EPFL

Additive Manufacturing in the Aerospace Sector

ME-413

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X.x. Template

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- Subtitle: 18
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- Text: 15 , 1.5
- Spacing: 1.5

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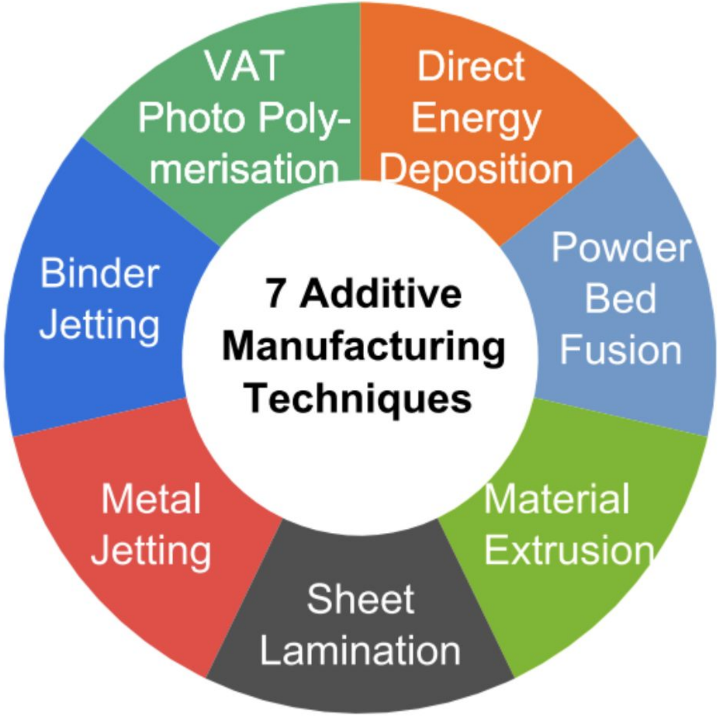
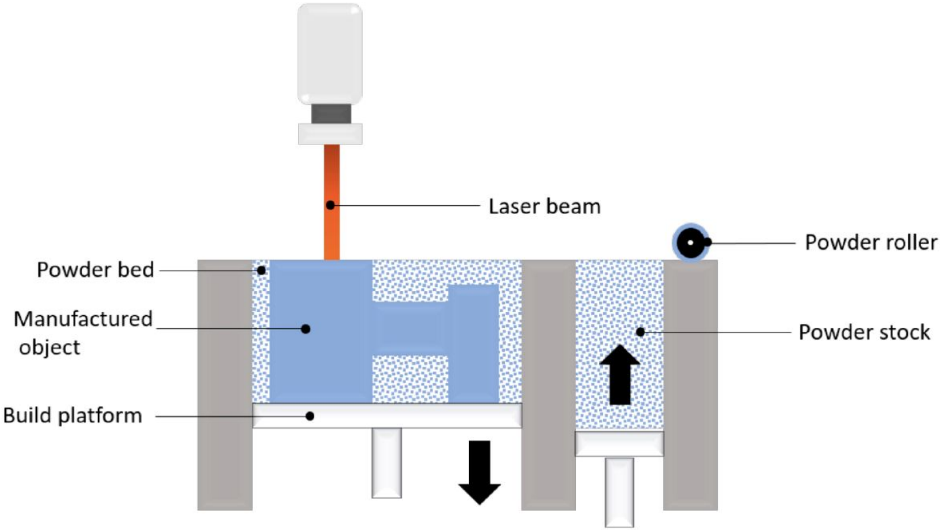
Introduction

1. AM Processes

1.1. AM Process Families

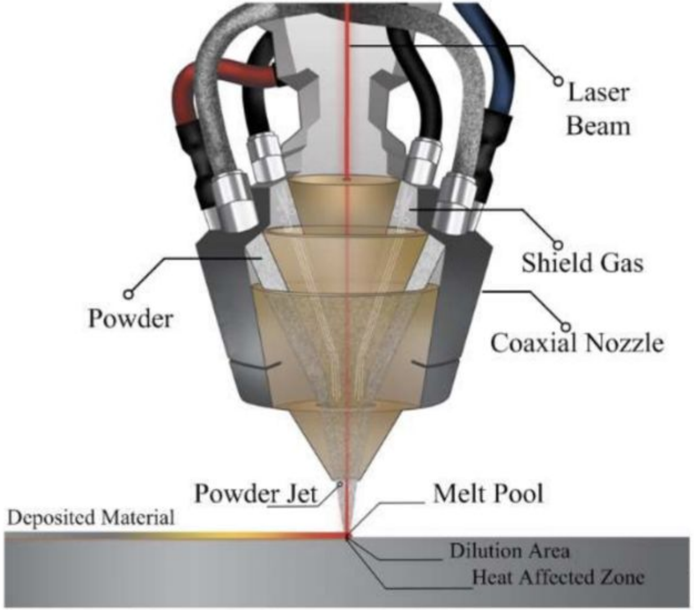


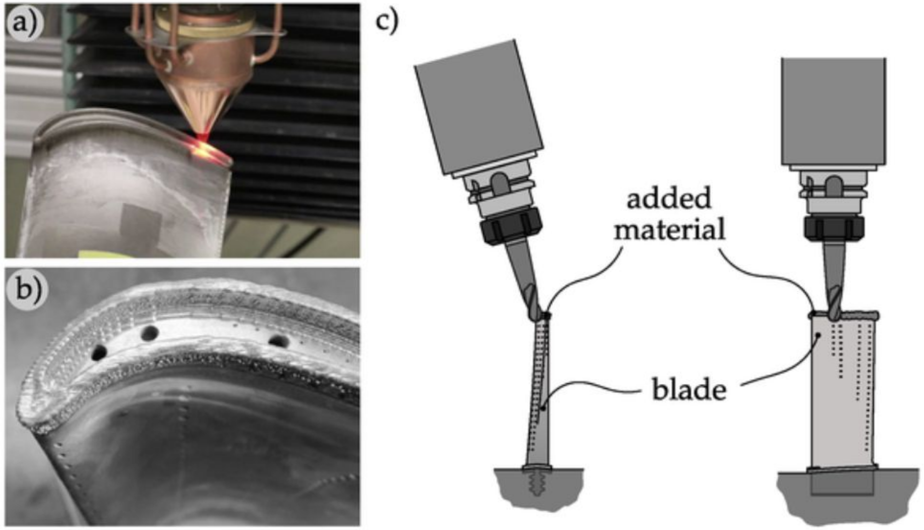
1.2. Selective Laser Melting (SLM)



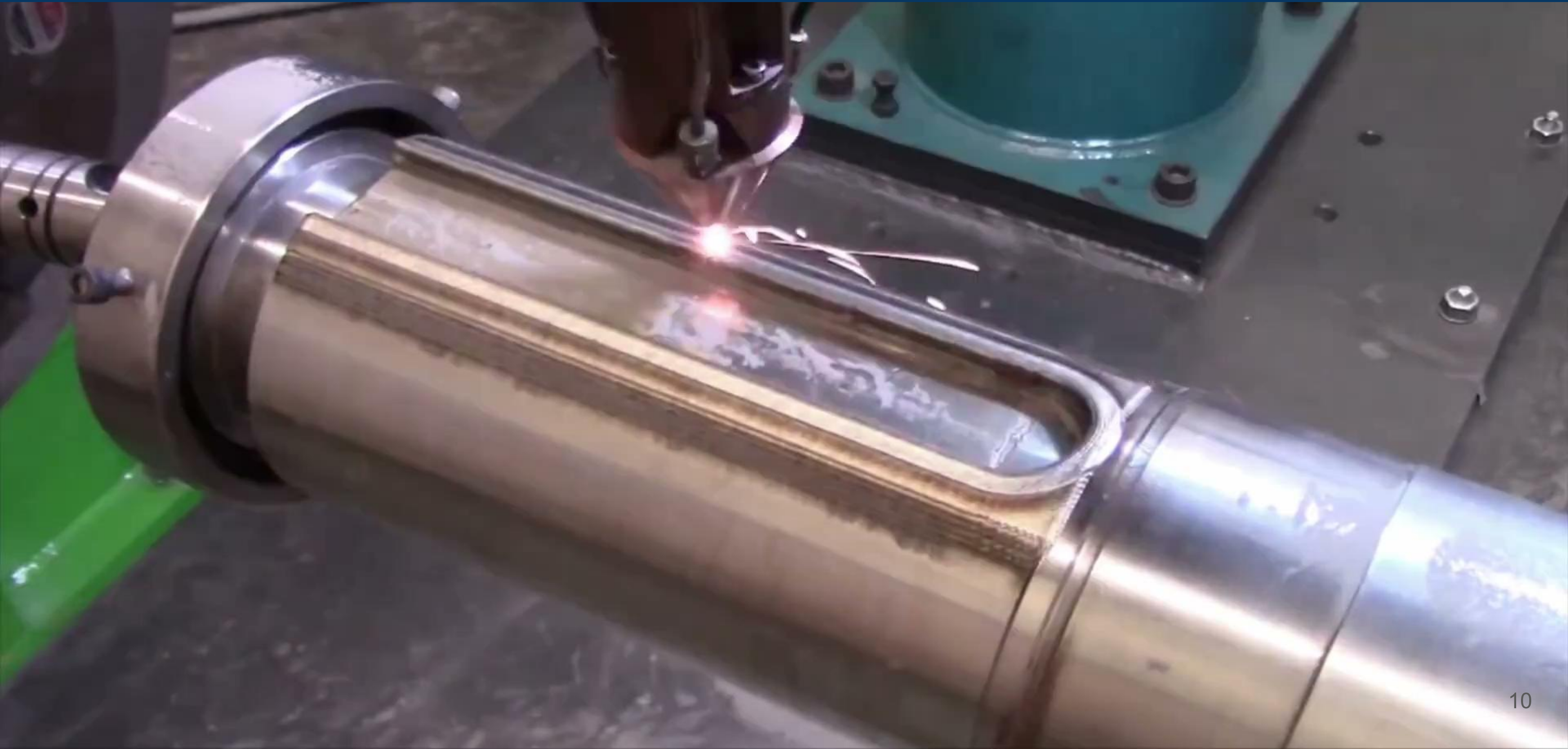
1.2. Selective Laser Melting (SLM)

