Selecting the Correct Material and Technology for Metal AM Applications

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About EWI

- **Non-profit applied manufacturing R&D company**
  - Develops, commercializes, and implements leading-edge manufacturing technologies for innovative businesses
- **Thought-leader in many cross-cutting technologies**
  - >160,000 sq-ft in 3 facilities with full-scale test labs (expanding)
  - >$40 million in state of the art capital equipment (expanding)
  - >170 engineers, technicians, industry experts (expanding)

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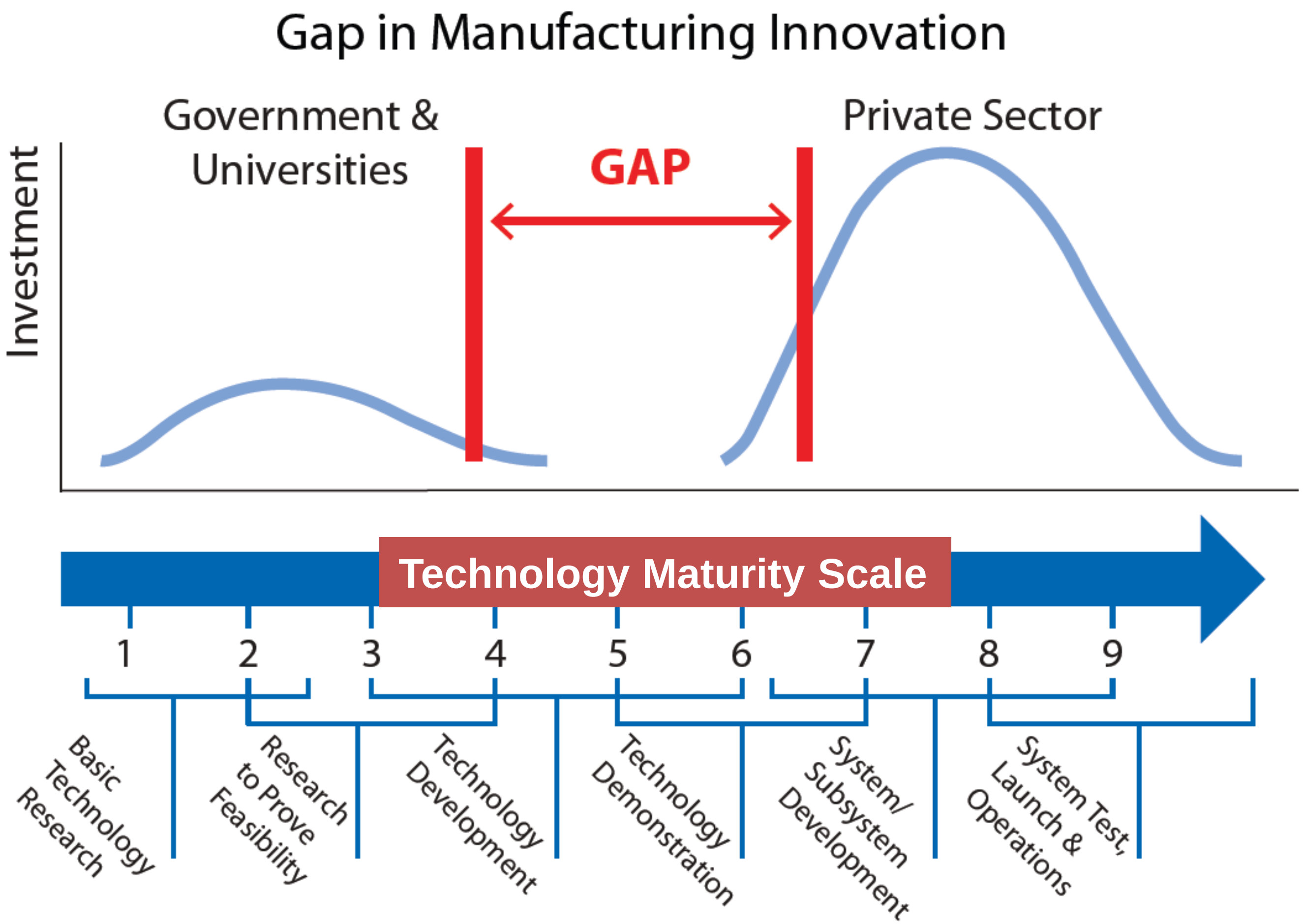
Structural Gap between Research and Application



Source: NIST AMNPO presentation Oct. 2012

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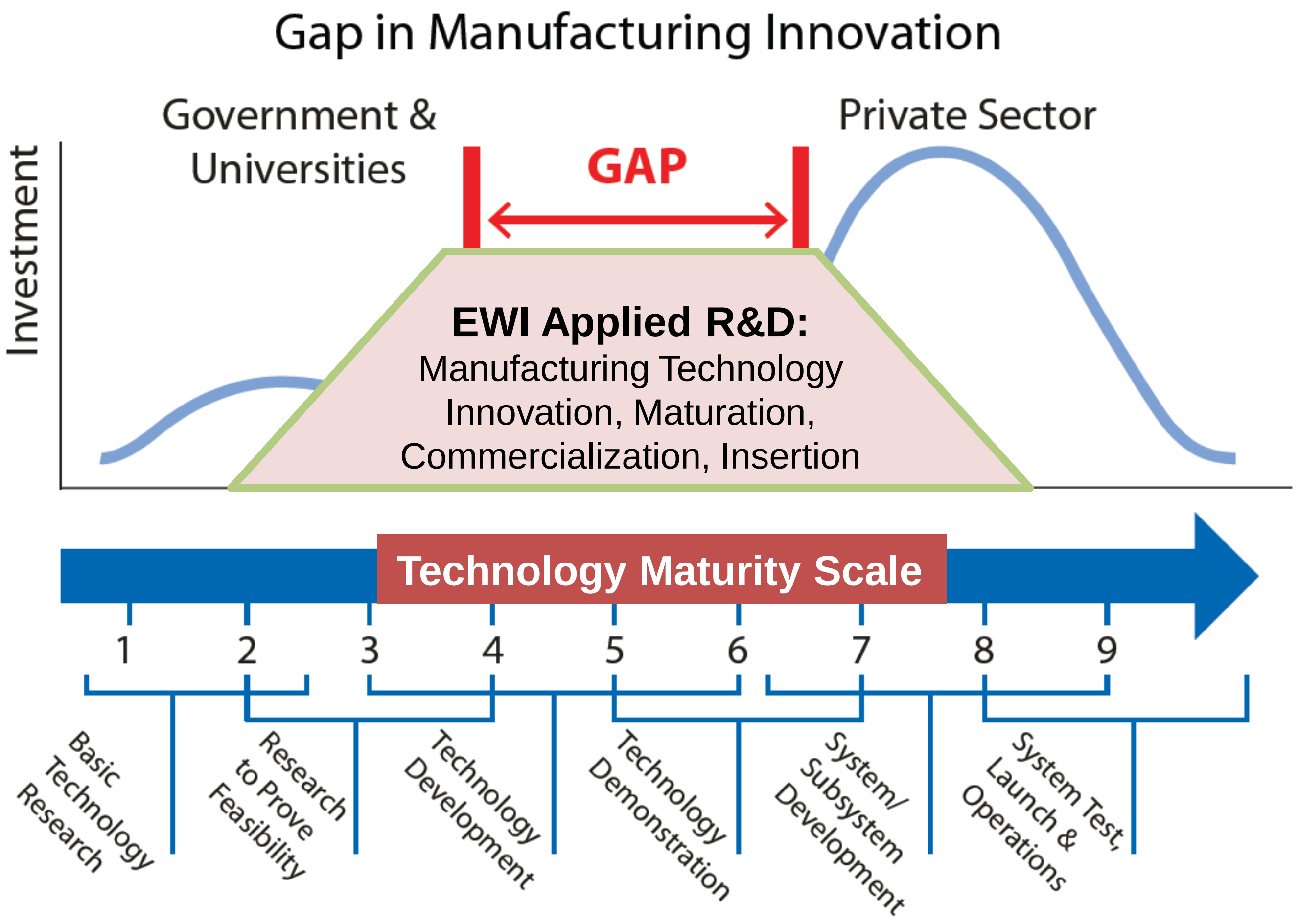
EWI Applied R&D Bridges the Gap Between Research and Application



Source: NIST AMNPO presentation Oct. 2012

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Connecting Colorado to EWI's Capabilities Nationally

- EWI Colorado opened in 2016
- Customers have access to EWI capabilities nationally
- Among the broadest range of metal AM capabilities

FOURFRONT OF COLORADO MANUFACTURING

1984 Columbus OH:
Joining, forming, metal additive mfg, materials characterization, testing

2016 Loveland CO:
Quality assessment: NDE, process monitoring, health monitoring

2015 Buffalo NY:
Agile automation, machining, metal additive mfg, metrology

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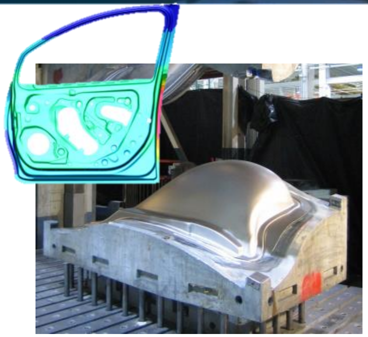
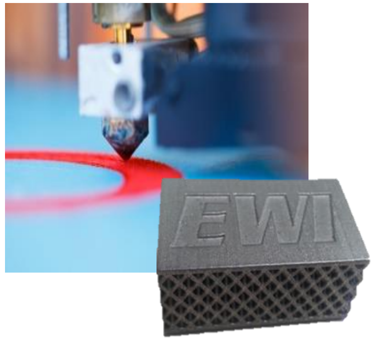
Growing Range of Cross-Cutting Manufacturing Technologies

Materials Joining



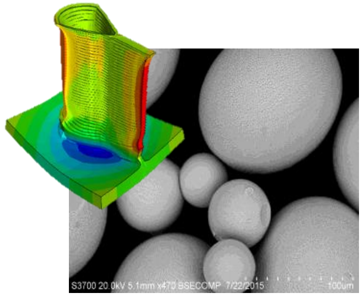
Forming

Machining & Finishing

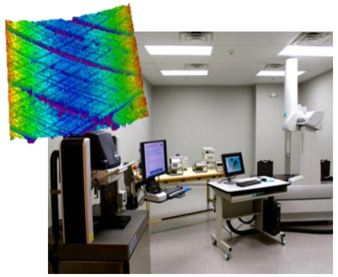


Additive Manufacturing

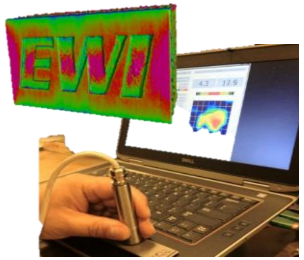
Agile Automation



Applied Materials Science



Testing & Characterization



Quality Measurement

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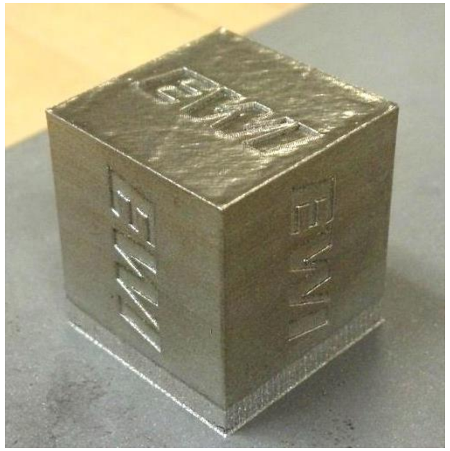
AM is Materials Joining

