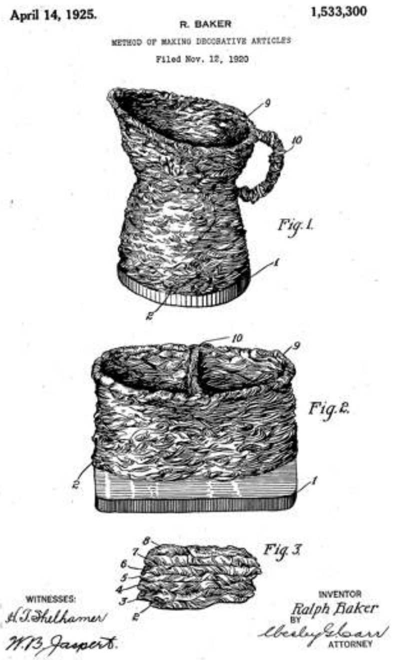
Survey of Additive Manufacturing Techniques

Craig A. Brice

ADAPT Members Meeting
8 August 2018

Development of AM Technology

- ”Additive manufacturing” is almost 100 years old!
    - 1920 US patent on “Method for Making Decorative Articles”
    - Arc welding by hand
- AM truly enabled by:
    - Development of high energy density heat sources (laser & electron beam)
    - Development of computer numerical control (CNC) for machine manipulation



Milestones in AM Development

- United Technologies Research Center
  - US Patent 4,323,756 – ”Method for Fabricating Articles by Sequential Layer Deposition” - 1982
  - Broad description of both energy source and feedstock form

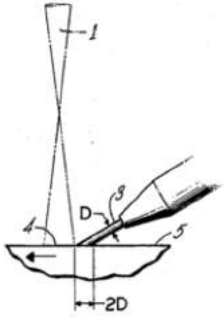
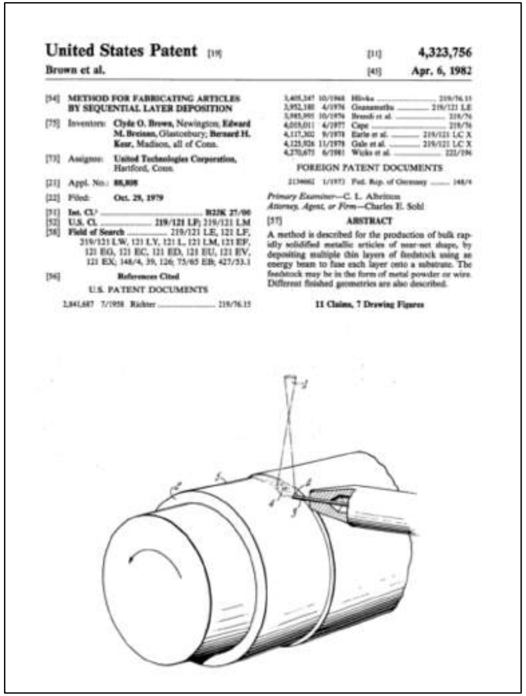


FIG. 2

FIG. 4



United States Patent [19] [11] 4,323,756
Brown et al. [45] Apr. 6, 1982

[54] METHOD FOR FABRICATING ARTICLES BY SEQUENTIAL LAYER DEPOSITION

[75] Inventors: Clyde O. Brown, Newington; Edward M. Breinan, Glastonbury; Bernard H. Kear, Madison, all of Conn.

[73] Assignee: United Technologies Corporation, Hartford, Conn.

[21] Appl. No.: 88,808

[22] Filed: Oct. 29, 1979

[51] Int. Cl.[3] B22K 27/00
[52] U.S. Cl. .... 219/121 LF; 219/121 LM
[58] Field of Search .... 219/121 LE, 121 LF, 219/121 LW, 121 LY, 121 L, 121 LM, 121 EF, 121 EG, 121 EC, 121 ED, 121 EU, 121 EV, 121 EX; 148/4, 39, 126; 75/65 EB; 427/53.1

[56] References Cited

U.S. PATENT DOCUMENTS

2,841,687 7/1958 Richter 219/76.15
3,405,247 10/1968 Hlivka 219/76.11
3,952,180 4/1976 Gnanamuthu .... 219/121 LE
3,985,995 10/1976 Brandi et al. 219/76
4,015,011 4/1977 Cape 219/76
4,117,302 9/1978 Earle et al. .... 219/121 LC X
4,125,926 11/1978 Gale et al. .... 219/121 LC X
4,270,675 6/1981 Wicks et al. 222/196

FOREIGN PATENT DOCUMENTS

2134062 1/1973 Fed. Rep. of Germany 148/4

Primary Examiner—C. L. Albritton
Attorney, Agent, or Firm—Charles E. Sohl

[57] ABSTRACT

A method is described for the production of bulk rapidly solidified metallic articles of near-net shape, by depositing multiple thin layers of feedstock using an energy beam to fuse each layer onto a substrate. The feedstock may be in the form of metal powder or wire. Different finished geometries are also described.

