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Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components

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Presenter Biography

Paul Gradl

Paul Gradl is a Senior Propulsion Engineer at the NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama, United States. Mr. Gradl serves as Principal Investigator and leads several projects for additive manufacturing of liquid rocket engine combustion devices and supports a variety of development and flight programs over the last 17 years. He authored and co-authored over 60 journal articles and conference papers; holds four patents in additive; and regularly teaches courses in additive manufacturing. Gradl is the recipient of numerous NASA and industry awards including two NASA Exceptional Achievement Medals, NASA Exceptional Service Medal, NASA Research and Technology, and a NASA Space Flight Honoree to name a few. Mr. Gradl is an Associate Fellow of American Institute of Aeronautics and Astronautics (AIAA), serves on several committees across industry and chairs various sessions at leading conferences on additive manufacturing, and a PhD candidate at Delft University of Technology. Mr. Gradl is currently authoring a textbook on metal additive manufacturing for propulsion. Gradl was named one of “The Most Influential Personalities of Additive Manufacturing in 2020” by 3Dnatives.

Background of AM at NASA

- NASA has been adopting additive manufacturing (AM) to replace and augment traditional manufacturing techniques for various components.
- AM allows for schedule (2-10x) and cost reduction (>50%) in addition to new design opportunities for complexity, novel alloys, unique features.
- NASA is investigating various metal AM processes for use in propulsion applications through hot-fire testing and developing standards for human space flight qualification (e.g. NASA-STD-6030).






Motivation for this Research

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- Process selection for aerospace components using AM require proper balance between design features, AM process capabilities and limitations, and metallurgical characteristics resulting from AM.
- The resulting metallurgy from each metal AM process will be different and must be accounted for in the design.
- Several metal AM processes exist, and the selection criteria and balancing the trade considerations can be challenging.
- Aerospace components serve critical functions and use of AM requires a detailed understand of all steps necessary when selecting the proper AM process.
- The goal is to optimize technical performance of AM aerospace hardware with proper process selection and balancing programmatic improvements.

Presentation based on: Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2021). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". (Journal Article In Review)

Outline of Presentation

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- AM Process Lifecycle for Aerospace Components
- Metal AM Processes and Alloys for Aerospace
- Selection Criteria and Attributes for AM Process Selection
- TRL Advancements for AM Aerospace Components
- Post-Processing of AM Components
- Variations in AM Microstructures and Properties
- Performance Considerations for AM Components
- Conclusions

Presentation based on: Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2021). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". (Journal Article In Review)

AM Process Lifecycle

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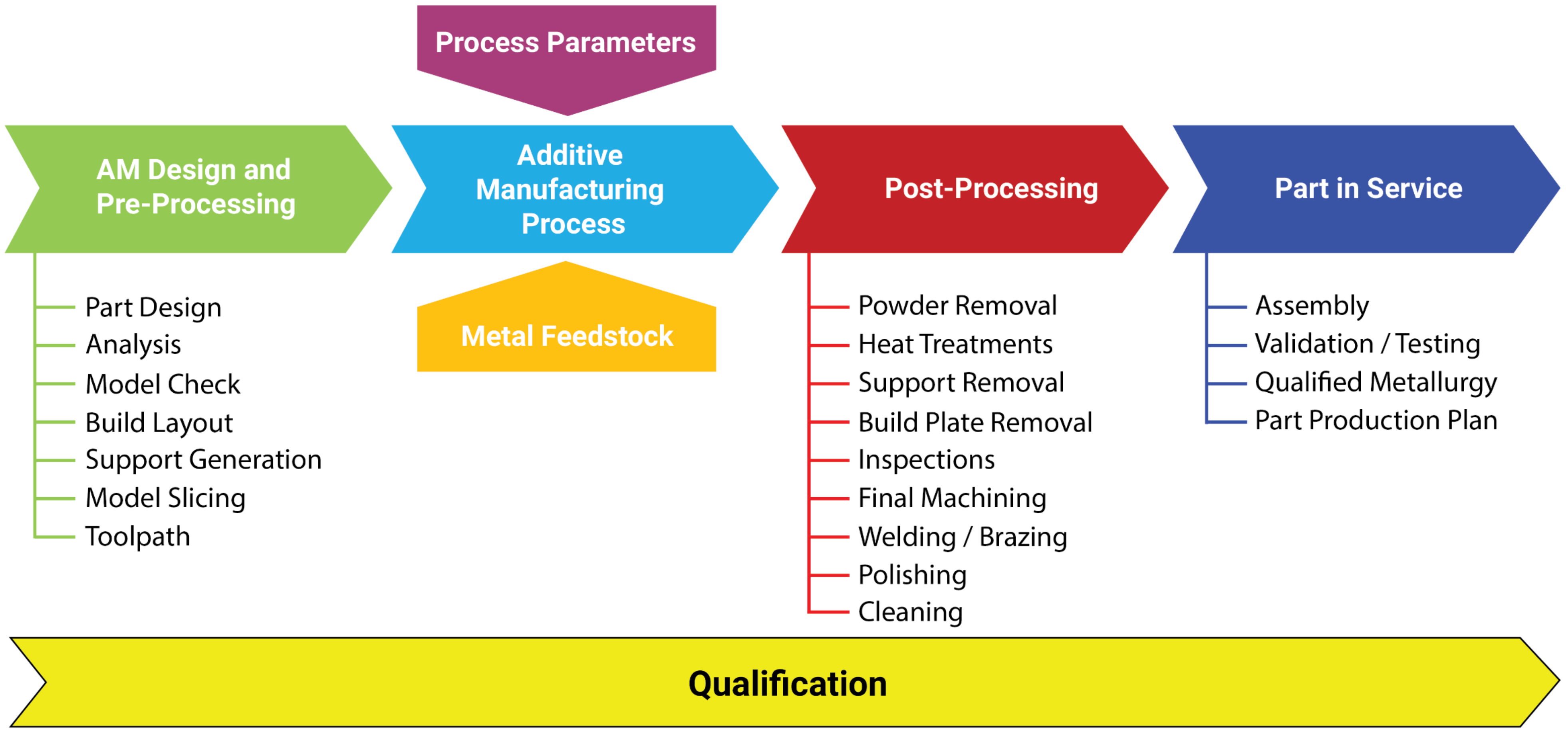

Proper AM process selection requires an integrated evaluation of all process lifecycle steps

