BUSINESS YOUNGSTOWN INCUBATOR

The Youngstown Business Incubator

the future rebooted

Guha Manogharan, EIR-AM, 10-22-2014

1st Best University Affiliated Incubator…

IN THE WORLD!

- University Business Incubator Index (UBII) in Stockholm, Sweden
- Youngstown State University

UBI Index
University Business Incubator

UBI INDEX
University Business Incubator of 2013
TOP GLOBAL

Outline

YBI-Introduction
AM Overview
Applications
Cost/Economics

Additive Manufacturing

Local Partners

- YBI
- Youngstown State University
- M7 Technologies
- RTI Titanium
- Applied Systems & Technology Transfer (AST2)

America Makes

National Additive Manufacturing Innovation Institute

YOUNGSTOWN BUSINESS INCUBATOR

NCDMM

NATIONAL CENTER FOR DEFENSE MANUFACTURING AND MACHINING

RTI

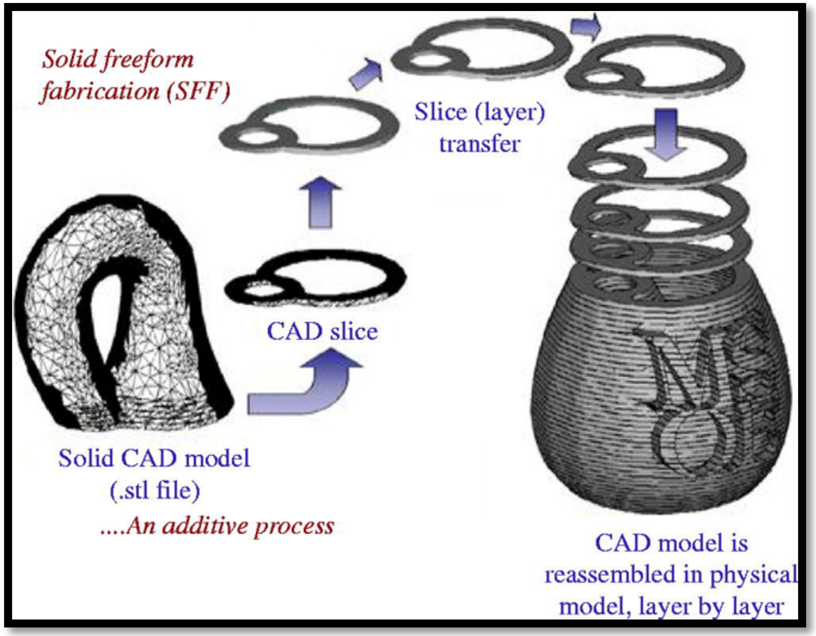
M-7 TECHNOLOGIES

Federal Funding From:

- Department of Defense
- Department of Energy
- NASA
- National Science Foundation
- National Institute of Standards and Technology

What is 3D Printing? (Additive Manufacturing)

- A method of creating an object by building it layer by layer on top of each other.
- Like the floors on a tall building.
- Additive process as oppose to traditional machining where material is removed



History of 3D Printing (RP)

- 1983 Charles Hull invents the Stereolithography Apparatus (SLA)
- 1984 Carl Deckard invents Selective Laser Sintering (SLS)
- 1986 the SLA is patented and 3D Systems is founded
- 1988 Scott Crump invents Fused Deposition Modeling (FDM)
- 1989 Stratasys is founded (FDM)
- 1989 EOS in Germany is founded (SLA and later on SLS)
- 1989 DTM Corp in founded and SLS is commercialized
- 1993 Three-Dimensional Printing (3DP) developed at MIT by Emanuel Sachs
- 1995 Z-Corp obtains exclusive license from MIT for the 3DP

From Polymers to Metals

EOS founded in 1989
- SLS of polymers first
- DMLS of metals in 1994
- Powder Bed Laser System

DTM introduced SLS 1992
- Polymer coated metal powder
- Powder Bed Laser System
- Acquired by 3D Systems in 2001

Concept Laser 2000
- Powder Bed Laser System
- Full melting

Renishaw (former MTT UK)
- Powder Bed Laser System
- Development started in 1995

SLM Solutions (former MTT Germany 2000)
- Powder Bed Laser System
- Development started in 1995

Phenix Systems (founded in 2000)
- Powder Bed Laser System
- Recently Acquired by 3D Systems

LENS introduced 1995 by Sandia
- Only fully melted metals
- Powder Fed Laser System

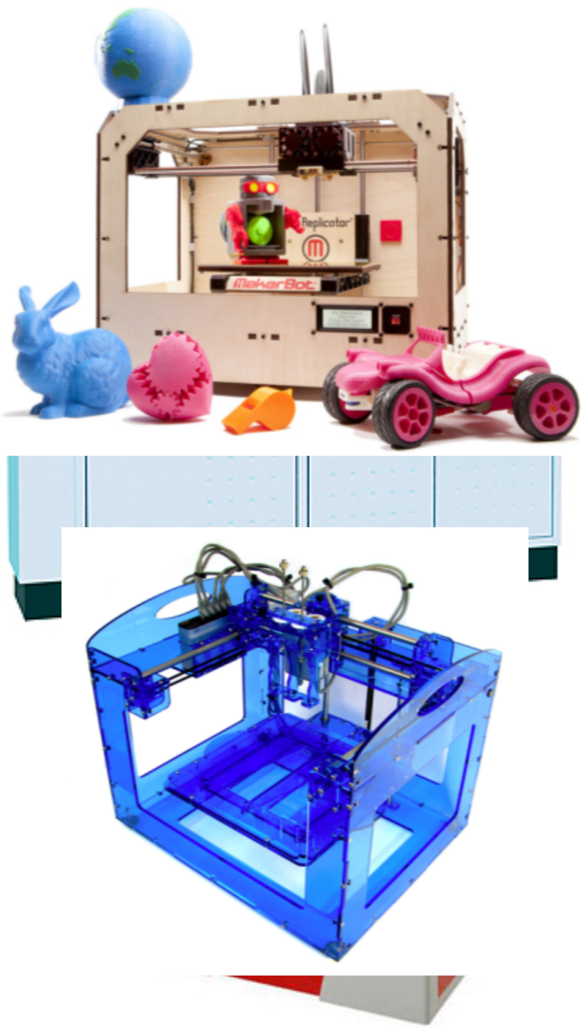
EBM introduced by Arcam 2002
- Only fully melted metals
- Powder Bed Electron Beam System

Sciaky
- Only fully melted metals
- Wire Fed Electron Beam System
- Developed by NASA