11 Claims, 7 Drawing Figures

Milestones in AM Development

- First patents filed 1984 (but heritage goes back to the 50s and 60s)
  - Selectively adding material layer by layer – stereolithography (aka vat photopolymerization)
- 1986 patents for laminated object manufacturing, selective laser sintering, and others
- 1989 fused deposition modeling (FDM) patented by Stratasys
- 1994 ink jet / binder jet tech patented
- As patents expire, new companies can get into the game and advance the tech faster, e.g. MakerBot-type

Milestones in AM Development

- First commercially-available metal AM system produced in 1998
  - Optomec LENS machine (laser blown powder) →
  - Technology developed at Sandia National Laboratory
- Powder bed systems became available in the early 2000s
  - Arcam, EOS, etc

dapt

ISO/ASTM 52900 Standard Definitions

1. Vat photopolymerization
2. Powder bed fusion
3. Material extrusion
4. Material jetting
5. Binder jetting
6. Sheet lamination
7. Directed energy deposition

ISO/ASTM 52900:2015(E)

Standard Terminology for Additive Manufacturing – General Principles – Terminology[1,2]

This standard is issued under the fixed designation ISO/ASTM 52900; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision.

1. Scope

1.1 This International Standard establishes and defines terms used in additive manufacturing (AM) technology, which applies the additive shaping principle and thereby builds physical 3D geometries by successive addition of material.

1.2 The terms have been classified into specific fields of application.

1.3 New terms emerging from the future work within ISO/TC 261 and ASTM F42 will be included in upcoming amendments and overviews of this International Standard.

2. Referenced Documents

2.1 *ISO Standards:*[3]

ISO 841 Industrial automation systems and integration—Numerical control of machines—Coordinate system and motion nomenclature

ISO 10303 Industrial automation systems and integration—Product data representation and exchange

ISO 17296-2 Additive manufacturing—General priniciples—Part 2: Overview of process categories and feedstock

2.2 *ISO/ASTM Standards:*[3,4]

ISO/ASTM 52915 Standard specification for additive manufacturing file format (AMF)

ISO/ASTM 52921 Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies

3. Terminology

3.1 *General Terms*

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

additive manufacturing (AM), *n*—process of joining materials to make **parts** from 3D model data, usually **layer** upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies.

DISCUSSION—Historical terms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, solid freeform fabrication and freeform fabrication.

DISCUSSION—The meaning of "additive", "subtractive" and "formative" manufacturing methodologies are further discussed in Annex A1.

additive system, *n*—**additive manufacturing system,** additive manufacturing equipment, machine and auxiliary equipment used for **additive manufacturing**.

AM machine, *n*—section of the **additive manufacturing** system including hardware, machine control software, required set-up software and peripheral accessories necessary to complete a **build cycle** for producing **parts**.

AM machine user, *n*—operator of or entity using an AM **machine**.

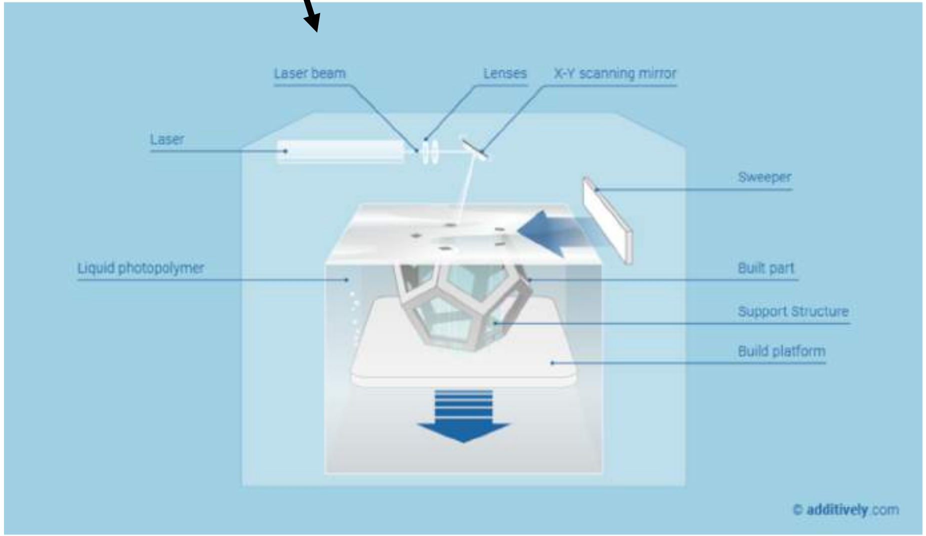
AM system user, *n*—additive system user, operator of or entity using an entire **additive manufacturing system** or any component of an additive system.

