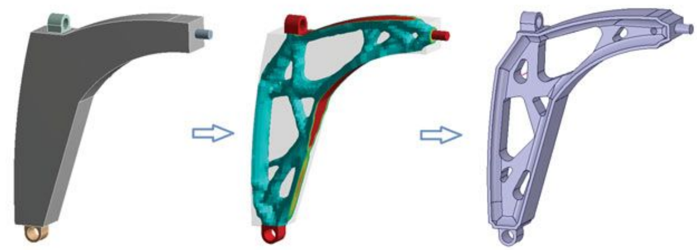
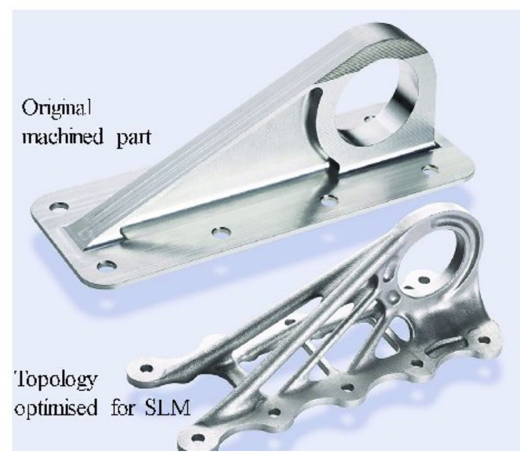
香港中文大學
The Chinese University of Hong Kong