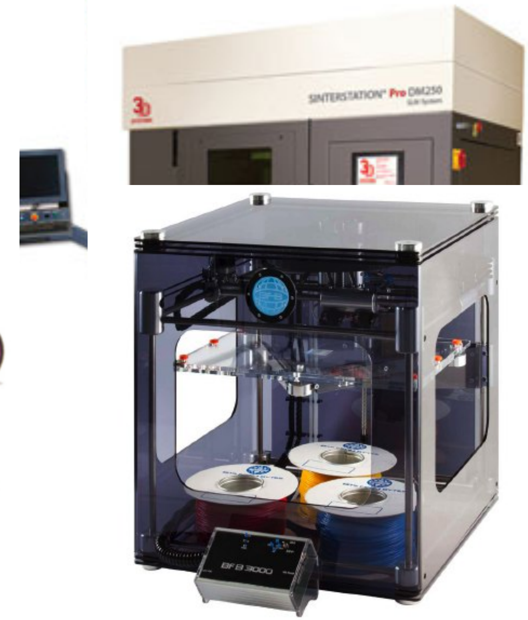
ExOne (founded in 2005)
- Powder Bed Printing System
- Post sintering and infiltration

RP to AM (3D Printing)

PolyJet



SLA

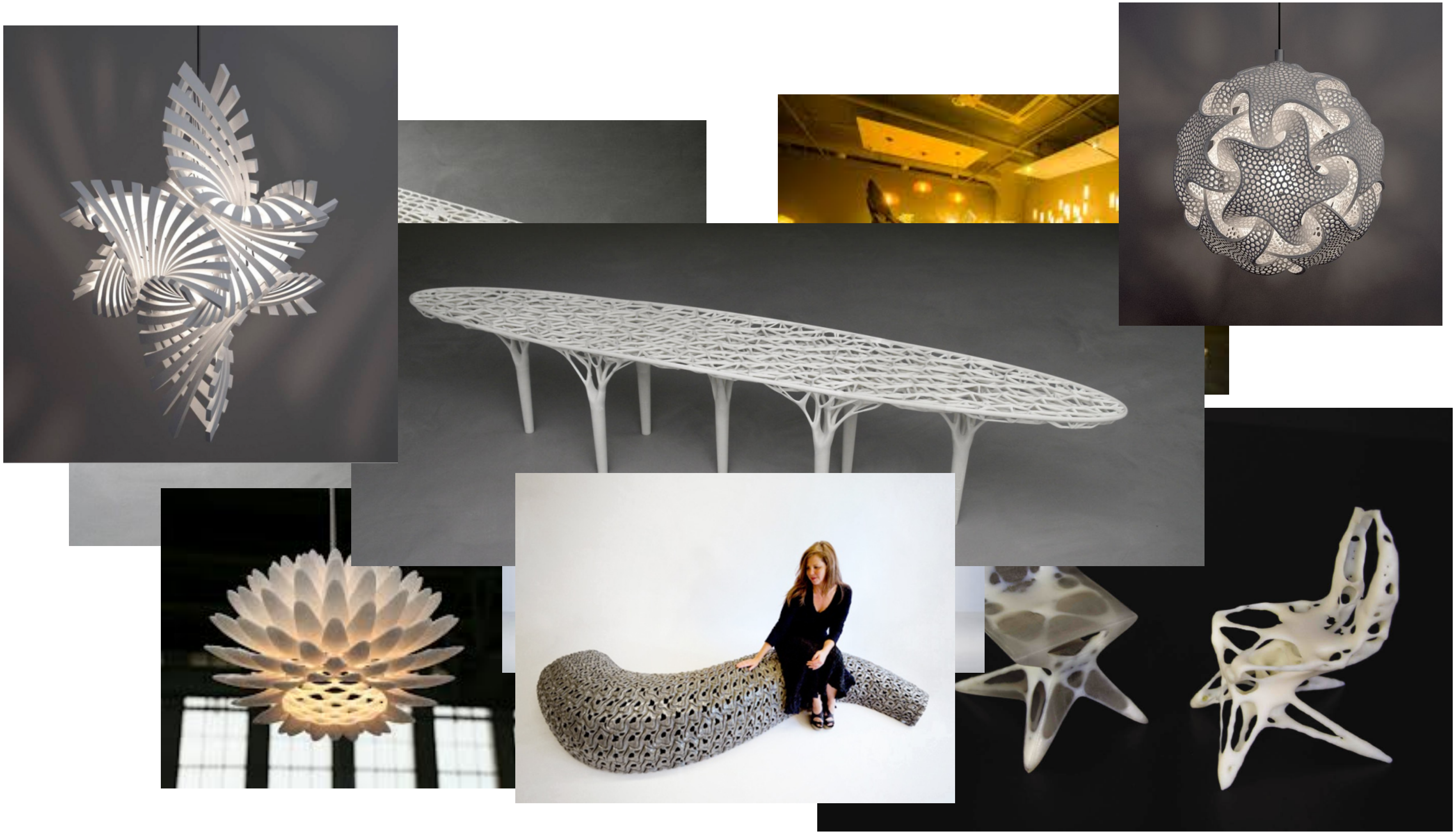


Medical

Aerospace

Architecture

Home and Decor



Consumer Products

Clothing and Accessories

Classification ASTM F2792-12a:

- Binder Jetting (Exone system)
- Directed Energy Deposition (LENS, EBF3)
- Material Extrusion (FDM)
- Powder Bed Fusion (EBM, DMLS)
- Sheet Lamination (Ultrasonic Consolidation and Mcorr)
- Vat Polymerization (SLA)

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Binder Jetting

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

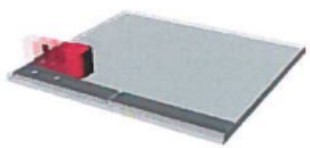
- **Materials: Metals, Ceramics and Sand**
- **Attributes:**
  - **Powders → Binding → Sintering**
  - **‘Processing’ Temperature Independent**
  - **Porosity → Infiltration**
  - **e.g. Z-Corp, Ex-One**

Binder Jetting

Powdered Metal: The re-coater applies a layer of powdered metal onto the build platform.

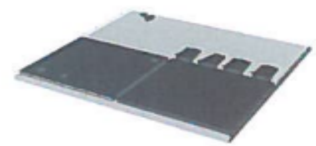
Bound Metal: The printhead selectively dispenses a proprietary resin onto the bed of powdered metal. This process is repeated until the entire job is printed. The printed parts are then sintered in a vacuum furnace.

1. Binder print



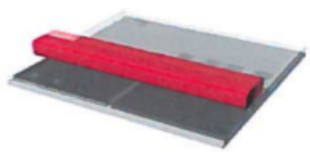
The binder is selectively dispensed.

2. New Layer



The build platform is lowered by a set increment.

3. Next layer



A new layer of powdered metal is spread.

