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Metal additive manufacturing and powder metallurgy

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IMAM Conference, 2020 New Mexico

Metal Additive Manufacturing and Powder Metallurgy

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Queensbury, NY

Presented by:
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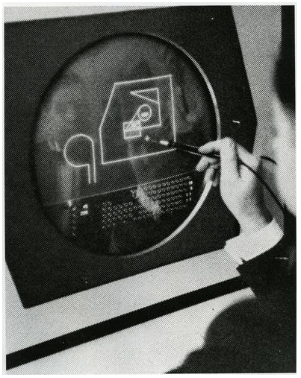
Kymera International

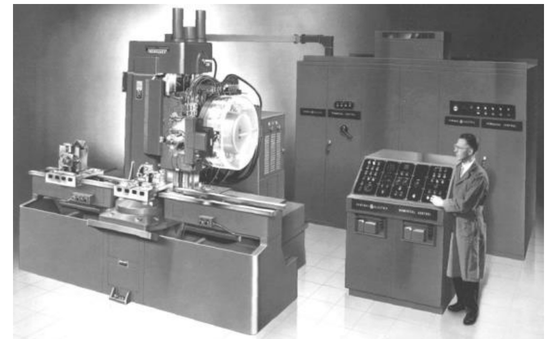
- **I** Introduction
  - History: Rapid Prototyping to Additive Manufacturing
  - Present: Additive Manufacturing & PM
- **II** Types of AM using Metal Powders
- **III** Powder Production and Requirements for Additive Manufacturing
- **IV** AM & PM: Compete or Compliment?
- **V** Summary

Rapid Prototyping Terminology:

- Rapid Prototyping (RP)
- Rapid Manufacturing (RM)
- Stereolithography (SLA)
- Free-form Fabrication (FFF)
- Additive Fabrication (AF)
- Additive Layering (AL)
- Direct Digital Manufacturing (DDM)
- 3D Printing (3DP)
- ***Additive Manufacturing (AM)***

I Introduction, History





1960’s - 1970’s:

- **CNC**: Computer Numerical Control:
  Computer controlled machine motion:
- **CAD**: Computer Aided Design:
  Graphics (2D, 3D)
  Design analysis, properties
- **CAM**: Computer Aided Manufacturing:
  Enabled machine tool path/motion (CNC)
  directly from the computer model.
- **Photopolymers**
- **High energy lasers** (affordable)
- **Inkjet printers**

1980's:

- **CAD**: 3D solid manipulation:
  - .stl file format: Defines surfaces only.
  - Enabled layering process.

Rapid Prototyping combines all of the above technologies:

1) **CAD representation** of the part

    3D solid model, <u>sliced into layers</u>.

2) **Easily manipulated build material** (liquid, powder)

    to be distributed layer by layer (slice by slice).

3) **Precision scanning** to fix the build material

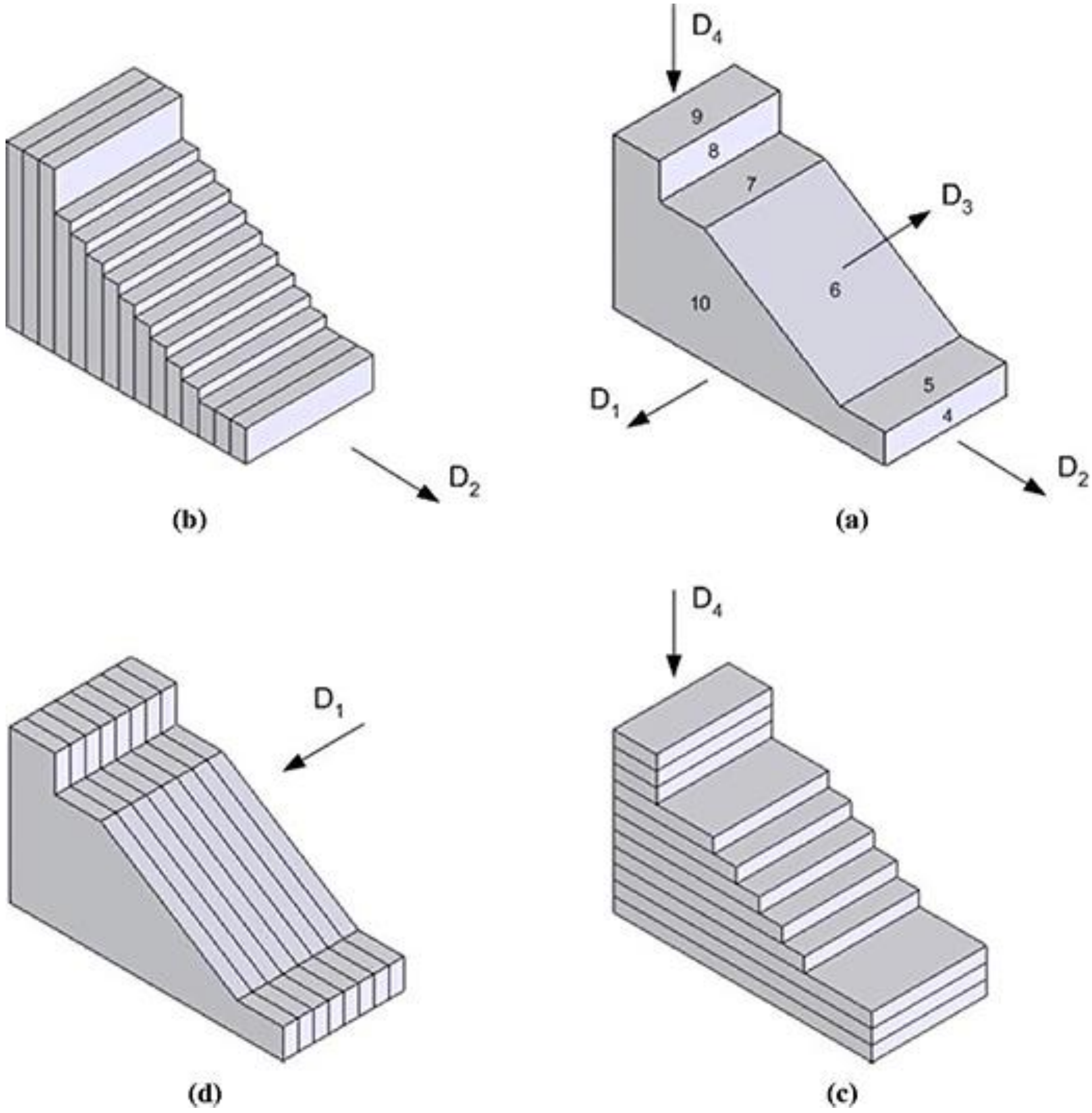
    High energy laser

    CNC (motion control for laser)

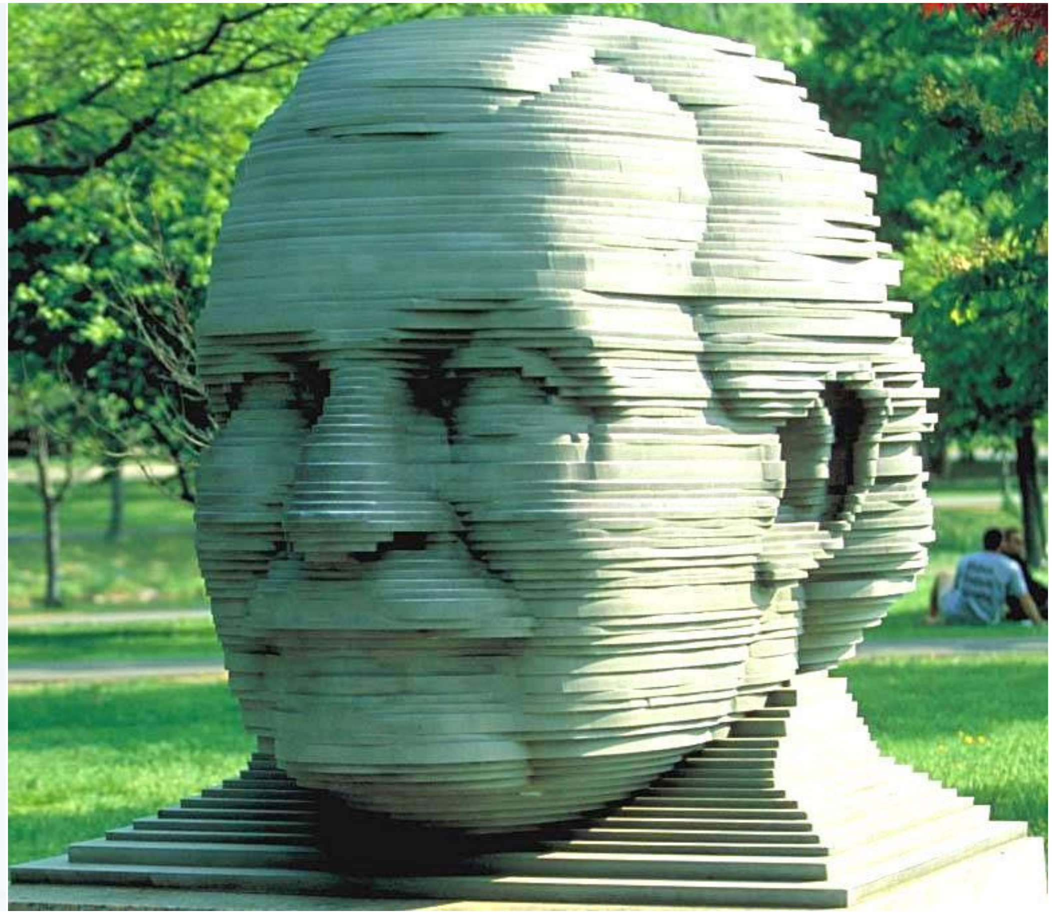
1980’s:

- **Stereolithography,** SLA (Charles Hull)
  - UV laser and photopolymer (now Vat Photopolymerization)
- **Selective Laser Sintering,** SLS (Carl Deckard)
  - Laser and polymer powder (now Lasering Sintering Powder Bed Fusion)
- **Fused Deposition Modeling,** FDM (Scott Crump)
  - Extruded polymer from filament (now Material Extrusion)

- **Rapid Prototyping**
  - Buildup of a part layer by adding material layer by layer
  - “Additive” rather than “Subtractive”

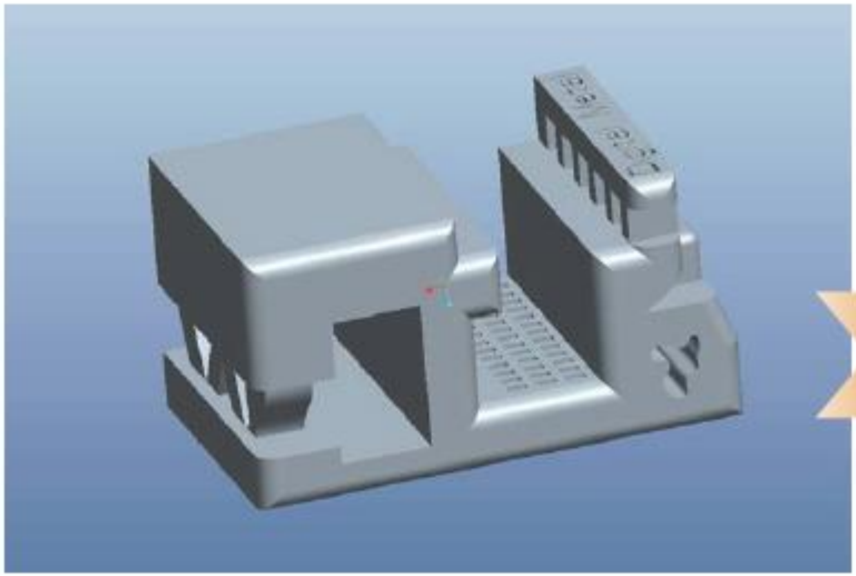


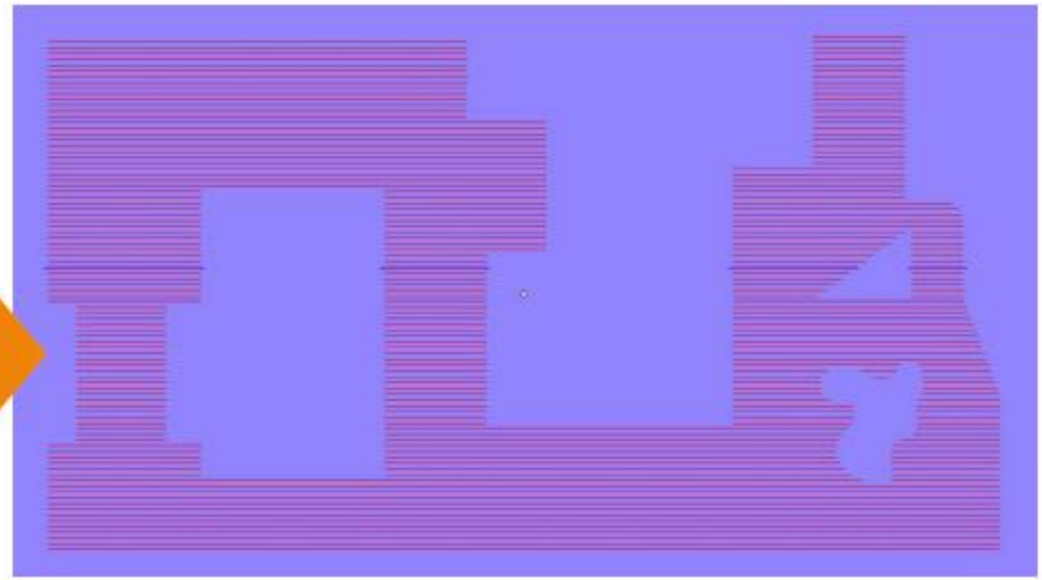
D4
9
8
7
D3
6
10
5
4
D1
D2
D2
(b)
(a)
D1
D4
(d)
(c)



Arthur Fiedler
By Ralph Helmick

Layering a CAD (.stl) file:





Design and fabrication opportunities

- **No specific tooling: flexible process**
- Freedom of design
- Complexity for free
- Mass customization

"DESIGN-BASED MANUFACTURING PROCESS"

Design not limited by current manufacturing technology's limitations and constraints.

Rapid "**Prototyping**":

Fabrication of a REPRESENTATION of a part; a **model**.

Compromises in:

- Material
- Tolerances
- Dimensions
- Surface finish

Summary of Early RP (1986-1990's):

- Tolerances: Unusably wide
- Surface finish: Very poor
- Material cost: Prohibitively expensive
- Material properties: Substandard **(and plastic…)**
- Equipment: Expensive and unreliable

➡ "Communications tool"

Rapid Prototyping → "Additive Manufacturing"

Rapid Prototyping ➡ "Additive Manufacturing"

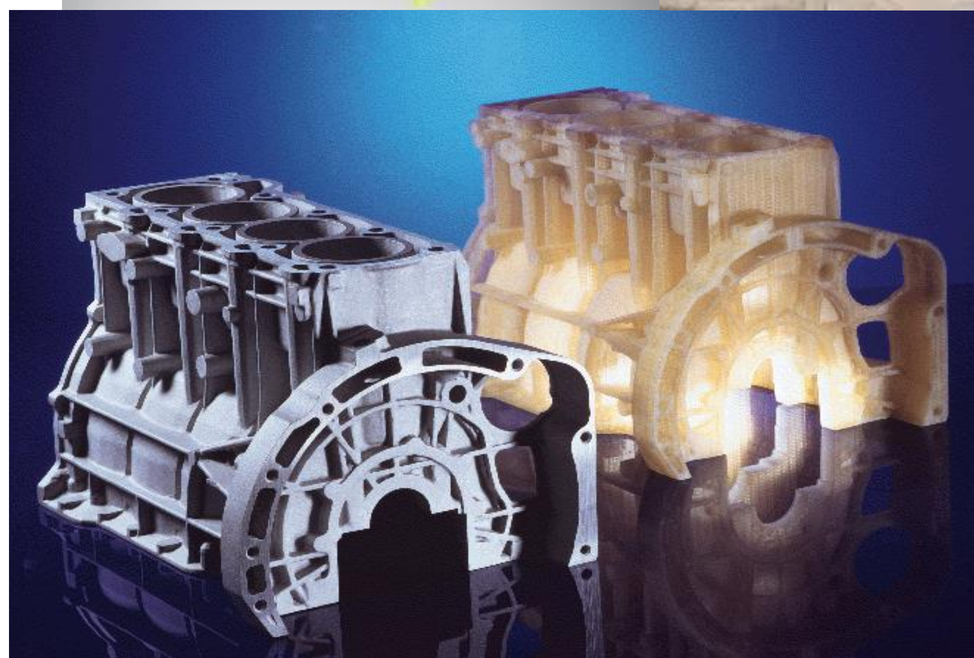
- Improved machines
- Improved processes
- Improved materials
- Improved tolerances, repeatability
- Real parts, not just prototypes


spirax
sarco
S4
S1
S3









Additive Manufacturing ➡ Powder Metallurgy

Additive Manufacturing ➡ Powder Metallurgy

- Improved machines
- Improved processes
- **Improved materials: METAL**
- Improved tolerances, repeatability
- **Real METAL parts, not just plastics!**

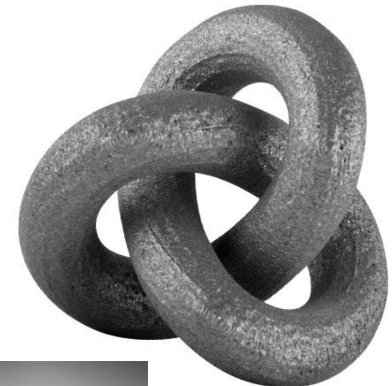
Additive Manufacturing & Powder Metallurgy:

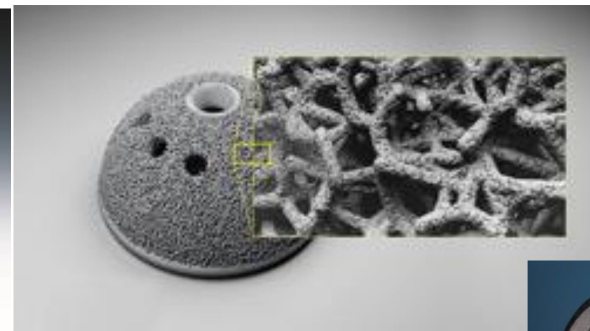
- Metal additive manufacturing uses metal powder as the “easily manipulated material” to make parts.
- Powder Metallurgy is the use of metal powder to make parts.