# MAEG5160: Design for Additive Manufacturing

## Lecture 23: Case study – AM applications in aerospace industry

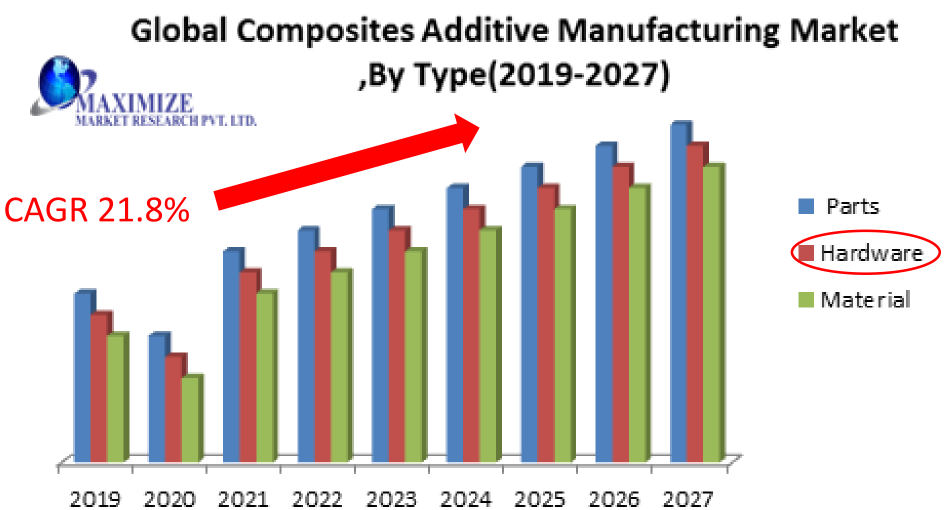



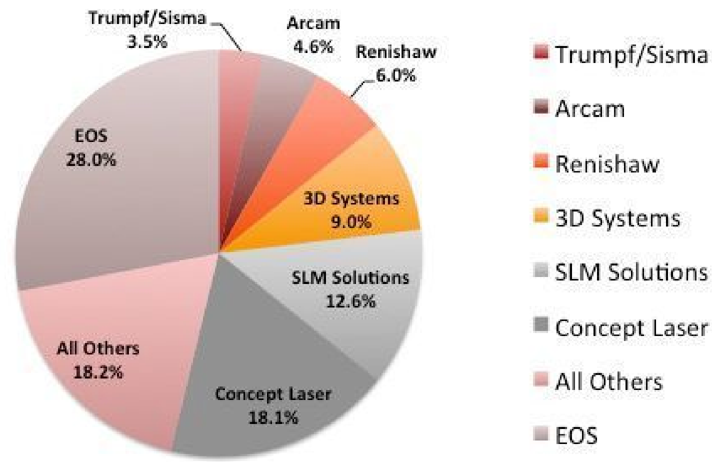


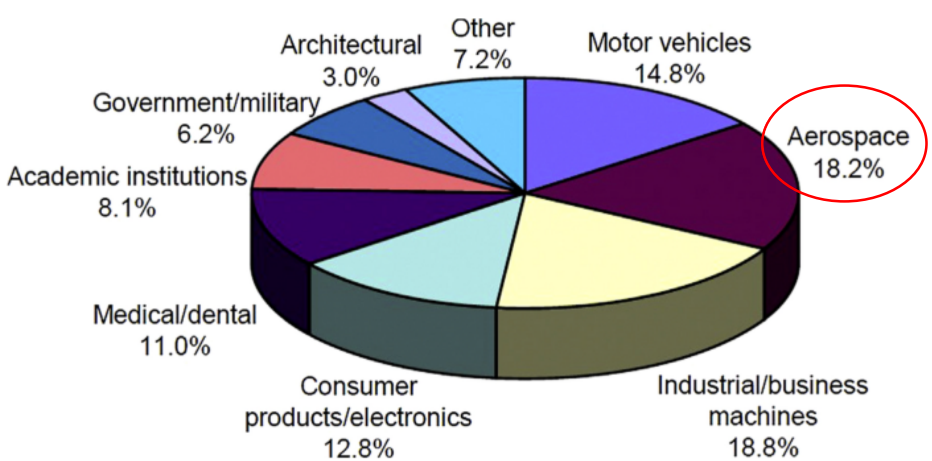

Prof SONG Xu
Department of Mechanical and Automation Engineering,
The Chinese University of Hong Kong.

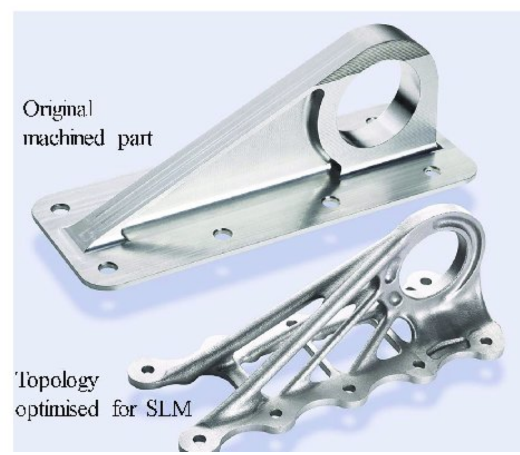
# Lecture 23: Case study – AM applications in aerospace