General Terminology and Assumptions

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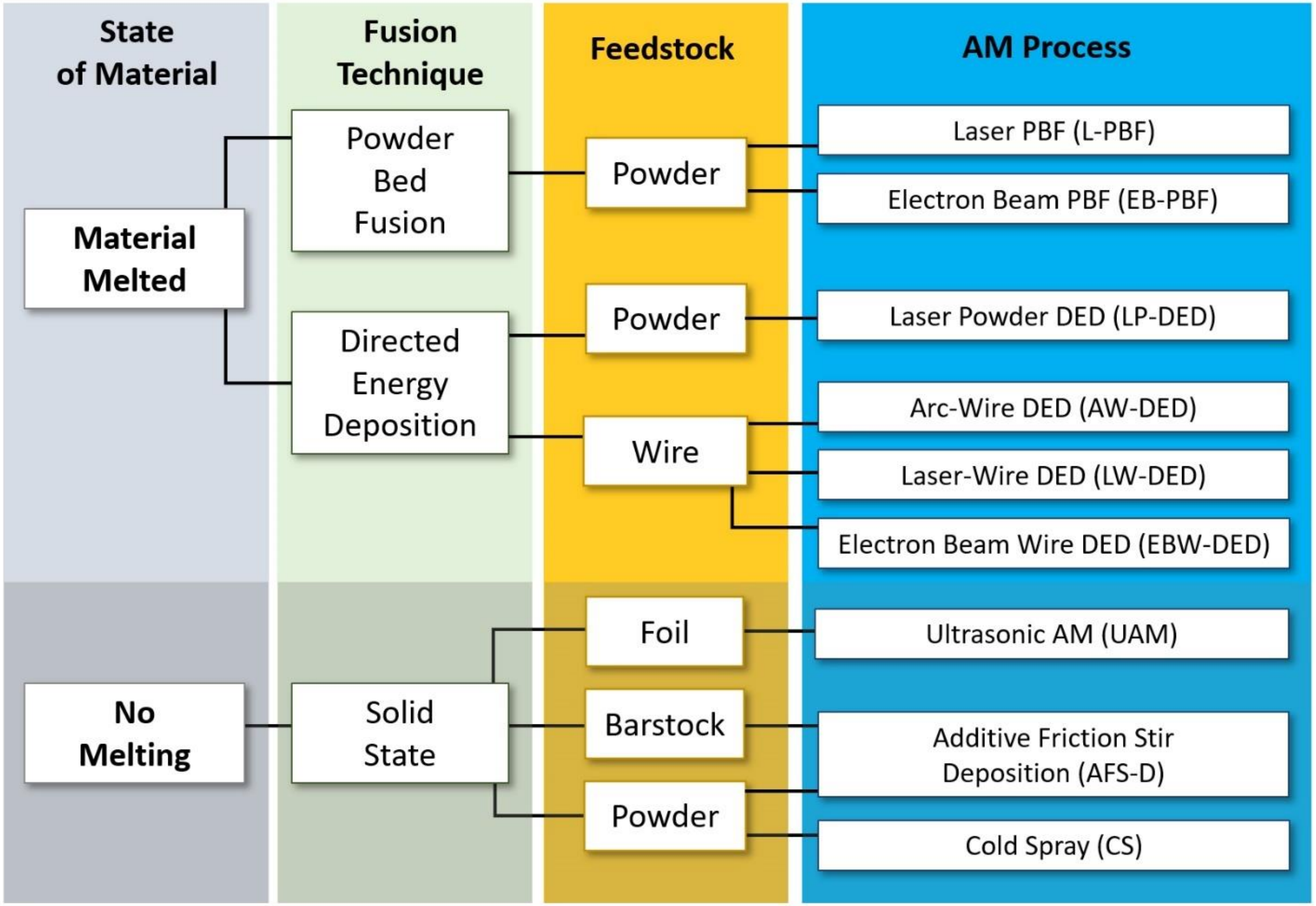
- AM = Additive Manufacturing
- AFS-D = Additive Friction Stir Deposition
- DED = Directed Energy Deposition
  - AW-DED = Arc Wire DED
  - EBW-DED = Electron Beam Wire DED
  - LP-DED = Laser Powder DED
  - LW-DED = Laser Wire DED
- PBF = Powder Bed Fusion
- TRL = Technology Readiness Level
- UAM = Ultrasonic Additive Manufacturing

Metal AM Processes for Aerospace



Metal AM Processes for Aerospace

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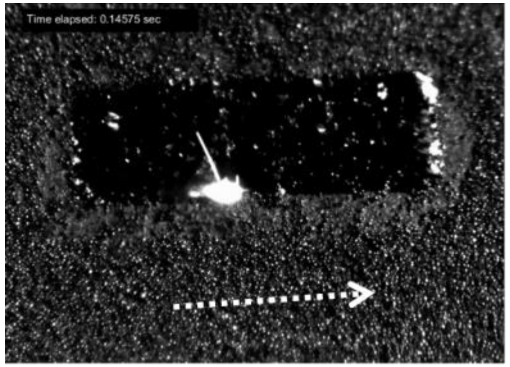
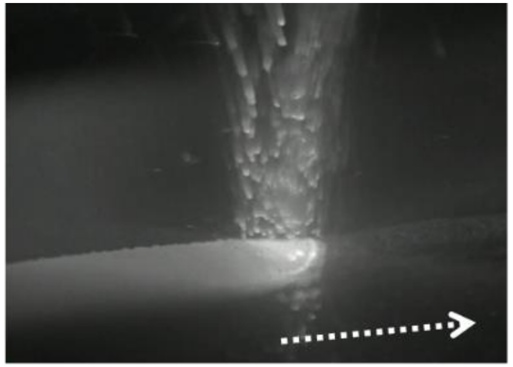
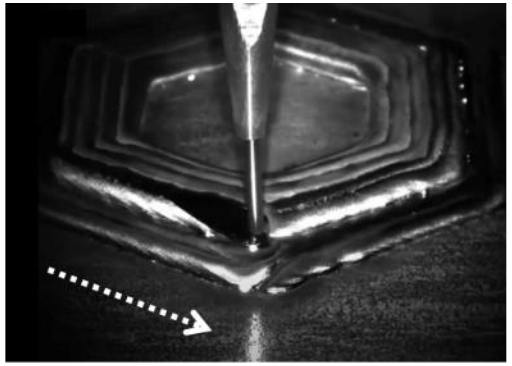


