An Introduction to Additive Manufacturing

DMG Mori Lasertec, 2014

John Hart
Mechanical Engineering, MIT
ajhart@mit.edu | mechanosynthesis.mit.edu

Cima, Sachs, et al, ~1995.

US005387380A

United States Patent [19]
Cima et al.

[11] **Patent Number:** **5,387,380**
[45] **Date of Patent:** **Feb. 7, 1995**

[54] **THREE-DIMENSIONAL PRINTING TECHNIQUES**

[75] Inventors: **Michael Cima**, Lexington; **Emanuel Sachs**, Somerville; **Tailin Fan**, Cambridge; **James F. Bredt**, Watertown; **Steven P. Michaels**, Melrose; **Satbir Khanuja**, Cambridge; **Alan Lauder**, Boston; **Sang-Joon J. Lee**, Cambridge; **David Brancazio**, Cambridge; **Alain Curodeau**, Cambridge; **Harald Tuerck**, Cambridge, all of Mass.

[73] Assignee: **Massachusetts Institute of Technology**

[58] **Field of Search** 264/63, 69, 71, 109, 264/113, 123, 128, 308; 425/130, 218, 425; 222/171

[56] **References Cited**

U.S. PATENT DOCUMENTS

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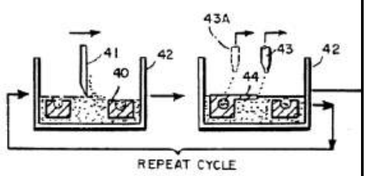
Primary Examiner–
Attorney, Agent, or
D. Pahl, Jr.



What is claimed is:

1. A process for making a component comprising the steps of

(1) depositing a preselected quantity of a powder material;
(2) spreading said powder material in a layer of preselected thickness over a predetermined confined region;
(3) applying a further material to selected regions of said layer of powder material which will cause said layer of powder material to become bonded at said selected regions;
(4) repeating steps (1), (2) and (3) a selected number of times to produce a selected number of successive layers, said further material causing said successive layers to become bonded to each other;
(5) removing unbonded powder material which is not at said one or more selected regions to provide the component.

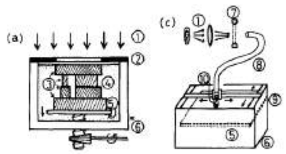
2. A process as set forth in claim **1** wherein said powder comprises essentially spherical particles.

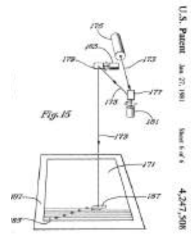
MIT 3D printer v1.1

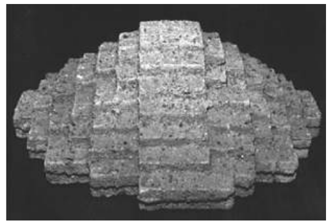
Photo taken in Fall 2013 at MIT IDC

Earlier AM parts (arguably not the earliest)

Photopolymerization
Kodama, 1981 (Rev Sci Instr)







Sintering of metal/ceramic powder
Housholder, 1979 (Patent)

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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.

The term **'3D printing'** is increasingly used as a synonym for AM. However, the latter is more accurate in that it describes a professional production technique which is clearly distinguished from conventional methods of material removal.

From the International Committee F42 for Additive Manufacturing Technologies, ASTM.
and http://www.eos.info/additive_manufacturing/for_technology_interested

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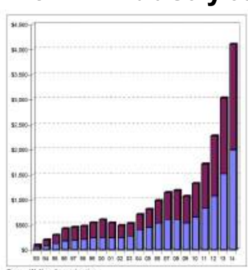
The AM industry today



Services

Machines

Wohlers report 2015

2014: $4.1B AM machines and services

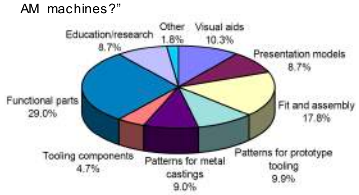
2014 growth = 35%

26-year CAGR = 27%

Worldwide mfg is ~$15 trillion (16% of the world economy)

AM = 0.03%.

"How do you use the parts made on your industrial AM machines?"



Orthodontic aligners
(Align Tech)

Ti64 hip implant cups
(Arcam)

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Some References

- Section 20.3 (through 20.3.6): Additive Processes.
  From Manufacturing Engineering and Technology 7th edition, Kalpakjian.
- Standard Terminology for Additive Manufacturing Technologies ASTM F2792 (2010)
- i.Materialise 3D printing processing and materials guide, e.g. https://i.materialise.com/materials/abs/design-guide
- 3D Printing Scales Up. From *The Economist*.
- Harvard Business Review: The 3D Printing Revolution

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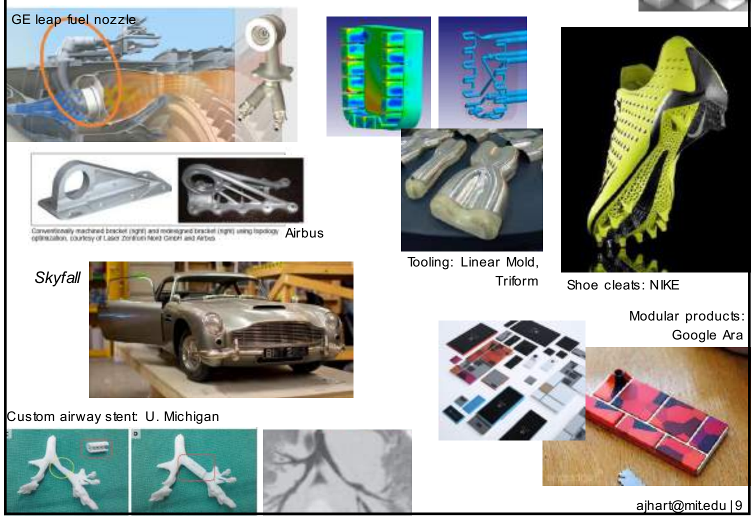
The diverse industrial uses of AM



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What AM / 3DP processes have you used?

What did you think of those?

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How good is additive manufacturing?

Rate

Quality

Cost

Flexibility

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Why is AM the big thing now?

- Wide availability of CAD/CAM software.
- Improved equipment and component technologies, especially low-cost motion systems and high-power lasers.
- A wider library of ‘printable’ materials (filaments, powders, photocurable resins, blends, etc.)
- Freedom to operate enabled by patent expirations.
- Major industry and government initiatives.
- Momentum, confidence, and creative vision.

