Aerospace Applications

Introduction to additive manufacturing
ME-413

Monday, 02.12.2024

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Agenda

1. **Context, advantages, and limitations** (Nils FALCOZ-RAVASSE)
2. **Technologies and materials** (Leo DIGONZELLI)
3. **Quality control and Certifications** (Victor CHARTRAIN)
4. **Case study 1 : Space** (Jérémie HUSER)
5. **Case study 2 : Aviation** (Guillaume VULLIOUD)
6. **Acknowledgement**

Context

Context

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Major Challenge

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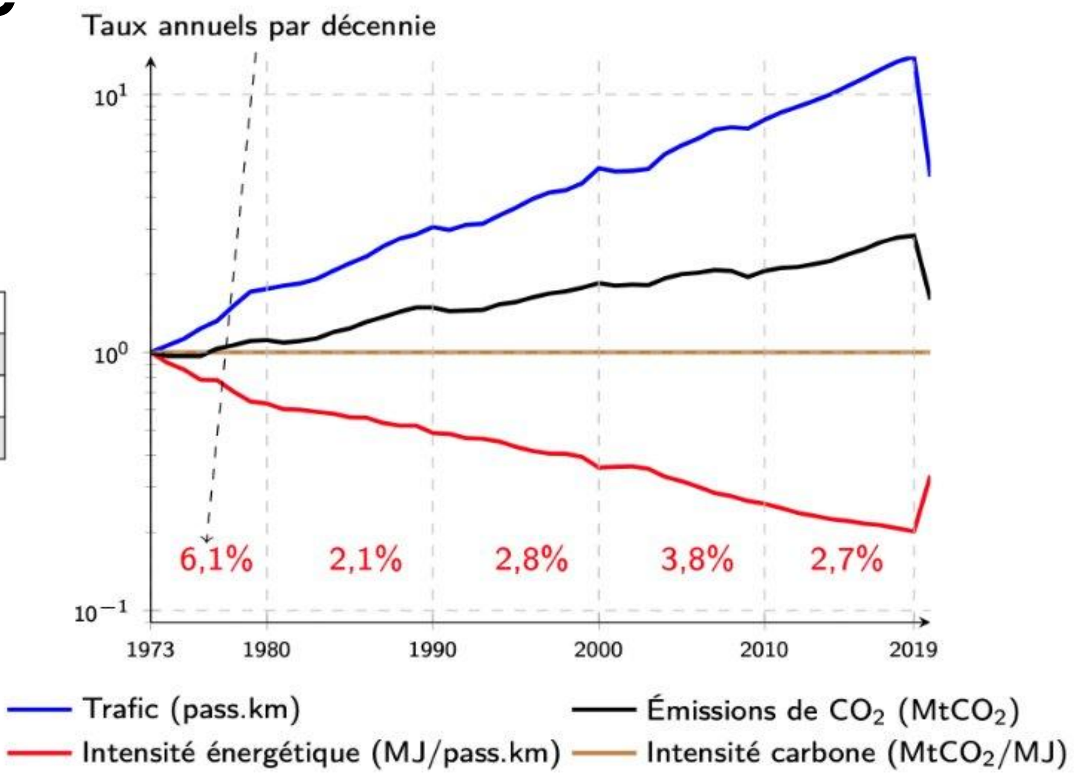
Évolution période
1973–2019

Trafic	+1 302%
Intensité énergétique	−80%
Intensité carbone	0%
Émissions de CO_2	+184%

Environmental challenges are becoming central !



Source : Delbecq et al., Référentiel, 2023

History

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1980s - 1990s

Rapid prototyping of non-critical parts.

- Exploring phase : limited by insufficient precision and materials.

2010s

Turning point occurred

- Advanced processes such as powder bed fusion and laser metal printing improvement.
- These technological advances paved the way for practical applications.

2020s

Exponential growth scale.

- SpaceX and Relativity Space are pushing technological boundaries by printing not only engines but entire rockets.
- The AM market in aerospace is expected to reach USD 3.187 billion by 2025, with a compound annual growth rate of 20.24%, reflecting its growing adoption in critical applications and its central role in the Industry 4.0

Manufacturing

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Enlèvement de matière → Ajout de matière

Usinage

- Précision
- Cadence élevée
- Perte de matière
- Outillage

Forge

- Très bonne caractéristique mécanique
- Cadence élevée
- Précision
- Géométrie limitée

Fonderie

- Forme relativement complexe
- Cadence très élevée
- Caract. méca. assez faibles
- Outillage cher
- Précision

Fabrication Additive

- Pas ou peu d’outillage
- Forme complexe
- Cadence faible
- Caract. méca. entre forge et fonderie
- Précision fonction de la techno.

Source : Kamel MOUSSAOUI, 2023

Manufacturing Sequence

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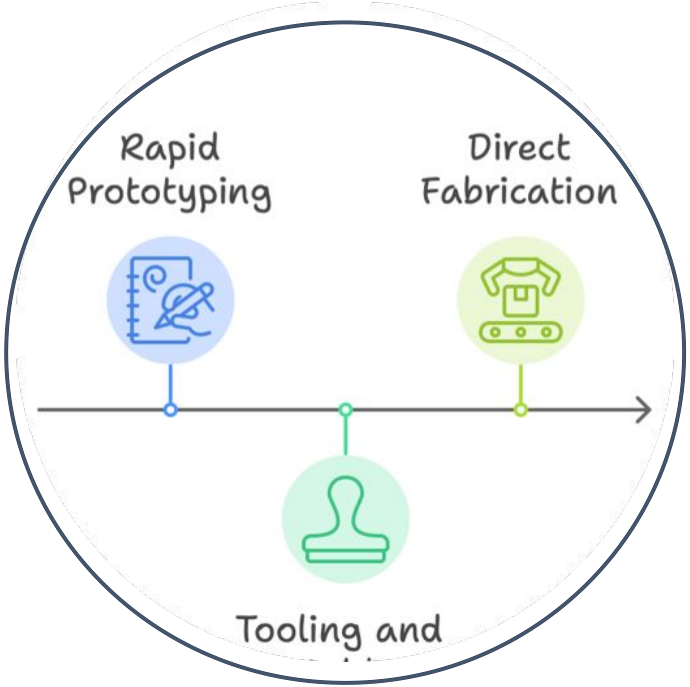
1. Creating models and prototypes to test designs.
2. Manufacturing custom tools and complex molds
3. Producing functional components, including final parts



Advantages

Limitations

Advantages & Limitations

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Multiple Avantages:
- Performance
- Supply Chain
- Financial Impact
- Sustainable

But some drawbacks :
- Technical challenge
- Certification
- Economic and production Constraints

Performance measure	Advantages of AM	Limitations of AM
Cost	• Lower minimum efficient scale of production • Cheaper tooling and jigs • Reduction of logistics and transportation cost • Lower labor cost	• Expensive AM equipment • High material cost
Quality	• Weight reduction	• Low quality consistency • Talent and expertise shortage • Certification and material characterization
Lead time	• Lower inventory • Faster product development • Simplification of the supply chain network and logistics	• Slow build time - does not compete with mass production for large volumes
Variety	• Design flexibility • Manufacturing functional assemblies • More accessible mass-customization • Allows economies of scope	• Limited size of product • Limited range of materials
Other	• Improved process sustainability • Contribution in Lean manufacturing • Contribution in Agile manufacturing • Reshoring manufacturing jobs	• Low general understanding of the technology • Intellectual property protection

Source : Integration of Additive Manufacturing in the Aerospace Industry, G. Doré, 2016

Performance

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- **Weight reduction and performance gain** : Significant material savings with optimized, lightweight designs.
  - **Topology Optimization** : Advanced algorithms for creating efficient structures
  - **Revolutionary Part Design** : Geometries previously impossible with traditional manufacturing.
- **Integration of Multiple Functions** : Combining functionalities into single, seamless components.
  - **Customizable internal geometries**, such as cooling channels or honeycomb patterns.
  - **Monolithic Parts** : Eliminating assemblies by producing single, unified pieces.

Source : **Additive manufacturing and HIP, a bright future, Hiperbaric**

Supply Chain

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- Storage :
  - Reduce cost
- Flexibility, Polyvalence
  - Allow a single machine to produce multiple part
- Even more gain for isolate place

Table 5-7 Cost results at 98% quality using CM

Process	98%	Conventional Manufacturing (CM)			
Technology	Casting (C)				
Part Size	500mm * D 75mm	558mm * D 72mm	304mm * D 70mm	445mm * D 72mm	56mm * D 33mm
Number of produced units	409.69	357.04	755.46	174.73	652.11
Production Cost per unit	€ 12,000.00	€ 12,152.00	€ 4,776.00	€ 10,274.00	€ 2,262.00
Total Production Cost	€ 4,916,280.00	€ 4,338,750.08	€ 3,608,076.96	€ 1,795,176.02	€ 1,475,072.82
Number of holding units	16.39	16.39	12.04	18.77	14.99
Holding cost (h)/unit/year	€ 3,598.90	€ 3,646.35	€ 1,434.45	€ 3,080.60	€ 678.90
Total Holding Cost	589,859.71	597,636.77	172,707.78	578,228.62	101,767.11
Number of shortage units	0.00	0.00	0.03	0.00	0.01
Shortage cost (b) per unit	€ 100,000.00	€ 100,000.00	€ 100,000.00	€ 100,000.00	€ 100,000.00
Total Shortage Cost	€ 300.00	€ 94.00	€ 3,000.00	€ -	€ 692.00
Total Cost In 10 Y	€ 5,506,439.71	€ 4,936,480.85	€ 3,783,784.74	€ 2,373,404.64	€ 1,577,531.93
Total Cost Per Year	€ 550,643.97	€ 493,648.08	€ 378,378.47	€ 237,340.46	€ 157,753.19