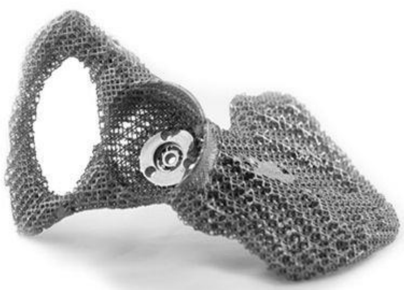
Additive Manufacturing & Powder Metallurgy:

- Metal additive manufacturing uses metal powder as the “easily manipulated material” to make parts.
- Powder Metallurgy is the use of metal powder to make parts.
- **Additive Manufacturing is a Powder Metallurgy technology!**

I Introduction and Present



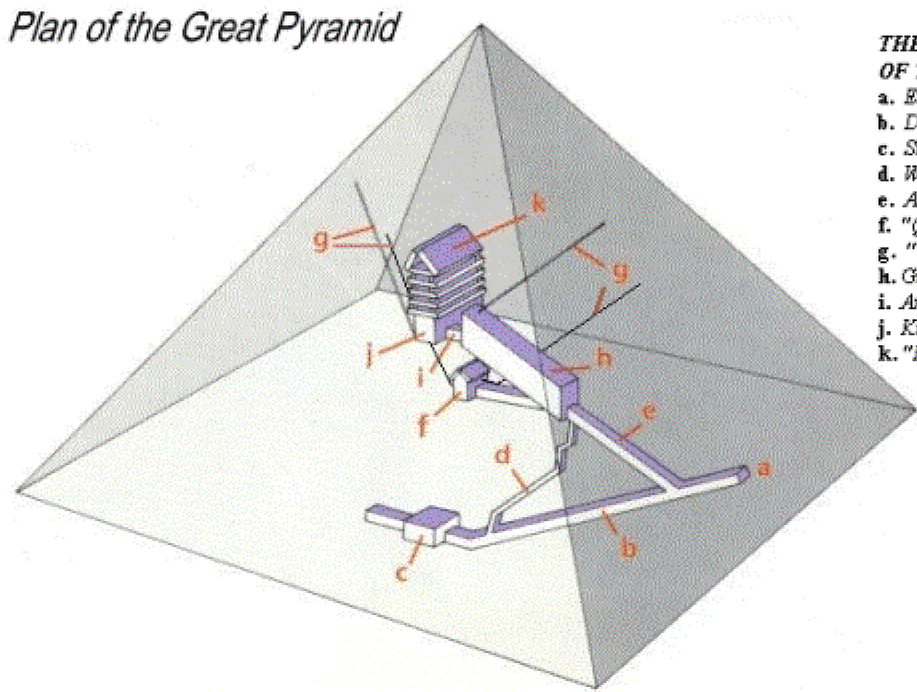




Additive Manufacturing:

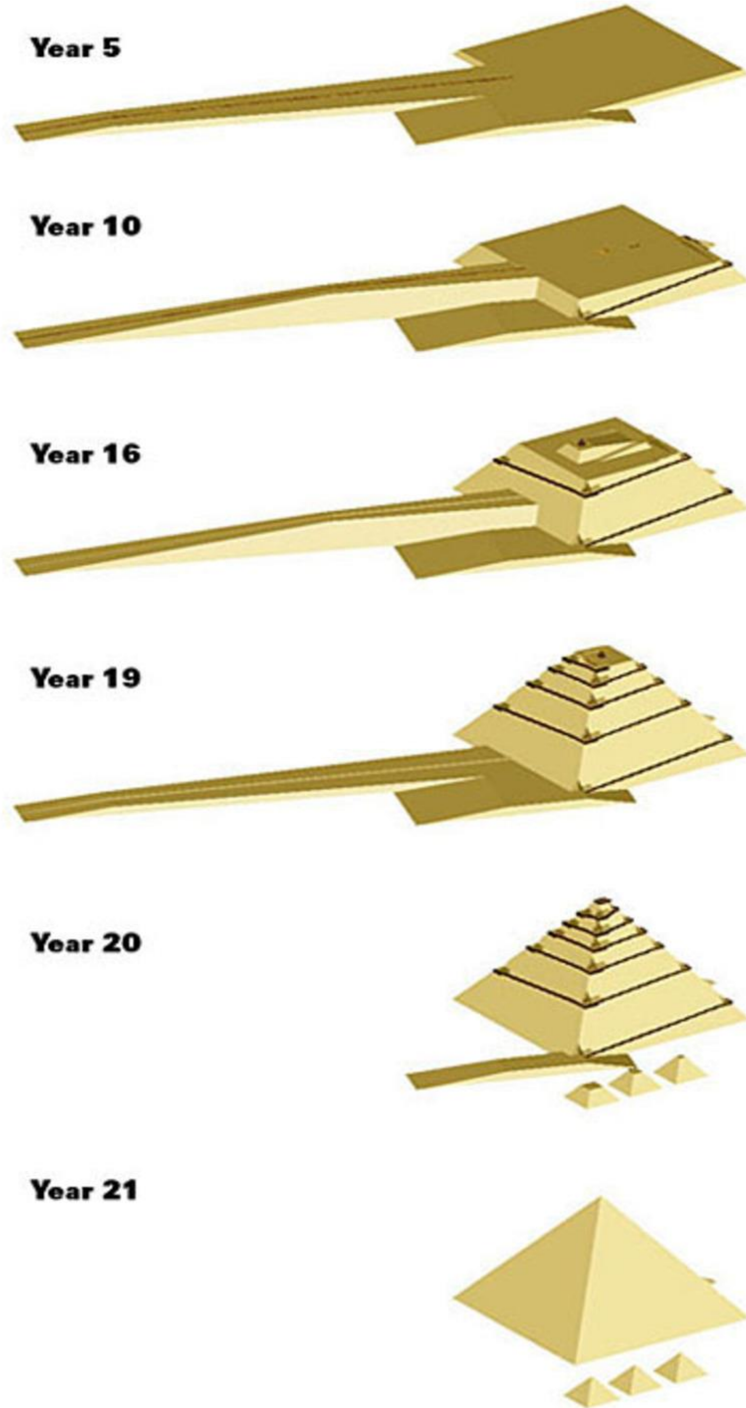
Is it really new?


13,000 BC!!



THE INTERNAL ARRANGEMENT OF THE PYRAMID OF KHUFU

a. *Entrance*
b. *Descending Passageway*
c. *Subterranean Chamber*
d. *Well Shaft*
e. *Ascending Passageway*
f. *"Queen's" Chamber*
g. *"Ventilation Shafts"*
h. *Grand Gallery*
i. *Antechamber*
j. *King's Chamber*
k. *"Relieving Chambers"*



Iron Pillar of Delhi, India

400 CE (AD)

- Layer by layer build
- Sponge iron powder
- Precision hammered

II Types of AM using metal powders 2019

Available METAL Additive Manufacturing technologies:

1) Laser Sintering (L-PBF)*
2) Electron Beam Melting (E-PBF)*
3) Directed Energy Deposition (DED)
4) Cold Spray
5) Binder Jetting (BJ)*
6) Material Extrusion (ME)
7) Material Jetting (MJ)
8) Vat Photopolymerization

* Powder Bed process
RED: not a fusion process
BOLD FACE: New in 2018

II Types of AM using metal powders ***2014-2016***

1. Laser Sintering/Laser Melting (powder bed):

Essentially laser melting of the powder layer

~9 Equipment manufacturers world-wide

- **Concept Laser, Germany ***
- **EOS, German/Finland ***
- **Phenix, France/US (3D Systems) ***
- **Realizer, Germany ***
- **Renishaw, UK ***
- **SLM, Germany ***
- Farsoon, China
- Inss Tek, Korea
- Wuhan Binhu, China

*** major equipment manufacturers**

Laser Powder Bed Fusion Systems

~9 Equipment manufacturers world-wide 2014-2016

- **Concept Laser, GE Germany***
- **EOS, German/Finland ***
- **Phenix, France/US (3D Systems)***
- **Realizer/DMG Mori, Germany/Japan***
- **Renishaw, UK ***
- **SLM, Germany ***
- **Farsoon, China***
- Inss Tek, Korea
- Wuhan Binhu, China

*** major equipment manufacturers**

2017

Additive Industries, Netherlands

Addup, France

Aurora, Australia

DDM, USA

OR Laser, Germany

Sodick (hybrid), UK

Trump, Germany

Xact Metal, US

Asian companies too numerous to count.

