Additive Manufacturing

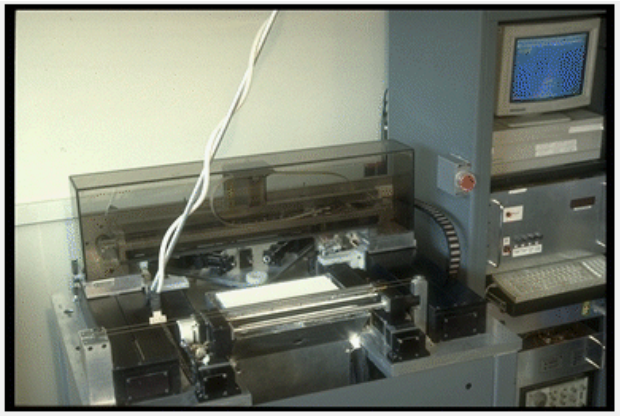
The Economist

Additive Manufacturing agenda:

Heat transfer for FDM/FFF, and SLM/SLS, and Overview by John Hart Oct 21

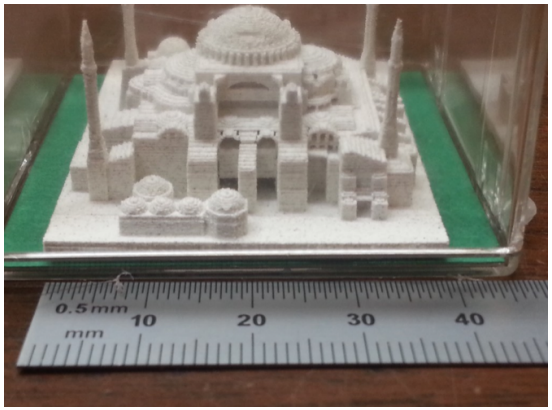
3D Printing History at MIT

Ely Sachs & Mike Cima Developed 3D Printing At MIT ~ 1990s



MIT Alpha 3D Printer (Image Credit: Mit.edu)

Early version of the binder jet printing process invented by Ely Sachs and Mike Cima at MIT



Model of Hagia Sophia Printed 1995-96 at MIT

US005204055A

United States Patent [19]

Sachs et al.

[11] **Patent Number: 5,204,055**

[45] **Date of Patent: Apr. 20, 1993**

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

[75] Inventors: **Emanuel M. Sachs**, Somerville; **John S. Haggerty**, Lincoln; **Michael J. Cima**, Lexington; **Paul A. Williams**, Concord, all of Mass.

FOREIGN PATENT DOCUMENTS

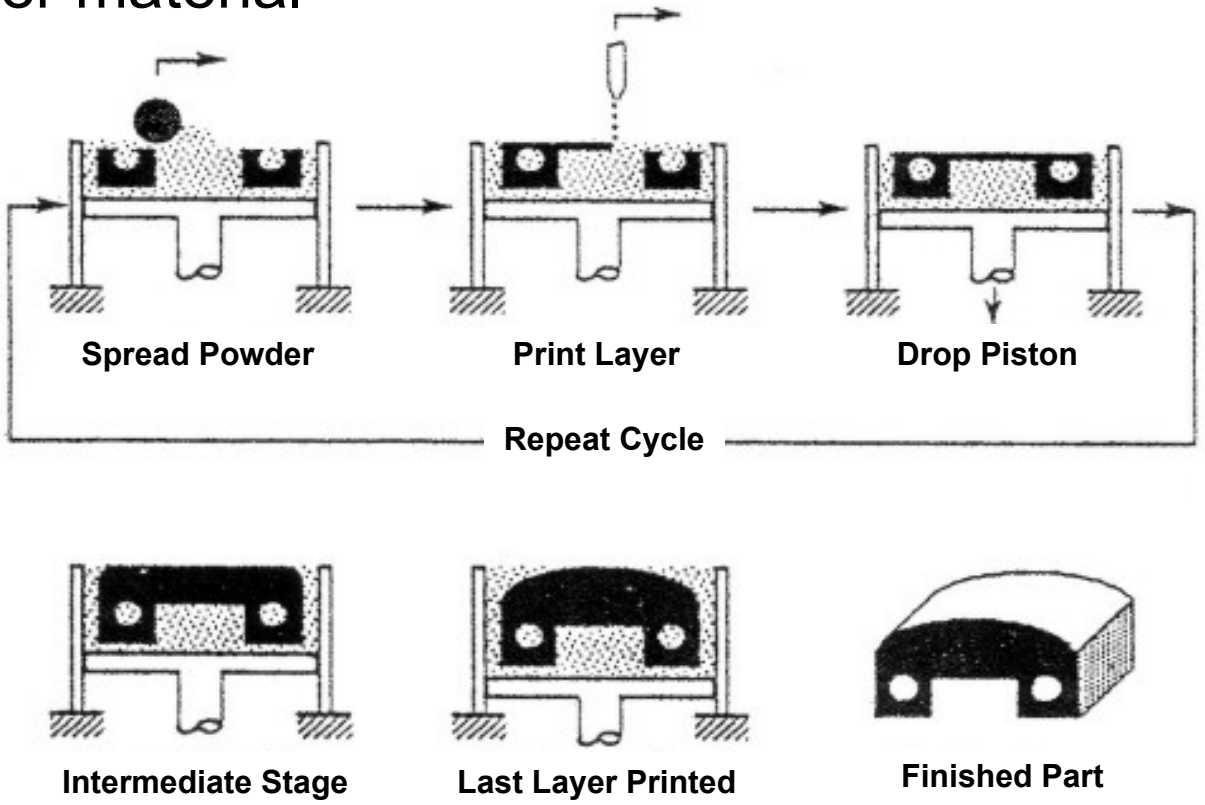
226377 7/1973 Fed. Rep. of Germany .
WO90/03893 4/1990 World Int. Prop. O. .