## 1. AM industry overview




A350 cabin bracket connector

*No design course is completed until a case study ~*

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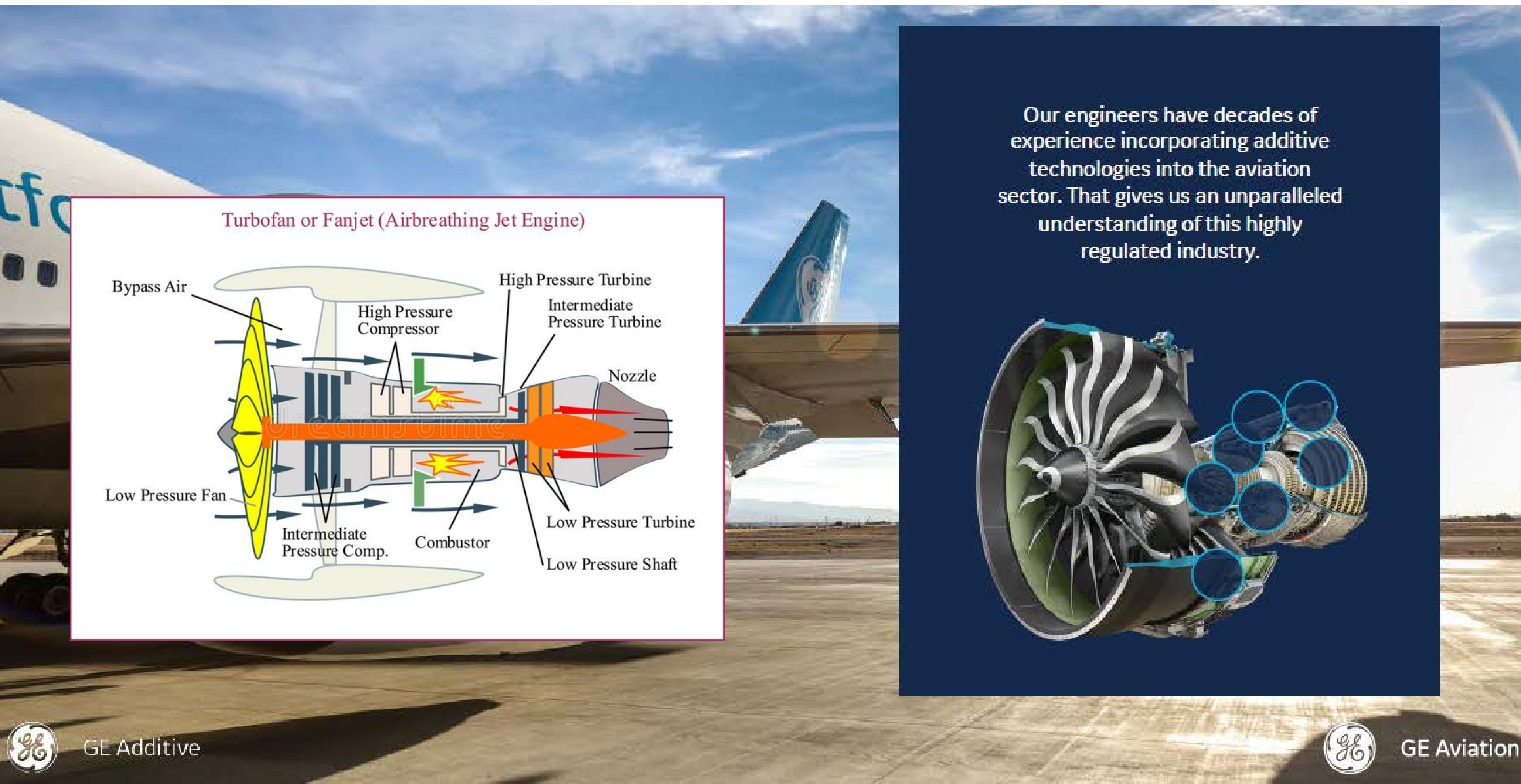
*An example of GE additive on GE9X (copyright belongs to GE)*


Boeing 777X

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## Fuel nozzle tip

**WHY ADDITIVE?:**

- Solving for fuel mixing, fuel emissions and cost savings

**ADDITIVE BENEFITS*:**

- 5X more durable
- 20 parts printed as one

**MACHINE:**
Concept Laser M2

**POWDER:**
Cobalt-chrome alloy

*Compared to traditional manufacturing

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## Low pressure turbine (LTP) blades

