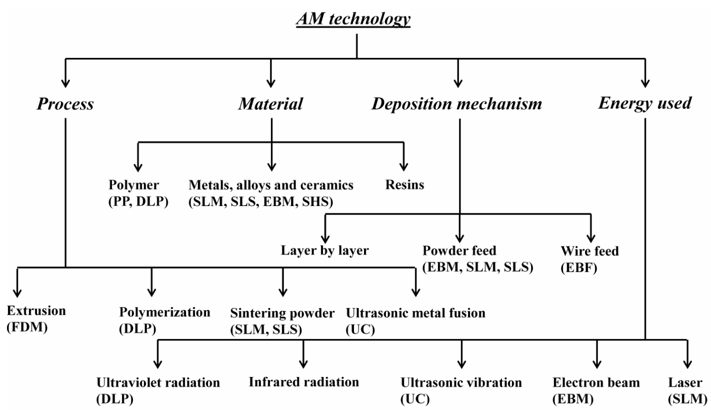
Pros and Cons

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

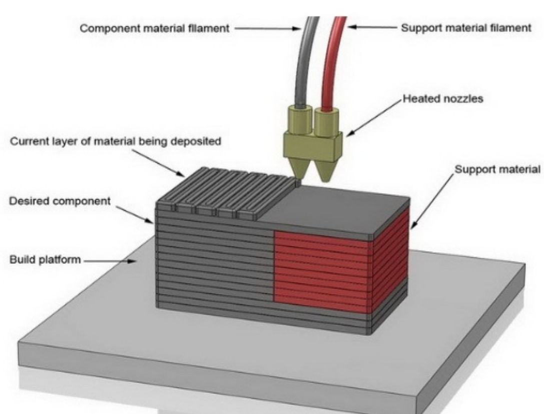
AM Process Classification

1. **Liquid-based:** Stereolithography and mask projection stereolithography
2. **Powder-based:** Selective laser sintering, selective laser melting, Selective electron beam melting, Laser metal deposition
3. **Molten material:** Fused deposition modeling and droplet deposition manufacturing
4. **Solid-based:** Laminated object manufacturing



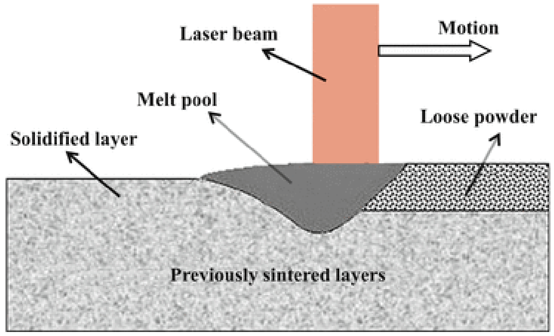
Fused Deposition Modeling (FDM)

RP process in which a long filament of wax or thermoplastic polymer is extruded onto a substrate from a workhead to complete each new layer



Fused Deposition Modeling

Selective Laser Melting (SLM)



Working principle - three stages (Scherer, 1977)

(1) A layer of powder is spread (typically ~0.05 mm thick) over the elevator and pressed; each layer of powder is pre-heated before the scanning to minimize heat input from laser. Pre-heating of powder – uniform temperature within the build platform, prevent warping of the part during the build due to non-uniform thermal expansion and contraction.

(2) Laser radiation sinters the powder to form the profile of the section.

(3) The elevator drops through a distance equivalent to the thickness of the section, and the process is repeated until the prototype is completed.

- The heat generated causes powder particles to melt and form a melt pool which solidifies as a consolidated layer of material.
- Full melting and resolidification of powder allow the fabricated parts to exhibit density very close to the theoretical one.

- Areas that have been scanned by the laser will become solid while those not scanned by the laser will remain in powder form and serve as support material. The entire fabrication process occurs generally in inert environment.
- To prevent oxidation, degradation and interaction of the molten material with the surroundings argon gas environment is used.
- After the entire fabrication process is complete the supporting powder will be collected and sieved for reuse.