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THE BIG IDEA

THE 3-D PRINTING REVOLUTION

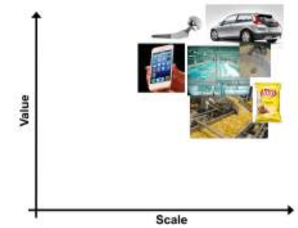
IT'S HAPPENING, AND IT WILL TRANSFORM YOUR OPERATIONS AND STRATEGY

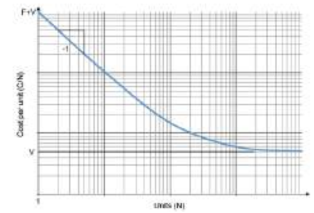
by Richard D'Aveni

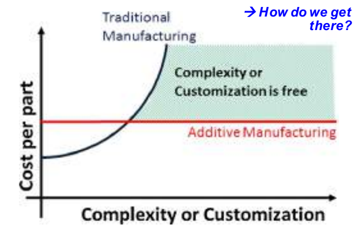
Industrial 3-D printing is at a tipping point, about to go mainstream in a big way. Most executives and many engineers don't realize it, but this technology has moved well beyond prototyping, rapid tooling, trinkets, and toys. "Additive manufacturing" is creating durable and safe products for sale to real customers in moderate to large quantities.

R. D'Aveni, Harvard Business Review, May 2015

AM lets us rethink *value at scale*







Conner et al. *Additive Manufacturing* 2014.

Conner et al. *Additive Manufacturing* 2014.

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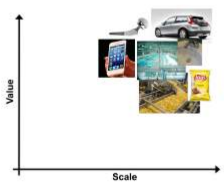
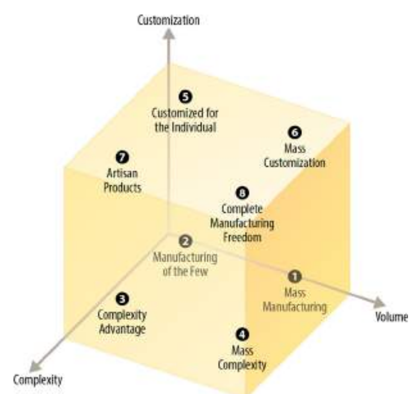
Dream: complete manufacturing freedom





Conner et al. *Additive Manufacturing* 2014.

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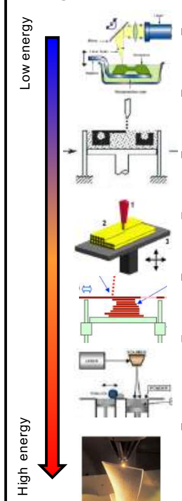
The 7 AM methods (from ASTM F42)



- Vat photopolymerization (→ SLA): material is cured by light-activated polymerization.
- Material jetting (→ Objet): droplets of build material are jetted to form an object.
- Binder jetting (→ 3DP): liquid bonding agent is jetted to join powder materials.
- **Material extrusion (→ FDM)**: material is selectively dispensed through a nozzle and solidifies.
- Sheet lamination (→ LOM): sheets are bonded to form an object.
- **Powder bed fusion (→ SLS/SLM)**: energy (typically a laser or electron beam) is used to selectively fuse regions of a powder bed.
- Directed energy deposition (→ LENS): focused thermal energy is used to fuse materials by melting as deposition occurs.

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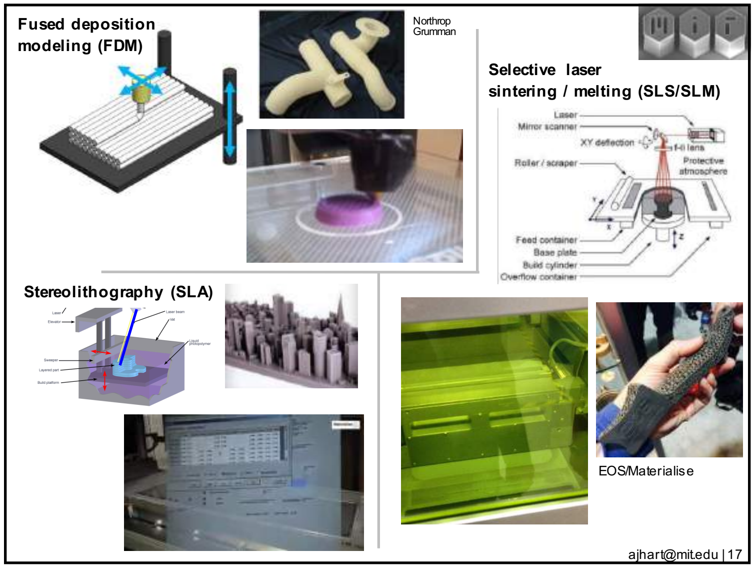
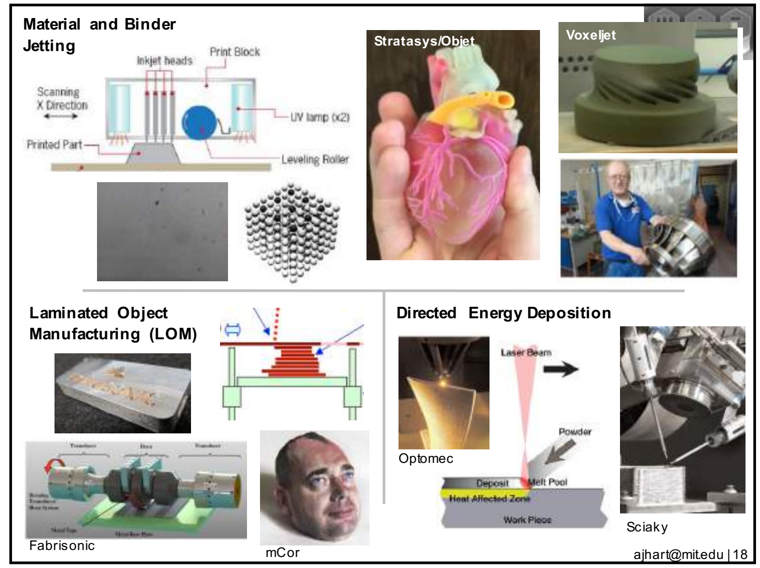
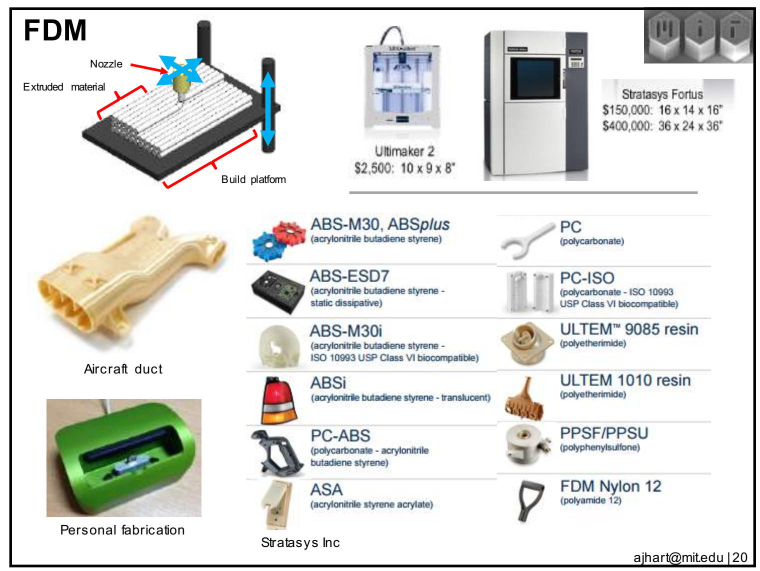