1.3. Laser Metal Deposition (LMD)

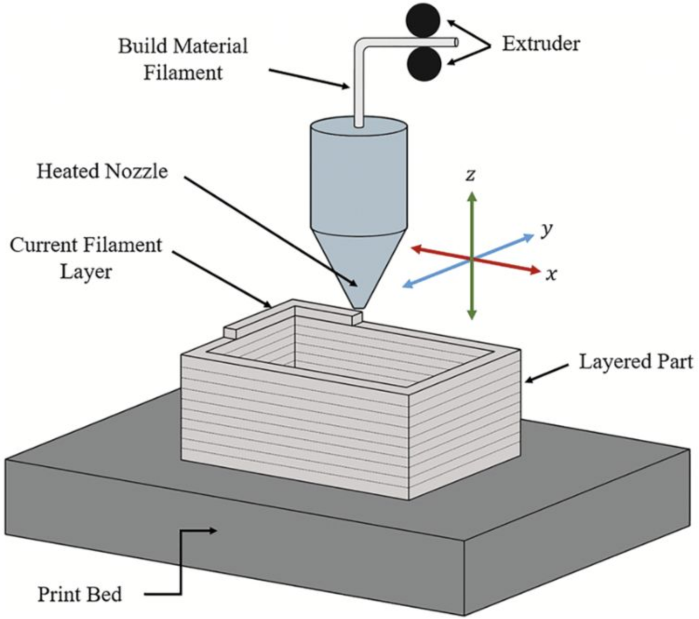




1.3. Laser Metal Deposition (LMD)



1.4. Fused Deposition Modeling (FDM)

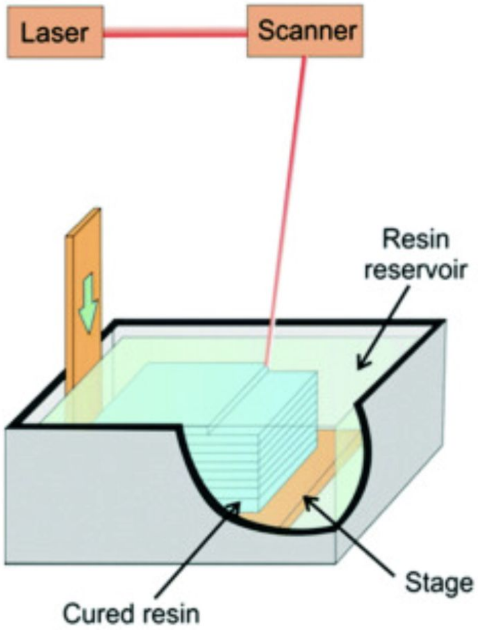


1.4. Fused Deposition Modeling (FDM)

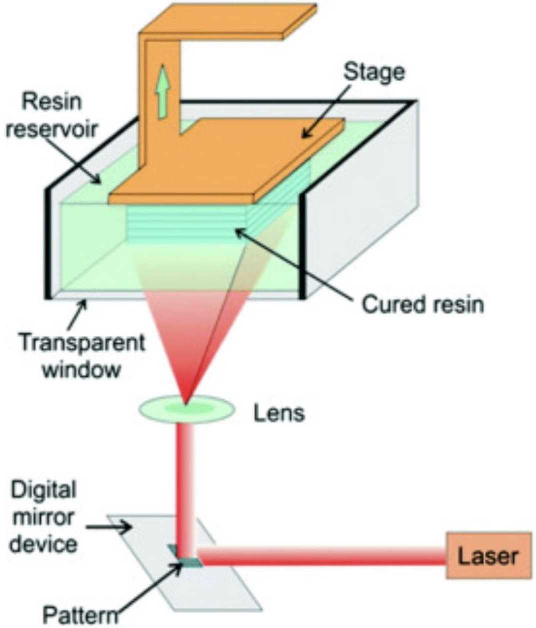
1.4. Fused Deposition Modeling (FDM)

1.5. Stereolithography (SLA)

Top-down System



Bottom-up System

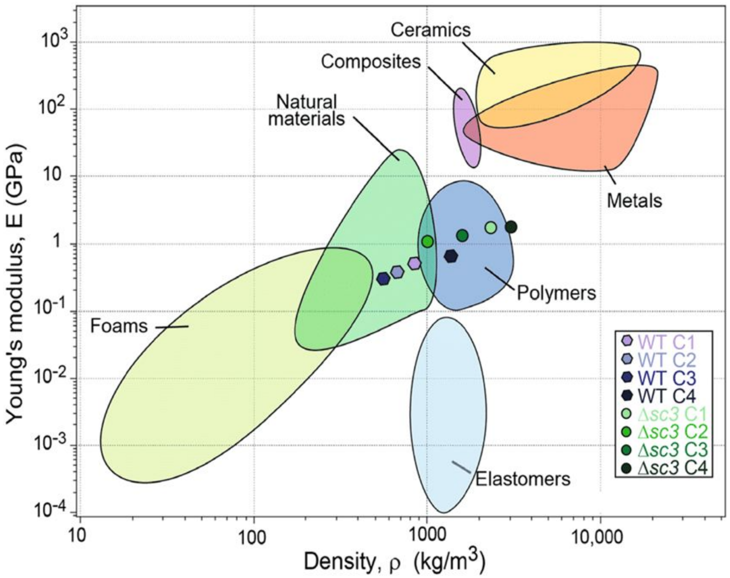


1.5. Stereolithography (SLA)

2. Materials in Aerospace

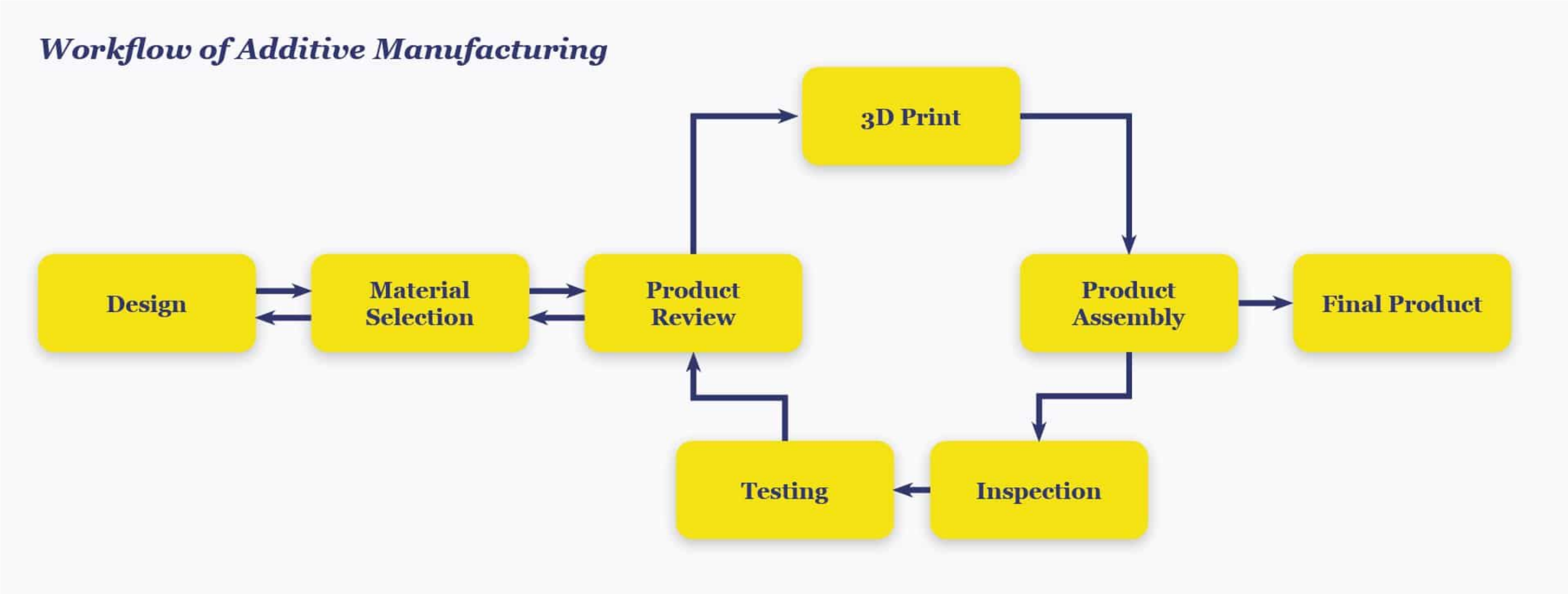
2.1. Overview

- Material: *"Substance or a mix of substances from which a part or structure is made, characterized by physical, chemical, and mechanical properties that determine its performance."*