Materials

- Stainless steel
- Cobalt-Chrome alloys
- Titanium alloys
- Bronze-nickel alloys
- Tool steels
- Nickel based super alloys
- Composites
- Plastics and polymer

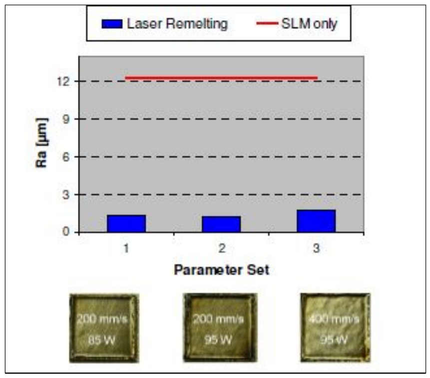
Material name	Material type	Typical applications
Stainless Steel	1.4404 (316L) stainless steel	functional prototypes
Tool Steel	1.2344 (H13) tool steel	Injection moulding tooling; functional prototypes
CpTi	Commercially Pure Titanium	Implants and medical devices
Ti64	Ti6Al4V	Implants and high performance functional components
Ti6Al7Nb	Ti6Al7Nb	Implantable devices
Aluminium	Aluminum Silicon Alloy	Functional prototypes and series parts;
Cobalt Chrome	CoCrMo superalloy	Functional prototypes and series parts; medical, dental

Challenges in SLM

- **Surface Finish**
- **Density Problem**
- **Residual Stress**
- **Balling**

Surface Finish

- SLM parts often require post-processing operations such as surface machining, polishing and shot peening to attain final part surface finish
- Surface roughness is heavily dependent on laser processing parameters and control of melt pool.



Density Problem

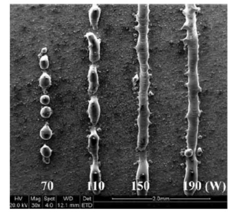
- Scan speed has a significant effect on density .
- At sufficiently low scan speeds, the relative density is almost independent of the layer thickness, and a maximum of 99% relative density is achievable.

Residual Stress

- Due to localized heating, complex thermal and phase transformation stresses are generated during SLM.
- In addition, frequent thermal expansion and contraction of the previously solidified layers during the process generates considerable thermal stresses and stress gradients that can exceed the yield strength of the material.
- Residual stresses can lead to part distortion, initiate fracture, and unwanted decrease in strength.

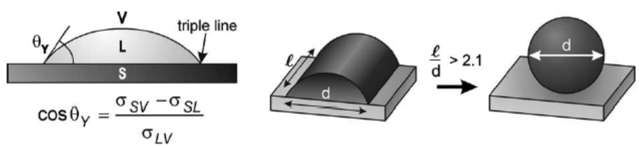
Balling

- Instability of a liquid on a solid where the liquid splits into smaller entities in order to reduce the surface tension variations is called balling



Cause:

- In the SLM process when the total surface of the melt pool becomes larger than that of a sphere of the same volume then balling occurs.
- If the length (l) to diameter (d) ratio of the melt pool is greater than 2.1 then the molten metal would break up into small droplets instead of a continuous line.



Simplified Model for Applied Energy

- Melt pool formation and characteristics are fundamentally determined by the total amount of applied energy which is absorbed by the powder bed as the laser beam passes.
- Both the melt pool size and melt pool depth are a function of absorbed energy density.
- A simplified energy density equation has been used by numerous investigators as a simple method for correlating input process parameters to the density and strength of produced parts
- In their simplified model, applied energy density E_a (also known as the Andrews number) can be found using

$$E_a = P/(U \times SP)$$

P = laser power

U = scan velocity

SP = scan spacing between parallel scan lines

For SLM , typical scan spacing values are 100 µm , whereas typical laser spot sizes are 300 µm. Thus, typically every point is scanned by multiple passes of the laser beam.