Fused Deposition Modeling (FDM)



What the part looks like (always)

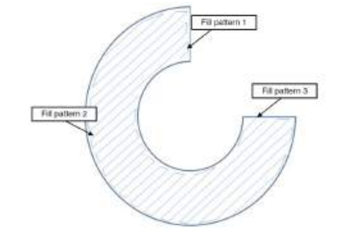
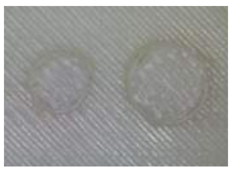


Fig. 6.3 A typical fill pattern using an extrusion-based system, created in three stages (adapted from [5])



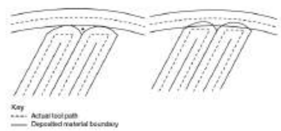


Fig. 6.5 Extrusion of materials to maximize precision (*left*) or material strength (*right*) by controlling voids

Custom made parts; figures from Gibson, Rosen and Stucker, Additive Manufacturing Technologies

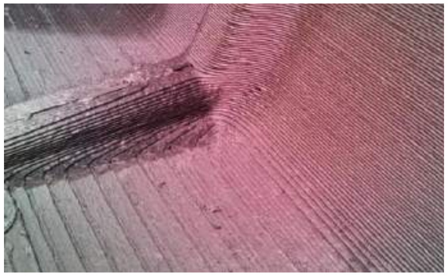
Big area additive manufacturing (BAAM!)

Feedstock

- Chopped carbon fiber ABS blend
- ~1/2" (~10 mm) bead size (= resolution)

At IMTS 2014, https://www.dropbox.com/s/snjr9eqchkxobze/BAAM-IMTS2014-close.MOV?dl=0

BAAM part quality



Fiber composites (Markforged)

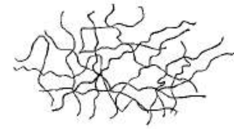
Pipe bending fixture

Integrated electronics (Voxel8)

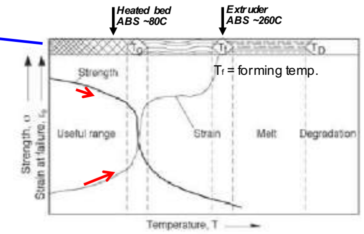
X-ray of printed quadrotor

Polymer extrusion in FDM

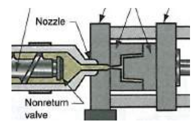
Thermoplastic
→ amorphous polymer network, linear chain architecture

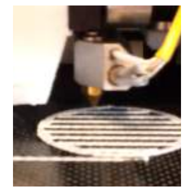


The chains align then slip during flow

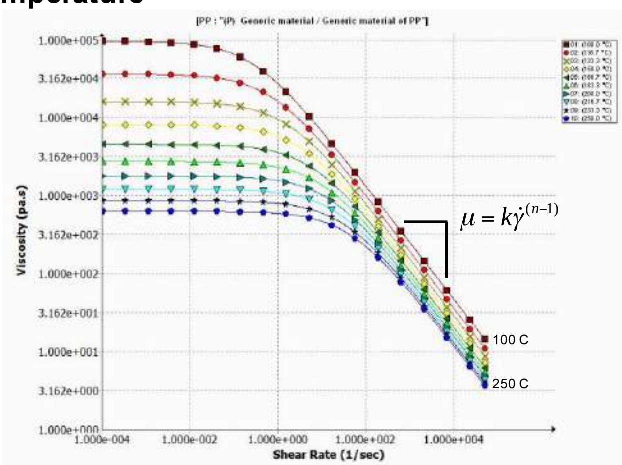


Comparison to injection into a mold



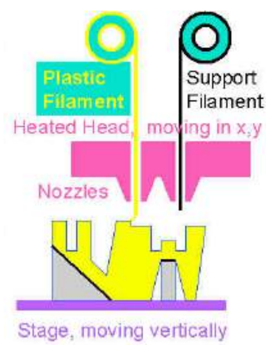


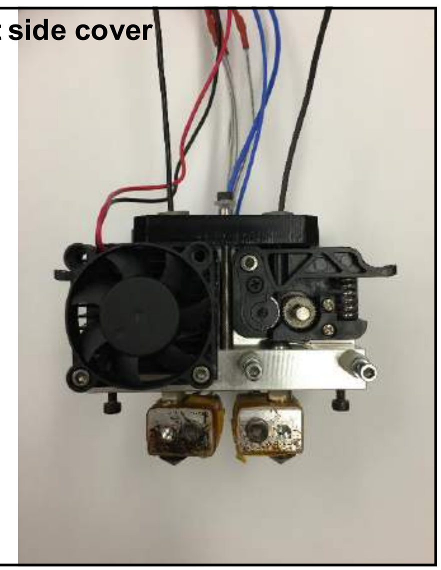
Viscosity of versus shear rate and temperature



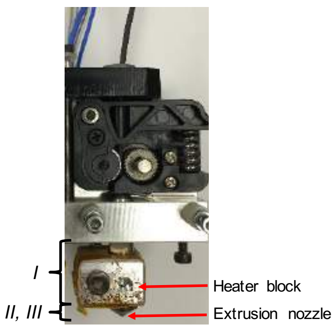
From Solidworks Plastics

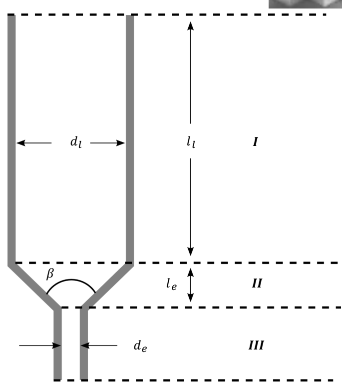
A dual extruder (right side cover removed)





