Additive Manufacturing

John Hart (ajhart@mit.edu)
MIT 2.810
December 2, 2013

Making news recently.

London museum turns 3D-printed Liberator guns into works of art

By Matt Brian posted Sep 16th, 2013 at 6:15 AM

MANUFACTURING TECHONOMY DETROIT

EMAIL PRINT

Can 3D Printing Revive America's Middle Class?

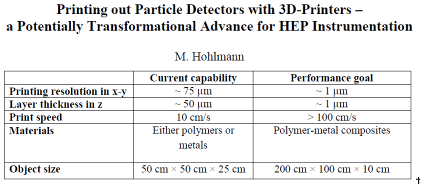
By Marleen Vogelaar | September 16, 2013, 1:25 PM | Techonomy Exclusive

Shapeways Shop Owner Stijn van der Linden of Virtox designs holds the popular selling Gyro Cube.

3D printing has been posited as the catalyst of the next industrial revolution. To make a difference to America's middle class, whose median annual household income has dropped by more than $4,000 since 2000, the technology will have to bring about an economy as bustling as the first industrial revolution.

Fewer than one-third of Americans believe economic conditions will improve next year. Could 3D printing turn things around?

http://techonomy.com/2013/09/can-3d-printing-revive-americas-middle-class/



Printing out Particle Detectors with 3D-Printers –
a Potentially Transformational Advance for HEP Instrumentation

M. Hohlmann

	Current capability	Performance goal
Printing resolution in x-y	~ 75 µm	~ 1 µm
Layer thickness in z	~ 50 µm	~ 1 µm
Print speed	10 cm/s	> 100 cm/s
Materials	Either polymers or metals	Polymer-metal composites
Object size	50 cm × 50 cm × 25 cm	200 cm × 100 cm × 10 cm

What is Additive Manufacturing?

- 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).

- 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. Instead of milling a workpiece from solid block, for example, AM builds up components layer by layer using materials which are available in fine powder form. A range of different metals, plastics and composite materials may be used.

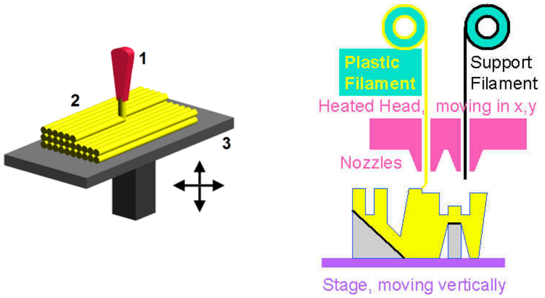
From http://www.eos.info/additive_manufacturing/for_technology_interested

References

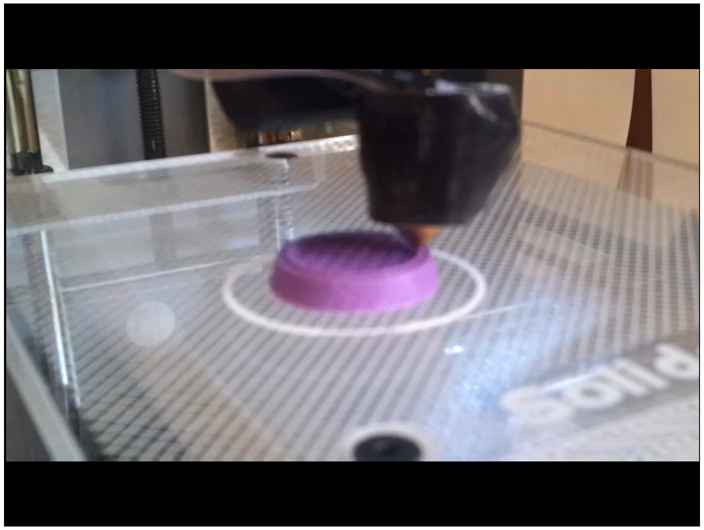
- Textbook: Ian Gibson, David W. Rosen, Brent Stucker. Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing. http://library.mit.edu/item/001725616 (full text access via MIT-SFX)
- Popular interest book: Hod Lipson and Melba Kurman. Fabricated: The New World of 3D Printing. http://www.amazon.com/Fabricated-The-New-World-Printing/dp/1118350634
- Good online reference: http://www.solidconcepts.com/
- Wikipedia is (surprisingly) sparse on technical details of AM.

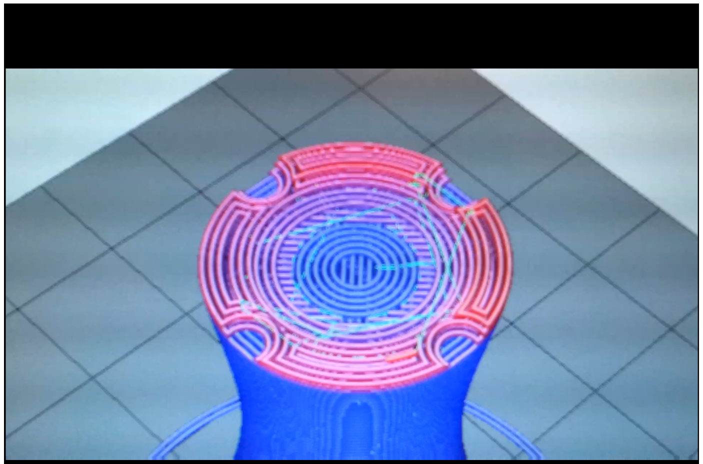
Fused deposition modeling (FDM)

- A nozzle deposits molten polymer by an extrusion head onto a support structure or the part layer-by-layer.



http://www.cs.berkeley.edu/~sequin/CAFFE/cyberbuild.html





+ camera on rook texture

www.3ders.org/pricecompare/3dprinters/

www.3ders.org
3D printer and 3D printing news

Home | Videos | Blog | Stats | 3D Printing Basics

Price compare - 3D printers

General | Details

Shop	Country	Manufacturer	Model	Assembled	Build envelope (W x D x H mm)	Image	Technology	Price (US$)	Lead time
Makible	Hong Kong	Makible	A6 LT no heat bed	DIY kit	150x110x90		FFF	$ 200.00	Not available yet
Printrbot	USA	Printrbot	Printrbot Simple	DIY kit	-		FFF	$ 299.00	-
Makible	Hong Kong	Makible	A6 HT Acrylic with heat bed	DIY kit	150x110x90		FFF	$ 300.00	Not available yet
Pirate 3D	Singapore	Pirate 3D	Buccaneer 3D printer	Yes	150x100x120		FFF	$ 347.00	Dec. 2013
Makible	Hong Kong	Makible	A6 HT Stainless	DIY kit	150x110x90		FFF	$ 350.00	Not available yet
Printrbot	USA	Printrbot	Printrbot jr	DIY kit	114x140x102		FFF	$ 399.00	2-3 weeks
Mixshop	Canada	Mixshop	Prusa Mendel Full Kit (Excluding Printed Plastic Parts)	DIY kit	200x200x140		FFF	$ 439.00	In stock
Sumpod	UK	Sumpod	Sumpod Delta	Yes	180x180x200		FFF	$ 463.00	May 2013
Mixshop	Canada	Mixshop	Mix G1 Full Kit (Including all the parts)	DIY kit	170x150x170		FFF	$ 495.00	In stock
Solidoodle	USA	Solidoodle	Solidoodle 3D Printer, 2nd Generation	Yes	152x152x152		FFF	$ 499.00	In stock
Portabee	Singapore	Portabee	Portabee 3D printer kit (unassembled)	DIY kit	120x120x120		FFF	$ 499.00	3 weeks

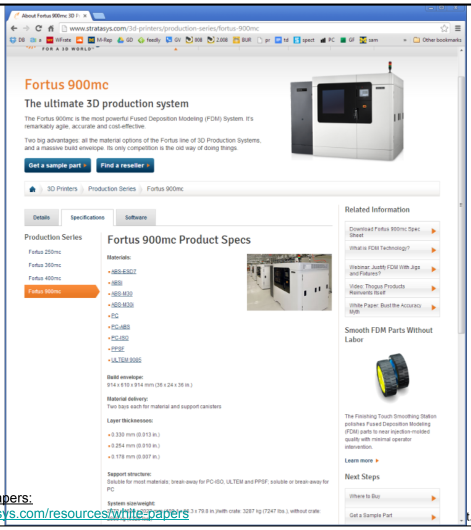
Products:
3D printers (selected)
Materials/filament

Order by:
Shop
Manufacturer
Model
Assembled
Weight
Technology
Price (selected)
Lead Time
Build Envelope
Speed
Nozzle Diameter
Layer Thickness
Positioning precision
Input format
Software
System compatibility
Power supply

Filters (Clear filters):

Countries:

Hong Kong	(3)
USA	(56)
Singapore	(4)
Canada	(6)
UK	(16)
France	(4)
India	(6)
Spain	(1)
Korea	(1)
China	(6)
Germany	(8)
Italy	(7)
Taiwan	(4)
Finland	(1)



Fortus 900mc

The ultimate 3D production system

The Fortus 900mc is the most powerful Fused Deposition Modeling (FDM) System. It's remarkably agile, accurate and cost-effective.

