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EARLY INNOVATION PROGRAM OFFICE

Additive Manufacturing for Aerospace Flight Applications

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Additive Manufacturing for Aerospace Flight Applications Overview

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I. Context
- Focus
- Process
- Machines

II. Materials and Manufacturing

III. Software

IV. Seven Relevant Applications
- New Design Frontiers
- Combination of Multiple Assemblies
- High Complexity Parts
- Mass Reduction
- Research and Tailoring
- In-Situ Fabrication and Assembly
- In-Situ Resource Utilization

V. Challenges
- Process Challenges
- Residual Stresses
- Defects

Additive Manufacturing Focus

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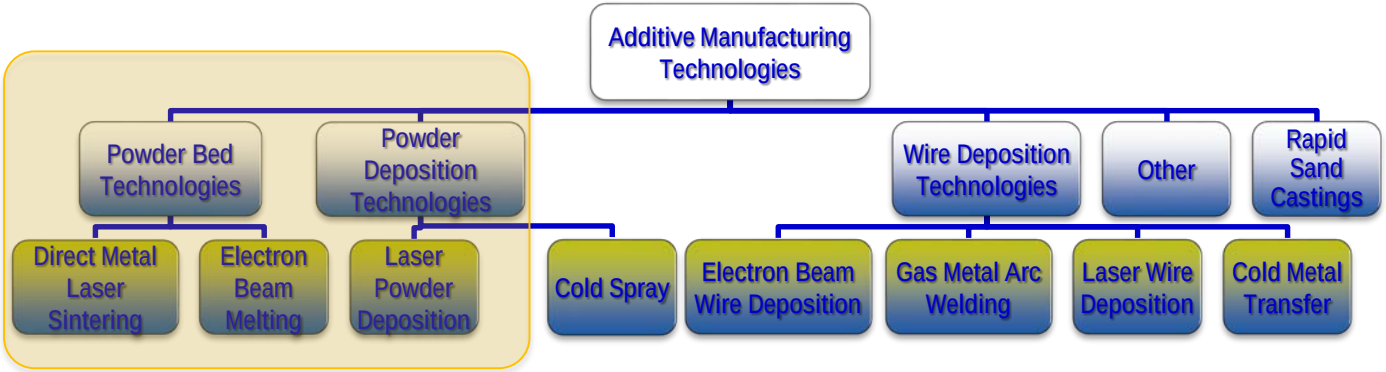
ASTM F2792-12a : 7 CATEGORIES

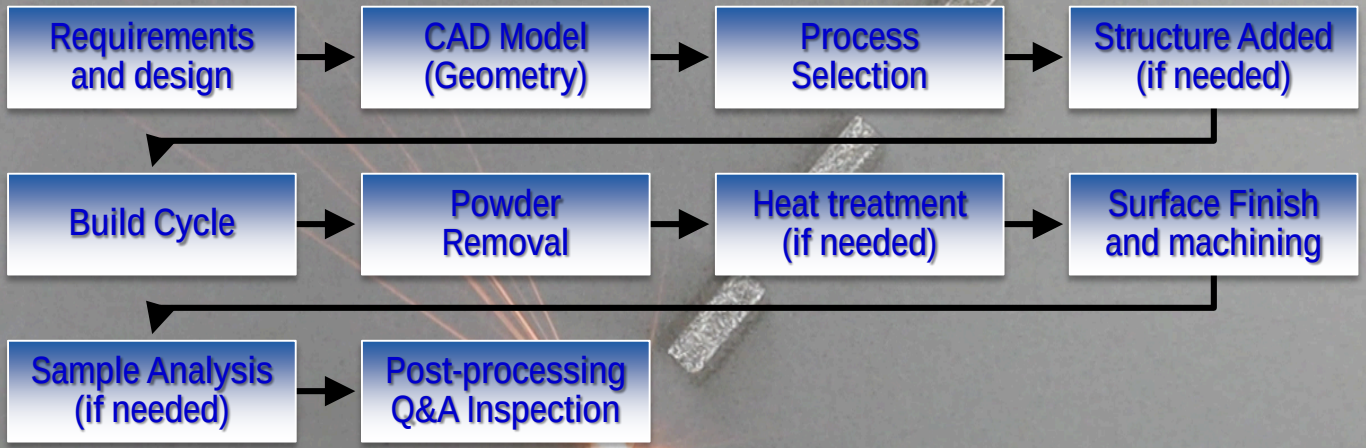
1. Directed energy deposition
2. Material extrusion
3. Powder bed fusion
4. Material jetting
5. Binder jetting
6. Sheet lamination
7. Vat photopolymerization