Xact Metal

State College, PA

XM200

JUAN MARIO GOMEZ

CHIEF EXECUTIVE OFFICER

MATT WOODS

CHIEF TECHNICAL OFFICER

TIM SIMPSON

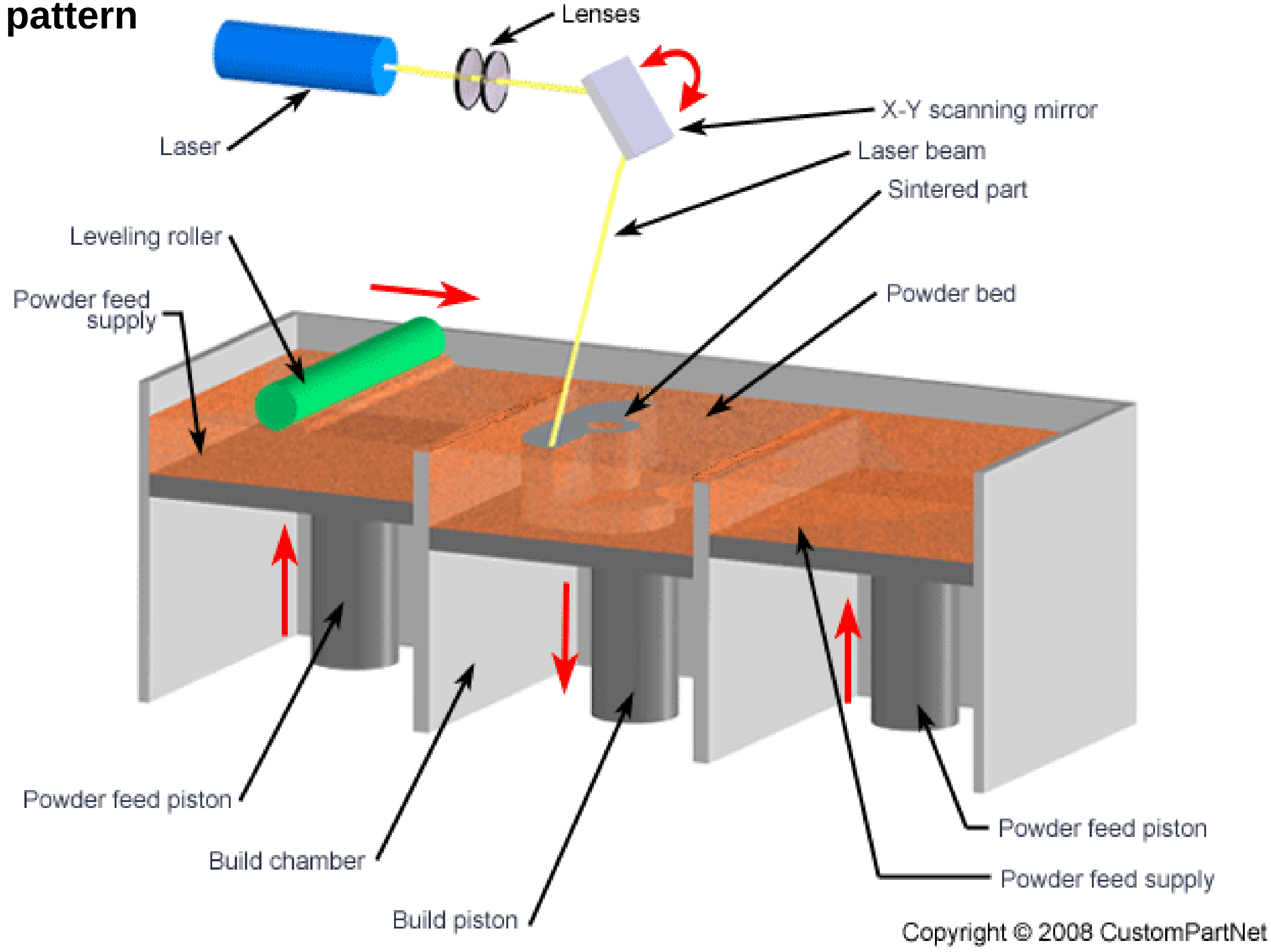
ADVISOR

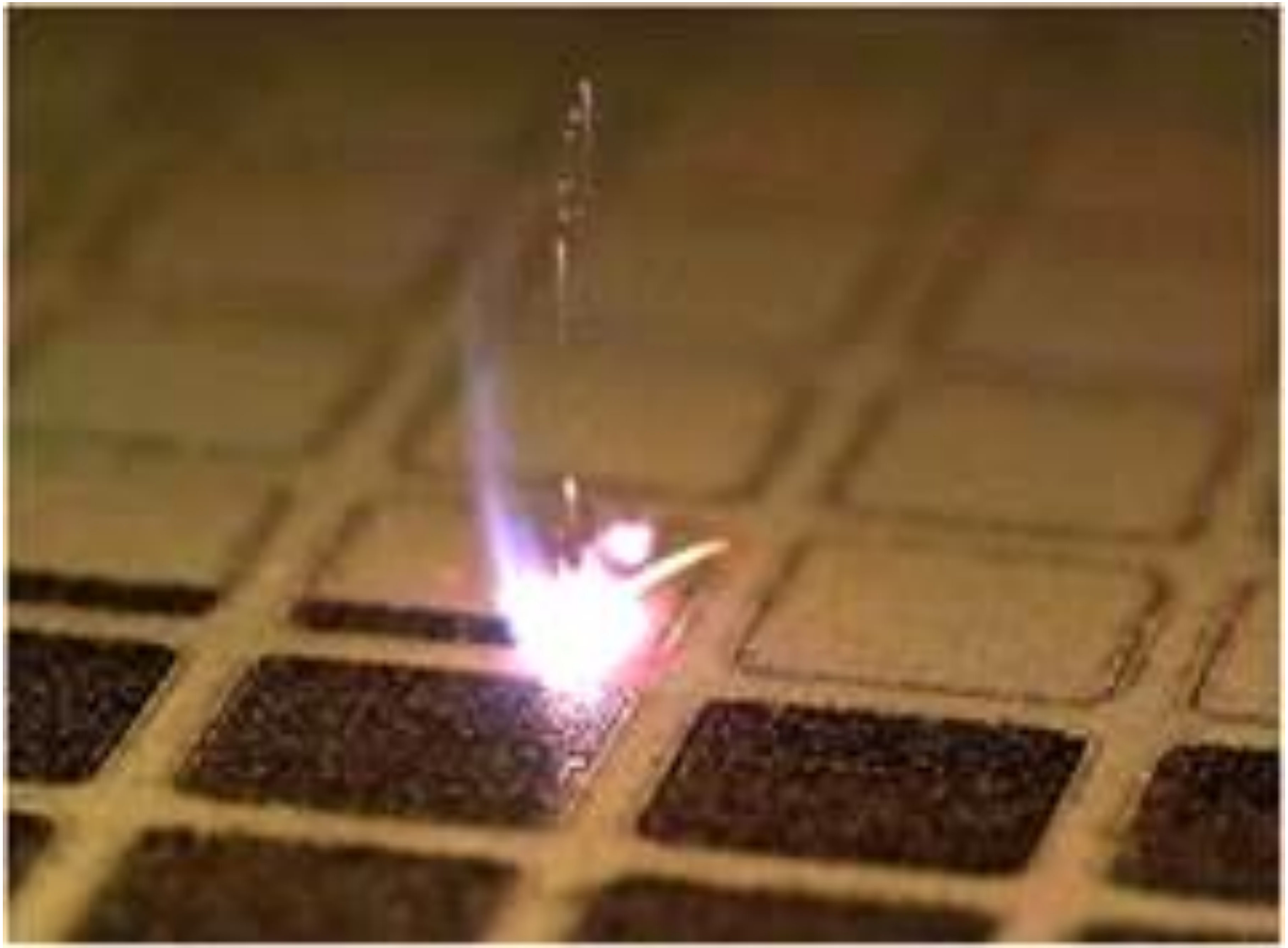
Laser Sintering

L-PBF

Laser Powder Bed Fusion

- Metal powder spread into layers
- Laser scanned, melting 2D pattern
- Repeat

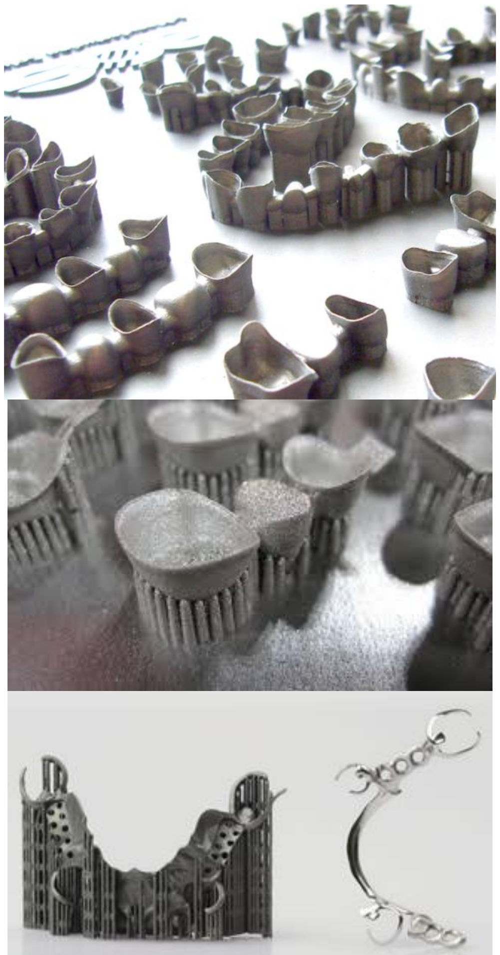




Metal Parts via Laser Sintering

Laser Sintered Metal Parts IN PRODUCTION

Co-Cr dental parts



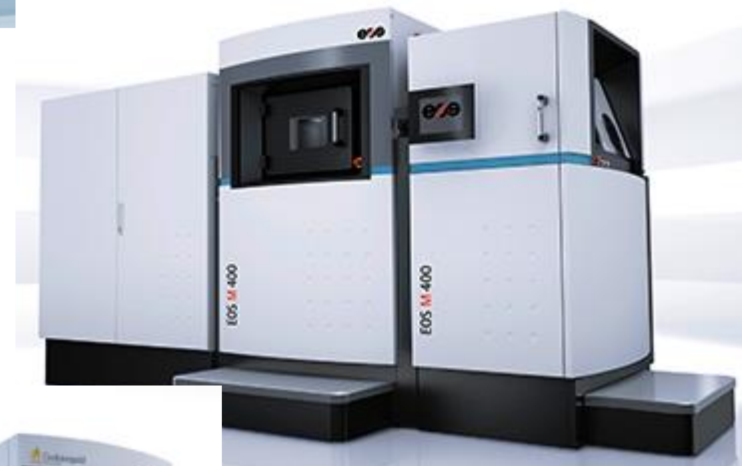
GE Leap
Fuel Nozzle

Tooling

“Design” Objects

- EOSINT M 280/290
  - All-round system for DirectMetal and DirectSteel materials
  - Build volume 250 x 250 x 325 mm*
  - Yb fiber laser, 200 Watt (400 optional)

- EOSINT M 400
  - Top-end system for DirectMetal, DirectSteel, largest system
  - Build volume 400 x 400 x 400 mm*
  - Yb fibre laser, 1000 Watt



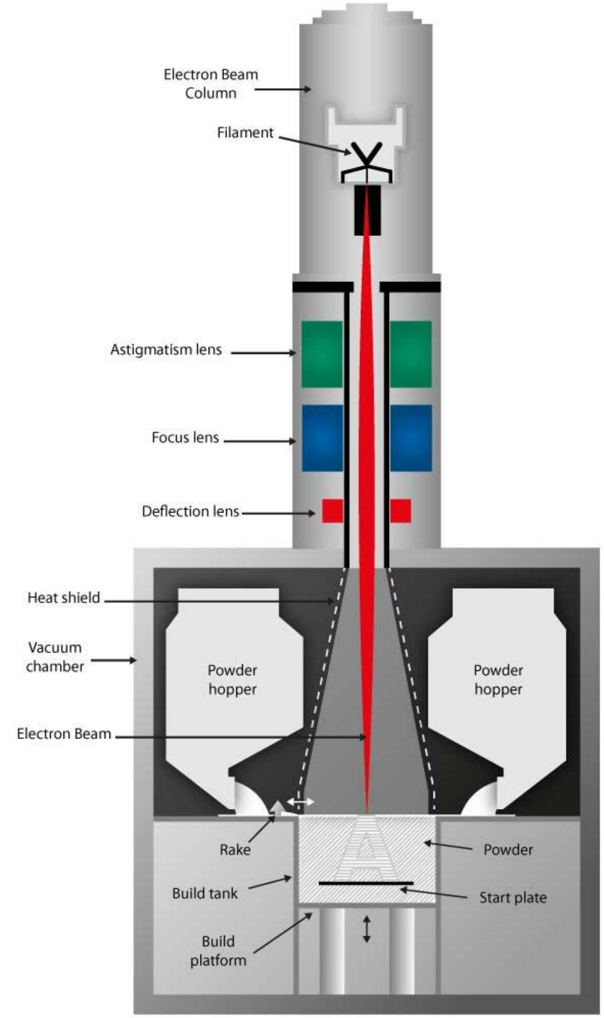
- Precious M 080
  - For precious metal alloys
  - Yb 100 watt laser, small focus spot
  - Cassette build chamber

2. Electron Beam Melting (E-PBF):

Uses an electron beam to melt the powder layer

Only 1 Equipment manufacture

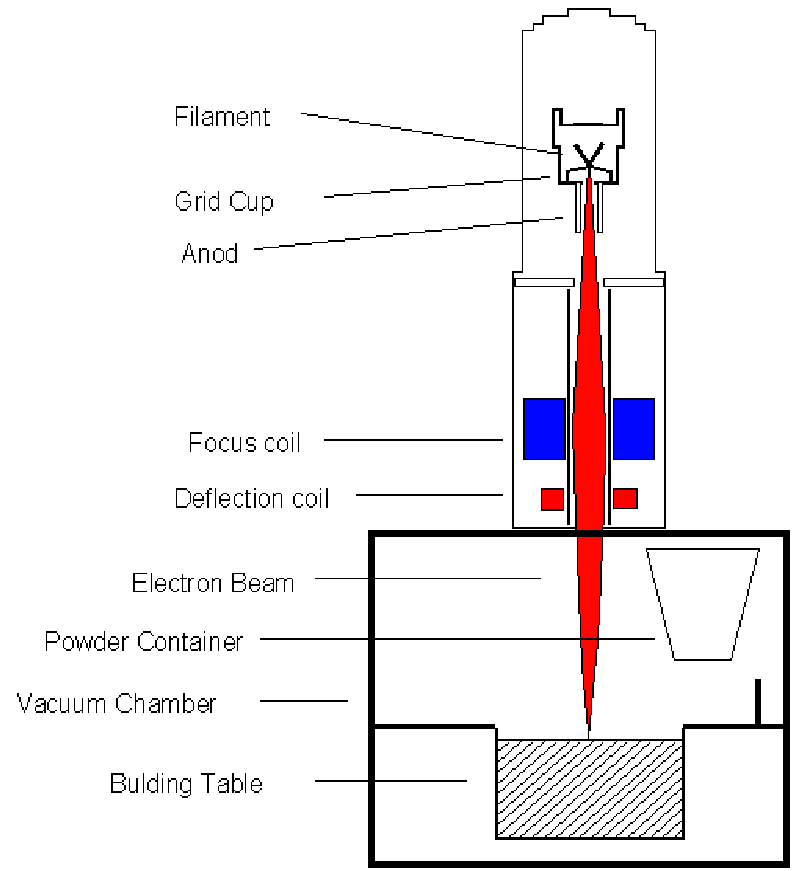
- Arcam, Sweden
  - Now owned by GE



Electron Beam Melting (E-PBF)

- Electrons are emitted from a filament which is heated to >2500° C.
- The electrons are accelerated through the anode to half the speed of light.
- A magnetic field lens brings the beam into focus.
- Another magnetic field controls the deflection of the beam.
- When the electrons hit the powder kinetic energy is transformed to heat.
- The heat melts the metal powder.

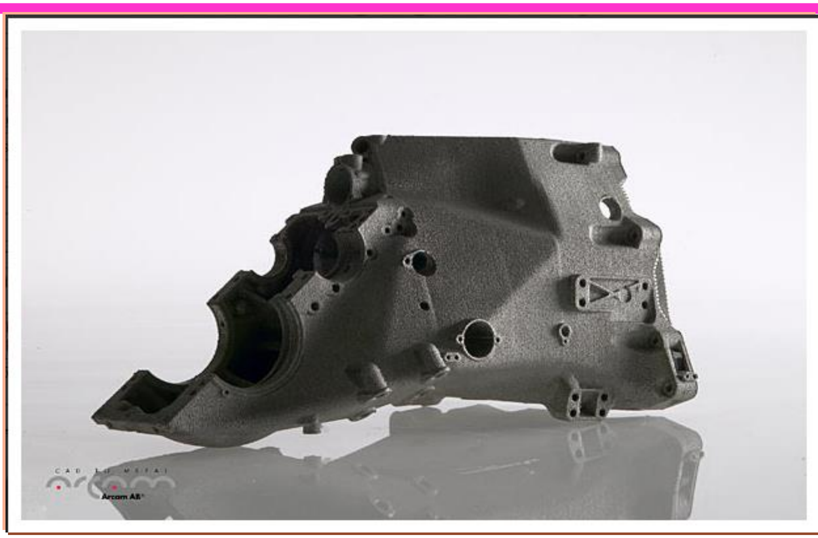
- **Faster build rates than laser**
- **Poorer resolution/surface finish than laser**
- **Operates in vacuum: very clean**

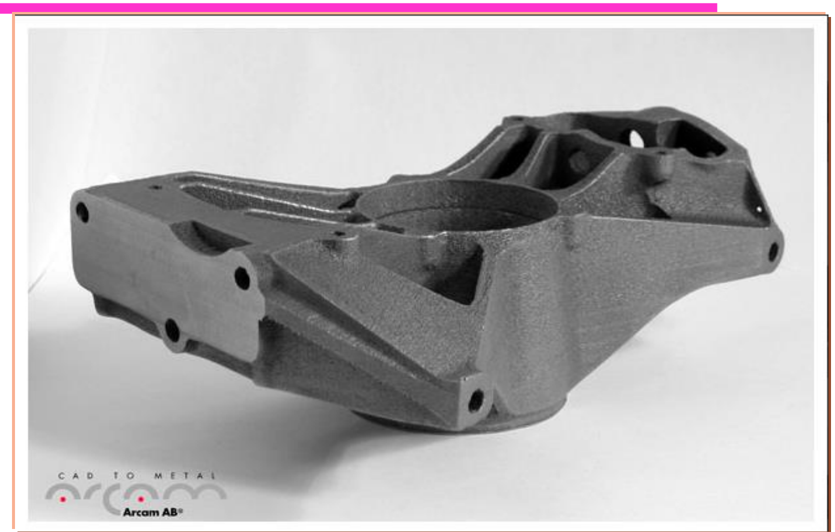


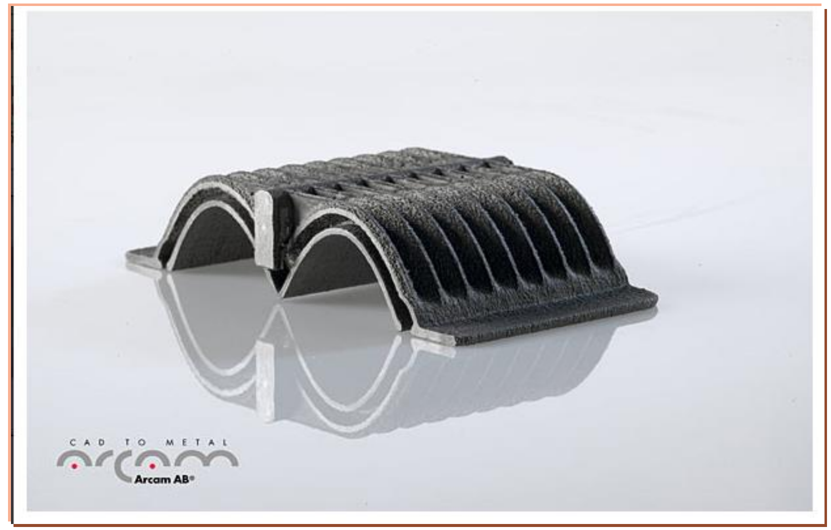
Electron Beam Melting (EBM) Arcam

Materials (Qualified)
—Titanium Alloys
└ Ti6Al4V
└ Pure
— Steel Alloys
└ Arcam Low Alloy 200
└ Arcam Tool Steel
Materials (R&D)
— Inconel 620
— Inconel 625
— Inconel 718
— Beryllium
— Aluminium-Beryllium
— MMC's
— Stainless Steel 316L
— Gradient Materials

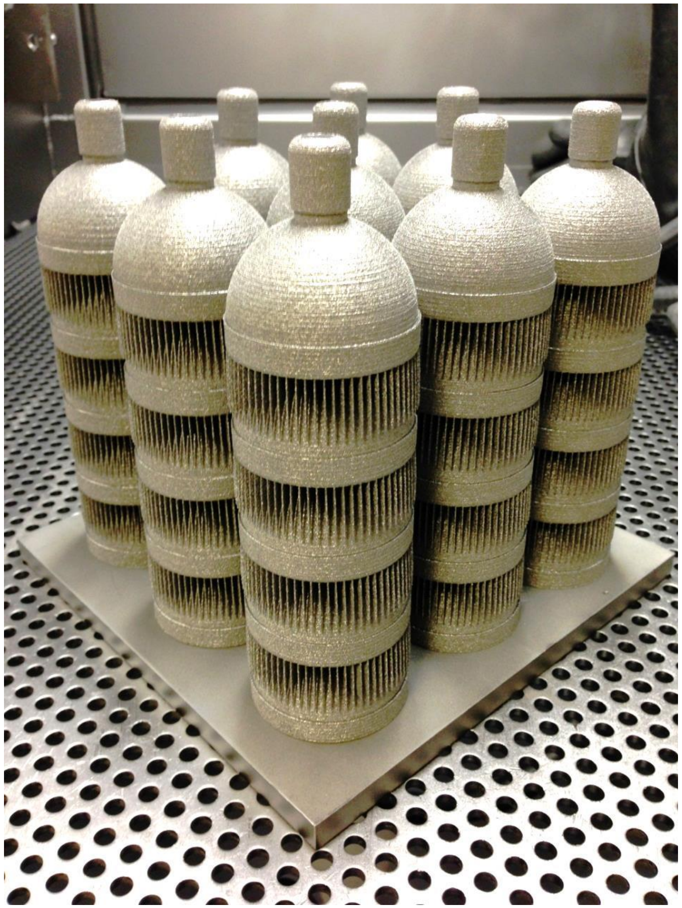
EBM parts: Titanium (Ti-6Al-4V)







EBM parts: Titanium



Titanium acetabular cups

3. Direct Energy Deposition (DED) :

Essentially a precision thermal sprayer or laser cladding operation.

Six equipment manufacturers world-wide (?)

- Optomec, USA: LENS
  (Laser Engineered Net Shaping) License from Sandia National Lab
- DM3D Technology, LLC., USA: DMD (Direct Metal Deposition)
- Trumpf (Germany)
- Aurora (Australia)
- BeAM (France)
- Laserline (Germany)

4. Direct Energy Deposition (DED) :

Essentially a precision laser cladding operation.