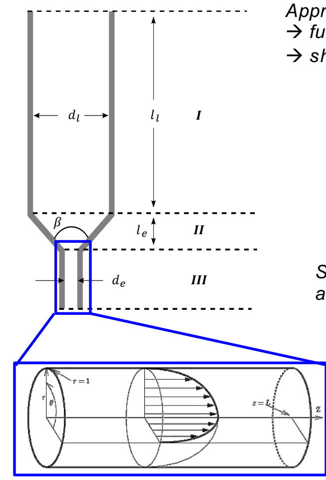
Geometry of the FDM nozzle





Zone I: heating
Zone II: transition
Zone III: area reduction (dominates pressure drop)

Model of the FDM nozzle



Approximate the nozzle (zone III) as a pipe
→ fully-developed laminar flow
→ shear thinning behavior (n <1)

$$\frac{dp}{dz} = \mu \frac{1}{r}\frac{d}{dr}\left(r\frac{du_z}{dr}\right)$$

$$\mu = k\dot{\gamma}^{(n-1)} \qquad \dot{\gamma} = \frac{d^2 u_z}{dr^2}$$

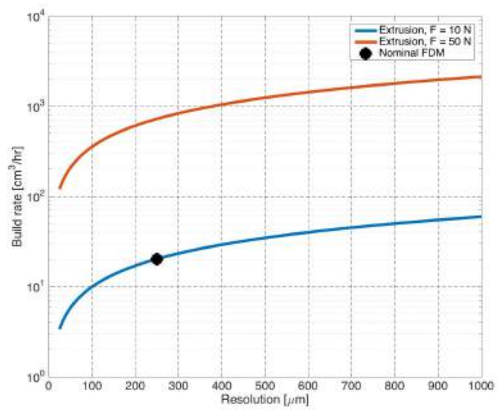
Solving the above gives:

$$Q = \frac{\pi R^3}{\frac{1}{n}+3}\left(\frac{\Delta P R}{2Lk}\right)^{1/n}$$

if Newtonian behavior (n=1)

$$Q = \frac{\pi R^4 \Delta P}{8\mu L}, F = \frac{8\mu L}{\pi R^2}$$

Build rate at constant extrusion force

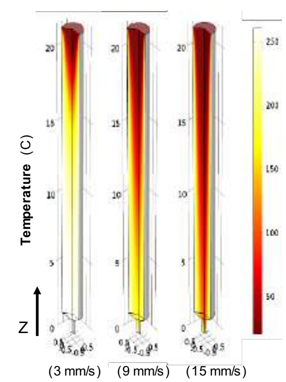


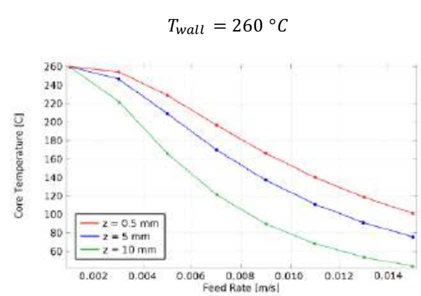
Higher build rate at constant force requires improved heating

Finer resolution requires faster gantry motion

Extrusion rate is limited by heat transfer

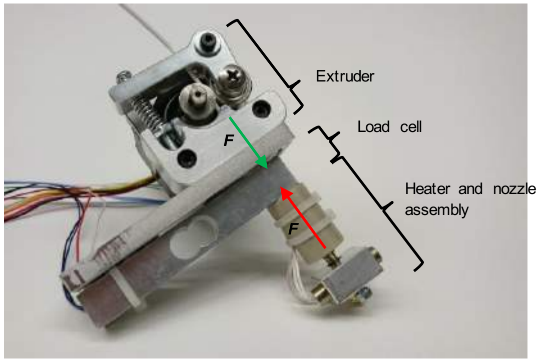
→ Feed rates found to cause extrusion failure correspond with inadequate filament core temperatures



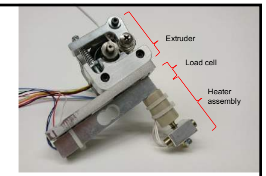


Jamison Go, Scott Schiffres

Measuring FDM extrusion force



Extrusion force vs temperature

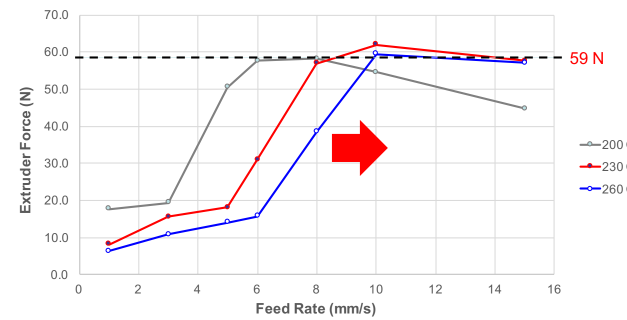


What do you expect to see?

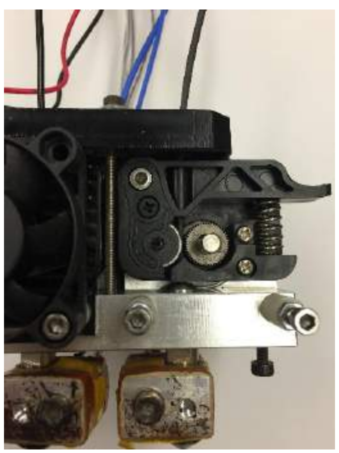
→ Force increases with feed rate

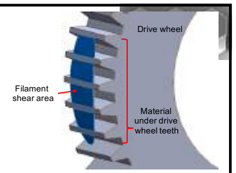
→ Force is greater at lower temperature

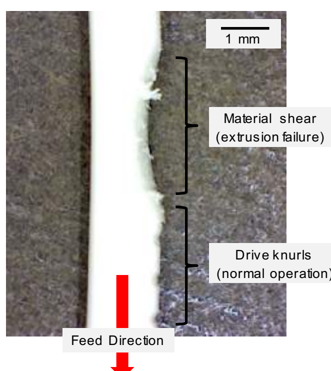
→ Force saturates at ~59 N



Shear failure of the filament



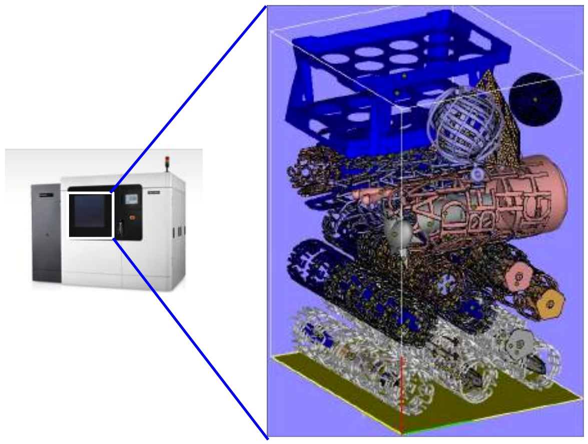




What does "mass production" look like?