4. Repeat

Steps 1-3 are repeated until the part is built.

5. Finishing

The unbound metal is removed, and the metal parts are sintered.

https://www.youtube.com/watch?v=NVJifm2b6-c

Source: Ex-One

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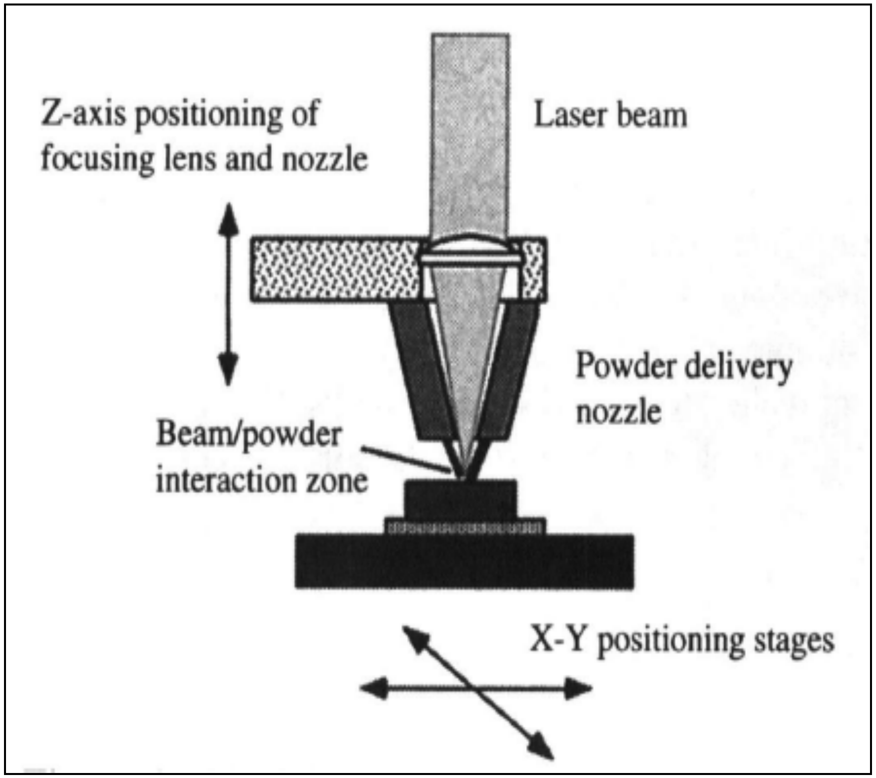
Directed Energy Deposition

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.

- **Materials: Metals**
- **Source: Laser or Electron Beam**
- **Attributes:**
  - **Started from 'Cladding' operation**
  - **Powders → NC control → Melting**
  - **e.g. LENS, Sciaky**

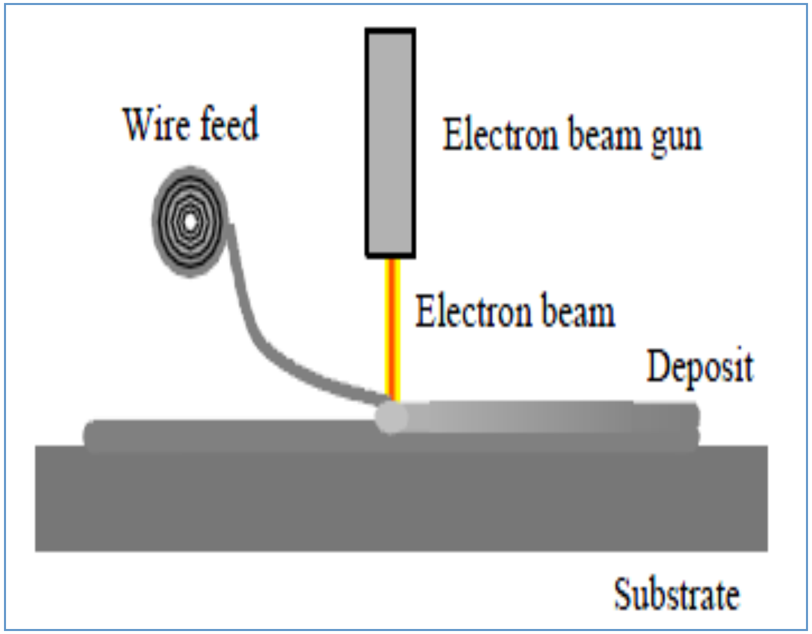
LENS



- Laser Engineered Net Shaping
- Ideal for Repairing
- Some ‘Hybrid’ processing
- ‘Gradient’ Materials
- Higher Deposition Rate

https://www.youtube.com/watch?v=d2foaRi4nxM&src_vid=SYbw1oSzPVA&feature=iv&annotation_id=annotation_3035698617

EBF^3 - Sciaky



- Electron Beam Freeform Fabrication
- Wire-based
- Higher Deposition Rate
- Lower Resolution

https://www.youtube.com/watch?v=A10XEZvkgbY

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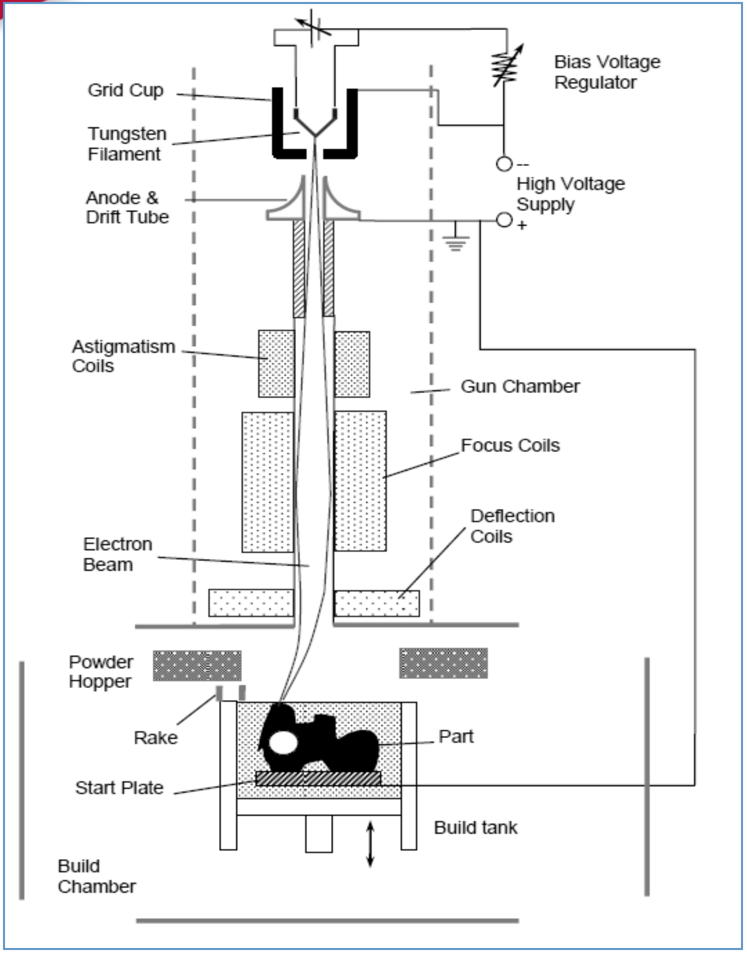
Powder Bed Fusion