Two big advantages: all the material options of the Fortus line of 3D Production Systems, and a massive build envelope. Its only competition is the old way of doing things.

Fortus 900mc Product Specs

Materials:

- ABS-ESD7
- ABSi
- ABS-M30
- ABS-M30i
- PC
- PC-ABS
- PC-ISO
- PPSF
- ULTEM 9085

Build envelope:
914 x 610 x 914 mm (36 x 24 x 36 in.)

Material delivery:
Two bays each for material and support canisters

Layer thicknesses:

- 0.330 mm (0.013 in.)
- 0.254 mm (0.010 in.)
- 0.178 mm (0.007 in.)

Support structure:
Soluble for most materials; break-away for PC-ISO, ULTEM and PPSF; soluble or break-away for PC

System size/weight:
3.3 x 79.8 in.)/with crate: 3287 kg (7247 lbs.), without crate:

Related Information

- Download Fortus 900mc Spec Sheet
- What is FDM Technology?
- Webinar: Justify FDM With Jigs and Fixtures?
- Video: Thogus Products Reinvents Itself
- White Paper: Bust the Accuracy Myth

Smooth FDM Parts Without Labor

The Finishing Touch Smoothing Station polishes Fused Deposition Modeling (FDM) parts to near injection-molded quality with minimal operator intervention.

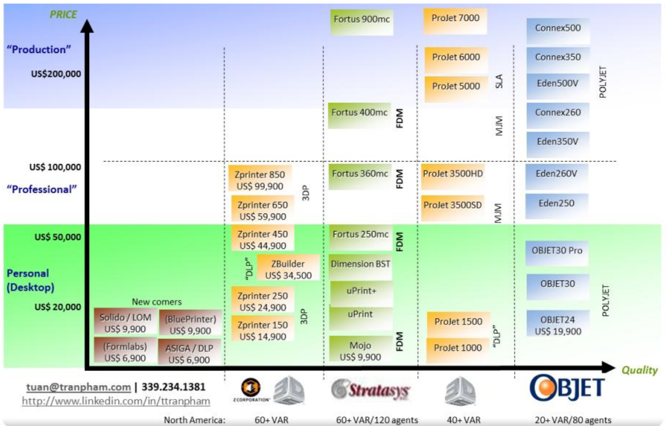
Learn more

Next Steps

- Where to Buy
- Get a Sample Part

Stratasys whitepapers:
http://www.stratasys.com/resources/white-papers

TRANPHAM Overview



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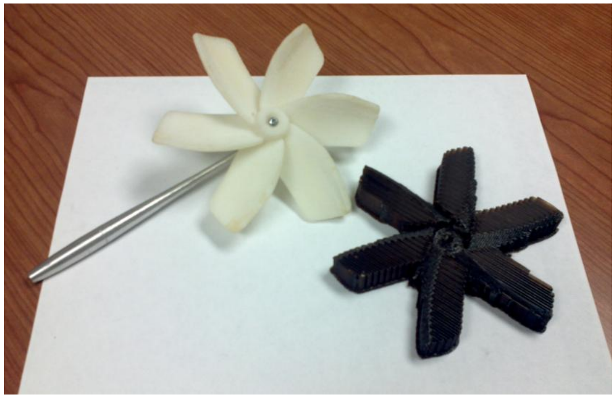
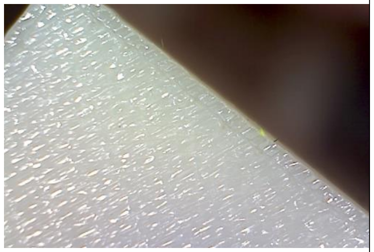
http://www.linkedin.com/in/ttranpham

North America: 60+ VAR 60+ VAR/120 agents 40+ VAR 20+ VAR/80 agents

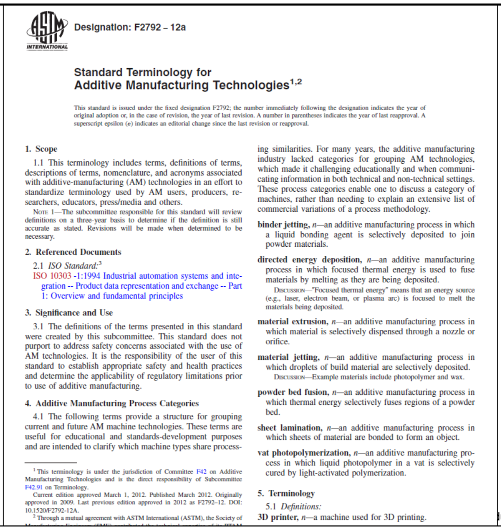
Pinwheel made by FDM (Fall 2002)



Pinwheel, 2002



Box, 2012



Designation: F2792 – 12a

Standard Terminology for Additive Manufacturing Technologies[1,2]

This standard is issued under the fixed designation F2792; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This terminology includes terms, definitions of terms, descriptions of terms, nomenclature, and acronyms associated with additive-manufacturing (AM) technologies in an effort to standardize terminology used by AM users, producers, researchers, educators, press/media and others.

NOTE 1—The subcommittee responsible for this standard will review definitions on a three-year basis to determine if the definition is still accurate as stated. Revisions will be made when determined to be necessary.

2. Referenced Documents

2.1 *ISO Standard:*[3]

ISO 10303 -1:1994 Industrial automation systems and integration -- Product data representation and exchange -- Part 1: Overview and fundamental principles

3. Significance and Use

3.1 The definitions of the terms presented in this standard were created by this subcommittee. This standard does not purport to address safety concerns associated with the use of AM technologies. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use of additive manufacturing.

4. Additive Manufacturing Process Categories

4.1 The following terms provide a structure for grouping current and future AM machine technologies. These terms are useful for educational and standards-development purposes and are intended to clarify which machine types share processing similarities. For many years, the additive manufacturing industry lacked categories for grouping AM technologies, which made it challenging educationally and when communicating information in both technical and non-technical settings. These process categories enable one to discuss a category of machines, rather than needing to explain an extensive list of commercial variations of a process methodology.

binder jetting, *n*—an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.

directed energy deposition, *n*—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

DISCUSSION—"Focused thermal energy" means that an energy source (e.g., laser, electron beam, or plasma arc) is focused to melt the materials being deposited.

material extrusion, *n*—an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.

material jetting, *n*—an additive manufacturing process in which droplets of build material are selectively deposited.

DISCUSSION—Example materials include photopolymer and wax.

powder bed fusion, *n*—an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.

sheet lamination, *n*—an additive manufacturing process in which sheets of material are bonded to form an object.

vat photopolymerization, *n*—an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

5. Terminology

5.1 *Definitions:*

3D printer, *n*—a machine used for 3D printing.

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[1] This terminology is under the jurisdiction of Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.91 on Terminology.

Current edition approved March 1, 2012. Published March 2012. Originally approved in 2009. Last previous edition approved in 2012 as F2792–12. DOI: 10.1520/F2792-12A.

[2] Through a mutual agreement with ASTM International (ASTM), the Society of

The Economist Technology Quarterly September 7th 2013 — 3D printing 7

3D printing scales up

Digital manufacturing: There is a lot of hype around 3D printing. But it is fast becoming integrated with mainstream manufacturing

PEEK through the inspection windows of the nearly 100 three-dimensional (3D) printers quietly making things at RedEye, a company based in Eden Prairie, Minnesota, and you can catch a glimpse of how factories will work in the future. It is not simply that the machines, some as big as delivery vans, run day and night attended by just a handful of technicians. Instead it is what they are making that shows how this revolutionary production process is entering the manufacturing mainstream.

3D printers make things by building them up, a layer at a time, from a particular material, rather than removing it by cutting, drilling or machining—which is why the process is also called additive manufacturing. There are many ways in which this can be done (see box on next page), and with only a tweak of software each item can be different, without the need for costly retooling of machines. This has made 3D printing a popular way to make one-off items, especially prototype parts, mock-ups, gadgets and craft items.

And that is about all that 3D printers are good for, reckon the doubters. Chief among them is Terry Gou, the boss of Foxconn, the world's largest contract manufacturer of electronic goods, which makes many of Apple's products in China. He thinks 3D printing is just "a gimmick" without any commercial value in the manufacture of real finished goods, and he has vowed to start spelling his name backwards if proved wrong.