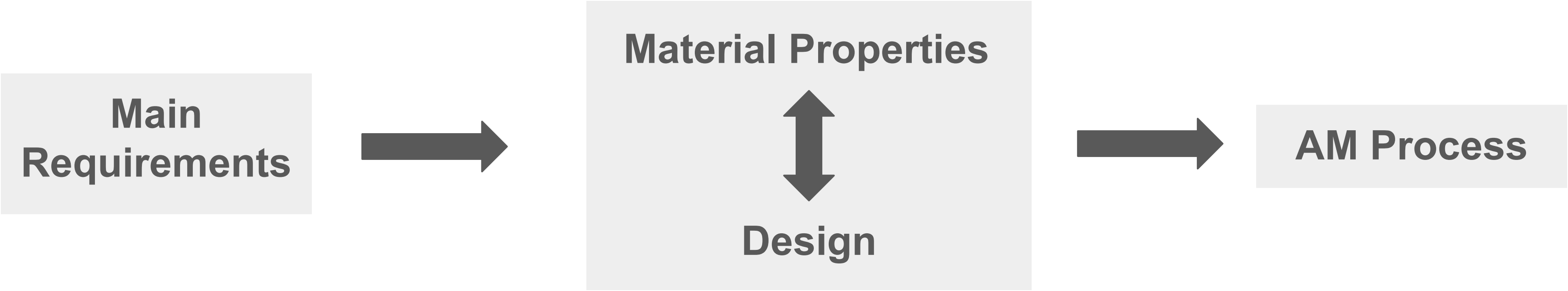


Ashby Diagrams

2.1. Overview


Workflow of Additive Manufacturing
3D Print
Design
Material Selection
Product Review
Product Assembly
Final Product
Testing
Inspection

2.2. Aerospace Key Requirements



2.3.1 Material in Aerospace - Metals

Advantages	Limitations
- Mechanical strength/ Ductility	- Residual stresses
- Thermal Resistance	- Porosity
- Corrosion resistance	- Anisotropy
- Lightweight Options	

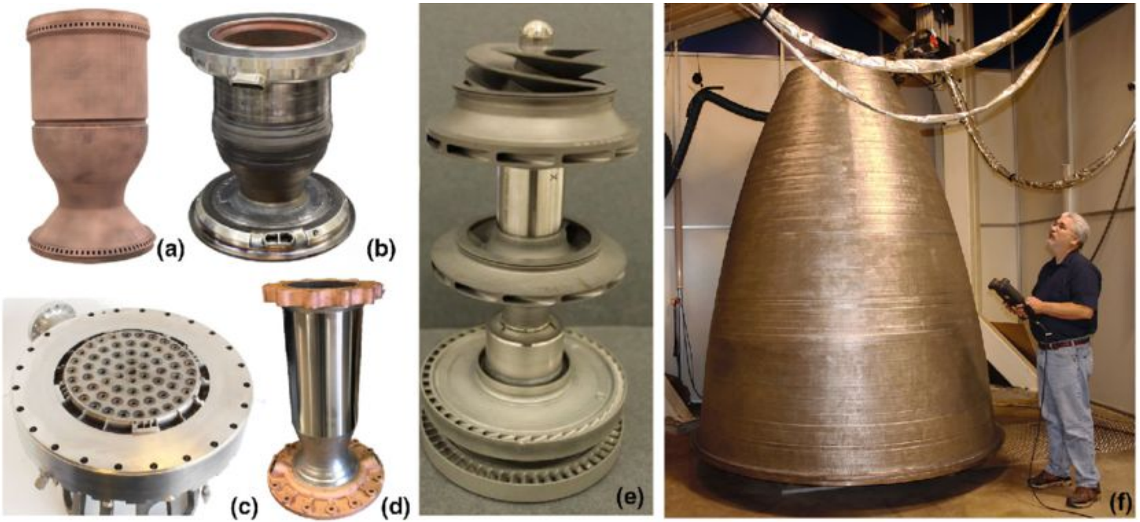
2.3.1 Material in Aerospace - Metals

Application:

- Structural Elements
- Cryogenic fuel tanks/pump/…
- Components with cooling challenge

Process

- SLM - Selective laser Melting
- LMD - laser Metal Deposition
- WAAM - Wire Arc Additive Manufacturing
-



2.3.2 Material in Aerospace - Polymer

Advantages	Limitations
- Lightweight - Corrosion-resistance - Can be recyclable (thermoplastics) - Lowcost	- Low mechanical/thermal resistance/ - Outgassing/UV problem - Porosity/ Anisotropy/ Residual stress (AM)

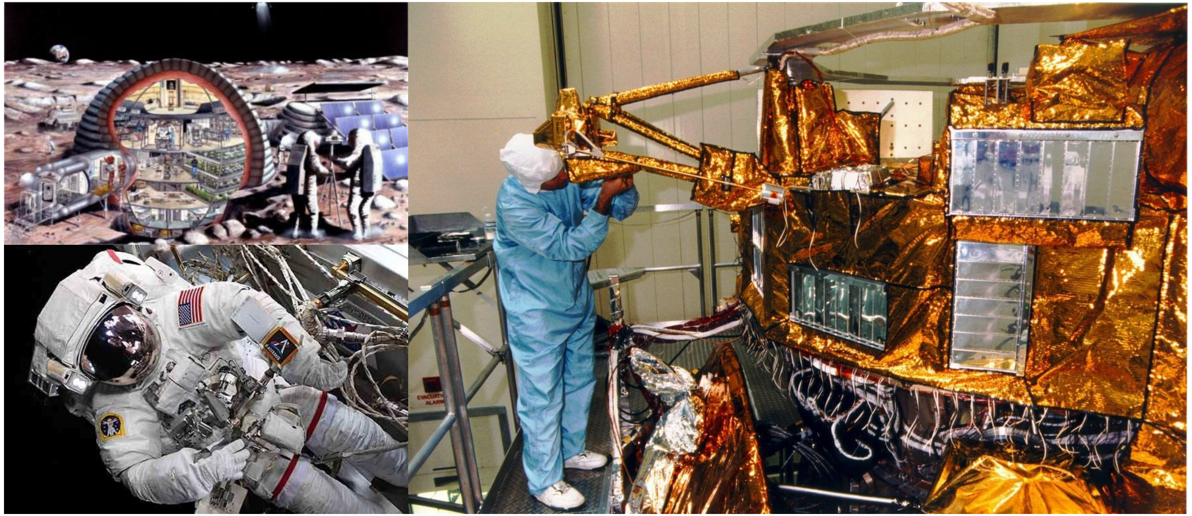
2.3.2 Material in Aerospace - Polymer

Application:

- Thermal Blanket
- Lubricants/ Coating/ Adhesive
- Inside parts
- Prototyping

Process

- FDM - Fused Deposition Modeling
- SLA – Stereolithography
- MJM - Multi-Jet Modeling



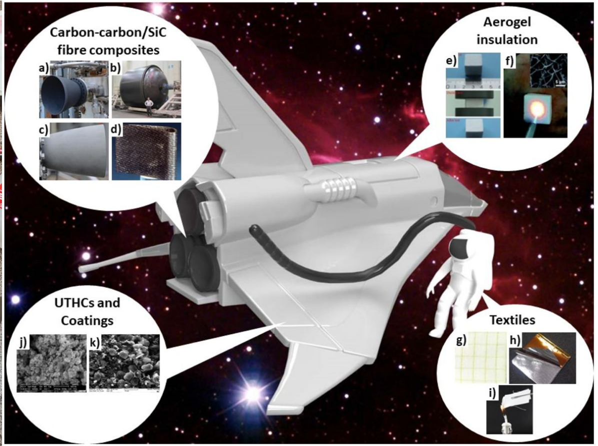
2.3.3. Material in Aerospace - Composites

Advantages	Limitations
- High strength to weight ratio - Anisotropic behavior (optimise strength and stiffness + Electrical/ Thermal Conduction)	- Difficulty to repair - Porosity/ Residual stress - Layer adhésion + fiber placement

2.3.3. Material in Aerospace - Composites

Application:
- Everywhere (Structural elements/ Surface/Coating/…)

Process:
- Powder bed fusion
- LOM - Laminated object manufacturing
- Photopolymérisation



2.3.4. Material in Aerospace - Ceramics

Advantages	Limitations
- High Temperature Resistance - Oxidation resistance - Lightweight - Electrical resistance	- Brittleness - Porosity/ Residual stress - Sintering & densification