Manufacturing of complex 3D parts by *joining* successive beads and layers

675 feet of weld
(Audi R8)

1-inch L-PBF Cube



5 miles of weld

3,400 feet of weld

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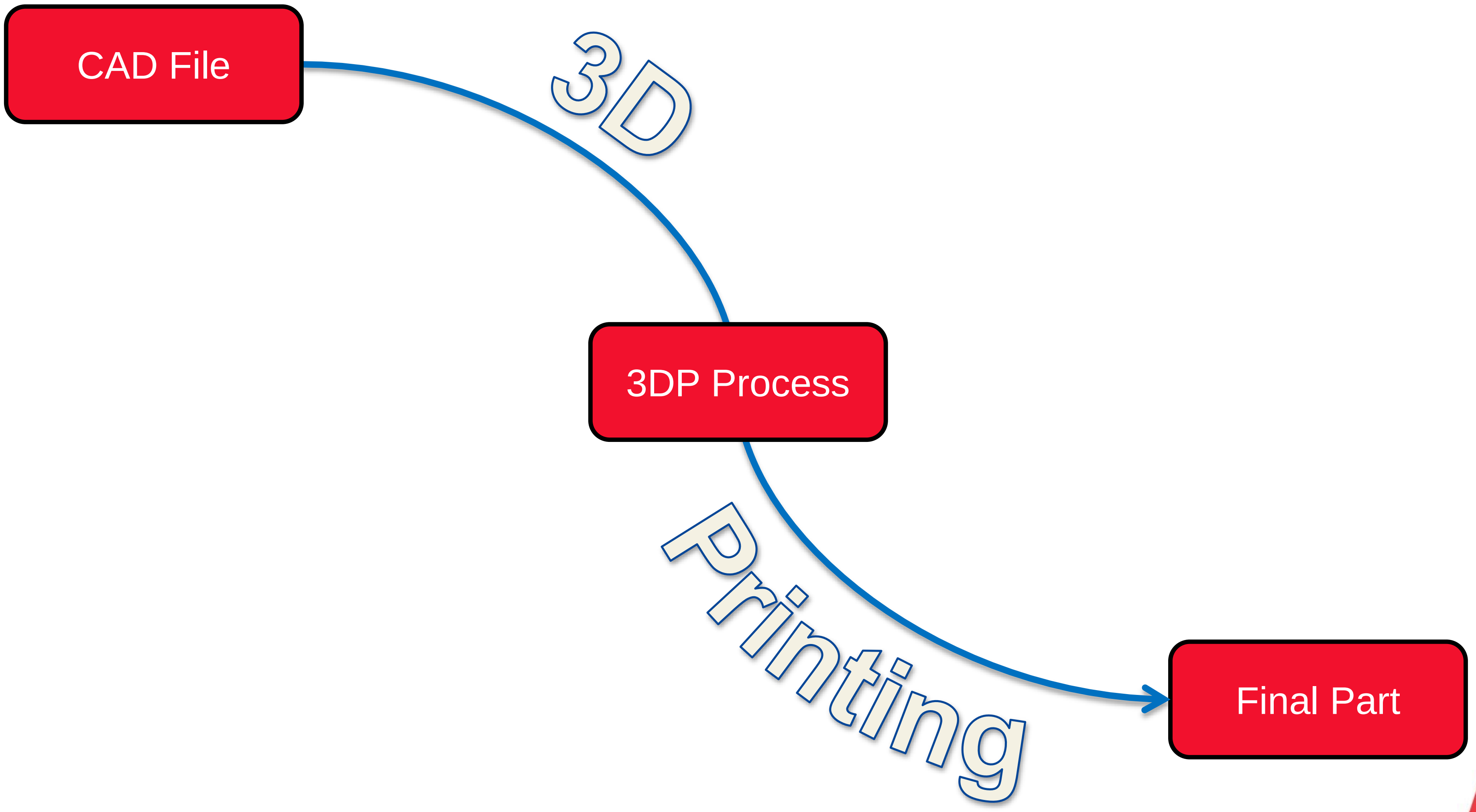
A Holistic View of Additive Manufacturing Process Chain



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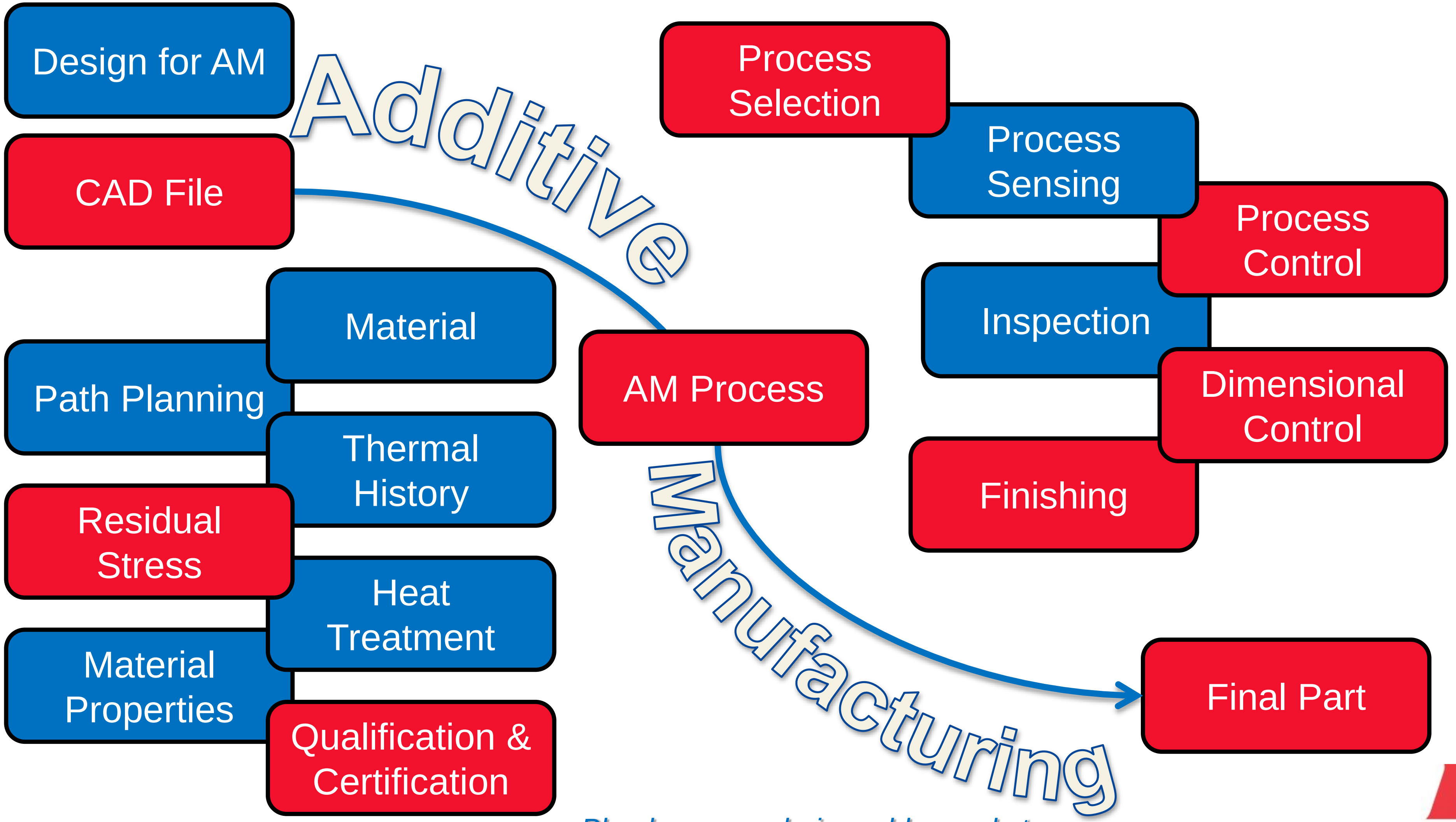
Additive Manufacturing Supply Chain



Blue boxes are being addressed at EWI presently

EWI's Focus Areas are Aligned with the Needs of Industry

EWI Metal AM Focus Areas

- In Process Quality Control
- Post Process Inspection
- Materials and Process Development
- Support Design Allowable Database Generation
- Advancements for Manufacturing Machines
- Design for Additive / Technology Application
- Industry Support: Additive Manufacturing Consortium

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Seven AM Technologies

In order to help standardize additive manufacturing in the United States the ASTM F42 Committee on Additive Manufacturing Technologies was formed in 2009 and categorized AM technologies into seven categories

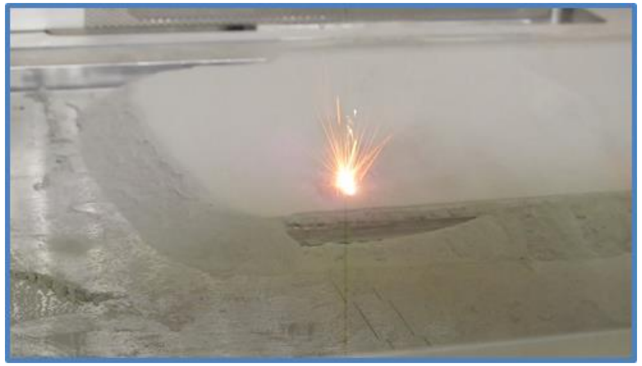
- **Powder Bed Fusion**
- **Sheet Lamination**
- **Material Extrusion**
- **Directed Energy Deposition**
- **Material Jetting**
- **Vat Photopolymerization**
- **Binder Jetting**

EWI has all Seven AM Technologies

EWI AM Capabilities Overview

Laser PBF
EOS M280

Laser PBF – Open Architecture
EWI-Designed and Built



Electron Beam PBF
Arcam A2X

Sheet Lamination UAM
Fabrisonic

Laser DED
RPM 557

Electron Beam DED
Siacky EBAM 110

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Key Considerations for an AM Part

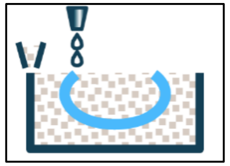
- **Every part is not an ideal candidate for AM!**
- **Critical questions to ask before considering AM:**
  - Do current manufacturing constraints limit parts performance?
  - Can sub-components be merged to avoid assembly?
  - Can number of joints be minimized?
  - Can weight & material be reduced and achieve the same function?
  - Is extensive tooling needed to manufacturing part?
  - Can new material combinations increase part performance?
  - Can part durability be maximized?