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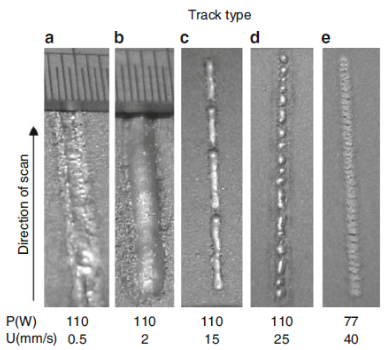
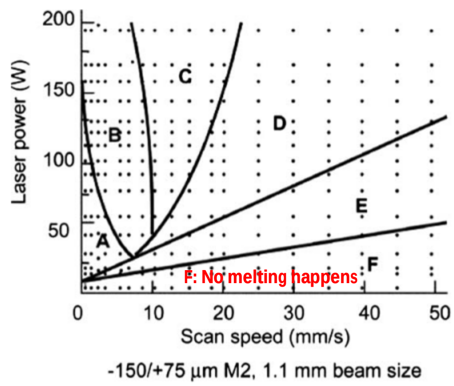
A = Continuous and flat topped or slightly concave
B = Rounded and sank into the bed
C = Occasionally broken
D = Regularly and frequently broken tracks are perfect examples of the balling effect
E = Fragile tracks were formed maximum temperatures exceed the solidus temperature but do not reach the liquidus temperature

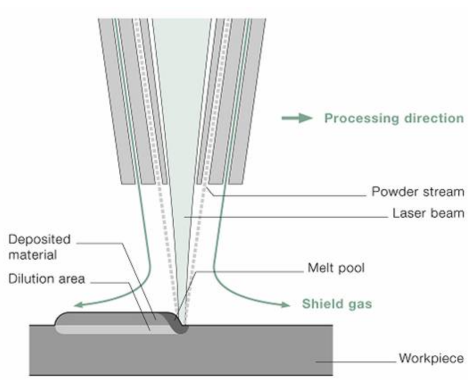


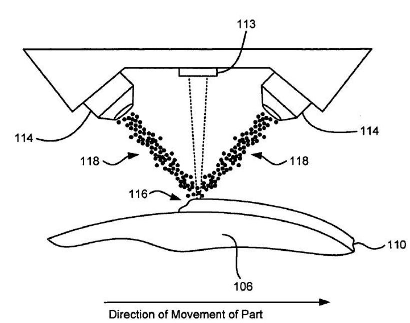


Within process map regions A and B, this strategy could still be used as a guide for process optimization.

$$E_a = P/(U \times SP)$$

LMD / LENS





LENS (Laser Engineered Net Shaping)

- **A type of Beam Deposition (BD) Process**
- Uses a high power laser to melt metal powder that is deposited onto the susbtrate. Metal powder is sprayed onto the focal point of the laser where the metal becomes fused together. It uses a layered approach to manufacture the components.
- In many ways, BD techniques can be used in an identical manner to laser cladding and plasma welding machines.

- The machine employs powder delivery through a nozzle placed above the part.
- The powder is melted where the material converges with the laser and the substrate.

Steps in LENS Fabrication Process

1) Solid model is sliced electronically into a sequence of layers of a given thickness

↓

2) To build a metallic part, a solid substrate is used as a base and the laser beam is focused on the substrate to create a molten pool into which powder is simultaneously fed.

↓

3) Substrate is moved beneath the laser beam tracing the pattern, melting material is added to the surface as a narrow strip of added material.

- Starting from the bottom of the part, one layer is produced at time.
- After formation of a layer, the powder feeding nozzle and laser beam assembly is moved in the z direction.
- Accordingly, the part is then built line by line and layer by layer.

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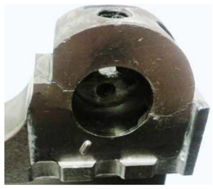
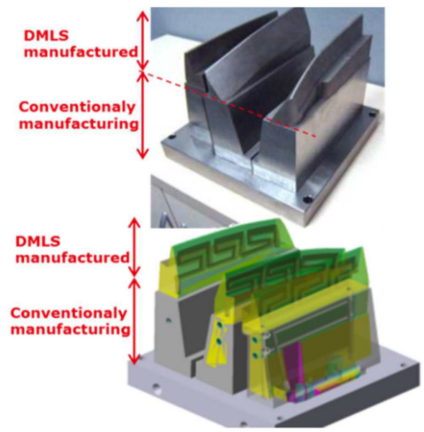
Repair of tooling inserts