Steps for Ceramic AM

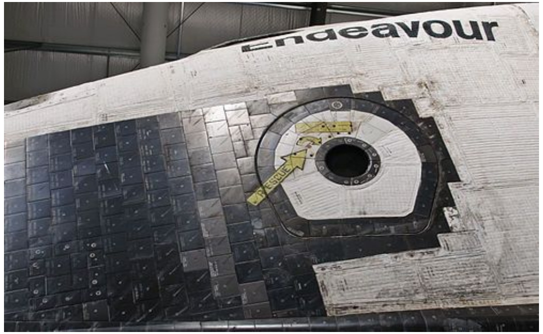
2.3.4. Material in Aerospace - Ceramics

Application:

- Thermal protection tiles
- Thermal heat shield
- Insulating spacer
- Propulsion Nozzle / blades

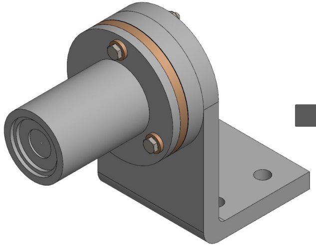
Process:

- FEF - Fused Extrusion Fabrication
- SLA - Stereolithography



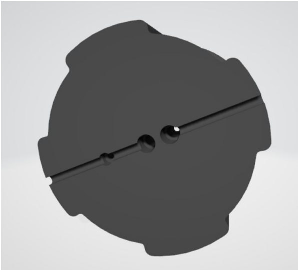
AM Real Case exemple

Ceramic Part Formlab SLA + PETG Prototyping

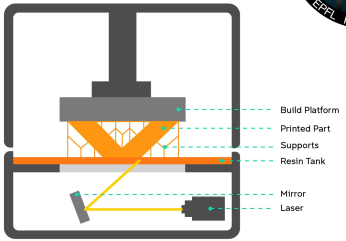


- Design
- Material choice

- 1st Prototype
- Spacing
- Wiring



- depressurized canals
- Shrinkage dimensionnement



- SLA
- Maintenance

Source	XY Shrinkage	Z Shrinkage	Comment
Formlabs Datasheet	21.8%	26%	Official reference values provided by Formlabs for Alumina 4N resin
Dilatometry Test	20.8 %	16%	Small 5 mm test sample. Shrinkage began at 1150°C
Measured on Thruster Parts	$18.2 \pm 0.9\%$	$21 \pm 0.8\%$	Measured from printed thruster components after sintering

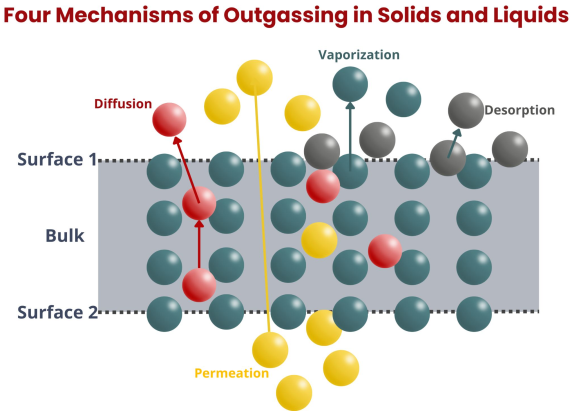
2.4 Material Challenges in Aerospace

- Vacuum Compatibility
- Atomic oxygen erosion
- UV radiation
- Other Phenomena

2.4.1. Vacuum compatibility

- **Outgassing:**
  - Condensation near elec components (short circuits, arcing, sensibility,...)
  - Structural damage
  - Surface/Coating changements
- **Cold welding**
- **Heat Transfer**

- **Criterias Outgassing:**
  - **TML <1%**
  - **CVCM < 0.1%**
  - **Outgassing rate < Requirements**



Outgassing principle

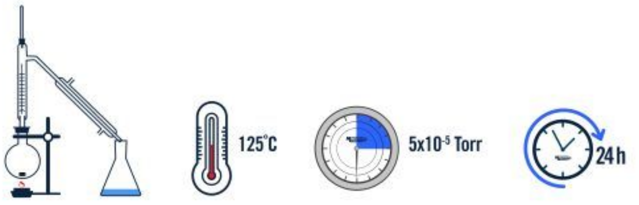
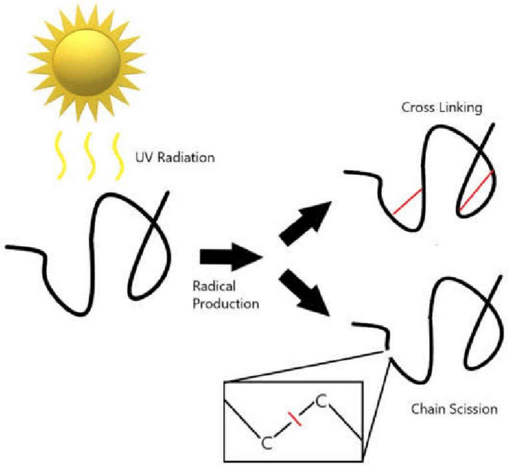


Figure 1: Basic test setup for performing outgassing per ASTM E595

Outgassing Quantification

2.4.2. UV Radiation

- **UV Radiation**
  - Photolysis: Bond breaking (Polymer)
  - Atomic oxygen (Next slide)
  - Cross linking
  - UV heating => increase outgassing
- **Mitigation**
  - Resilient material (Fluoropolymer
  - Shielding)



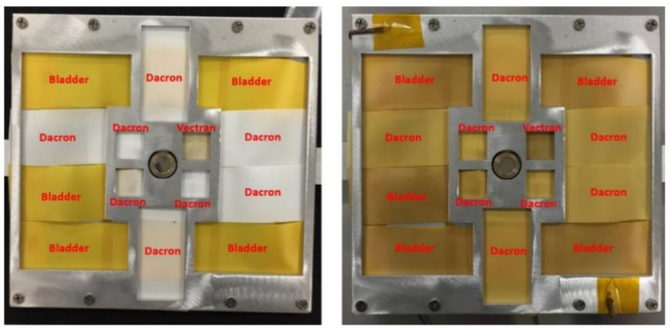


Fig. 5: Pre/Post Radiation of Polycarbonate after UV radiation

500 day Mars condition

- Vectran 59% tensile strength decrease
- yellowing (visibility issue)
- <0.5% mass loss
- structure changes

2.4.3 AO Compatibility

- **Atomic Oxygen Compatibility**
  - Oxygen absorb UV light => dissociation O vs O2
  - Oxidiser => Material Degradation
- **Mitigation**
  - Protective Coating
  - Resistant material (silicones and epoxies)

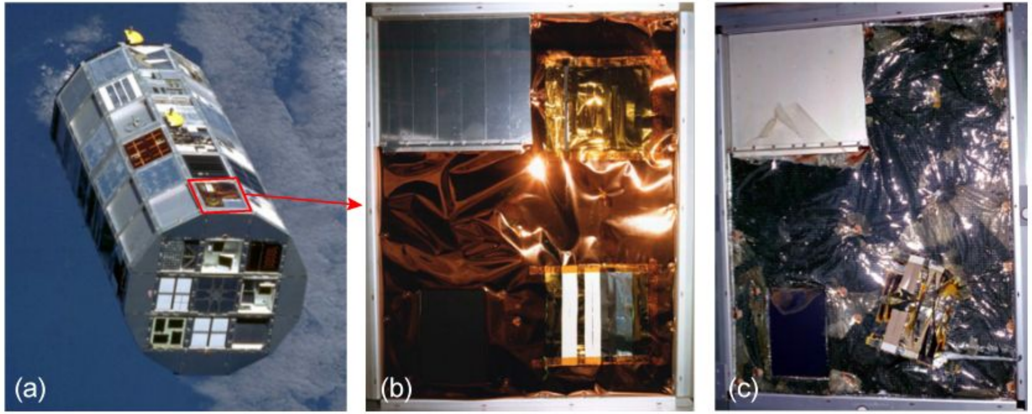
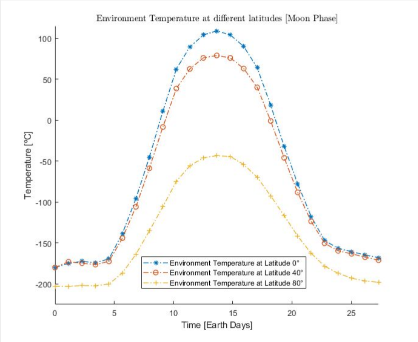


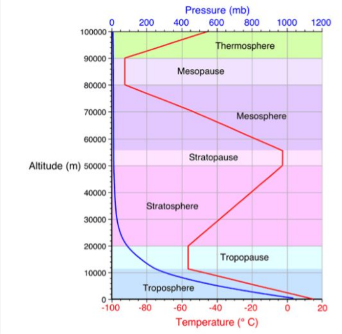
Figure 2.—Atomic oxygen erosion of a Kapton® insulation blanket from LDEF experiment Tray F-9, located on the leading edge and exposed to direct-ram AO for 5.8 years.[7] (a) LDEF. (b) Tray F-9 pre-flight. (c) Tray F-9 post-flight.