http://www.stratasys.com/3d-printers/production-series/~/media/Image%20Gallery/900mc_row_of_machines.jpg

Increasing throughput: Shapeways printbed optimization



Production must master the whole process

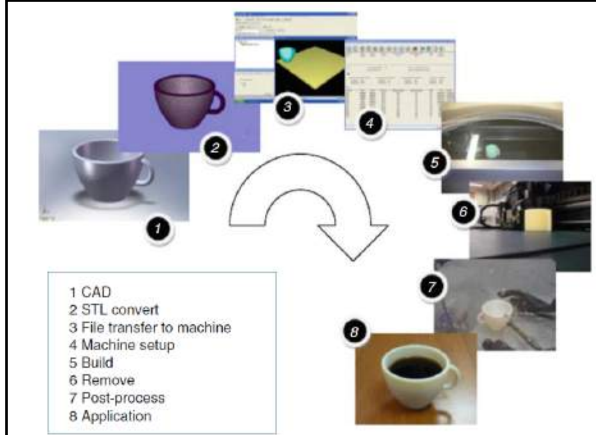


Fig. 1.2 Generic process of CAD to part, showing all 8 stages

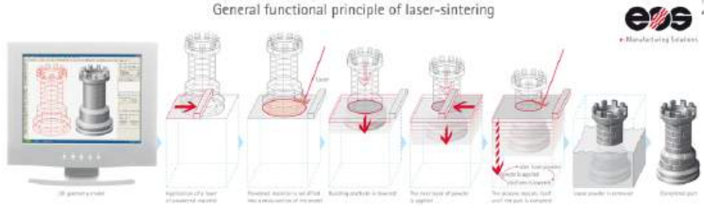
Gibson, Rosen and Stucker, Additive Manufacturing Technologies

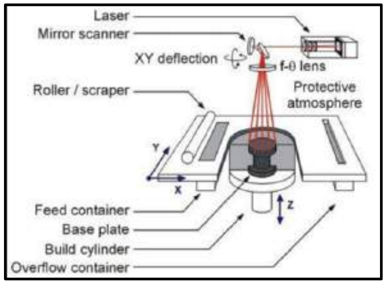
Invisalign continuous manufacturing

Selective Laser Melting (SLM)

Selective laser sintering/melting (SLS/SLM)

General functional principle of laser-sintering





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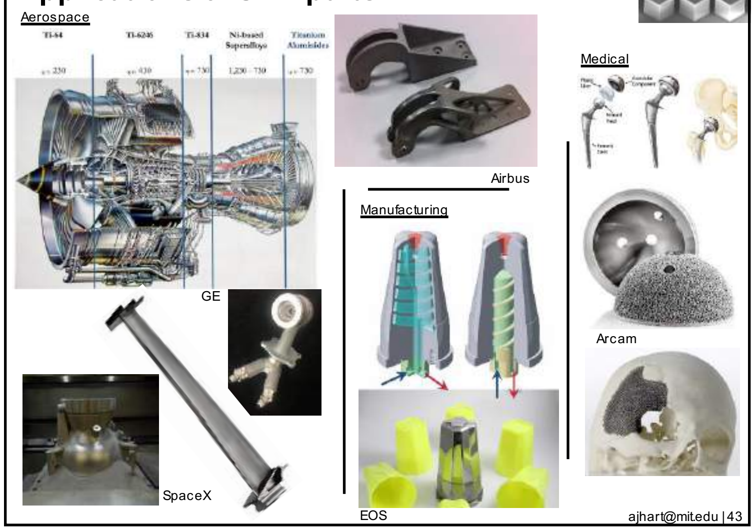
Applications of SLM parts



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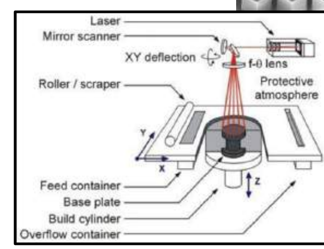
Critical process parameters: SLS/SLM

- Particle size and packing density
- Layer uniformity and thickness
- Bed temperature
- Laser speed
- Laser power
- Laser scan pattern
- Other?



In all cases!

- Control of process (temperatures, laser exposure, rate), porosity, mechanics all inextricably linked.
- Parasitic heating, material evolution, and shrinkage are critical issues and introduce machine design complexity (discuss later).

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Success! Lots of parts in close proximity.

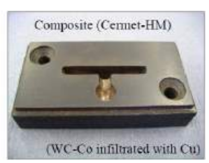
Ti frame = 1400g
Renishaw laser melting
- http://www.core77.com/blog/digital_fabrication/from_the_uk_the_worlds_first_3d-printed_bike_frame_26463.asp

What's different for SLM? (vs. FDM, SLA)

- Powder = can be ~anything (flexibility, bulk properties!)
  - Typically ~10-100um diameter (wide size distribution)
- Complexity of powder handling (why?)
  - Flammable
  - Inhalation risk
  - Oxidation/contamination → often need inert atmosphere for metals
- Energy required = high
  - SLA: 0.1 W for photopolymerization (at ~1 m/s scan)
  - FDM: 1-10 W for melting the filament
  - SLM: 100-1000 W for melting the powder (at 1-10 m/s scan)
- Post-processing: powder removal, machining away metal support.

Example powder-fused parts

Dyson



From J.P. Kruth; see also Nike shoe, GE nozzle, Airbus brackets

at Nanyang Technological University (Singapore) August 2014

Lasers: wavelength and absorption

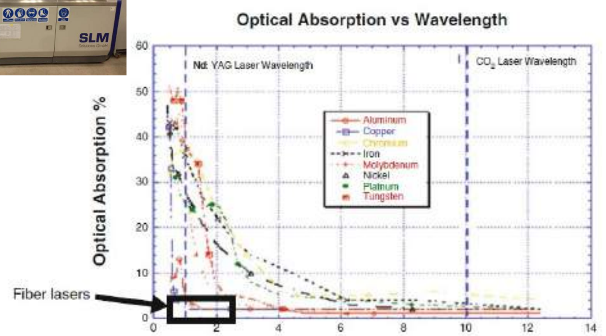
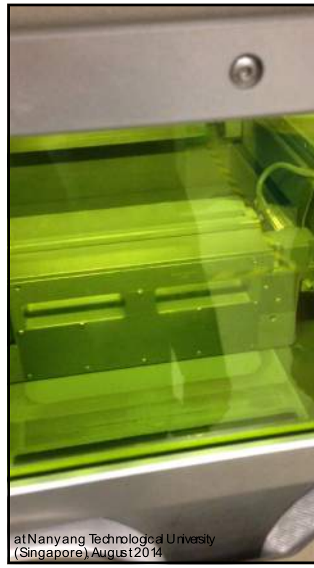
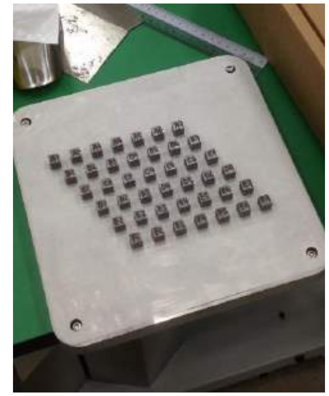