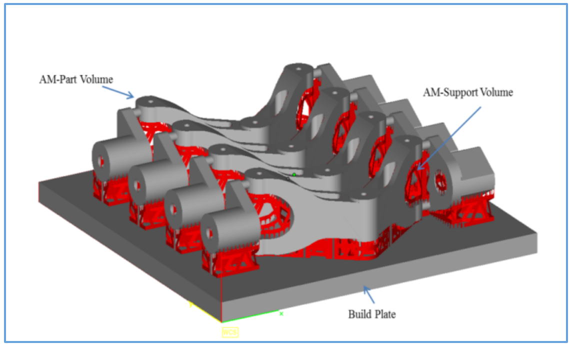
powder bed fusion, *n*—an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.

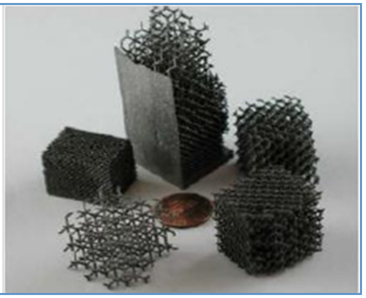
- **Materials: Metals and Plastics**
- **Source: Laser or Electron Beam**
- **Attributes:**
  - **Higher Density**
  - **Powders → Optics/EM control → Melting**
  - **Cold-bed vs. Hot-Bed process**
  - **e.g. EBM, DMLS**

EBM - Arcam



- Hot-Bed process
- Popular for Ti64
- Complete melting
- Pre-heating of bed
- Contour-Melt-Support
- In Vacuum





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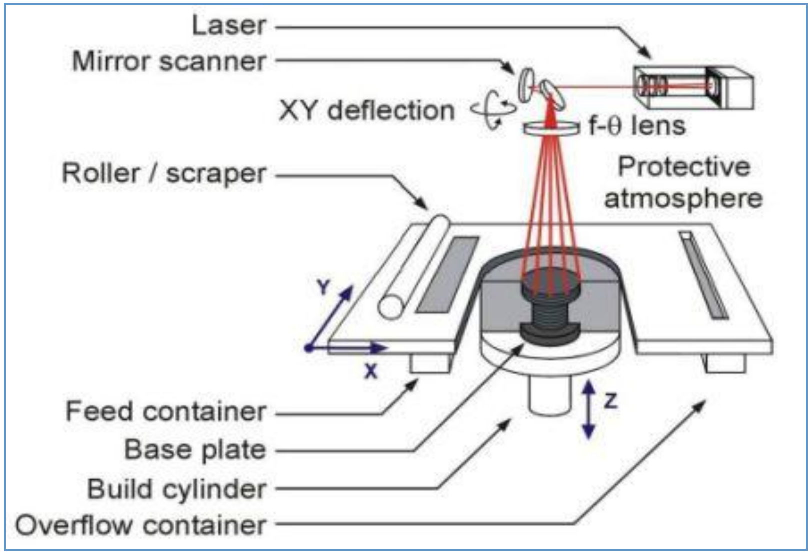
DMLS/EOS/SLM/Phenix



- **Cold-Bed process**
- **Better resolution → EBM**
- **Parts at an angle to plate**
- **CoCr, SS are popular metals**
- **Stress-Relieving Annealing**
- **Inert gas atmosphere**
- **Scope for process modelling**

Sheet Lamination

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

- **Materials: Metals**
- **Solidica – OEM**
- **Embedded Sensors applications**
- **Limited geometric freedom**
- **Lower production rate**

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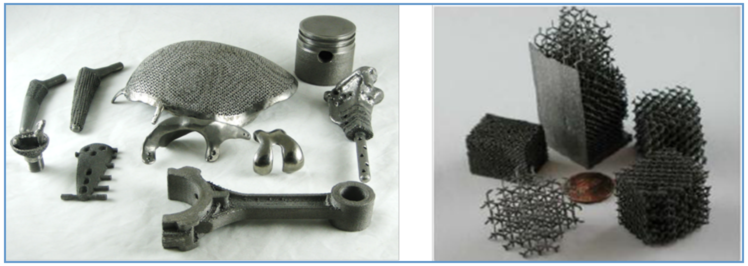
Attributes of AM

- 'Freeform' Fabrication
  - Part design complexities
  - Eliminates expensive tooling
  - Fixture cost
  - Ideal for low-volume batch
  - Higher material utilization
  - Tough-to-process alloys
    - Non-homogeneity in cast ingots
- Poor surface finish
- Part feature inaccuracies
- Bonding of unprocessed powder
  - 'As-cast' surface textures
- Warping and Shrinkage during post-processing



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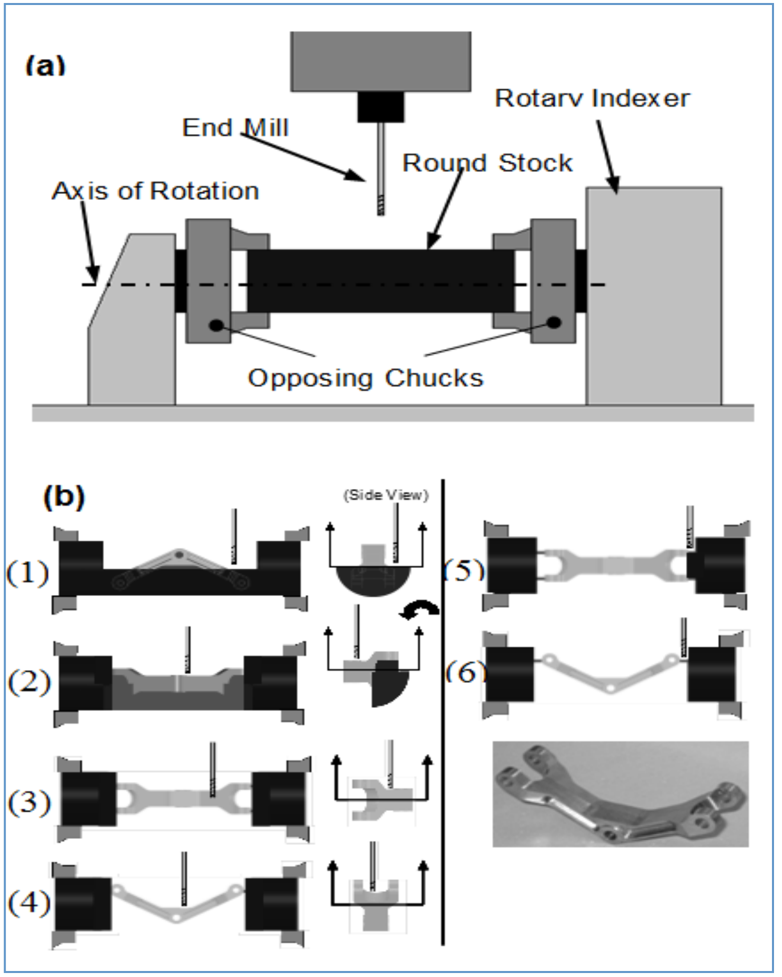
Takeaways