Primary systems (metals) utilize laser- or electron-beams for melting

- Approximatively 15 years of system development
- Initial work primarily focused on lower-value materials (e.g. steels, brass, etc.)
  - Some applications to high-value alloys for jewelry (e.g. gold, etc.)



Process Flow Map: *Powder Bed*



At a "40,000 ft view", we are enabling a new paradigm in which the "cost of the information content in a component vs. the material cost" is balanced towards the content being managed in the part (e.g. CAD model) and not in tooling and associated heavy machinery. Bill Coblenz, Program Manager, DARPA

Background Image by CalRam

Machine Technology

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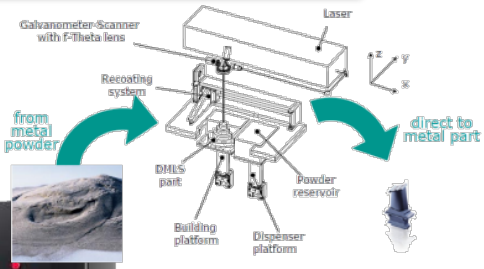
EOS			Concept Laser		Rennishaw		SLM				Arcam		
M270	M280	M Lab	M2	XL 1000R	AM125	AM250	125HL	250HL	500HL	280HL	A1	A2	A2X

Powder Bed Process

(Refined detail resolution)

- **Selective Laser Melting (SLM)**
  - Argon environment
  - 400 W laser
  - 20-40 µm build layers
  - 250 RA finish
  - No pre-heat (high stresses)
- **Electron Beam Melting (EBM)**
  - Vacuum environment (10^{-5} mBar)
  - 3,500 W Electron Beam
  - 80 µm build layers
  - 500 - 1000 RA finish
  - Each layer pre-heated to 1,000 °C



Images courtesy Concept Laser and Arcam

Materials and Manufacturing

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Materials

- Fe and Fe alloys
- Ti6Al4V
- AlSi10Mg
- Cu
- $PbZrO_3 \cdot TiO_2$
- TiO_2
- YSZ
- Al_2O_3

Post Processing

- HIPing
- Surface Finishing
  - Shotpeening
  - Vibrahoning
  - Chemical Etching
- Annealing

Limitations

- Powder size, uniformity, distribution
- Oxidation
- Mechanical increments
- Beam size
- Emissivity and reflectivity
- Quality of model

Materials and Manufacturing Approach for Qualification

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- Testing
  - Detailed testing required for applications
  - Testing incorporates a wide range of parameters (-300 °C < T < 3500 °C)
  - Typical minimum data set shown at right
  - Expensive (~$0.5 – 2M per alloy)
- Modeling
  - ICME maturing
  - Requires detailed understanding of flaw sizes, distributions and types
  - Insufficient for current risk management approaches

LCF (Strain Controlled Fatigue)
- Room temperature
- Elevated temperatures
- Cryogenic temperatures

Tensile Strength
- Room temperature
- Cryogenic temperatures
- Elevated temperatures
- Thermal exposure
- Hydrogen Environment
- Other relevant environments

Shear Strength

Physical Properties
- Density
- Thermal Conductivity
- Poisson's Ratio
- Specific Heat
- Thermal Expansion Coefficient