Mr Gou (or should that be Uog?) is right about one thing: additive manufacturing is not about to replace mass manufacturing. Even though the technology is improving, the finish and durability of some printed items can still fall short of what producers require. And nor can 3D printers crank out zillions of identical parts at low cost, as mass-production lines can. Nevertheless, 3D printers have their virtues, which is why they are starting to be used by some of the world's biggest manufacturers, such as Airbus, Boeing, GE, Ford and Siemens.

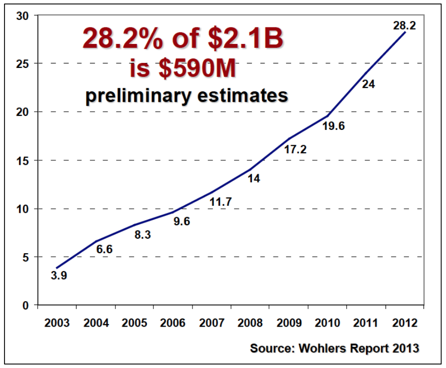
The market for 3D printers and services is small, but growing fast. Last year it was worth $2.2 billion worldwide, up 29% from 2011, according to Wohlers Associates, a consultancy. As producers become more familiar with the technology, they are moving from prototypes to final products. Last year Wohlers reckons more than 25% of the 3D-printing market involved making production-ready items.

Some of those parts are taking shape in RedEye's printers. In many cases they are low-volume items, such as components used to build specialist pharmaceutical or paper-making equipment. Other components, such as 3D-printed tools and jigs, will actually enhance mass-production: BMW's assembly-line workers design and print custom tools to make it easier to hold and position parts. 3D-printed plastic moulds and dies are also being printed to help set up and trial new production lines. Some of these printed parts are even used as temporary stand-ins for broken steel tools, which can take weeks to replace.

Hard-to-find spare parts are also being 3D printed, in one case helping a large American airline to get some of its aircraft back into the air. The carrier was frequently having to ground its ageing McDonnell Douglas MD-80 jets because of leaking toilets. Production of these aircraft ceased long ago, and the airline was struggling to find spare parts. Its new plumbing is now being 3D printed in an aerospace-grade plastic (which does not ignite or produce noxious fumes if burned).

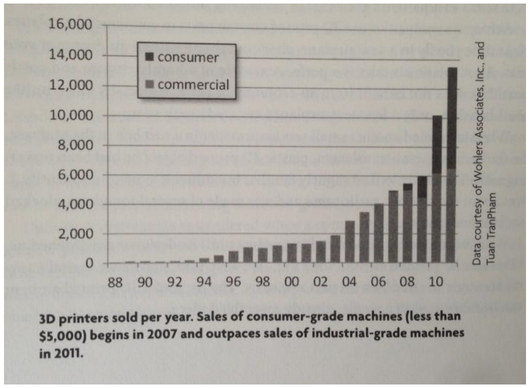
As 3D printers get better and printed materials improve, the quality and finish of prototypes is becoming harder to distinguish from things made in traditional factories, says Tim Thellin, RedEye's manager. Despite the hype around desktop 3D printers aimed at hobbyists and consumers, it is the big, industrial-grade printers that are ▸▸

(y-axis is annual growth rate of AM equipment and services market)



Source: Wohlers Report 2013

The consumer market is responsible for the hype, and huge potential?



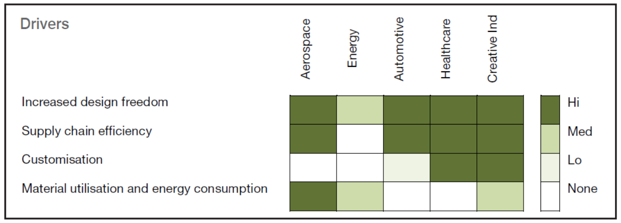
3D printers sold per year. Sales of consumer-grade machines (less than $5,000) begins in 2007 and outpaces sales of industrial-grade machines in 2011.

Lipson and Kurman, Fabricated: The New World of 3D Printing.

Industry drivers

Figure 1

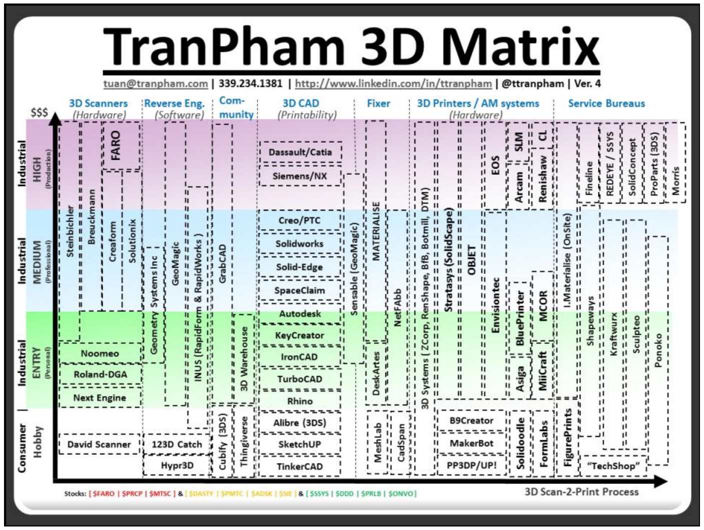
Generic drivers for AM technology adoption



Drivers	Aerospace	Energy	Automotive	Healthcare	Creative Ind
Increased design freedom	Hi	Med	Hi	Hi	Hi
Supply chain efficiency	Hi	None	Hi	Hi	Hi
Customisation	None	None	Lo	Hi	Hi
Material utilisation and energy consumption	Hi	Med	None	None	Med

🟩	Hi
🟩	Med
☐	Lo
☐	None

"SHAPING OUR NATIONAL COMPETENCY IN ADDITIVE MANUFACTURING" (UK industry interest group)"



TranPham 3D Matrix

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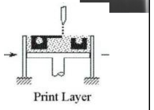
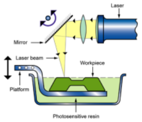
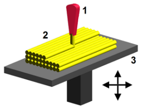
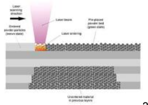
Common AM methods / classification

- **"3-D Printing"**
  - Utilizes powder or liquid resin, deposited in layers, and cured with ultraviolet light and/or heat.
  - → Sachs and Cima (MIT), Patent issued 1995, ZCorp
- **FDM – Fused Deposition Modeling**
  - A nozzle deposits molten polymer onto a support structure layer-by-layer.
  - → Scott Crump (patent 1992): Stratasys Inc
- **SLA – Stereolithography**
  - Converts liquid plastic resins and composites into solids layer-by-layer using light.
  - → Chuck Hull (patent 1986): 3D systems Inc
- **SLS – Selective Laser Sintering / Melting (SLS/SLM)**
  - Fuses powdered material (polymer, metal, or ceramic) using a laser or electron beam.
  - → UT Austin mid-1980's (Deckard, Beaman et al.)



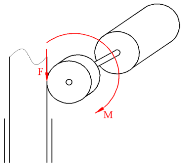


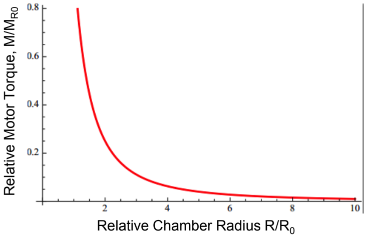




FDM physics: extrusion

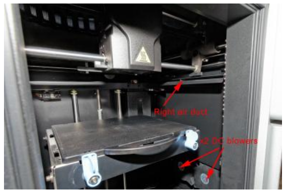
$$\Delta P = -\frac{8\mu \Delta x}{\pi R^4} Q$$

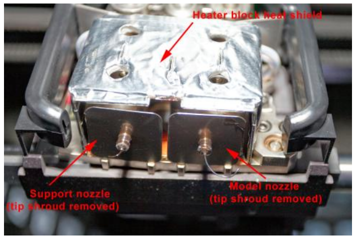




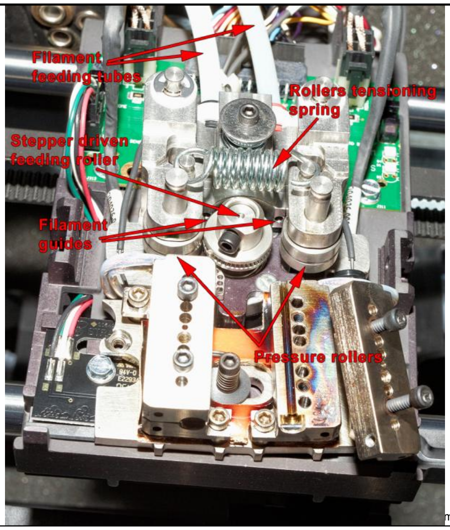
Analysis by Arjun Chandar, Aleksandra Gorkina, Andrey Vyatskikh – 2.S981 F13