Fig. 5.10 Optical Absorption % (absorptivity) of selected metals vs. wavelength (courtesy Optomec)

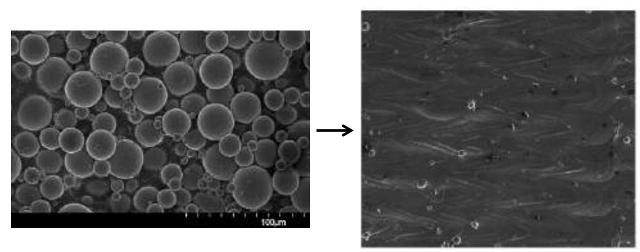




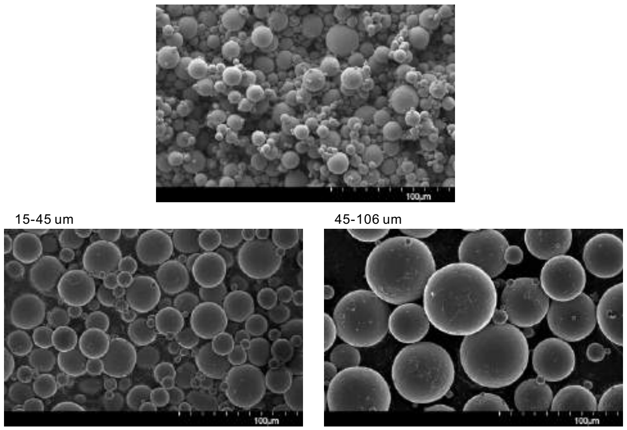
Powder AM: full process cycle

- Mount platform, home/calibrate
- Heat bed
- Perform cycle (many repeats)
  - Coat powder
  - Bind powder (i.e., laser scan causing melting)
- Cool
- Remove platform
- Dismount part and clean excess powder
- Post-process, such as.
  - Remove support (e.g. CNC mill, wire EDM)
  - Finish surface (e.g., polish- can also re-melt the surface in situ)
  - Anneal
  - Machine, assemble, etc. for final use.

Before and after



Ti6Al4V powder: various sizes



From advancedpowders.com

SLM: Mechanism

Cross-section of SLM part

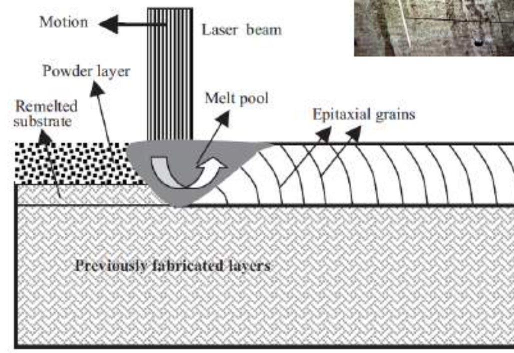


Fig. 2. Laser Material Interaction in SLS.

Prof. JP Kruth says…

Part and material properties in selective laser melting of metals

J.-P. Kruth[1*], M. Badrossamay[1], E.Yasa[1], J. Deckers[1], L. Thijs[2], J. Van Humbeeck[2]
[1]Department of Mechanical Engineering, Catholic University of Leuven, Leuven, Belgium
[2]Department of Metallurgy and Materials Engineering, Catholic University of Leuven, Leuven, Belgium
*Email: Jean-Pierre.Kruth@mech.kuleuven.be

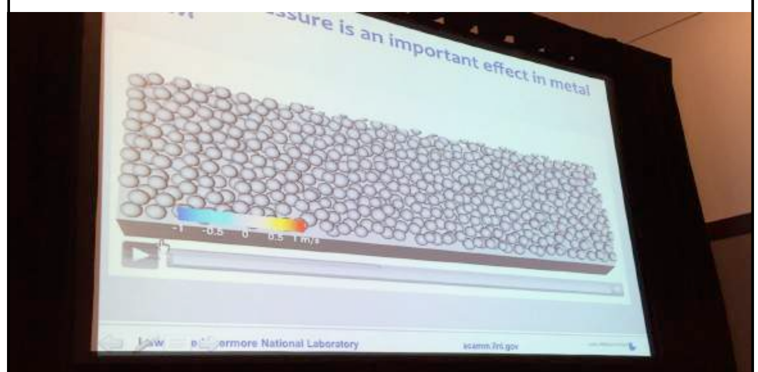
During SLM, **the short interaction of powder bed and heat source caused by the high scanning speed of the laser beam leads to rapid heating, melting followed by drastic shrinkage (from 50% powder apparent density to ~100% density in one step), and circulation of the molten metal driven by surface tension gradients coupled with temperature gradients**.

The resulting heat transfer and fluid flow affect the size and shape of the melt pool, the cooling rate, and the transformation reactions in the melt pool and heat-affected zone.

The melt pool geometry, in turn, influences the grain growth and the resulting microstructure of the part.

Chaos in the melt pool!

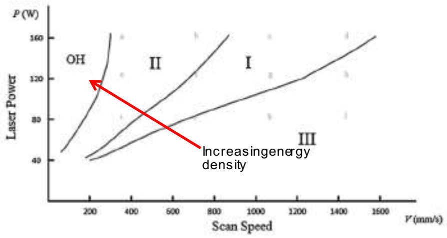
→ Evaporation and recoil
→ Ejection of 'sparks' (hot droplets)

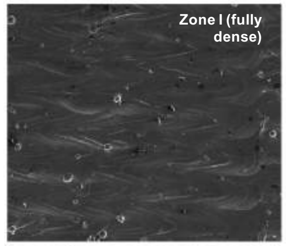


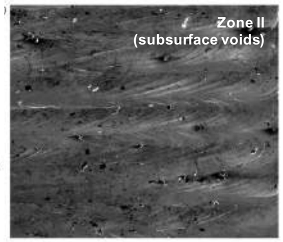
Presented by Dr. Wayne King (LLNL) at ASME AM3D 2015

Process map: SLM of Ti64

Zone I: Fully dense (few defects)
Zone II: Sub-surface porosity due to excess heating (gas bubble generation, trapped, do not appear on surface)
Zone III: Insufficient melting
OH: Serious surface deformation (jams recoater)







Gong, *et al*, "Analysis of defect generation in Ti-6Al-4V parts made using powder bed fusion additive manufacturing processes," Additive Manufacturing 2014.