LENS™ System

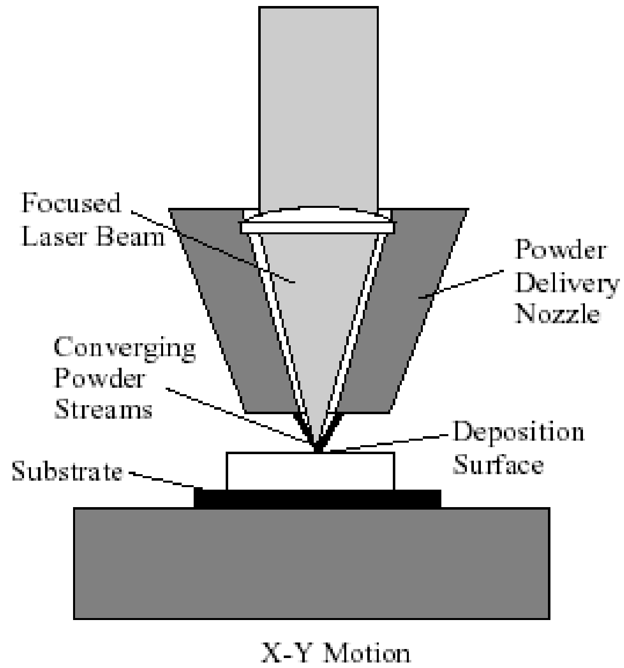
Nd:YAG Laser

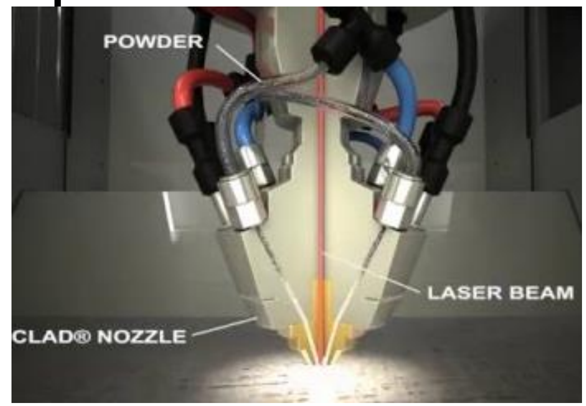
650W to 3kW lasers

4 Powder Nozzles

5-axis laser wrist

2+ powder feeders





Low:

- Detail
- Surface finish
- Resolution

But:

- Not confined to one plane
- Switch/mix materials

LENS™ is a registered trademark of Sandia National Labs and Sandia Corporation

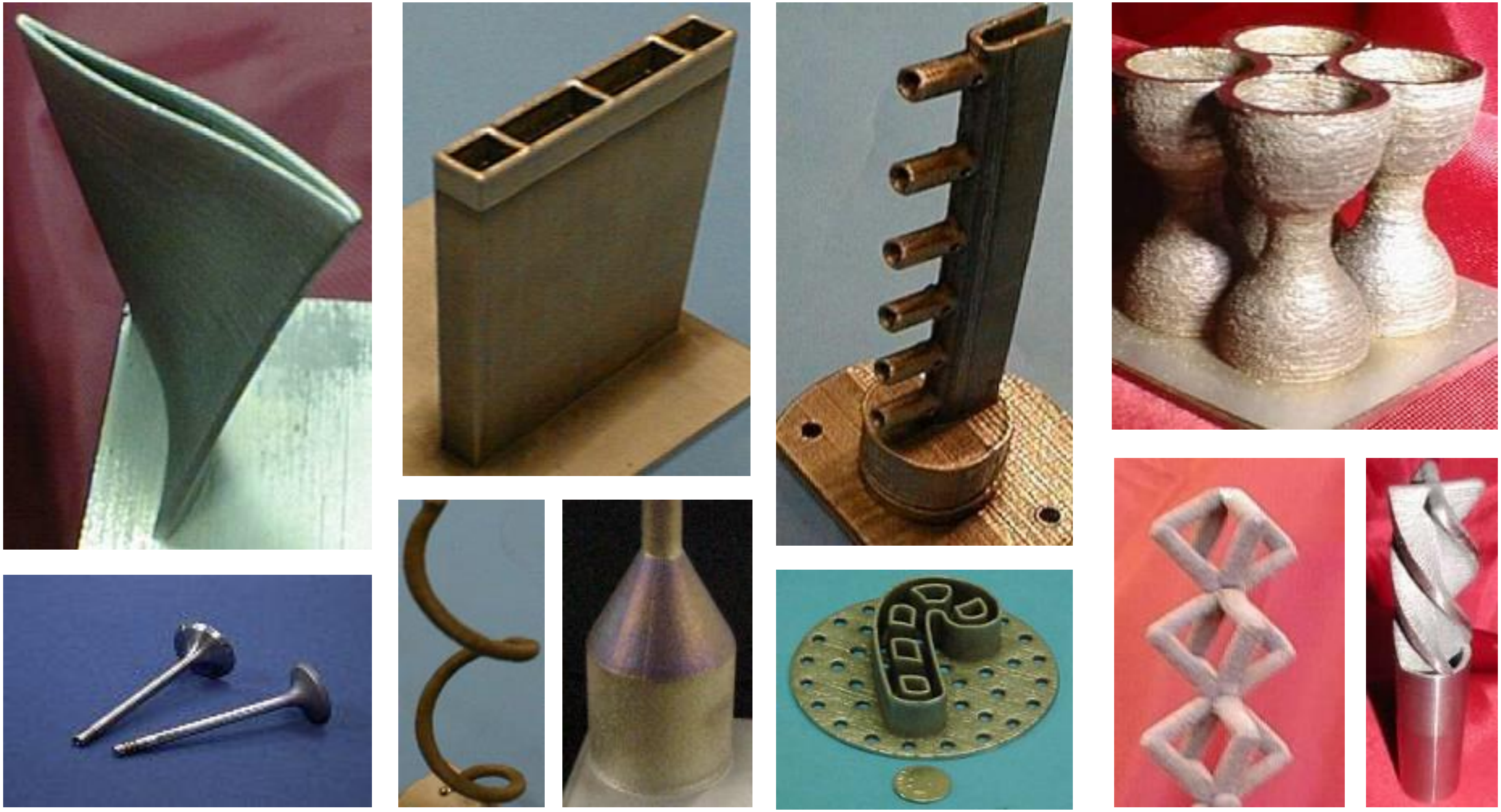
LENS™ Systems

Environmentally Controlled Chamber

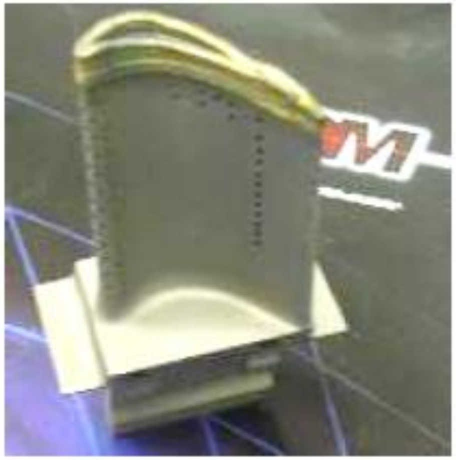
Motion Control to within 0.001"

Part Fabrication or Repair

LENS^{TM} Example Parts



LPF for Repairs (DM3D Technology)



SQUEELER TIP RESTORATION

Base Material : Rene 77 SX

Filler Material: Inc 625/617

Deposition speed: 400mm/min

Z NOTCH WELDING

Base Material : Inc 738

Filler Material: Stellite 694/6

KNIFE EDGE BUILDUP

Base Material : Inc 738

Filler Material: Inc 625/617

Deposition speed: 400 mm/min

Rebuild Flanges
Filler Material: IN625

Hybrid AM Systems

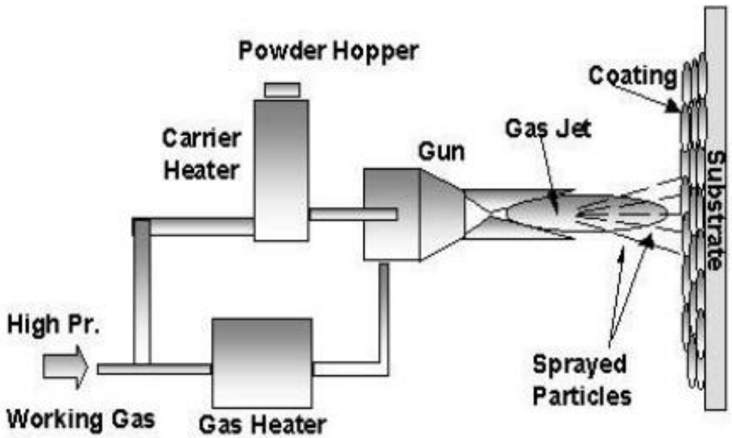
Combination of CNC machining and LENS

- LENS become another “tool in the turret”
- Additive and subtractive machining

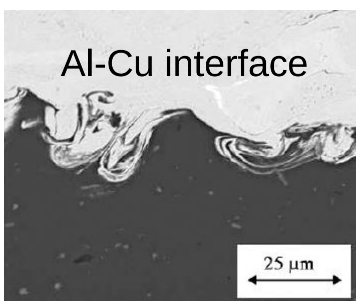
Jason Jones
Hybrid Manufacturing Tech.

II Types of AM using metal powders (2018)

4) Cold Spray: Kinetic impact of metal particles on substrate.
Bulk deposition, requires machining but FAST!
Large parts, not near net shape.



ASB Industries



COC Aerospace

II Types of AM using metal powders (2018)

- SPEE3D: Australia: “Guided” Cold Spray only.
- Hermle Hybrid: Germany: CS + CNC machining.

SPEE3D

Hermle Hybrid

5. Binder Jetting:

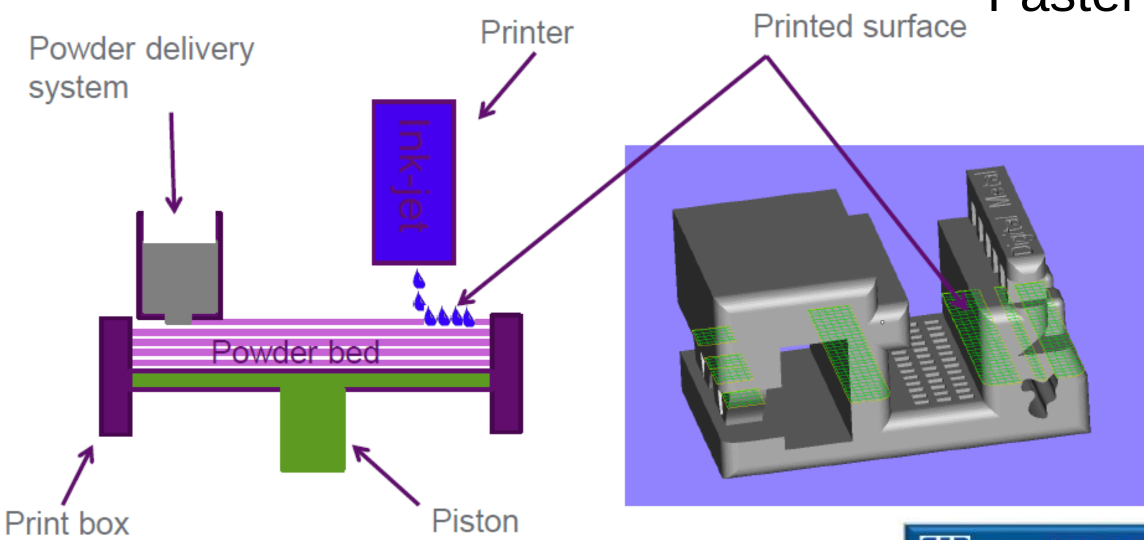
- Powder bed method
- Inkjet head deposits binder on powder layer
- Part subsequently debound and sintered

  - **Digital Metal,** Sweden (Höganäs) Equipment and Toll processing
  - **Exone,** USA Equipment manufacturer, toll processing
  - Desktop Metals, USA Equipment manufacturer
  - GE Additive, USA Equipment manufacturers (?)
  - HP, USA Equipment manufacturer
  - 3DEO, USA Hybrid print/machine, toll services

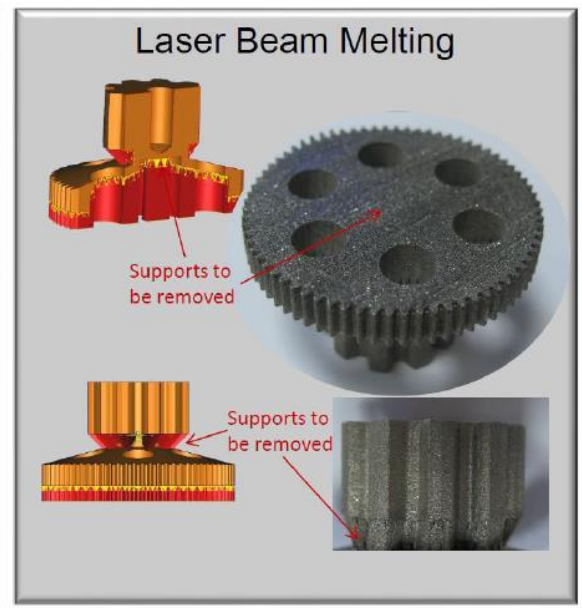
BOLDFACE: Originators

Binder Jetting

- Powder bed method
- Inkjet head deposits binder on powder layer
- Part subsequently debound and sintered
- Faster than laser or E-beam



- Printing at RT
- No supports are needed during printing

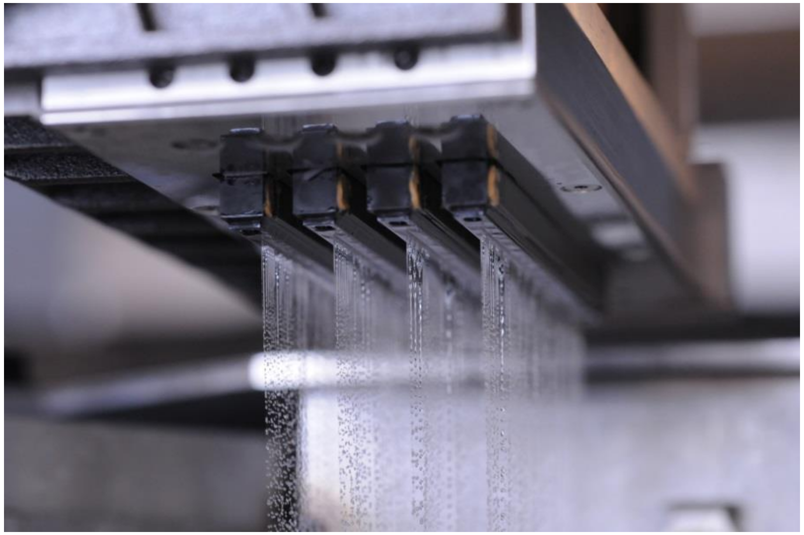


Digital Metal (Höganäs))

5. Binder Jetting:

- Printed parts are metal powder and polymer:
  - Essentially a MIM part.
    - Uses MIM-grade powder
    - Subsequently debound and sintered
    - Much lower binder content:
      - Faster debind cycle
        - Can be integrated with sintering cycle
  - **Parts on the same scale as MIM parts.**

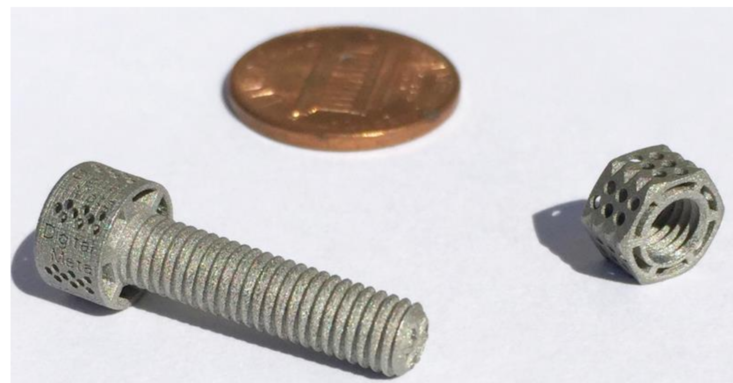
Selective Inkjet Binding/Binder Jetting



ExOne

Part Shrinkage (before and after sintering, 12-20% linear shrinkage across the industry, 14-17% typical)

Selective Inkjet Binding/Binder Jetting



Digital Metal (Höganäs)

6. Material Extrusion (ME)

Fused Deposition Modeling (FDM):

- 1998 S. Crump: Stratasys
  - Extruded polymer filament
- Think “MAKERBOT”

3D Systems Cube

Stratasys

5. *Material extrusion*

- Direct deposit a metal-filled polymer (MIM feedstock).
- Conventional debind and sinter.
- Turn-key systems commercially available.
- Metal-filled filament available from 3rd party (BASF).
- Parts larger than conventional MIM parts.