AO Influence on material

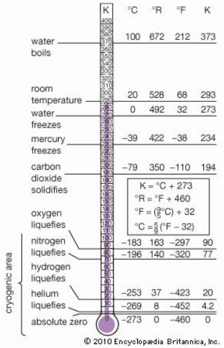
2.4.4. Other Phenomena

Thermal Changements





Cryogenic Temperature



Requirements

- Cryogenic Toughness (no ductile to brittle transition)
- Low Thermal contraction
- Superconductivity (lost electric resistance)

Mechanical Load

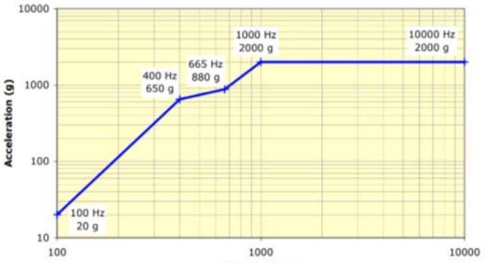


Figure 3.2.6.a – Envelope shock spectrum at spacecraft separation plane

of Ariane 5

Shock Response spectrum

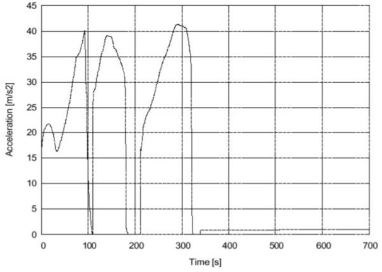
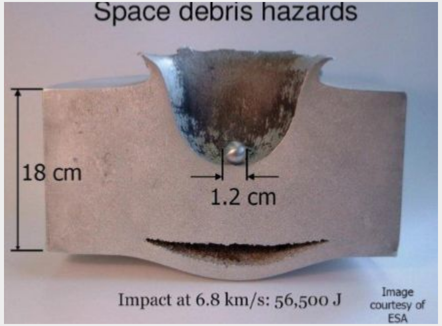
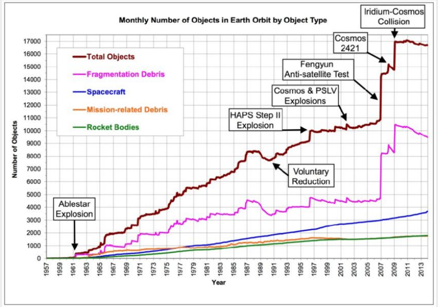


Figure 3.1 – Typical Longitudinal Steady-state Static Acceleration for the reference mission.

of the Vega Launcher

Micrometeoroid and orbital debris impacts





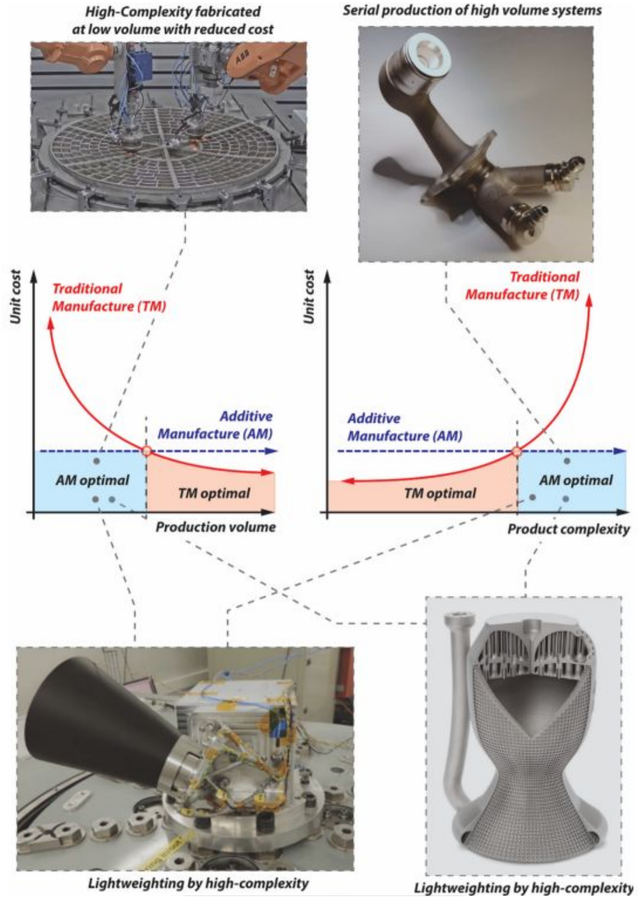
3. Applications in Spacecraft and Launchers

3.1 Overview

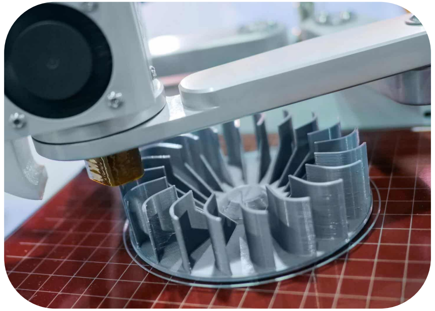
Context : After 2010 → projection of 430 billion USD by 2025

Additive Manufacturing in Space:

- Cuts lead times
- Material waste
- Optimized designs
- Enables lightweight,
- Mass reduction = fuel savings = greater range and payload.
- Very good for complex part with less important volume
- Examples: Ariane 6 injector (248 → 1 part).