Table 5-8 Cost results at 98% quality using AM

Process	Additive Manufacturing (AM) - 98% Quality				
Technology	Selective Laser Melting (SLM)				
Part Size	500mm * D 75mm	558mm * D 72mm	304mm * D 70mm	445mm * D 72mm	56mm * D 33mm
Number of produced units	439.14	384.13	770.08	202.64	694.35
Production Cost per unit	€ 10,723.50	€ 11,043.00	€ 4,102.20	€ 9,819.00	€ 2,007.00
Total Production Cost	€ 4,709,117.79	€ 4,241,947.59	€ 3,159,022.18	€ 1,989,722.16	€ 1,393,560.45
Number of holding units	0.34	0.36	0.11	1.23	0.19
Holding cost (h)/unit/year	€ 3,215.65	€ 3,312.74	€ 1,230.05	€ 2,945.55	€ 602.25
Total Holding Cost	10,933.21	11,925.86	1,353.06	36,230.27	1,144.28
Number of shortage units	3.97	2.65	6.41	0.45	10.45
Shortage cost (b) per unit	€ 100,000.00	€ 100,000.00	€ 100,000.00	€ 100,000.00	€ 100,000.00
Total Shortage Cost	€ 397,000.00	€ 265,000.00	€ 641,000.00	€ 44,800.00	€ 1,045,000.00
Production Machine Value	€ 200,000.00	€ 200,000.00	€ 200,000.00	€ 200,000.00	€ 200,000.00
Amortization/10Y	€ 200,000.00	€ 200,000.00	€ 200,000.00	€ 200,000.00	€ 200,000.00
Bad Quality Units	7.32	6.10	9.05	2.70	12.16
Bad Quality cost/unit	11,795.85	12,147.30	4,512.42	10,800.90	2,207.70
Total BQ/Recycling Cost	€ 86,345.62	€ 74,098.53	€ 40,837.40	€ 29,162.43	€ 26,845.63
Total Cost IN 10 Y	€ 5,403,396.62	€ 4,792,971.98	€ 4,042,212.63	€ 2,299,914.86	€ 2,666,550.36
Total Cost Per Year	€ 540,339.66	€ 479,297.20	€ 404,221.26	€ 229,991.49	€ 266,655.04
Percentage Reduction using AM	1.91%	2.99%	-6.39%	3.20%	-40.84%

Source : Albraa NOORWALI, IMPACT DE LA FABRICATION ADDITIVE SUR LA PERFORMANCE DE LA SUPPLY CHAIN, 2023

Financial Impact

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- **Cost Reduction**
  - Minimizing material waste (near-net shape), not negligeable for high value material present in aerospace (Inconel, titanium)
  - Eliminating intermediate steps like assemblies or manual adjustments, AM significantly reduces production times and associated costs
- **Time Reduction**
  - Accelerate product development cycles (reduce design, testing, and iteration timelines)
  - Reduces time-to-market through accelerating industrialization cycles

Sustainability

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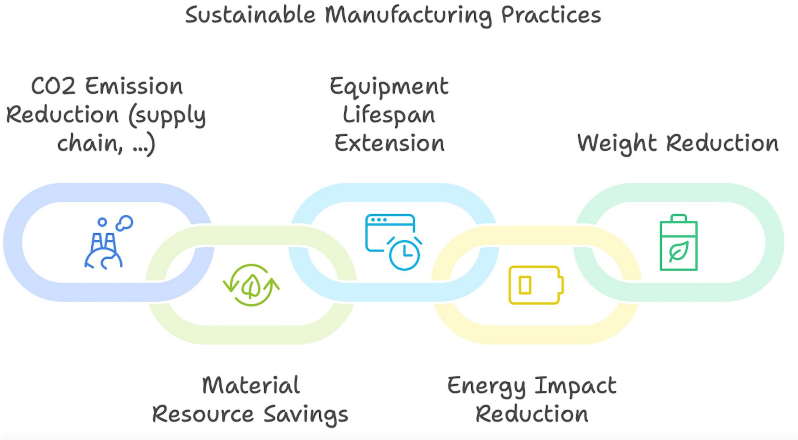
- AM plays a central role in sustainability objectives, a priority in aerospace.
  - **Weight reduction** decreases fuel consumption, reducing CO2 emissions over an aircraft's life-cycle.
  - **Energy efficiency** gains/ better performance from optimized designs.
  - Ability to **reduce manufacturing waste** and stock rare or expensive materials supports a more sustainable use of resources.



Technical Challenge and Material Limitation

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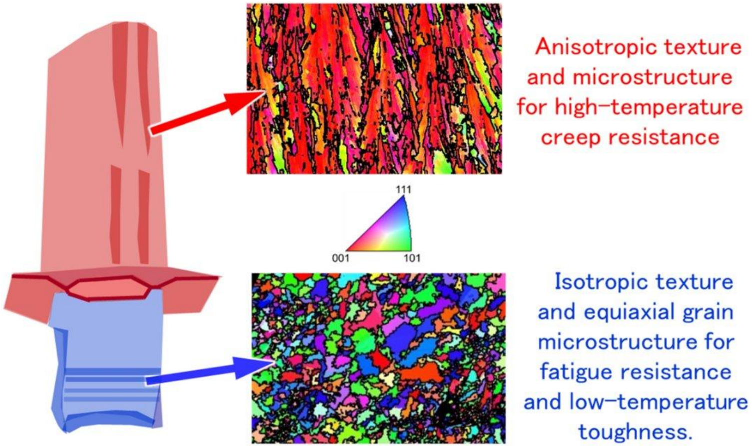
Extreme requirement

- Reliability and high mechanical performance
- Anisotropy
    - Post-processing (Hot Isostatic Pressing (HIP)

      longer production cycles and increase costs
- Prone to microstructure
- Struggles to integrate multiple materials

Source : K. Hagihara et al., Control of Anisotropic Crystallographic Texture […], 2023



Certification and Regulatory Constraints

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High requirement in aerospace
 --> Mismatch pace of technology advancement and regulatory advancement

The main challenge is demonstrating that we have control over the process and that the observed results are reproducible

Source : Integration of Additive Manufacturing in the Aerospace Industry, G. Doré, 2016

Table 4
Certification-related AM standards, including those under development (marked by *).

ISO/ASTM 52942–20	Qualifying Machine Operators of Laser Metal Powder Bed Fusion Machines and Equipment Used in Aerospace Applications
ASTM F3434-20	Installation/Operation and Performance Qualification (IQ/OQ/PQ) of Laser-Beam Powder Bed Fusion Equipment for Production Manufacturing
ISO/ASTM 52941–20	Acceptance Tests for Laser Metal Powder-Bed Fusion Machines
ISO/ASTM AWI 52,937 *	Qualification of Designers
ISO/ASTM CD 52,920 *	Quality Requirements for Industrial Additive Manufacturing Sites
ISO/ASTM AWI 52,935 *	Qualification of Coordinators for Metallic Production
ISO/ASTM CD TS 52,930 *	Installation, Operation and Performance (IQ/OQ/PQ) of PBF-LB Equipment
ISO/ASTM CD 52926–5 *	Qualification of Machine Operators for DED-ARC
ISO/ASTM CD 52926–4 *	Qualification of Machine Operators for DED-LB
ISO/ASTM CD 52926–3 *	Qualification of Machine Operators for PBF-EB
ISO/ASTM CD 52926–2 *	Qualification of Machine Operators for PBF-LB
ISO/ASTM CD 52926–1 *	General Qualification of Machine Operators
NASA-STD-6030	Additive Manufacturing Requirements for Crewed Spaceflight Systems
SAE AMS7032	Additive Manufacturing Machine Qualification
NASA-SPEC-6033	Additive Manufacturing Requirements for Equipment and Facility Control
NASA MSFC-SPEC-3716	Standard for Additivity Manufactured Spaceflight Hardware by Laser Powder Bed Fusion of Metals
NASA MSFC-SPEC-3717	Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes

Economic and Production Constraints

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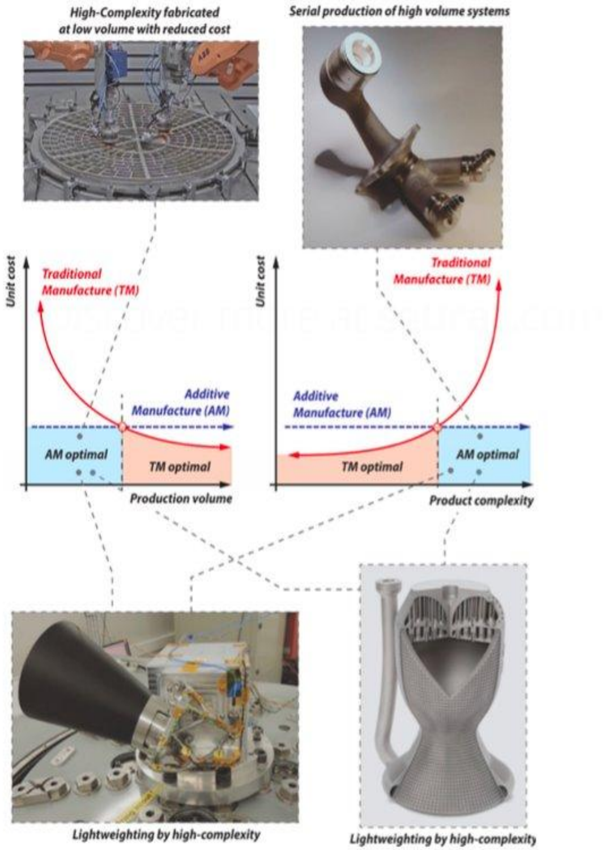
Not a miracle solution

- Expensive, only some operation is worth it
- Well-suited for small series production and complex parts, its profitability remains uncertain for mass production or long printing durations.