**WHY ADDITIVE?:**

- Reduce weight

**ADDITIVE BENEFITS*:**

- Hot process allows production of crack-prone materials
- 50% weight reduction

**MACHINE:**
Arcam EBM A2X

**POWDER:**
Titanium aluminide (TiAl)

*Compared to traditional manufacturing

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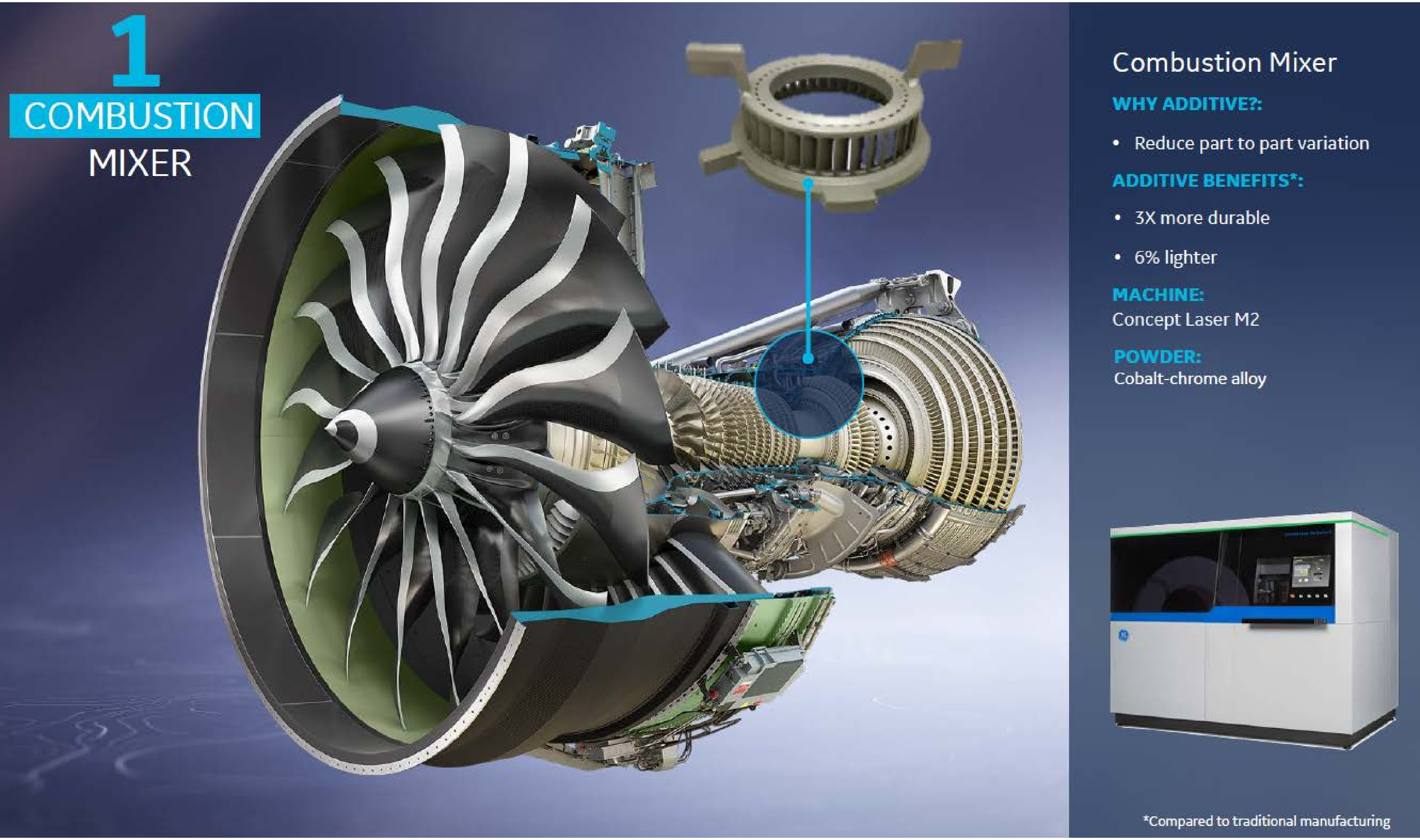