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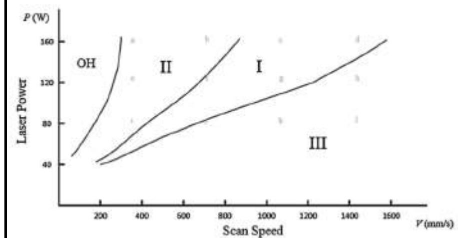
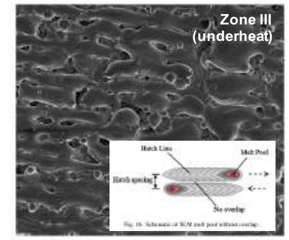
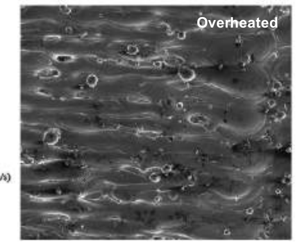
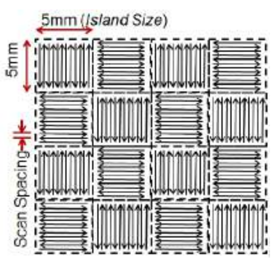




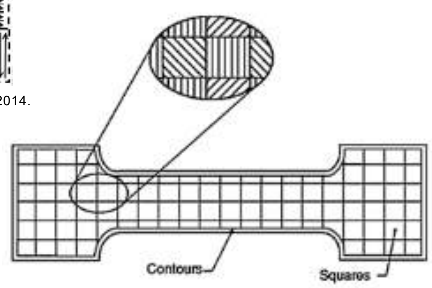


Gong, *et al*, "Analysis of defect generation in Ti-6Al-4V parts made using powder bed fusion additive manufacturing processes," Additive Manufacturing 2014.

Typical (general) scan patterns



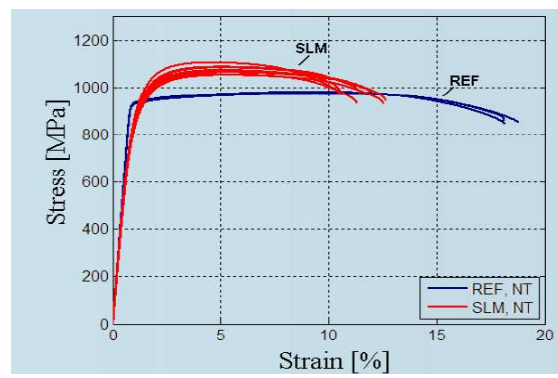
Carter et al. *J. Alloys and Compounds* 2014.



Rosen et al. 2014

Mechanical properties of SLM Ti64

→ Fine microstructure = high strength
→ Small defects = lower ductility than standard (wrought) material
→ Highly dependent on process parameters including post-print annealing!



J.P. Kruth (KU Leuven)

SLM productivity analysis

EOS M 400

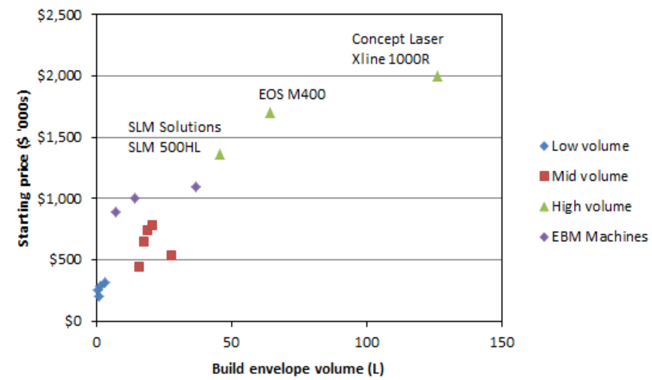
"For Industrial Production of High-Quality Large Metal Parts"

12h 7min per part

- 6 pieces, identical
- Layer thickness: 90µm
- Material: EOS AluminumAlSi10Mg
- Build rate: 105 cm^3/h
- Platform Temperature: 200C
- Inert Gas: N2

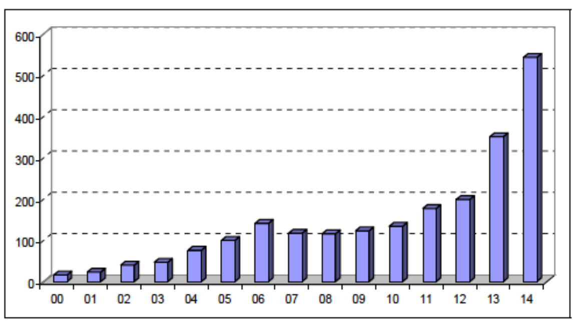
Cycle time analysis		
Set-up	42min	0.96 %
Heat	60min	1.38 %
Flood	30min	0.69 %
Exposure	67h 16min	92.55 %
Recoat	1h 42min	2.34 %
Cool-down	55min	1.26 %
Removal	36min	0.83 %
Total time	4361min	100 %

Machine cost: metal SLM and EBM



From manufacturer data, 2015.

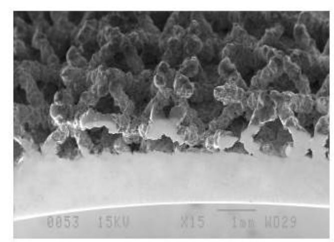
Metal 3DP machine sales growing fast (# machines versus year)



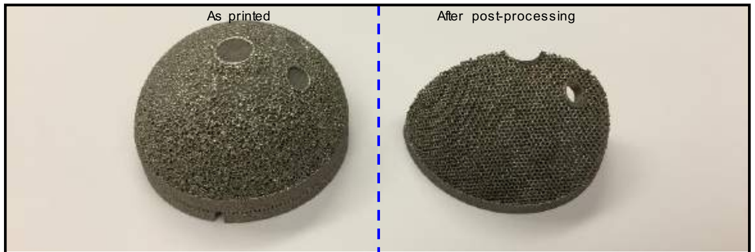
Wohlers Report 2014 (not for distribution).

Ti6Al4V hip implant cups

- >40,000 acetabular (hip cup) implants in patients (Wohlers 2014); approved in Europe and US.
- Surface texture promotes osseointegration (bone attachment).
- Arcam (EBM):
  - "now allows the ability to specify pore geometry, pore size, and density and roughness of structures for trabecular structures and surfaces."
  - 16 cups built simultaneously in 8 hours → then post-processing (intensive).