Laser Powder Bed Fusion

Electron Beam Powder Bed Fusion

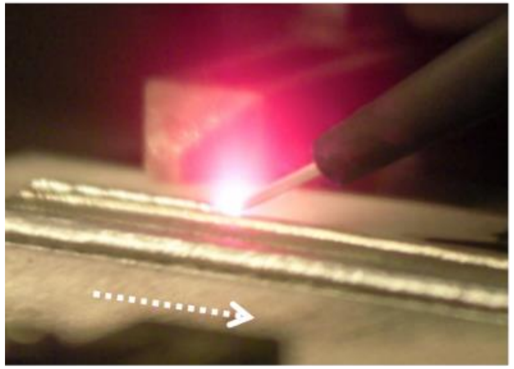


Laser Powder DED

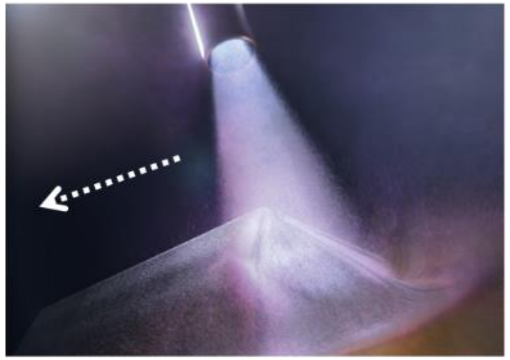


Laser Wire DED

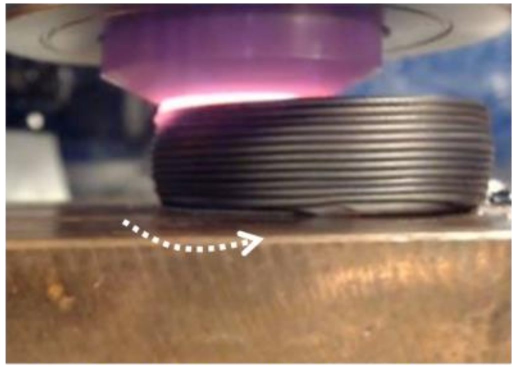
Arc Wire DED



Electron Beam Wire DED



Cold Spray



Additive Friction Stir Deposition

Ultrasonic Additive Manufacturing

A) Laser Powder Bed Fusion [https://doi.org/10.1016/j.actamat.2017.09.051], B) Electron Beam Powder Bed Fusion *[Credit: Courtesy of Freemelt AB, Sweden]*, C) Laser Powder DED *[Credit: Formalloy]*, D) Laser Wire DED *[Credit: Ramlab and Cavitar]*, E) Arc Wire DED *[Credit: Institut Maupertuis and Cavitar]*, F) Electron Beam DED *[NASA]*, G) Cold spray *[Credit: LLNL]*, H) Additive Friction Stir Deposition [NASA], I) Ultrasonic AM *[Credit: Fabrisonic]*.

Examples of Aerospace Components

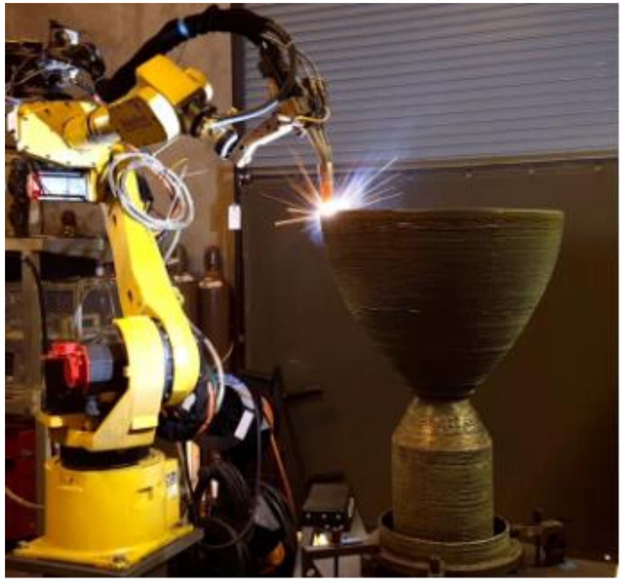
Examples of Aerospace Components using select AM Processes

L-PBF

EBW-DED

Cold Spray

LP-DED



AW-DED

L-PBF

L-PBF

AM Alloys for Aerospace

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Ni-Base
Inconel 625
Inconel 713
Inconel 718
Inconel 738
Inconel 939
Hastelloy-X
Haynes 214
Haynes 230
Haynes 233
Haynes 282
Monel K-500
C276
Rene 80
Rene 142
Waspalloy

Fe-Base
SS 17-4PH
SS 15-5 GP1
SS 304
SS 316L
SS 410
SS 420
SS 440
4140/4340
Invar 36
SS347
JBK-75
NASA HR-1

Co-Base
CoCr/CoCrMo
Haynes 188
Stellite 6, 21, 31

Cu-Base
Pure Cu
GRCop-84
GRCop-42
C18150
C18200
Glidcop
CU110
Monel K500

Ti-Base
Ti6Al4V
γ-TiAl
Ti-6-2-4-2

Platinum Group
Ir, Pt, Rh, Ru, Pd, Au, Ag

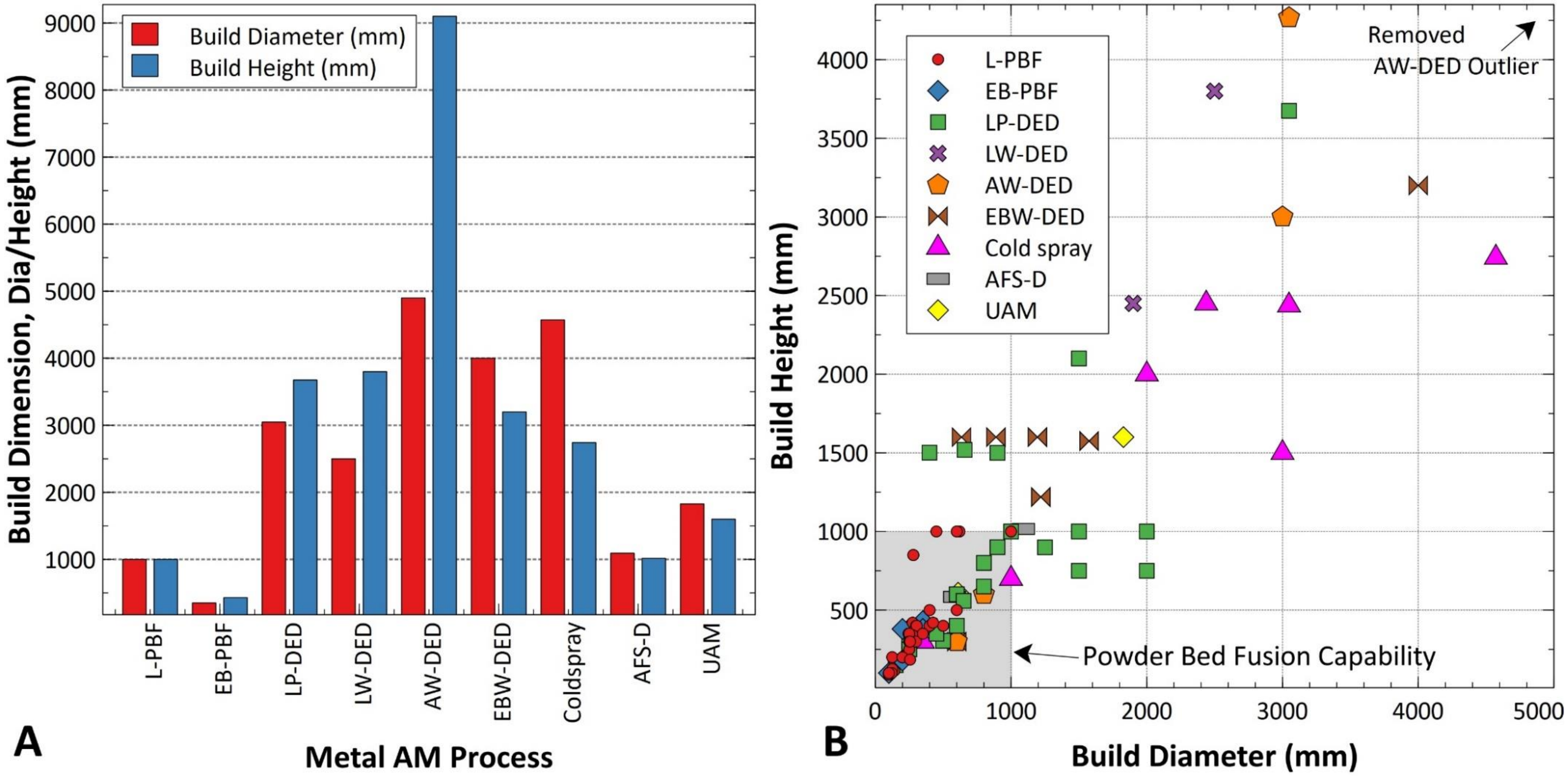
Refractory
W
WRe
Mo
MoW
MoRe
Ta
TaW
Re
Nb
C103
FS85
High Entropy