Source :Byron Blakey-Milner Metal additive manufacturing in aerospace: A review, 2021

Technology

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Materials

AM technologies in aerospace

Metal-based additive manufacturing for aerospace

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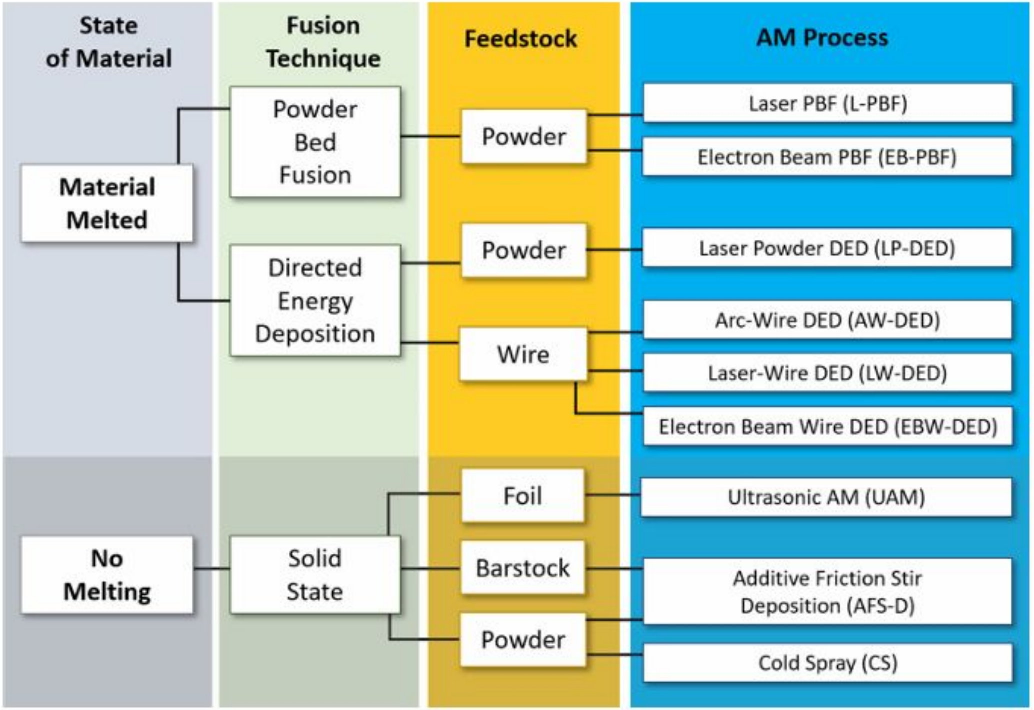

Powder Bed Fusion processes

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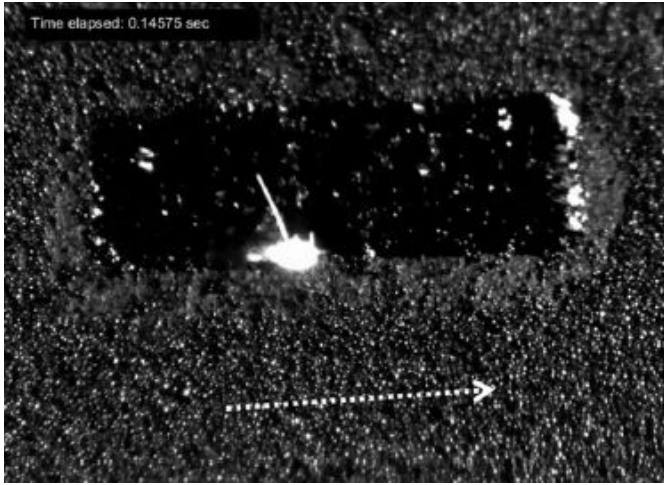
Laser Powder Bed Fusion (L-PBF)

- High power laser to selectively melt layers of metal powder bed
- Most widely adopted metal AM in aerospace

- Applications : lightweight structural components, heat exchangers, engine parts

- Feature size ~0.2-0.4mm
- Max part size ~300-400mm

- Recent advancement : multi-laser systems, build volume up to 500x280x850mm



Powder Bed Fusion processes

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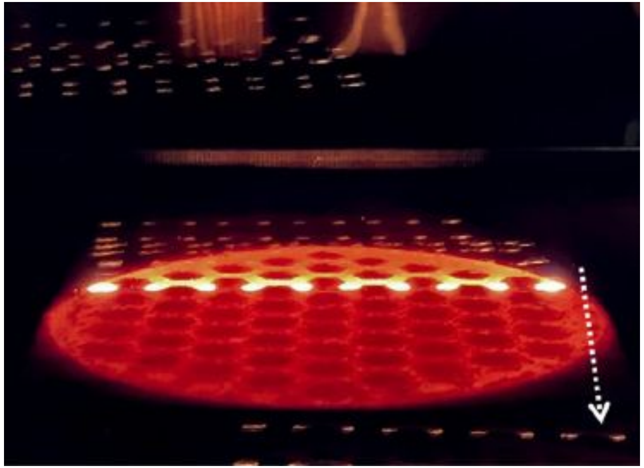
Electron Beam Powder Bed Fusion (EB-PBF)



- Electron beam to selectively melt metal powder layer by layer in vacuum environment
- Pre-heating step to reduce residual stresses
- Maximum size similar to L-PBF (recent systems with 350x380 mm dimensions)
- Mechanical properties comparable to casted parts, but increased surface roughness compared to L-PBF

Directed Energy Deposition processes

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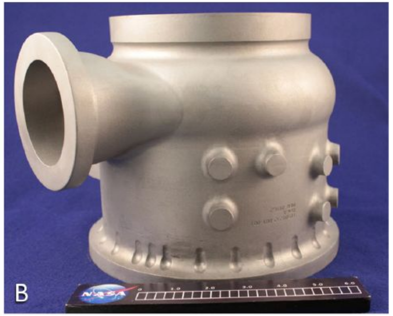
- Material deposited directly into a melt pool, generated by an energy source
- Geometric flexibility and freedom
- Suitable for very large components
- Lower resolution than PBF (~1mm)

AW-DED



L-PBF

Directed Energy Deposition processes

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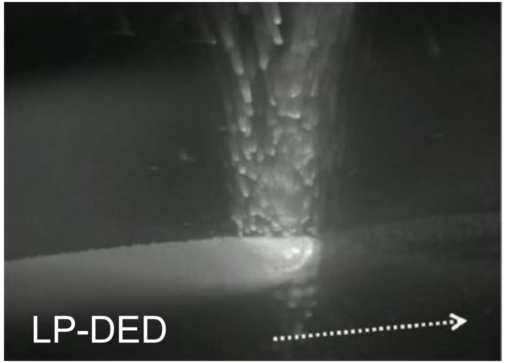
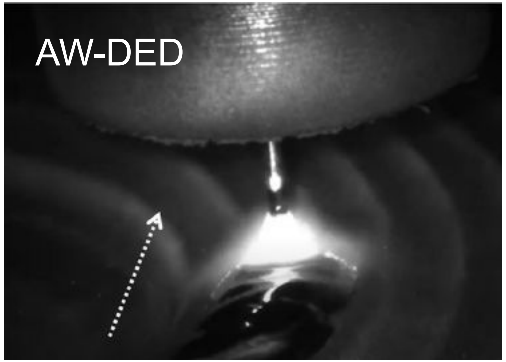
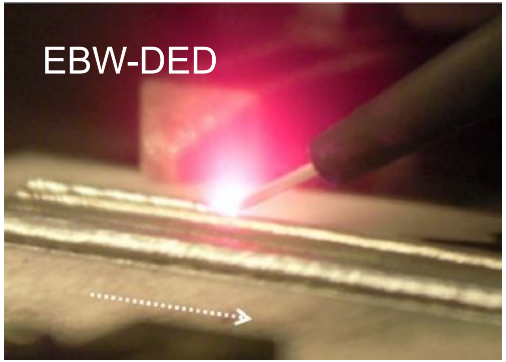
Laser Powder & Laser Wire DED

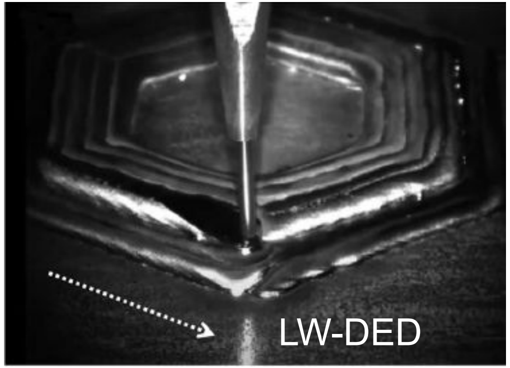
Electron beam Wire DED

Arc Wire DED









Solid-State and other processes

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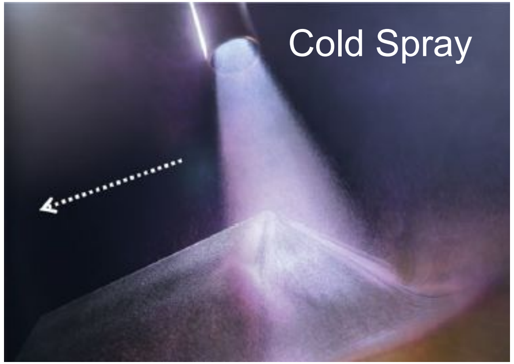
Cold Spray

Ultrasonic AM (UAM)

Binder jetting

…



Non-metallic additive manufacturing for aerospace

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Selective Laser Sintering (SLS)

Stereolithography (SLA)

Fused Deposition Modeling (FDM)

Polyjet

AM materials in aerospace

AM metals and alloys in aerospace

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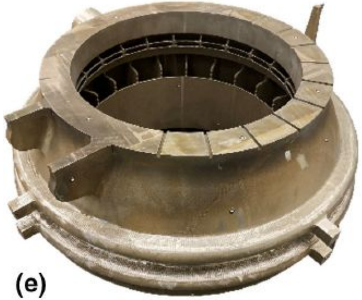
Nickel and Iron-based superalloys

- Most used in aerospace applications (Ni-based = 50% mass of aircraft engine)
- Excellent mechanical properties at high temperature, high pressure & in harsh environments, high creep resistance
- Turbines, combustion chambers, discs and blades in high pressure turbines, high-pressure hydrogen env.

