



Selecting the Correct Material and Technology for Metal AM Applications

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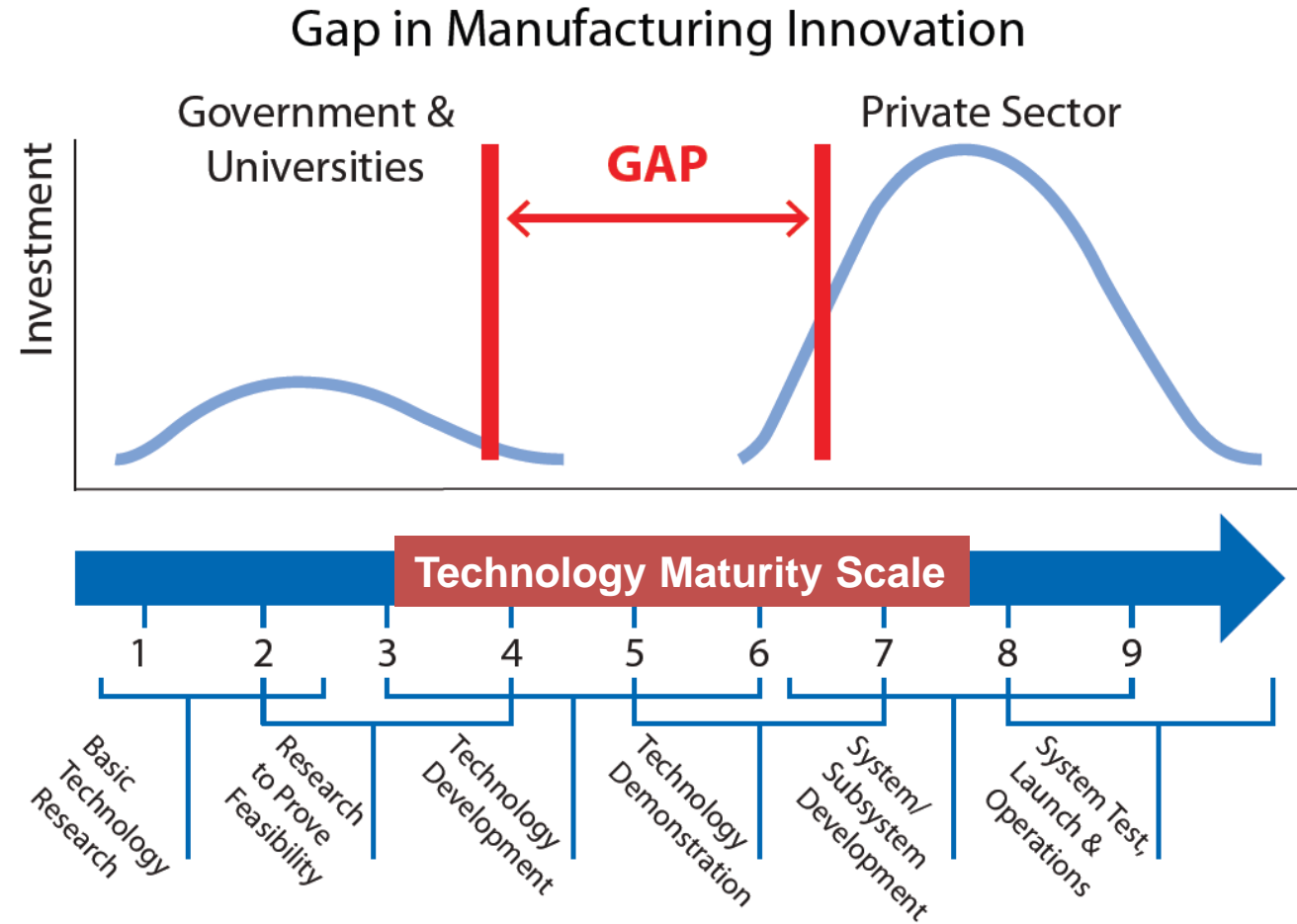
About EWI



- ◆ **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)

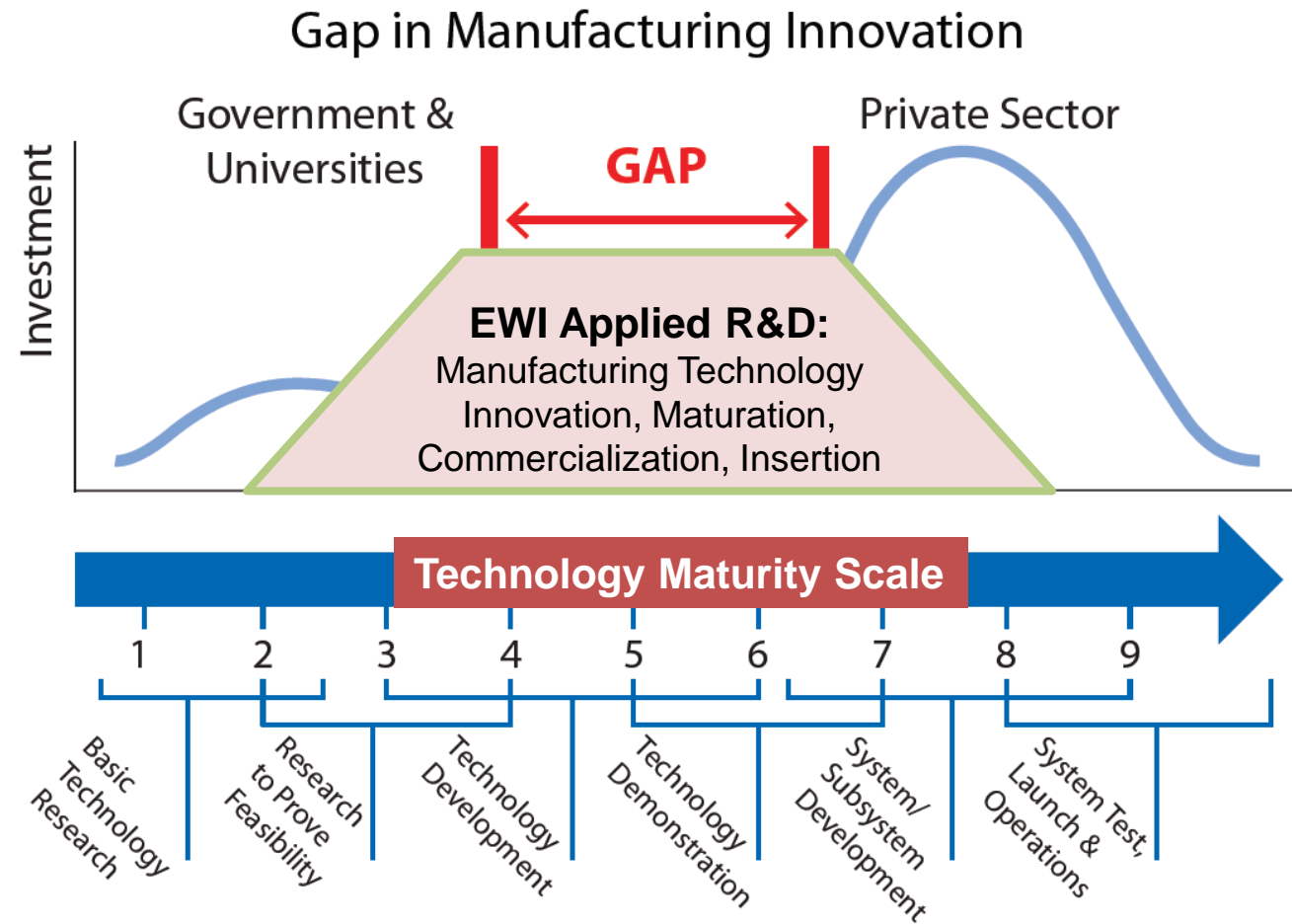


Structural Gap between Research and Application



Source: NIST AMNPO presentation Oct. 2012

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



Source: NIST AMNPO presentation Oct. 2012

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



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



1984 Columbus OH:

Joining, forming, metal additive mfg,
materials characterization, testing



2015 Buffalo NY:

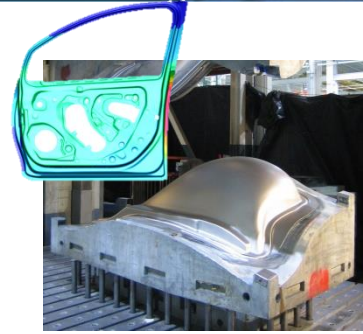
Agile automation, machining, metal
additive mfg, metrology