The extruder (Stratasys Dimension)



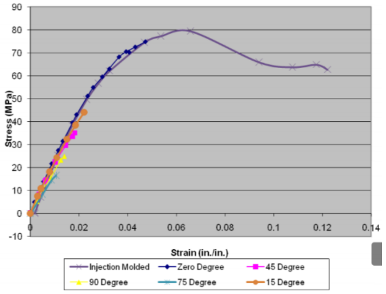


http://kisslicer.com/forum/index.php?topic=375.0



FDM part mechanical properties

Stress-Strain Curve for Various Orientation Angles
(0 deg = loaded parallel to filament)



Raster Angle	Modulus of Elasticity (MPa)	Ultimate Tensile Strength (MPa)	Yield Strength (Mp)	Ductility Elong. %
0 °	2539.40 ± 104	78.60 ±3.44	57.5 ± 4.60	4.38 ±0.15
45 °	2424.6 ±166	56.76 ±4.64	44.89 ± 4.14	3.31 ±0.38
90 °	2327.8 ±178	45.70 ±8.71	42.85 ± 6.19	2.37 ±0.81

Source: Stratasys Material Analysis for Ultem-9085

Finishing Touch Smoothing Station

FDM parts that look injection molded

Streamline your finishing process. The Finishing Touch Smoothing Station polishes Fused Deposition Modeling (FDM) parts to near injection-molded quality with minimal operator intervention.

This automated finishing system works on parts from any material in the ABS family of FDM thermoplastics, including ABSi, ABS-M30, ABS-M30i and ABSplus. More custom 3D parts are possible.

Finishing Touch Smoothing Station Specs

Chamber size:
330 x 406 x 508 mm (13 x 16 x 20 in.)

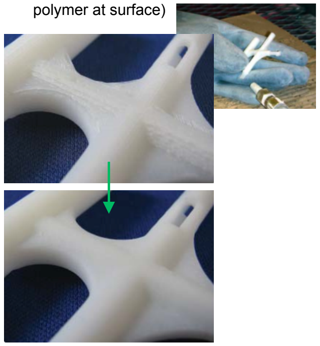
Smoothing fluid:
Order Smoothing Station Fluid directly from:
www.SmoothingFluids.com
Local regulations for use of industrial solvents should be observed.

System size/weight:
Crated: 1511.3 x 1092 x 1485.89 mm (59.5 x 43 x 58.5 in.)/~272.16 kg (~600 lbs.); uncrated: 1333.5 x 812.8 x 1168.39 mm (52.5 x 32 x 46 in.)/182 kg (400 lbs.)

Operator attendance:
Intermittent to expose parts

Operating environment:

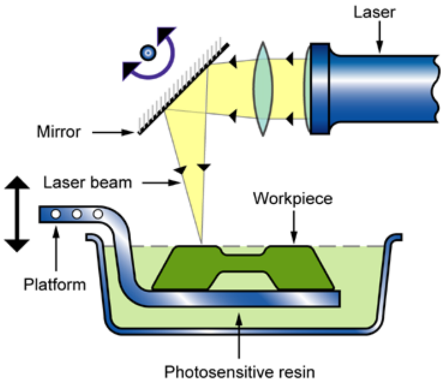
"Vapor smoothing"
(solvent vapor dissolves polymer at surface)



http://www.shapeways.com/blog/archives/295-the-stratasys-fdm-vapor-smoothing-process-for-our-white-glaze-material.html

Stereolithography (SLA)

- Principle: converts photo sensitive liquid resins and composites into solids layer-by-layer using light (usually UV)



D. Dutta

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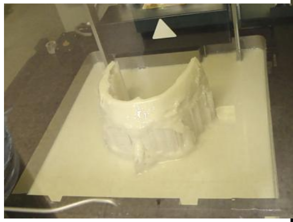
formlabs

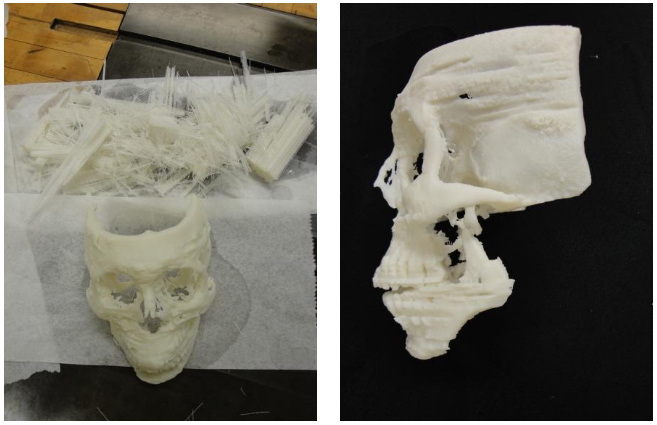
Printing Properties	**Technology:**	Stereolithography (SLA)
	Canvas Size:	125 x 125 x 165 mm 4.9 x 4.9 x 6.5 in
	Feature Size: X / Y Axis Resolution	300 microns* (0.012 in) * See F.A.Q.
	Min Layer Thickness: Z Axis Resolution	25 microns (0.001 inches)
	Supports:	Auto Generated Easily Removable
Form 1	**Dimensions:**	30 x 28 x 45 cm 12 x 11 x 18 in
	Weight:	8 kg 18 lbs
	Power Requirements:	100-240V 1.5A 50/60Hz 60W
Material Properties	• Acrylate Photopolymer Resin • Long shelf life when not exposed to light • Easily remove extra resin from parts using Form Finish • Safe to use in a controlled environment • Low environmental impact with proper disposal	

SLA skull prototype (*video)



T. Donajkowski / UMich Medical Innovation Cente

ajhart@mit.edu | 2.008-F13 | 33



$P\text{-}I \rightarrow \text{-}I\bullet$ (free radical formation)

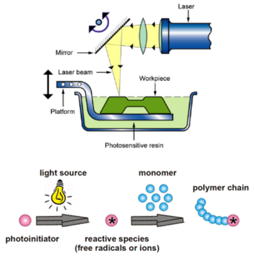
$I\bullet + M \rightarrow I\text{-}M\bullet$ (initiation)

$I\text{-}M\bullet \rightarrow \rightarrow I\text{-}M\text{-}M\text{-}M\text{-}M\ldots\text{-}M\bullet$ (propagation)

$\rightarrow I\text{-}M\text{-}M\text{-}M\text{-}M\ldots\text{-}M\text{-}I$ (termination)

Fig. 4.4 Free-radical polymerization process

Photoinitiator: converts light into free radicals to initiate chain



http://web.itu.edu.tr/

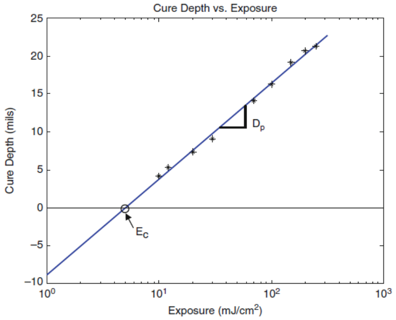
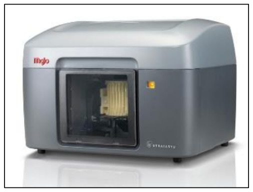


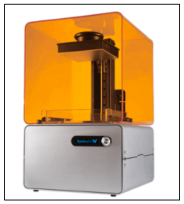
Fig. 4.8 Resin "working curve" of cure depth vs. exposure

Gibson and Rosen, Additive Manufacturing Technologies

Part comparison: FDM vs. SLA

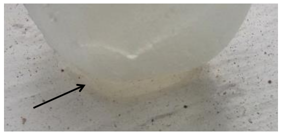


Mojo, $10,000



Form1, $4,000

A sphere made on the Form1: post-print curing



Tolerances: where is FDM, SLA?

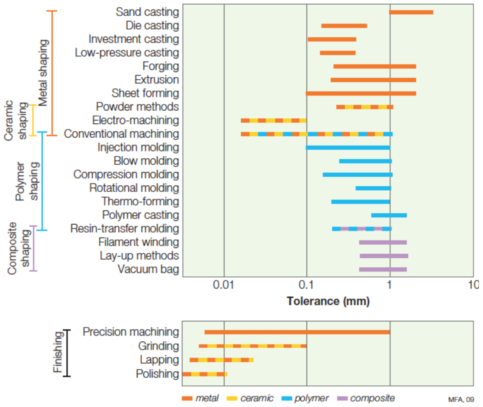


FIGURE 13.30
The process-tolerance chart. The inclusion of finishing processes allows simple process chains to be explored.

Ashby.

Surface roughness: where is FDM, SLA?