Types of Additive Manufacturing

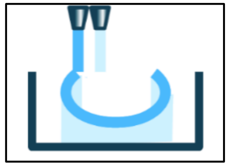
ASTM International:
Technical Committee F42 on Additive Manufacturing

Vat Photo-polymerization

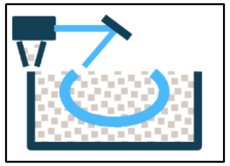
Material Jetting



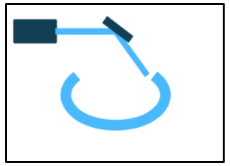
Binder Jetting



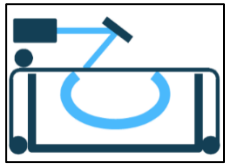
Material Extrusion



Powder Bed Fusion



Directed Energy Deposition



Sheet Lamination

Roland Berger
Strategy Consultants

Types of Additive Manufacturing

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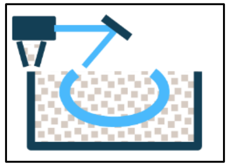
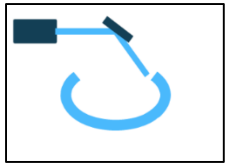
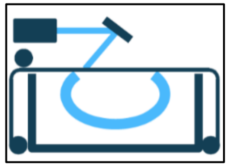
Technical Committee F42 on Additive Manufacturing



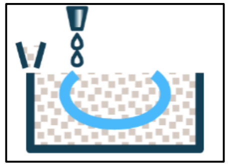
Powder Bed Fusion



Directed Energy Deposition



Sheet Lamination

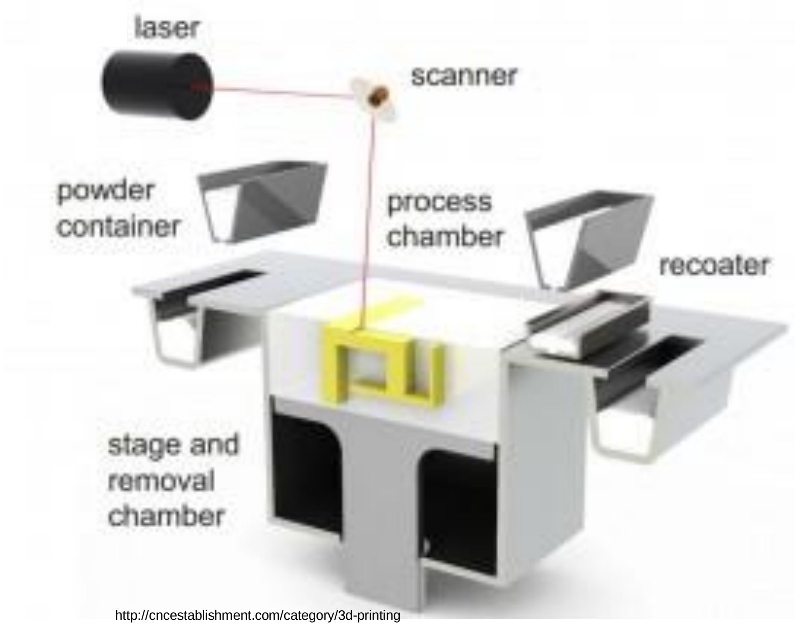


Binder Jetting

Roland Berger
Strategy Consultants

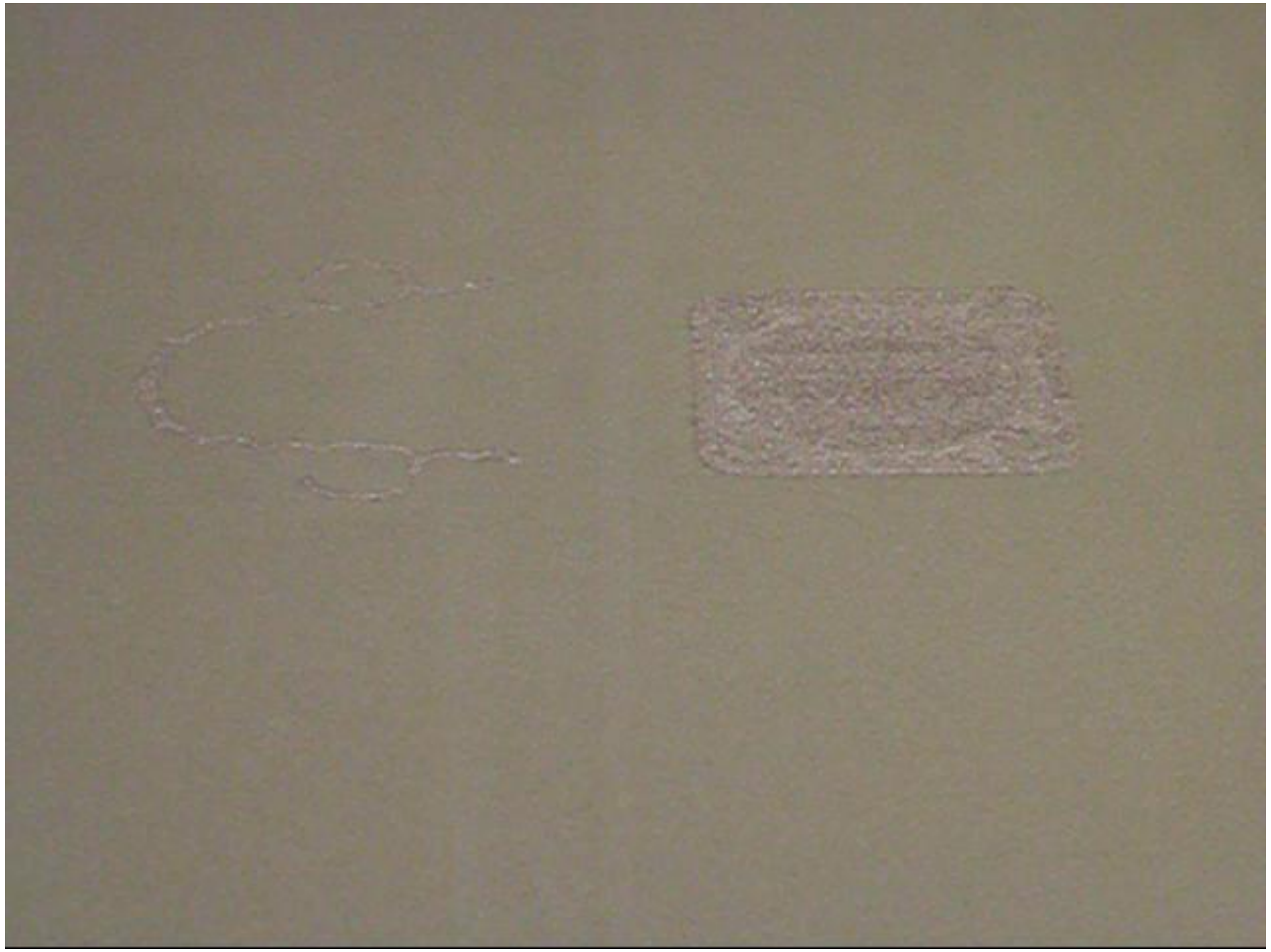
Powder Bed Fusion Processes

- **Laser powder bed fusion:**
  - Laser selectively melts and consolidates fine powder layer-by-layer
  - Systems operate at room temperature under Nitrogen or Argon environment depending on build material.
  - Maximum build chamber size: 31.5”X16”X20”
  - Deposition rate: ~ 0.02- 0.2 lbs/hr
  - Materials: AlSi10Mg,CoCr, Ni alloys, Steels, titanium alloys and some refractory metals.
  - Surface Roughness: 10-20μm Ra



http://cncestablishment.com/category/3d-printing

Powder Bed Fusion Processes



e-Manufacturing Solutions

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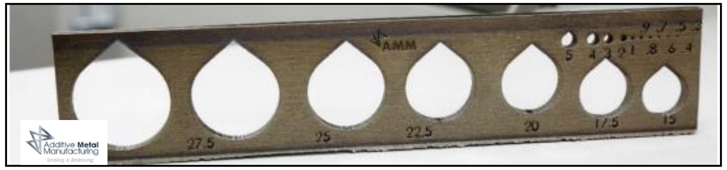
Laser Powder Bed Fusion Processes

- **Design Considerations:**
  - **Overhang features:**
    - Most materials are able to build features 45^0 off vertical.
    - Support structures need to be added for greater overhanging features.
    - Supports not only act as mechanical structures but are required to mitigate internal stress build u in parts
    - Circular/rectangular features can be redesigned into tear drop shape (self-supporting) to avoid use of supports.
  - **Surface roughness:**
    - Surface roughness is dependent on material, layer thickness and part orientation.
    - Vertical side walls usually have a better Ra than horizontal or angular surfaces.



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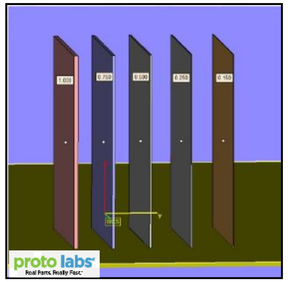
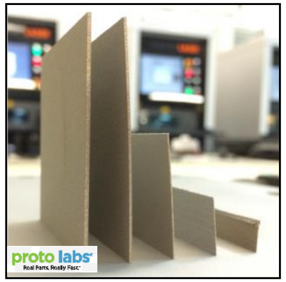
Laser Powder Bed Fusion Processes

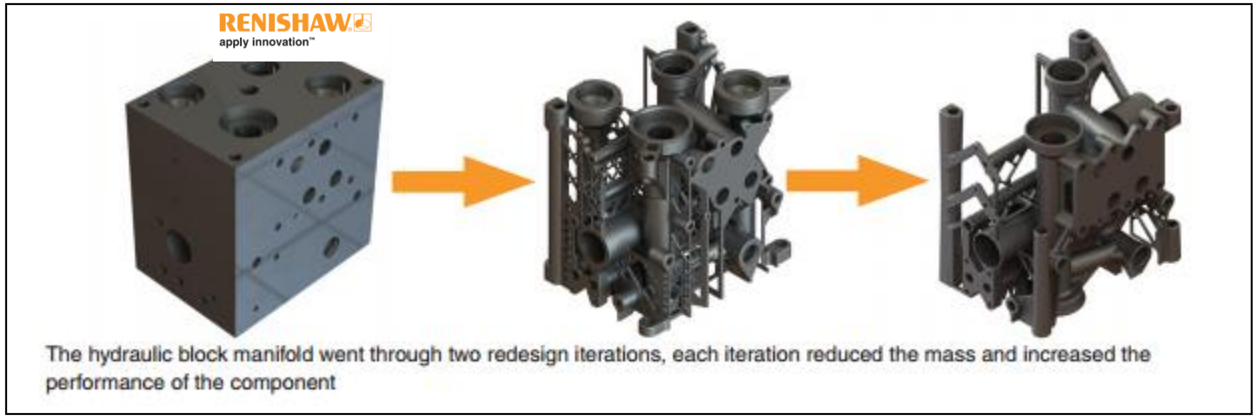
- **Design Considerations:**
  - **Minimum feature size:**
    - The minimum feature size is dependent on the spot size of the laser beam.
    - Best possible spot size is ~50 μm.
    - Important to consider while support removal.
  - **Aspect ratio:**
    - Typically a height to width ratio of 40:1 is considered as a rule of thumb for laser powder bed systems.
  - **Internal channels:**
    - Complex internal channels are possible as long as overhang lengths and self-supporting angles as considered.
    - If channels need support, support accessibility for removal should also be considered.
    - Design should also account for powder removal before stress relief.