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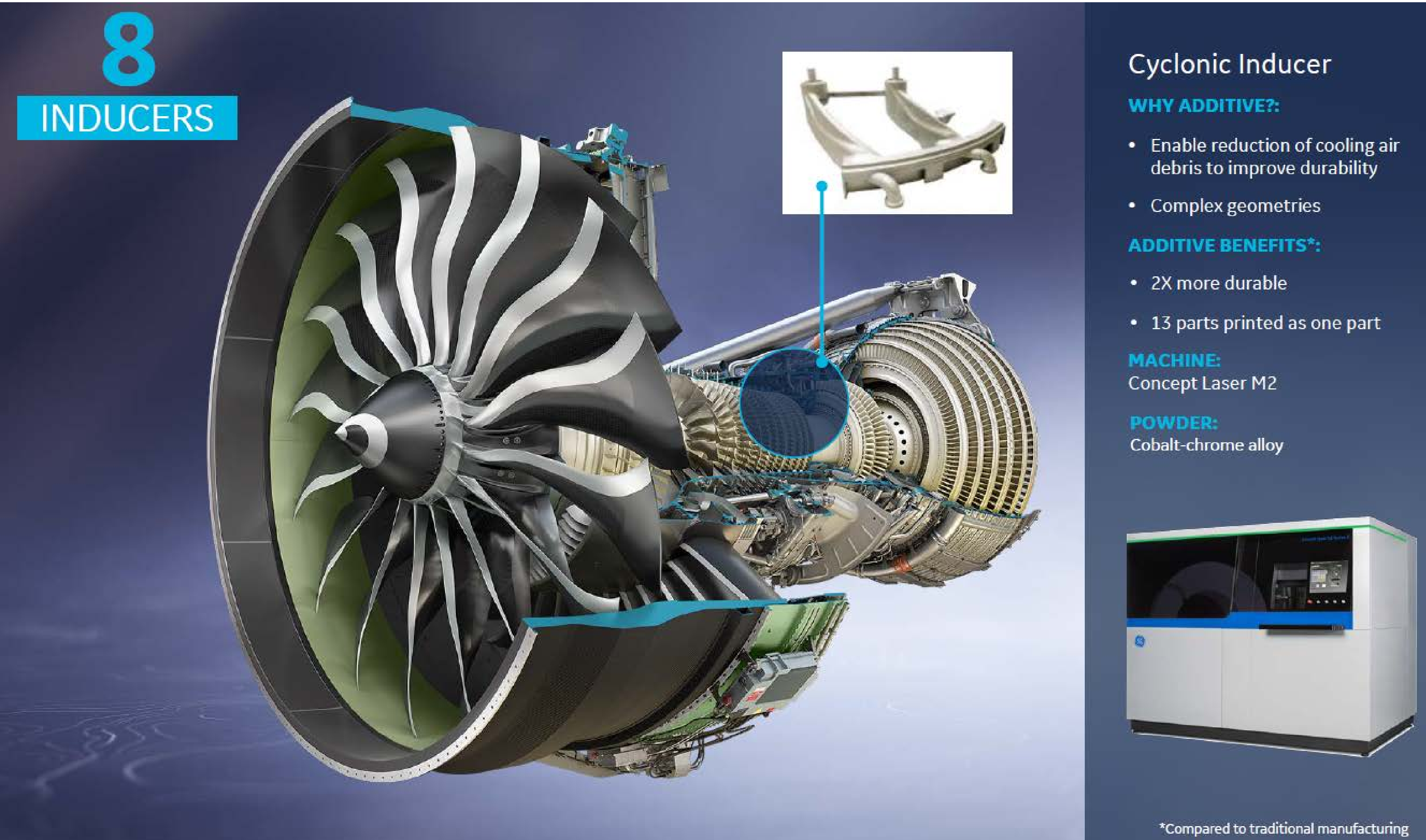