Stress Rupture

Elastic Modulus
- Room temperature
- Cryogenic temperatures
- Elevated temperatures

Elongation

Dynamic Modulus

FCGR Properties
- Crack growth
- Toughness, plane strain
- Toughness, plane stress

HCF (Load controlled Fatigue)
- Room temperature
- Cryogenic temperatures
- Elevated temperatures

Reduction of Area

Stress Strain Curves (Full)

Materials and Manufacturing Allowables

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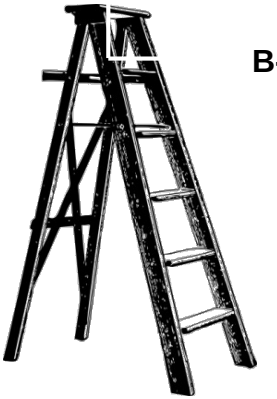
MMPDS = Metallic Materials Properties Development and Standardization Handbook (formerly MIL HDBK 5)

A-Basis A value which 99% of the measured values will exceed, associated with a 95% confidence level (single loadpath structures)



B-Basis A value which 99% of the measured values will exceed, associated with a 95% confidence level (multiple loadpath structures)

Point Design Associated with a unique structure and valid only for that particular configuration

S-Basis A value associated with specification acceptance values. No statistical significance may be assumed (initial designs)

Software and Design

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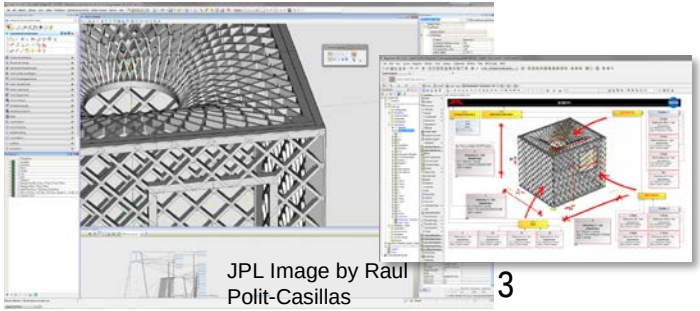
1. Topology and structure optimization
   - Simultaneous structure analysis and geometry definition based on loads, interfaces and component envelope
2. Optimized geometries for AM
   - Hollow parts
   - Organic shapes based on previous design technique
   - Rapid response to one-offs
3. Generative Design
   - Geometries generated by mathematical algorithmic using system design variables (e.g., MBSE)
4. Multifunctional integrated design (4D)
   - Interdisciplinary design techniques to simulate and embed dynamic and functional behaviors within the geometry



JPL Image by Raul Polit-Casillas

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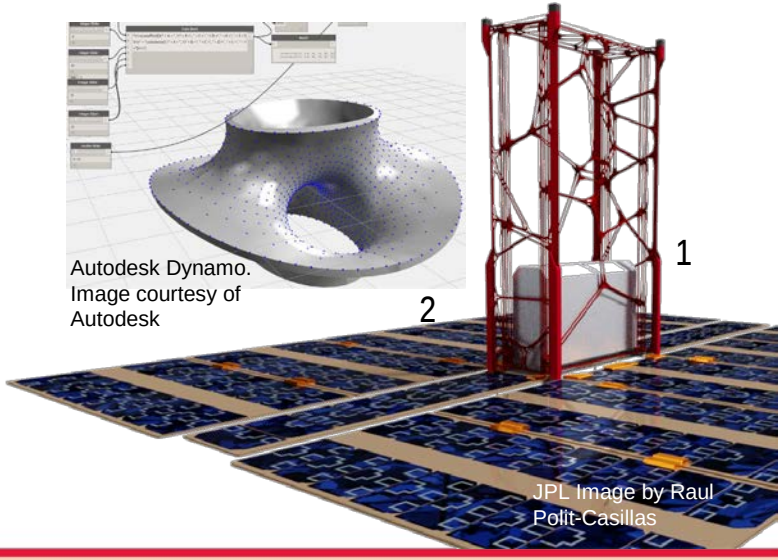
Autodesk Dynamo. Image courtesy of Autodesk