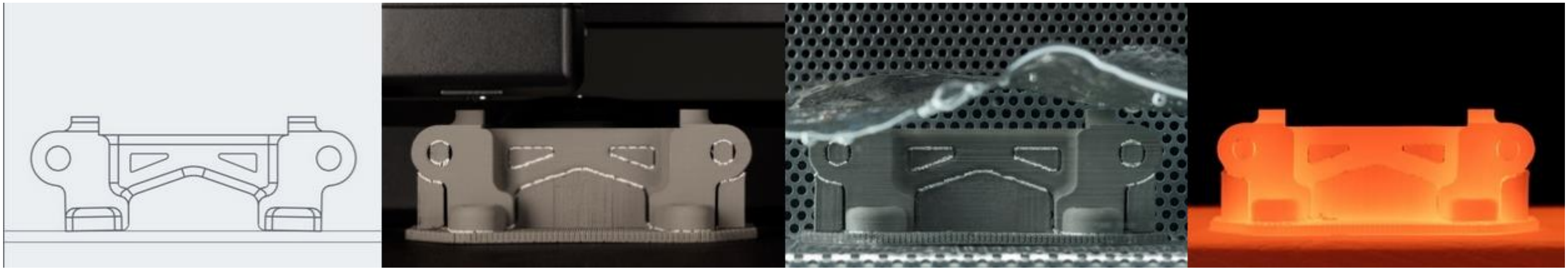
Desktop Metals

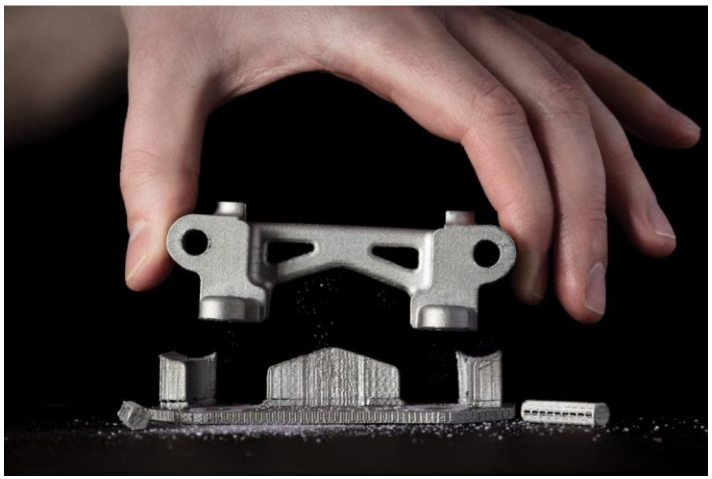
Markforged

Rapidia

Material Extrusion

Parts larger than MIM parts





Desktop Metals
Ceramic Release Layer

Markforged

Rapidia

II Types of AM using metal powders

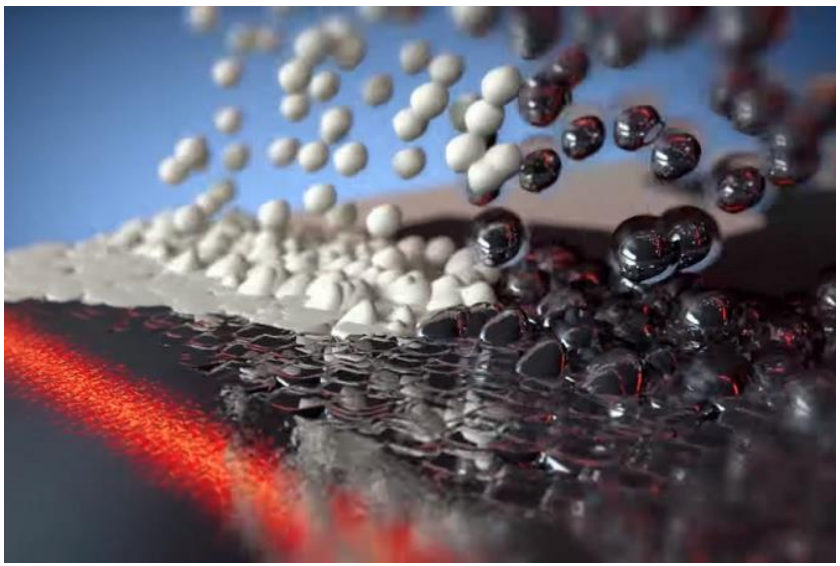
6) Metal Jetting: Build material directly applied through inkjet head.

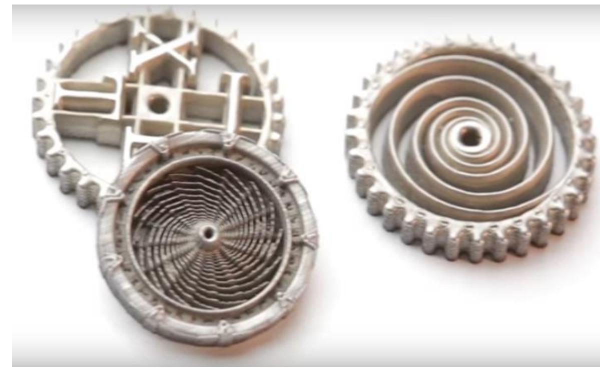
- **Xjet** (Israel): Metal powder filled ink.

II Types of AM using metal powders

6) Material Jetting: Build material directly deposited through an inkjet head.

- Metal powder filled ink.
- Debinding and sintering required.
- Parts MIM scale and smaller.



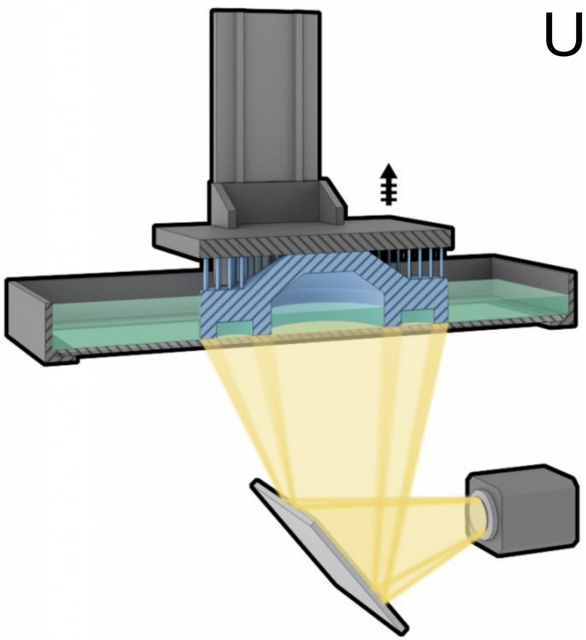


Xjet, Israel

7) Vat Photopolymerization:

UV curing of a metal-loaded photopolymer.

UV laser or DLP (Digital Light Processing)



Manufacturing Guide

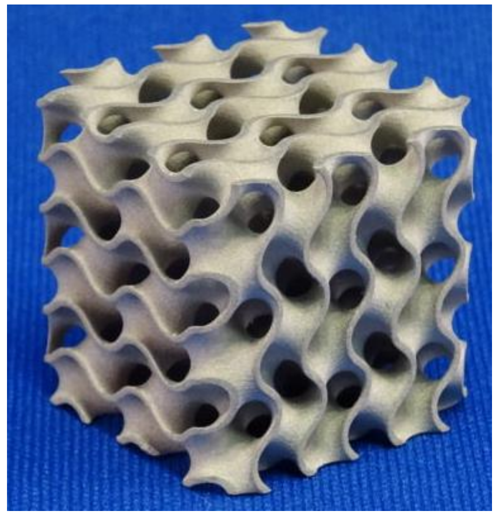
Print, debind, sinter

- Highly complex, MIM size and smaller.

Admatec

II Types of AM using metal powders

7) Vat Photopolymerization:



Admatec

Lithoz

AM and PM: General Comparison

Process	Small production numbers	Geometric complexity	Productivity (build speed)	Surface finish	Resolution	Part size, Large/ Small	Material selection
Press and Sinter	- - -	0	++++	+++	- -	++/+++	++
MIM	- - -	++	++++	+++	++	0/+++	+++
Laser Sintering	+++	+++	0	-	+	+++/+++	+++
E-Beam Melting	+++	+++	++	- - - -	-	+++/+	+++
Direct E. Dep.	+++	+	+++	- - - - -	- - -	+++++/- -	+++
Binder Jetting	++	+++	++	++	++	0/+++	++
Material Extr.	++	++	+++	+	- -	++/0	++
Material Jetting	++	+++	- -	+++	+++	- - -/++++	- - -
Vat Photopolymerization	++	+++	-	+++	++	0/+++	- -
Cold Spray	+++	- - -	+++++	- - - - -	- - - - - -	+++++/- - -	0

Format from Digital Metal

Powder Production

✓ ***Atomization***

- Chemical, reduction
- Carbonyl process
- Oxide reduction
- Electrolytic, precipitation
- Mechanical

Powder Production

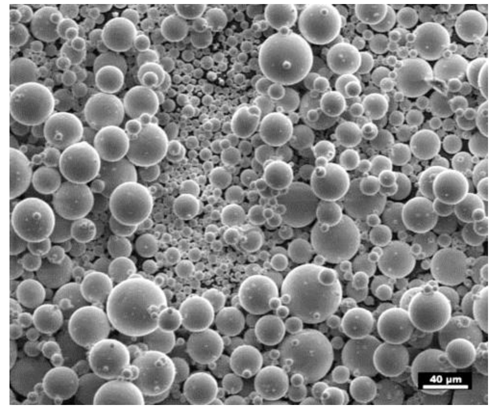
✓ ***Atomization***

Atomization: The disintegration of a **molten material** into droplets.

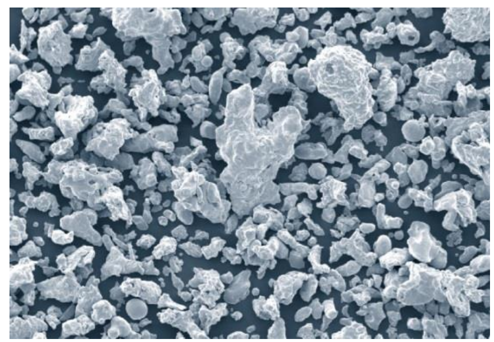
Powder production by **Atomization**:

Disintegration of liquid by a second fluid

- Inert Gas Atomization:
  Spherical powder particles
  Good "flowability“
  (Most times)



- Water Atomization:
  Irregular powder particles
  Poor “flowability”
  (Most times)

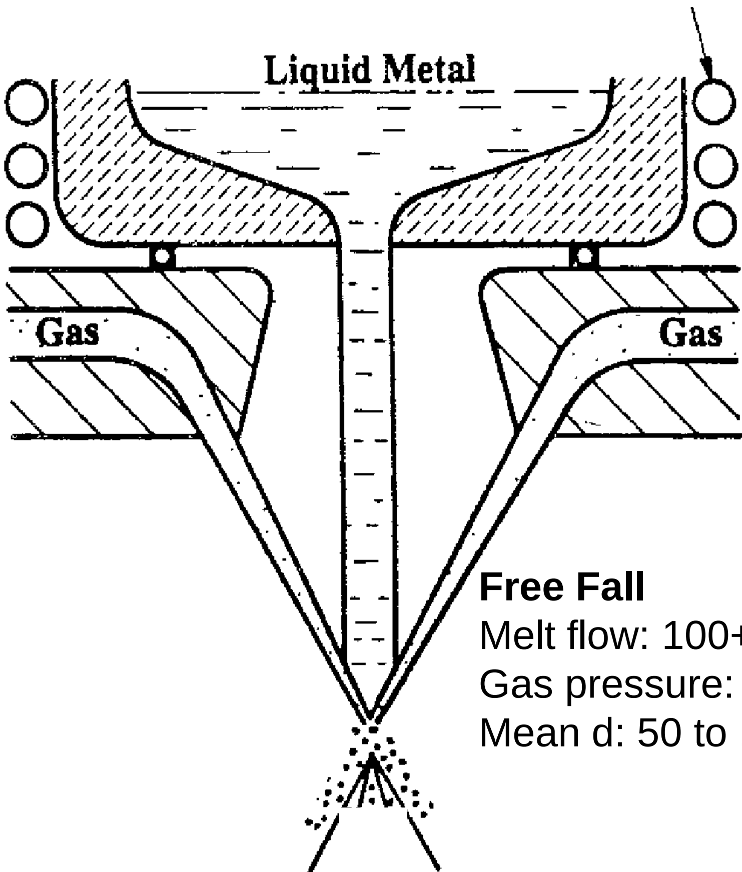


Gas Atomization Configurations

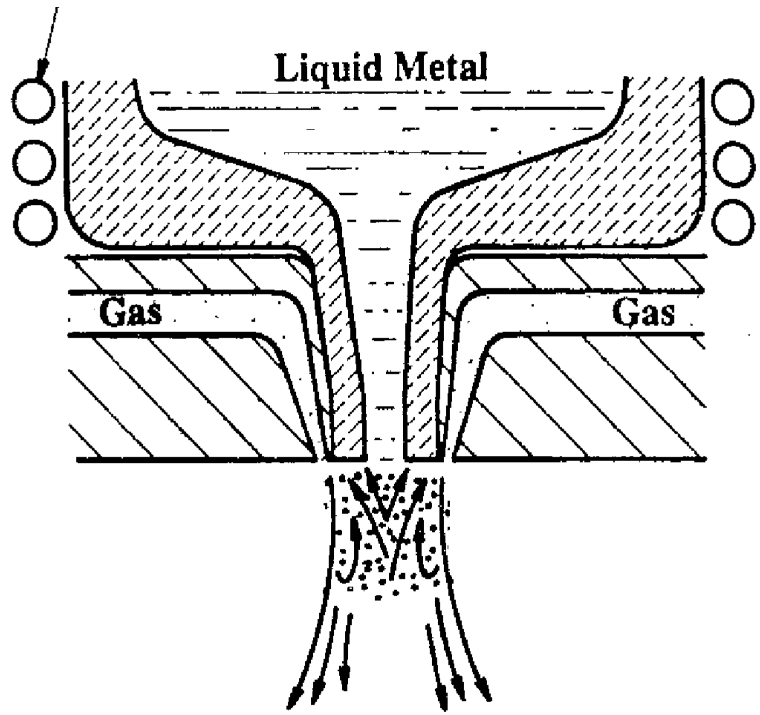
Free Fall

Induction Coil

Close-Coupled

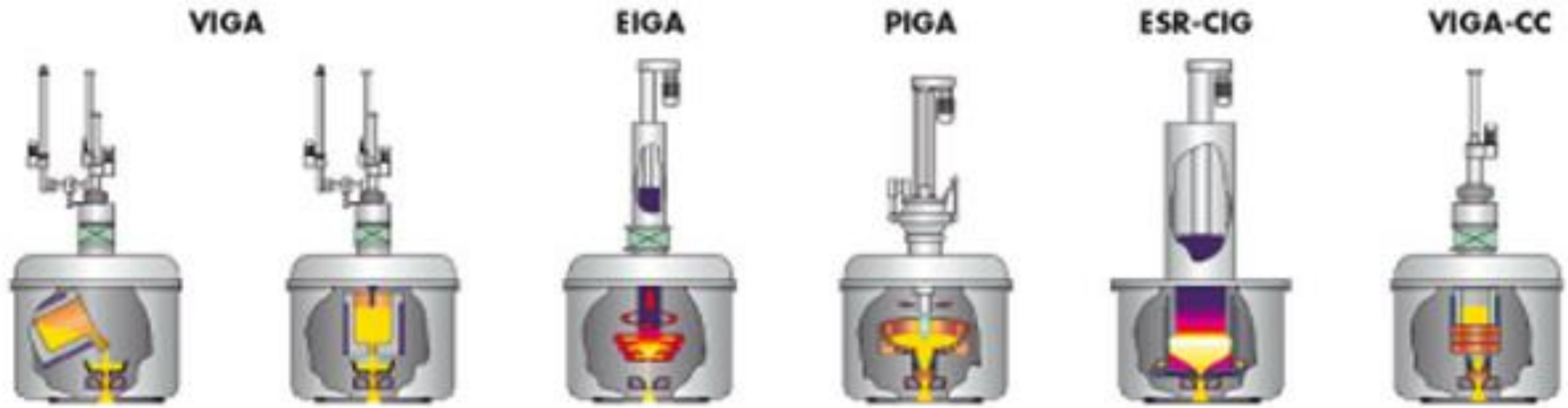


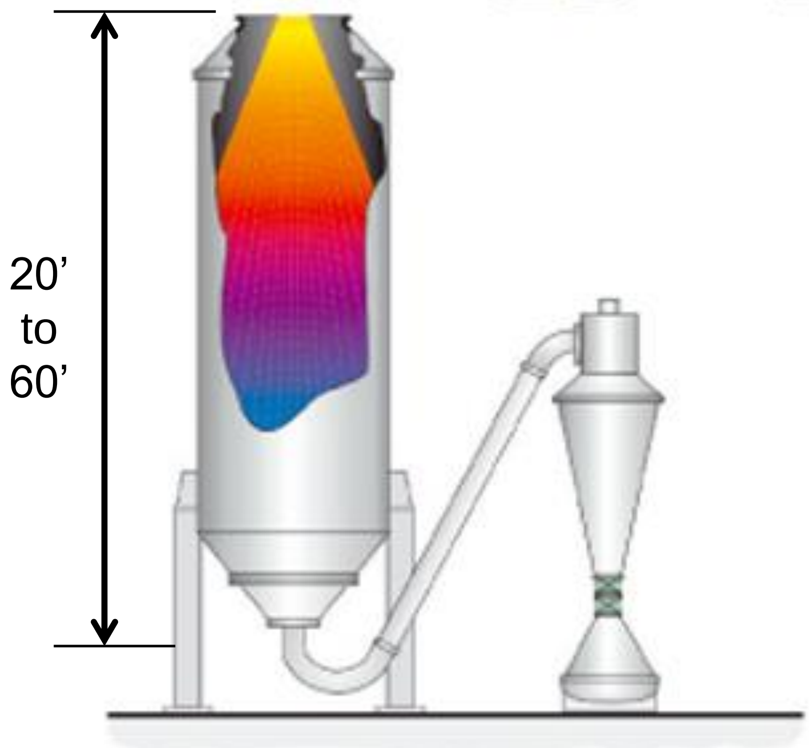
(a)