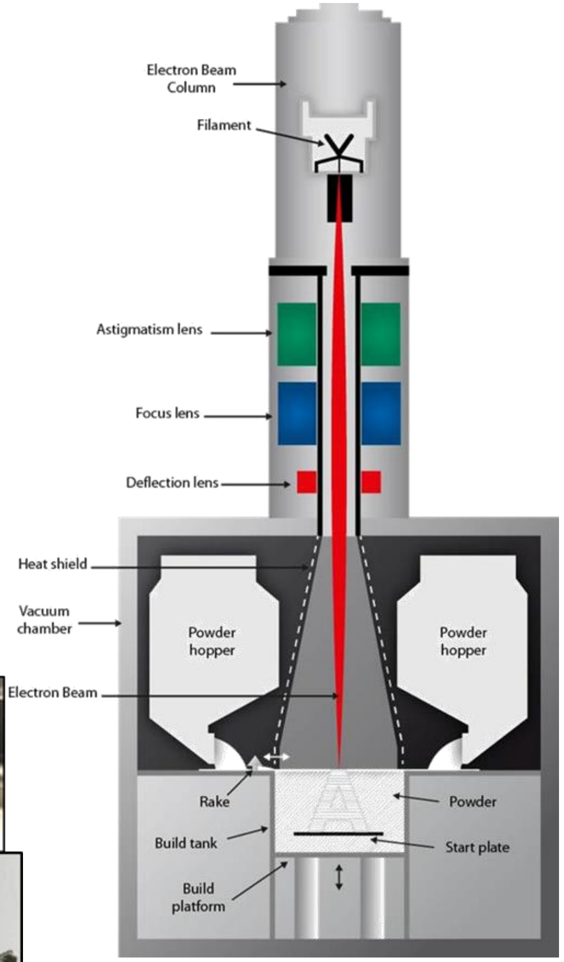
Laser Powder Bed Fusion Processes

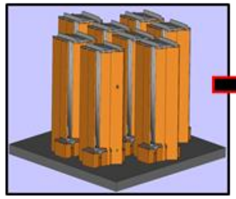
- Some Examples:



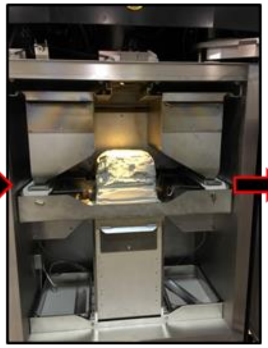
Powder Bed Fusion Processes

- **Electron beam powder bed fusion:**
  - High energy electron beam melt layers of powder to create the desired geometry under controlled vacuum.
  - Maximum build chamber size: 13.7380” dia. X 15” H
  - Deposition rate: ~ 0.1- 0.5 lbs/hr
  - Materials: Titanium alloys, CoCr, Ni alloys, TiAl, Cu, Niobium, Mg, Steels, Nb, Tantalum
  - Surface Roughness: 15-30μm Ra




Build setup in Magics

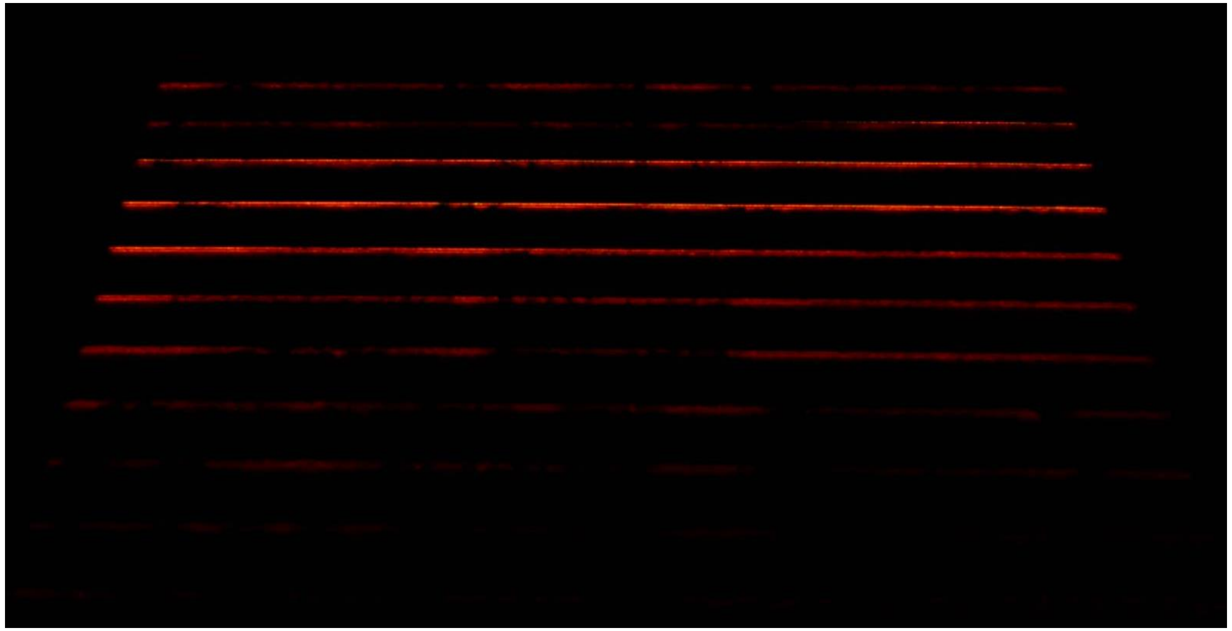

Machine Setup


Build Completed


Powder Recovery System


Final Part

Electron Beam Melting



CAD TO METAL®
Arcam AB®

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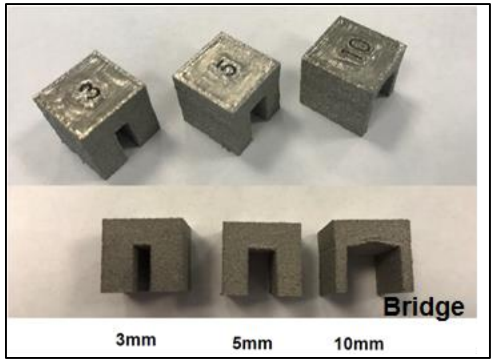
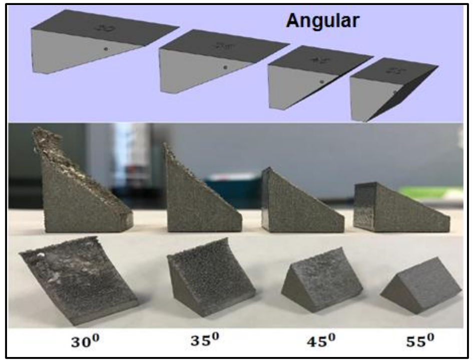
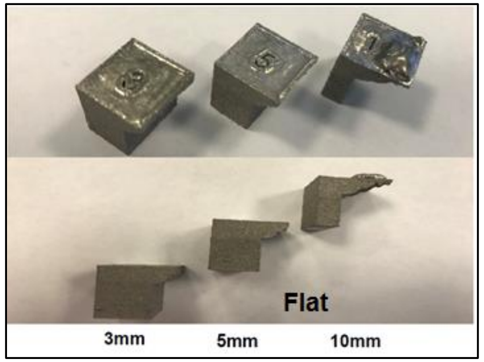
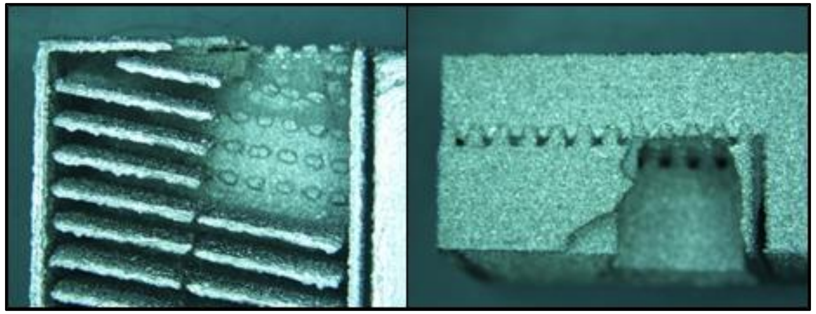
EB Powder Bed Fusion Processes

- **Design Considerations:**
  - **Overhang features:**
    - Most materials are able to build features 45^0 off vertical.
    - Support structures need to be added for greater overhanging features.
    - Most alloys can build with free hanging supports.
    - Surfaces in contact with support have bad surface quality.

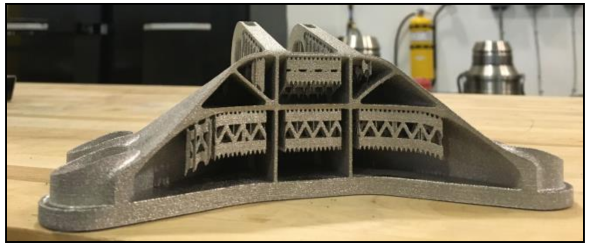








Surface in contact with supports



Free hanging supports

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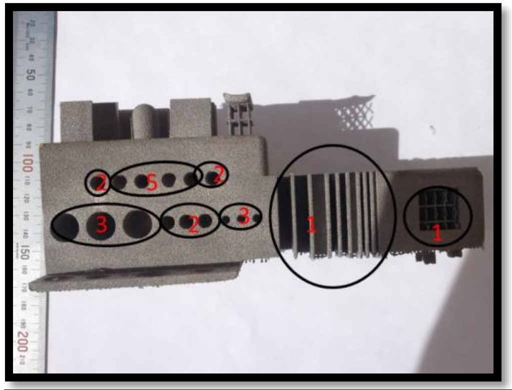
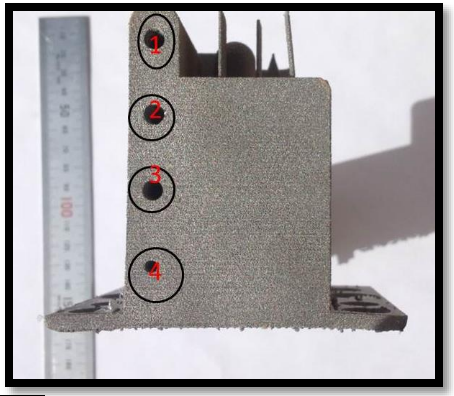
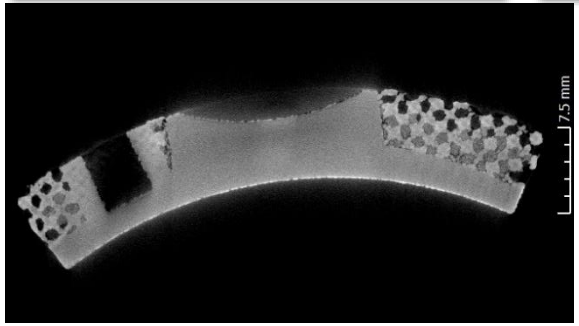
EB Powder Bed Fusion Processes

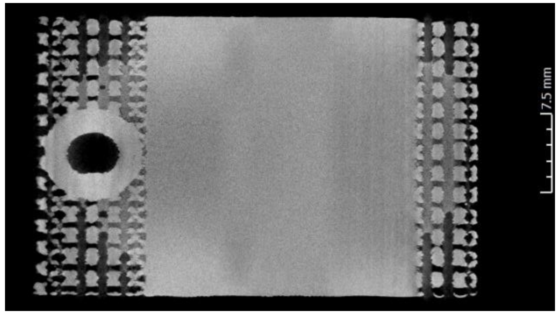
- **Design Considerations:**
  - **Semi-sintered powder removal:**
    - Powder removal becomes difficult in case of mesh structures, blind holes and internal channels.
    - Pore size of ~ 400 μm is possible
    - It is dependent on the depth and size of the feature.