OTHER PUBLICATIONS

Deckard, C. and Beaman, J., "Solid Freeform Fabrica-

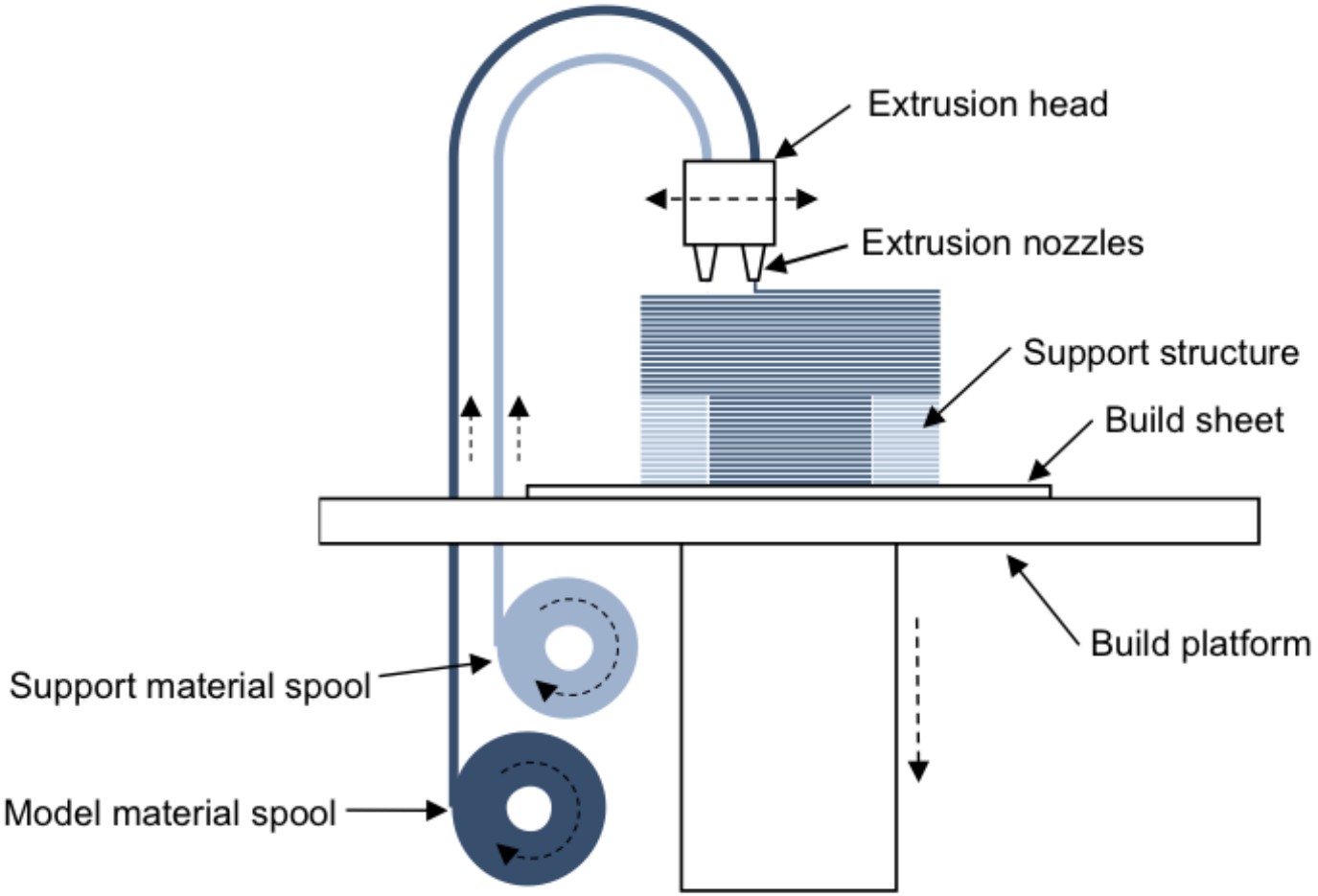
“3D Printing” binder jetting

Selective joining of powder using ink-jet printing of a binder material

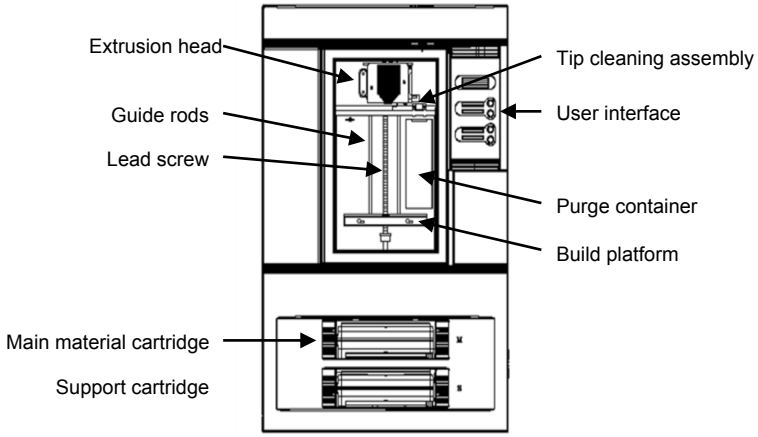


* Source: Kruth, J.P. (1991), “Material incress manufacturing by rapid prototyping techniques”

Plastics Extrusion (FDM)



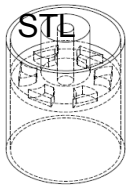
Stratasys Dimension Elite FDM system



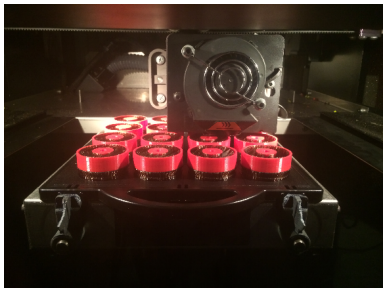
Build Envelope (XYZ)	8 x 8 x 12 inches (203 x 203 x 305 mm)
Main material	ABSplus
Support	P400SR (SR-10) - Synthetic thermoplastic polymer
Material Delivery	One build material canisters 56.3 in³ (923 cm³) One support material canisters 56.3 in³ (923 cm³)

FDM wheel manufacturing steps

CAD
STL



FDM printing process

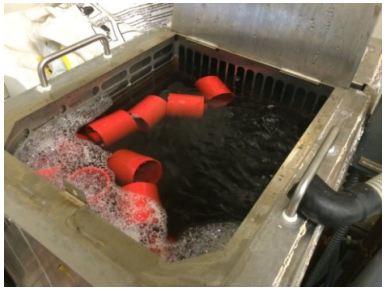


Parts in build chamber

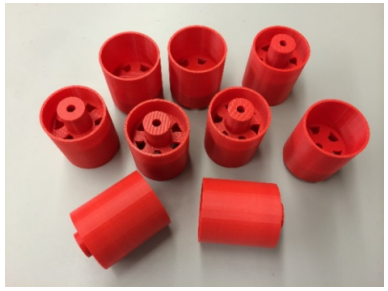
Wheels on build sheet

Detaching from base layers

Support removal (~4h)