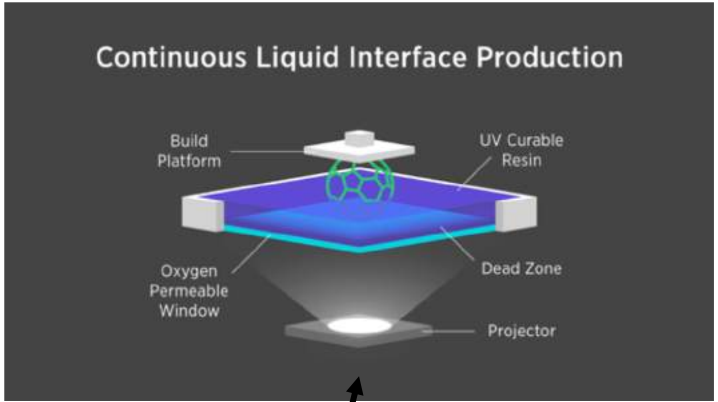
front, *n*—*of a machine, unless otherwise designated by the*

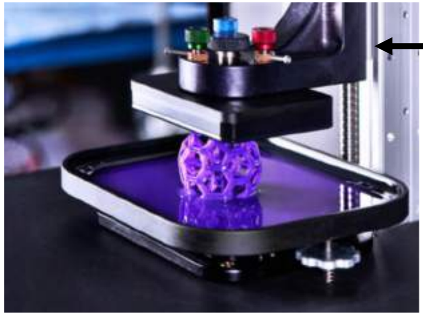
dapt

Vat Photopolymerization (VP) Process

Conventional rastered point source using mirror galvanometer



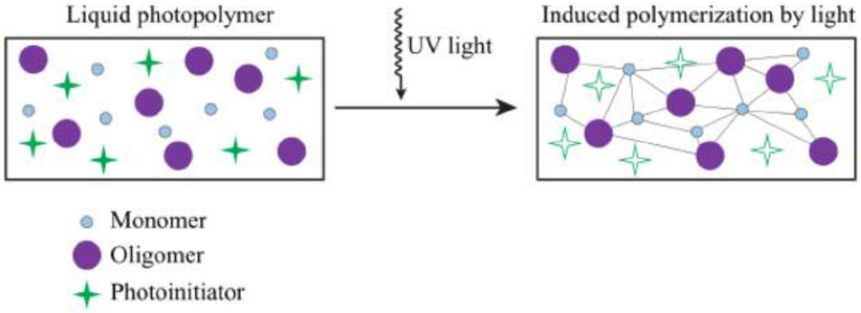




Digital Light Processing (DLP) via micromirror

VP Materials

- Radiation-curable photopolymers
  - Various curing radiations including:
    - Gamma rays
    - X-rays
    - Electron beams
    - *UV (most common, used in commercial machines)*
    - Visible light (used in commercial machines)
- Generally for prototyping only due to material property constraints (though improving rapidly)