Stainless steels

- Very high strength-to weight ratio, outstanding durability
- Engine and exhaust systems, hydraulic parts, structural joints, landing gear systems, heat exchangers
- But high density, some are prone to cracking with AM



L-PBF Inconel 718 integrated heat exchanger

LP-DED Nasa HR-1 Nuclear thermal propulsion chamber

AM metals and alloys in aerospace

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Titanium alloys

- Very high strength-to-weight ratio & high temperature stability, corrosion resistance
- Ti6Al4V : bearing frames, landing gears, compressor discs & frames, cryogenic propellant tanks, rotating machinery, …
- Ti6242 : compressor blades, rotating machinery

Aluminium alloys

- Good strength-to-weight ratio, low cost
- Some alloys prone to cracking when produced with traditional AM (PBF, DED) → solid-state processes
- 1xxx, 2xxx, …, 7xxx series; AlSi10Mg

L-PBF Ti6Al4V cabin bracket connector of Airbus A350 XWB

Mass-optimized AlSi10Mg cryogenic propellant injector

AM metals and alloys in aerospace

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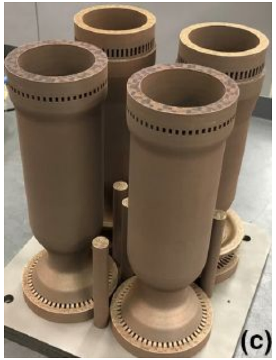
Copper and Cobalt alloys

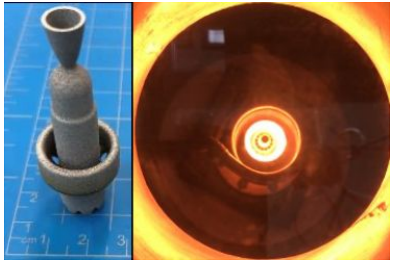
- High temperature applications
- Co → no need for high thermal conductivity
  - CoCr, Stellite
- Cu → very high thermal conductivity
  - heat exchangers
  - GRCop-42 & GRCop-84, CU110

Refractory alloys

- Niobium (C-103), Tantalum, Tungsten, molybdenum, …
- Used for extremely high temperatures
  - Space nuclear power & propulsion
  - Thermal protection of vehicles



L-PBF GRCop-84 combustion chambers



L-PBF W chamber test at 1900°C

L-PBF C-103 heat pipe segments

Development of new AM aerospace alloys

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Initial application of AM in aerospace:

- Use of alloys traditionally processed through conventional methods
    - Chosen for traceability and well-known properties
    - Not well suitable for AM
    - Challenges : cracking, porosity, oxidation, …

Today:

- Specialized alloys tailored for improved AM processability and performance
    - Custom aluminium alloys for high strength and successful AM production (7A77, AlSi10Mg, Scalmalloy, …)
    - NASA GRCop-42 and GRCop-84 copper alloys for high-heat flux applications
    - NASA HR-1 superalloy for high pressure hydrogen environment
    - NASA GRX-810

Bi- or Multi-metallic materials

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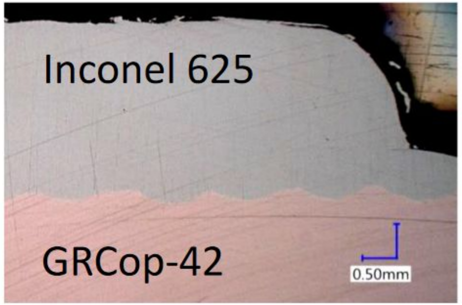
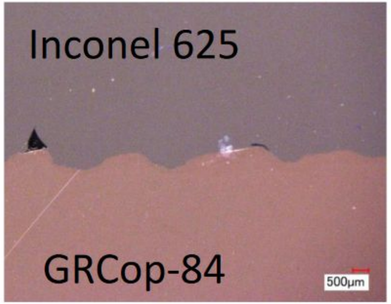
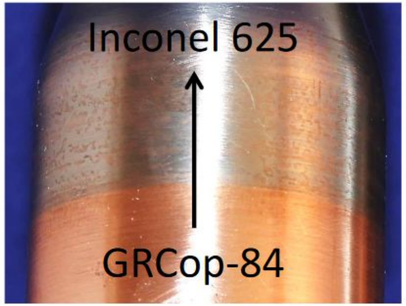
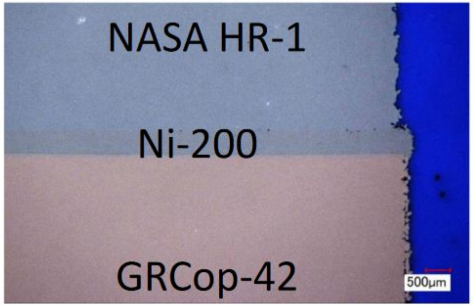
- Localised optimization for thermal or structural performance
- AM allows various options for multi-alloys joints
  - Discret transition
  - Gradual compositional changes
  - Layer of a third alloy









Bi- or Multi-metallic materials

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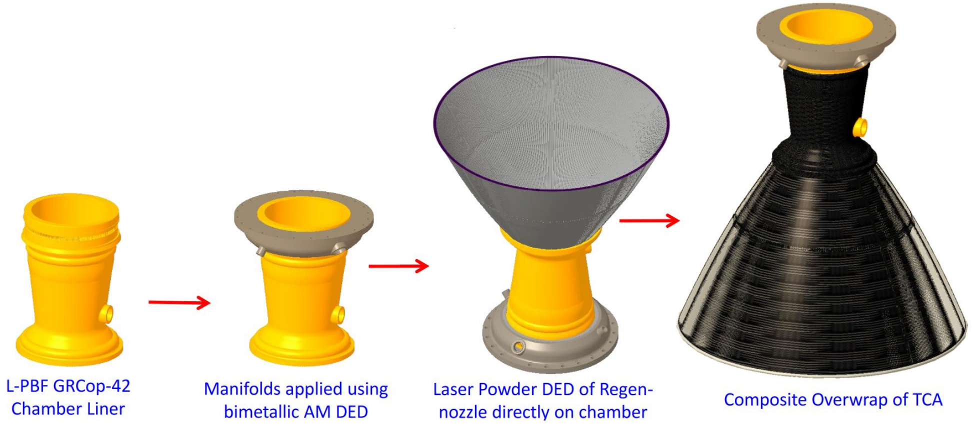
NASA advances for rocket engine optimization (RAMPT project)

- GRCop-42 or GRCop-84 L-PBF chamber liner for high thermal conductivity
- Inconel 625 or NASA HR-1 DED nozzle for extreme strength and heat resistance



Quality Control

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Certifications

Quality Control

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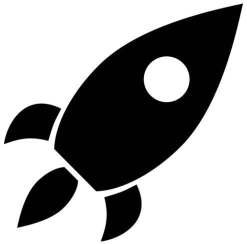
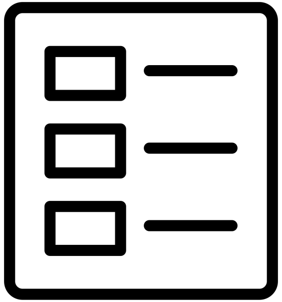


High quality parts required for aerospace applications

Need for **Quality control**



Printing process control VS evaluation process

Quality Control - Printing Process

Victor CHARTRAIN

- Optimize relevant printing process parameters to ensure in-situ correction of defects

- Real time monitoring
  - Very efficient
  - Difficult to implement in the process sometimes

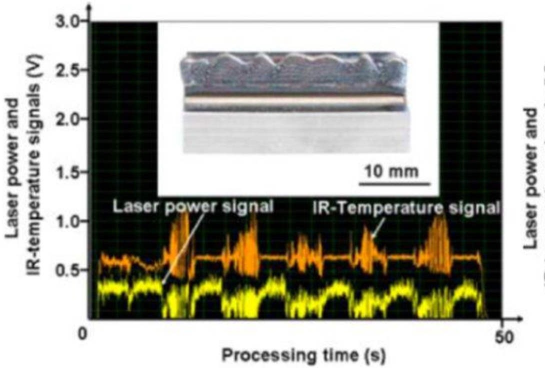
- Comparison with benchmark parameters
  - Easier to use as a first approximation
  - Less efficient
  - Lack of knowledge for very specific applications

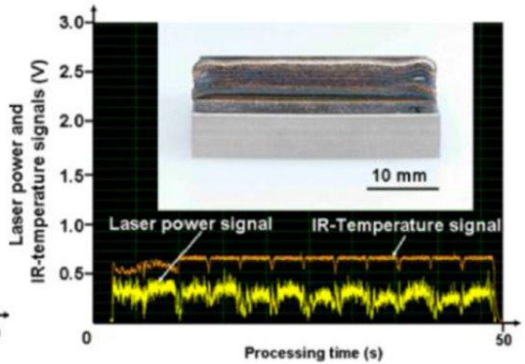
Quality Control - Printing Process

Victor CHARTRAIN

Direct Metal Deposition processes (DMD), AM with metals

- Quality issues
  - heterogeneous melt pool temperature
  - heterogeneous laser powder density
  - heterogeneous material delivery rate
- IR pyrometer measures melt pool temperature + close-loop controller adjust laser power density --> reduced stair-step effects





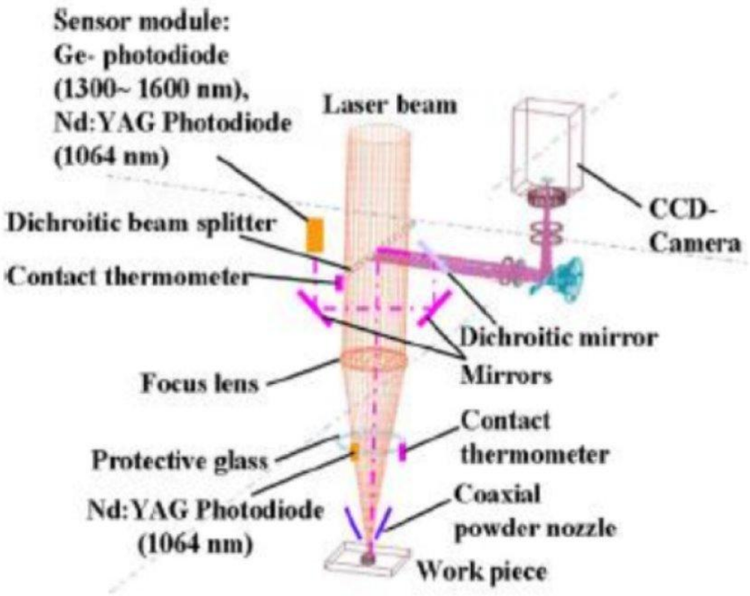
Source: Hoejin et al., 2018

Quality Control - Printing Process

Victor CHARTRAIN

Powder Bed Fusion processes (PBF), AM with metals

- Quality issues:
  - heterogeneous distribution of the powder bed temperature
  - heterogeneous laser output power
- Pyrometers (photodiodes, digital camera) monitor temperature
  - More widely used than thermocouples
  - Can be included inside laser cladding head



Source: Guijun Bi et al., 2007

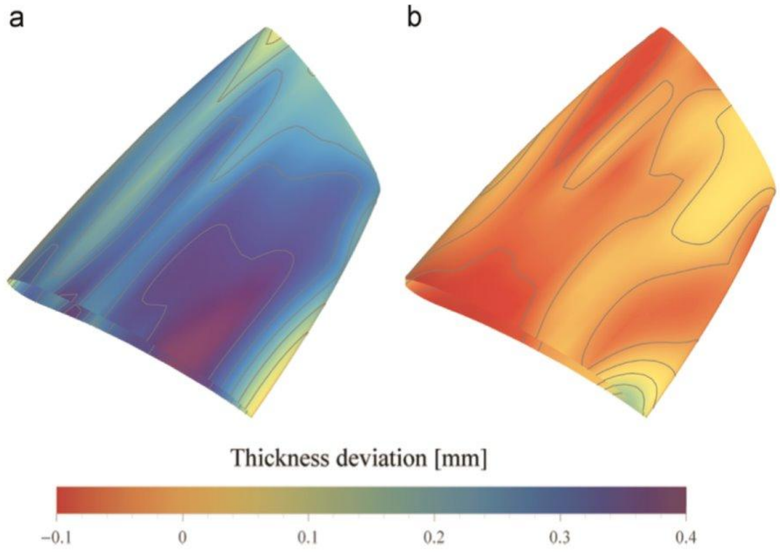
Quality Control - Printing Process

Victor CHARTRAIN

Fused Deposition Modeling

processes (FDM), AM with polymers

- Quality issues:
  - surface roughness
  - resolution limited to filament thickness (stair-case effect)
  - thickness deviations
- Good practices:
  - features in plane size, spacing between adjacent features > 1mm
  - post-processing (hot cutting, CNC machining)
  - proper design for manufacture



Source: Alberto Boschetto et al. (2016)

Quality Control - Evaluation Process

Victor CHARTRAIN

- Evaluate part's reliability after it has been manufactured

- External measurement techniques = evaluate overall dimensions, geometry, surface roughness, etc.