2



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JPL Image by Raul Polit-Casillas

Aerospace Areas Of Focus

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There are currently 7 areas of significant interest to aerospace that haven't received sufficient focus, yet offer significant benefits to their study

1. **New Design Frontiers**
   - **Gradients**
   - **Ceramics**
   - **Multi-materials**
   - **Multi-functional Structures**
2. **Combination of Multiple Assemblies**
3. **High Complexity Parts**
4. **In-Situ Fabrication**
5. **Mass Reduction**
6. **A Tool for Materials Research & Tailoring**
7. **In Situ Resource Utilization**

New Design Frontiers

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- **Gradients** – creating axial- or radially-graded materials enables enhanced design, such as tailored thermal expansion, thermal conductivity, or weldability, where required within the structure
- **Ceramics** – advanced properties, beyond purely structural (e.g. electrical, magnetic, dielectric) can be tailored as well
- **Multi-materials** – multiple materials systems (ceramics, metals, polymers) within the same structural geometry
- **Multi-functional Structures** – enabling smart structures with integrated functions such as embedded sensors within structural members
- **Fabrics** – allow for flexible applications with multiple properties and materials

Image courtesy Ashley Reichardt under the direction of Professor Peter Hosemann, UC Berkeley under a contract for JPL

JPL Image by Raul Polit-Casillas

Combination of Multiple Assemblies

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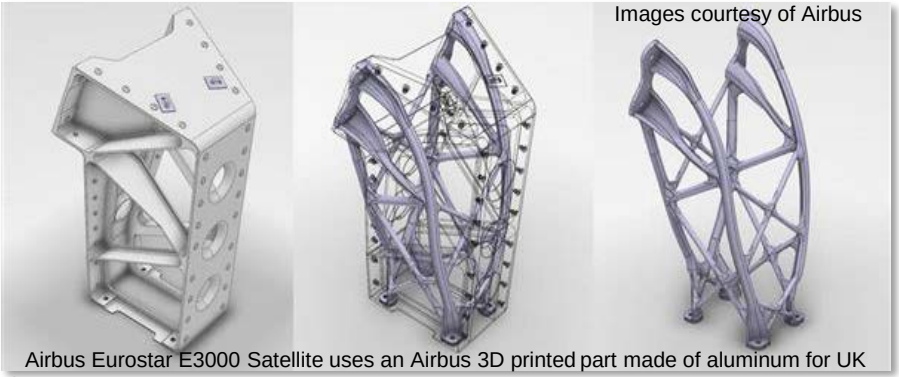

Airbus Eurostar E3000 Satellite uses an Airbus 3D printed part made of aluminum for UK Space Agency

- The elimination of joints through the intelligent combination of multiple parts, coupled with design optimization methodologies
- Eliminate or minimize welding/brazing, bolted or riveted designs, which can simultaneously reduce weight, cost, complexity, integration and schedule
- Design optimization can result in unique or organic part architectures that cannot be accomplished for the same cost using conventional processing methods