Growing Range of Cross-Cutting Manufacturing Technologies



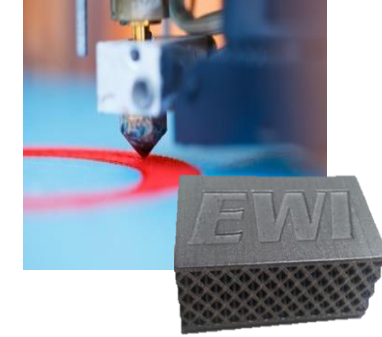
***Materials
Joining***



Forming



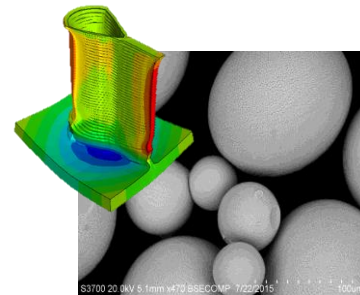
***Machining &
Finishing***



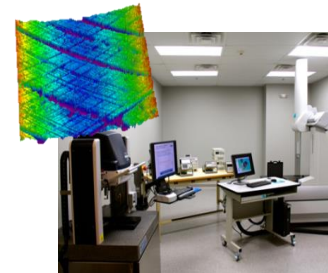
***Additive
Manufacturing***



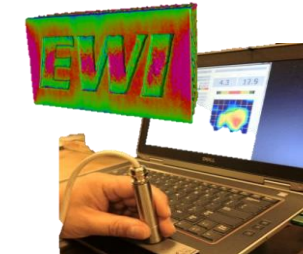
***Agile
Automation***



***Applied Materials
Science***



***Testing &
Characterization***



***Quality
Measurement***

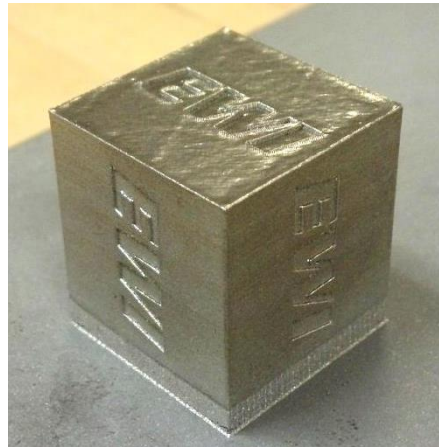
AM is Materials Joining

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



675 feet of weld
(Audi R8)

1-inch L-PBF Cube

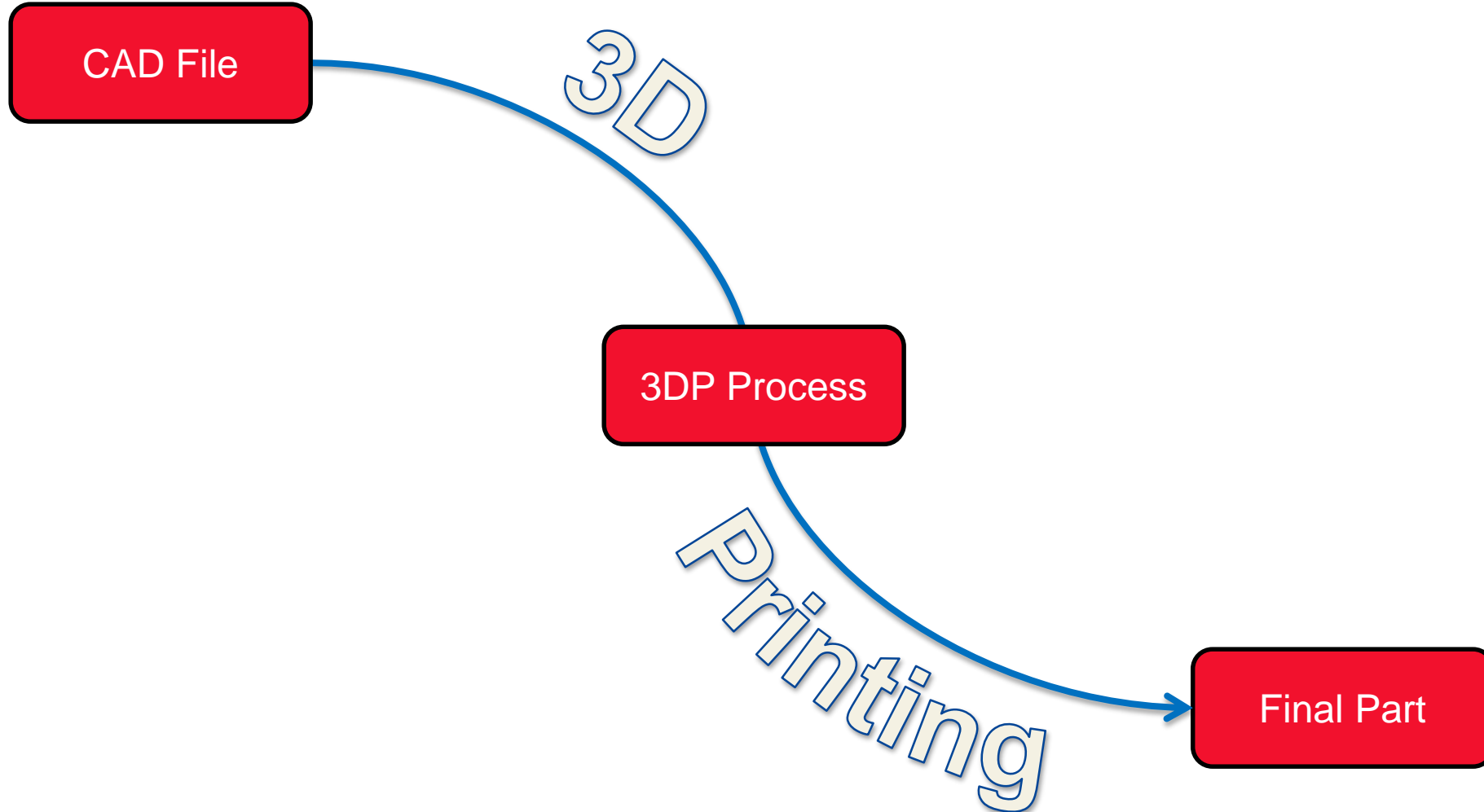


5 miles of weld

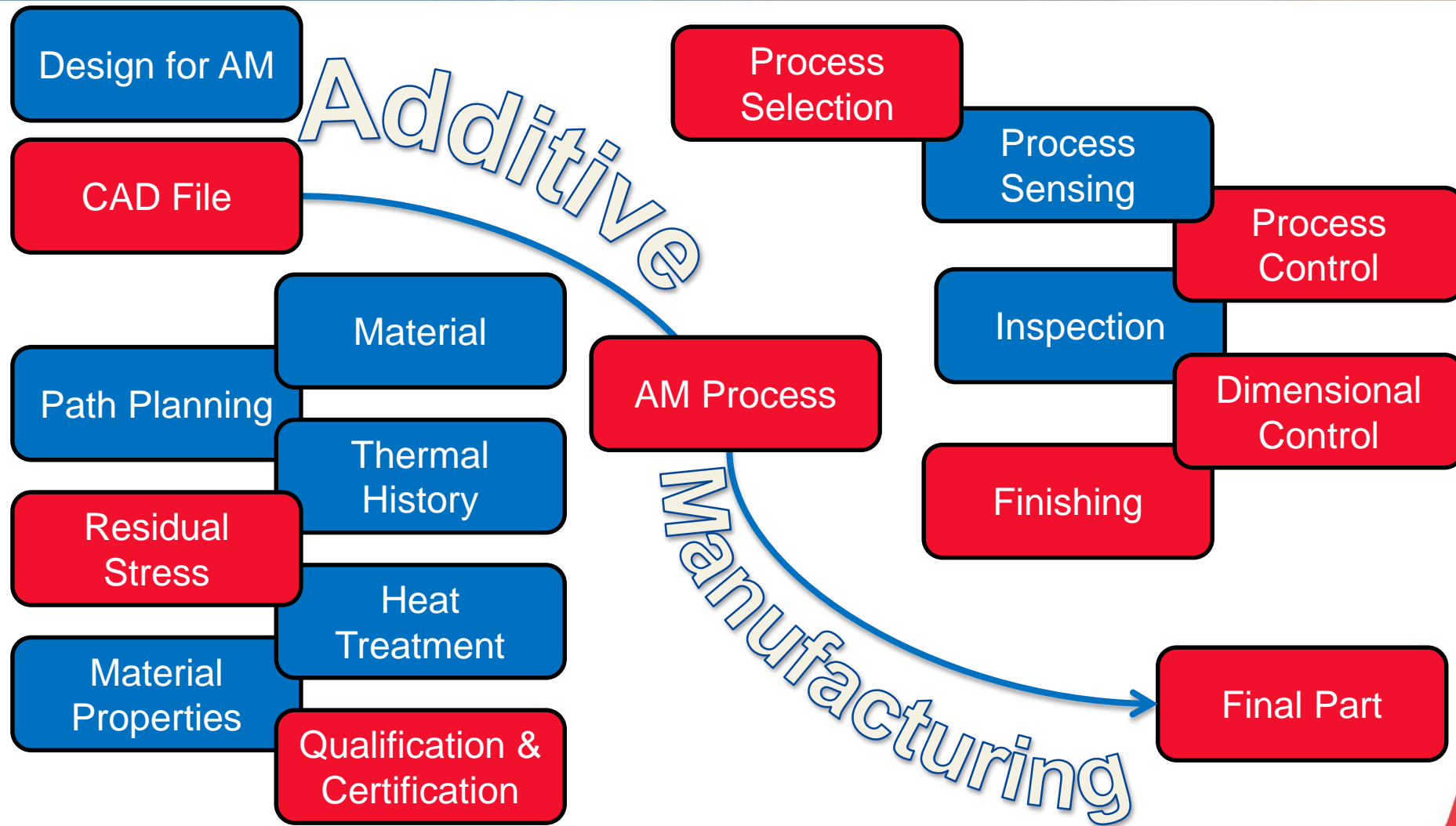


3,400 feet of weld

A Holistic View of Additive Manufacturing Process Chain



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

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



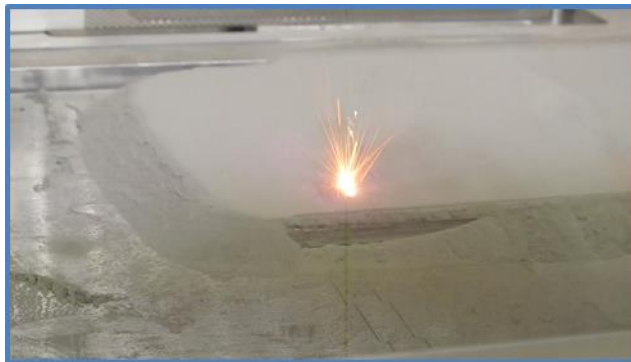
Electron Beam PBF
Arcam A2X



Laser DED
RPM 557



Laser PBF – Open Architecture
EWI-Designed and Built



Sheet Lamination UAM
Fabrisonic



Electron Beam DED
Siacky EBAM 110



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:

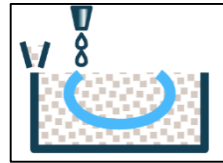
Technical Committee F42 on Additive Manufacturing



**Vat Photo-
polymerization**



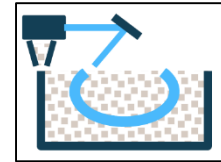
**Material
Jetting**



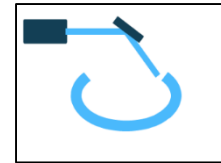
**Binder
Jetting**



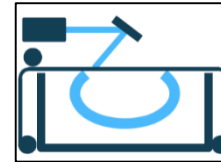
**Material
Extrusion**



**Powder Bed
Fusion**



**Directed Energy
Deposition**

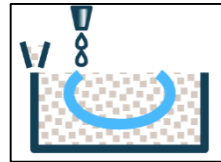


**Sheet
Lamination**

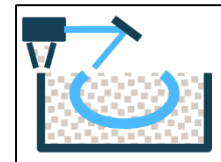
Types of Additive Manufacturing

ASTM International:

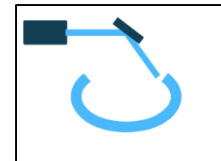
Technical Committee F42 on Additive Manufacturing



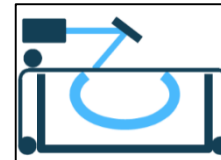
**Binder
Jetting**



**Powder Bed
Fusion**



**Directed Energy
Deposition**

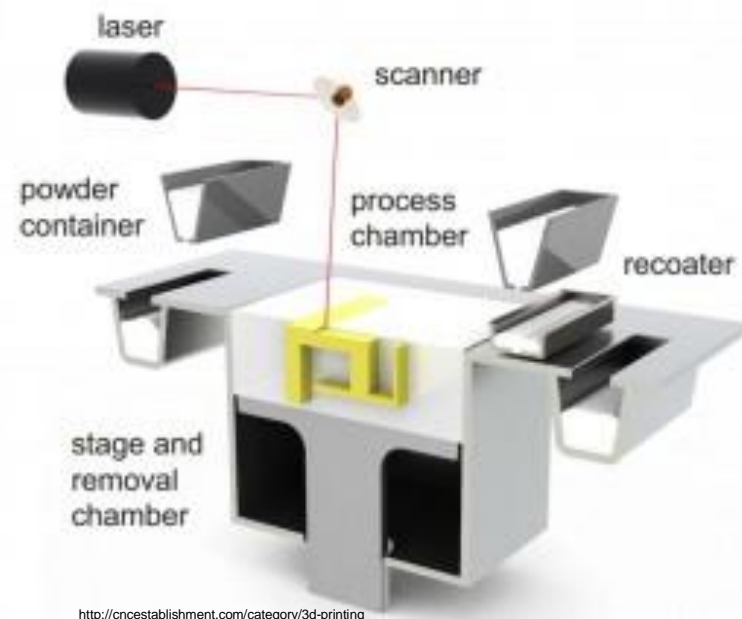


**Sheet
Lamination**

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: 10-20 μm Ra



Powder Bed Fusion Processes



e-Manufacturing Solutions

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Laser Powder Bed Fusion Processes

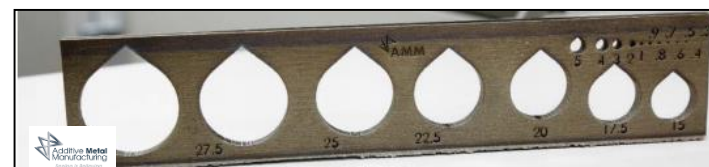
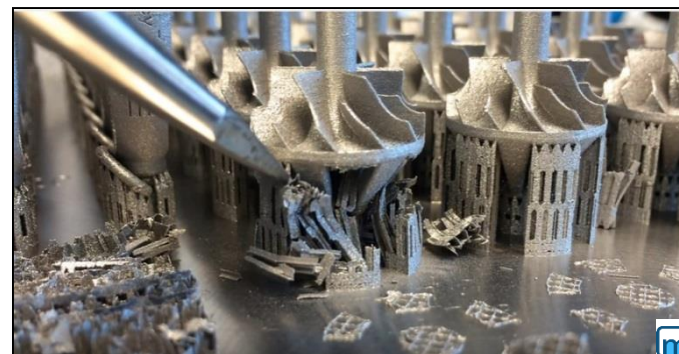
◆ Design Considerations:

— Overhang features:

- Most materials are able to build features 45° 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 up 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.



Laser Powder Bed Fusion Processes

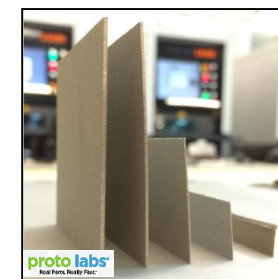
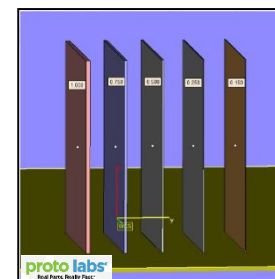
◆ Design Considerations:

— Minimum feature size:

- The minimum feature size is dependent on the spot size of the laser beam.
- Best possible spot size is $\sim 50 \mu m$.
- 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.



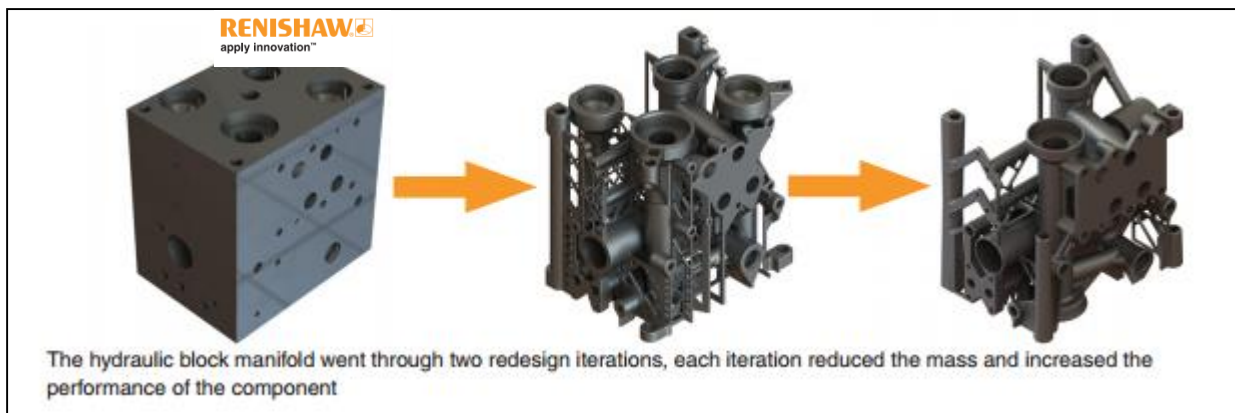
— Internal channels:

- Complex internal channels are possible as long as overhang lengths and self-supporting angles are 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

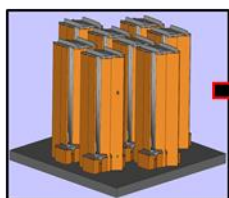
◆ Some Examples:



Powder Bed Fusion Processes

◆ Electron beam powder bed fusion:

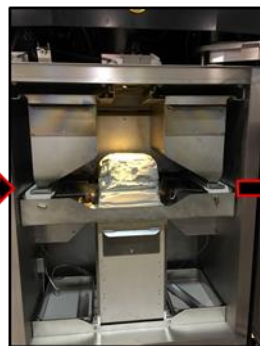
- High energy electron beam melt layers of powder to create the desired geometry under controlled vacuum.
- Maximum build chamber size: 13.7380" dia. X 15" H
- Deposition rate: ~ 0.1- 0.5 lbs/hr
- Materials: Titanium alloys, CoCr, Ni alloys, TiAl, Cu, Niobium, Mg, Steels, Nb, Tantalum
- Surface Roughness: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