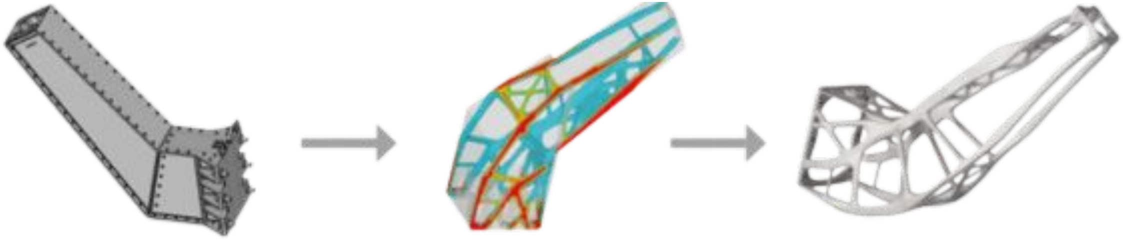
3.1 Overview

Part production	Prototyping	Repair and restore	Rapid tooling
			

3.2 Part Production for Spacecraft Structures

3.2.1 Selective Laser Melting (SLM): Sentinel-1

- AlSi10Mg
- Topology work
- 40 % of mass reduction



Original Component Topology simulation Final Part

RUAG
Aerospace Defence Technology

eos

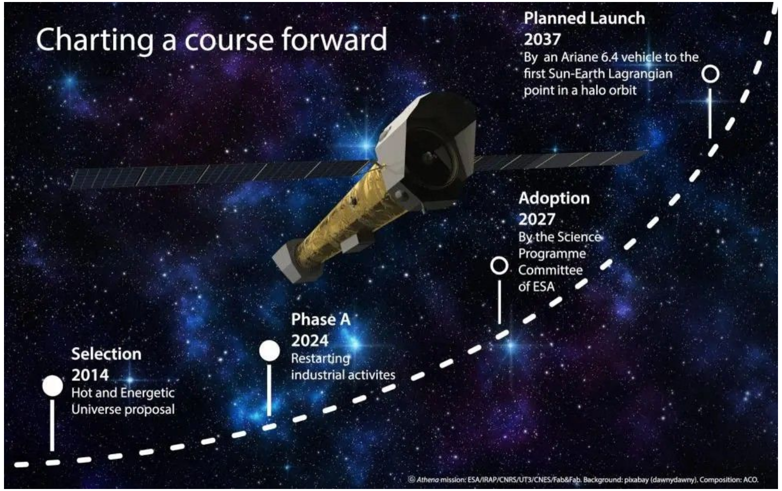
ALTAIR

NASA

3.2 Part Production for Spacecraft Structures

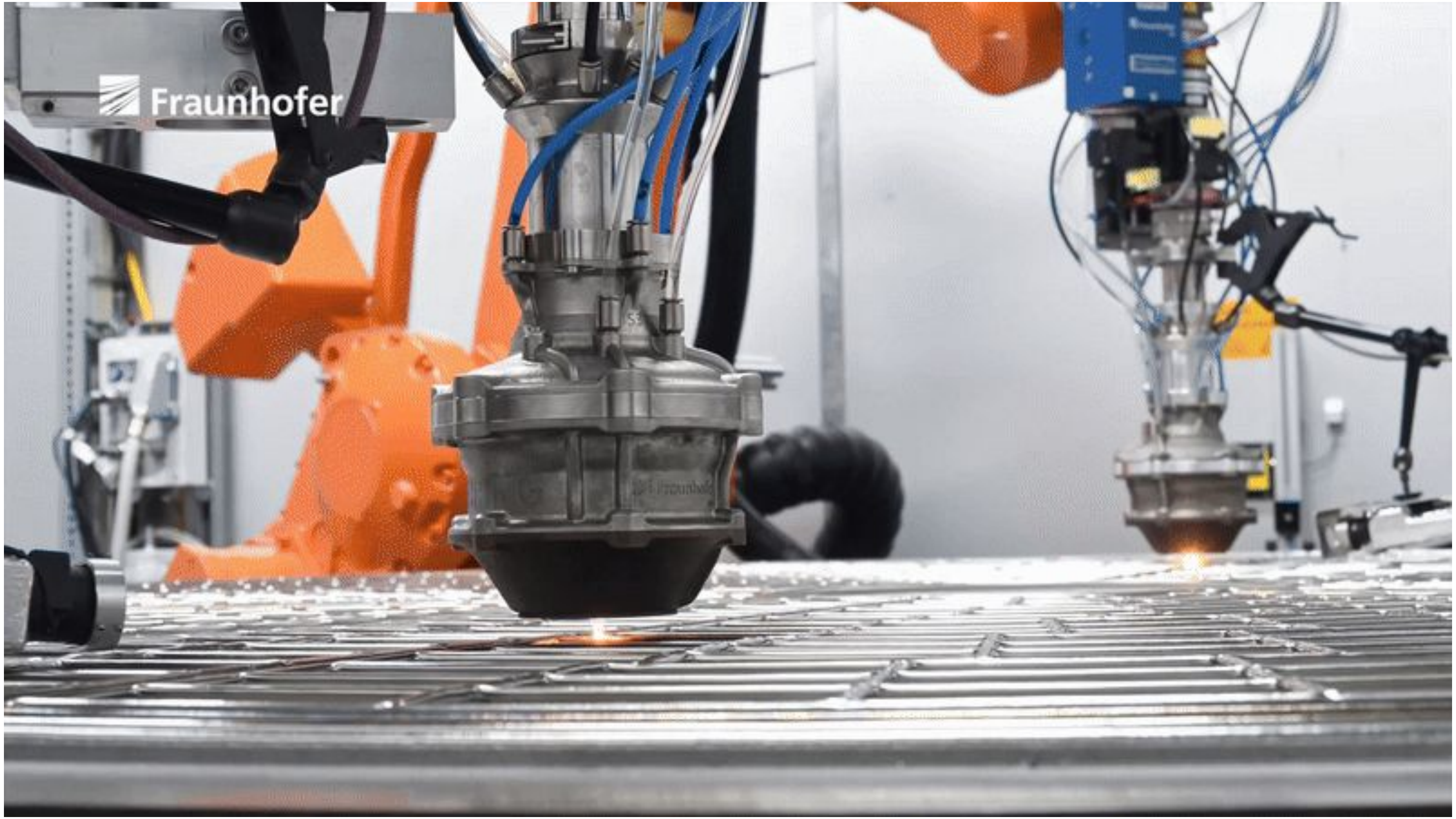
3.2.2 Direct Energy Deposition (DED): New ATHENA

- Hybrid cryogenic machining
- Ti6Al4V
- Volumetric Part



3.2 Part Production for Spacecraft Structures

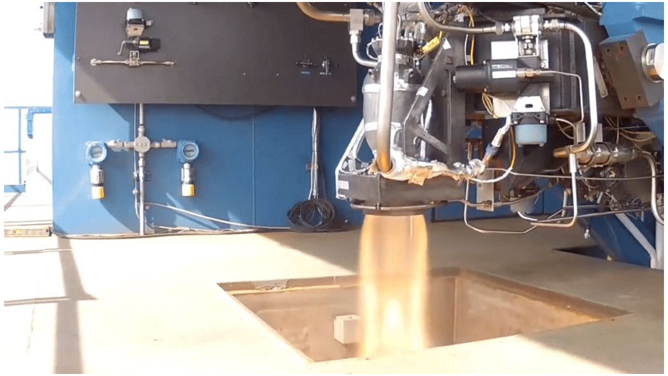
3.2.2 Direct Energy Deposition : New ATHENA



3.3 AM for Propulsion

3.3.1 Direct metal laser sintering (DMLS) : SuperDraco

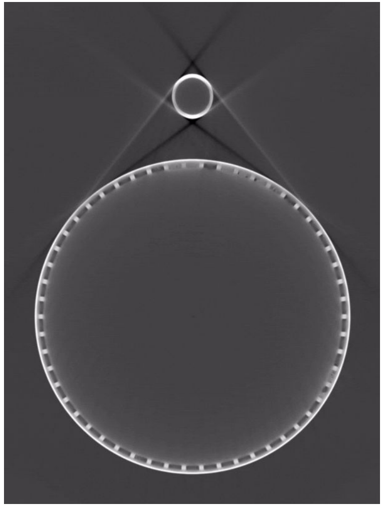
- Inconel 625
- Very high stress and temperature constraint [69 bar-3200K]
- Complex internal geometries (Injector, cooling channel)
- Reduces welds and joints
- Superior ductility + higher fracture resistance

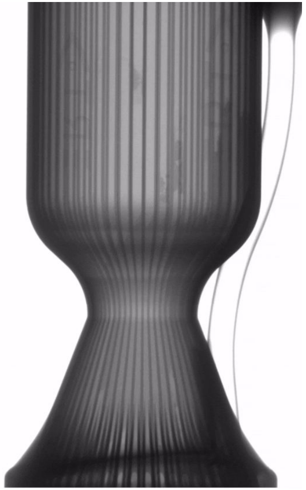


3.3 AM for Propulsion

3.3.2 Electron-Beam Direct Manufacturing (EBDM) : B2

- Inconel 718
- High stress and temperature constraint [but less than Superdraco…]
- Complex internal geometries (Injector, cooling channel)
- Printed in one part !





SBO

EPFL ROCKET TEAM

3.4 Example of reparation and restoration

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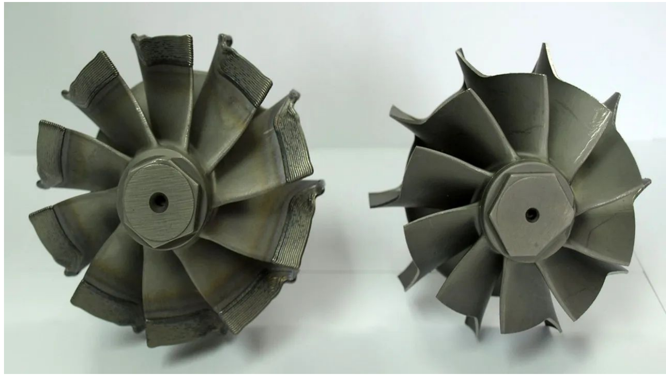
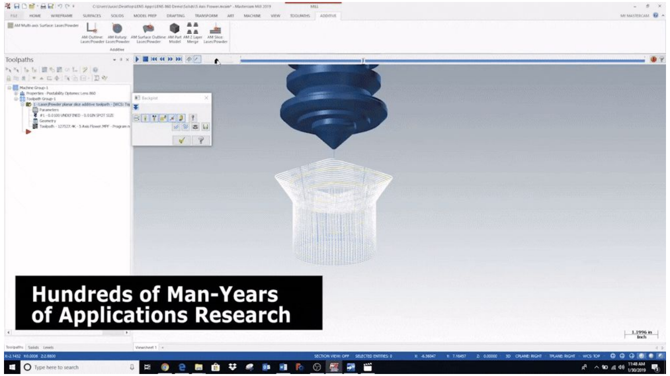
3.4 Laser-Engineered Net Shaping (LENS): Optomec

- Turbine reparation
- 10 million turbine blades yet
- Replacing manual welding
- Creation of adaptive Control Softwares : AutoCad and Autoshape

OPTOMEC®

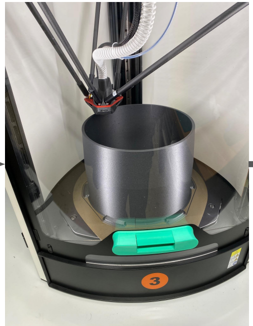




3.5 Rapid Tooling: PET CF Mold for Prepreg Carbon Layup - Bachelor Project

3.5 Fused Deposition Modelling (FDM)

- PET-CF mold (avoid swelling)
- Anneal mold before use



Laboratory for Processing of Advanced Composites

4. Applications in Aircraft and Engines

4.1.1 The Benefits Of AM in Aviation

- **Topology optimisation** → Structural weight reduction
- **Fewer parts** → Fewer assemblies, smaller inventory
- **Shorter production time**
- **Better inventory system**

4.1.2 Example of Weight Reduction

- AddUp's **floor bracket** with SLM at 50 µm layer thickness.
- ↘ 10.83 kg of raw material savings.
- ↗ More resistant.

Machining time :

14.5 hours → 11.5 hours

Mass :

3kg → 1.17 kg

4.1.3 Example of Fewer Parts

- GE aerospace's **fuel nozzle** with LPBF using cobalt-chrome alloy.

↘ Reduction from 20 to only 1 part.

↘ 25 % weight reduction.

↗ 5 times more durable.

↗ 30 % cost efficiency improvement.

↘ 95 % inventory reduction.

Better in every point !