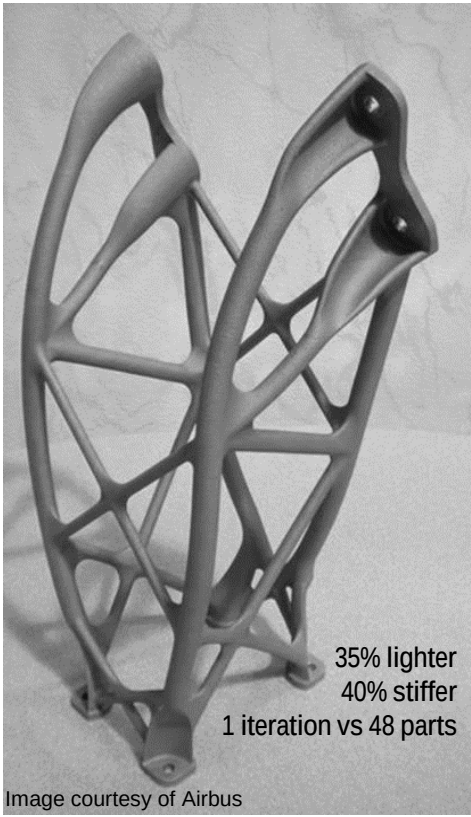

Image courtesy of Airbus

High Complexity Parts

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- A major thrust, that has been underutilized in aerospace, is the creation of high complexity parts that have both internally and externally complex features
- Complex functions can now be tailored to meet space constraints, such as multiple attachment points with 3-D flow passages

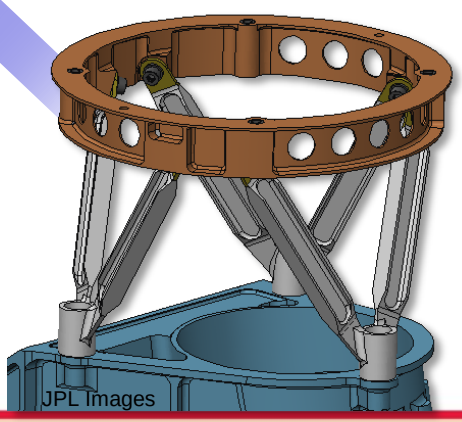
Optimized complex 3-D Printed Part.
Image courtesy of ARUP

Image courtesy of ESA.

Mass Reduction

Mars Science Laboratory UHF Antenna Assembly

- Initial state (above left): 4-piece assembly with 6 bolted joints
- Final state (above right): 1-piece assembly
- 19% reduction in mass, as well as part count reduction



JPL Images

- Deep space exploration, and satellite launch, both have significant weight constraints ($10,000/lb to low earth orbit)
- Reduction of mass and part count can provide significant cost benefits or enable greater capability for a number of missions, particularly landers where the weight reduction goals are even more extreme

A Tool for Materials Research and Tailoring

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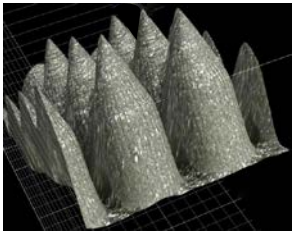
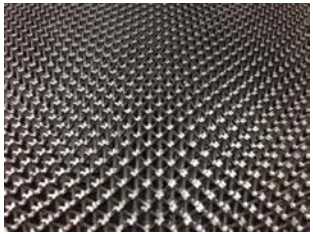
- Development of new materials can be costly, particularly with more expensive alloy components or ceramic compositions.
  - Additive manufacturing allows for reduced material/lot sizes, which can enable research opportunities that otherwise may not be financially feasible
- Microstructural tailoring, which is impossible on a large scale for a number of processes, can be readily undertaken
  - In a single specimen, you can tailor a fatigue sensitive portion of a specimen with a fine-grained microstructure, whereas a coarse (e.g. faster build, slower dwell) microstructure will suffice for the remainder of the specimen, allowing micro-scale manipulation of the microstructure
  - The additive of selective agents, such as microspheres or toughening/hardening agents, akin to the original oxide dispersion strengthened superalloys, can be readily achieved and demonstrated for viability, further enabled by the rapid number of variations that can be procured in a single build





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In Situ Fabrication and Assembly