- **Variety of Materials**
- **Variety of Applications**
- **Variety of Processing Technologies**
- **What are the <u>Challenges</u> in achieving complete 'Rapid Production' ?**

SM-Background

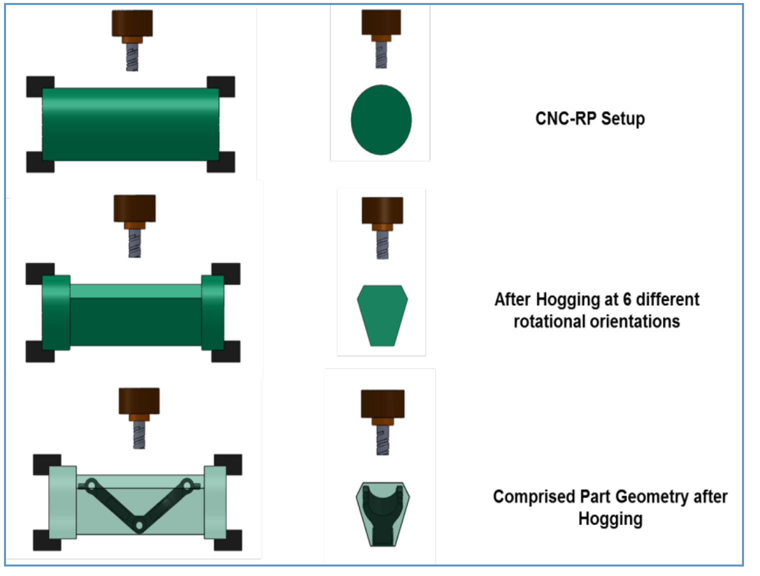
- CNC-RP
- 'CAD-to-produce' AM-like approach
- Layer-based island milling
- 4-axis CNC setup
- Sacrificial fixturing
  - Material and machining conditions→ Deflection during machining
- Visibility analysis
  - Minimum amount of rotational indexing with maximum facet visibility



Principle of CNC-RP

CNC-RP

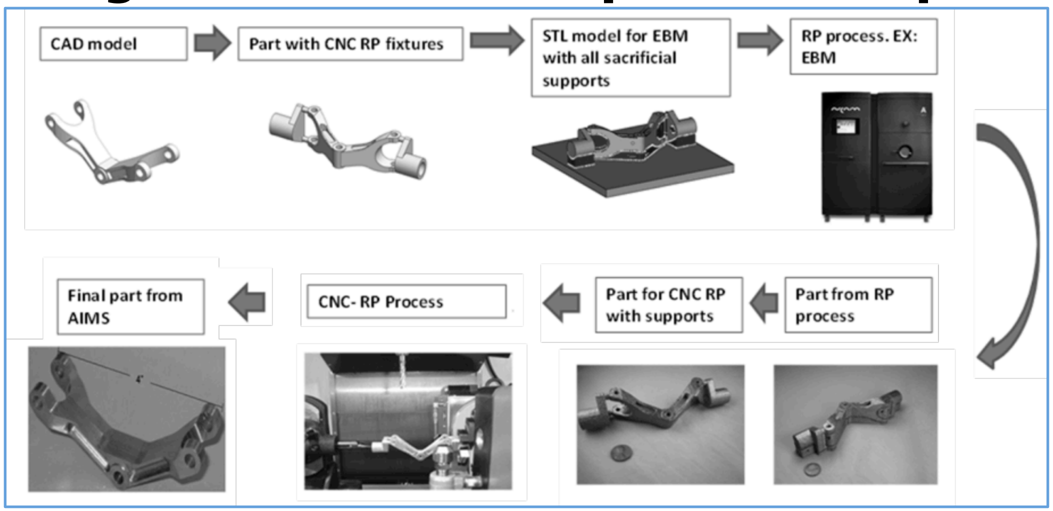
- **CNC-RP stages based on machining parameters and tooling:**
  - **Hogging**
  - **Roughing (*feature-dependent)***
  - **Finishing (*feature-dependent)***
- **Attributes of CNC-RP**
  - **Superior part accuracy and surface finish**
  - **Geometric limitations**
  - **Loss of material as scrap and chips**
  - **Machining of superalloys**
    - **Lower machinability**
    - **Tooling cost**



Hogging; Area-clearance

AIMS System Architecture

- **Incorporating CNC-RP fixtures prior to AM processing (e.g. EBM)**

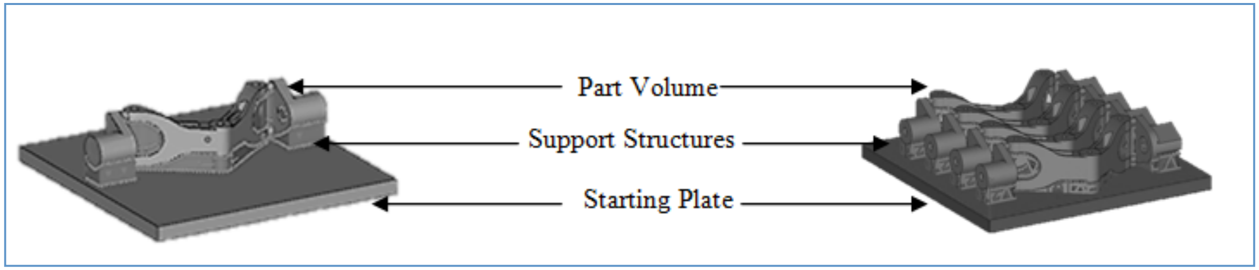


AIMS Process flow

- **Part surface overgrowth for 'finish machining'**
- **Near-net AM part eliminates hogging and roughing (in CNC-RP)**
- **Single CAD file for entire process planning**
- **Two support structures:**
  - **Overhanging edges in AM**
  - **Fixturing supports for CNC-RP**