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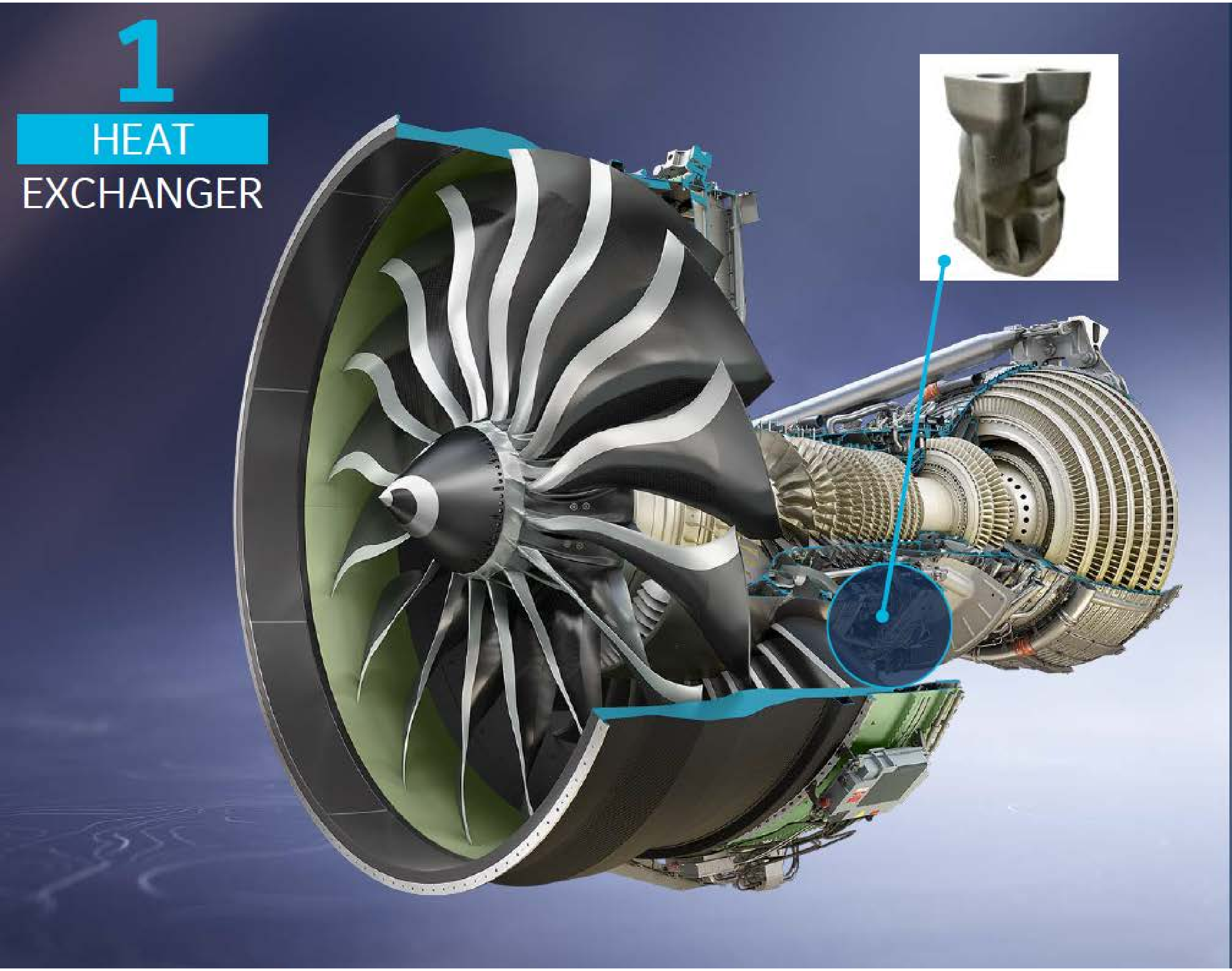


## Heat Exchanger

**WHY ADDITIVE?:**

- Smaller, lighter, cheaper, improved durability

**ADDITIVE BENEFITS*:**

- 40% lighter
- 163 traditionally manufactured parts, now additively printed as one part
- 25% less cost to produce

**MACHINE:**
Concept Laser M2

**POWDER:**
Aluminum (F357)

*Compared to traditional manufacturing

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Manufacturing in the aerospace sector is subject to numerous interacting technical and economic objectives of: functional performance, lead time reduction, lightweighting, complexity, cost management, and sustainment.

The aerospace sector requires the delivery of safety–critical components that must operate in their intended environment (functional performance) in small production volumes with relatively inflexible delivery schedule. Lead time reduction is therefore highly relevant to the aerospace sector as this allows rapid product certification and retains flexibility in design of high value components.

Lightweighting is relevant to the technical and economic performance of aerospace structures. Specifically, the technical performance and allowable mission-defined payload of aerospace structures is physically limited, meaning that system mass reduction directly relates to enhanced economic and technical performance, including reduced fuel costs, lower emissions, larger payloads and increased range.