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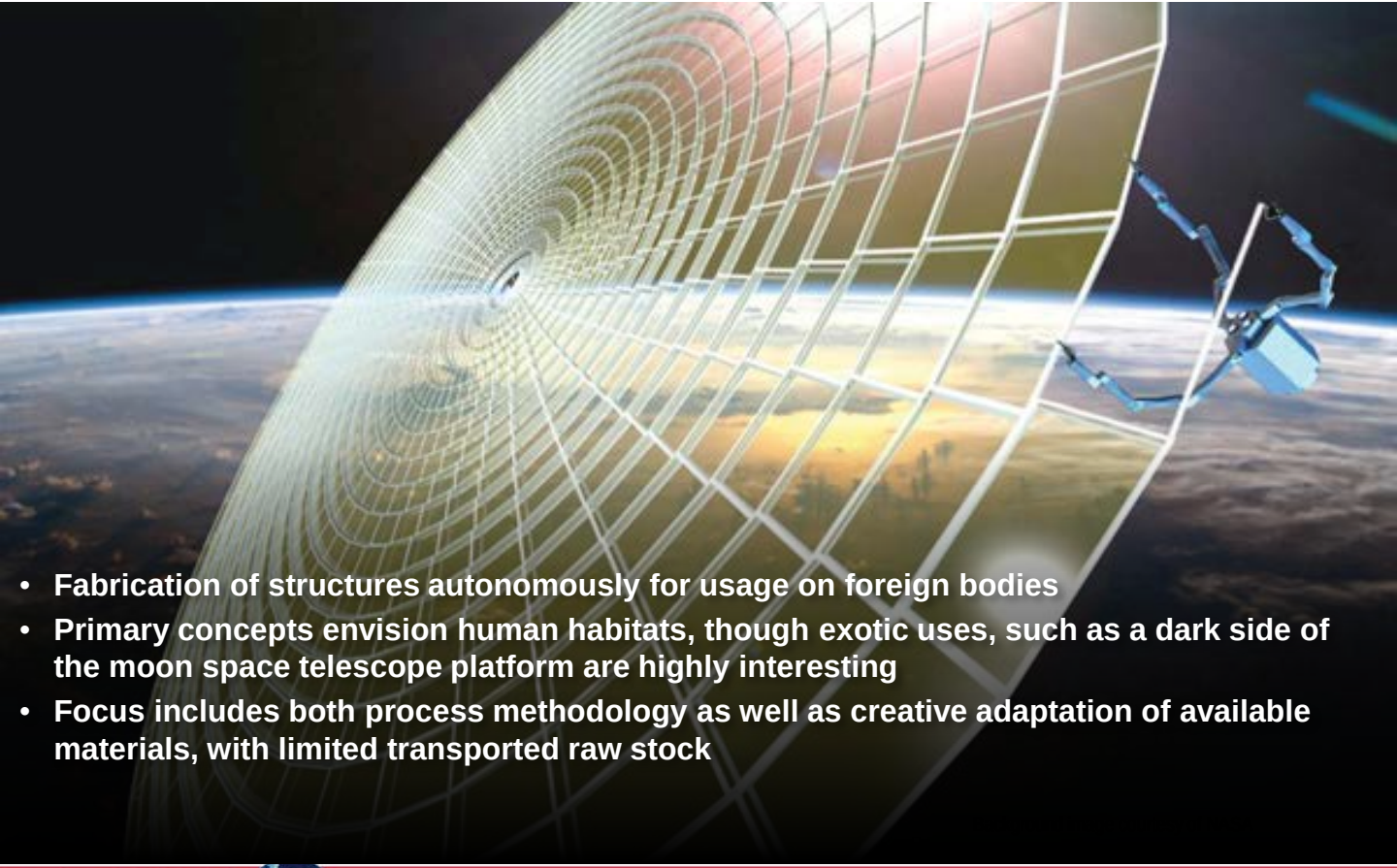
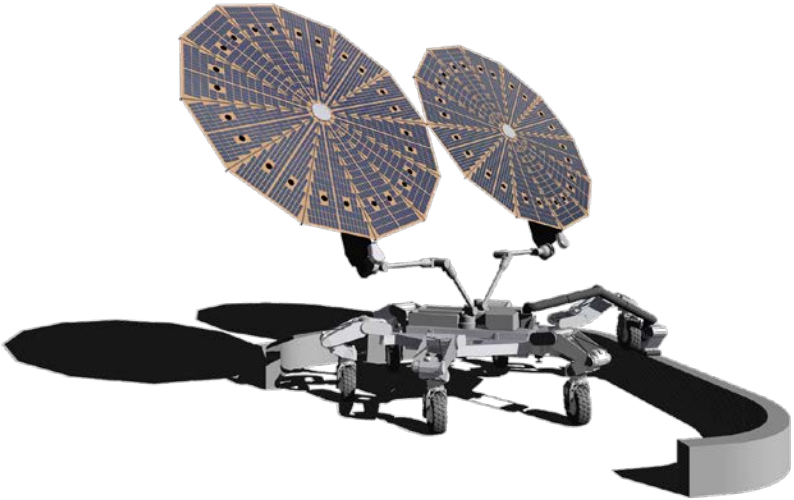