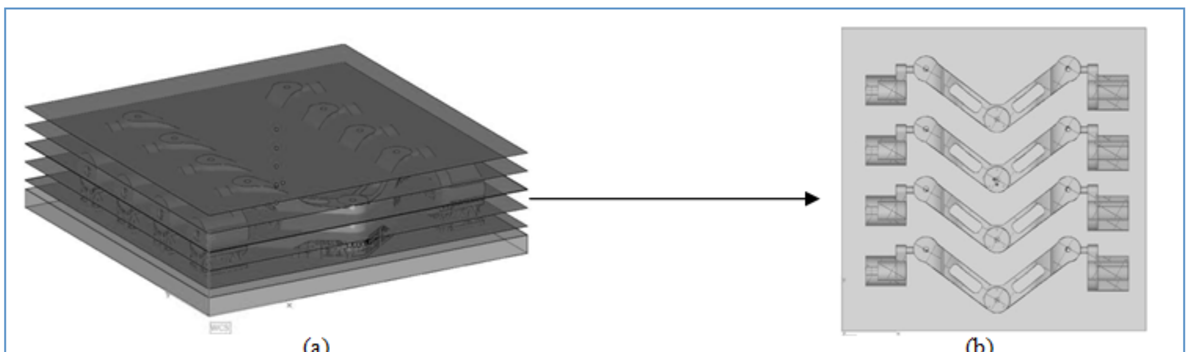
Case Study: Cost Model

- Suspender part:



Low-volume Batch production

- Batch size considerations due to AIMS physical components → Build volume and Orientation



EBM Build Schematics

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Economic Model- Cost factors

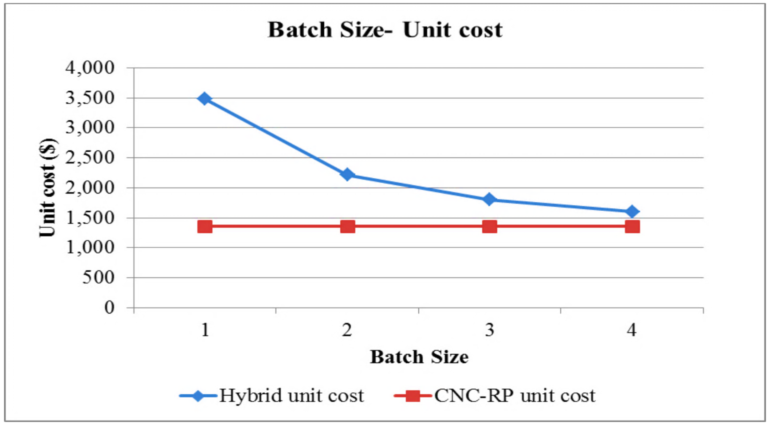
Major Notations	Unit	Comments
		General factors
C_{unit}	$	Cost per unit
Pv	mm^3	Part volume
SPv	mm^3	Support volume- sacrificial supports
$C_{process}$	$/hr	Operating cost for each process
C_{mat}	$	Cost of material in each process
t_{build}	hr	Time to fabricate the part in additive process
$t_{setup\_process}$	hr	Setup time in each process
$t_{post\_process}$	hr	Post-processing time in each process
		CNC-RP specific factors
Sv	mm^3	Volume of bar stock
t_{hog}	hr	Time for hogging operation
t_{rough}	hr	Time for roughing operation
t_{finish}	hr	Time for finishing operation
t_{tool_life}	hr	Cutting tool life duration
t_{tool_change}	hr	Time for changing tool and tool set-up time
	mm^3	Total volume removed at each stage in CNC-RP
MRR	mm^3/hr	Material Removal Rate at each stage in CNC-RP
$C_{tooling}$	$/tool	Cost of cutting tools
nt	--	Number of tool changes in each stage
$C_{tooling}$	$/tool	Cost of cutting tools
		EBM specific factors
n_{EBM}	--	Number of layers in EBM fabrication
ρ	kg/mm^3	Density of metal powder used
t_{EBM}	hr	Total build time in EBM
t_{plate}	hr	Time to preheat the start plate to required temperature before fabrication
t_{cool}	hr	Time to cool the build volume, retrieve part and recycle unused powder

Case Study: Results

- Breakdown of AIMS operation and tooling cost:

Batch Size	Hybrid Process						
	EBM stage			CNC-RP		Total Cost ($)	Unit Cost ($)
	Time (hrs)	Material Cost ($)	EBM Cost ($)	Time (hrs)	CNC-RP Cost ($)		
1	28.03	104.23	3,019.54	10.38	359.50	3,483.27	3,483.27
2	33.98	138.97	3,672.93	20.76	619.00	4,430.90	2,215.45
3	39.93	185.30	4,337.91	31.14	878.50	5,401.71	1,800.57
4	45.88	247.07	5,018.32	41.52	1,138.00	6,403.39	1,600.85

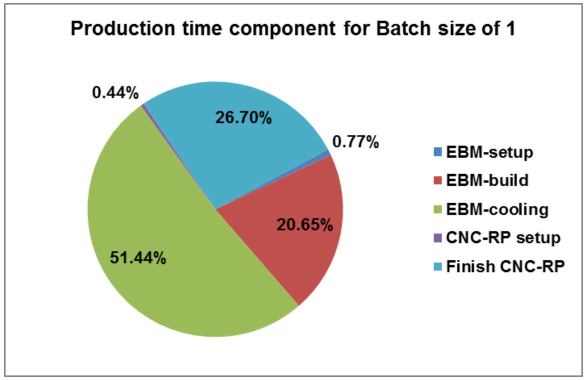
AIMS Unit cost

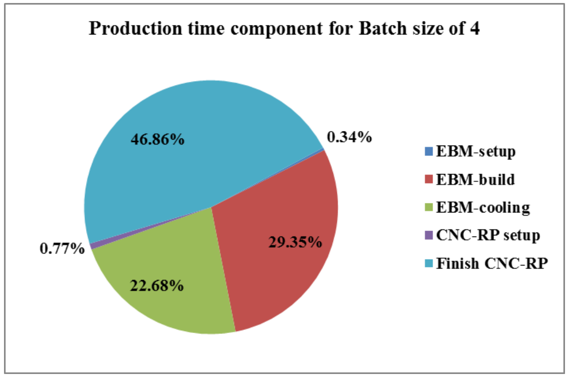


AIMS vs. CNC-RP Comparison

Case Study: Results

- No effect of batch size on CNC-RP
- Batch size reduces EBM and AIMS cost, due to amortized cooling and layer time





Time Components in AIMS

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Case Study: Sensitivity Analysis