EOS/Arcam/Within; orthoinfo.aaos.org/topic.cfm?topic=a00377

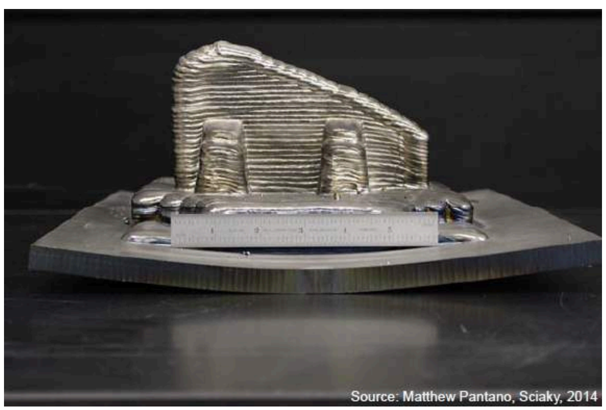


Large-scale: wire-feed E-beam melting

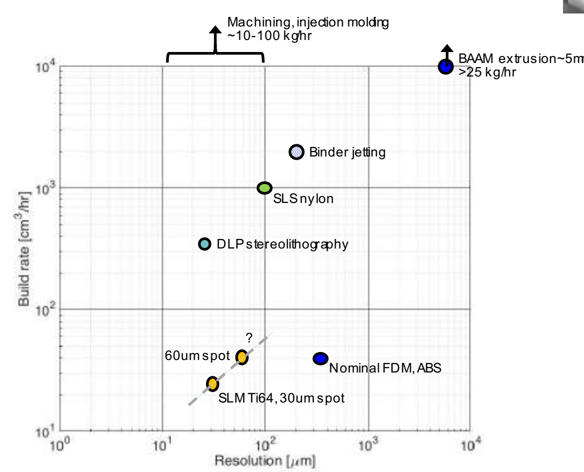
- Chamber: 300” (7.6m) x 108” x 132”
- Work volume: 280” (7.1m) x 48” x 48”
- Vacuum = 5×10^{-6} Torr
- Power = 42-60 kW

HUGE residual stress!

Solution: build on both sides of the plate



Perspective: rate and quality



Major applications and markets for AM

- Components that have advantageous performance if made by AM:
  - e.g., save material, enhance performance; make assemblies as one; use materials not easily otherwise formed.
  - or generate value externally, e.g., saving inventory.
  - begin with applications that can embrace low volume and high unit cost, e.g., aerospace, boutique.
- High value personalized products (e.g., dental, medical).
- Rapid prototyping (and short run manufacturing) and tooling (becoming compelling vs. CNC machining).

The hype curve

Challenges for wider adoption of AM

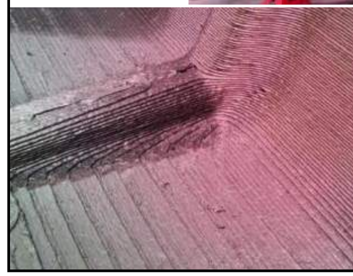
- Machine cost (barrier to entry, limited volume)
- Material cost (specialized, limited volume)
- Throughput (AM is pretty slow..)
- Quality (e.g., surface finish, residual stress)
- Process control (feedback and metrics enable higher quality at faster rate)
- Increased validation and demonstration, supported by standards for certification and process operation.
- EDUCATION (knowledge@ MIT 1988 vs. 2015)

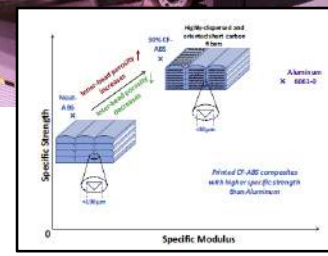
Five important emerging AM technologies

1. Large extrusion AM

ORNL, Cincinnati Machine, Local Motors, Lockheed Martin

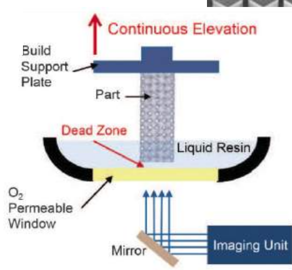
At IMTS 2014, https://www.dropbox.com/s/snjr9eqchkxobze/BAAM-IMTS2014-close.MOV?dl=0

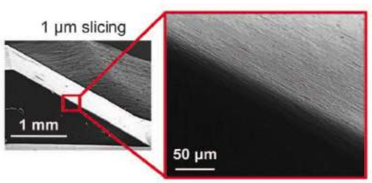




Tekinalp et al. *Comp Sci Tech* 2015.

2. High-speed polymer AM, e.g. continuous liquid interphase production (CLIP; Carbon3D)





Dead zone thickness ~20-30 µm

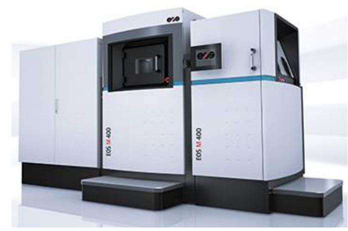
Ford / carbon3D

Legacy effects / carbon3D

carbon3d.com/ Tumbleston et al. *Science*, 2015.

TED talk by Prof. Joe DeSimone: https://www.ted.com/talks/joe_desimone_what_if_3d_printing_was_25x_faster?language=en

3. High productivity SLM



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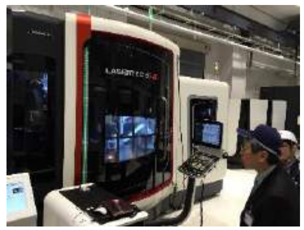
Set-up	42min	0.96 %
Heat	60min	1.38 %
Flood	30min	0.69 %
Exposure	**67h 16min**	**92.55 %**
Recoat	1h 42min	2.34 %
Cool-down	55min	1.26 %
Removal	36min	0.83 %
Total time	**72h 41min**	**100 %**

EOS / Concept Laser

4. Hybrid additive and subtractive



DMG Mori Tokyo, Jan 2015

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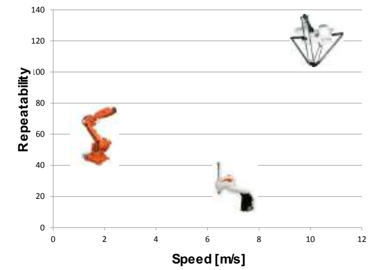
5. Electronics and robotics



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The future: AM includes everything

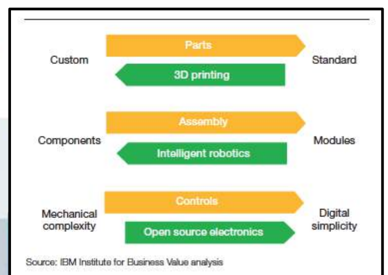

Figure 5: Traditional product design and manufacturing rules are being rewritten today in the digital era.

http://www-935.ibm.com/services/us/gbs/thoughtleadership/software-defined-supply-chain/

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Thank you

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