Al-Base
AlSi10Mg
A205
F357
1000
6061
2024
7075
7050
Scalmalloy
7A77

Criteria for AM Process Selection

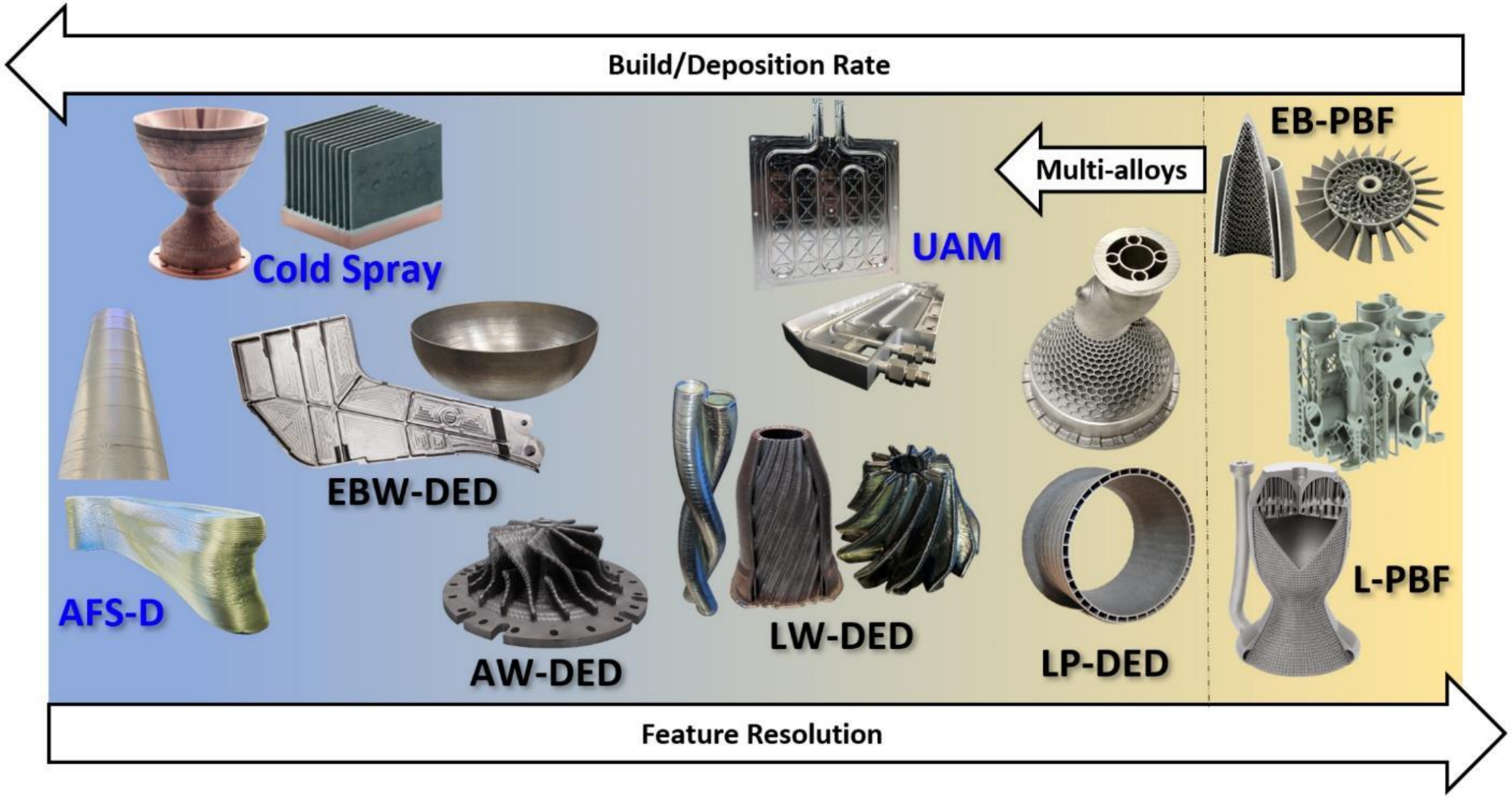
- What is the **alloy** required for the application?
- What is the **overall part size**?
- What is the **feature resolution** and internal **complexities**?
- Is it a **single alloy or multiple**?
- What are **programmatic requirements** such as cost, schedule, risk tolerance?
- What are the end-use environments and **properties required**?
- What is the **qualification/certification** path for the application/process?