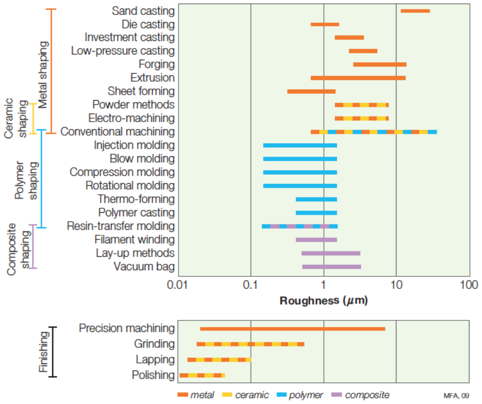
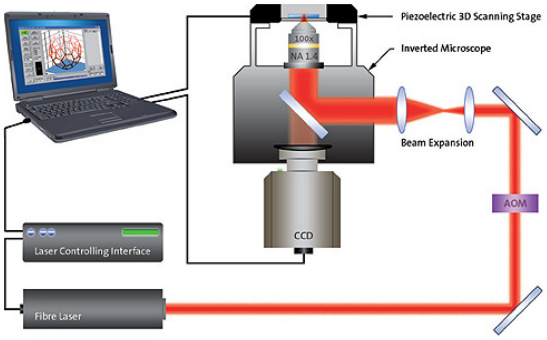


FIGURE 13.31
The process–surface roughness chart. The inclusion of finishing processes allows simple process chains to be explored.

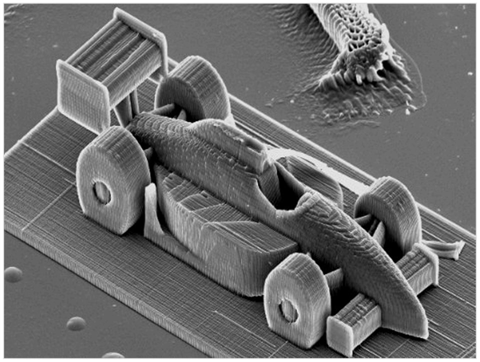
Ashby.

Micro-SLA (in some cases known as "two-photon polymerization")



nanoscribe.de

F1 car 0.285 mm long!

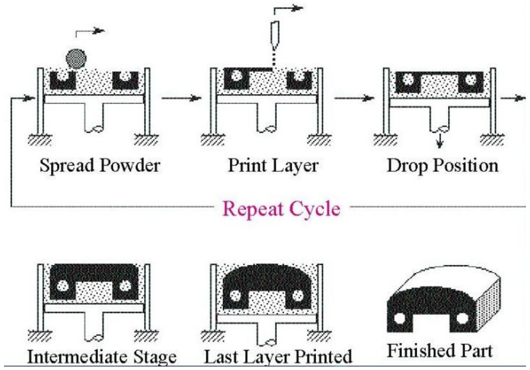


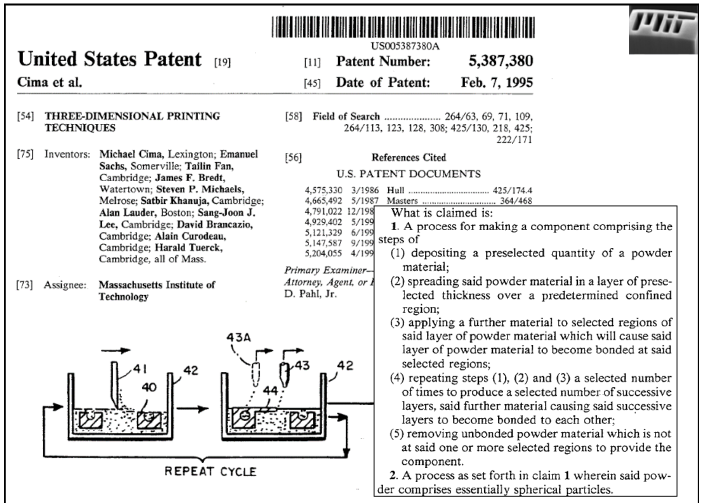
A 285-Micrometer Indy Car Printed With Two-Photon Lithography Captured by a scanning electron microscope. *Vienna University of Technology*

http://www.youtube.com/watch?feature=player_embedded&v=5y0j191H0kY#!

"3D printing" (as it was named)

- Utilizes ink-jet technology to apply binder to powder, deposited in layers, and binder is cured (optionally with added ultraviolet light and/or heat)





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

4,575,330	3/1986	Hull	425/174.4
4,665,492	5/1987	Masters	364/468
4,791,022	12/198		
4,929,402	5/199		
5,121,329	6/199		
5,147,587	9/199		
5,204,055	4/199		

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;

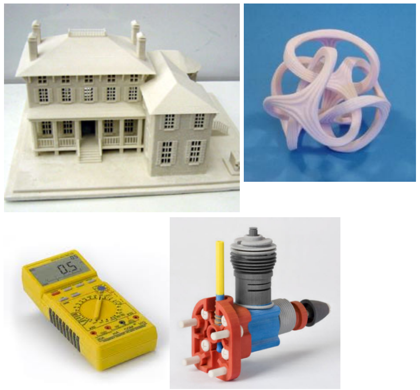
(3) applying a further material to selected regions of said layer of powder material which will cause said layer of powder material to become bonded at said selected regions;

(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.

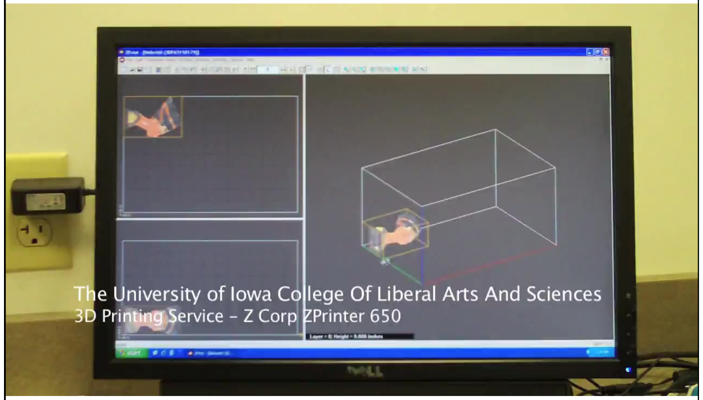
Example "3D printed" parts (quality?)



Z-corp 3D printer

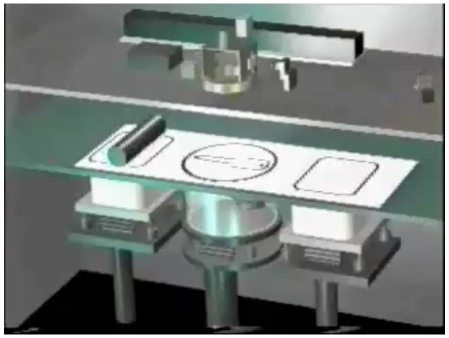
D. Dutta

Powder 3D printing (Z-Corp)



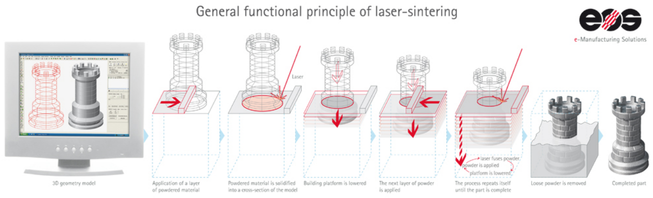
http://www.youtube.com/watch?v=OpGrFBHhlsM

Selective laser sintering (SLS)



Video from QR code in Kalpakjian (7th ed)

Selective laser sintering (SLS)

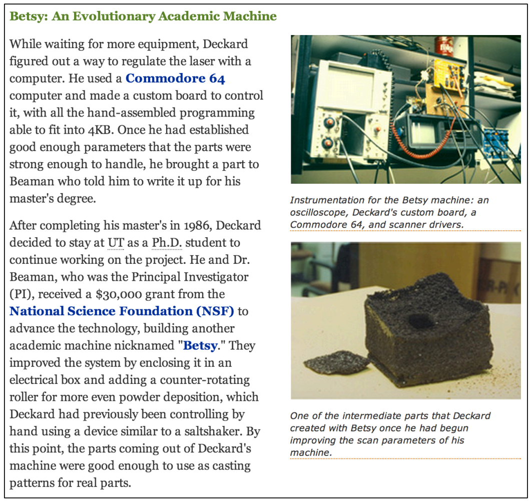


Thin layer of heat fusible powder is laid out

Laser bonds the powder together

Table indexes down.

Roller lays out a new layer of powder



Betsy: An Evolutionary Academic Machine

While waiting for more equipment, Deckard figured out a way to regulate the laser with a computer. He used a **Commodore 64** computer and made a custom board to control it, with all the hand-assembled programming able to fit into 4KB. Once he had established good enough parameters that the parts were strong enough to handle, he brought a part to Beaman who told him to write it up for his master's degree.