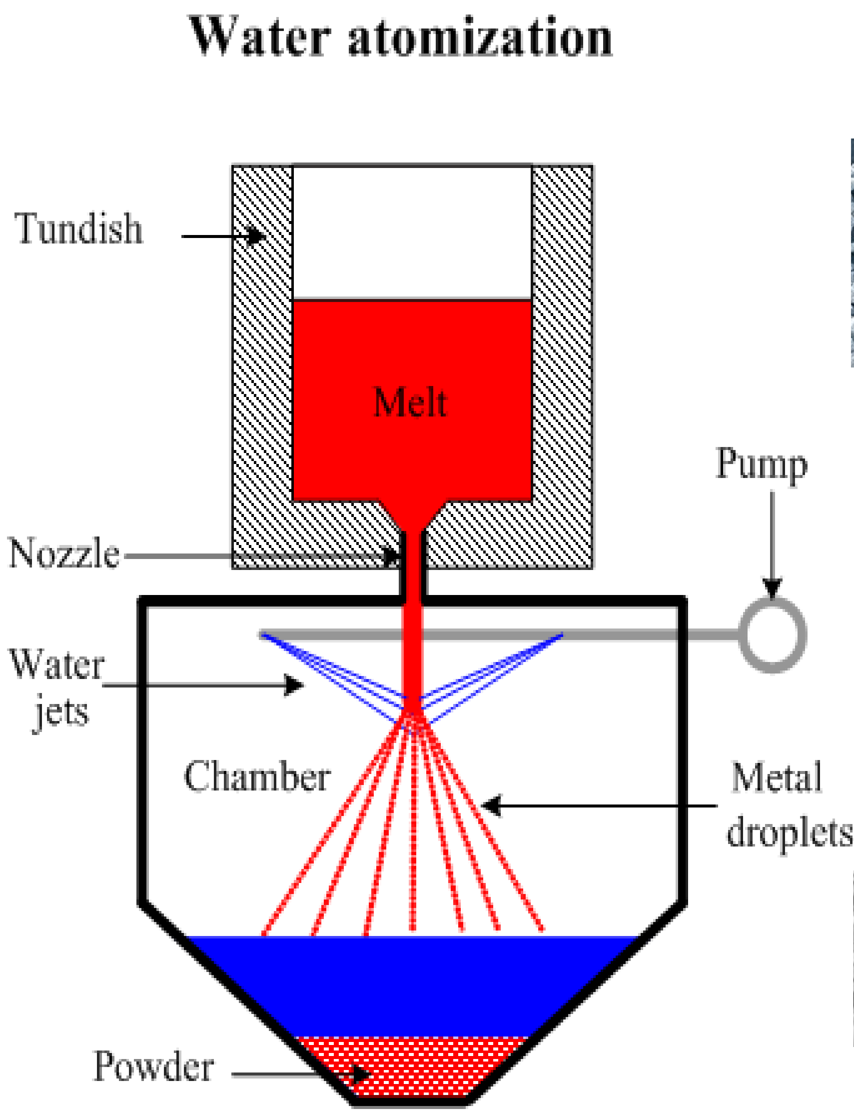
Free Fall
Melt flow: 100+ lbs/min.
Gas pressure: < 500 psi
Mean d: 50 to 150 microns

Close-Coupled
Melt flow: 10-75 lbs/min.
Gas pressure: 250 to 1500 psi
Mean d: 10 to 50 microns

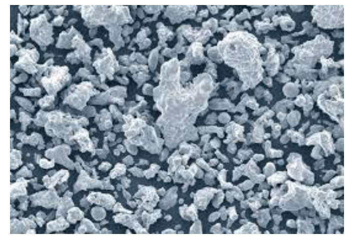




ALD, Germany

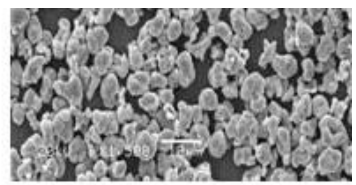


Conventional:



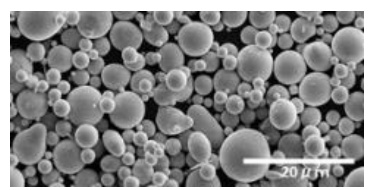
Pressure to 3000 psi
Melt rates 50-300 lbs/min
Coarse powder
Irregular powder shape
Inexpensive unit operation

High Pressure:



Pressures 3000-15,000 psi
Melt rates 50-300 lbs/min
Finer powder (<100 microns)
Mixed morphology

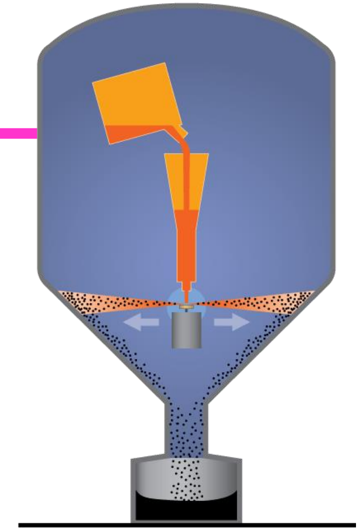
Very High Pressure:



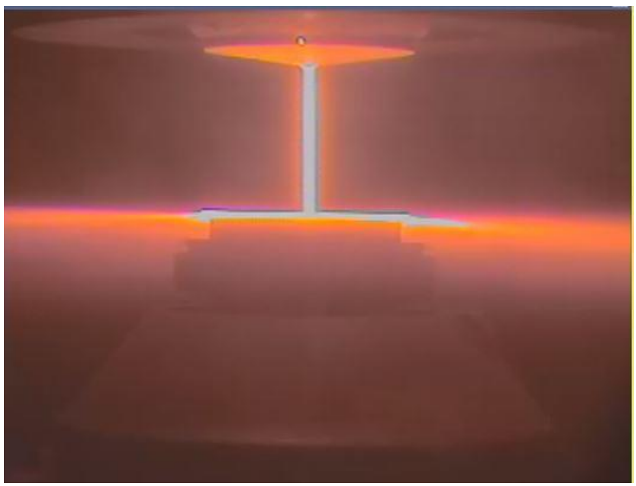
Pressures up to 50,000 psi
Melt rates low (<50 lbs/min)
Fine powder (< 20 microns)
Spherical morphology
$$$ unit operation

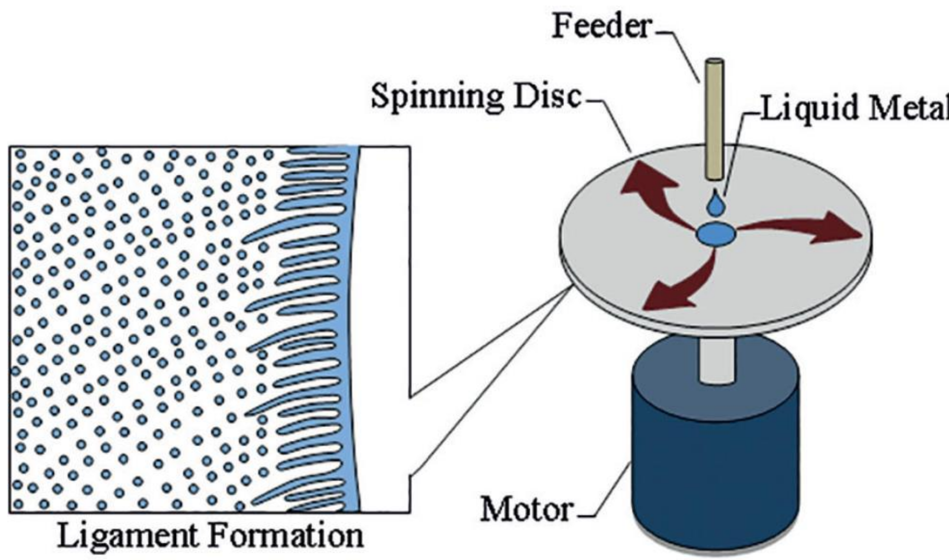
Water atomization Epson Atmix

Spinning Disk Atomization (centrifugal)



Powder: very spherical, low satellite content
Powder size: Very narrow distribution
Powder: Coarse to fine.



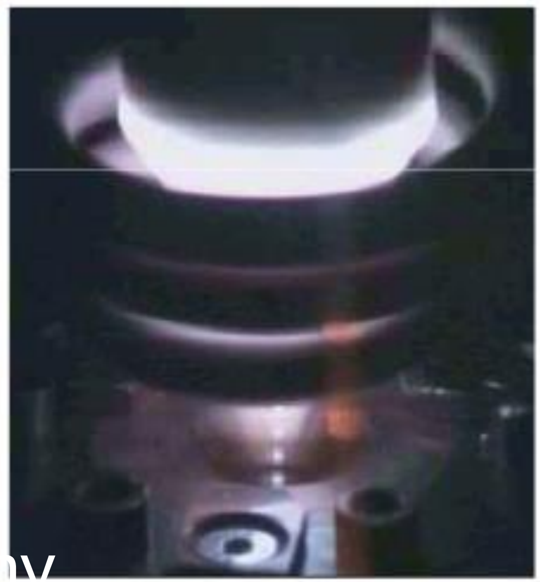


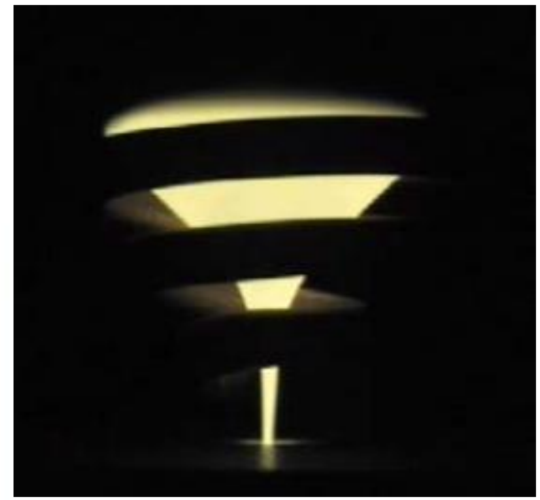
Alloys via Bulk Melt Atomization:

- Fe alloys:
  - Low alloy steels (4140, etc.)
  - Tool steels (T15, D2, M2, etc.)
  - Stainless steels (316:, 17-4PH, 430, 440, etc.)
  - Binaries with Co, Ni, and Si
- Ni-based Superalloys
  - 625, 718, Rene's, etc.
- Cobalt alloys
  - Co-Cr-Mo (F75's)
- Copper and alloys
- Precious metals and alloys
- Aluminum, magnesium, and alloys
- Titanium and alloys (limited)

Non-bulk melt atomization processes

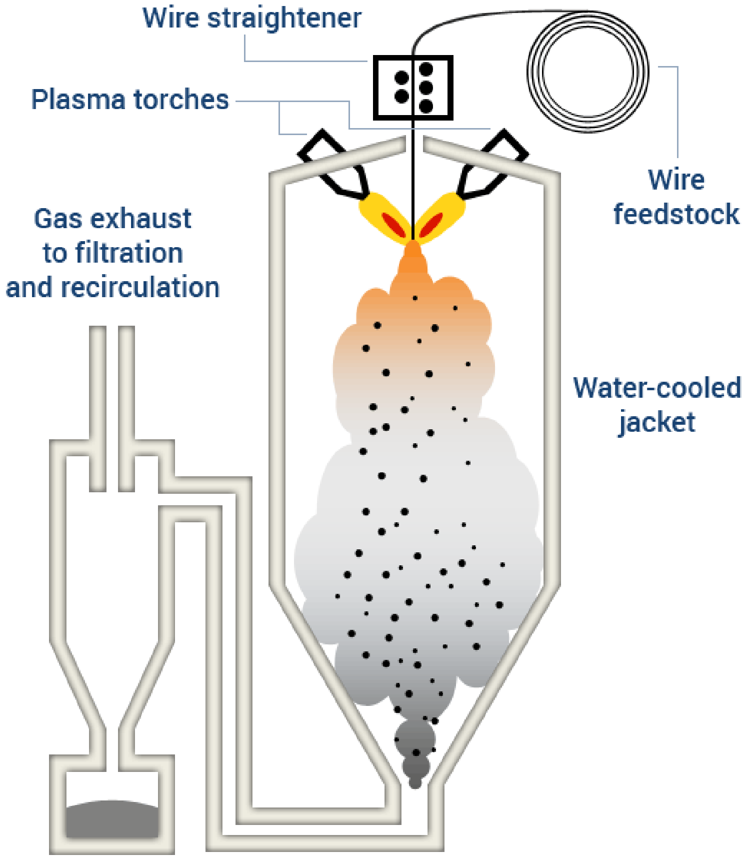
EIGA*





- Any material in rod (cast ingot) form
    - Ti, Mo/Ta/W
- No crucible or refractory contact
- Low production rates (1 kg/min)
- Low yield of fines

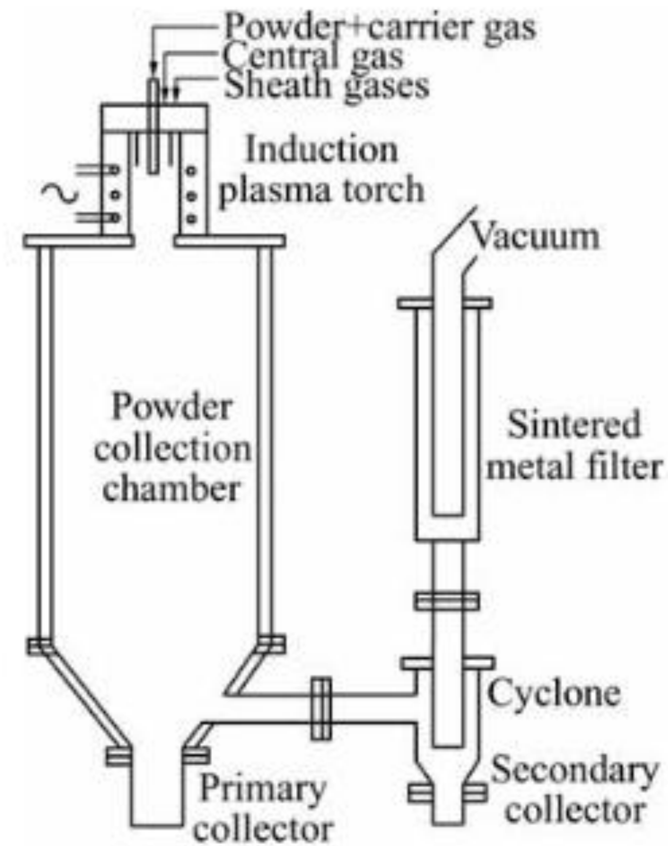
Plasma Atomization of Titanium* Wire



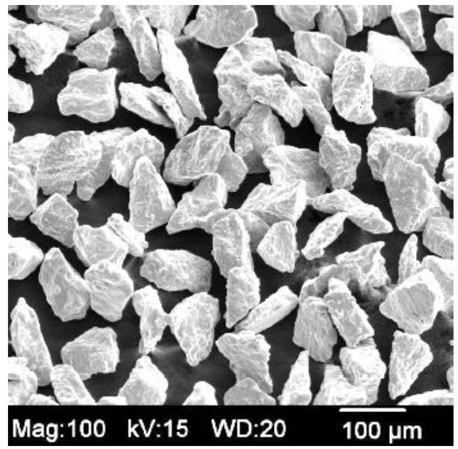
AP&C/Arcam

* Applies to any material in wire form.

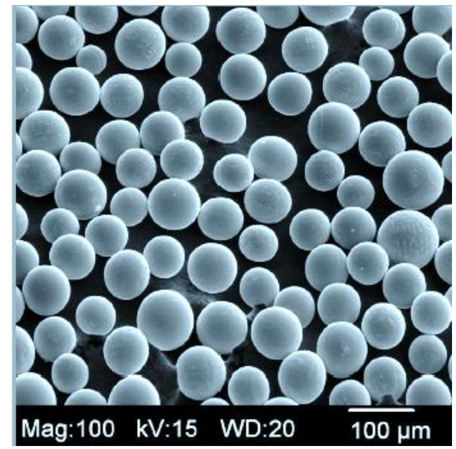
Plasma ***Spheroidization*** of HDH* Titanium**



Before



After



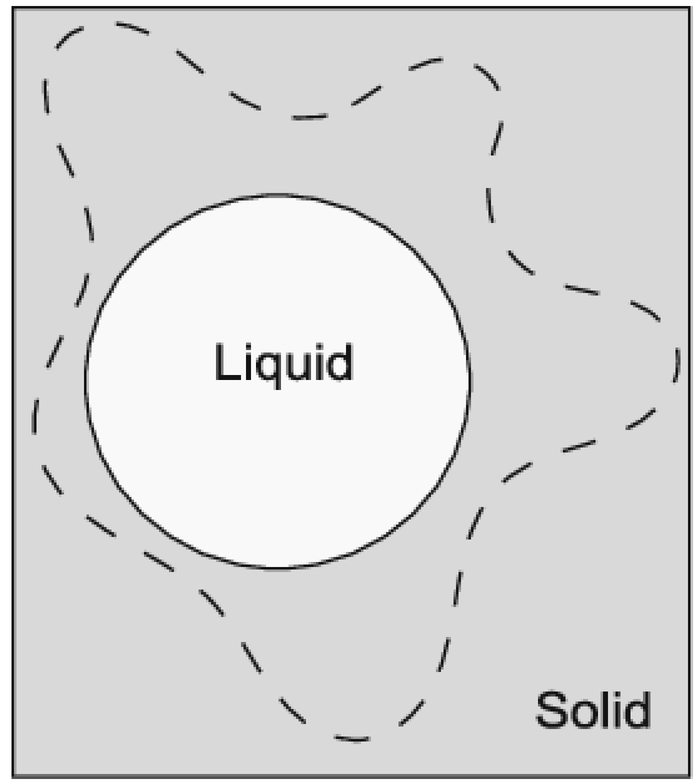
Ametek, USA

* Hydride-Dehydride
** Applies to any powder.