Final wheels



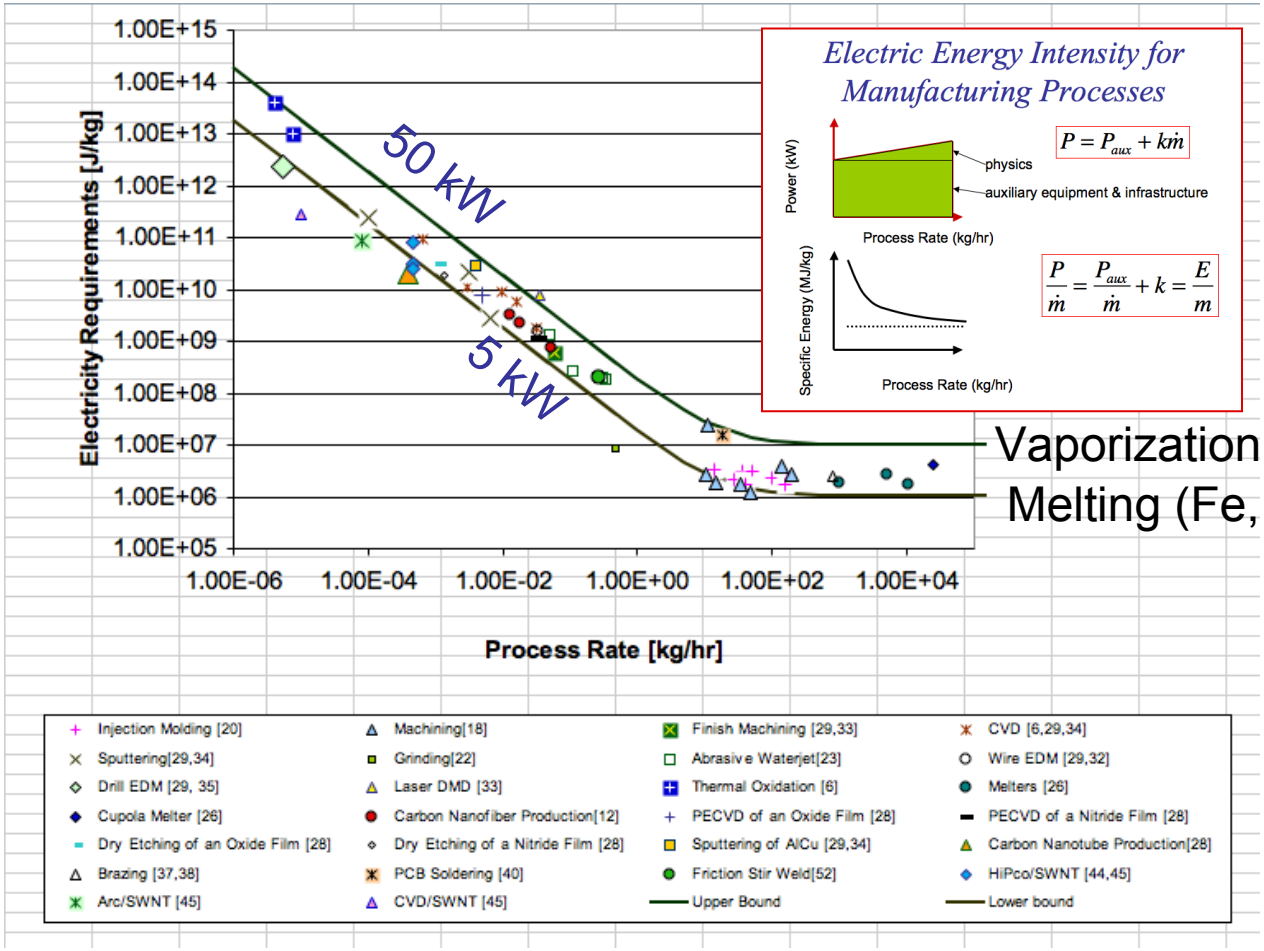
FDM Systems Studied

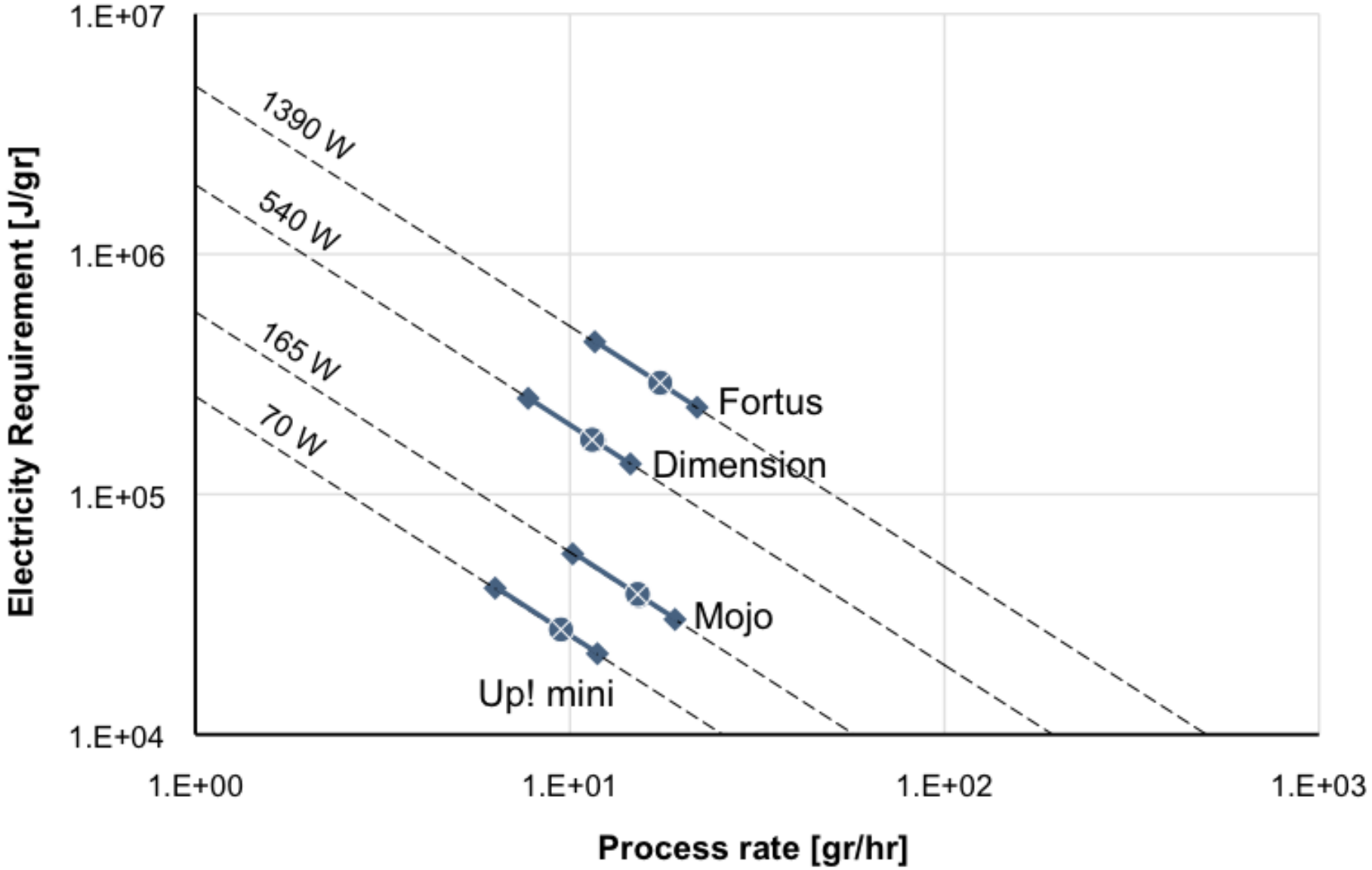
Fortus 360mc
Stratasys Inc.
Production Series
$85,000 base price

Dimension Elite
Stratasys Inc.
Design Series
$29,900 base price

Mojo
Stratasys Inc.
Idea Series
$9,500 base price

Up! mini
Beijing Tiertime
$890 price


Electricity Requirements [J/kg]
1.00E+15
1.00E+14
1.00E+13
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E-06
1.00E-04
1.00E-02
1.00E+00
1.00E+02
1.00E+04
Process Rate [kg/hr]
50 kW
5 kW
Electric Energy Intensity for Manufacturing Processes
Power (kW)
Process Rate (kg/hr)
physics
auxiliary equipment & infrastructure
$P = P_{aux} + k\dot{m}$
Specific Energy (MJ/kg)
Process Rate (kg/hr)
$\frac{P}{\dot{m}} = \frac{P_{aux}}{\dot{m}} + k = \frac{E}{m}$
Vaporization (Al)
Melting (Fe, Al)
Injection Molding [20]
Machining[18]
Finish Machining [29,33]
CVD [6,29,34]
Sputtering[29,34]
Grinding[22]
Abrasive Waterjet[23]
Wire EDM [29,32]
Drill EDM [29, 35]
Laser DMD [33]
Thermal Oxidation [6]
Melters [26]
Cupola Melter [26]
Carbon Nanofiber Production[12]
PECVD of an Oxide Film [28]
PECVD of a Nitride Film [28]
Dry Etching of an Oxide Film [28]
Dry Etching of a Nitride Film [28]
Sputtering of AlCu [29,34]
Carbon Nanotube Production[28]
Brazing [37,38]
PCB Soldering [40]
Friction Stir Weld[52]
HiPco/SWNT [44,45]
Arc/SWNT [45]
CVD/SWNT [45]
Upper Bound
Lower bound