Build setup in
Magics



Machine Setup



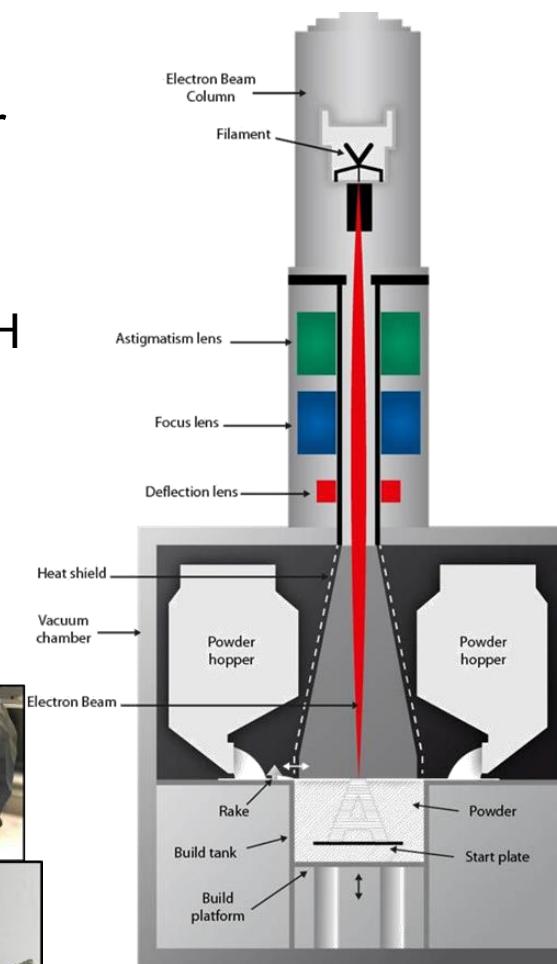
Build Completed



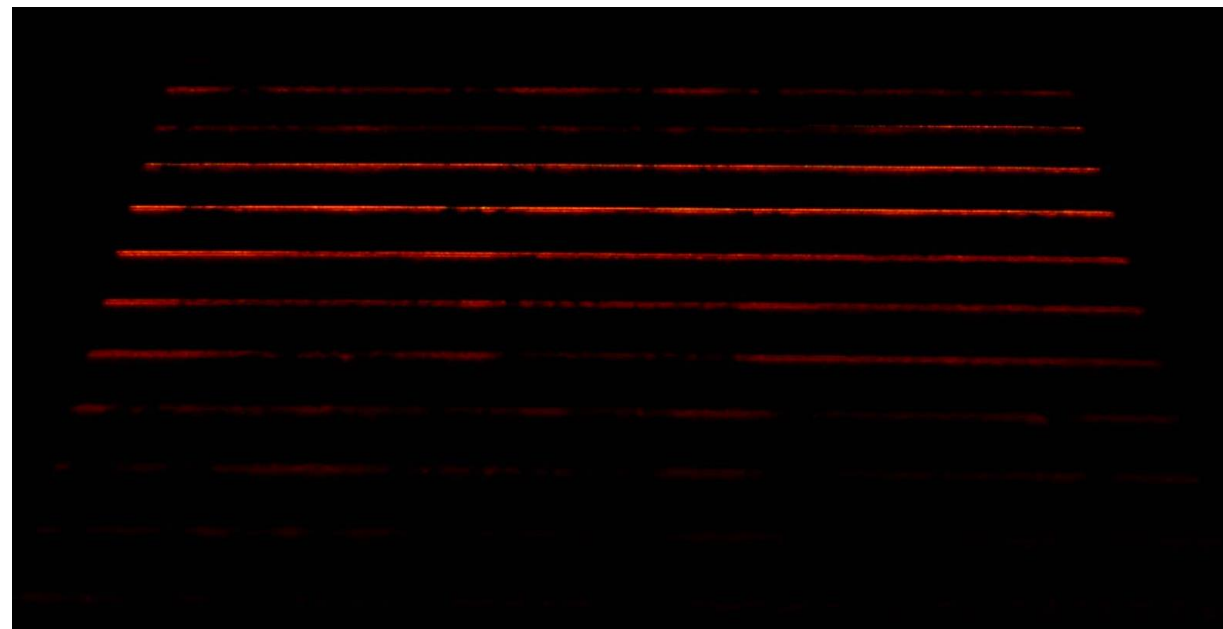
Powder Recovery
System



Final Part



Electron Beam Melting

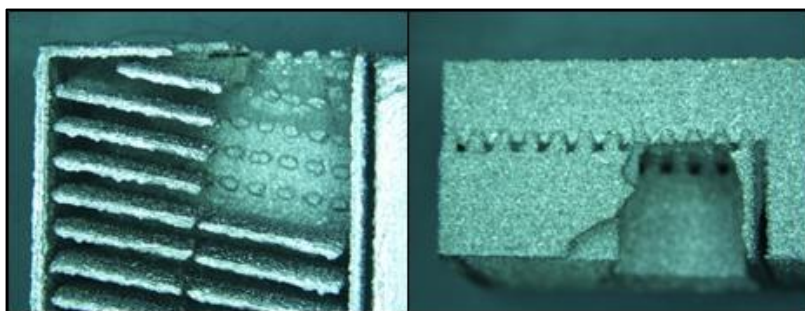
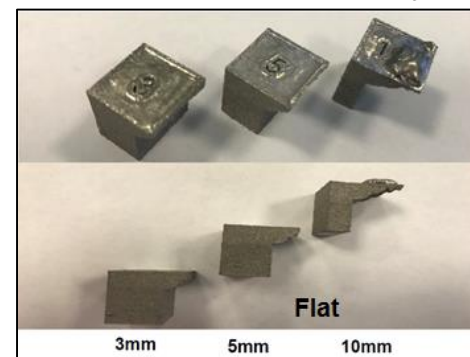
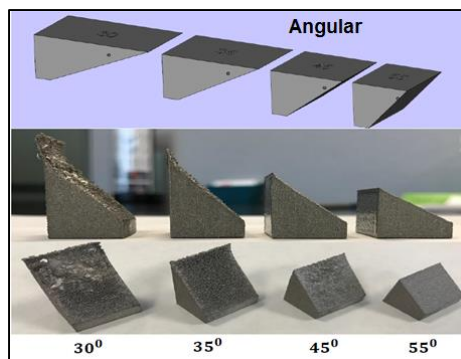
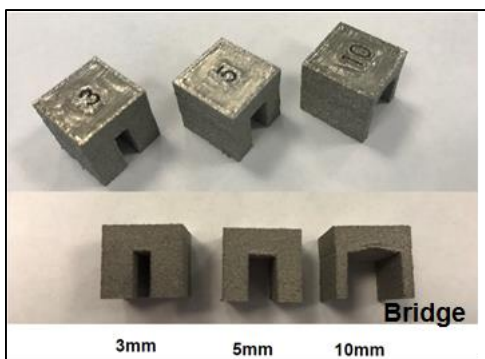


EB Powder Bed Fusion Processes

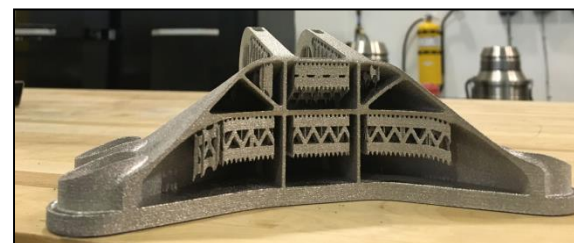
◆ Design Considerations:

— Overhang features:

- Most materials are able to build features 45° 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



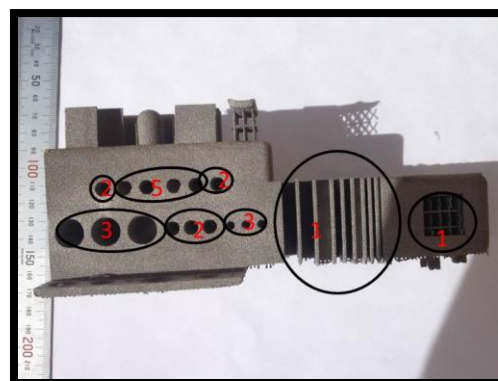
Free hanging supports

EB Powder Bed Fusion Processes

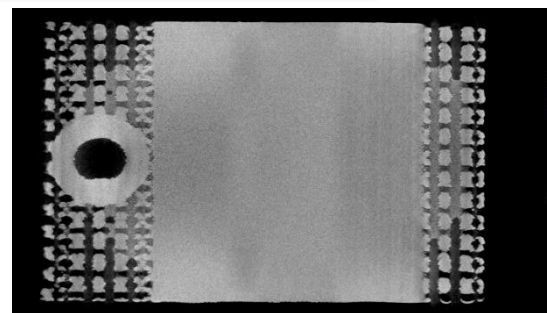
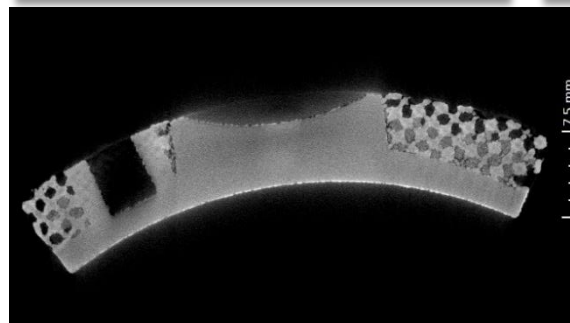
◆ Design Considerations:

— Semi-sintered powder removal:

- Powder removal becomes difficult in case of mesh structures, blind holes and internal channels.
- Pore size of $\sim 400 \mu\text{m}$ 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

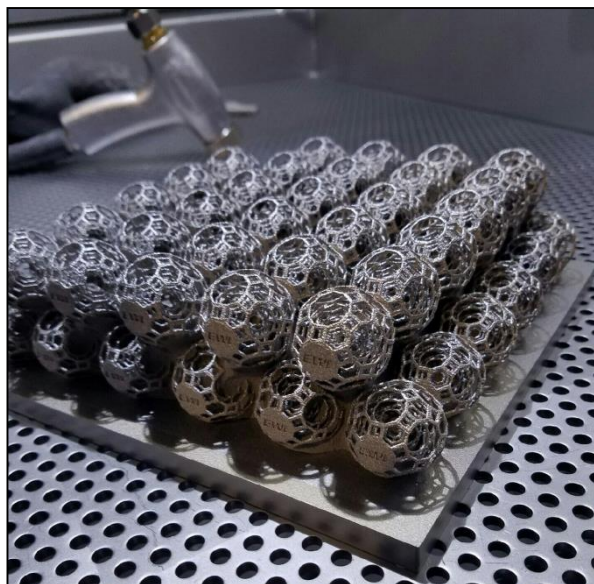
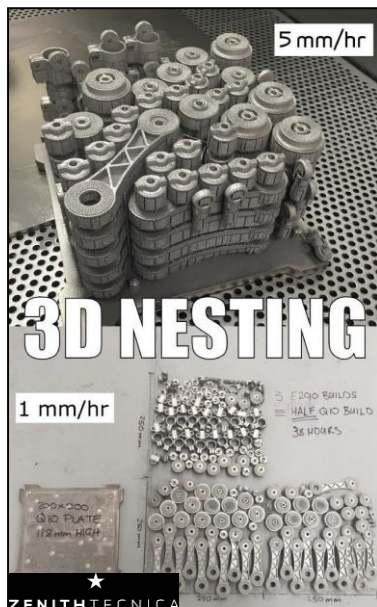


Powder Bed Fusion Processes

◆ 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

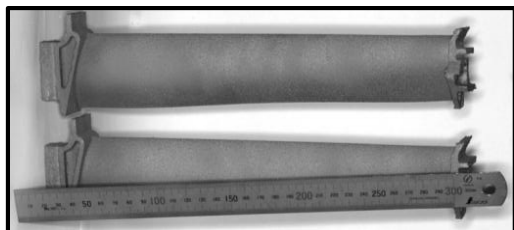


Heat build up



Powder Bed Fusion Processes

◆ Some Examples:



Turbine blades



Race car gear box



Adler Ortho, IT
(2007)



Lima, IT
(2007)



Acetabular cups with trabecular structures



Housing combining lattice structures and solid sections



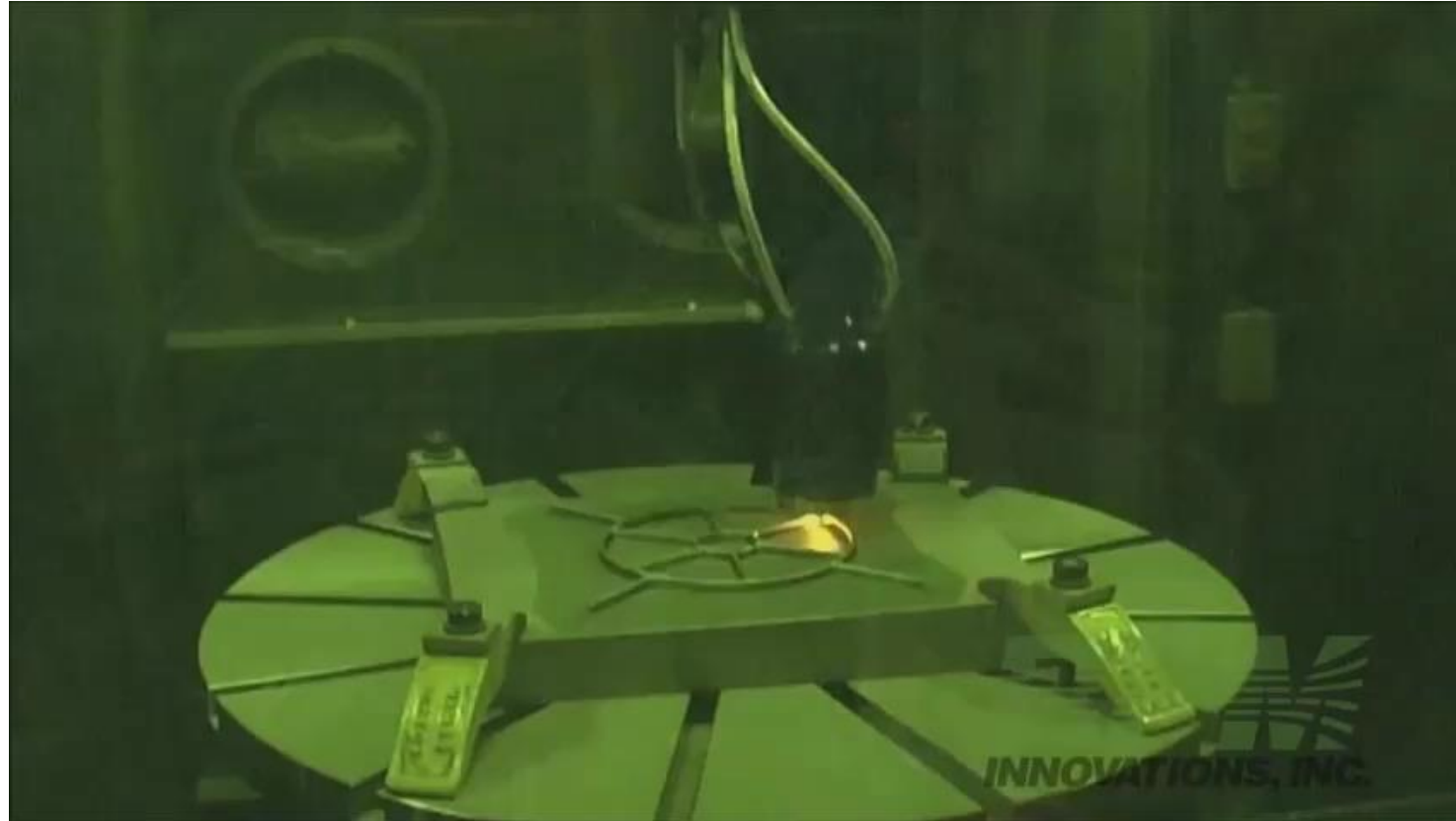
Custom cranial implant

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



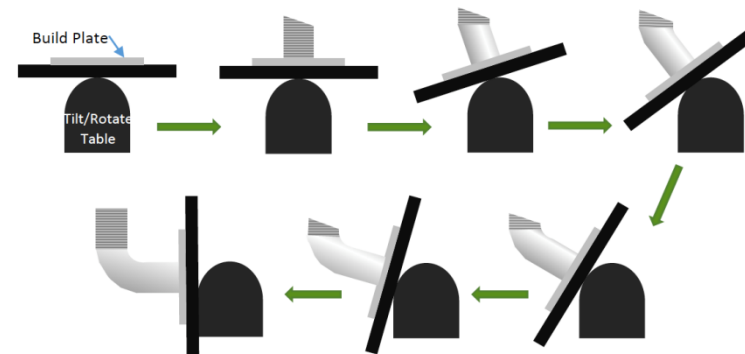
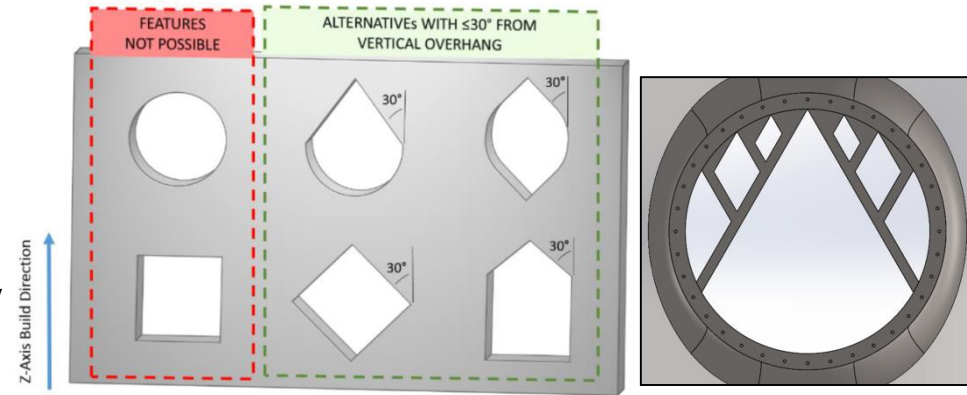
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Laser Direct Energy Deposition Processes

◆ 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.