Why is having a melt phase important for AM?

Particle Morphology: *Spherical powders flow best*.

- Melt phase: liquid with surface energy/tension
- Spherical shape minimizes surface energy
- Spherical powder: lower SSA* & interparticle friction.
- **Most AM powders have evolved from a melt phase.**



* SSA= Specific Surface Area (area/mass)

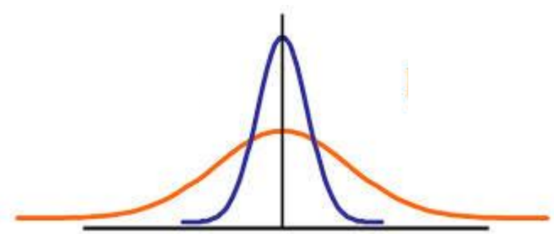
All **additive manufacturing methods rely on:**

1) An easily manipulated material (powder).
2) Material to be transported and dispensed with precision and repeatability.

FLOWABILITY!!!!! Especially important for PBF

Transport and dispense powder with precision and repeatability.

- **Particle morphology:** Shape
- **Particle size: $\bar{d}$**, (mean particle size)
- **Particle size distribution**



FLOWABILITY:

Particle size and size distribution

Size ($\bar{d}$): Specific Surface area (SSA)

Interparticle friction

As $\bar{d}$ ↓ SSA and friction ↑ and flowability ↓

Distribution: Particle packing efficiency (PE)

As distribution widens PE ↑ and flowability ↓

Powder Flow tests:

Mass Flow rate: Hall test: ASTM B214, MPIF 03
Carney test: ASTM B964

Volume Flow rate: Arnold test: ASTM B855

Tap to Apparent Density ratio: Hausner or Carr

Torque Rheometry: Texture Technologies (US)
Freeman Technology (UK)

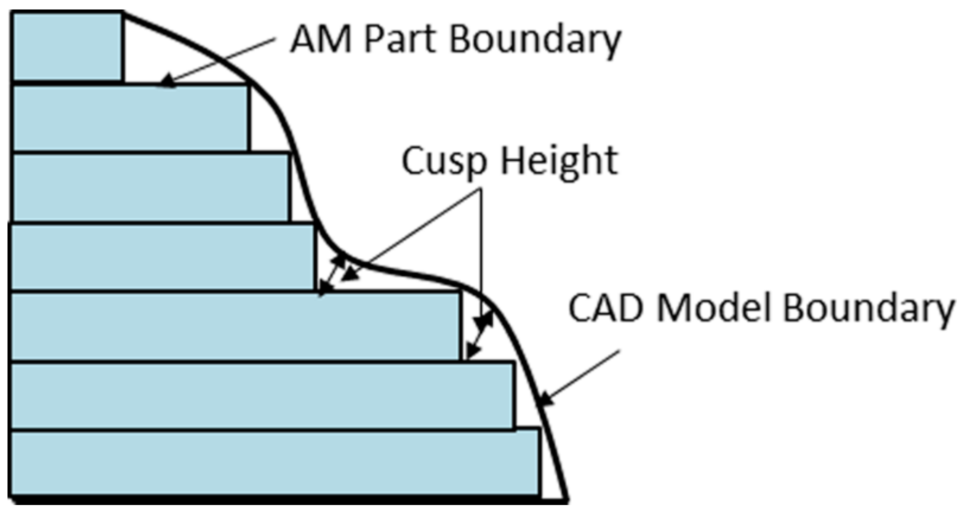
Angle of Repose: Grantools (BE)
Mercury Scientific (US)

What powder size is right for AM?

AM Z axis resolution:

Minimize build layer thickness

- Minimize particle size
- Narrow particle size distribution



What powder size is right for AM?

- **Energy coupling**
- **Charging effects (e-beam)**
- **Vaporization**
- **Sintering**
- **Material Jetting/Vat Photopolymerization**

Metallurgical considerations?

Conventional PM processes:

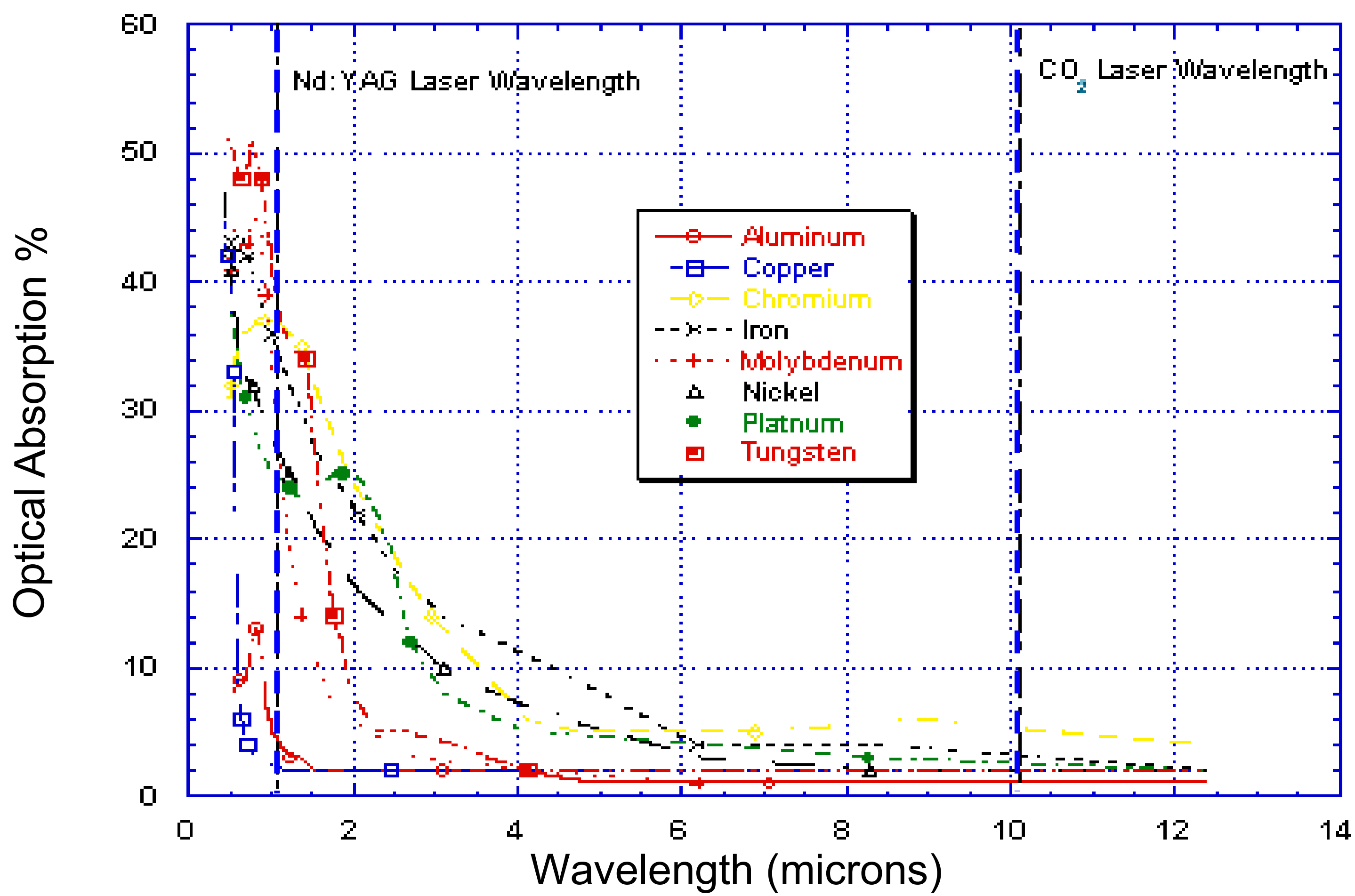
- Sintering response: temperature, time
- Reactivity: environment, furnace atmosphere

Metal Additive Manufacturing:

- Sintering response: temperature, time
- Reactivity: environment, machine atmosphere
- Laser absorption
- Thermal conductivity

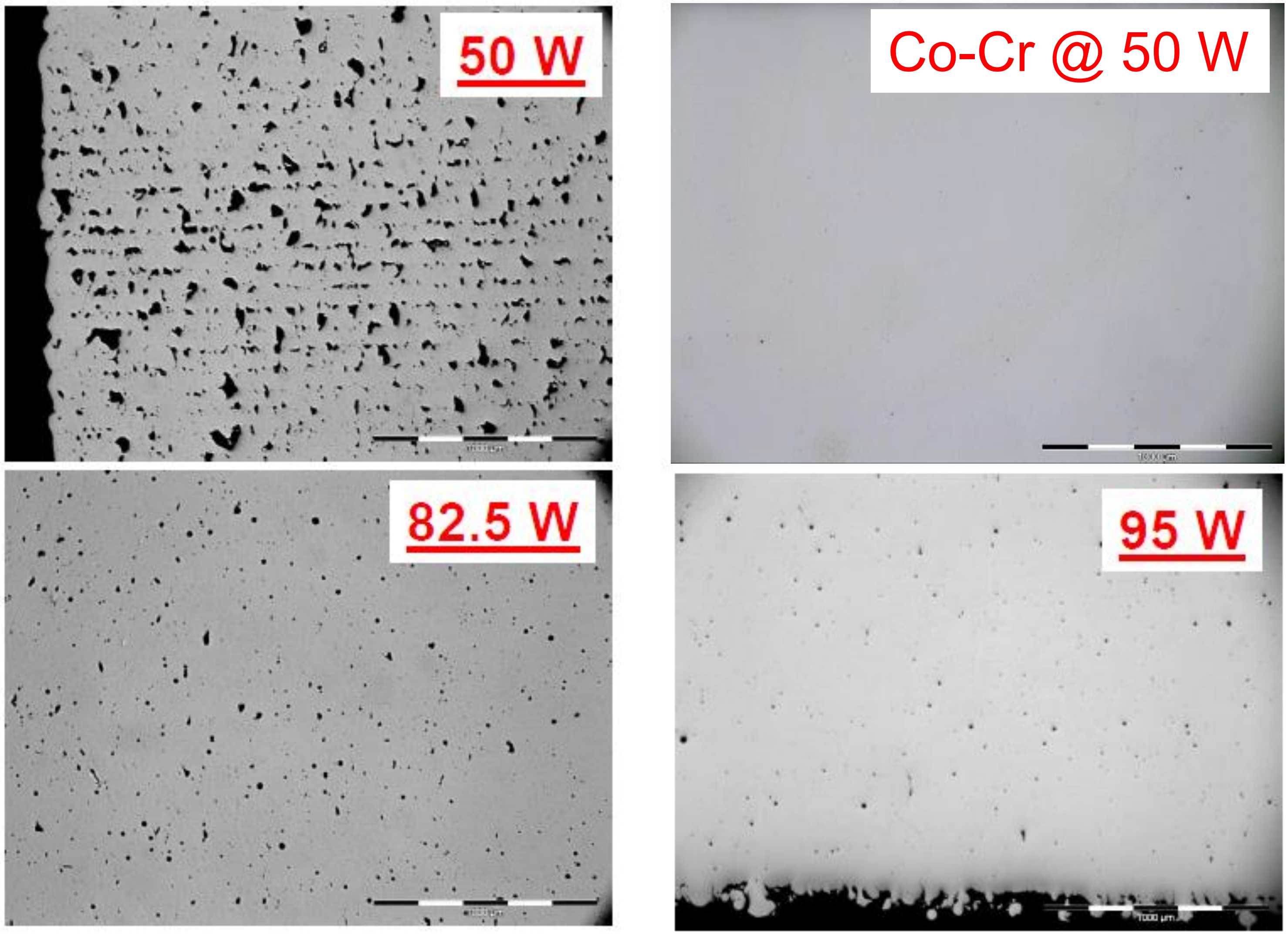
III Powder Production and Requirements for Additive Manufacturing

Optical Absorption vs. Wavelength

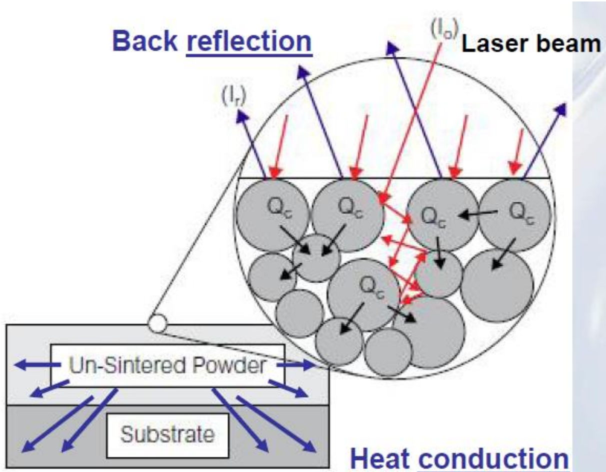


Porosity : Influence of laser power

18k YELLOW GOLD 3N
20 µm / 200-400 mm/s



Material	Thermal Conductivity, W/m-K
Ag	420
Au	315
Cu	401
Co-Cr-Mo (F75)	13
316 stainless steel	21
Ti (Ti alloy)	20
Ti alloyed	6



Co-Cr

Au-alloy

Powder Requirements for Additive Manufacturing

Process	Particle size range, microns	Preferred particle morphology
Press and Sinter	20-150	Irregular
MIM	< 30	Primarily spherical
Laser Melting	15-60	Spherical
E-Beam Melting	50-150	Spherical
Direct E. Dep.	30-150	Spherical
Binder Jetting	<30	Spherical
Material Extr.	<30	Primarily spherical
Material Jetting	< 5	Either
Vat Polymerization	< 10	Either
Cold Spray	10-100	Primarily spherical

Particle size range is approximate and will depend on:

- Specific equipment
- Alloy
- Layer thickness
- “Sinterability”

Why do AM powders cost so much?

Why do AM powders cost so much?

AM applications are still small wrt other PM or thermal spray markets.

Market size

Total AM market for metal powder =

??% of atomized metal powder for PM and thermal spray

$$\% = 100 * \frac{AM}{PM+TS}$$

Market size

Total AM market for metal powder =

<1 % of atomized metal powder for PM and thermal spray

$$\% = 100 * \frac{AM}{PM+TS}$$

Why do AM powders cost so much?

- Metal powder used for AM comes from the existing PM and Thermal Spray industries

- **Need to compare to other similar powders:**

Application 316 stainless steel	Particle size, Microns	Production Method	Relative Cost	Quantity, Lbs./month per customer	# of Customers
Press & Sinter	-175	H_20	1	Tonnage	Many
HIP	-500	Gas	1.5	Tonnage	Many
MIM	-30	Gas	3	1000+	Many
Thermal Spray	-106/+45 -53/+20	Gas	5-8	100-1000	Many
Filter	-25	H_20	8-10	100's	Few
AM Laser Powder Bed from manufacturer	-45/+10	Gas	8-10	100's	Few
AM Laser Powder Bed From OEM	-45/+10	Gas	10-20	100	Few

- Powder prices ↓ as production volumes ↑
- Powder prices ↓ with fewer processing steps:

Equipment, time
material, scrap

IV AM & PM: Compete or Compliment?

Will AM replace:

Machine shops?

Casting houses?

Press and sinter PM?

MIM?

IV AM & PM: Compete or Compliment?

Can these new AM technologies replace existing manufacturing technologies:

- Without manufacturing infrastructure?
- Without manufacturing experience?
- ***With a bucket of powder and a push of a button?***

IV AM & PM: Compete or Compliment?

Traditional Powder Metallurgy processes:

Press and sinter:

- Production > 10,000 parts (economy of scale)
- High tolerance, 0.001 "/" possible
- High productivity (low unit cost)
- Controlled porosity, density (85% to 90%)
- Excellent surface finish
- *Some anisotropy*
- *High tooling costs requires high production numbers*
- *Geometrical Limitations:*
  - *Axis-symmetric*
  - *No undercuts*
  - *No off-axis attributes*
  - *L/D <5*

IV AM & PM: Compete or Compliment?

Traditional Powder Metallurgy processes:

MIM:

- Complex Shapes
- High density metal parts (> 95%)
- Economy of Scale (high productivity)
- Good tolerance, .003 "/" possible, .005-.008 "/" typ.
- Good to excellent surface finish
- Isotropic properties
- Competes with investment casting and discrete machining
- *High tooling costs requires high production numbers*
- *Complexity costs $$ and there are limitations*
- *Long lead times*

IV AM & PM: Compete or Compliment?

Traditional Powder Metallurgy processes:

Press and sinter and MIM:

- Developed and mature industries
- Many sources: equipment, parts producers
- Working processes
- Material standards capable of meeting industrial qualifications
- Product quality independent of processing equipment
- *Economical for large production numbers*
- *Geometries limited or costly*

IV AM & PM: Compete or Compliment?

Metal Additive Manufacturing

- New and exciting
- Speed to market
- Flexible designs, **unique** designs/features
- High level of complexity with no extra cost
- *No tooling (?)*
- High density parts
- Economy (?) at low production numbers

IV AM & PM: Compete or Compliment?