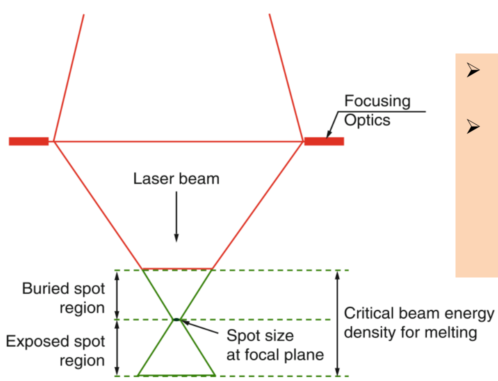
- Laser direct metal deposition for shaft refurbishment
- In the aircraft engine market, for repair of blades and seal segments

Optimized solution with hybrid design

Upper part DMLS / Lower part conventional



- When a laser is focused to a small spot size, there is a region above and below the focal plane where the laser energy density is high enough to form a melt pool.
- If the substrate surface is either too far above or too far below the focal plane, no melt pool will form.



- ➢ First layer – a mixture of melted substrate + powder.
- ➢ If little mixing of the substrate and deposited material is desired, then the focal plane should be placed above the substrate surface to minimize melting of the substrate – resulting in a melt pool made up almost entirely of the powder material.

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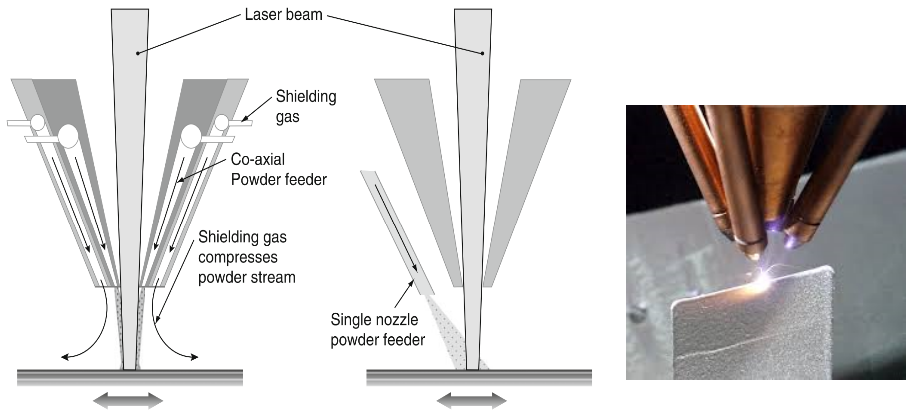
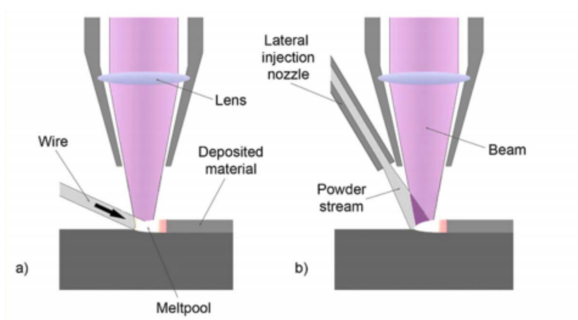


Powder nozzle configurations: (a) co-axial nozzle feeding; and (b) single-nozzle feeding; (c) 4 nozzle feeding

Wire Feeding

- In the case of wire feeding, the volume of the deposit is always the volume of the wire that has been fed, and there is 100% feedstock capture efficiency.
- This is effective for simple geometries, coating of surfaces, and/or deposits where porosity is acceptable.



- Track width hatch spacing must be set so that adjacent beads overlap, and layer thickness settings must be less than the melt pool depth to produce a fully dense product.

- Success of this method depends on the interaction between the laser beam and the powder. Generally, increasing the power of laser beam and decreasing the laser beam diameter and the scan speed increase the specific laser energy input using the equation.

$$I = \frac{P}{vD}$$

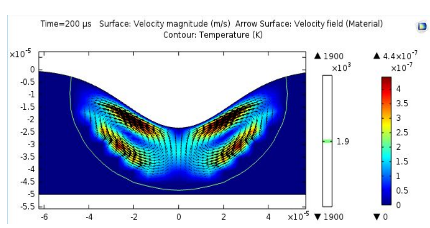
where: *I* is laser energy input, *P* is power of laser beam, *v* is scan speed, *D* is laser beam diameter