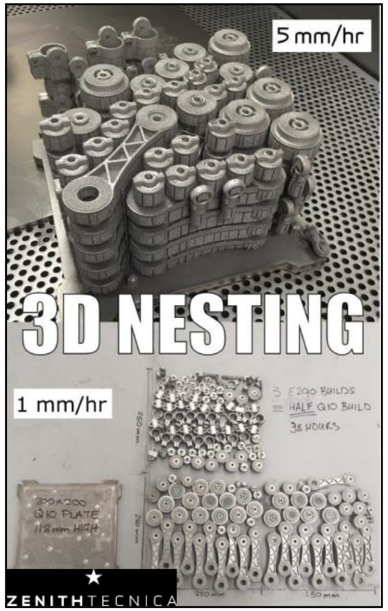
Difficulty scale
1-very easy (PRS)
2- easy (PRS)
3-medium
4-hard
5-very hard

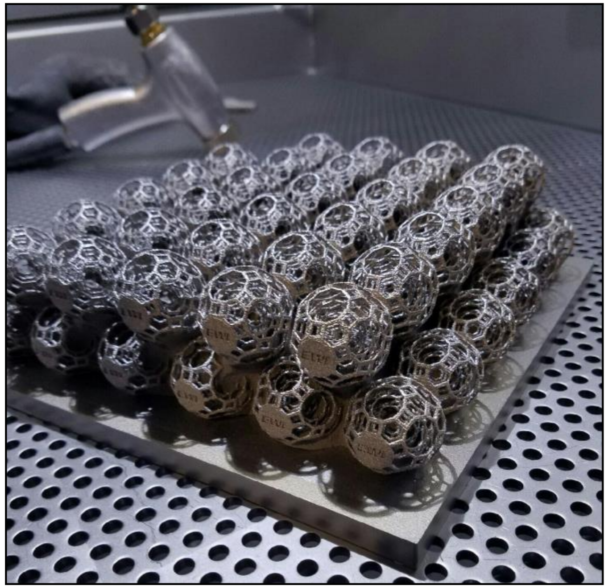




Powder Bed Fusion Processes

- **Design Considerations:**
  - **Part nesting:**
    - EBM technology allows us to stack parts through out the height of the build chamber.
    - Ensure that parts are in contact with each other through supports
    - Distribute parts evenly across a the build plate to avoid heat build up and deformation.





Part Nesting

Heat build up

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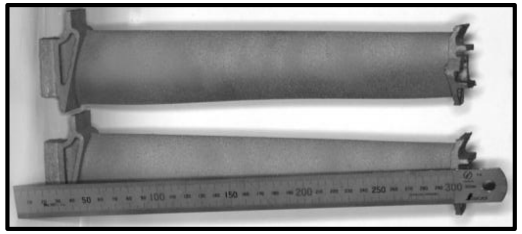
Powder Bed Fusion Processes

- **Some Examples:**

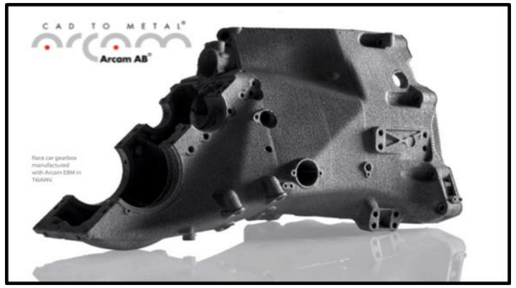


Turbine blades

Adler Ortho, IT
(2007)

Lima, IT
(2007)

Acetabular cups with trabecular structures



Race car gear box

Housing combining lattice structures and solid sections

Custom cranial implant

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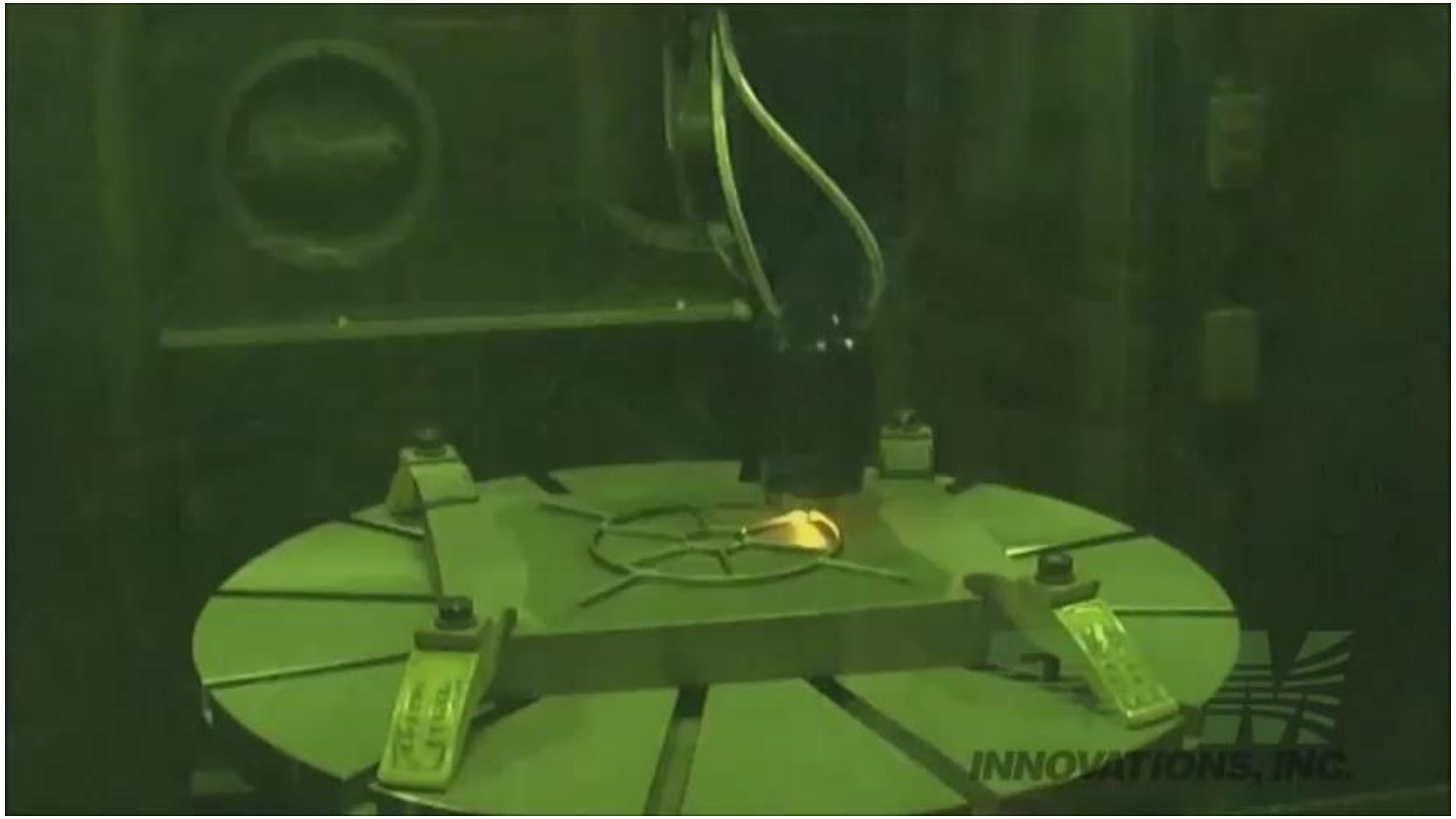
Direct Energy Deposition Processes

- **Laser Direct Energy Deposition:**
  - High power laser is fired at a target to create a localized melt pool.
  - A stream of metal powder is delivered into the melt pool and a weld bead is created.
  - Maximum build chamber size:
    - 5’X5’X7’
  - 5 axis motion – non coordinated motion
  - Deposition rate: ~ 5 lbs/hr
  - Materials:
    - Titanium alloys, steel alloys, aluminum, nickel alloys, cobalt alloys, tungsten carbide
  - Surface Roughness
    - ~30 μm+

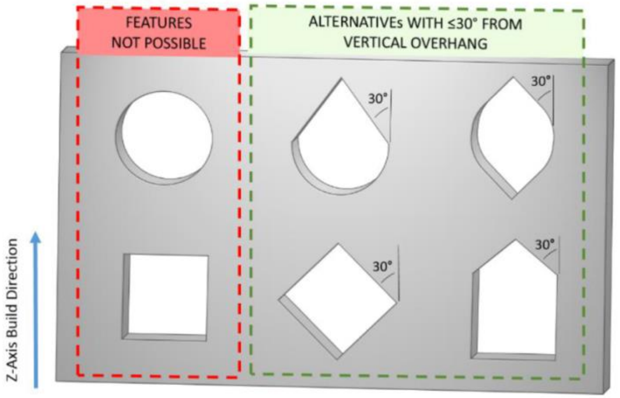
RPM Innovation

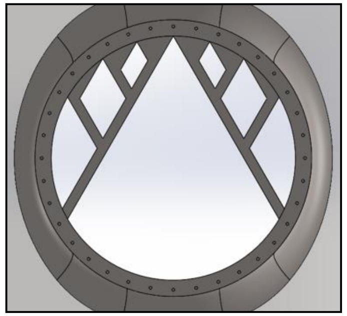


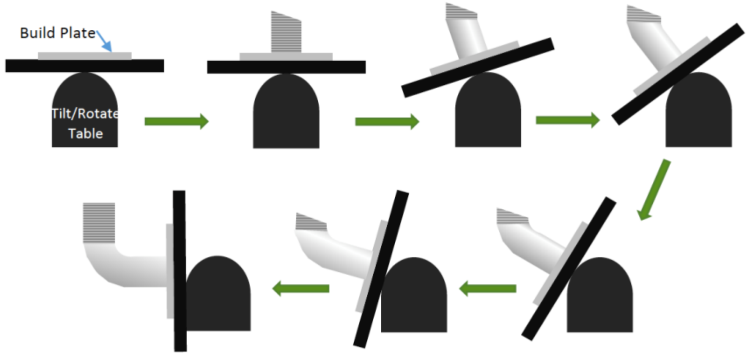
RPM INNOVATIONS, INC.

Laser Direct Energy Deposition Processes

- **Design Considerations:**
  - Holes and channels:
    - Holes and channels normal to the build direction need to be modified to tear drop, lemon shaped, diamond shaped or by adding angled support into the design.
  - Ducts:
    - Bend-like features are made possible by utilizing the tilt/rotate table in incremental steps.
    - Each section is designed as a separate CAD file.