After completing his master's in 1986, Deckard decided to stay at UT as a Ph.D. student to continue working on the project. He and Dr. Beaman, who was the Principal Investigator (PI), received a $30,000 grant from the **National Science Foundation (NSF)** to advance the technology, building another academic machine nicknamed "**Betsy**." They improved the system by enclosing it in an electrical box and adding a counter-rotating roller for more even powder deposition, which Deckard had previously been controlling by hand using a device similar to a saltshaker. By this point, the parts coming out of Deckard's machine were good enough to use as casting patterns for real parts.

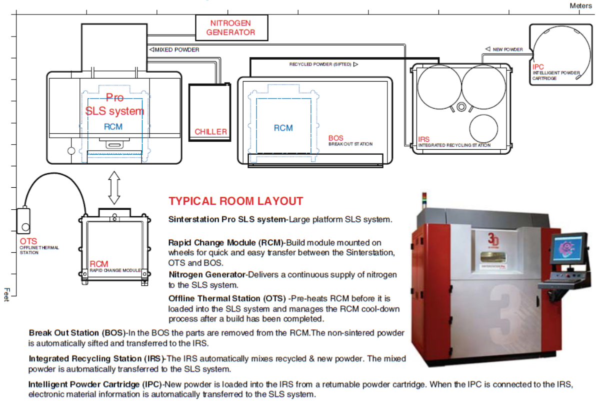
Instrumentation for the Betsy machine: an oscilloscope, Deckard's custom board, a Commodore 64, and scanner drivers.

One of the intermediate parts that Deckard created with Betsy once he had begun improving the scan parameters of his machine.

http://www.me.utexas.edu/news/2012/0712_sls_history.php (Betsy, Godzilla, Bambi, etc..)

Selective laser sintering (SLS)

Sinterstation® Pro SLS® system



TYPICAL ROOM LAYOUT

Sinterstation Pro SLS system-Large platform SLS system.

Rapid Change Module (RCM)-Build module mounted on wheels for quick and easy transfer between the Sinterstation, OTS and BOS.

Nitrogen Generator-Delivers a continuous supply of nitrogen to the SLS system.

Offline Thermal Station (OTS) -Pre-heats RCM before it is loaded into the SLS system and manages the RCM cool-down process after a build has been completed.

Break Out Station (BOS)-In the BOS the parts are removed from the RCM.The non-sintered powder is automatically sifted and transferred to the IRS.

Integrated Recycling Station (IRS)-The IRS automatically mixes recycled & new powder. The mixed powder is automatically transferred to the SLS system.

Intelligent Powder Cartridge (IPC)-New powder is loaded into the IRS from a returnable powder cartridge. When the IPC is connected to the IRS, electronic material information is automatically transferred to the SLS system.

Fig. 5.8 3D Systems Sinterstation Pro and its modular layout (replaced by the sPro Systems in May 2009, courtesy 3D Systems)

SLS – metal parts

T. Donajkowski

Sintering mechanism

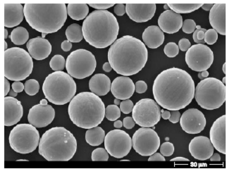


Figure 3 SEM Micrograph of the unsintered Titanium powder

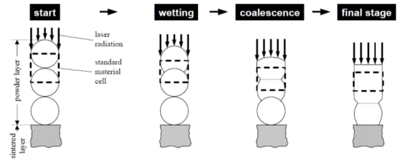


Fig. 4: Model of the standard material cell

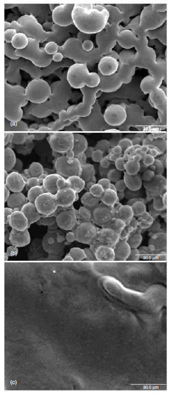
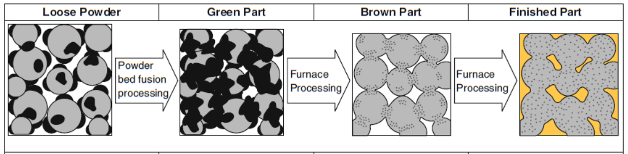


Figure 4 Sintered Titanium plates with different porosities: a) as sintered b) enhanced porosity by mixing with 50 vol.% NaCl, that was washed out after sintering, c) surface densification by post processing with a Nd:Glass laser

Infiltration after sintering



Loose Powder	Green Part	Brown Part	Finished Part
Metal or ceramic particles mixed with polymer binders.	Melting and resolidification of polymer binders enable complex parts to be formed without thermally affecting the metal or ceramic powders.	Polymer vaporization and particle sintering at elevated temperatures results in a porous, sintered component.	Infiltration with a lower-melting-temperature metal results in a dense, finished component.

- Consider methods for metals, polymers, ceramics
- SLS (sinter) vs. SLM (melt) vs. binding | infiltrate | anneal

Dyson SLA/SLS prototyping

- Likely chosen due to combination of geometry, material properties, throughput.
- http://www.youtube.com/watch?v=nlCLNZq3vC4

http://vacuumcleaners-reviews.net/

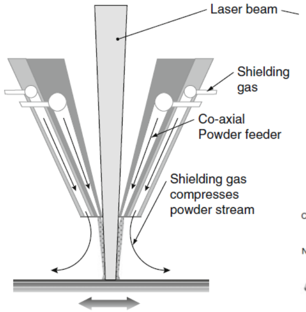
Simultaneous deposition and fusion
“Laser Engineered Net Shaping” (Sandia Natl Labs)

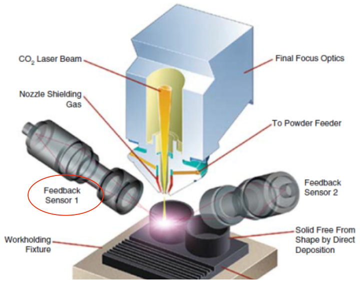
- http://www.optomec.com/Additive-Manufacturing-Technology/Laser-Additive-Manufacturing

LENS 850R No Sound

http://www.youtube.com/watch?feature=player_embedded&v=Z4kNkwmeqz8

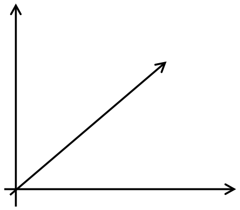
LENS nozzle designs





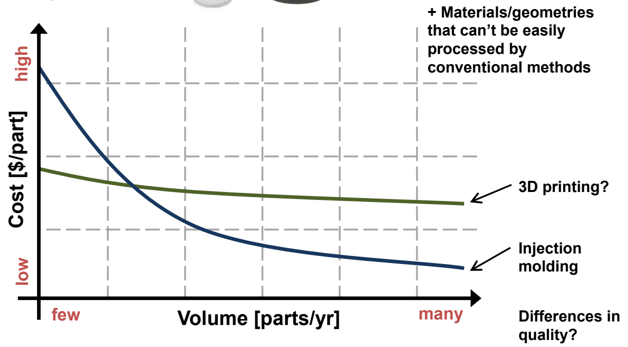
Unifying attributes of AM methods?

- Deposition/bonding method
- Material (e.g., polymer, metal, ceramic, bio)
- Scale / geometry
- Other?



Cost versus throughput (volume)

For example, what will it cost to make this plastic cup or cupholder?



Real applications and markets

- High value personalized products
- Rapid prototyping and tooling (esp. for short run manufacturing)
- Components that have advantageous attributes if made by AM
  - e.g., save material if made by AM, materials not easily machined
  - begin with markets that can afford low throughput, e.g., aerospace, medical

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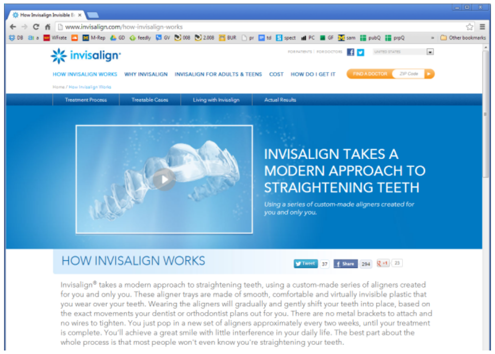
Invisalign

- Market cap. $3.72B 9/10/2013
- 2012: revenue $0.5B, net income $0.05B



INVISALIGN TAKES A MODERN APPROACH TO STRAIGHTENING TEETH

Using a series of custom-made aligners created for you and only you.

HOW INVISALIGN WORKS

Invisalign® takes a modern approach to straightening teeth, using a custom-made series of aligners created for you and only you. These aligner trays are made of smooth, comfortable and virtually invisible plastic that you wear over your teeth. Wearing the aligners will gradually and gently shift your teeth into place, based on the exact movements your dentist or orthodontist plans out for you. There are no metal brackets to attach and no wires to tighten. You just pop in a new set of aligners approximately every two weeks, until your treatment is complete. You'll achieve a great smile with little interference in your daily life. The best part about the whole process is that most people won't even know you're straightening your teeth.