- Small heating zone and high cooling rate result in fine microstructure of deposited material. Controlling the microstructure in this method is easily possible by altering the cooling rate. During solidification, thermal gradient (*G*) and solidification velocity (*R*) determine the cooling rate ($\partial T/\partial t$)

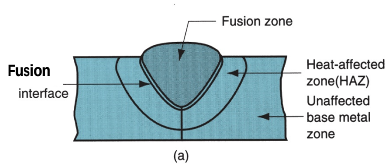
$$R = \frac{1}{G}\frac{\partial T}{\partial t}$$

Numerical Modeling and Simulation

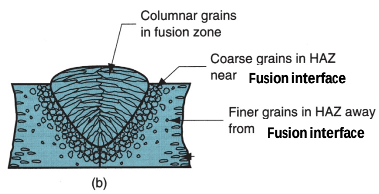
Powder bed fusion based AM processes



Typical Fusion Zone



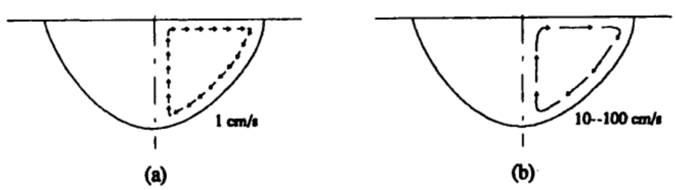
principal zones



typical grain structure

Melt Pool Shape

Govern by various convective forces
- Buoyancy
- Surface tension



Buoyancy or Gravity Force $\mathbf{F}_b = -\rho B g(T - T_0)$

Surface Gradient Force or Marangoni Convection $\mathbf{F}_\gamma = -\frac{d\gamma}{dT}\nabla T$

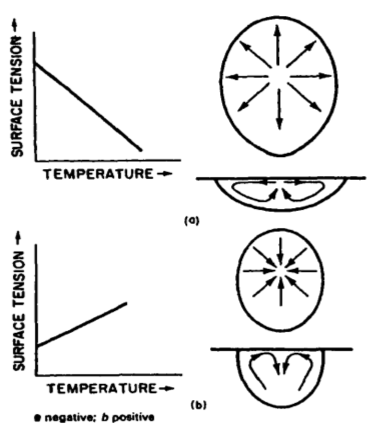
where γ is the surface tension of the molten metal, T is the temperature, and ∇T is the temperature gradient at the molten pool surface

Thus, whenever a temperature gradient exists in a liquid, so does a gradient in surface tension, too. This gradient exerts a force

Impurities in metal often alter the surface tension of the molten metal through their surface activity.

The surface tension gradient at the molten pool surface could be changed by the addition of surface-activating agents such as O, S, Se, and Te.

Surface Gradient Force or Marangoni Convection $\mathbf{F}_\gamma = -\frac{d\gamma}{dT}\nabla T$



Different convective flow patterns produced by different temperature coefficients of surface tension.

In (a), the pattern of convective flow without a surface-active agent; in (b) the effect of adding a surface-active agent

Boundary conditions. At the top surface, the thermal boundary condition is given by

$$-k\frac{\partial T}{\partial y} = \underbrace{-q''_{\mathrm{arc}}}_{\text{HEATFLUX INPUT}} + \underbrace{h_{\mathrm{convective}}(T - T_{\mathrm{ambient}})}_{\text{CONVECTIVE LOSSES}} + \underbrace{\sigma_r \varepsilon_r[(T)^4 - (T_{\mathrm{ambient}})^4]}_{\text{RADIATIVE LOSSES}} \quad (12)$$

Boiling of the surface can be allowed for by assuming that if the boiling point is reached at a certain grid point, then that point will disappear, allowing the power to fall on the grid point beneath it, with some absorption loss accounted for by the Beer–Lambert absorption law, or Bouguer's exponential law

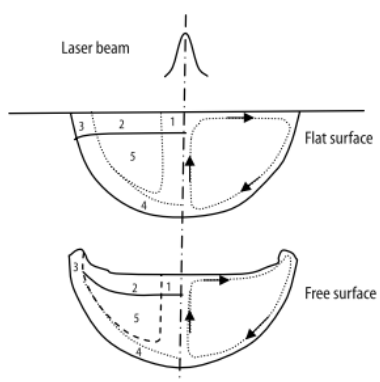
$$P_{x,y} = P_0 e^{-\beta \Delta z},$$

where β is the absorption coefficient (m^{-1})