Criteria – Machine Size / Build Platform



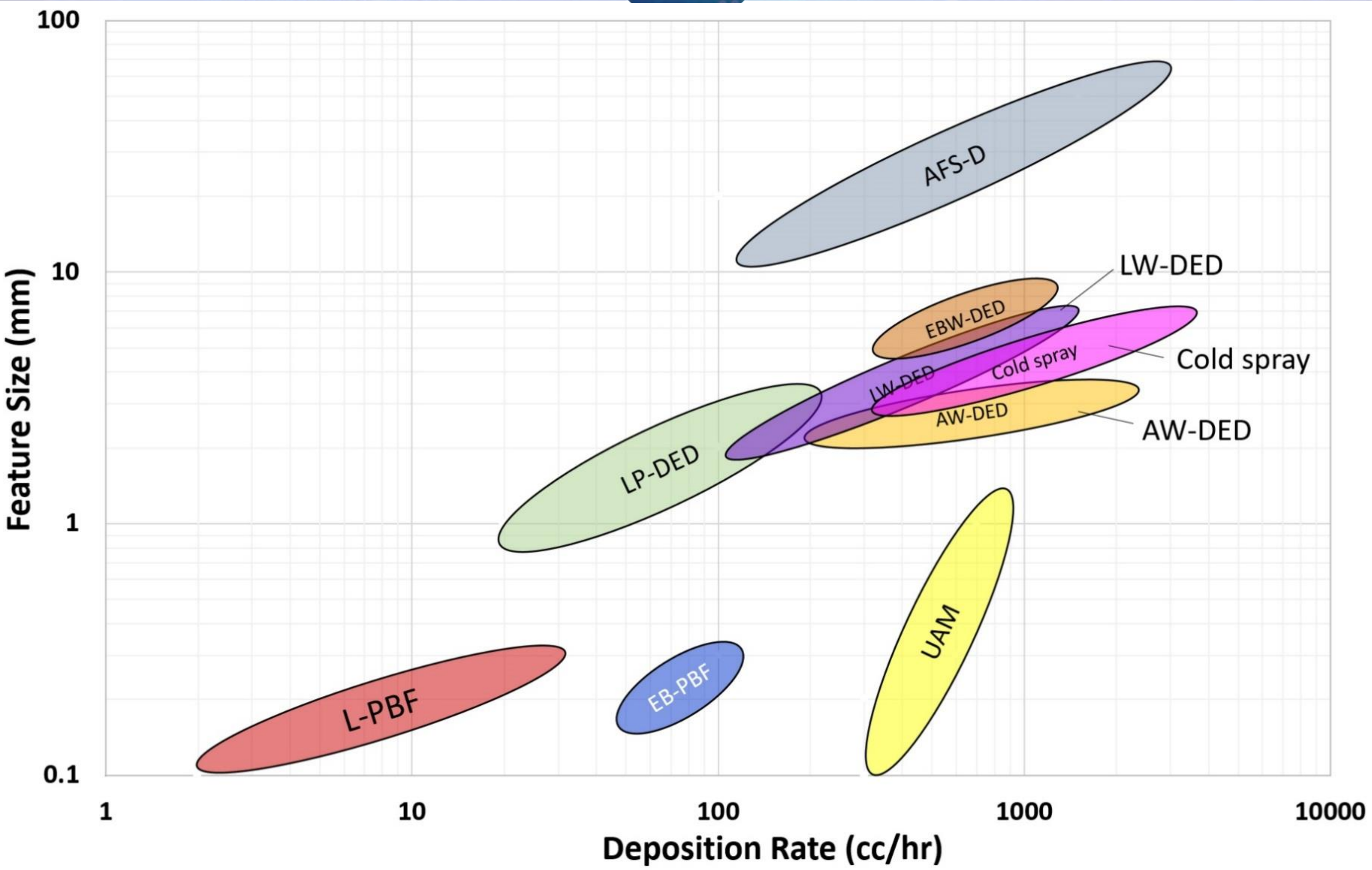
Machine platforms (size) have increased across most all AM processes, but must be traded with all other factors (build times, feature resolution, metallurgy…)

Criteria for AM Process Selection



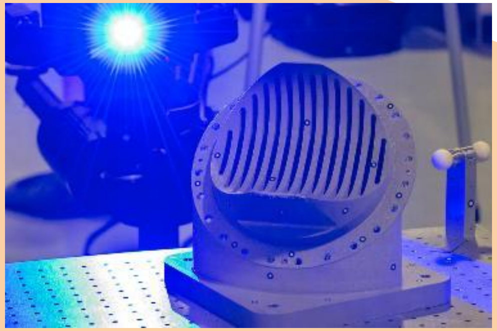
CREDITS: AFS-D image credits to MELD™ Manufacturing, Cold spray image credits to Spee3D, EBW-DED image credits to Sciaky and Lockheed Martin Corporation, AW-DED image credits to Gefertec, LW-DED image credits to Meltio, UAM image credits to Fabrisonic and NASA JPL, LP-DED image credits to DEPOZ project led by IRT Saint-Exupery and Formalloy, L-PBF image credits to Renishaw plc and CellCore GmbH/Sol Solutions Group AG, EB-PBF image credits to Wayland and GE Additive/Arcam.

Deposition Rate and Feature Size



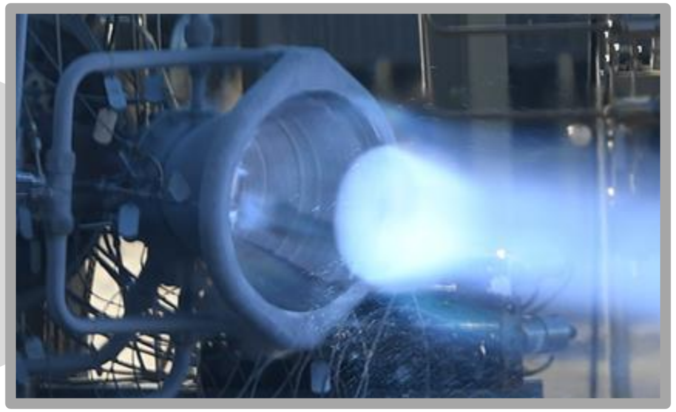
There is a clear relationship between feature resolution and deposition rate