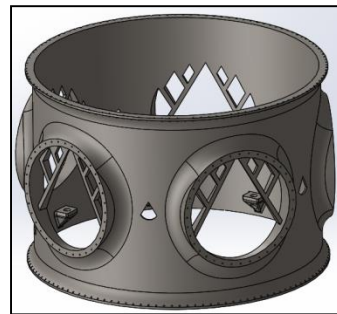
Laser Direct Energy Deposition Processes

◆ Design Considerations:

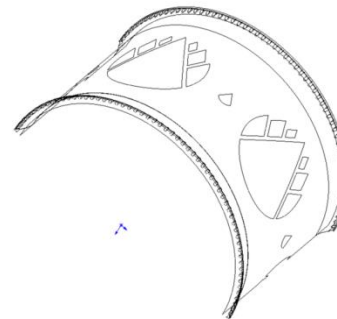
- The technology favors thin walled parts.
- Single walled parts have to be redesigned as surface models.
- Different features of the part require different parameters and thus have to be designed as separate files and arranged accordingly.
- Additional supporting structures need to be added to the part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



Secondary payload adapter



Modified part



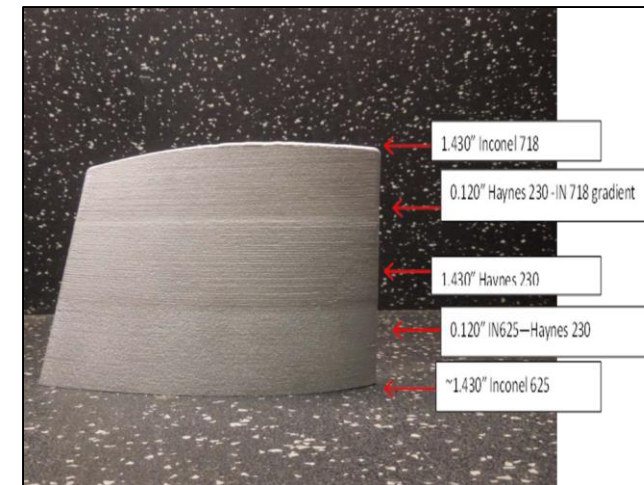
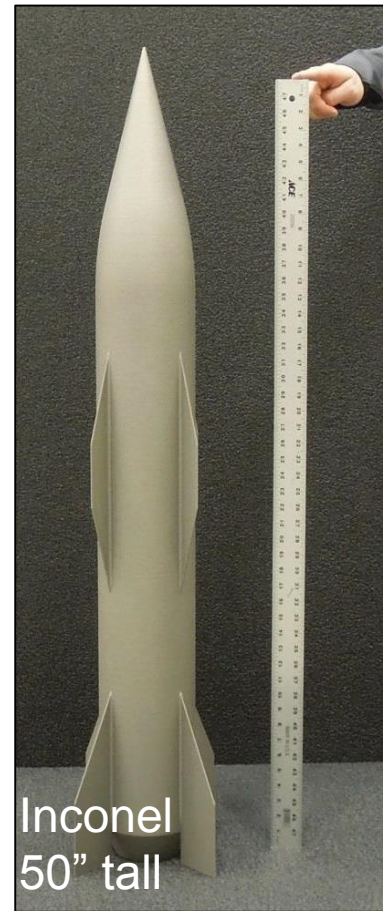
Surface Model



Final part

Laser Direct Energy Deposition Processes

◆ Some Examples :



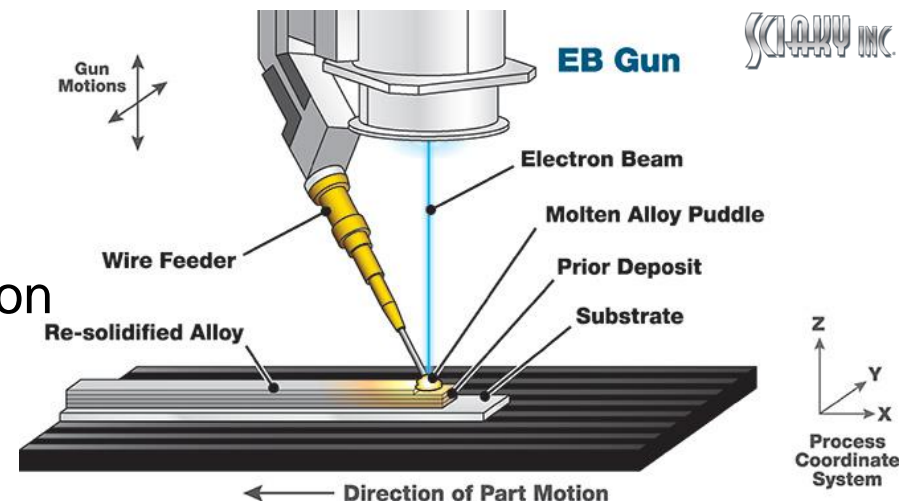
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Direct Energy Deposition Processes

◆ 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



EB Direct Energy Deposition Processes

◆ Design Considerations:

— Overhanging features:

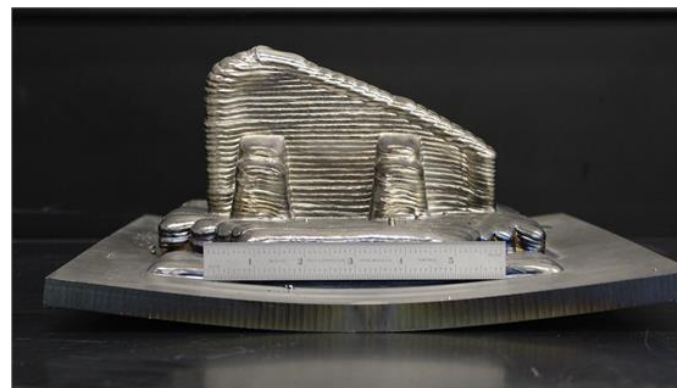
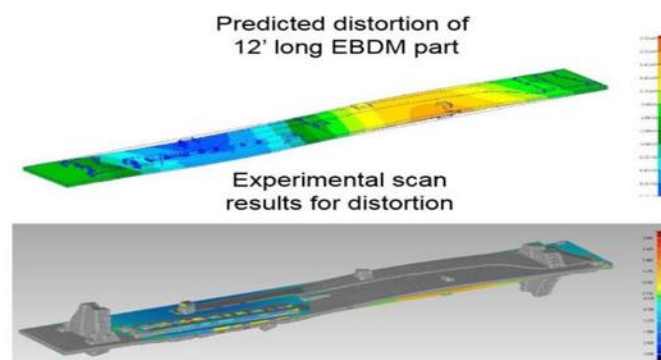
- All tool path must be supported by either the substrate or a previous deposit.
- This limitation can be compensated for through 4+ Axis part manipulation, and / or secondary set-up operations.

— 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

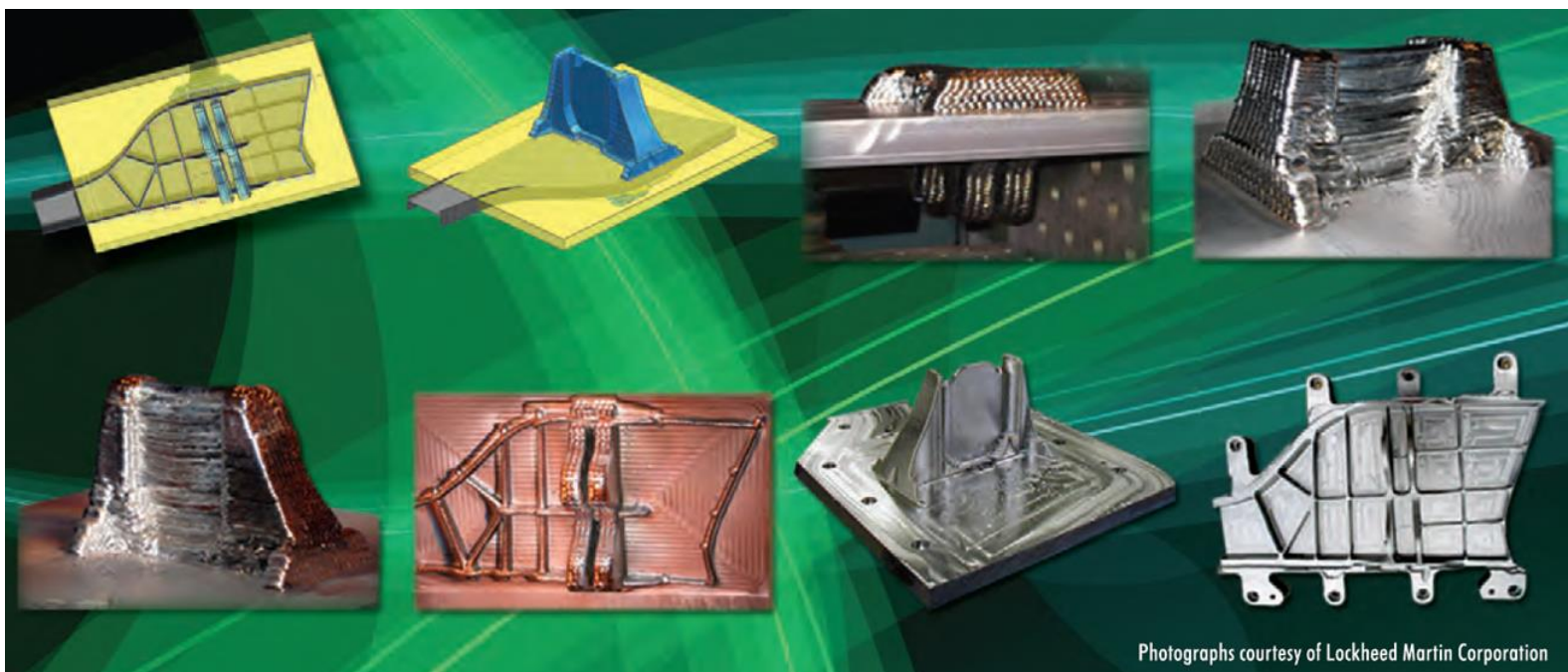


EB Direct Energy Deposition Processes

◆ 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



EB Direct Energy Deposition Processes

◆ Sample Examples:

Satellite propellant tank
~60" dia.