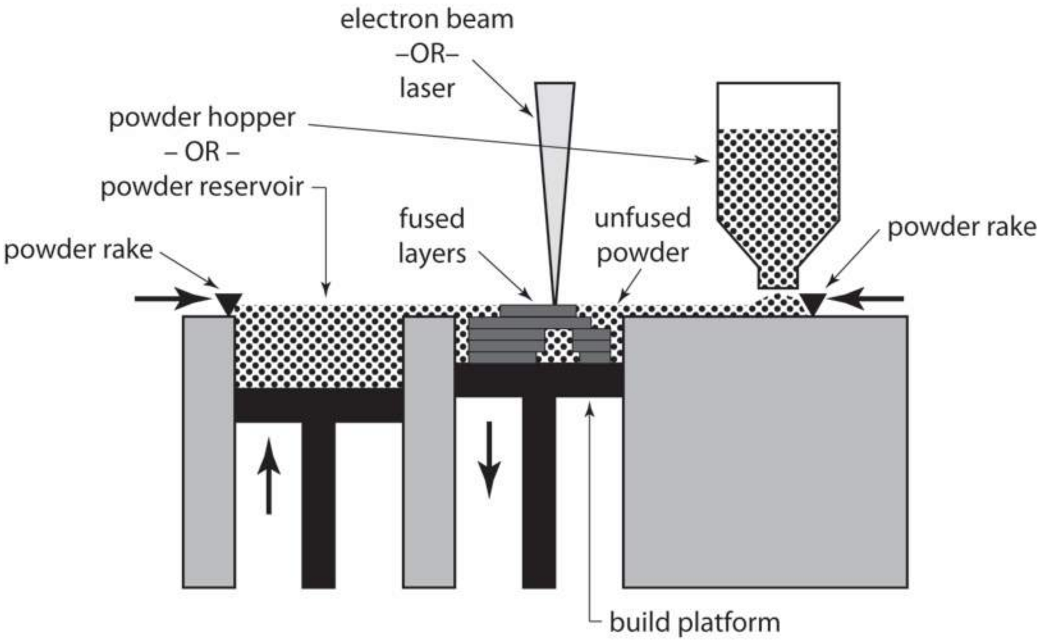
VP Process Benefits and Drawbacks

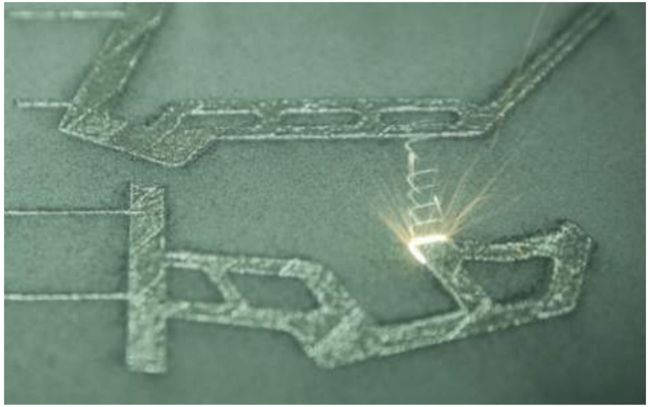
- Benefits:
    - Part accuracy
    - Surface finish
    - Flexibility of machine configurations and sizes
    - Speed of process
- Drawbacks:
    - Limited photopolymer compositions available
    - Little impact strength or durability compared to injection molded parts
    - Parts age and degrade over time

Powder Bed Fusion Processes

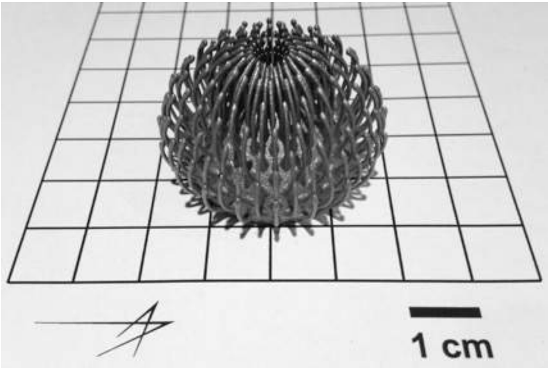
- Originally developed at University of Texas Austin
- First commercialized process was selective laser sintering (SLS)
- Basic set of characteristics shared by all powder based processes:
  - Thermal source for inducing fusion in powder
  - Method to control fusion to a prescribed region in a single layer
  - Mechanism for adding and smoothing powder
- Works with weldable metals and semi-crystalline polymers
- Usually conducted in inert environment (argon, vacuum)