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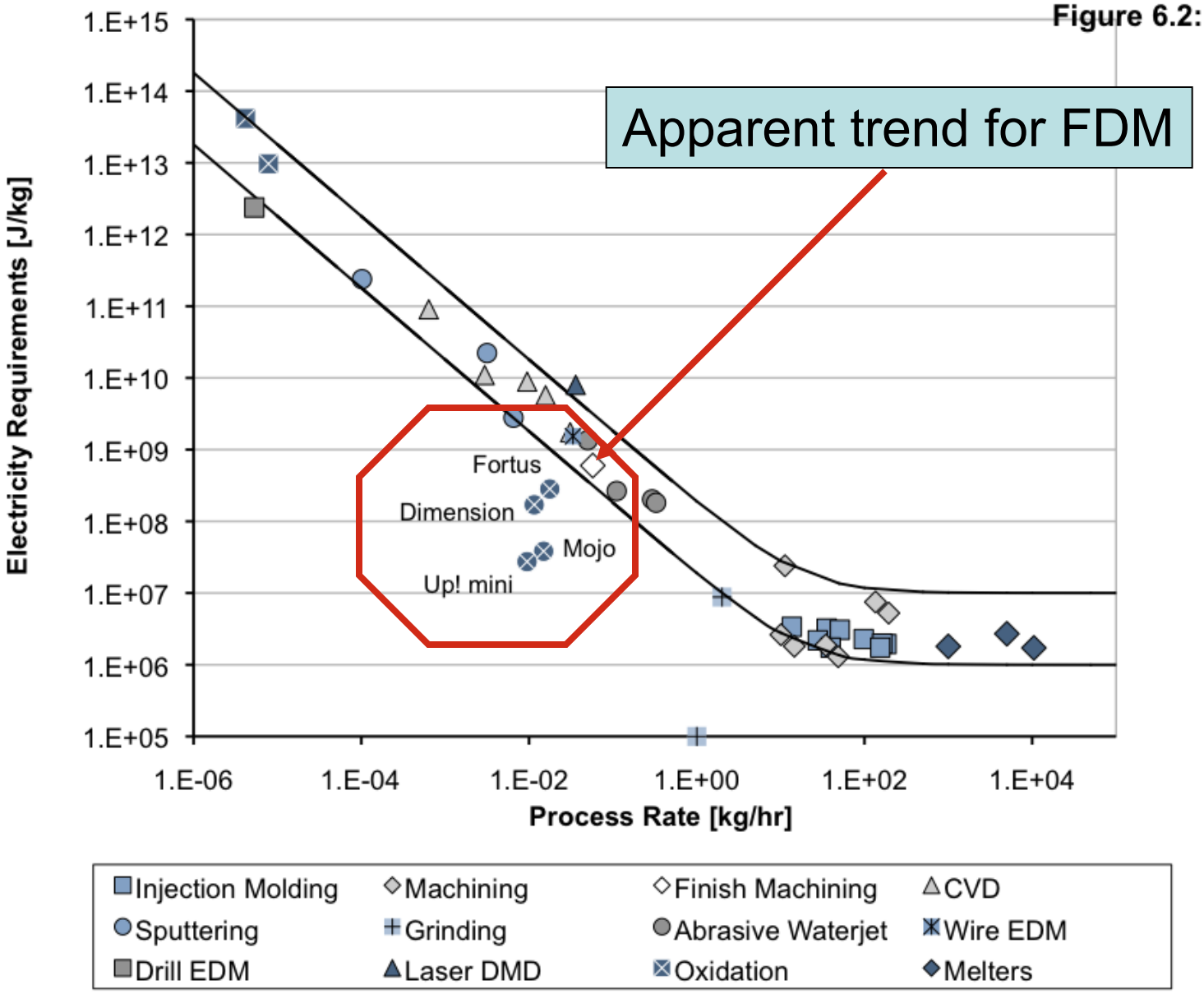

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Printer and printing properties

Technology	Fused deposition modeling (FDM)
Print head	Dual-extrusion print head with an auto-nozzle lifting system and swappable print cores
Build volume	Left nozzle: 215 x 215 x 200 mm Right nozzle: 215 x 215 x 200 mm Dual material: 197 x 215 x 200 mm
Filament diameter	2.85 mm
Layer resolution	0.4 mm nozzle: 200 - 20 micron
XYZ accuracy	12.5, 12.5, 2.5 micron
Print head travel speed	30 - 300 mm/s
Build speed	0.40 mm nozzle: up to 16 mm^3/s
Build plate	Heated glass build plate
Build plate temperature	20 - 100 °C
Build plate leveling	Active leveling
Supported materials	Nylon, PLA, ABS, CPE, CPE+, PC, TPU95A, PP, PVA
Nozzle diameter	0.40 mm, 0.80 mm
Nozzle temperature	180 - 280 °C
Nozzle heat up time	< 2 min
Build plate heat up time	< 4 min (20 - > 60 °C)

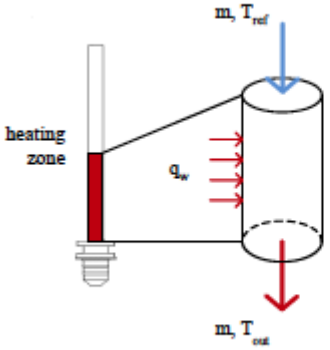
Power requirements

Input

100 - 240 V
4 A, 50 - 60 Hz
221 W max.

Output

24 V DC, 9.2 A



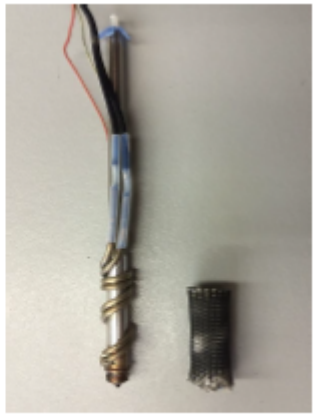
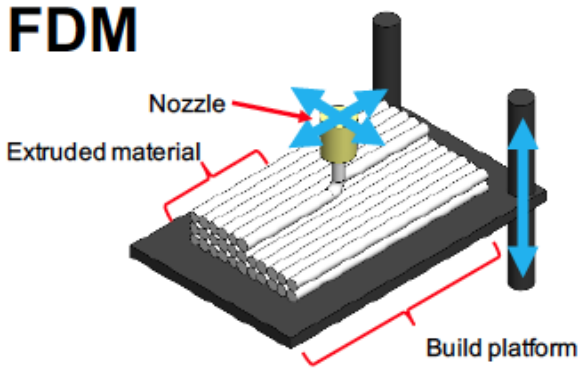


Figure II.3 Print head nozzle used in Mojo system [20]



Times to print the juice squeezer by FDM:

About 12 hours (100% fill); Wt about 100grams

Between 8 to 10 hours (20% fill); Wt about 70 grams

Print rate about
10^{-2} kg/hr

Approxomate Heat Transfer Analysis for FDM

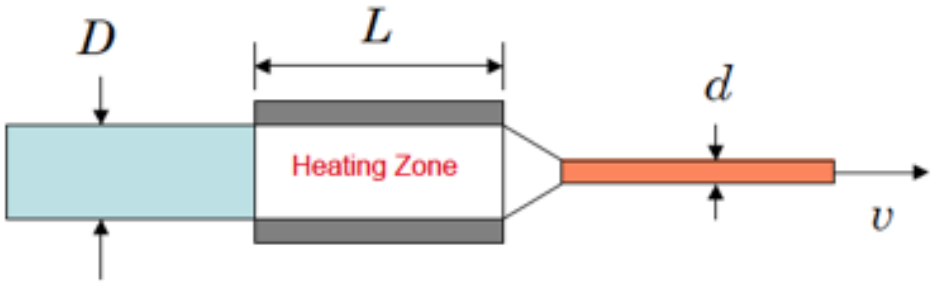
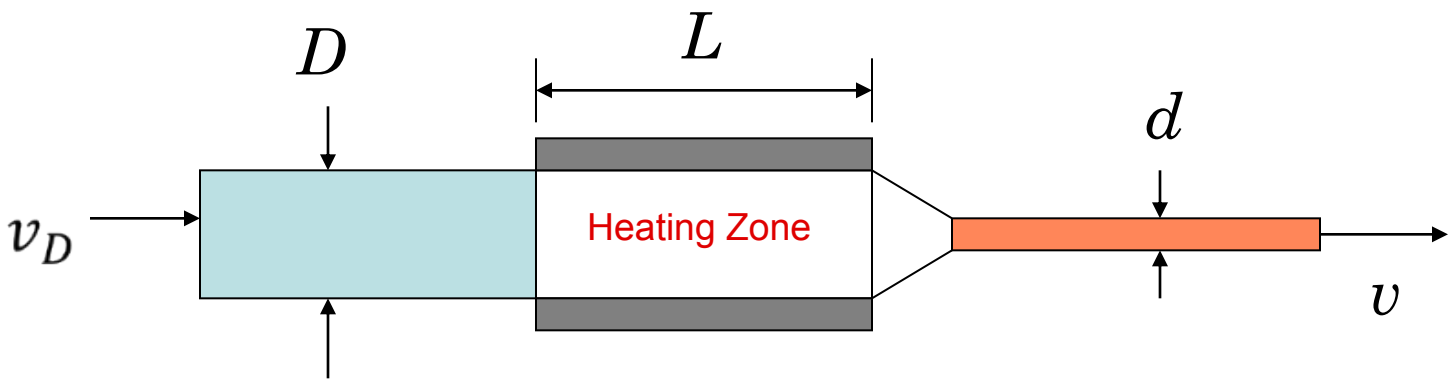


Figure 4 Heating zone for the plastics extrusion process (sometimes called fused deposition modeling – FDM). The cylindrical filament enters as a solid with diameter D on the left, is heated by conduction from the wall in a zone of length L and exits as a molten polymer of diameter d and velocity v on the right.

Quick scaling estimate:



$$\dot{Vol} \sim D^2 \cdot v_D = d^2 \cdot v$$

$$v_D = \frac{L}{t} \sim \alpha \frac{L}{D^2}$$

$$\dot{Vol} \sim \alpha \cdot L$$

length L

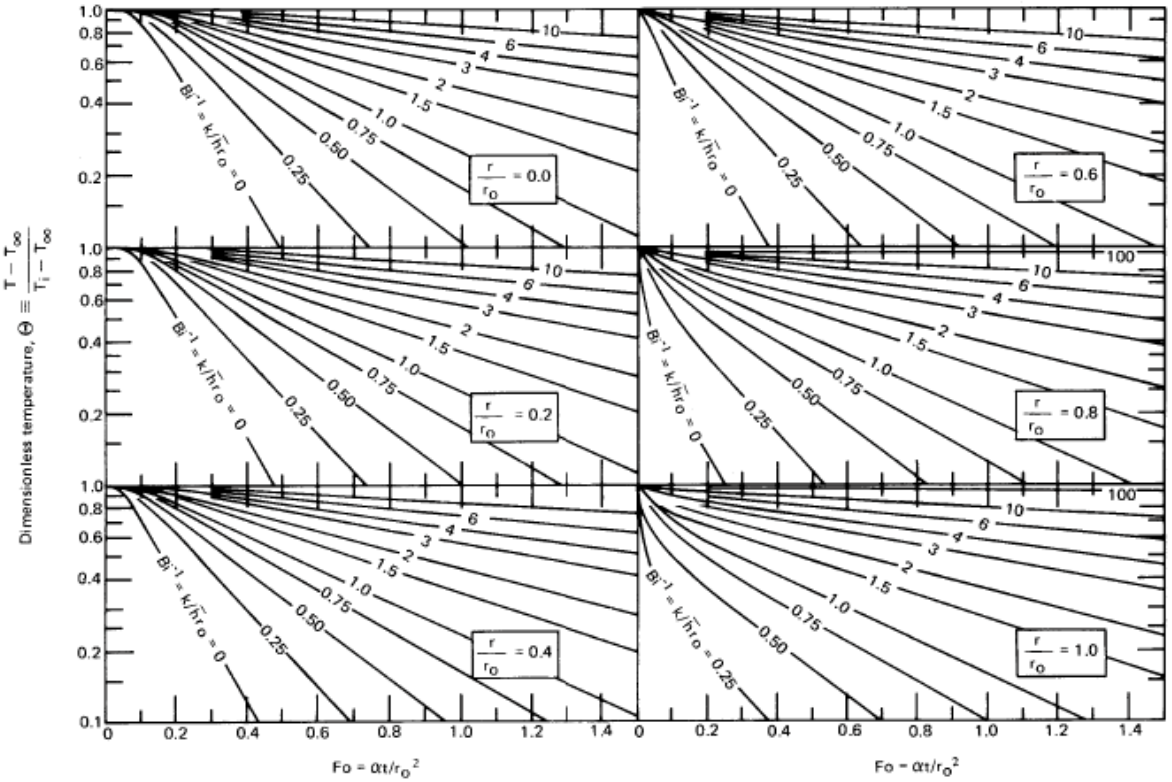


Figure 5.8 The transient temperature distribution in a long *cylinder* of radius r_o at six positions: $r/r_o = 0$ is the centerline; $r/r_o = 1$ is the outside boundary.