- Material cost: Aluminum vs. Inconel, atomization method, batch size, powder size, bar stock
- MRR: Machinability and part overgrowth
- Production time: EBM vs. DMLS vs. other AM technologies, Machining Ti64 vs. Al6065
- Production cost: Machining vs. AM technologies

Variables	Case-study-Section.3	Level #2	Level #3
EBM material cost ($/kg)	300	30	150
CNC-RP stock cost ($/unit)	400	200	40
Ratio: MRR/MRR-case study	1	0.5	0.1
EBM production time (hr/part)	20	10	2
EBM operating cost ($/hr)	104	66	33
CNC-RP operating cost ($/hr)	25	50	75
Finish machining allowance (mm)	2.54	0.25	1.25

Variable conditions

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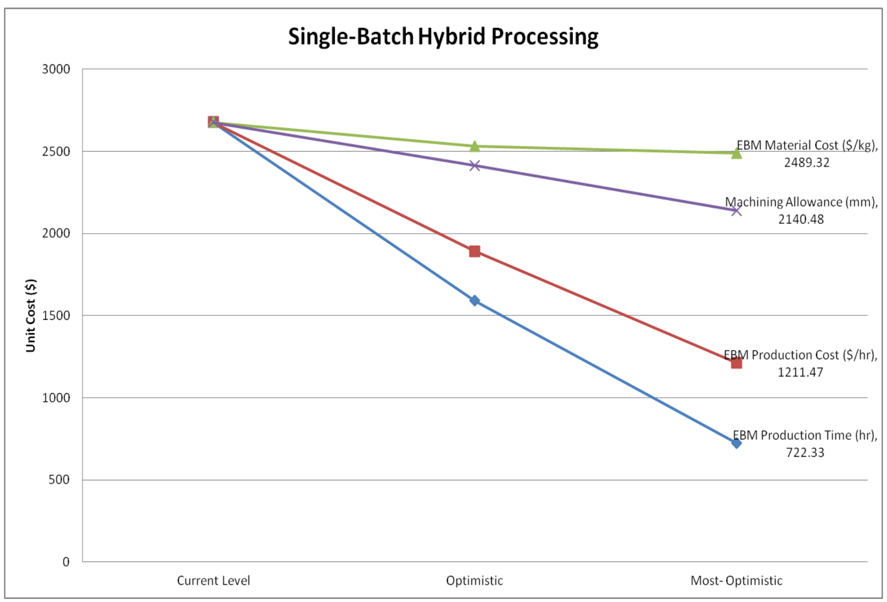
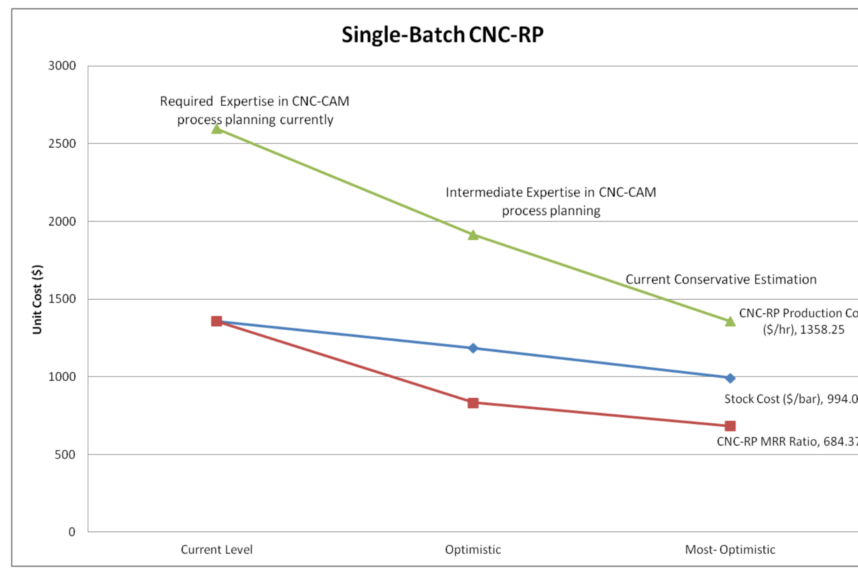
Case Study: Sensitivity Analysis

- CNC-RP benefits the most from increased MRR ratio
- Machining time influences more than stock cost
- Production time influences the most in AIMS (cooling)
- Lower production cost reduces the unit cost in AIMS
- Advantage of AIMS:
  - Machinability has smaller effect on unit price → Superalloys