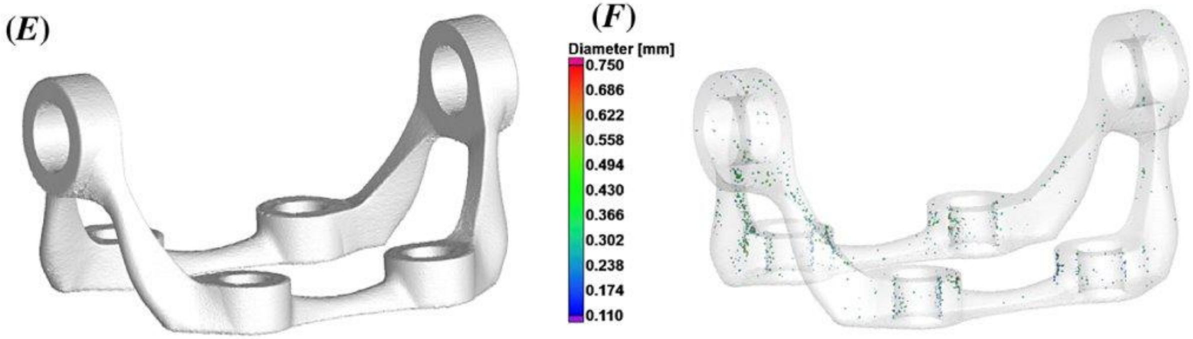
- Internal measurement techniques = characterize mechanical properties
  - Destructive testing
  - Non-destructive testing (NDT)

Quality Control - Evaluation Process

Victor CHARTRAIN

Non-destructive testing techniques (NDT)

- X-ray computed tomography (CT) widely used
  - Inspects cracks, pores, trapped unmelted metallic powder, etc.
  - Can document time-related damages (crack formation/propagation, wear, etc.)
  - Poor resolution for large parts and components with thick walls
  - Not fitted to high X-ray absorbing metals



Source: Du Plessis et al. (2020)

Certifications

Victor CHARTRAIN

- Aerospace industry highly regulated through strict **standards**
- **Goal**: ensure repeatability of product process and consistent quality of parts manufactured
- **Manufacturers obligations**: should be able to track each part through entire production and supply chain
- **Challenges** for developing certifications: lack of prior knowledge on the subject, precise property databases, understanding of failure mechanisms
- **Subject** to change in the future

Case Study 1
Space

Introduction - AM FOR Space

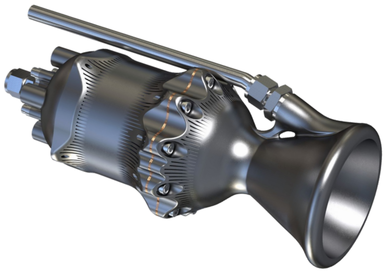
Jérémie HUSER

- **Mass Reduction**
- **Complexe Shape**
- **Performance**
- **Monolithic**

Antenna Support

Raptor 3, SpaceX

RF Antennas & Waveguides, Swissto12



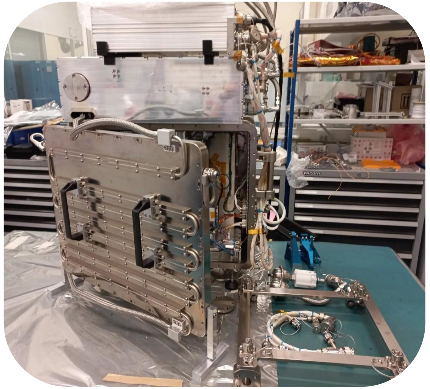
Demo-B1, EPFL Rocket Team

Introduction - AM IN Space

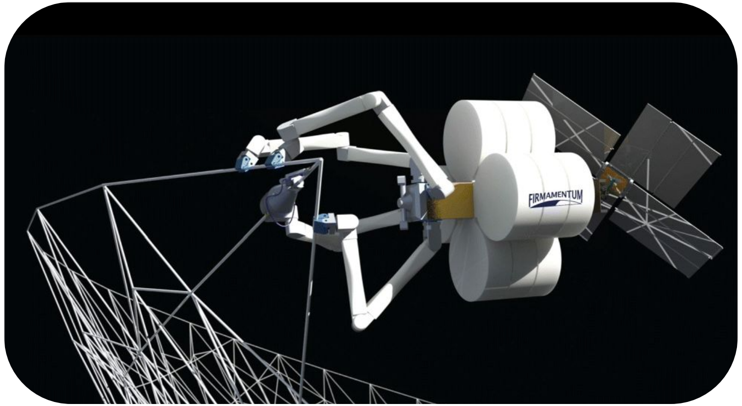
Jérémie HUSER

- Microgravity
- Flexibility
- Cost Reduction
- New Structures

Concrete structures on the moon



The first metal 3D printer for space



SpiderFab Bot creating a truss in obit

Swissto12

Jérémie HUSER

History

- Founded in 2012 by *Dr. Emile de Rijk* (PhD in Physics at EPFL)
- Swiss-based, Renens
- Pioneer in the use of AM to create RF components.
- In 2019, first antenna in space
- > 1000 components in space

Products

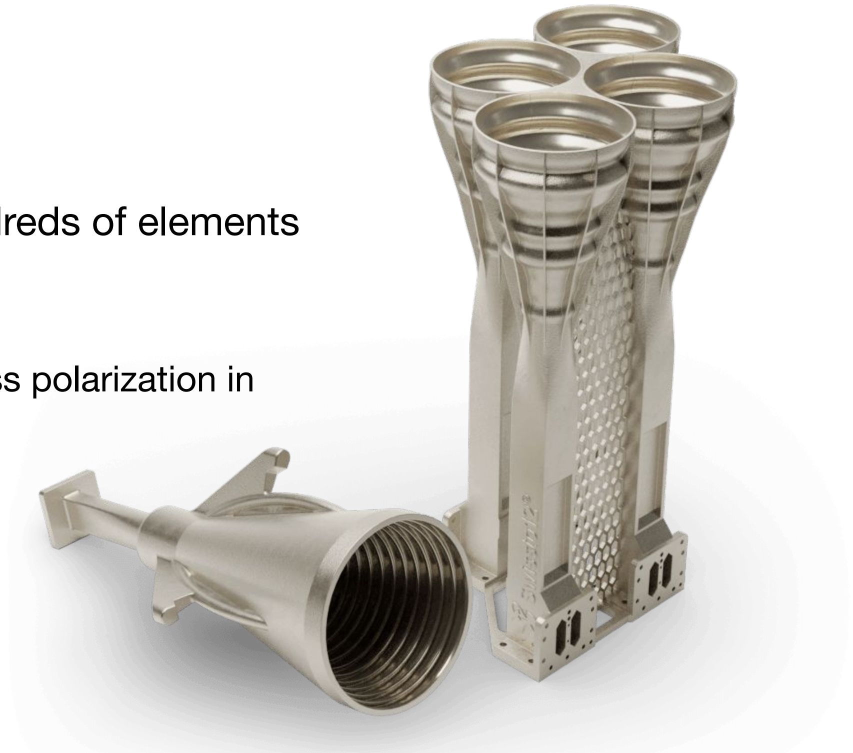
- RF components
    - Antennas
    - Waveguides
- Satellite, *HummingSat*
    - World’s first commercial GEO SmallSat.

Swissto12 - RF Antennas and Waveguides

Jérémie HUSER

RF Antennas

- Monolithic
  - Antenna clusters can contain hundreds of elements
- X-band example (4 elements 2x2):
  - X-band military band (≈7.5 GHz);
  - dual-circular polarization in with a cross polarization in excess of 30 dB;
  - low insertion loss (typically 0.35 dB);
  - total weight < 250 g;
  - total length: < 350 mm;
- **3x Lighter** than conventional antennas
- **Mechanical** and **RF** properties increased
- Copper, Aluminum or Titanium alloys



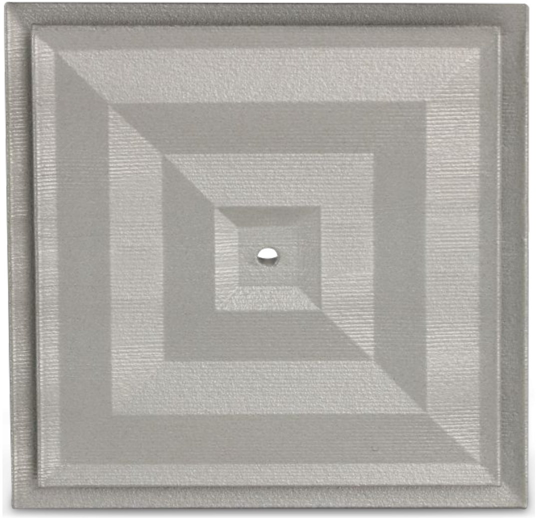
Ku-band Antenna (left) and X-band Antenna (right)