- **Fabrication of structures autonomously for usage on foreign bodies**
- **Primary concepts envision human habitats, though exotic uses, such as a dark side of the moon space telescope platform are highly interesting**
- **Focus includes both process methodology as well as creative adaptation of available materials, with limited transported raw stock**

In Situ Resource Utilization



From: JPL/KSC Wilcox, Howe and Mueller

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- Primary concepts envision human habitats, though exotic uses, such as a dark side of the moon space telescope platform are highly interesting
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Challenges

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Technical

- Basic science and engineering has not kept up with program/project desire (nationally)
- Current alloy selection non-ideal for many applications
- Materials insertion opportunities for prime missions
- Non-destructive evaluation

Programmatic

- Manned spaceflight and Class A missions require A-basis for primary structure, B-basis for secondary structure
- Robust supplier base

Process Challenges

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- **Electron beam (EBM)**
  - High heat flux results in complicated localized melting patterns
  - Fine particles can vaporize, resulting in larger powder sizes and increased surface roughness
  - Surface finish directly affects high-cycle fatigue strength
- **Laser process (powder bed)**
  - Residual stresses from rapid cooling are significant
  - Lack of high temperature (200 °C vs 700 °C) results in no stress-relief
- **Laser process (powder feed)**
  - Non-ideal for thick wall
  - Less atmospheric control

Ti-6Al-4V, as-built (EBM)

Images courtesy Aerojet Rocketdyne Inc.

Materials Development Data

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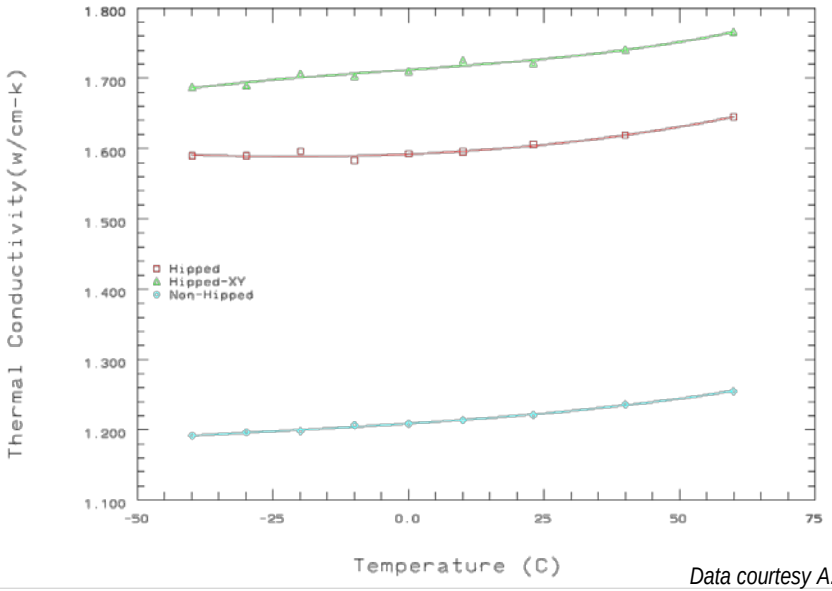
AlSi10Mg (Direct Metal Laser Sintering)