4.1.4 Major Firms Using AM

EPFL

GE Aerospace

100 YEARS OF POWERING THE FUTURE — PRATT & WHITNEY — DEPENDABLE ENGINES

AIRBUS

SAFRAN

LOCKHEED MARTIN

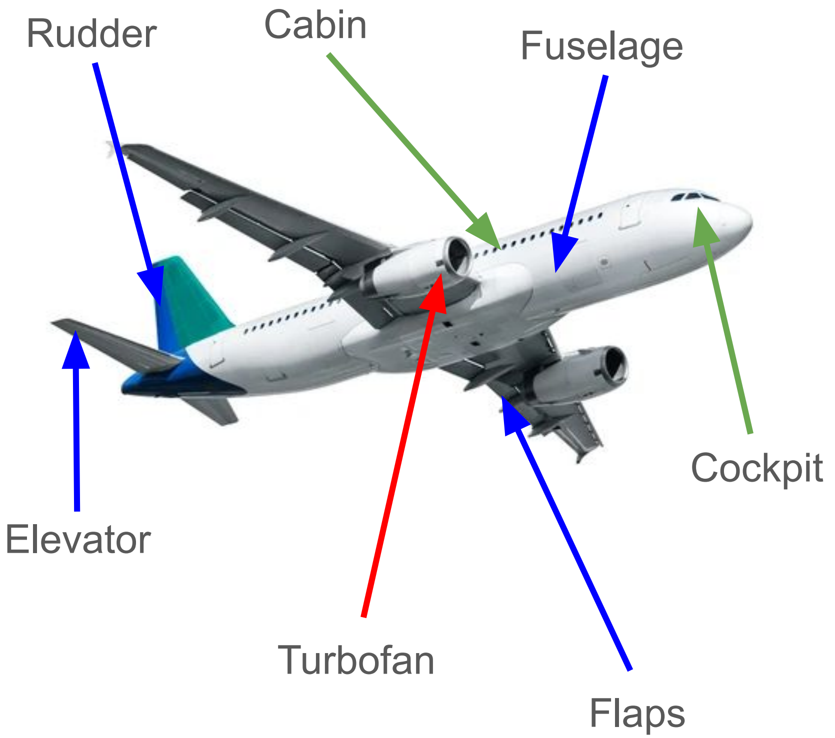
ROLLS-ROYCE

BOEING

Rolls-Royce

4.2.1 AM in Key Aircraft Components

- **Components and their main constraints :**
  - Engines and Turbines → high thermal and mechanical stress
  - Structural and control components → geometric precision and reduced mass
  - Interior parts → flame retardancy, vibrations and design



4.2.2 Engines and Turbines

- **Tail bearing housing** used on Rolls-Royce turbofan (SLM)
- Made with nickel-based and lightweight alloys

- **Turbofan** GE9X for the Boeing 777X
- Many printed components
- World's largest and most efficient commercial turbofan

Rolls-Royce

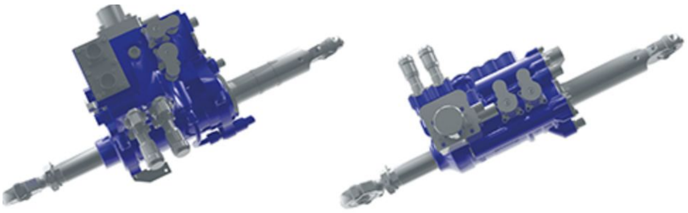
GE Aerospace

BOEING

4.2.3 Structural and Control Components

- Boeing 777 - Titanium **Structural Brackets**
- EBM (Electron Beam Melting)

- Airbus A350 - Titanium **Spoiler Bracket**
- LPBF (Laser Power Bed Fusion)



- **Actuator** developed by Liebherr
- Don’t know the process and materials

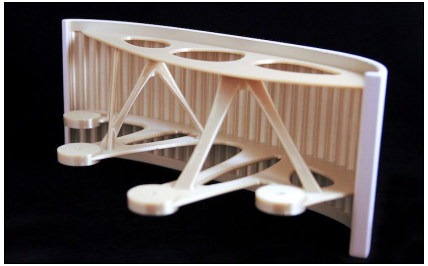
BOEING

LIEBHERR

AIRBUS

4.2.4 Interior Parts

- **Flame-retardant photopolymer** for AM (Still in development)
- **Little plastic parts** used by Airbus (SLA)
- A lot of **seat components** (FDM)



Lufthansa Technik

Marshall

AIRBUS

materialise
innovators you can count on

4.3.1 Maintenance, Repairs and Spare Parts (MRO)

EPFL

- **Faster**, **more flexible**, and more cost-effective maintenance operations
- **On-demand**, **localized production** of certified spare parts
- **Reduced material waste**, no tooling, and **direct manufacturing from digital files**

4.3.2 Essentium Partnership with USAF

EPFL

- USAF needs **fast, cost-efficient** aircraft repairs
- **Partnership** with Essentium to adopt high-speed extrusion solutions

- Reduces downtime **from weeks to hours/days**
- Other Partnerships for little pieces and optimisation

U.S. AIR FORCE

OPTOMEC®

BotFactory

ESSENTIUM

4.3.3 Boeing’s Flight-Ready Spare Parts

EPFL

- **3D-printed repair kits** for damaged aircraft panels (Boeing 737)

- **Durable** and **efficient**
- Reduces **costs**, **material waste**, and **turnaround time**
- Flame-retardant polyamide piece for the Dornier 328

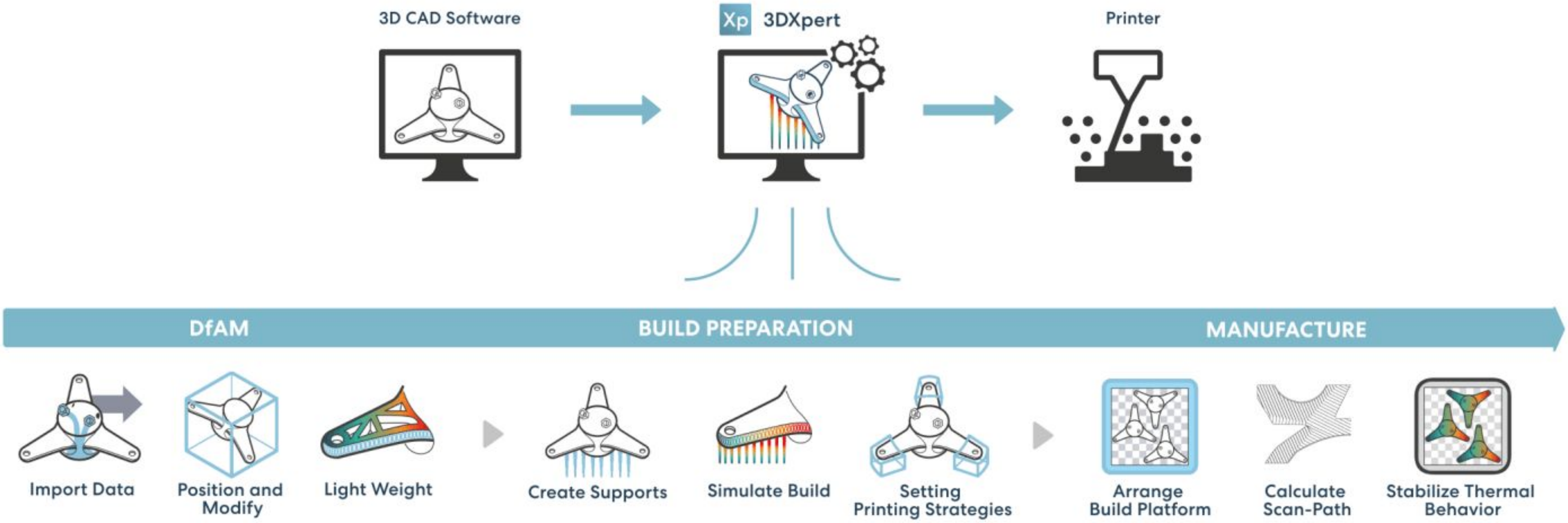
(expleo)

BOEING

DORNIER

materialise
innovators you can count on

4.4 Standards, Quality Control and Certifications



FAA Certified

EASA European Aviation Safety Agency

ASTM INTERNATIONAL

SAE Strategic Account Executive Certified Professional

EPFL

5. Limitations

5.1 Low fatigue performance (case study on Inconel 718)

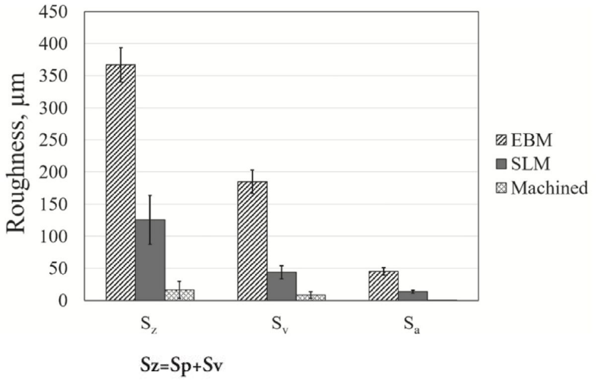
5.2 Process Induced Defects

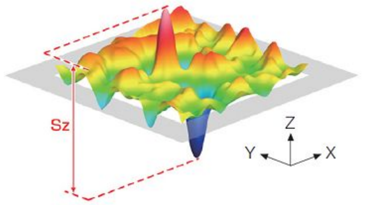
5.3 Certification and qualification

5.4 Low productivity (currently)

5.1 Limitations: Low fatigue performance of Inconel 718

- Pores and high roughness
- Early crack initiation
- Machining decreases roughness
- HIP and machining increase fatigue life