Powder Bed Fusion (PBF) Processes





PBF Examples

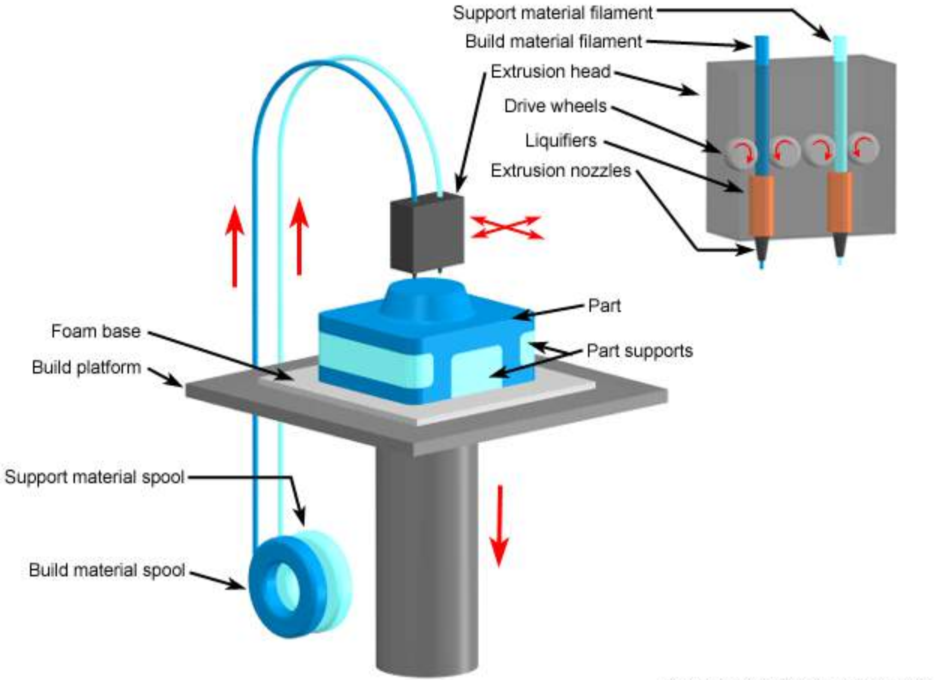


PBF Process Benefits and Drawbacks

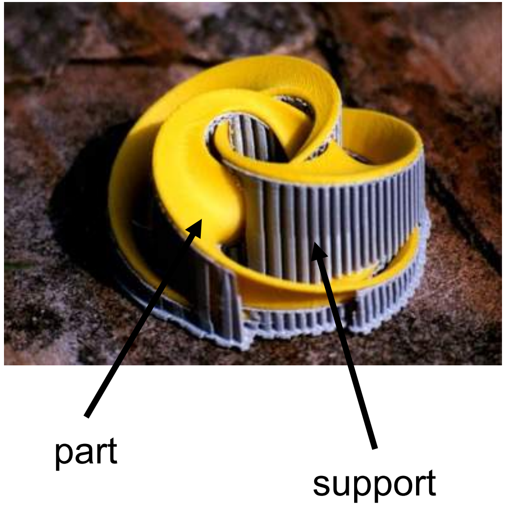
- Benefits
  - Wide array of materials to choose from (metals, plastics, ceramics)
  - Usually don’t need support material with plastics but often do with metals and some ceramics
  - Very high accuracy and good surface finish
  - Can build many parts at once in the same build volume without problem
- Drawbacks
  - Process can be relatively slow
  - Often need to remove support structure
  - As-deposited surface finish can be detrimental to properties

dapt

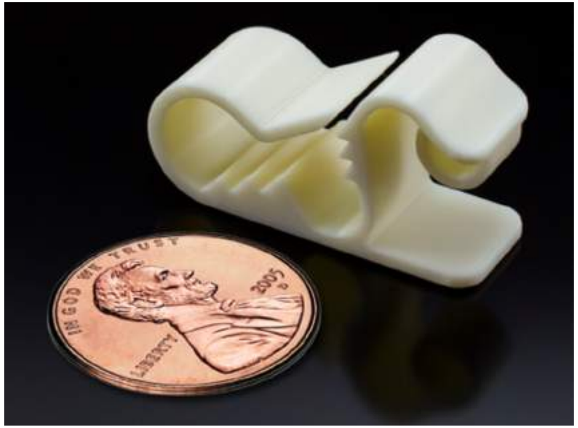
Material Extrusion (ME) Process



Copyright © 2008 CustomPartNet



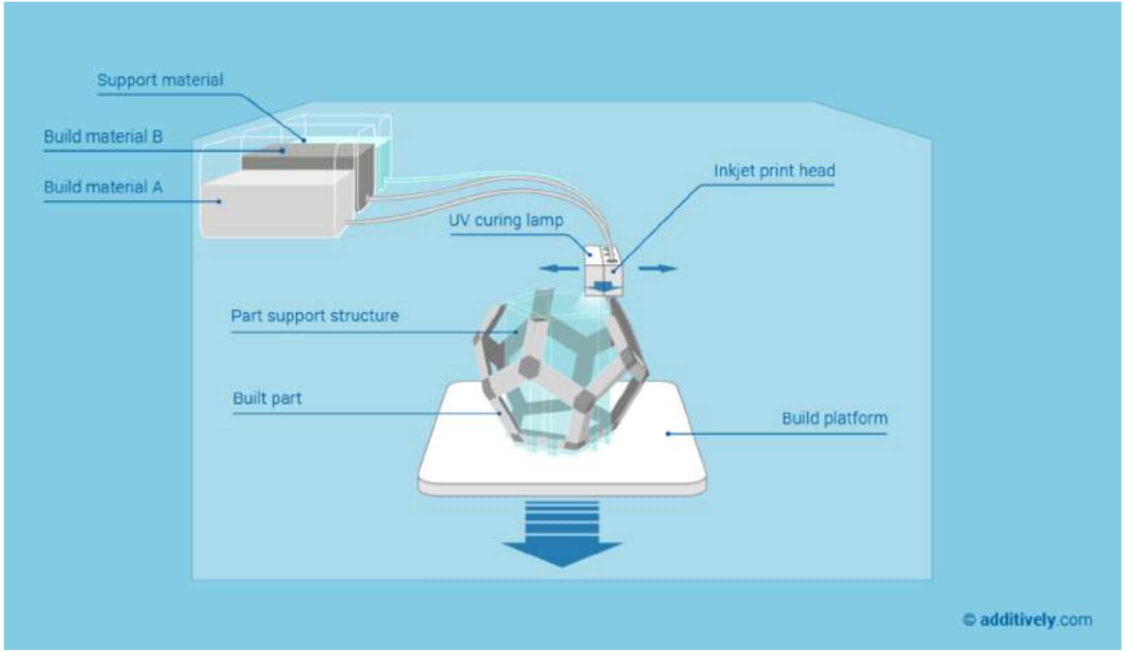
ME Example Parts



Benefits & Drawbacks of ME

- Benefits
  - Cheap and easily accessible by the most novice users
    - Consumer grade machines available for < $200
  - Wide variety of equipment at a wide variety of deposition rates/length scales
- Drawbacks
  - Speed and accuracy aren't great on many machines
  - Quality varies greatly – you get what you pay for!
  - Anisotropic effects of the way materials are laid down