Industrial Maturity and TRL



L-PBF

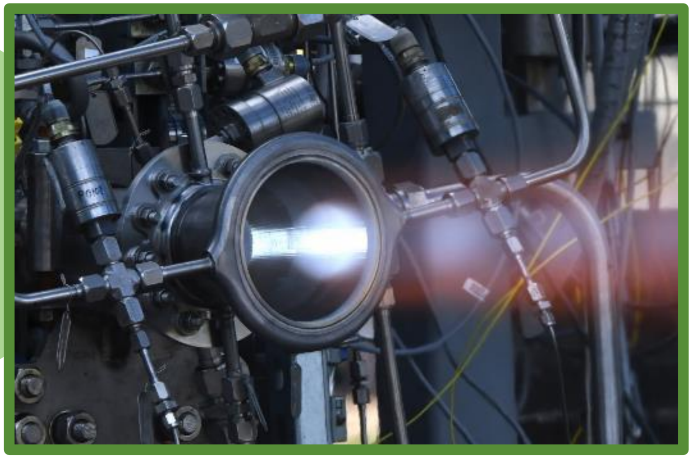
Cold spray LP-DED



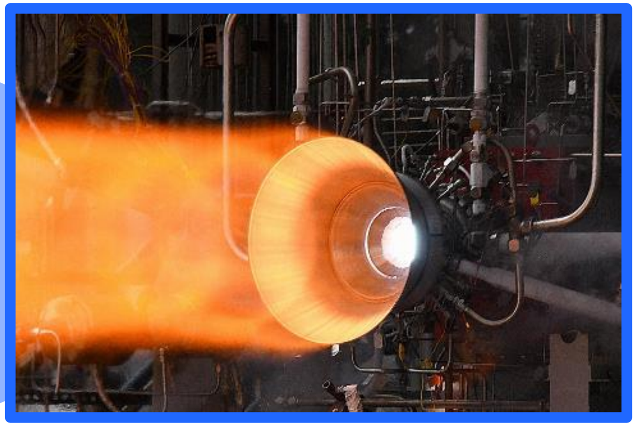
L-PBF

AW-DED

LW-DED



L-PBF EBW-DED



Post-Processing Requirements

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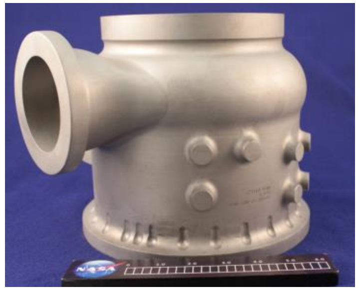
AM Process	Powder Removal and Verification	Support Removal *	Stress Relief **	Build Plate Removal	Heat Treatment	Final Machining ***
Laser Powder Bed Fusion (L-PBF)	Y	Y	Y	Y	Y	A
Electron Beam Powder Bed Fusion (EB-PBF)	Y	Y	-	Y	Y	A
Laser Powder Directed Energy Deposition (LP-DED)	Y	-	Y	Y	Y	Y
Laser Wire Directed Energy Deposition (LW-DED)	-	-	Y	Y	Y	Y
Arc Wire Directed Energy Deposition (AW-DED)	-	-	Y	Y	Y	Y
Electron Beam Wire Directed Energy Deposition (EBW-DED)	-	-	Y	Y	Y	Y
Cold Spray (CS)	-	-	A	Y	A	Y
Additive Friction Stir Deposition (AFS-D)	-	-	-	Y	A	Y
Ultrasonic Additive Manufacturing (UAM)	-	-	-	Y	A	Y

Y indicates generally required

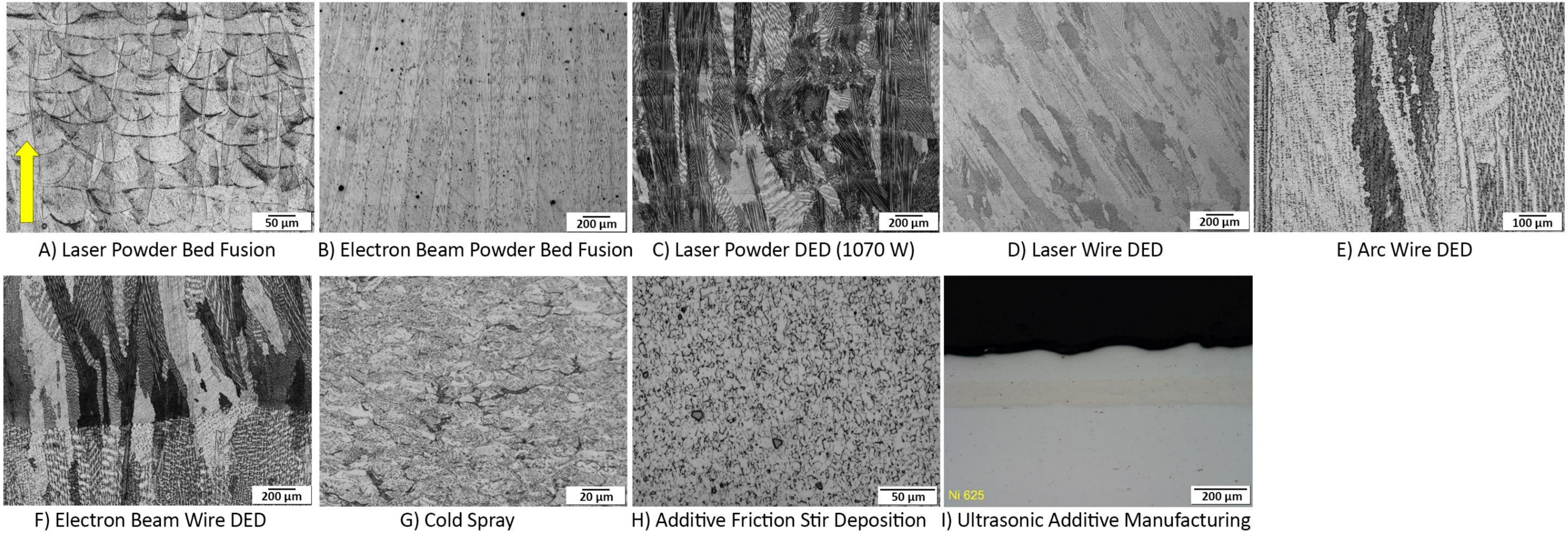
"-" indicates generally not required or easily removed

A indicates dependence on the part application

Machining Example



Microstructure of Inconel 625 following various AM Processes – As-Built



Microstructure of Inconel 625 following various AM Processes – Full Heat Treatment

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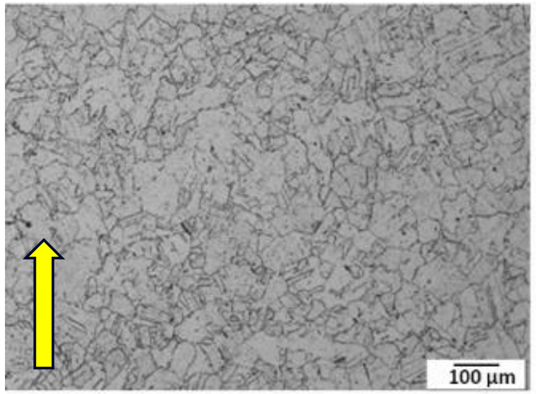
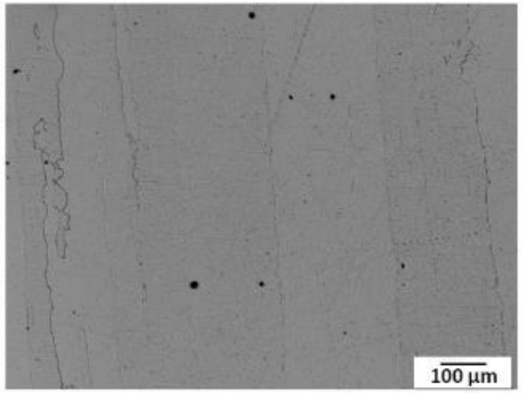
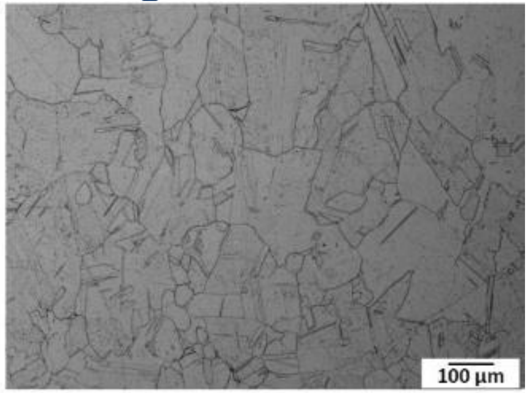