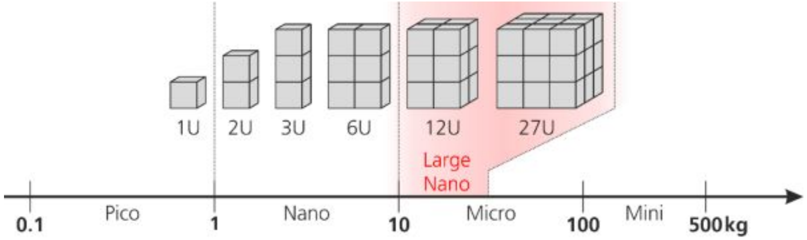
Swissto12 - Patch Antenna

Jérémie HUSER

Patch Antenna

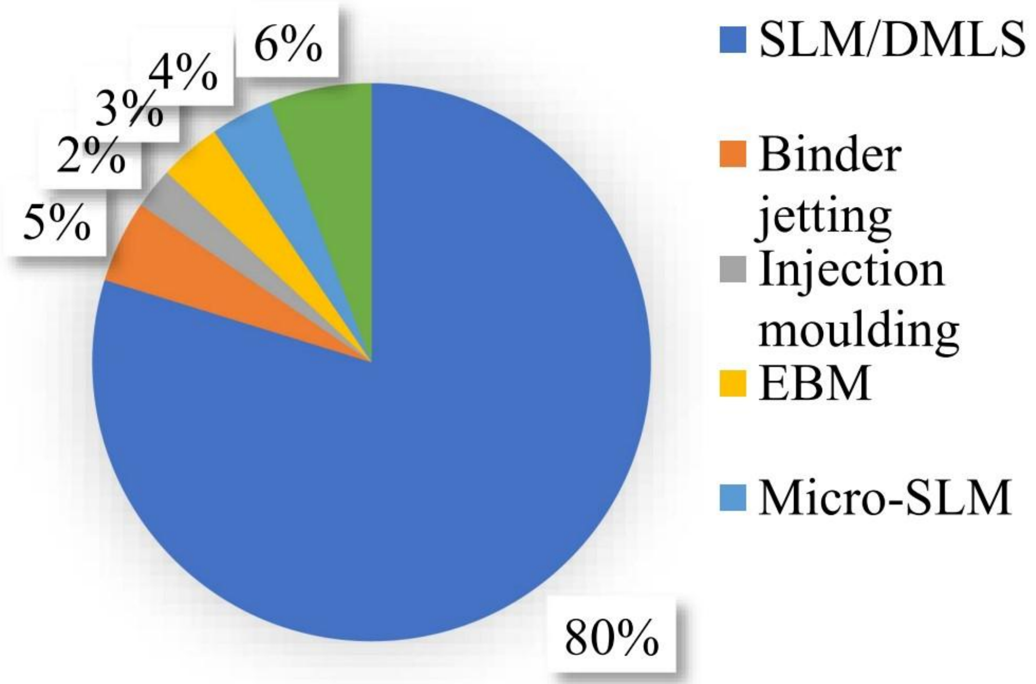
- Swissto12 & Fleet Space Technologies
- 2021, First-ever AM metal patch antennas
- Nanosatellites





RF Antennas - AM Process

Jérémie HUSER

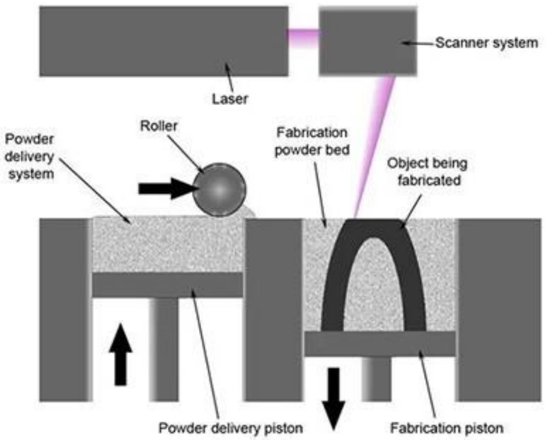


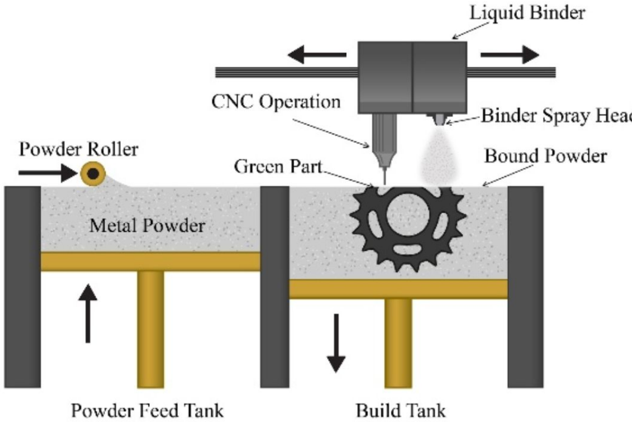
RF Antennas - AM Process

Jérémie HUSER

Process used

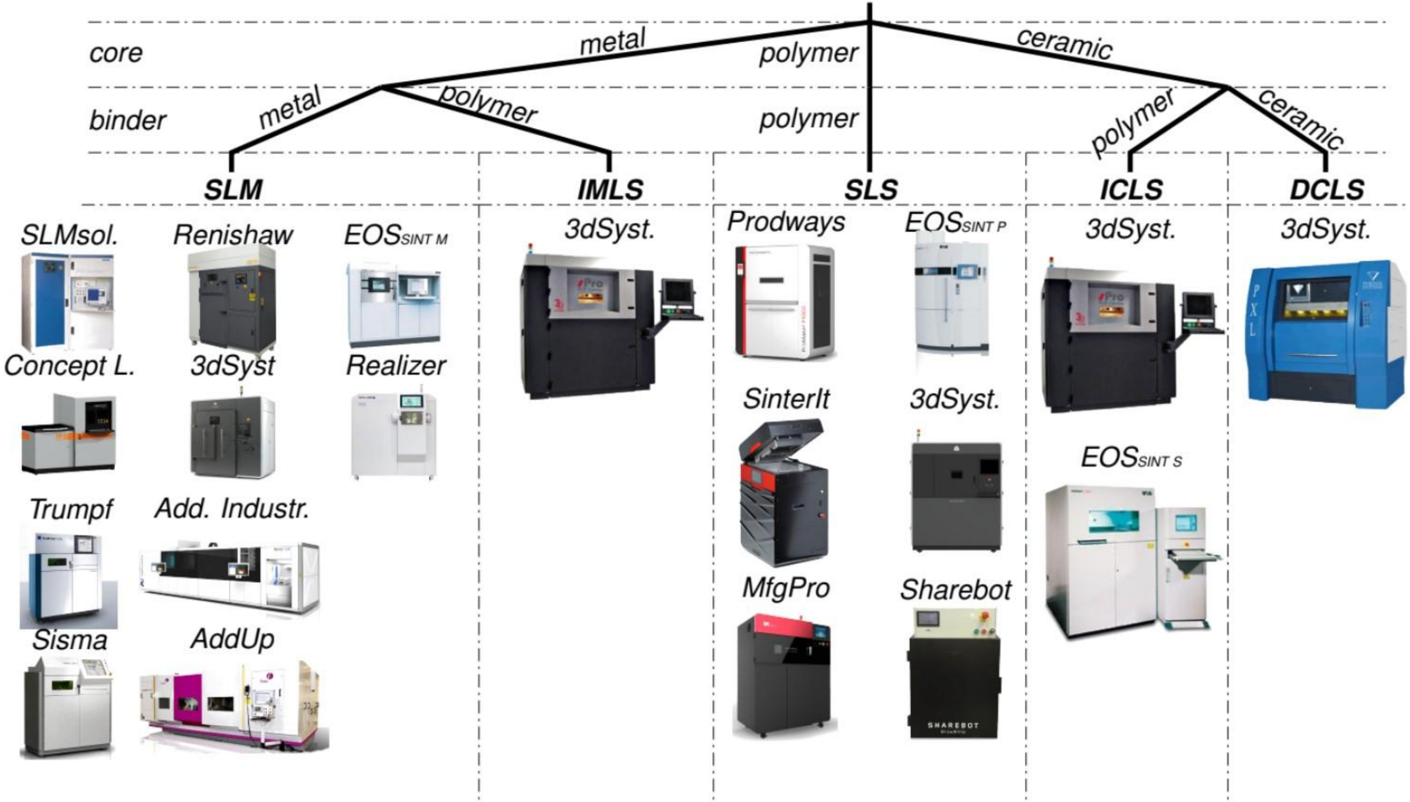
- **Selective Laser Melting** (SLM)
  - Ability to produce parts with good RF performance
  - Challenges with manufacturing tolerances and surface roughness
  - Time-intensive
  - Costly
- **Metal Binder Jetting** (MBJ)
  - Emerging as an alternative for high-frequency RF parts.
  - Lower costs (up to 10 times cheaper than SLM)
  - Involves high-temperature sintering
    - Can cause shrinkage and affect dimensional accuracy.