Material Jetting (MJ) Process



Jetting Fundamentals

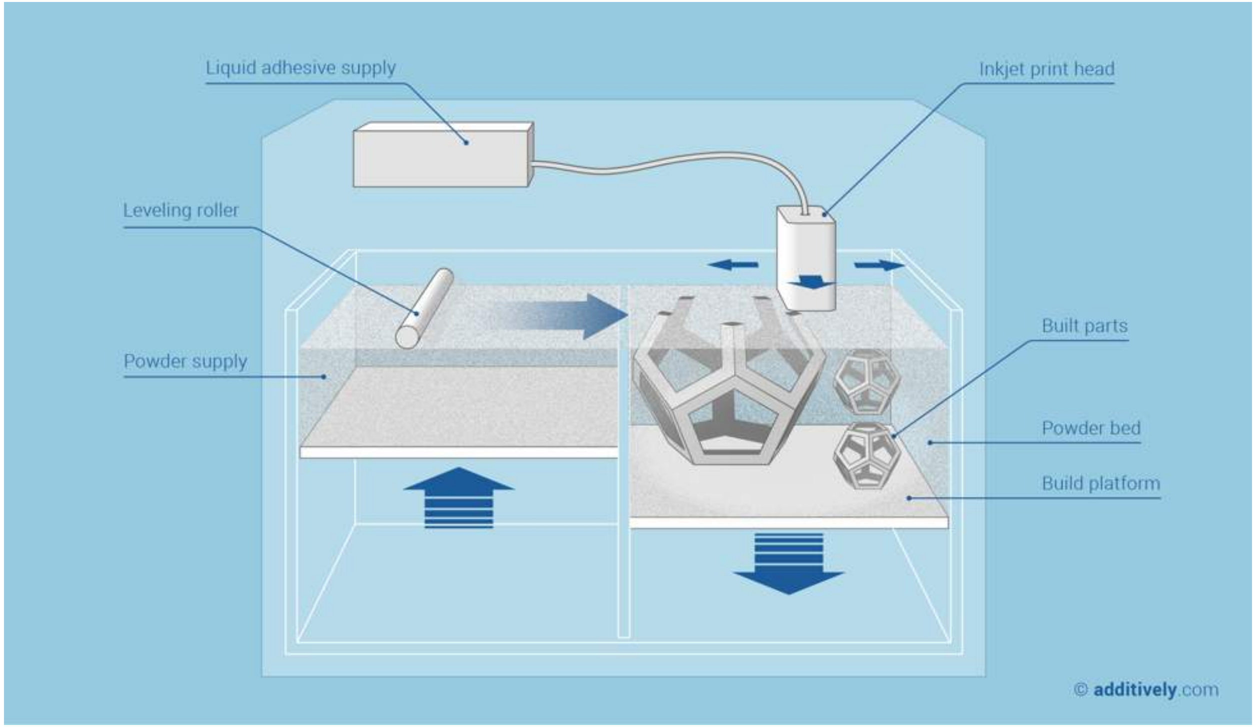
- Material must have the right properties
  - Ideal viscosity 20-40 centipoise (cP)
    - Most likely to cause processing problems if outside the ideal range
  - Liquified using heat (for thermally “curing” materials)
  - Can also take advantage of shear thinning liquids
    - Materials that change viscosity under shear load (e.g blood, ketchup)
    - Squeezed through a small nozzle, shear thinning fluids become more liquid and can flow
  - *For reaction cured materials (e.g. UV light + photoinitiators), liquid properties are easier to control*
  - Possible to get down to 10s of microns thick layers

dapt

MJ Process Benefits and Drawbacks

- Benefits
  - Low cost (relative)
  - High speed
  - Scalability (array of many nozzles)
  - Multi materials and/or colors
- Drawbacks
  - Material choices (outside of cosmetic, e.g. color)
  - Resolution (less than most comparable VP systems)