A) Laser Powder Bed Fusion

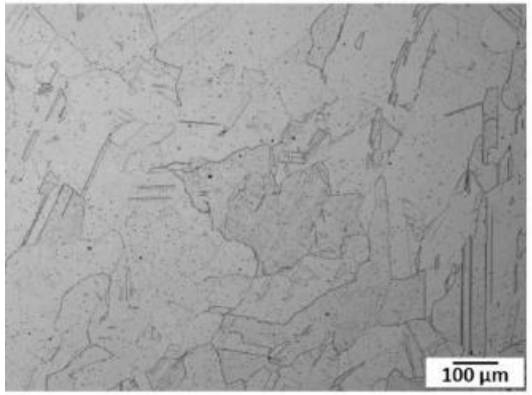


B) Electron Beam Powder Bed Fusion

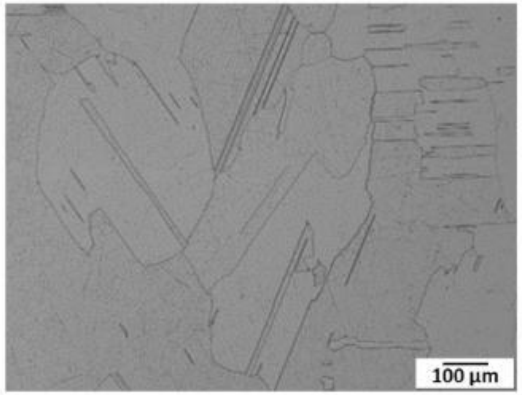


C) Laser Powder DED (1070 W)

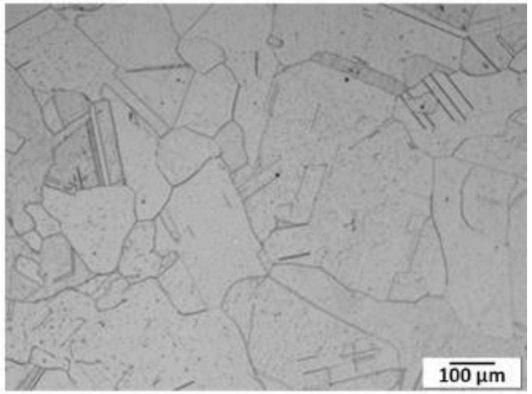
Stress Relief = 1066°C for 90 mins
HIP = Per ASTM 3301
Solution = 1177°C for 60 mins



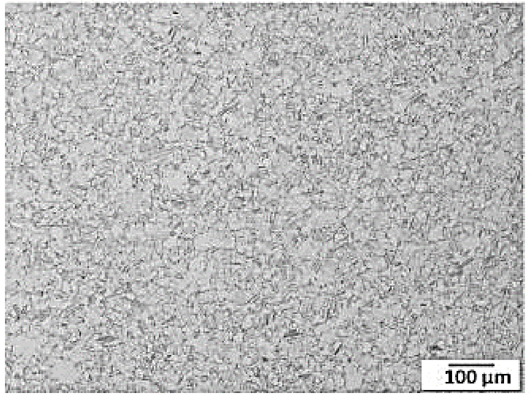
D) Laser Wire DED



E) Arc Wire DED



F) Electron Beam Wire DED



G) Cold Spray

Each AM process results in different grain structures, which ultimately influence properties

Properties for Various AM Processes

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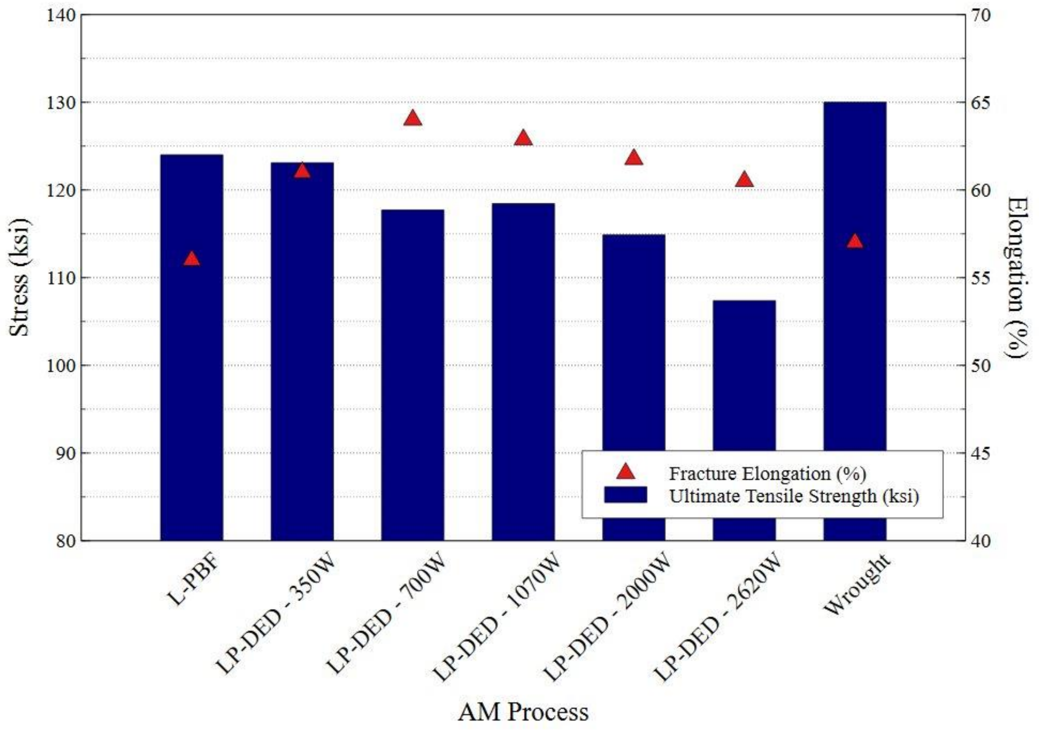
- Material properties are highly dependent on the type of process (L-PBF, DED, UAM, Cold spray….), the starting feedstock chemistry, the parameters used in the process, and the heat treatment processes used post-build
- Each AM process results in different grain distributions, precipitates, and porosity, all of which influence final properties
- Heat treatments should be developed based on the requirements and environment of the end component use
- Properties should be developed after AM process is stable and parameters confirmed