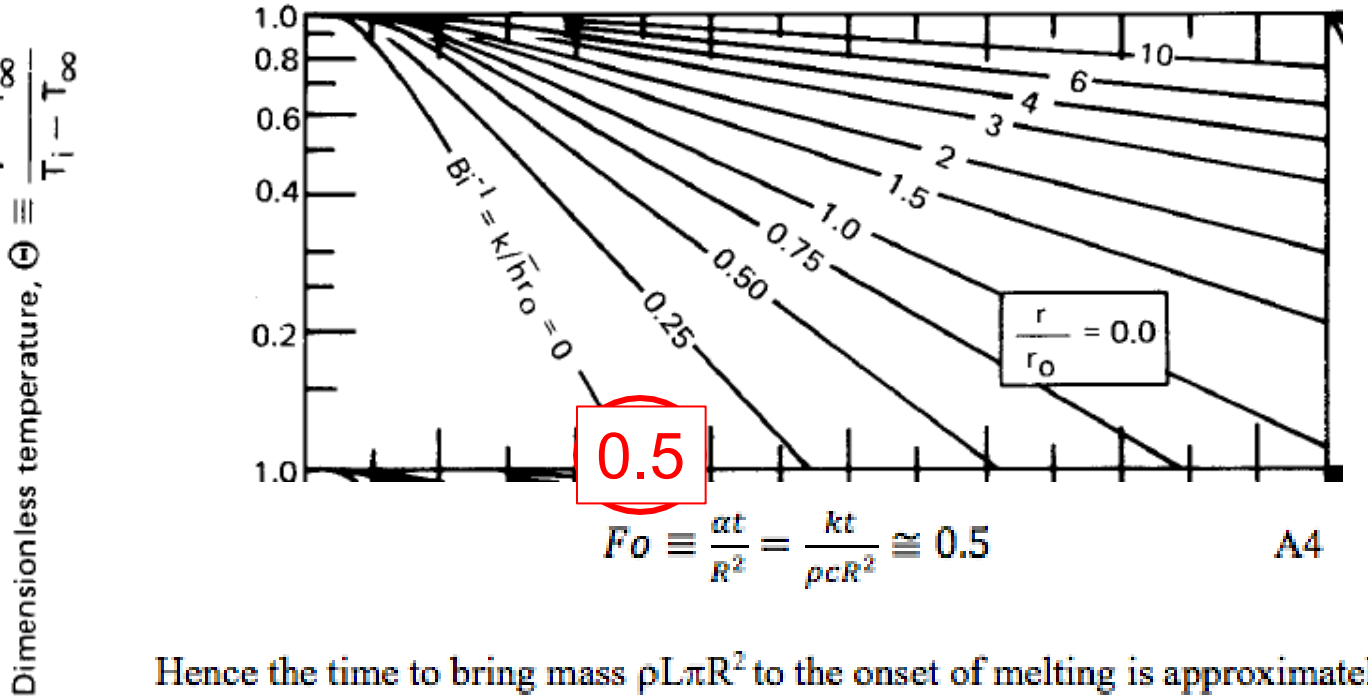
From Lienhard's book for the cooling and heating of cylinders.

For heating use:

$$\theta = \frac{T_\infty - T}{T_\infty - T_i}$$

Fig is from text by Lienhard

Diagram is for cylinders



$$Fo \equiv \frac{\alpha t}{R^2} = \frac{kt}{\rho c R^2} \cong 0.5 \qquad \text{A4}$$

Hence the time to bring mass $\rho L \pi R^2$ to the onset of melting is approximately, $t \cong \frac{\rho c R^2}{2k}$, The resulting mass process rate is then given by

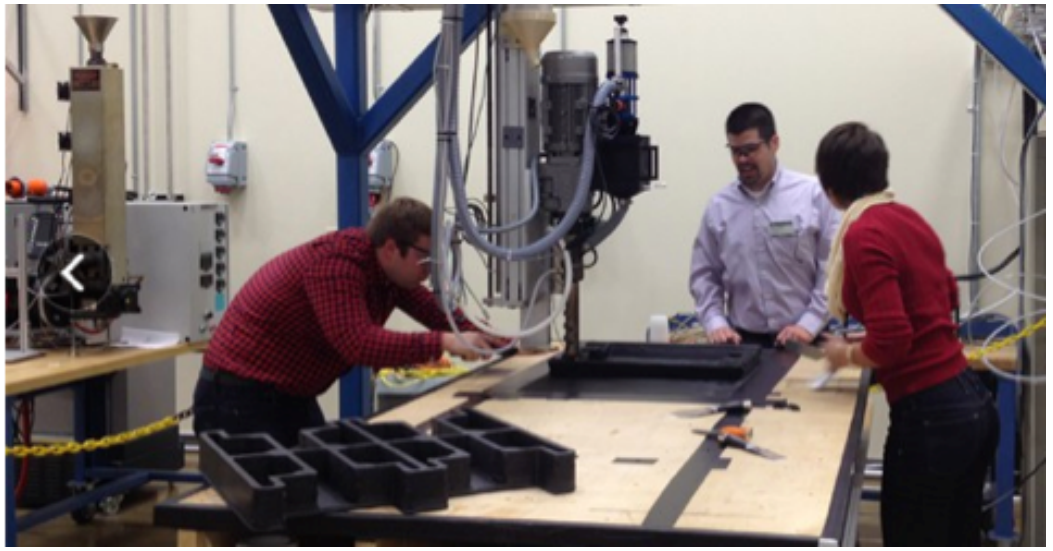
$$\dot{m} = 2\pi \frac{k}{c} L \qquad \text{A5}$$

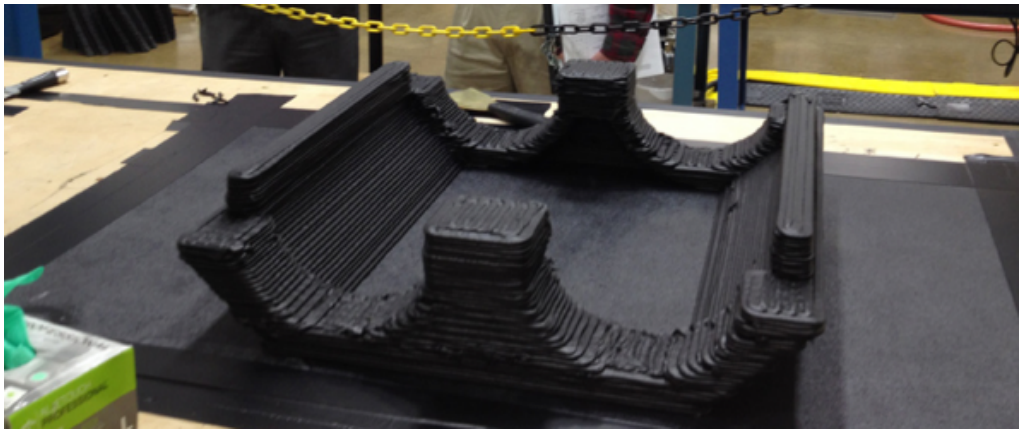
$$\dot{m} = 2\pi \frac{k}{c} L$$

Using nominal values from Table 3.1, $\dot{m} \cong 4 \cdot 10^{-2} \cdot L(\text{cm}) \cdot \frac{kg}{hr}$