Metal Additive Manufacturing

- Cost: Equipment, maintenance
- Cost: Material
- Cost: Build time
- Surface finish
- Tolerance
- Minimum detail size
- Material standards, specifications, qualifications

IV AM & PM: Compete or Compliment?

Metal Additive Manufacturing (laser processing)

- Cost: Equipment, maintenance: \$250K-\$800K + 10% annual maintenance
- Cost: Material: 3 to10 X (wrt MIM powder), lower utilization rate
- Cost: Build time: < 0.006 in^3/min (0.1 cm^3/min) (< 1 g/min 316 SS)
- Surface finish: 600/300 Ra (µin) orientation and material dependent
- Tolerance: +/- 0.005” for first inch,
- Minimum detail size: 0.006”/0.015”
- Material standards, specifications, qualifications
- Not that rapid, not a net shape part

Rapid? Must remove support structure!

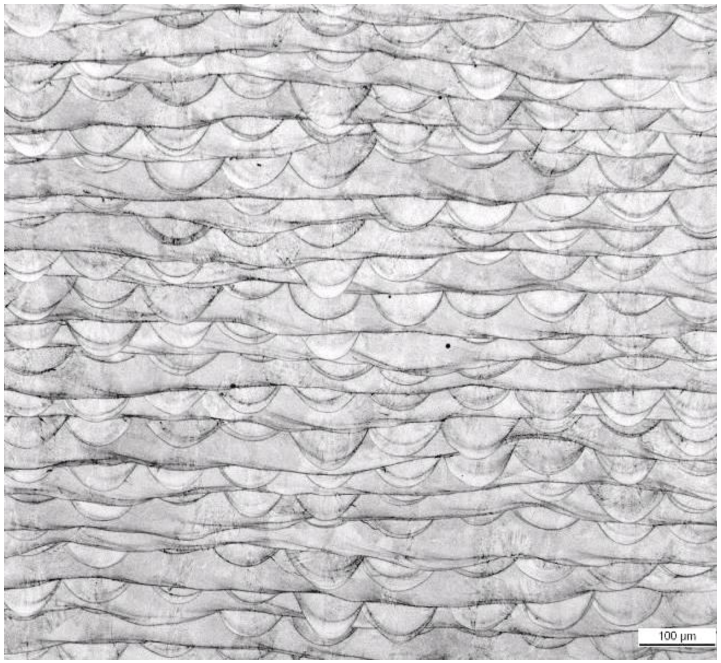
IV AM & PM: Compete or Compliment?

AM is NOT A NET SHAPE METHOD!!!

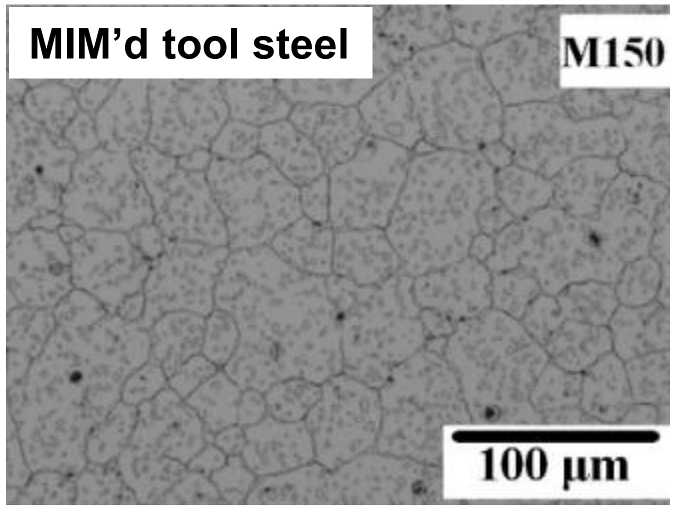
- Surface finishing (blasting/peening/polishing)
- Remove build structure
- Machining of critical attributes:
  - Holes
  - Threads
  - Sealing surfaces
  - Mold/Tool surfaces
  - Flat areas

Microstructures: SLS "Weld" vs. PM

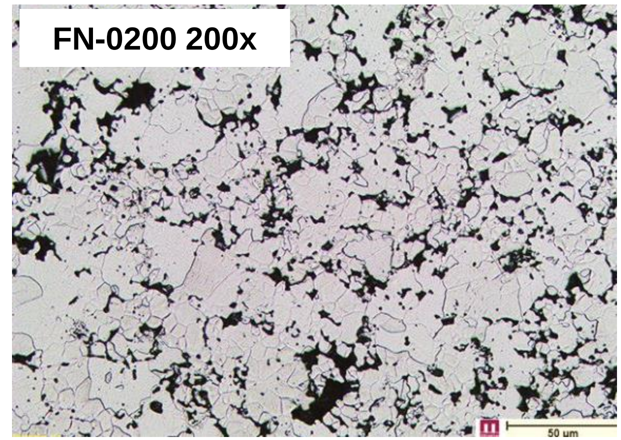
SLS F75 (Co-Cr-Mo)



Macro-etched



Effect of Sintering Parameters and Powder
Characteristics on the Performance of
Metal-Injection-Molded SKD11 Parts
Huan–Xi Chen, You–Tern Tsai, and Kuan–Hong Lin

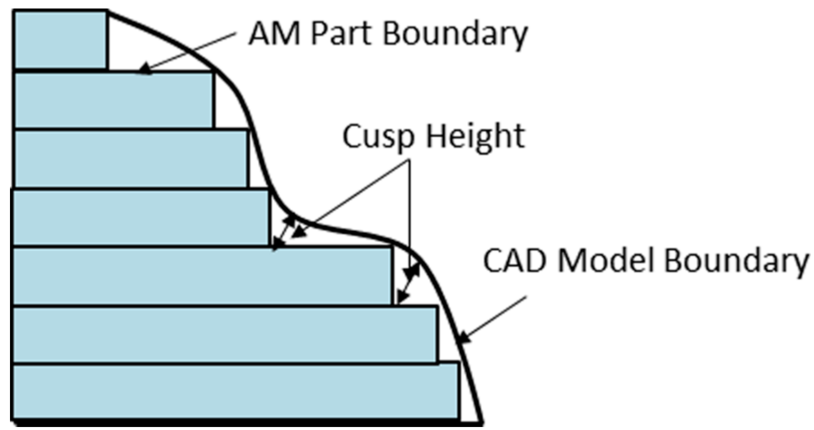


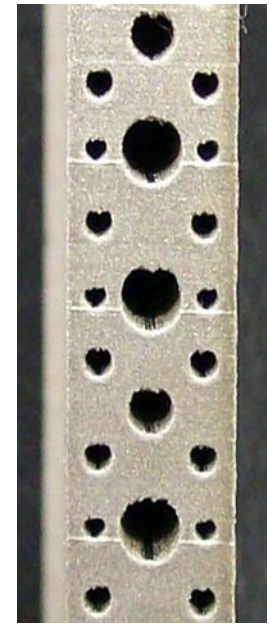
MPIF

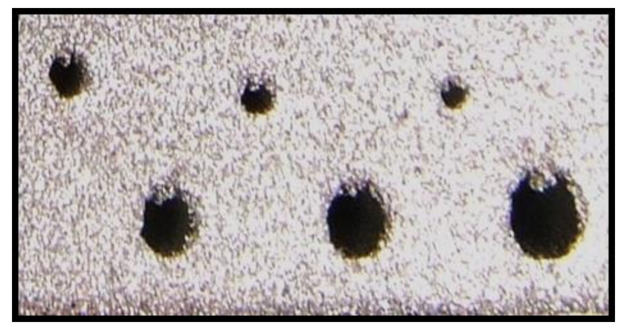
AM: Critical limitations

Attribute-orientation relationships

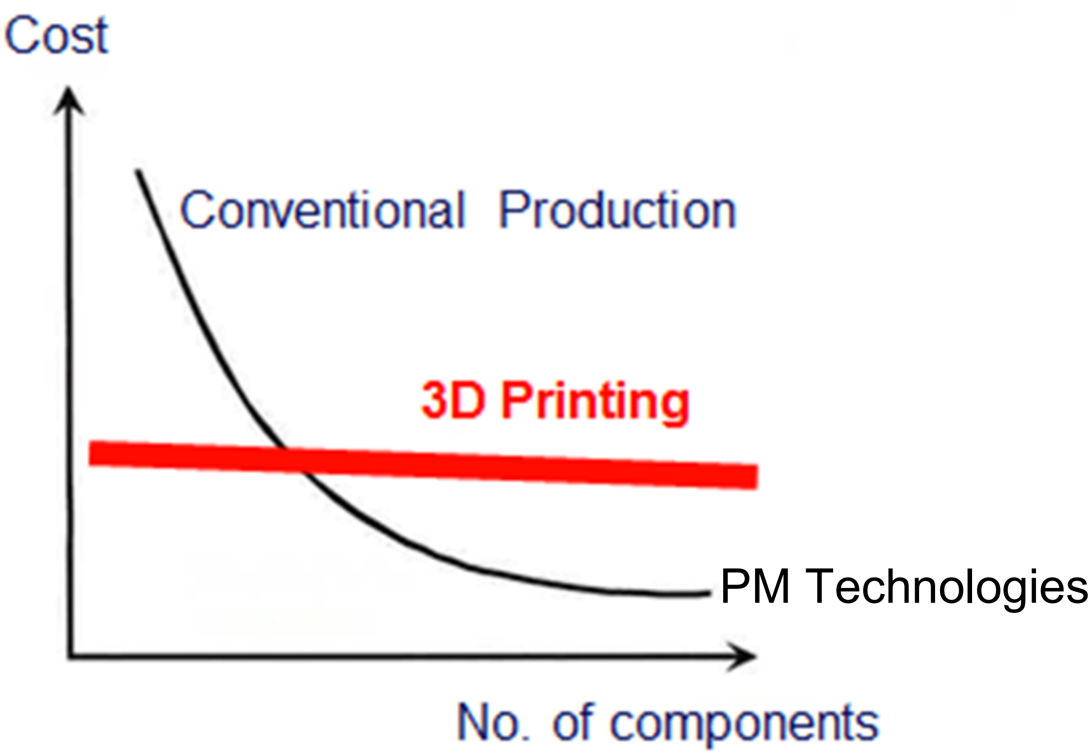
- Overhangs/Support
- Surface finish
- Holes, internal cavities
- Macro effects:
    - Residual stress
    - Curling/warping
    - Contraction

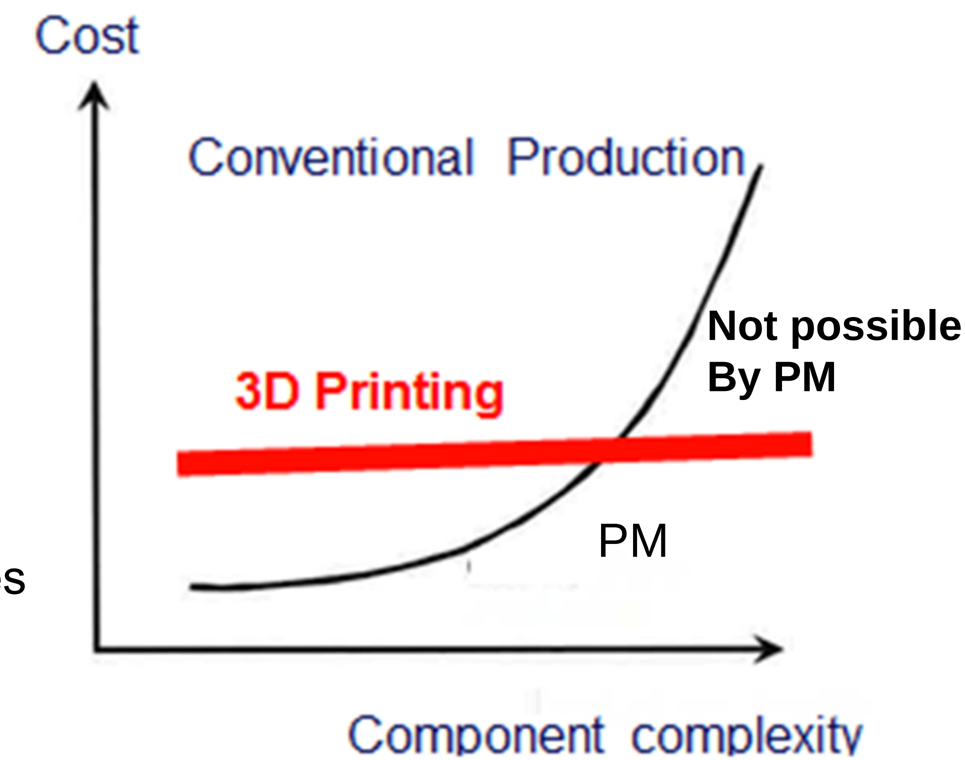






IV AM & PM: Compete or Compliment?





IV AM & PM: Compete or Compliment?

- **Additive manufacturing should not be used to compete with existing technologies to make the same part. AM cannot compete on a cost basis for the same part.**

- **AM must be used to make parts that exiting technologies cannot make. The high cost of AM can be only be justified by unique design attributes and life cycle benefits.**

AM Metal Parts IN PRODUCTION

Co-Cr dental parts

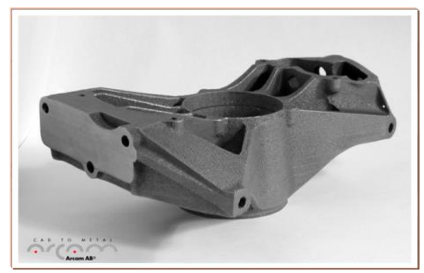
Tooling

GE Leap
Fuel Nozzle

“Design” Objects

Osseointegration

One-offs with unlimited budgets



- Design attributes
- Life cycle benefits

IV AM & PM: Compete or Compliment?

Additive Manufacturing will not compete or replace PM. AM is a new addition to PM as; MIM was new to PM 20 years ago.

Binder Jetting, Material Extrusion, Material Jetting and Vat Photopolymerization can provide material equivalent to MIM and can compliment and extend MIM capabilities.

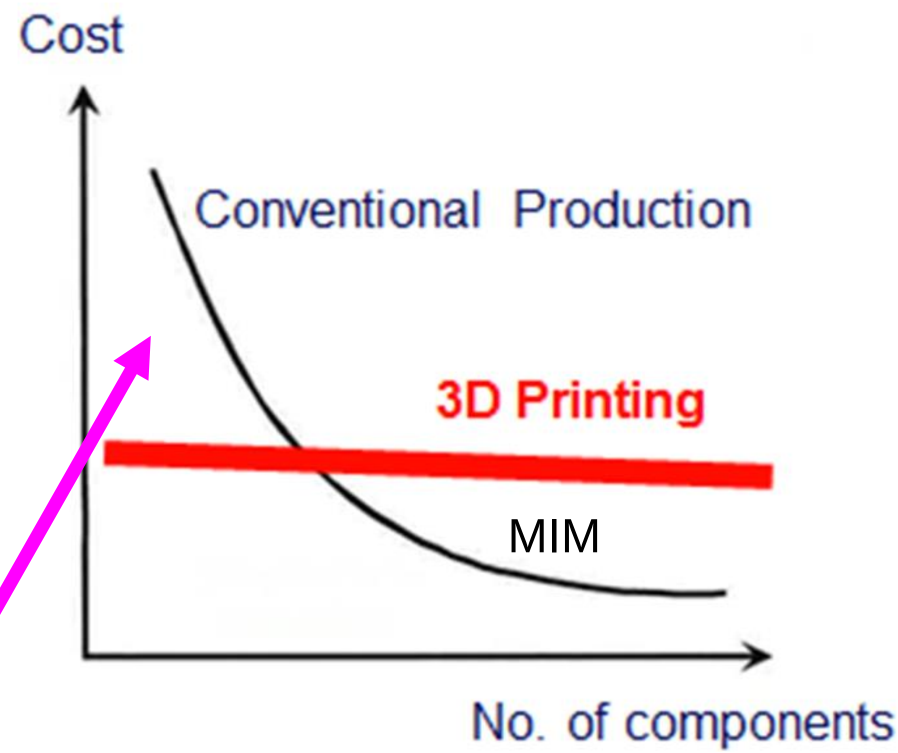
IV AM & PM: Compete or Compliment?

So what about:

Binder Jetting
Material Extruding
Material Jetting
Metal Vat Photopolymerization?

Debind and Sinter:

- Leverage existing technology and knowledge base as MIM.
- Produce similar material wrt density and microstructure.
- Fill in production volumes below MIM's economic feasibility limit.



V Summary

1) Additive Manufacturing is a Powder Metallurgy technology-although it did not originate within the PM community. AM shares PM's powder sources and many PM powder challenges and benefits.

2) Additive Manufacturing is capable of unique attributes and economies not possible with traditional manufacturing methods.

3) At present Additive Manufacturing growth will be by leveraging its ability to provide unique attributes and economies not by competition with existing technologies.

4) Metal AM technologies are continually improving and new metal AM technologies are being developed to further broaden the metal AM manufacturing environment.

5) Binder jetting, material extrusion, material jetting, and metal vat photopolymerization use MIM post processing and offer a unique addition to MIM in attributes and production volumes.

Micro MIM

1992

Questions?