Invisalign process (as of Kalpakjian): take tooth impression (mold), 3D scan mold, calculate aligner geometry, make aligner molds by SLA, thermoform aligners

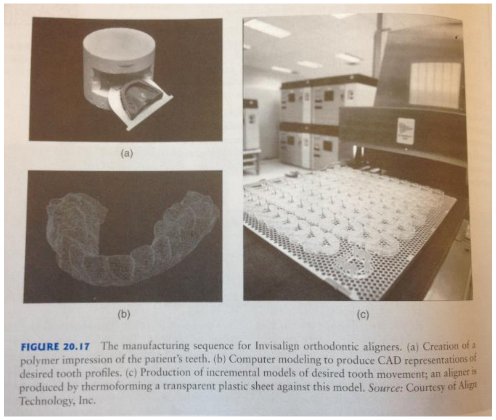
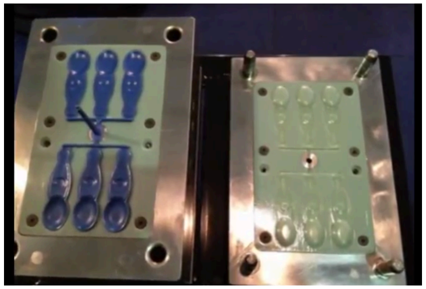


FIGURE 20.17 The manufacturing sequence for Invisalign orthodontic aligners. (a) Creation of a polymer impression of the patient's teeth. (b) Computer modeling to produce CAD representations of desired tooth profiles. (c) Production of incremental models of desired tooth movement; an aligner is produced by thermoforming a transparent plastic sheet against this model. *Source:* Courtesy of Align Technology, Inc.

Short run injection molding



- "Using 3D printing to make injection mold tools can not only save time but also expense over aluminum or steel molds."
- In the video below the molds were 3D printed in Objet Digital ABS material. These mold tools are then injected with real polypropylene at 220 degrees C.
- The Digital ABS molds were used in over 100 injection shots, producing a total of 600 ice cream spoons, without any visible deformation to the tools.
- It used only 7 hours to complete the process, while normally it might take 30 days for the work with traditional manufacturing. The cost saving - 44% over aluminium, 75% over steel is based on the data collected from two traditional CNC mold tool manufacturers in South America."

http://www.3ders.org/articles/20130408-making-short-run-injection-molds-with-3d-printing.html

Aircraft parts

Printing Parts

Systems that print mechanical components with metal powder could be used to build lighter, more efficient airplanes.

By Stuart Nathan on August 23, 2011

Before and after: Two versions of a hinge for a jet-engine cover illustrate the capabilities of 3-D printing. The one in the background is made with conventional manufacturing methods. The printed shape in the foreground weighs half as much. See how the parts are printed.

While the number of colleges offering online programs grows each year, few can claim the history, faculty, and technical expertise that goes along with a degree from Drexel University.

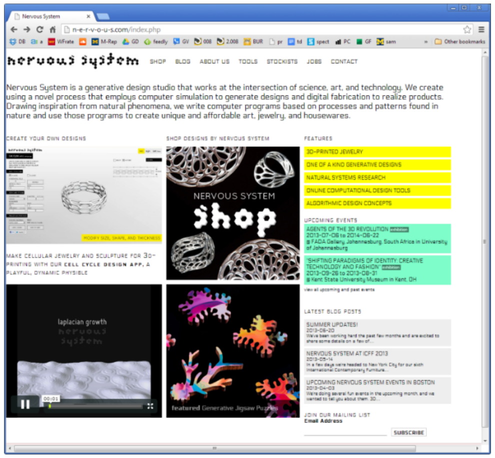
GET STARTED TODAY Drexel UNIVERSITY ONLINE

Also featured in:
MIT Technology Review Magazine
September/October 2011
More in this issue »

Chris Turner, an engineer at EADS Innovation Works near Bristol, England, twists a lever on a boxy black machine, and a porthole opens to reveal a dark cavity with a floor covered in gray powder. An invisible beam sweeps across the powder, and sparks fly. The box is an additive-layer manufacturing machine, sometimes known as a 3-D printer, and it is making a small part for an Airbus A380 airliner. EADS, which owns Airbus, hopes the device can transform manufacturing. Among other things, it could produce parts that make airplanes lighter, so they use less fuel.

http://www.technologyreview.com/demo/425133/printing-parts/?mod=MagOur

Individual design



Nervous System is a generative design studio that works at the intersection of science, art, and technology. We create using a novel process that employs computer simulation to generate designs and digital fabrication to realize products. Drawing inspiration from natural phenomena, we write computer programs based on processes and patterns found in nature and use those programs to create unique and affordable art, jewelry, and housewares.

CREATE YOUR OWN DESIGNS

MAKE CELLULAR JEWELRY AND SCULPTURE FOR 3D-PRINTING WITH OUR **CELL CYCLE DESIGN APP**, A PLAYFUL, DYNAMIC PHYSIBLE

SHOP DESIGNS BY NERVOUS SYSTEM

FEATURES

- 3D-PRINTED JEWELRY
- ONE OF A KIND GENERATIVE DESIGNS
- NATURAL SYSTEMS RESEARCH
- ONLINE COMPUTATIONAL DESIGN TOOLS
- ALGORITHMIC DESIGN CONCEPTS

UPCOMING EVENTS

AGENTS OF THE 3D REVOLUTION exhibition
2013-07-06 to 2014-06-22
@ FADA Gallery, Johannesburg, South Africa in University of Johannesburg

"SHIFTING PARADIGMS OF IDENTITY: CREATIVE TECHNOLOGY AND FASHION" exhibition
2013-09-26 to 2013-08-31
@ Kent State University Museum in Kent, OH

view all upcoming and past events

LATEST BLOG POSTS

SUMMER UPDATES!
2013-06-20
We've been working hard the past few months and are excited to share some details on a few of...

NERVOUS SYSTEM AT ICFF 2013
2013-05-14
In a few days we're headed to New York City for our sixth International Contemporary Furniture...

UPCOMING NERVOUS SYSTEM EVENTS IN BOSTON
2013-04-03
We're doing several fun events in the upcoming month, and we wanted to tell you about them. 3D...

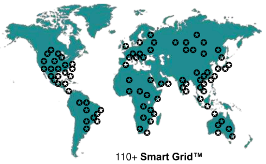
JOIN OUR MAILING LIST
Email Address

and who cares WHERE or HOW my part is made?

http://www.kraftwurx.com/
(see materials)

Kraftwurx's cloud-based 3D printing solution is called "Digital Factory™"

> *"In 2004, we set out to build a platform that empowers everyone to create, showcase, buy and sell personalized products with 3D Printing. We envision a world where the power to create and manufacture new products is placed into the hands of everyday people".* **Kraftwurx** (link)



110+ **Smart Grid™**
production facilities worldwide

> *"Digital Factory™ is a patented & patent-pending scalable cloud-based platform for on-demand 3D-Printing. We've combined a powerful e-commerce solution with Enterprise Resource Planning technology and powerful tools that empowers consumers to customize their own products, into one seamless solution.".* **Kraftwurx** (link)

Proposed “organ printing” method

- www.organovo.com

V. Mironov et al. / Biomaterials 30 (2009) 2164–2174 2169

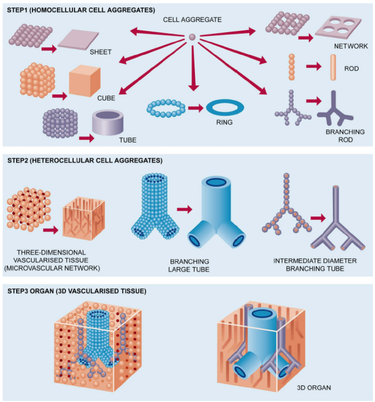
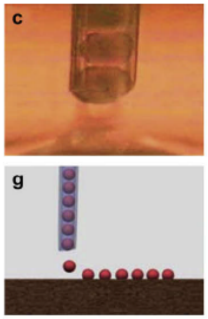


Fig. 4. Roadmap for organ printing.



Critical enablers of continued growth

- AM processes (seminal patents expired or expiring soon)
  → Needs for improvement (RATE, quality, COST, flexibility?)
- Printable materials, e.g.,
  - Aerospace-grade plastic that can make replacement toilet parts for out-of-production aircraft
  - Biocompatible plastics for hearing aids
  - Powders for SLS (or aerosol jet) deposition of different metals and semiconductors; “structured materials LLC”
- CAD systems and file formats
- 3D scanners
- Data infrastructure
- Standards!