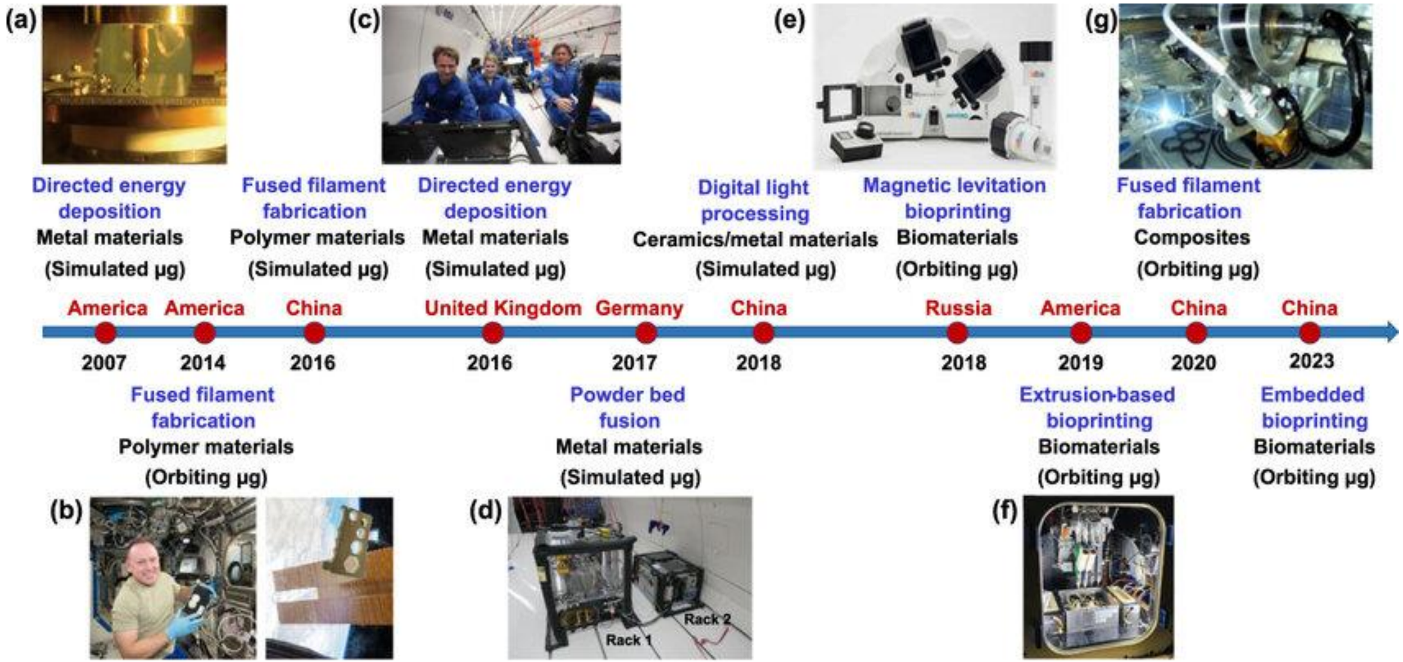
RF Antennas - Machines - SLM

Jérémie HUSER



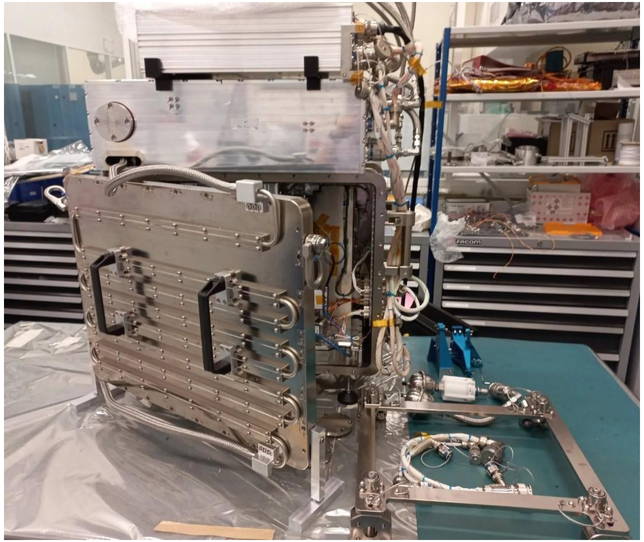
AM in Space - History

Jérémie HUSER



Metal AM in Space

Jérémie HUSER

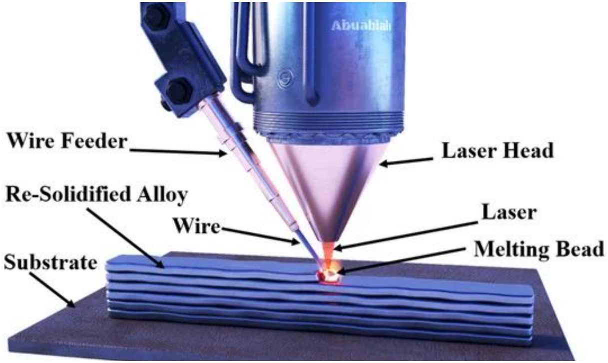


First metal 3D printer in Space

- Arrived aboard ISS in January 2024
- ISS's Columbus laboratory module
- Collaboration between ESA and Airbus

Description

- Air circulation & Filtration system
  - Evacuate Heat and capture particles
- Sealed box
  - Protect from laser heat and contamination
  - Nitrogen inside
- Laser and Wire feeder
  - To melt and deliver material
- Motion tables



Wire-based laser metal 3D printing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T1
Met

Metal AM in Space

Jérémie HUSER

First metal 3D printed parts in Space

- 200 Layers
- Finished in August 2024
- **Goal:** Gather data of the effects of microgravity on the printing performance

Parameter	Details
Printer size	80 x 70 x 40 cm
Printed part size	9 x 5 cm
Raw material used	Stainless steel wire
Melting temperature of material	Approximately 1400°C
Printing environment	Fully sealed box, nitrogen atmosphere
Time to print a single part	Around 40 hours
Primary use	Tools, mounting interfaces, and mechanical parts
Printing technology	Wire-based metal 3D printing

Case Study 2

Aviation

Impact of Aviation on climate

Guillaume VULLIOUD

- **2.5 %** of global emission
- **1 billion tons** of CO_2
- **95 billions gallons** of jet fuel in 2022
- 1 gallon = 9.57 kg of CO_2

What AM can change ?

Guillaume VULLIOUD

- An A380 weight 277 tons and consume 3’170 gallons of fuel per hours
- 1 kg save on an A380 saves 0.01 gallons of fuel per hours
- 3’000 flight hours a year

→ **30 gallons save a year per aircraft**

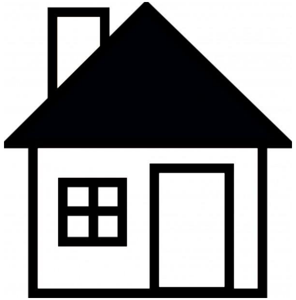
Airbus - Leading Aerospace Innovation

Guillaume VULLIOUD

- Founded in 1970
- Competition with Boeing

Airbus - Relation to AM

Guillaume VULLIOUD

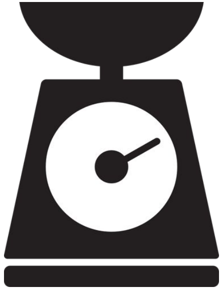


2010

Cabin interiors and structural components

By 2022

Over 1,000 AM parts integrated into the A350 XWB



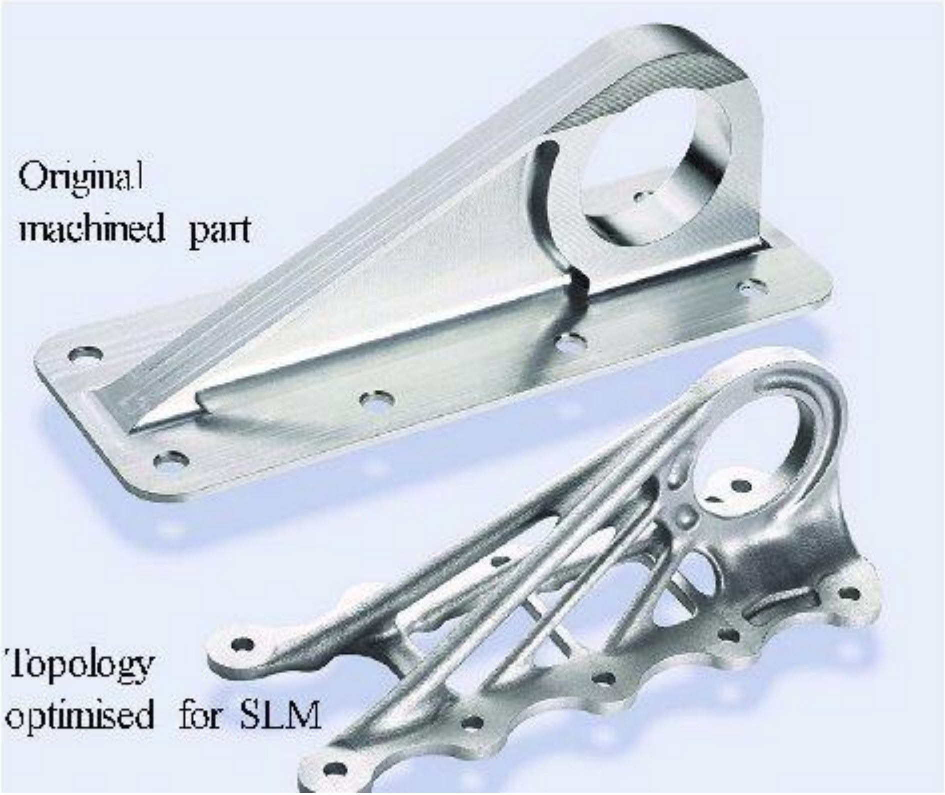
Impact

Reduce waist material, cost, supply chain length and fuel consumption

Airbus - A350 XWB Brackets

Guillaume VULLIOUD

- **Weight saving (up to 50%)**



Airbus - Machine used

Guillaume VULLIOUD

Feature	Details
Build Volume	Ø 300 mm x 400 mm height
Laser System	Three 500-watt fibre lasers with multi-laser scanning for high productivity
Layer Thickness	Adjustable from 20 to 150 micrometres
Materials Supported	Titanium alloys, aluminium alloys, nickel-based superalloys, stainless and tool steels
Preheating	Platform preheating up to 500°C to reduce residual stresses and improve material properties
Monitoring System	Real-time monitoring of powder bed and melt pool for process reliability
Automation	Fully automated powder and component handling
Precision	High precision and repeatability for meeting strict tolerances
Applications in Aerospace	Lightweight components (e.g., brackets, housings) and high-temperature parts (e.g., turbine blades)

Airbus - Machine used

Guillaume VULLIOUD

Feature	Details
Build Volume	245 x 245 x 350 mm
Laser System	Dual 400-watt (per laser)
Layer Thickness	Adjustable from 20 to 80 micrometers
Materials Supported	Titanium, aluminum, nickel-based alloys, cobalt-chromium, and stainless steels
Gas Flow Management	Patented **filterless gas flow technology** ensures uniform conditions and minimizes defects
Real-Time Monitoring	Includes **QM Meltpool 3D and QM Powder Bed** for in-process quality assurance
Automation	Powder-handling system integrated for closed-loop operation
High Precision	Precise control of part tolerances for demanding applications like aerospace and medical fields
Applications in Aerospace	Components like brackets, fuel nozzles, and high-performance engine parts