Data courtesy A.J. Mastropietro & D. Forgette (353K)

Residual Stresses

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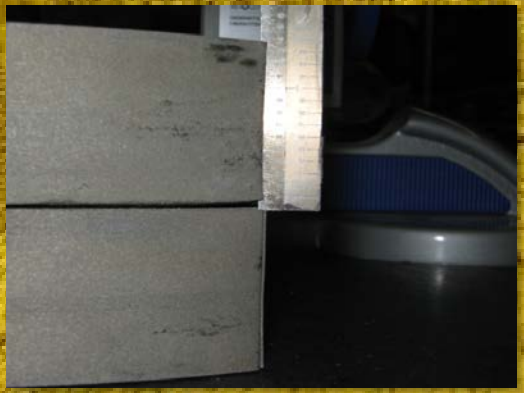

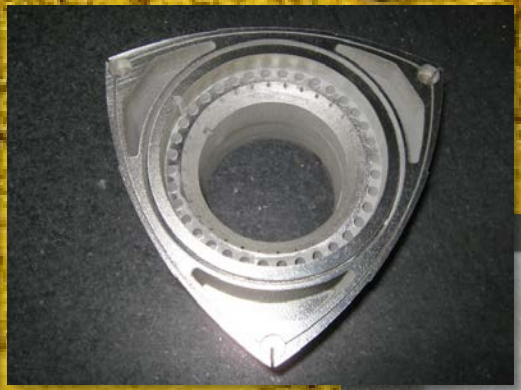

Direct Metal Laser Sintering (DMLS), EOS M270

Images courtesy Aerojet Rocketdyne Inc.

Typical Build Defects

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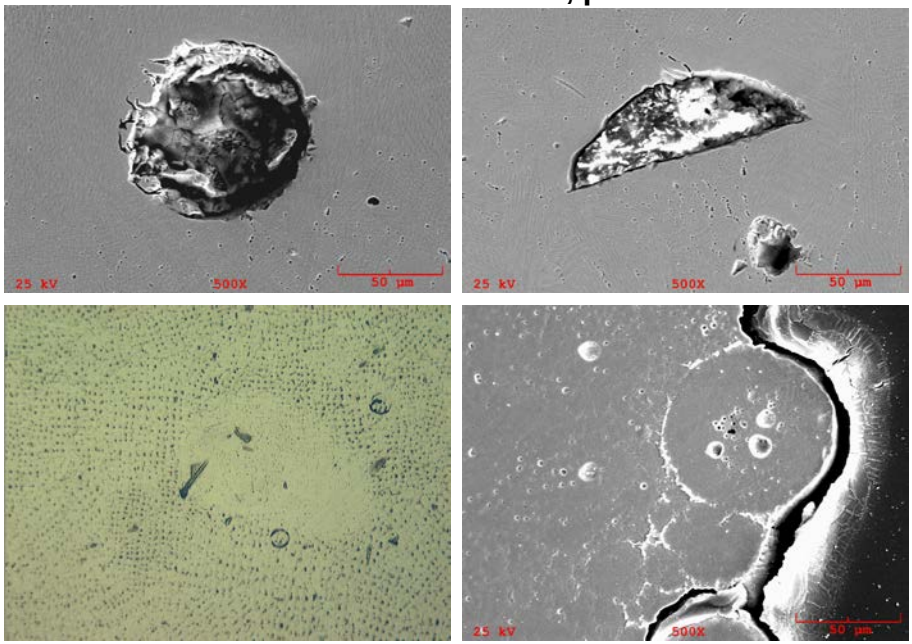
- Incomplete homogenization
- Particle knitting
- Trapped powder
- Porosity
- Non-equiaxed microstructures

Electron beam melted Inconel 625, polished and etched



Images courtesy Aerojet Rocketdyne, Inc.

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