Designation: F2792 – 12a

Standard Terminology for Additive Manufacturing Technologies[1,2]

This standard is issued under the fixed designation F2792; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This terminology includes terms, definitions of terms, descriptions of terms, nomenclature, and acronyms associated with additive-manufacturing (AM) technologies in an effort to standardize terminology used by AM users, producers, researchers, educators, press/media and others.

NOTE 1—The subcommittee responsible for this standard will review definitions on a three-year basis to determine if the definition is still accurate as stated. Revisions will be made when determined to be necessary.

2. Referenced Documents

2.1 *ISO Standard:*[3]

ISO 10303 -1:1994 Industrial automation systems and integration -- Product data representation and exchange -- Part 1: Overview and fundamental principles

3. Significance and Use

3.1 The definitions of the terms presented in this standard were created by this subcommittee. This standard does not purport to address safety concerns associated with the use of AM technologies. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use of additive manufacturing.

4. Additive Manufacturing Process Categories

4.1 The following terms provide a structure for grouping current and future AM machine technologies. These terms are useful for educational and standards-development purposes and are intended to clarify which machine types share processing similarities. For many years, the additive manufacturing industry lacked categories for grouping AM technologies, which made it challenging educationally and when communicating information in both technical and non-technical settings. These process categories enable one to discuss a category of machines, rather than needing to explain an extensive list of commercial variations of a process methodology.

binder jetting, *n*—an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.

directed energy deposition, *n*—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

DISCUSSION—″Focused thermal energy″ means that an energy source (e.g., laser, electron beam, or plasma arc) is focused to melt the materials being deposited.

material extrusion, *n*—an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.

material jetting, *n*—an additive manufacturing process in which droplets of build material are selectively deposited.

DISCUSSION—Example materials include photopolymer and wax.

powder bed fusion, *n*—an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.

sheet lamination, *n*—an additive manufacturing process in which sheets of material are bonded to form an object.

vat photopolymerization, *n*—an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

5. Terminology

5.1 *Definitions:*

3D printer, *n*—a machine used for 3D printing.

3D printing, *n*—the fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology.

DISCUSSION—Term often used synonymously with additive manufacturing; in particular associated with machines that are low end in price and/or overall capability.

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[1] This terminology is under the jurisdiction of Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.91 on Terminology.

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[2] Through a mutual agreement with ASTM International (ASTM), the Society of Manufacturing Engineers (SME) contributed the technical expertise of its RTAM Community members to ASTM to be used as the technical foundation for this ASTM standard. SME and its membership continue to play an active role in providing technical guidance to the ASTM standards development process.

[3] Available from International Organization for Standardization (ISO), 1, ch. de la Voie-Creuse, Case postale 56, CH-1211, Geneva 20, Switzerland, http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=20579

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3D scanning, *n*—a method of acquiring the shape and size of an object as a 3-dimensional representation by recording x,y,z coordinates on the object's surface and through software the collection of points is converted into digital data.

DISCUSSION—Typical methods use some amount of automation, coupled with a touch probe, optical sensor, or other device. Synonym: 3D digitizing.

additive manufacturing (AM), *n*—a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication.

additive systems, *n*—machines used for additive manufacturing.

binder jetting, *n*—an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.

direct metal laser sintering (DMLS®), *n*—a powder bed fusion process used to make metal parts directly from metal powders without intermediate "green" or "brown" parts; term denotes metal-based laser sintering systems from EOS GmbH - Electro Optical Systems. Synonym: direct metal laser melting.

directed energy deposition, *n*—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

DISCUSSION—″Focused thermal energy″ means that an energy source (e.g., laser, electron beam, or plasma arc) is focused to melt the materials being deposited.

facet, *n*—typically a three- or four-sided polygon that represents an element of a 3D polygonal mesh surface or model; triangular facets are used in STL files.

fused deposition modeling (FDM®), *n*—a material extrusion process used to make thermoplastic parts through heated extrusion and deposition of materials layer by layer; term denotes machines built by Stratasys, Inc.

laser sintering (LS), *n*—a powder bed fusion process used to produce objects from powdered materials using one or more lasers to selectively fuse or melt the particles at the surface, layer by layer, in an enclosed chamber.

DISCUSSION—Most LS machines partially or fully melt the materials they process. The word "sintering" is a historical term and a misnomer, as the process typically involves full or partial melting, as opposed to traditional powdered metal sintering using a mold and heat and/or pressure.

material extrusion, *n*—an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.

material jetting, *n*—an additive manufacturing process in which droplets of build material are selectively deposited.

DISCUSSION—Example materials include photopolymer and wax.

powder bed fusion, *n*—an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.

prototype tooling, *n*—molds, dies, and other devices used to produce prototypes; sometimes referred to as bridge tooling or soft tooling.

rapid prototyping, *n*—additive manufacturing of a design, often iterative, for form, fit, or functional testing, or combination thereof.

rapid tooling, *n*—the use of additive manufacturing to make tools or tooling quickly, either directly, by making parts that serve as the actual tools or tooling components, such as mold inserts, or indirectly, by producing patterns that are, in turn, used in a secondary process to produce the actual tools.

rapid tooling, *n—in machining processes*, the production of tools or tooling quickly by subtractive manufacturing methods, such as CNC milling, etc.

reverse engineering, *n—in additive manufacturing*, method of creating a digital representation from a physical object to define its shape, dimensions, and internal and external features.

selective laser sintering (SLS®), *n*—denotes the LS process and machines from 3D Systems Corporation.

sheet lamination, *n*—an additive manufacturing process in which sheets of material are bonded to form an object.

stereolithography (SL), *n*—a vat photopolymerization process used to produce parts from photopolymer materials in a liquid state using one or more lasers to selectively cure to a predetermined thickness and harden the material into shape layer upon layer.

stereolithography apparatus (SLA®), *n*—denotes the SL machines from 3D Systems Corporation.

subtractive manufacturing, *n*—making objects by removing of material (for example, milling, drilling, grinding, carving, etc.) from a bulk solid to leave a desired shape, as opposed to additive manufacturing.

surface model, *n*—a mathematical or digital representation of an object as a set of planar or curved surfaces, or both, that may or may not represent a closed volume.

DISCUSSION—May consist of Bezier B-spline surfaces or NURBS surfaces. A surface model may also consist of a mesh of polygons, such as triangles, although this approach approximates the exact shape of the model.

tool, tooling, *n*—a mold, die, or other device used in various manufacturing and fabricating processes such as plastic injection molding, thermoforming, blow molding, vacuum casting, die casting, sheet metal stamping, hydroforming, forging, composite lay-up tools, machining and assembly fixtures, etc.

vat photopolymerization, *n*—an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

5.2 *Acronyms:*

CAD, *n*—Computer-Aided Design. The use of computers for the design of real or virtual objects.

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CAM, *n*—Computer-Aided Manufacturing. Typically refers to systems that use surface data to drive CNC machines, such as digitally-driven mills and lathes, to produce parts, molds, and dies.

CNC, *n*—Computer Numerical Control. Computerized control of machines for manufacturing.

Discussion—Common CNC machines include mills, lathes, grinders, and flame, laser, and water-jet cutters.

IGES, *n*—Initial Graphics Exchange Specification, a platform neutral CAD data exchange format intended for exchange of product geometry and geometry annotation information; IGES version 5.3 was superseded by ISO 10303, STEP in 2006.

Discussion—IGES is the common name for a United States National Bureau of Standards standard NBSIR 80-1978, Digital Representation for Communication of Product Definition Data, which was approved by ANSI first as ANS Y14.26M-1981 and later as ANS USPRO/IPO-100-1996.

PDES, *n*—Product Data Exchange Specification or Product Data Exchange using STEP.

Discussion—originally a product data exchange specification developed in the 1980s by the IGES/PDES Organization, a program of US Product Data Association (USPRO), it was adopted as the basis for and subsequently superseded by ISO 10303 STEP.

STEP, *n*—Standard for the Exchange of Product Model Data.

Discussion—The common name for ISO 10303 that "provides a representation of product information, along with the necessary mechanisms and definitions to enable product data to be exchanged. [The standard] applies to the representation of product information, including components and assemblies; the exchange of product data, including storing, transferring, accessing, and archiving."

STL, *n*—*in additive manufacturing*, file format for 3D model data used by machines to build physical parts; STL is the de facto standard interface for additive manufacturing systems. STL originated from the term stereolithography.

Discussion—The STL format, in binary and ASCII forms, uses triangular facets to approximate the shape of an object. The format lists the vertices, ordered by the right-hand rule, and unit normals of the triangles, and excludes CAD model attributes.

6. Keywords

6.1 additive manufacturing; rapid prototyping; 3D printing

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