BAAMCI

BIG AREA ADDITIVE MANUFACTURING

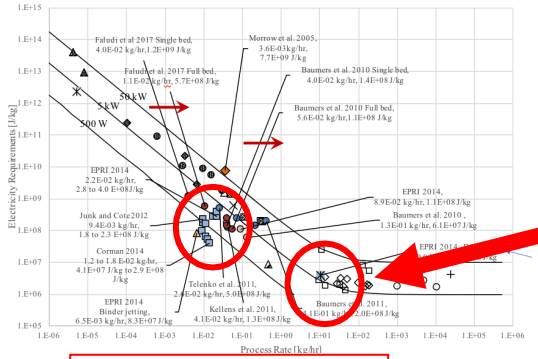




Made in Chicago: World's First 3D Printed Electric Car

POSTED 1:57 PM, SEPTEMBER 13, 2014, BY SEAN LEWIS, UPDATED AT 07:11AM, SEPTEMBER 14, 2014

Big Area Additive Manufacturing (BAAM)



$$\dot{m} = 2\pi \frac{k}{c} L.$$

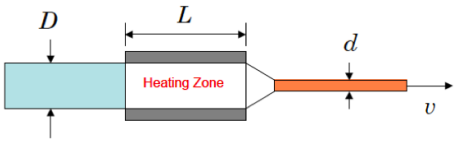
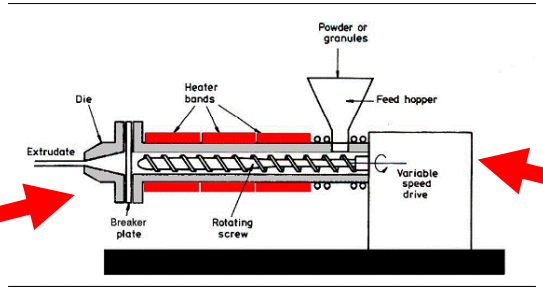
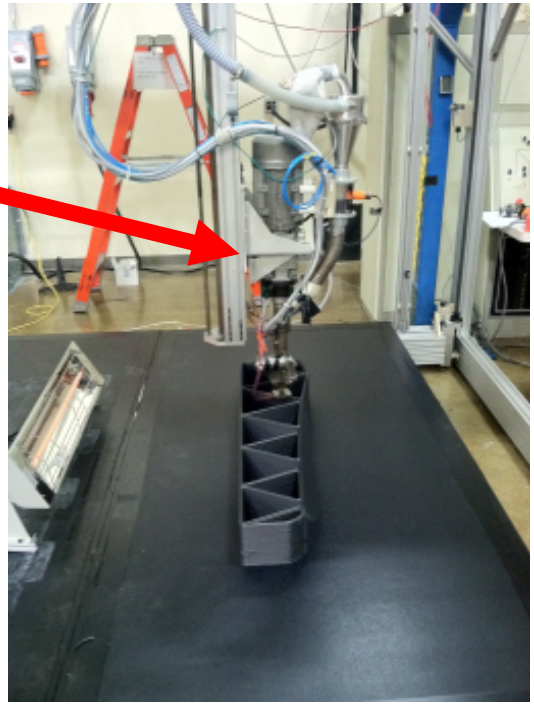


Figure 4 Heating zone for FDM. The cylindrical filament enters as a solid from the left, and exits as a molten polymer on the right

Single Screw Extruder





$$\dot{m} = 2\pi \frac{k}{c} L.$$

BAAM: longer heating zone, conductive polymer and bulk heating mechanism

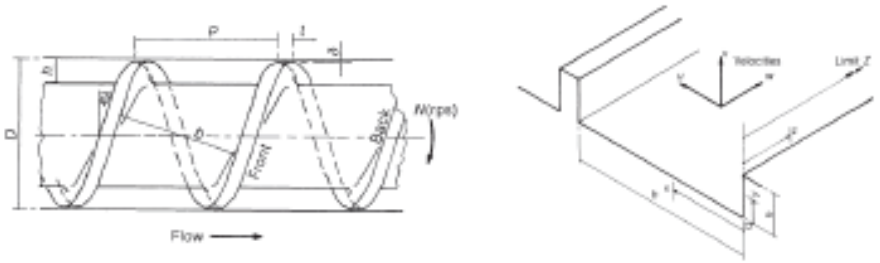


Figure II.10 Geometry of a single screw extruder and coordinates system for screw channel

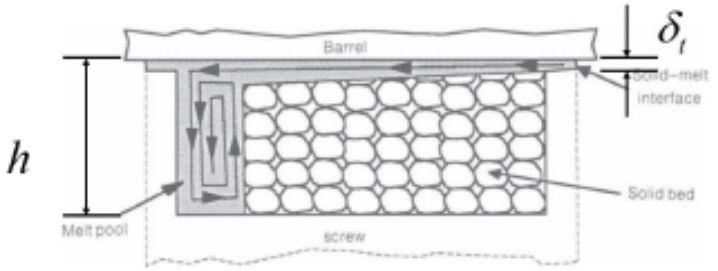


Figure II.12 Transvers flow in a single screw extruder at the melt zone [28]

Uncouple deposition scale from thermal scale

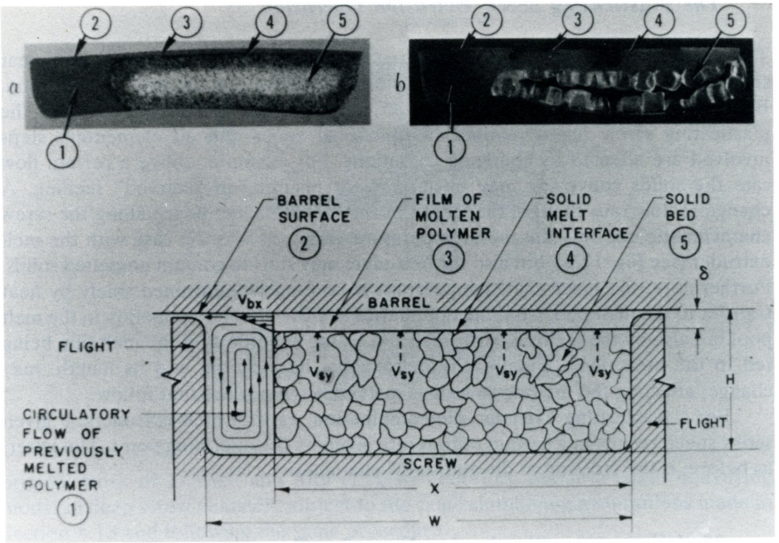
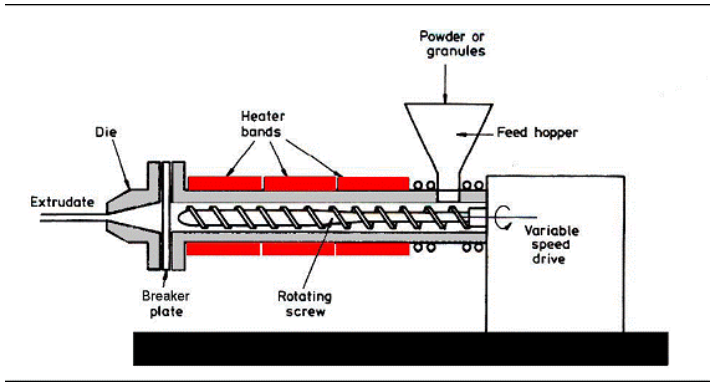


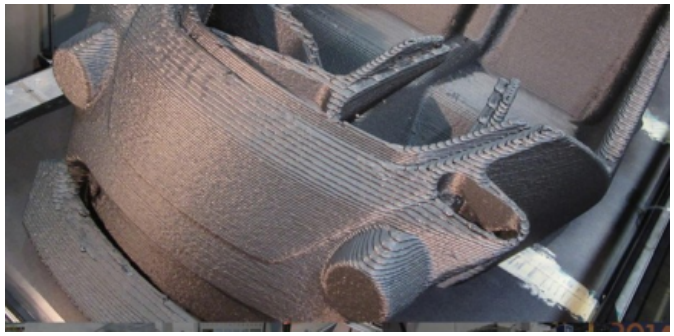
Fig. 12.15 Idealized cross section compared to (*a*) the cross section from a PVC "cooling" experiment and (*b*) the cross section from an LDPE "cooling" experiment. (Reprinted with permission from Z. Tadmor and I. Klein, *Engineering Principles of Plasticating Extrusion*, Van Nostrand Reinhold Book Co., New York, 1970.)