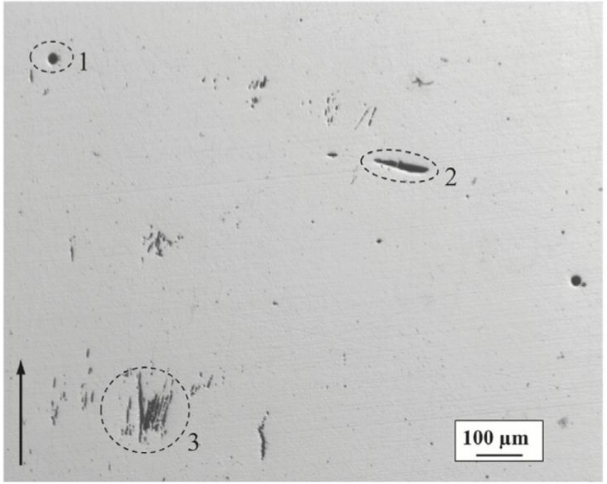
Material	Process	Fatigue life (cycles)	ΔK_{th} (MPa$\sqrt{m}$)	Remarks
Inconel 718	Forged and aged	10^5–10^6	5–6	Isotropic microstructure; intergranular cracks
Inconel 718	SLM / EBM as built	10^4–10^5	3–4	Crack initiation at pores and rough surfaces
Inconel 718	AM + HIP + machined	10^5–10^6	4–5	Comparable to wrought material

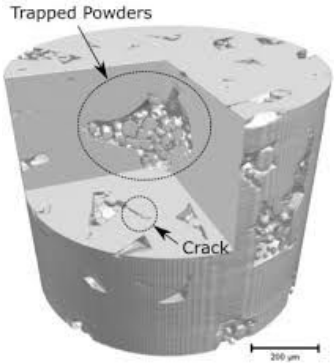
5.2 Limitations: Process Induced Defects

On the image:

- Pore
- Shrinkage porosity
- Lack of Fusion

- Residual stresses and distortion
- Importance of stress relief heat treatment





5.3 Limitations: Certification and Qualification

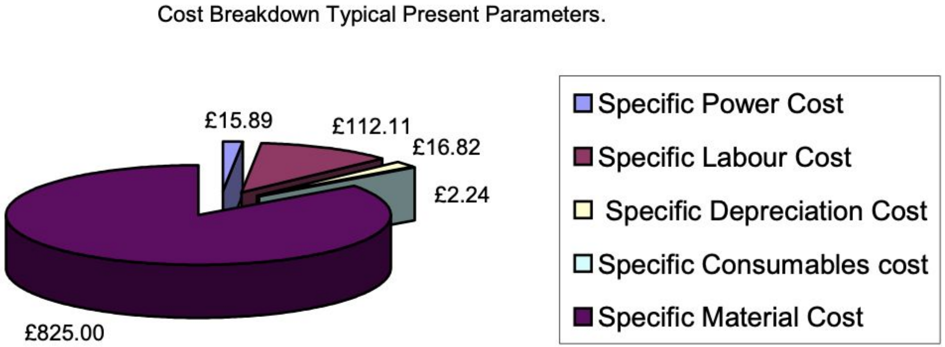
EPFL

Building Block Test Structure Required for Certification		Specimen Count	Cost ($M)	Time (Yrs)
Analysis Validation	Full-Scale Article	2-3	100-125	4
	Components	10-30	10-20	3
Design-Value Development	Sub-components	25-50	10-35	3
	Elements	2,000-5,000	10-35	3
Material Property Evaluation	Coupons	5,000-100,000	8-15	2

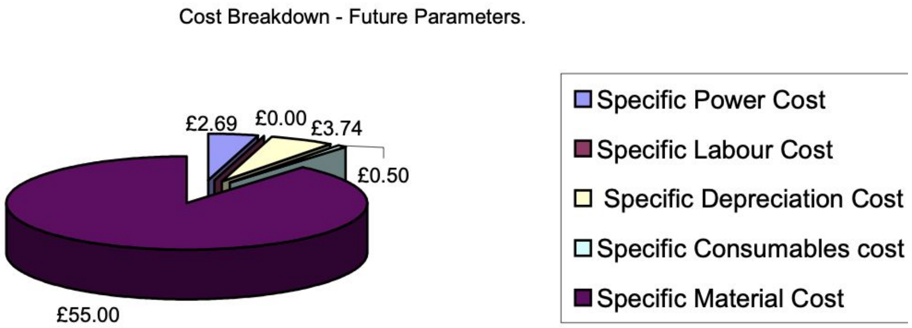
- Every process must be qualified
- High sensitivity and large variability
- Certification takes years and tens of millions

5.4 Limitations: Low productivity (currently)

Generic cost model for Ti 6Al 4V:



- Mass flow rate of 0.1kg/hour
- High machine hourly cost
- Long build times for large parts



- Mass flow rate of 2 kg/hour
- Productivity reduced cost by an order of magnitude

6. Future Trends

6.1. In situ Monitoring and Closed Loop

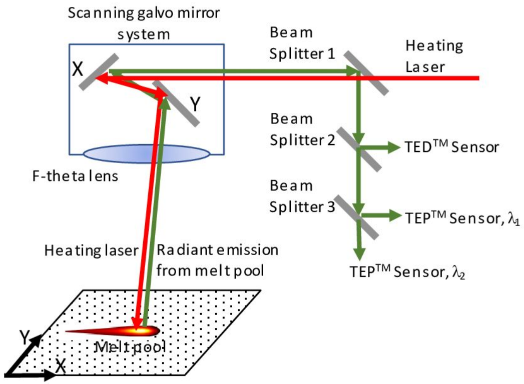
6.2 Digital Twins and Data Driven Qualification

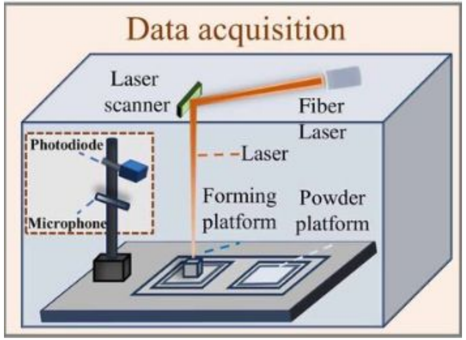
6.3 Large Scale AM

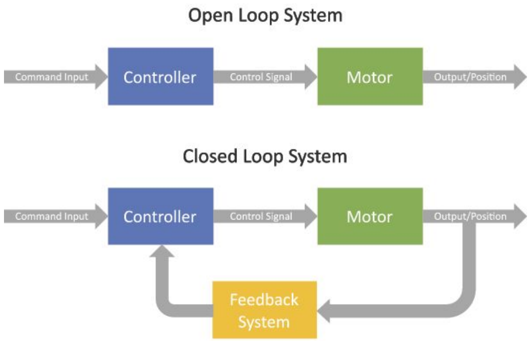
6.4 In space Manufacturing

6.1 Future trends: In Situ Monitoring and Closed Loop Control

- Coaxial melt pool monitoring
- Off axis photodiodes and microphones
- Layer temperature mapping
- Detection of porosity and lack of fusion
- Real time laser power and speed adjustment
- Objective: stable process and zero defect builds

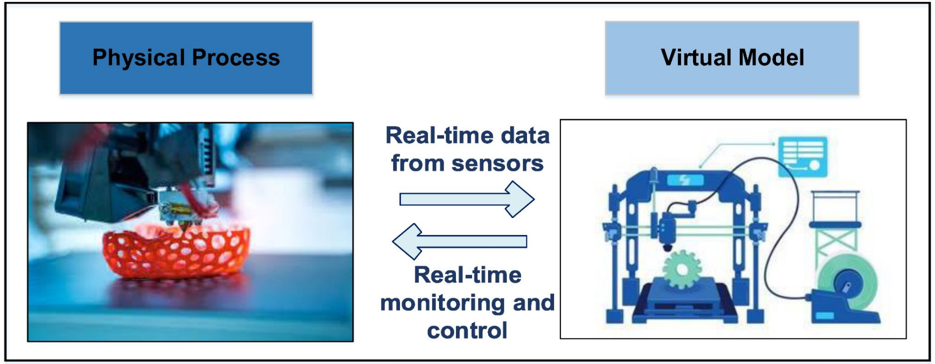






6.2 Future trends: Digital Twins and Data Driven Qualification

- Integration of CAD, process simulation and sensor data
- Prediction of melt pool, microstructure and defects
- Full traceability from powder to part
- Model based certification reduces testing



6.3 Future trends: Large Scale AM

EPFL

- WAAM enables meter scale metallic structures
- Deposition rates above two kilograms per hour
- Thermal management critical to limit distortion
- Path planning and interpass cooling essential
- Adaptive control improves dimensional accuracy

6.4 Future trends: In Space Manufacturing

- On orbit fabrication and repair
- Reduction of spare part mass and logistics
- Recycling and material reuse in microgravity
- Long duration missions need autonomous production

7. Conclusion

Thank You!