Airbus - Machine used

Guillaume VULLIOUD

Feature	Details
Build Volume	250 x 250 x 350 mm
Laser System	Quad 500-watt lasers
Layer Thickness	Adjustable from 20 to 100 micrometers
Materials Supported	Titanium alloys, aluminum alloys, nickel-based superalloys, cobalt-chromium, and stainless steels
Gas Flow Management	Advanced inert gas flow system ensures consistent build conditions and reduced contamination
Monitoring Technology	**In-process monitoring systems** (e.g., melt pool, powder bed, and laser power) for quality assurance
Automation	Fully integrated powder handling with automated sieving and recirculation
High Precision	Exceptional repeatability and accuracy for meeting aerospace and medical-grade tolerances
Applications in Aerospace	Lightweight components, turbine blades, and high-performance engine parts

Synthesis for SLM

Guillaume VULLIOUD

Feature	TruPrint 5000	Concept Laser M2	RenAM 500Q
Build Volume	Ø 300 mm x 400 mm height	245 x 245 x 350 mm	250 x 250 x 350 mm
Laser System	Three 500-watt fiber lasers	Dual 400-watt	Quad 500-watt lasers
Layer Thickness	20–150 micrometers	20–80 micrometers	20–100 micrometers
Materials Supported	Titanium, aluminum, nickel alloys, stainless steels	Titanium, aluminum, nickel alloys, cobalt-chromium	Titanium, aluminum, nickel alloys, cobalt-chromium
Preheating Capability	Up to 500°C	N/A	N/A
Gas Flow Management	Advanced flow for uniform conditions	Patented filterless gas flow	Advanced inert gas flow system
Automation	Fully automated powder and component handling	Integrated powder handling	Automated sieving and powder recirculation
Monitoring Technology	Real-time monitoring of melt pool and powder bed	QM Meltpool 3D and QM Powder Bed	In-process melt pool, powder bed, and laser power
Precision	High precision and repeatability	High precision for aerospace and medical applications	Exceptional repeatability and accuracy

Productivity

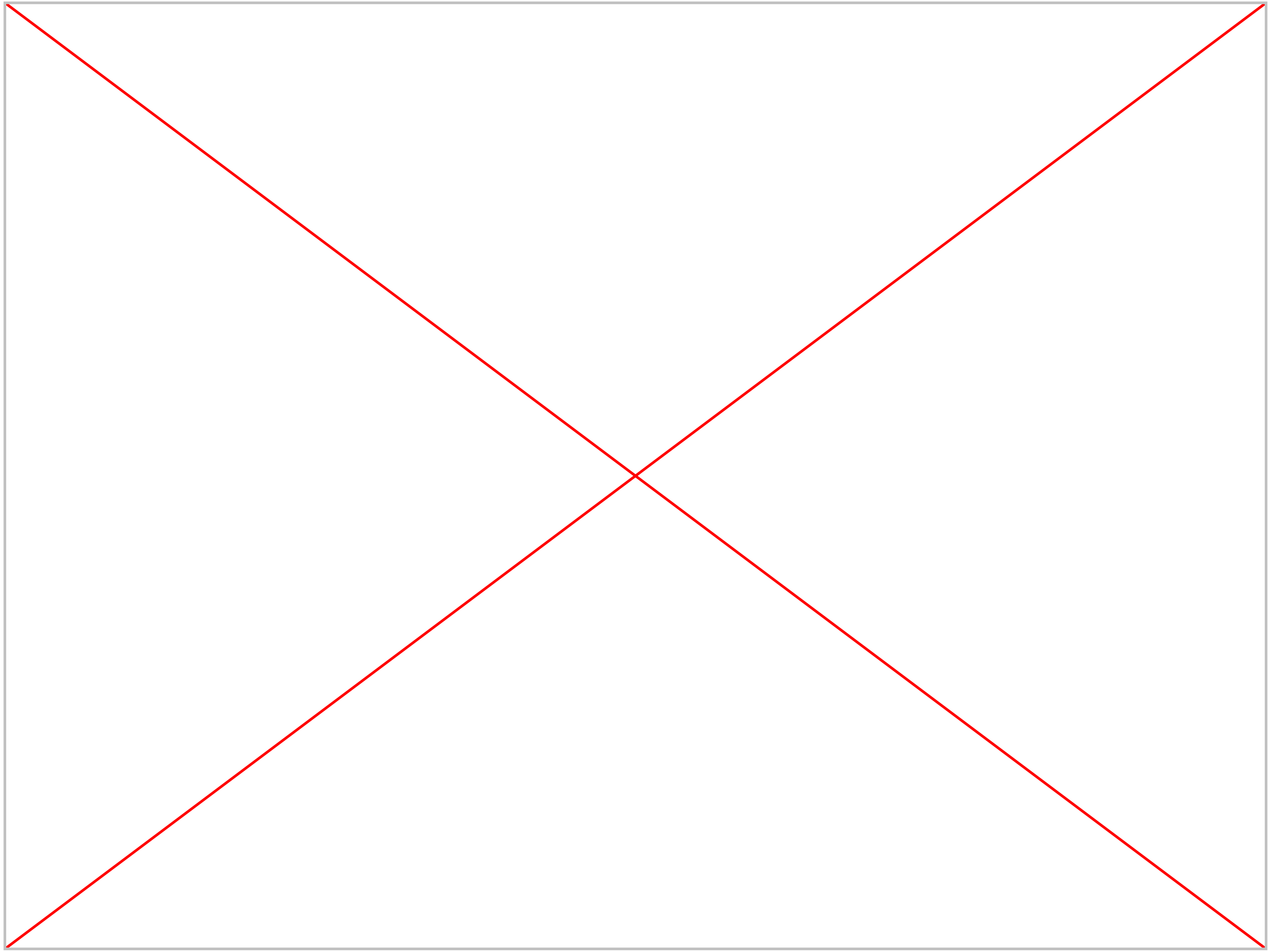
Monitoring

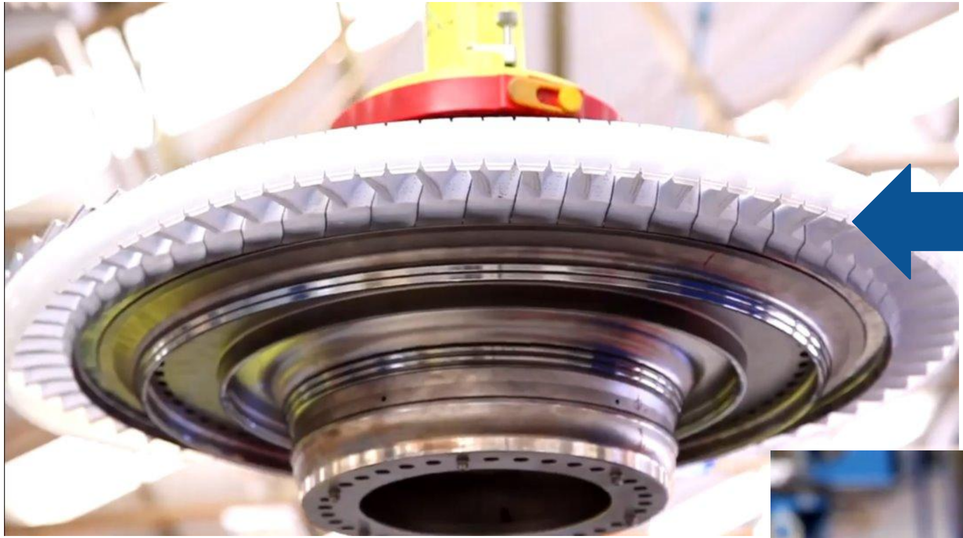
Innovation

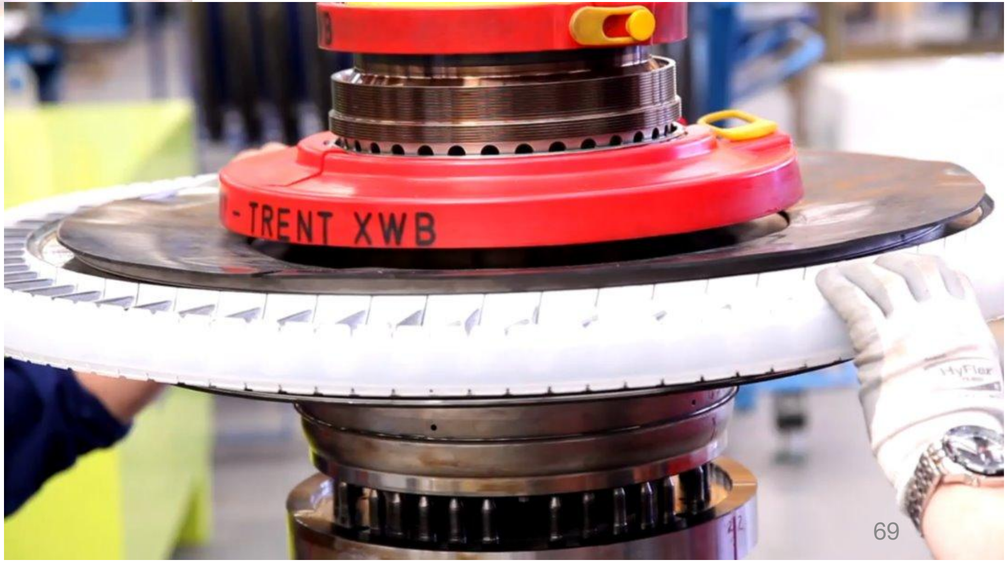
Rolls-Royce

Guillaume VULLIOUD

- **1.5-meter AM piece**
  - 48 aerofoil vanes, including internal passages for an anti-icing system






- TRENT XWB

Rolls-Royce - Machine used

Guillaume VULLIOUD

Feature	Details
Build Volume	Ø 350 mm x 380 mm
Technology	**Electron Beam Melting (EBM):** Operates in a vacuum with high temperatures, producing stress-relieved components.
Materials Supported	Titanium alloys (e.g., Ti6Al4V Grade 5 and Grade 23) and other high-performance metals
Laser/Electron Beam Power	3 kW electron beam
Advanced Features	- **Arcam xQam™:** Precision auto-calibration for beam control.
	- **LayerQam™:** In-process monitoring for part quality verification.
Automation	Integrated **powder recovery system** for safe and efficient powder handling.
Applications in Aerospace	Ideal for producing turbine blades, structural components, and other large, complex parts.
Productivity Enhancements	Up to 15% productivity improvement compared to earlier models due to optimized electronics and software.

Acknowledgement