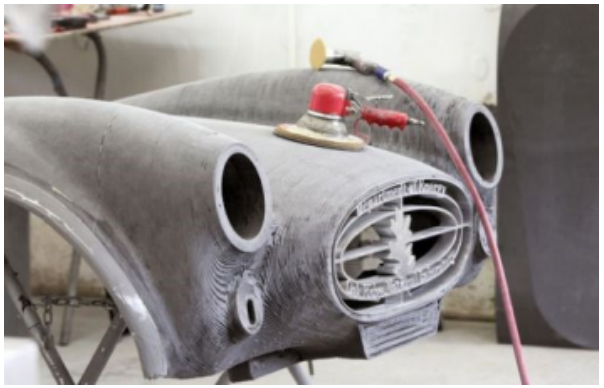


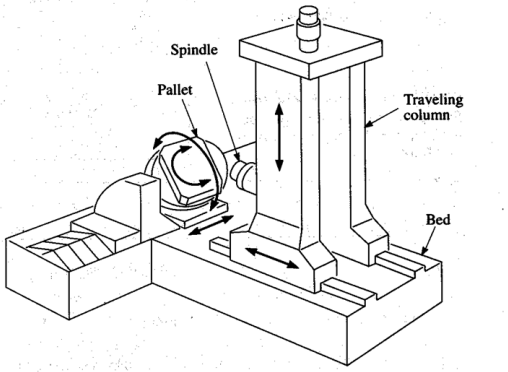
Tadmore and Gogos

Lonnie Love at Oak Ridge
Destructively testing
The BAMM material

Big Area Additive Manufacturing; some post processing required

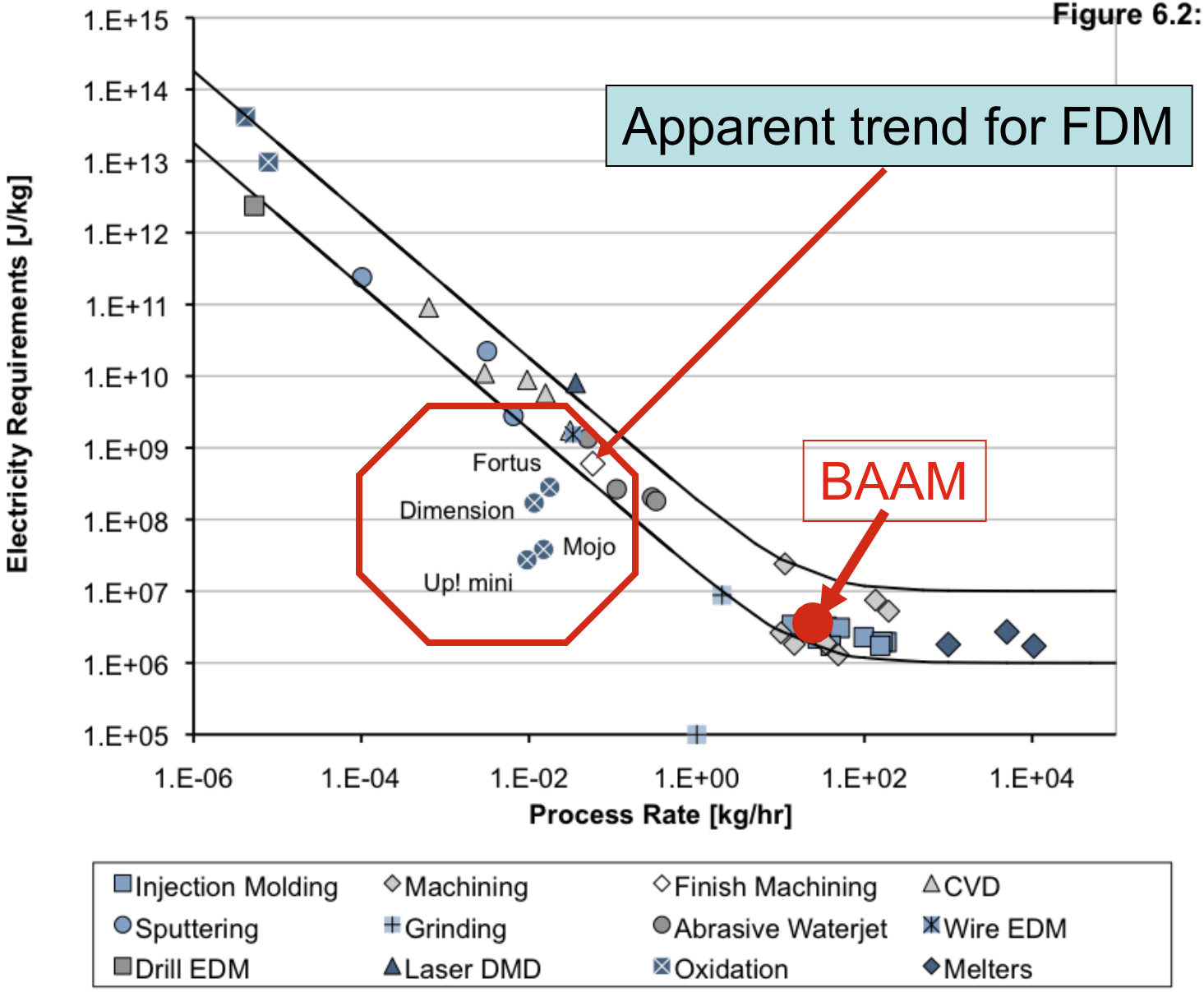






5 axis machine tool

Figure 6.2:



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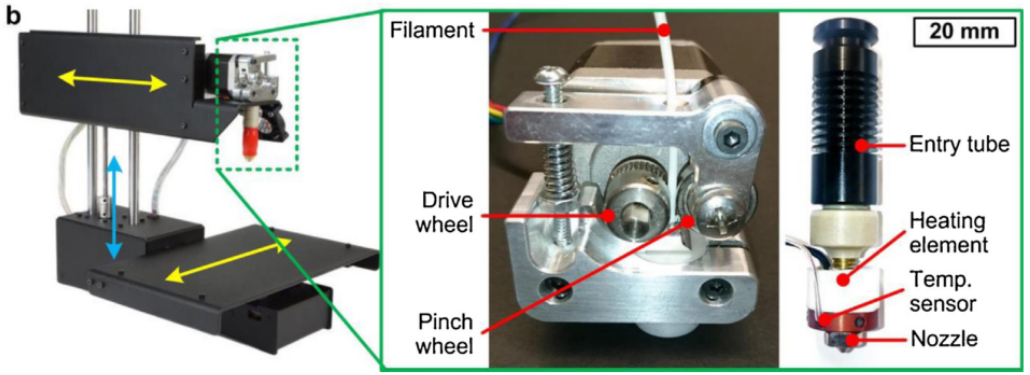
Extra Slides

Rate Limits on FDM

- Resolution
- Heating
- Grip force



Go, J., Schiffres, S. N., Stevens, A. G., & Hart, A. J. (2017). Rate limits of additive manufacturing by fused filament fabrication and guidelines for high-throughput system design. *Additive Manufacturing*, *16*,

Rate Limits for resolution below 0.5 mm