Binder Jetting (BJ) Process



BJ Fundamentals

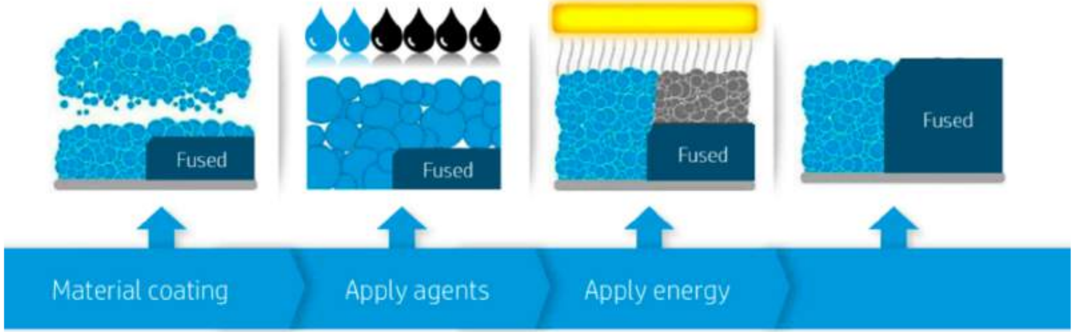
- Uses ink-jet technology just like material jetting
  - Jetted material is only binder, not the actual build material
- Highly scalable, line-wise process
- Often infiltrated with strengthening agent after initial cure
- Wide range of materials
  - Plaster with water binder
  - Sand for making casting molds and cores
  - Metal (mainly ferrous, mainly for tooling)

BJ Benefits and Drawbacks

- Benefits
  - Similar benefits to material jetting
    - Necessary to spread/level powder which add time and slows down the process compared to MJ
  - Powder bed gives high fraction solids – makes for easier densification of certain materials
  - Color options
- Drawbacks
  - Typically lower resolution than material jetting
  - Often need infiltration step to achieve full density

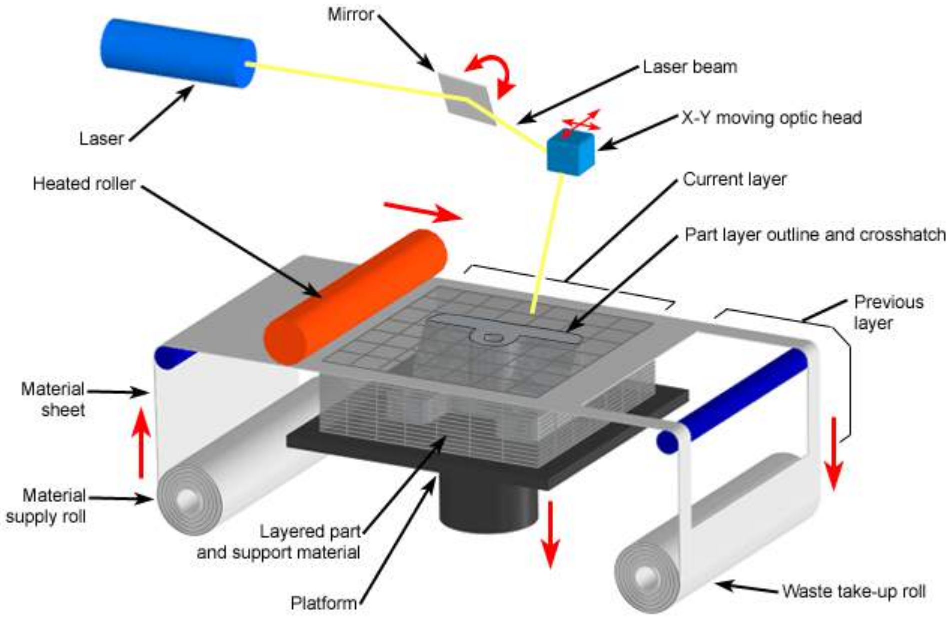
HP Jet Fusion

Does not fit neatly into any of the seven ISO/ASTM classifications



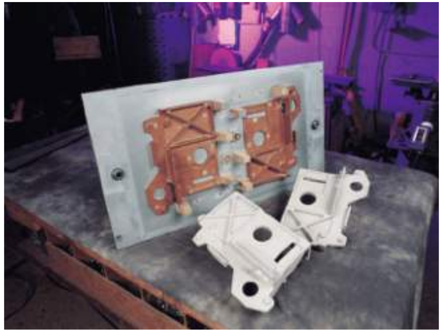
dapt

Sheet Lamination Process



Copyright © 2008 CustomPartNet

Sheet Lamination Processes



- Bonding methods
  - Gluing or adhesive bonding
  - Thermal bonding
  - Clamping
  - Ultrasonic joining
- All methods are solid-state in terms of the feedstock material though the glue or adhesive can be liquid