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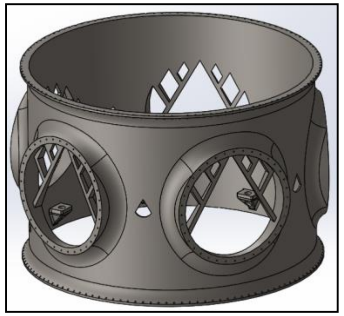
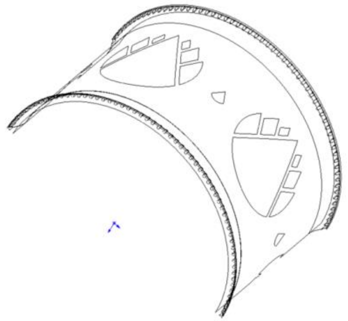
Laser Direct Energy Deposition Processes

- **Design Considerations:**
  - The technology favors thin walled parts.
  - Single walled parts have to be redesigned as surface models.
  - Different features of the part require different parameters and thus have to designed as separate files and arranged accordingly.
  - Additional supporting structures need to be added to the part to minimize part distortion due to stresses.

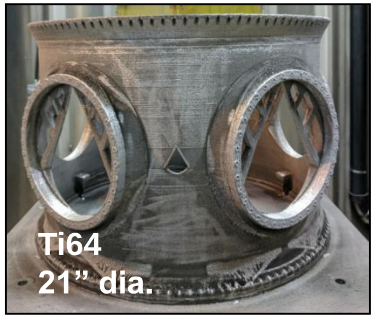
Secondary payload adapter



Modified part



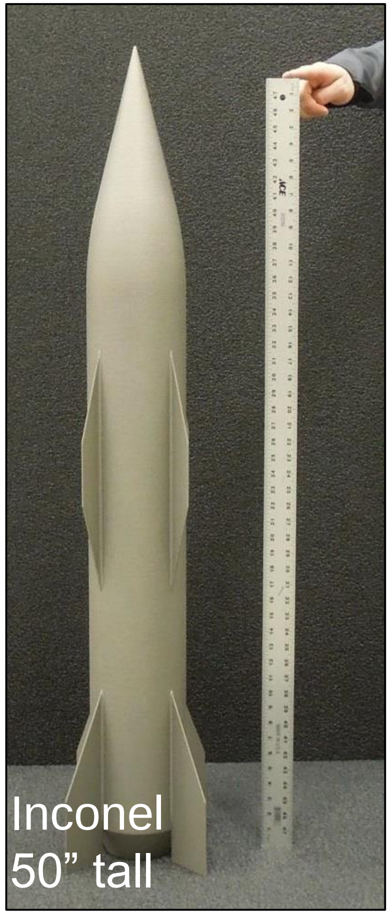
Surface Model

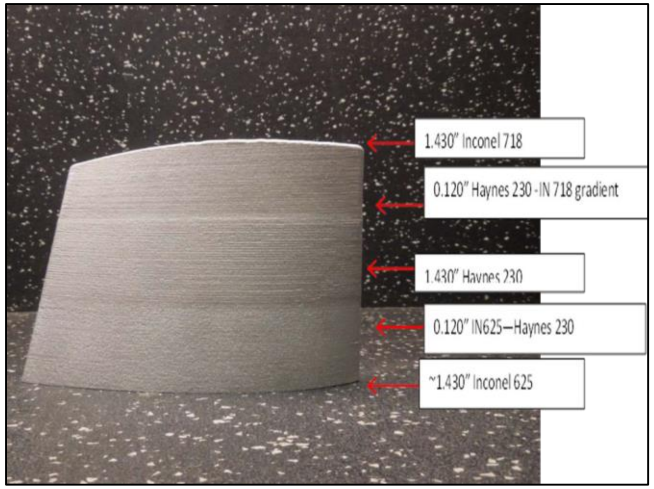


Final part

Laser Direct Energy Deposition Processes

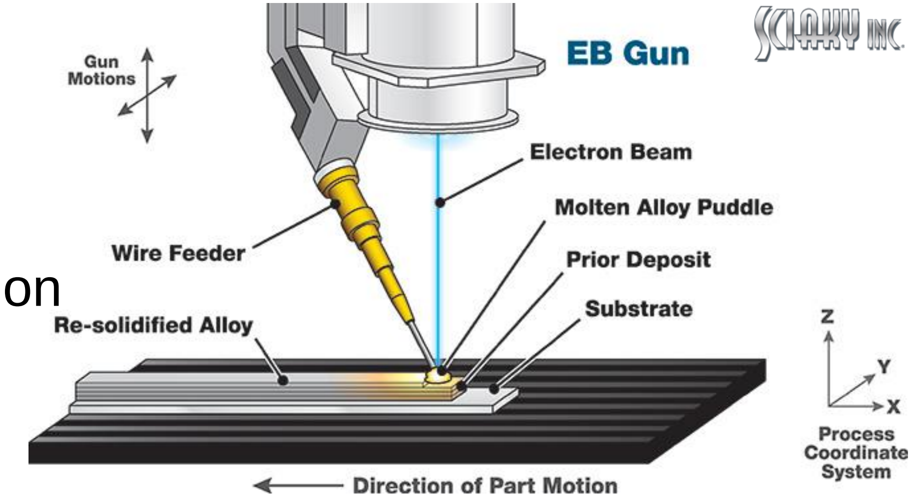
- **Some Examples :**





Direct Energy Deposition Processes

- **Electron Beam Direct Energy Deposition:**
  - Wire fed DED process derived from EB welding.
  - Near net shape manufacturing
  - Maximum build chamber size:
    - 8.8'X4'X5'
  - 5-7 axis motion coordinated motion
  - Deposition rate: 7-20 lbs/hr
  - Materials:
    - Titanium alloys, Nickel alloys, Tantalum, Tungsten, Niobium ,Stainless Steels, Aluminum (2310,4043),Magnesium
  - Surface Roughness
    - Irrelevant for near net shape



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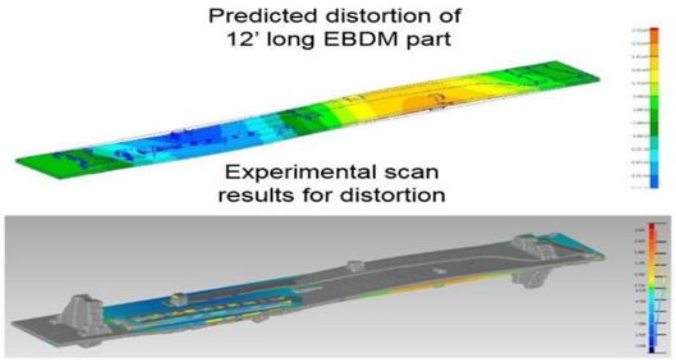
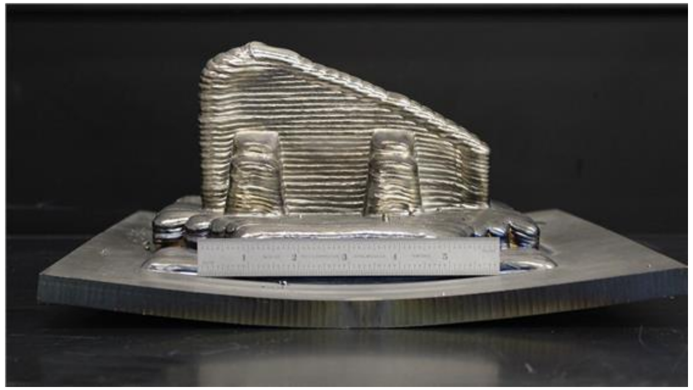
EB Direct Energy Deposition Processes

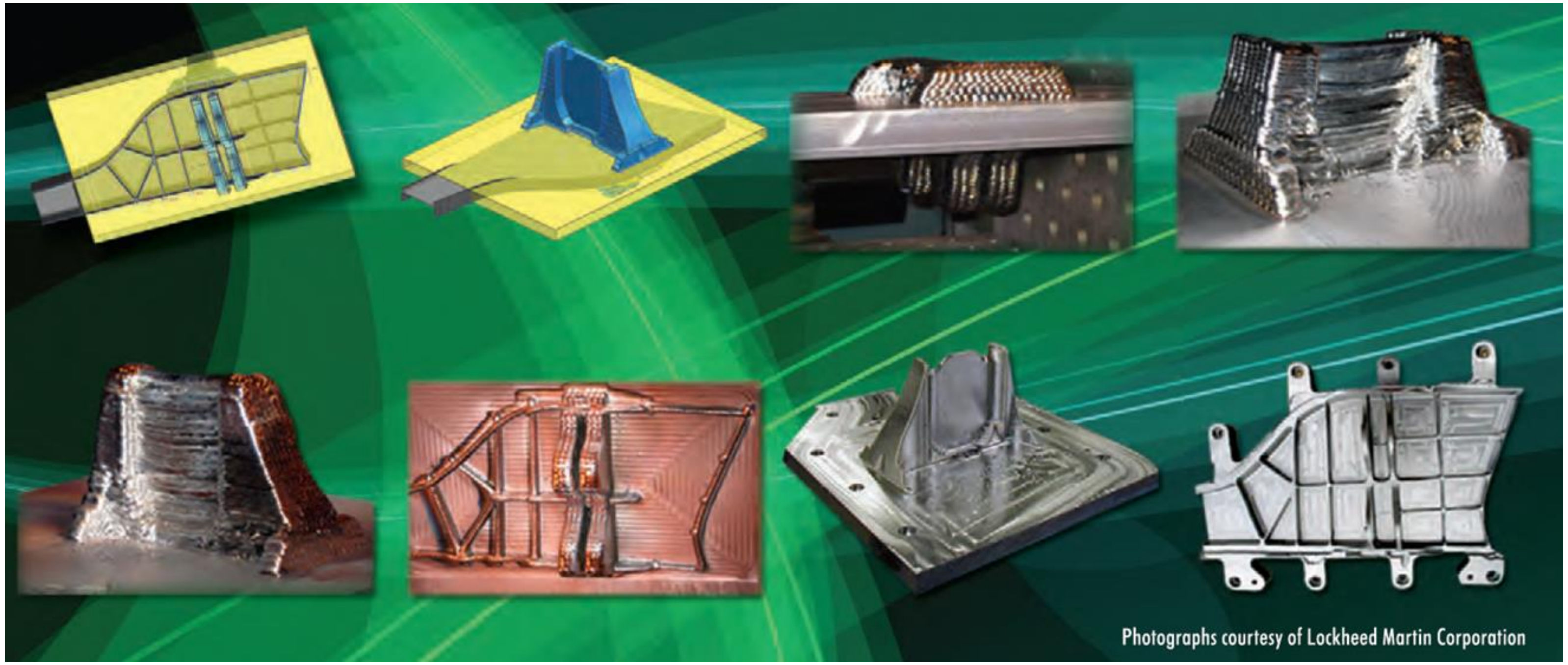
- **Design Considerations:**
  - **Overhanging features:**
    - All tool path must be supported by either the substrate or a previous deposit.
    - This limitation can be compensated for through 4+ Axis part manipulation, and / or secondary set-up operations.
  - **Feature size v/s deposition rate:**
    - Increase in deposition rate (wire size, travel speed) = decrease in feature resolution
  - **Thermal Distortion**:
    - High deposition rates and large melt pools generate significant thermal stresses which require substrate and fixture considerations in some circumstances