Modelling and simulations can provide

- Surface temperature
- Velocity field
- Solute redistribution
- Temperature field within the melt pool and powder
- Cooling rate and temperature gradients

Melt Pool Shape



1 Stagnation flow
2 Free surface boundary layer
3 Cooled corner region
4 Solid–liquid interface boundary layer region
5 Isothermal inviscid core

Gaussian Heat Source Model

- During SLM, a moving Gaussian heat source can be assumed to simulate the energy of laser beam

$$q = \frac{2AP}{\pi R^2} \exp\left(-\frac{2r^2}{R^2}\right),$$

Laser beam

where P is the laser power, R is the effective laser beam radius at which the energy density is reduced to $1/e^2$ at the center of the laser spot, r is the radial distance from a point on the powder bed surface to the center of the laser spot, and A is the laser energy **absorptivity** of the powder (affected by the laser wavelength and the surface conditions and physical properties of the powder).

Determination of Thermal Parameters

- The effective thermal conductivity of the loose powder bed is an important material property determining the accuracy of SLM simulation results.
- It is controlled by gas-filled pores and depends on the solid fraction and particle size.
- It can be defined by the following simplified generic relationship:

$$k_p = k_s(1 - \phi),$$

where k_p and k_s are the thermal conductivity of the powder bed and solid bulk material, respectively, ϕ is the porosity of the powder bed, which can be expressed as

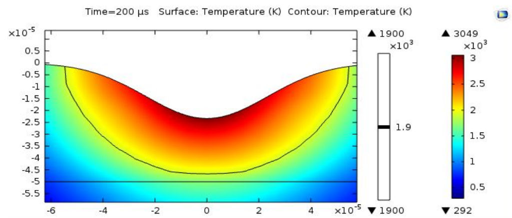
$$\phi = \frac{\rho_s - \rho_p}{\rho_s},$$

where ρ_s and ρ_p are the density of the solid bulk and the powder bed, respectively.

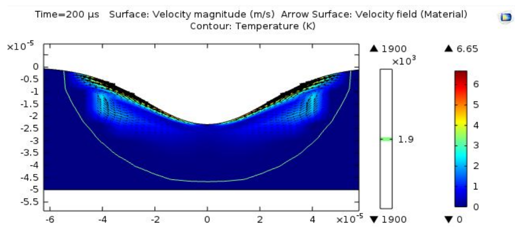
It is normally assumed that the porosity varies from φ = 0.40 for the powder state to φ = 0 for the solid state.

Simulation Result of Melt Pool

In this simulation laser beam is applied for t=200 µs, and then solidification starts.

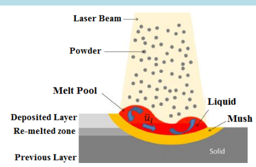


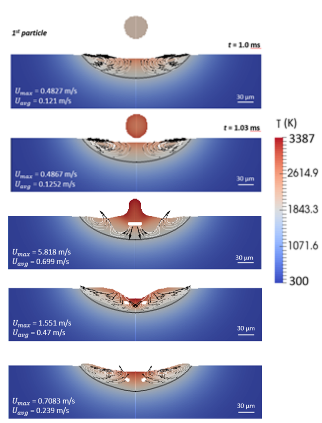
Temperature map

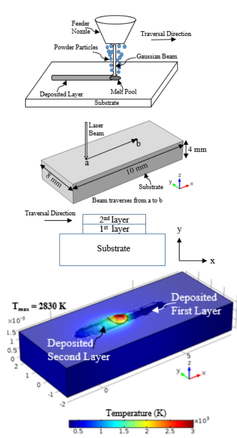


Velocity field

LMD Additive Manufacturing







Additive Manufacturing Lab

Additive Manufacturing Group

Recap of This Lecture

- Rapid prototyping
- Additive manufacturing
- FDM, SLM, LMD additive processes
- Modelling and simulation of metal AM

Next Lecture

3D Printing