Room Temperature UTS



*Not design data and provided as an example only

Maintaining Performance Throughout the AM Lifecycle

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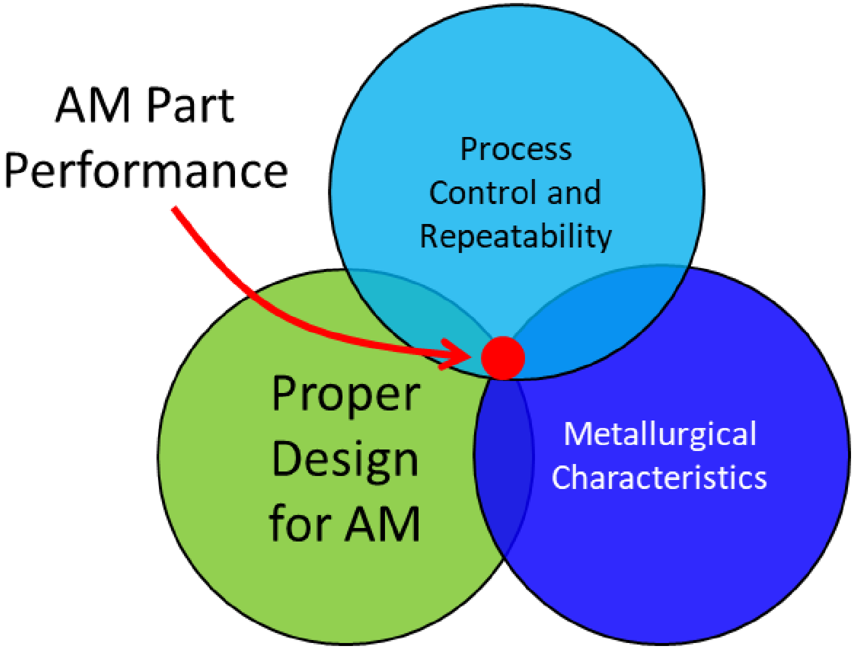

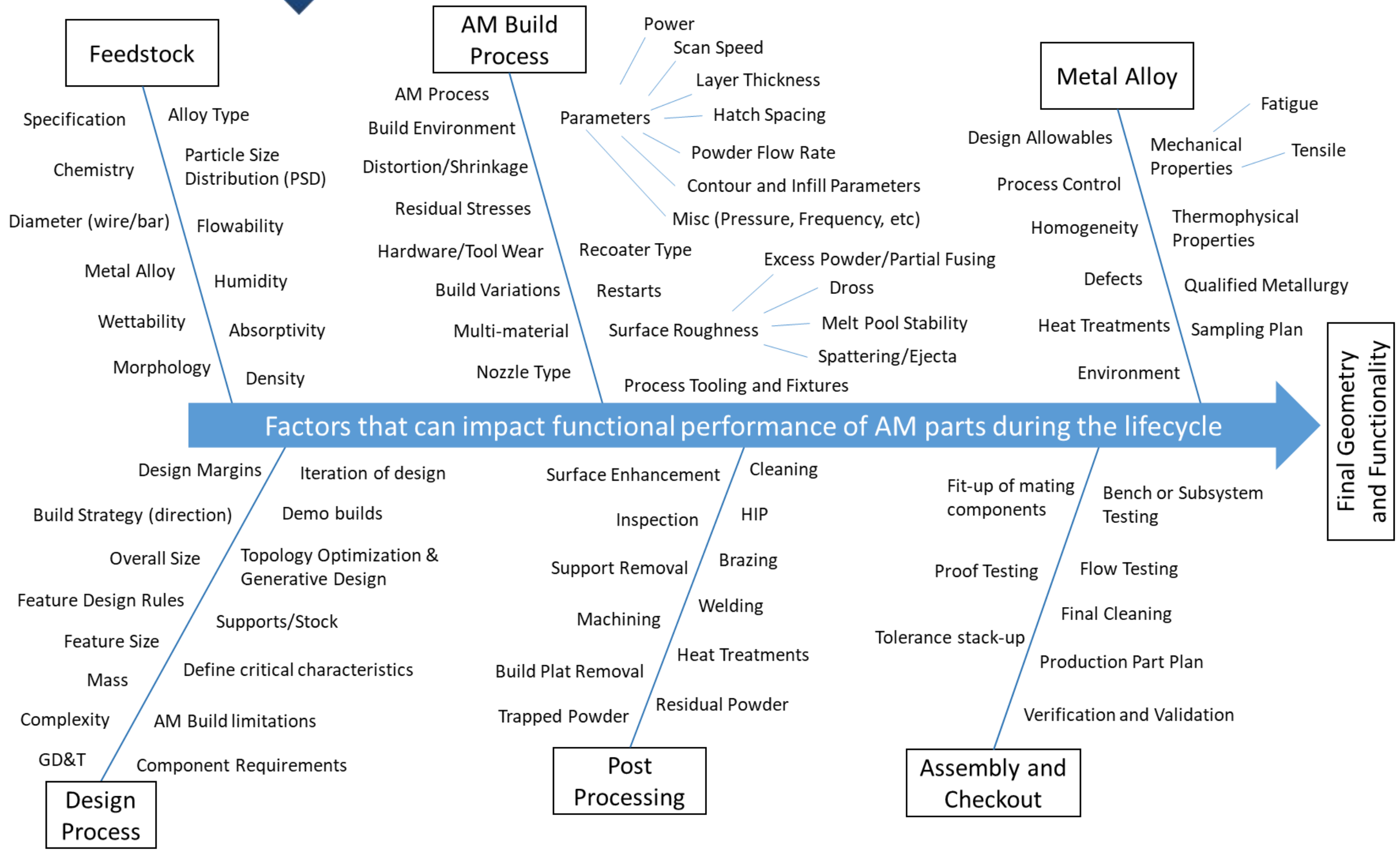

Proper Design, Process Control, and Metallurgy are always integral for AM

Conclusions

- Various metal AM processes exists for use in aerospace components, and each has unique advantages and disadvantages
- AM process selection and implementation is a highly integrated and iterative effort
  - Must understand the entire lifecycle and specifics of each process step
- High TRL exist for each of the AM processes discusses for aerospace
- Multiple selection criteria must be considered before determining the optimal process for a particular component
- Performance of an AM part will ultimately be dependent on the proper geometric design, process control, and subsequent metallurgical characteristics
- Processes will continue to evolve

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Thank you.

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