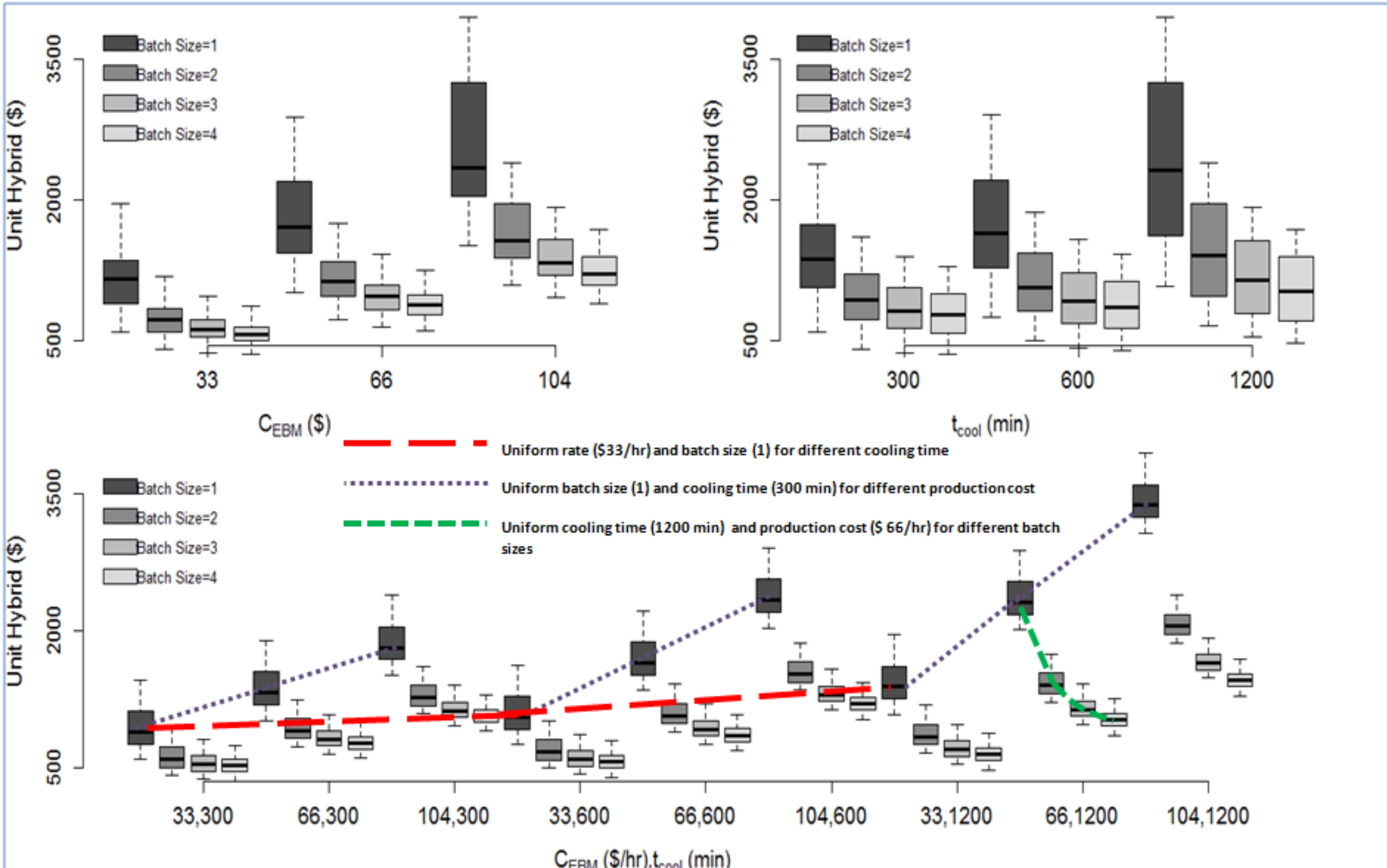


AIMS Unit cost



CNC-RP Unit Cost

AM Production Time- Cost



Summary

- Removal of hogging and roughing is a major contribution along with CNC-RP based re-orientation hybrid method
- Operation cost of CNC machine is lower →preference to produce Aluminum or Brass through conventional methods
- AM (e.g. EBM) cooling or secondary production time is very critical cost component
- Material utilization → More expensive difficult-to-machine alloys

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Summary

- Three-fold benefits:
  - Elimination of additional fixtures to AM
  - ‘Finish’ only CNC-RP leads to reduction in machining time and lower tooling cost
  - Higher material utilization through ‘near-net’ AM part approach
  - **Batch production** (Build volume, part design, build orientation constraints)
- **Criteria:**

$$t_{Pre-finishing} = t_{setup-CNC-RP} + t_{hog} + t_{rough}$$

$$C_{RoughStock} = (C_{machining} \times t_{Pre-finishing}) + C_{tool(H)} + C_{tool(R)} + C_{CNC-RP-stock}$$

$$C_{RoughStock} \leq C_{EBM}$$

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Contact

Questions!!

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Thank you!

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the future re-booted.

…questions?

Cost Models

- Cost of AM unit is a function of material and production time

$$C_{unit} = C_{material} + (C_{add} \times t_{add})$$

$$t_{add} = t_{setup\_add} + \sum_{i=1}^{n} (t_{build\_i}) + t_{post\_process}$$

- Cost of CNC-RP unit is a function of material, tooling production time

$$C_{unit} = (S_v \times C_{mat\_CNC-RP}) + (C_{CNC-RP} \times t_{CNC-RP}) + (C_{tooling} \times n_{stage})$$

$$t_{CNC-RP} = t_{setup\_CNC-RP} + t_{hog} + t_{rough} + t_{finish}$$

$$n_{stage} = \frac{(\Delta V)}{MRR} \times \left(\frac{1}{t_{tool\_life}}\right)$$

$$t_{stage} = \frac{(\Delta V)}{MRR} + (n_{stage} \times t_{tool\_change})$$

AIMS Cost Model

- In this study, EBM is the AM component. Hence, the EBM build time can be detailed for each layer '*i*' :

$$\sum_{i=1}^{n} (t_{build\ \_i}) = t_{plate} + t_{raking} + t_{pre\ heating} + t_{melt\ \_i} + t_{support\ \_i} + t_{post\ heating}$$

- The melting and support time for each layer can be expressed as:

$$t_{melt\_i} = \sum_{i=1}^{n} \left(\frac{Contour\ scan\ length}{Contour\ Speed}\right) + \sum_{i=1}^{n} \left(\frac{Melt\ scan\ length}{Melt\ Speed}\right)$$

$$t_{support\ \_i} = \sum_{i=1}^{n} \left(\frac{Support\ scan\ length}{Support\ Speed}\right)$$

AIMS Cost Model

- Hence, the EBM cost-component can be noted as:

$$t_{EBM} = t_{setup\_EBM} + \sum_{i=1}^{n} \left(t_{build\_i}\right) + t_{cool}$$

$$C_{EBM} = (\eta \times (P_v + SP_v) \times \rho \times C_{kg}) + (C_{EBM} \times t_{EBM})$$

- Including the finish CNC-RP component, AIMS unit cost is:

$$C_{Hybrid} = (C_{CNC-RP} \times (t_{setup\_CNC-RP} + t_{finish})) + \left(C_{tooling} \times n_{finish}\right) + C_{EBM})$$

Cost-Model Parameters

- CNC-RP: (Ti-64)
  - Operating cost → $ 25/hr
  - Stock setup time →10 minutes
  - Tool change → 10 minutes (including tool length qualification)
  - Cutting tools (four flute carbide flat end mills)
    - diameters of 25.40 mm, 6.35 mm and 3.18 mm for hogging, roughing and finishing respectively.
  - Machining parameters (surface speed of 508 mm/s)
    - Chip load of 0.05 mm in the case of hogging and roughing
    - Chip load 0.03 mm in the case of finishing.
    - Layer thickness (depth of cut) of 5.08 mm, 0.51 mm and 0.05mm in the case of hogging, roughing and finishing operation.
  - Stock volume → Diameter of 63.50 mm and a length of 203.20 mm and valued at $ 400 per stock.
  - Average tool life was assumed to be 100 minutes of machining time and tooling cost of $20/tool.

Cost-Model Parameters

- EBM: (Ti-64)
  - Operating cost → $ 104/hr
  - Layer thickness → 0.07 mm
  - Setup and plate pre-heating time →90 minutes
  - EBM cost → $ 300/kg, 5 % loss in powder handling
  - Constant beam speed conditions
  - Effective contour speed → 17.18 mm/s
  - Support speed → 50 mm/s
  - Beam overlap → 0.20 mm
  - Each layer:
    - Raking duration → 10 seconds
    - Preheating → 12.5 seconds
    - Post-heating → 12.5 seconds
    - Melt beam speed → 500 mm/s
  - Cooling and part retrieval time → 480 minutes