Variable ballast tank

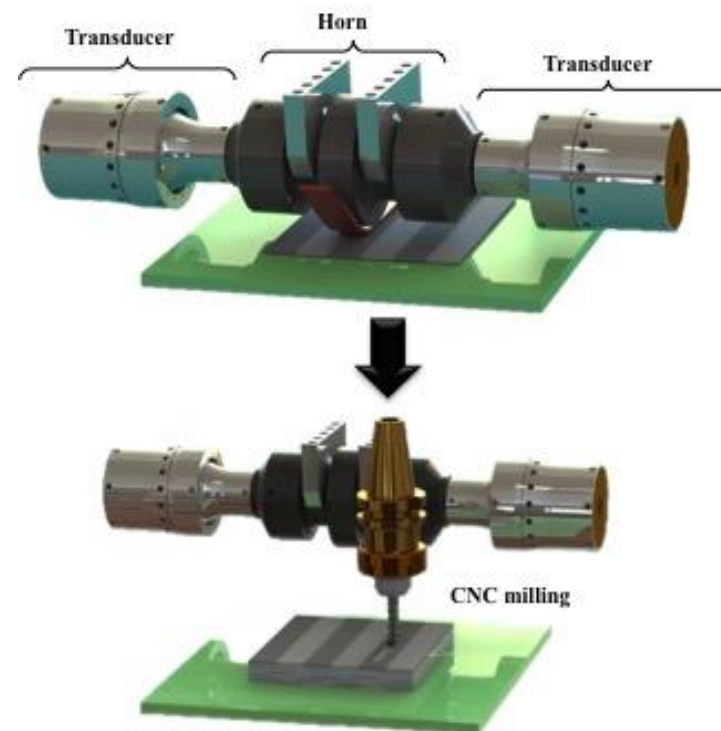


Airbus rear upper spar

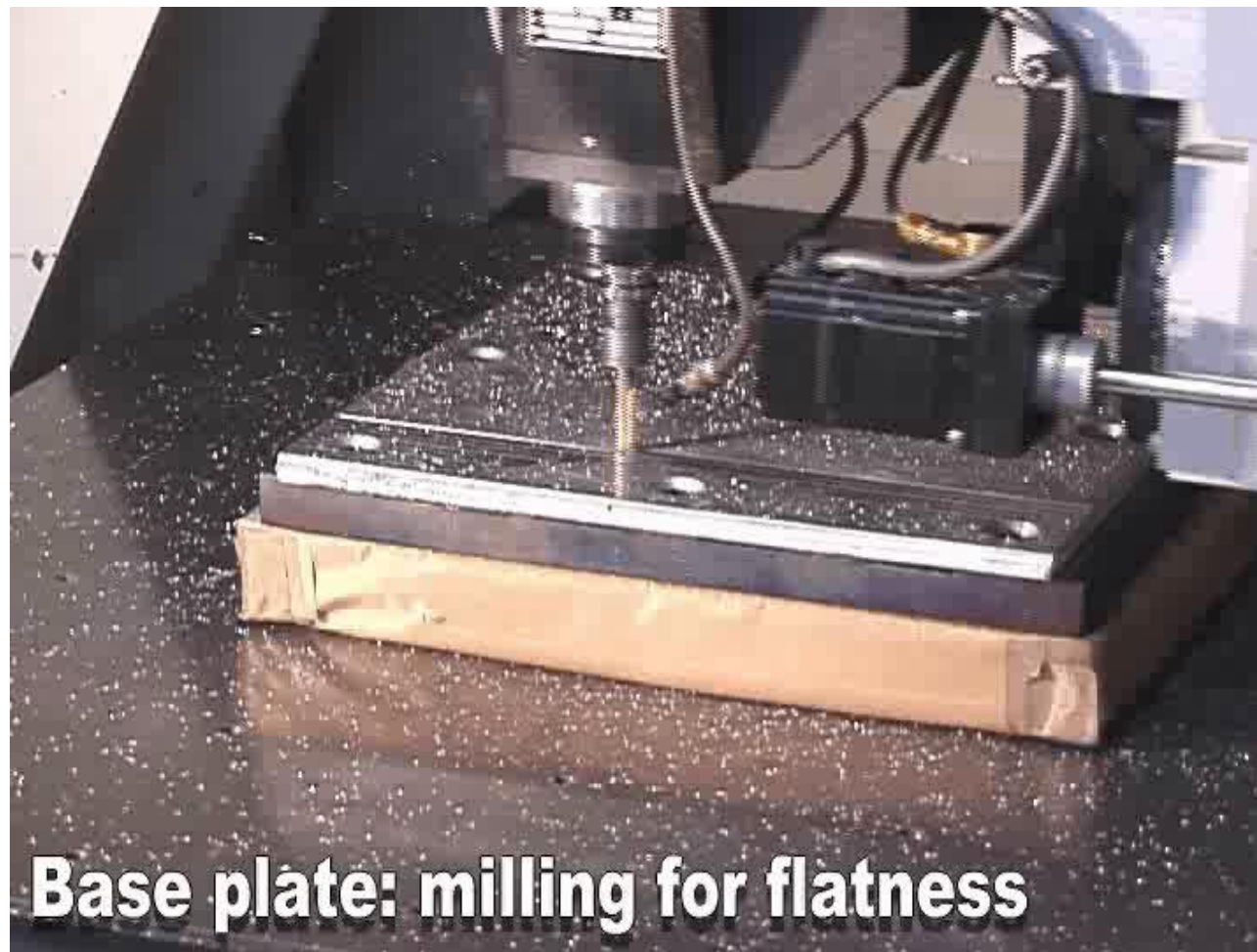
Sheet Lamination

◆ 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



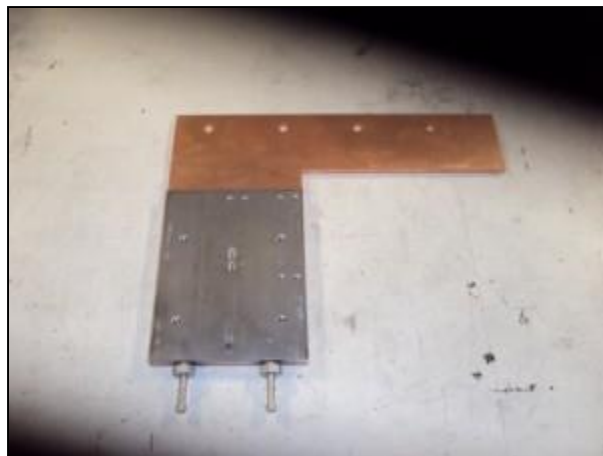
Ultrasonic Consolidation Process



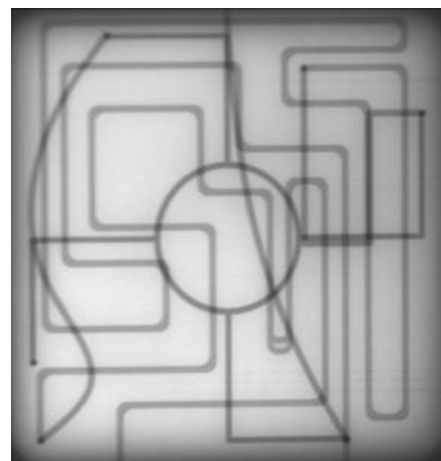
Base plate: milling for flatness

Sheet Lamination

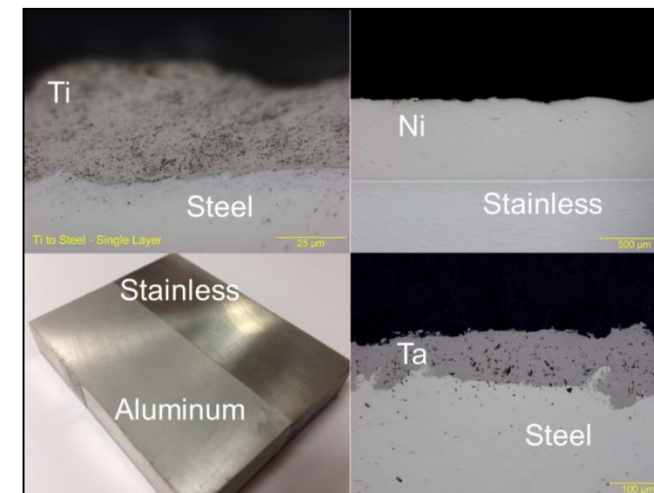
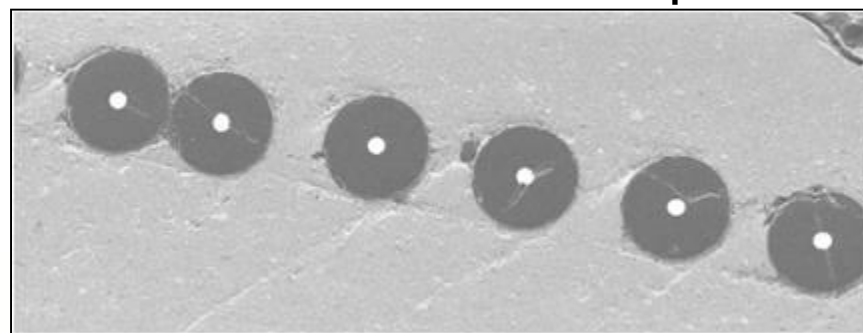
◆ Some Examples:



Multi-material heat exchanger



x-ray image of
complex internal flow
paths

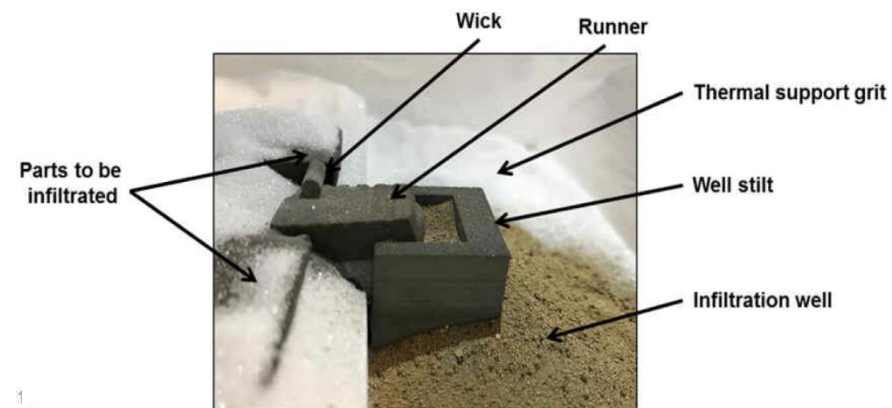


Dissimilar metals joining

Binder Jetting

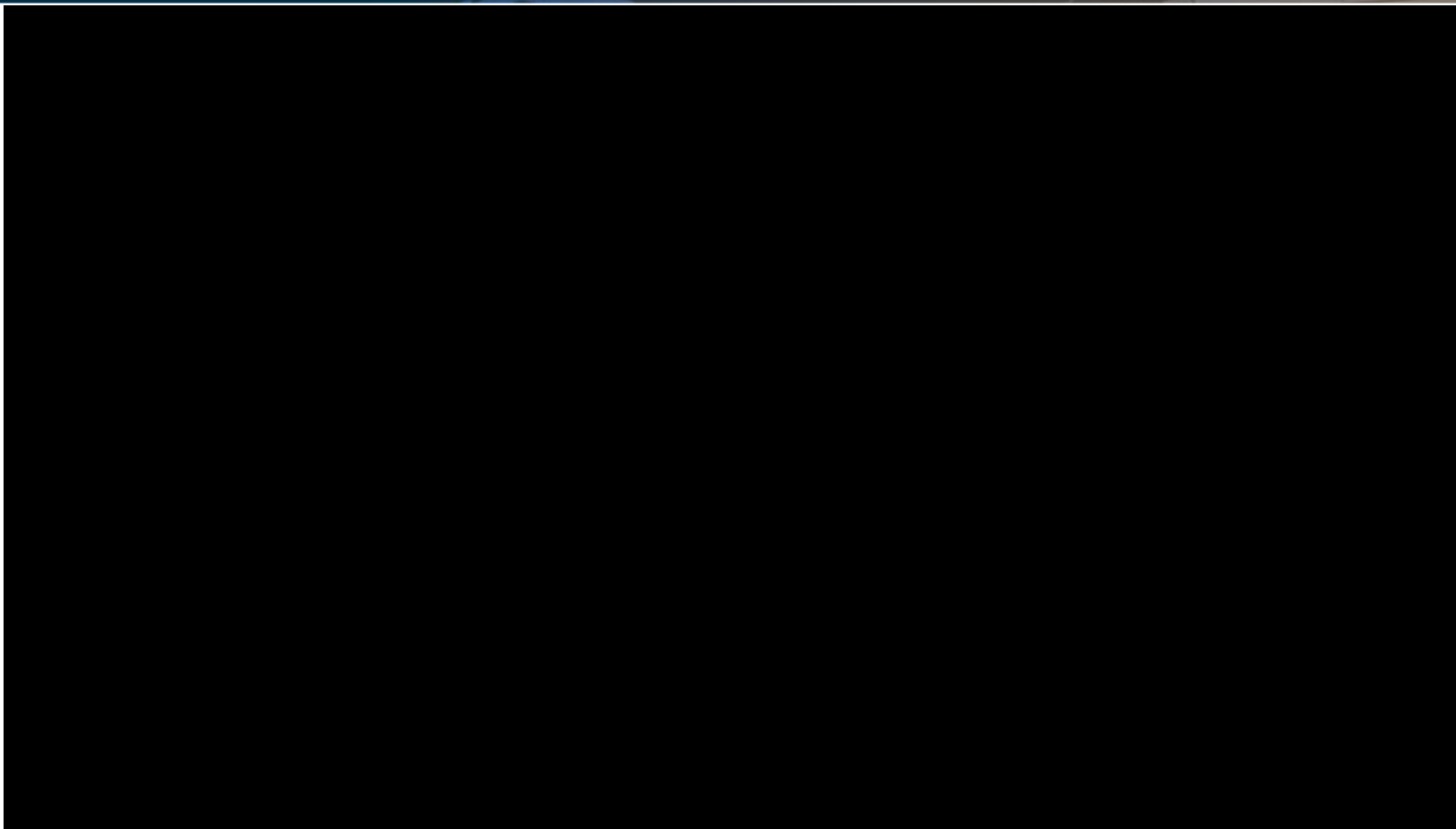
◆ Binder jetting :

- 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: $\sim 15 \mu m$



Infiltration process

Binder Jetting



Binder Jetting

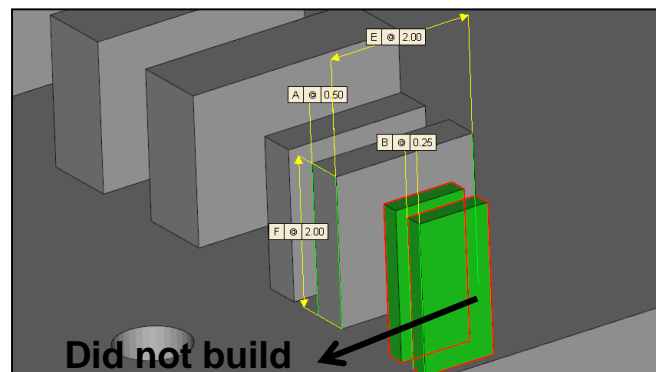
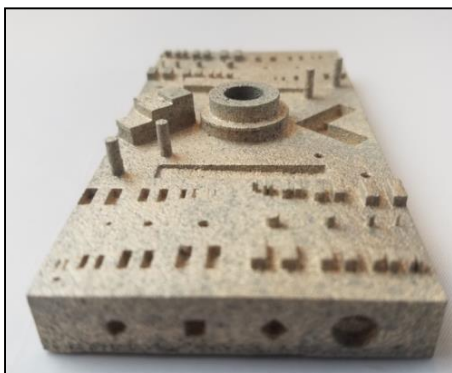
◆ Design Considerations:

— Overhanging feature:

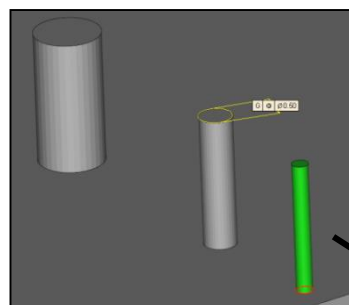
- Can build overhanging features without support structures

— 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



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 $> 2.5\text{mm}$, blind hole $> 3\text{mm}$ and min. gap between walls $> 1\text{mm}$ can be built after infiltration.
- These values are also dependent on the size of thermal support grit used during infiltration.



— Shrinkage factor:

- In case of direct sintering, shrinkage has to be accounted for during sintering based on the build material.

Binder Jetting

◆ Some Examples:



Prosthetic hand
Stainless steel/bronze matrix



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



Strainer plates

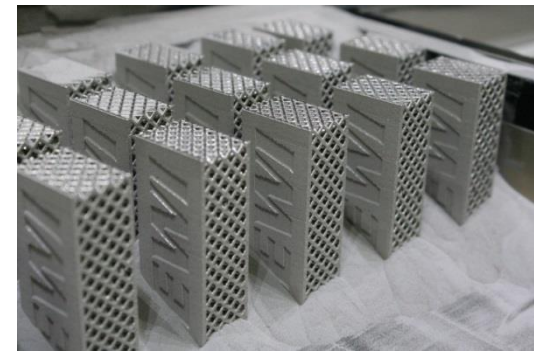
Overall Summary & Conclusions

- ◆ **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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