EB Direct Energy Deposition Processes

- **Design Considerations:**
  - **Time / material constraint:**
    - Limit of filament life is approximately 9hrs
    - Limit to material that can be placed on a spool / in the chamber for deposition



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EB Direct Energy Deposition Processes

- Sample Examples:

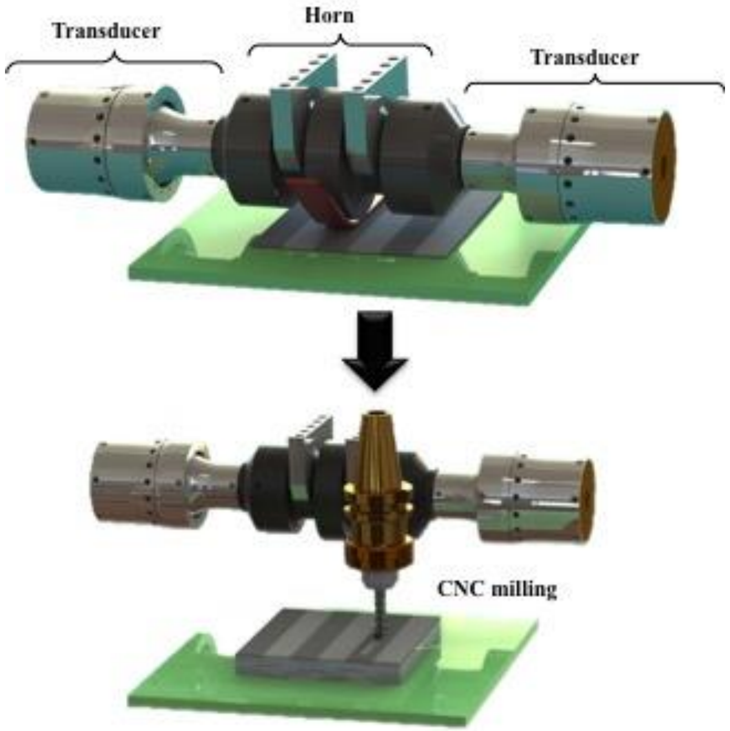
Satellite propellant tank
~60" dia.

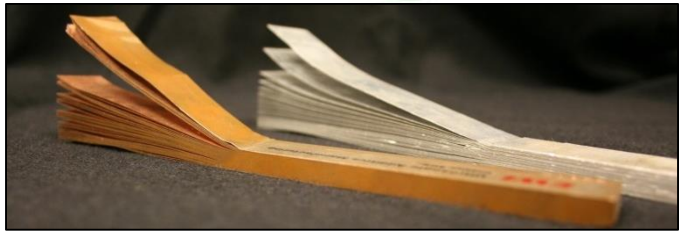
Variable ballast tank

Airbus rear upper spar

Sheet Lamination

- **Ultrasonic Additive Manufacturing**
  - A solid state bond is created between metal foils by using high frequency sound waves.
  - Waves are transmitted through a steel ‘horn’ causing the metal foils to vibrate and exposes the virgin material on the face of the foil creating a solid state bond.
  - Embedding electronics and sensor
  - Maximum build chamber size:
    - 6’X6’
  - Materials:
    - Steels, Aluminum, Nickel alloys, precious metals





FABRISONIC

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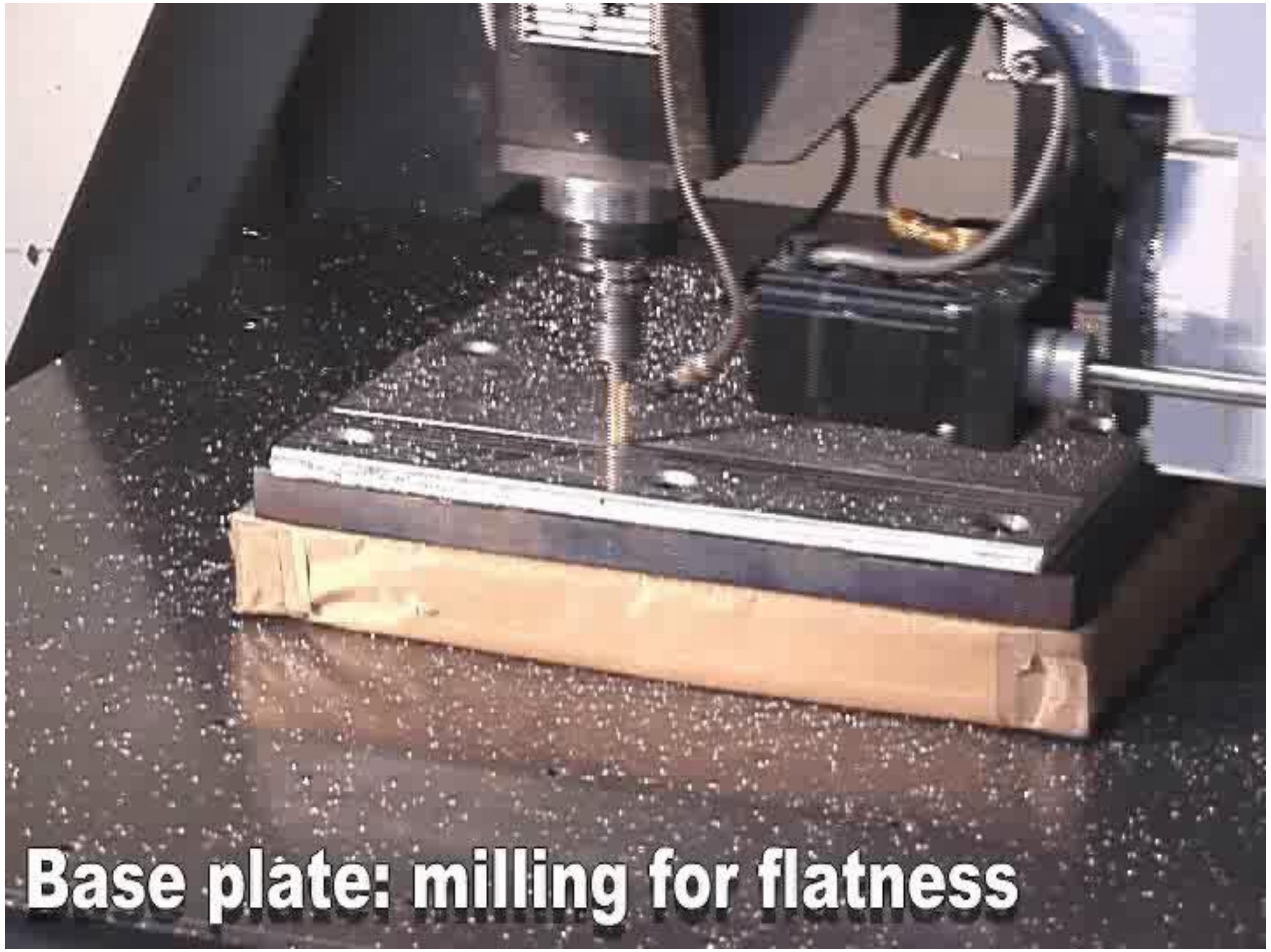
Ultrasonic Consolidation Process



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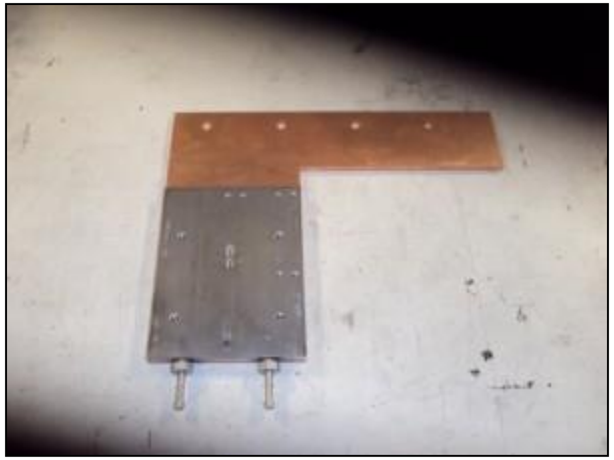
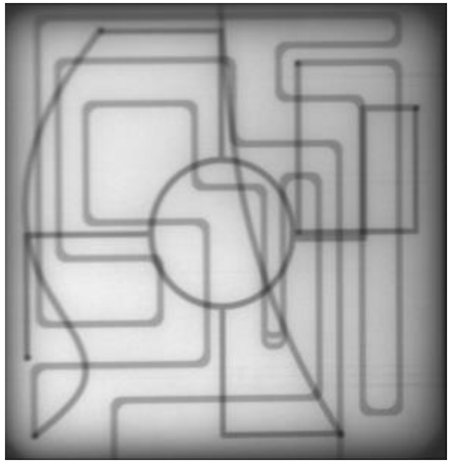
Sheet Lamination

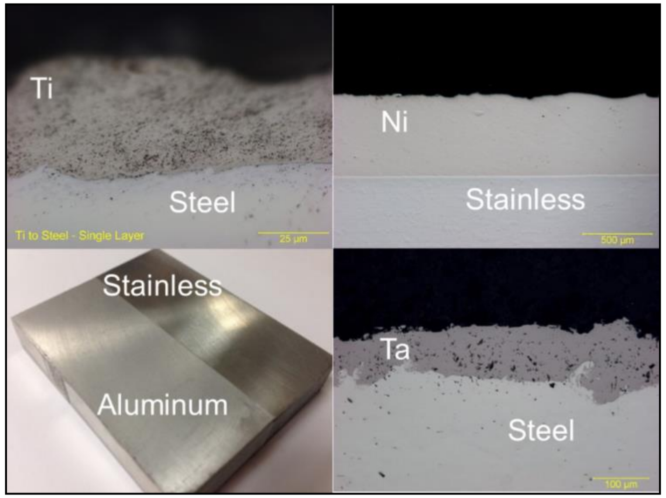
- Some Examples:



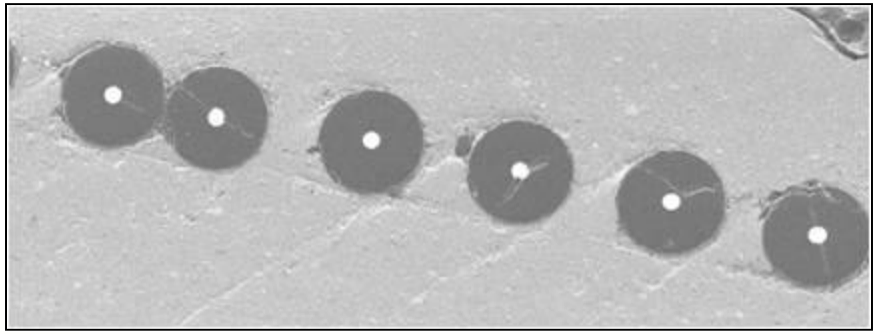
Multi-material heat exchanger



x-ray image of complex internal flow paths



Dissimilar metals joining



SiC fibers in aluminum laminate

FABRISONIC

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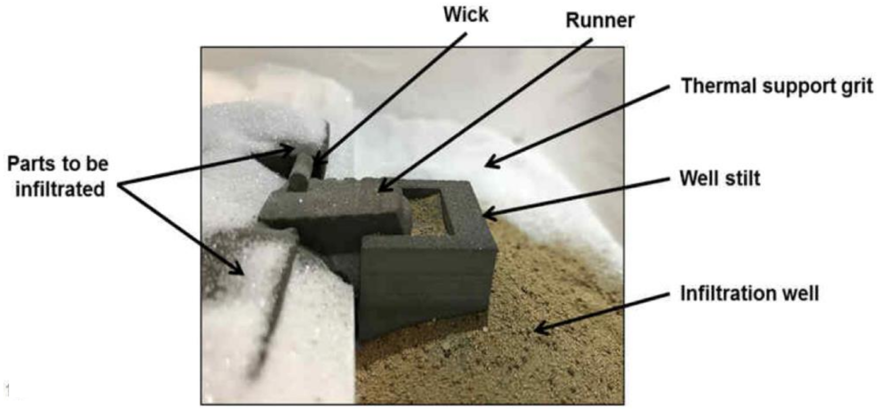
Binder Jetting

- **Binder jetting :**
  - Liquid binder is deposited on metal powder layers as per the desired geometry to set the part together.
  - This part is then cured followed by either direct sintering or infiltration to get the final part.
  - Maximum build chamber size: 31”X19”X15”
  - Materials: Steels, Ni alloys, Tungstens, Sand, Ceramics, CoCr, Iron, Carbon, SiC
  - Surface finish: ~15 μm



Infiltration process

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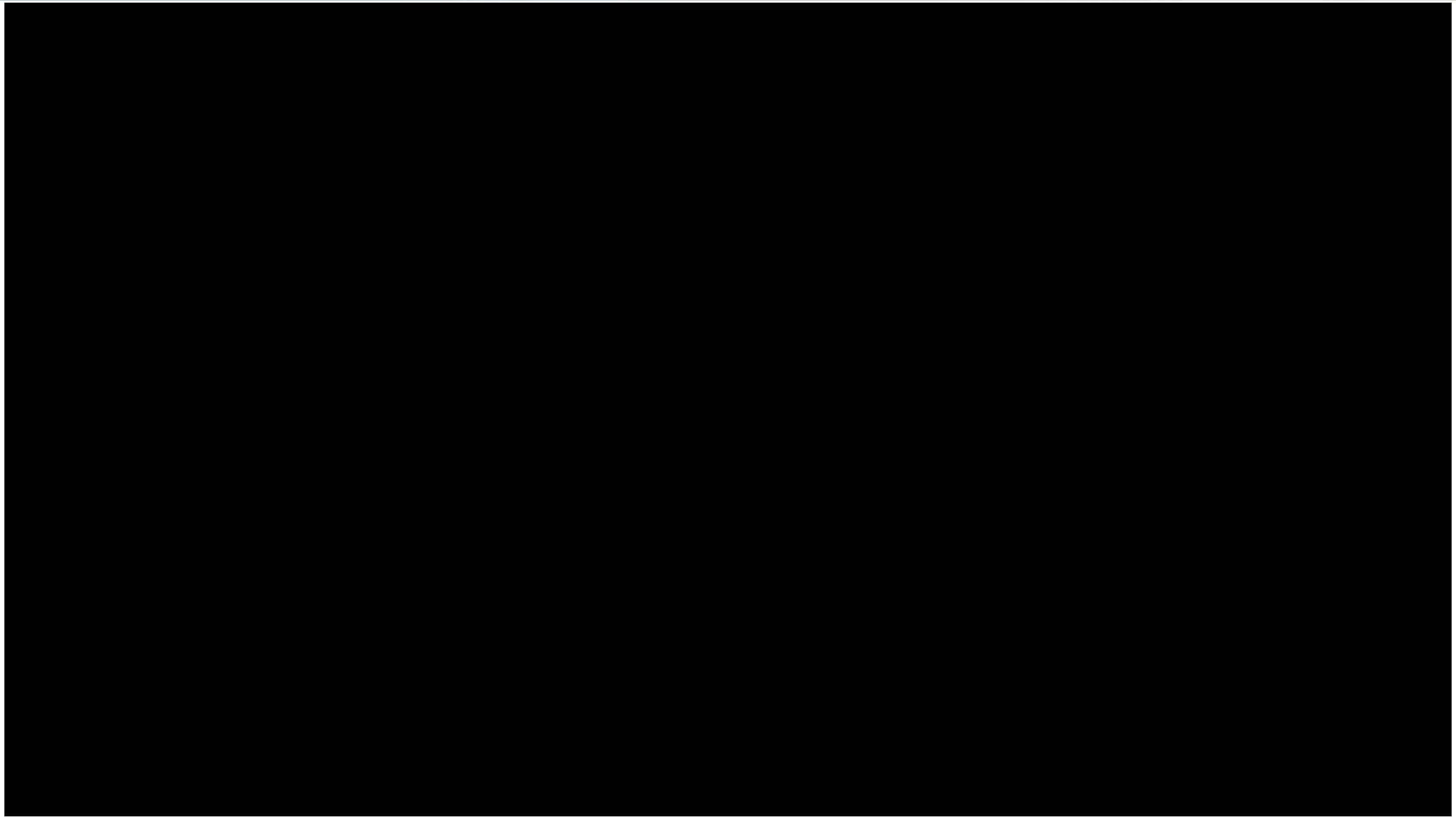
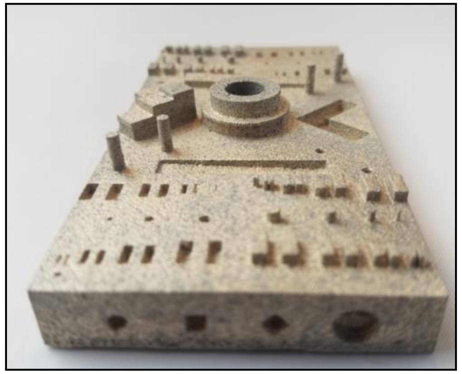
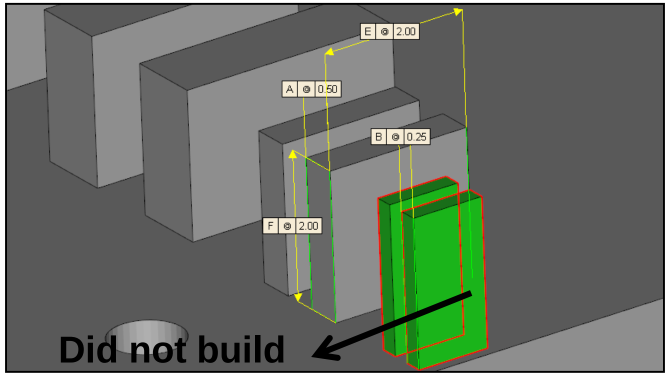
Binder Jetting

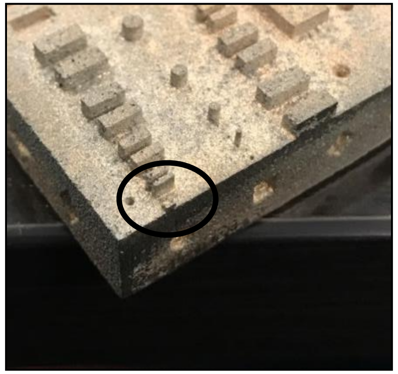


Binder Jetting

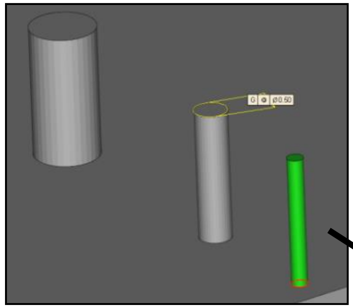
- **Design Considerations:**
  - **Overhanging feature**:
    - Can build overhanging features without support structures
  - **Minimum feature size**:
    - Minimum wall thickness of >0.5 mm can be built and infiltrated



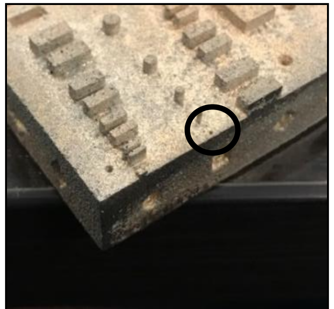




    - Minimum cylindrical feature >0.5 mm dia. can be built and infiltrated



Did not build



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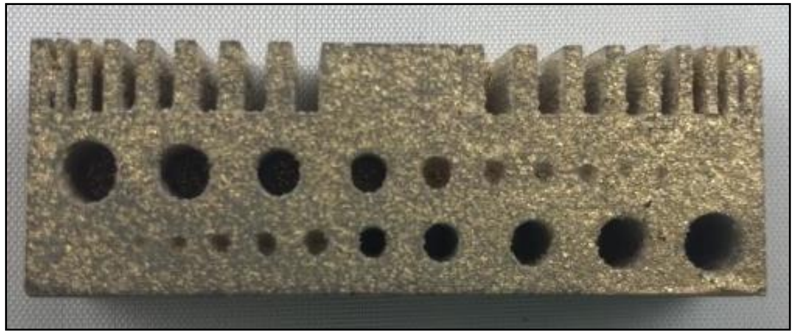
Binder Jetting

- **Design Considerations:**
  - **Wick and Runner design**
    - In case of infiltration, the wick and runner could be designed into the part itself.
  - **Minimum feature size**:
    - Minimum through hole > 2.5mm, blind hole > 3mm and min. gap between walls >1mm can be built after infiltration.
    - These values are also dependent on the size of thermal support grit used during infiltration.



  - **Shrinkage factor:**
    - Incase of direct sintering, shrinkage has to be accounted for during sintering based on the build material.

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Binder Jetting

- Some Examples:

Prosthetic hand
Stainless steel/bronze matrix

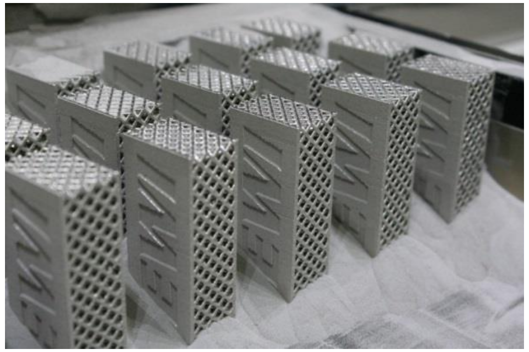
Stator(3”- 5”)
Stainless steel/bronze matrix

Strainer plates

Overall Summary & Conclusions

- **Metal Part Manufacture is now possible using many different AM techniques**
  - Tooling and Metal Part prototyping are common applications
  - Direct Manufacturing of Novel Designs, Compositions and Geometries is being actively pursued
  - Direct approaches are becoming increasingly available and reliable, but remain expensive for many types of geometries and volumes
  - Knowing the technology limitations is a good key for success

Questions



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