- Two primary approaches
  - Bond-then-form
  - Form-then-bond

dapt

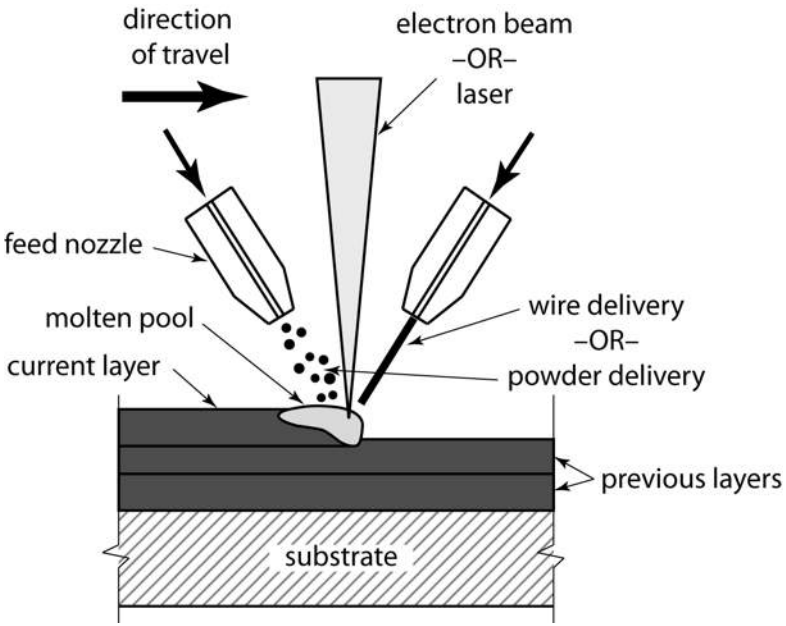
SL Benefits and Drawbacks

- Benefits
  - Desktop machines usable in office environment
  - Most basic systems use office paper and simple, cheap glue
  - Solid state (no melting) so can use multiple materials in same part
- Drawbacks
  - Structural integrity can be low – especially between layers
  - Prone to delamination defects & failure
  - Feedstock materials (beyond office paper) sometimes difficult to source
    - e.g., metal foil feedstocks

Directed Energy Deposition (DED)

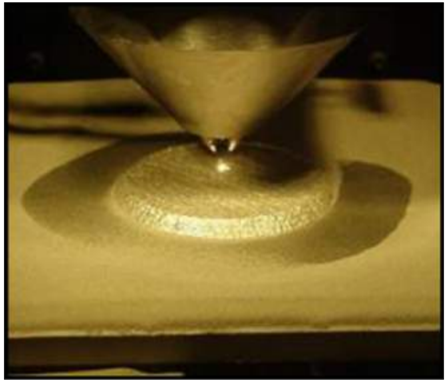
- Direct energy source onto substrate/previous layer and inject feedstock material to form a deposit of material
  - Can be though of as very similar to a welding process (without the joint)
  - In fact, welding processes can be adapted to perform AM
- Usually done with metal although plastic and ceramics are available
  - Can be done with powder or wire

DED Processes



DED Process

Small → Big



DED Benefits and Drawbacks

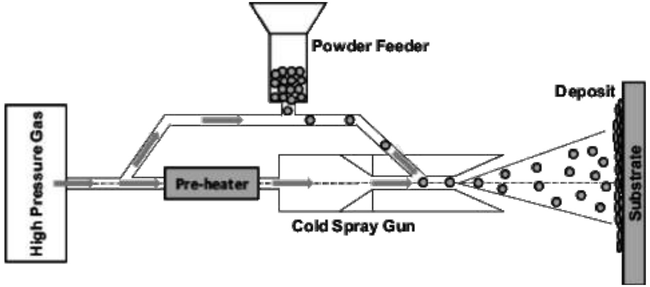
- Benefits
  - High control of microstructure
  - Can be used to repair/refurbish equipment
  - Can make heterogeneous parts and composites from varying the powder or wire feed
    - Multiple simultaneous feedstocks for new alloys
  - Can be used to make coatings
- Drawbacks
  - Can't produce complex structures comparable to powder bed fusion machines
  - Requires post processing due to poor part accuracy, etc

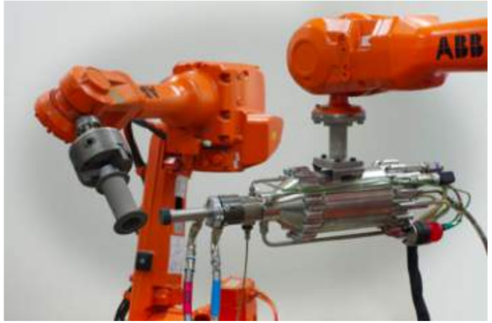
Direct Write (DW) Processes

- Direct write defined as small-scale freeform structures (50 μm or smaller resolution size)
- DARPA originally funded research in this area in the 1990s
  - MICE program: Mesoscopic Integrated Conformal Electronics
  - Variety of process variations came out of this project
- Does not generally use a heat source so not technically classified as DED, though fits best into this category
  - Often either aerosol jet or reactive ink

Cold Spray Process

- Like DW, does not fit neatly into any of the seven ISO/ASTM categories
- Process uses powder, supersonically accelerated through a nozzle, that is then impacted onto a substrate
  - Manipulation of this powder stream can create 3D parts
  - Solid state bonding holds the powders together





Questions?