A critical challenge to metal additive manufacturing (AM) applications in aerospace is the hurdle of ***certification***; requiring that regulatory bodies be confident that the AM systems are fundamentally well understood, and can be repeatably designed and inspected such that reliability and safety expectations can be satisfied. These certification requirements vary according to the criticality of the proposed AM system as being safety or mission-critical or otherwise. Practical certification requires connection with existing standards for traditional manufacturing as well as to standards emerging for AM processes.

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All aerospace manufacturing is subject to strict quality controls such as Quality Systems - Aerospace SAE AS9100 and Standard for Additively Manufactured Spaceflight Hardware MSFC-STD-3716, NASA Standard 6030, but this is further exacerbated by the complexity of the AM processes and many possible influences on component quality. This is especially true as the technology has matured only recently and many studies have reported widely disparate mechanical properties, especially fatigue performance. This leads to uncertainties in the material performance and in the required controls which may be different from traditional manufacturing.

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 |

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Aerospace-domain related AM:

- AM processes: mainly Laser Powder Bed Fusion, Electron Beam Powder Bed Fusion, Directed energy deposition
- AM materials: existing and specially developed for AM process

| Ni-base | Fe-base | Cu-base | Al-base | Refractory | Ti-base | Co-base | Bimetallic |
|---|---|---|---|---|---|---|---|
| Inconel 625 | SS 17-4PH | GRCop-84 | AlSi10Mg | W | Ti6Al4V | CoCr | GRCop-84/IN625 |
| Inconel 718 | SS 15–5 GP1 | GRCop-42 | A205 | W-25Re | γ-TiAl | Stellite 6 | C18150/IN625 |
| Hastelloy-X | SS 304L | C18150 | F357 | Mo | Ti-6–2-4–2 | Stellite 21 | |
| Haynes 230 | SS 316L | C18200 | 2024 | Mo-41Re | | Haynes 188 | |
| Haynes 214 | SS 420 | Glidcop | 4047 | Mo-47.5Re | | | |
| Haynes 282 | Tool Steel (4140/4340) | CU110 | 6061 | C-103 | | | |
| Monel K-500 | Invar 36 | | 7050 | Ta | | | |
| C-276 | SS347 | | | | | | |
| Rene 80 | JBK-75 | | | | | | |
| Waspalloy | NASA HR-1 | | | | | | |

- Advantages:

1. Reduction in processing time with simplified supply chain and reduction in lead time, including logistical benefits, presents a substantial opportunity to reduce cost. There are several examples that have demonstrated cost reductions of 50% and lead time reductions of 50% or more.
2. Reduction in weight, hence the operation cost and CO2 emission. Buy-to-fly ratio from 20:1 to 3:1. However, lightweighting is currently still not the primary driver for AM in aerospace. Lead time reduction is currently the main benefit, which can be significant for complex aerospace components often taking months or years of (traditional) fabrication time for complex systems.

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3. In the spacecraft, it is a different scenario: The quantity of China civil aviation (fleet size ~ 6000) vs. space exploration (~400 times, long-march). Then you can imagine: the technology synergises with space applications serving low quantities of components that exhibit mass and cost reductions crucial for increased development in space. With mission costs for space exploration exceeding €20,000 per kilogram, every gram saved translates to an increased payload capacity per launch and a consequent reduction in launch costs.

4. Besides lightweighting, part consolidation is another prominent benefit for the application of AM techniques in aerospace applications with nearly every example displaying massive reductions in part counts. Part consolidation has the primary benefits of reducing the assembly operations and minimizing the usage of joining methods such as bolting, welding, brazing, soldering and chemical bonding methods. Another advantage is the reduced number of components requiring certification and associated documentation. AM techniques also notably reduce the need for tooling to manufacture components. Last benefit to part consolidation is the reduced need for warehousing for components and legacy components, including components no longer available.

5. Multifunctional lightweighting such as heat transfer also sees strong demand.

6. Repairing high-value aerospace components using AM techniques also presents a major benefit to AM applications in aerospace.

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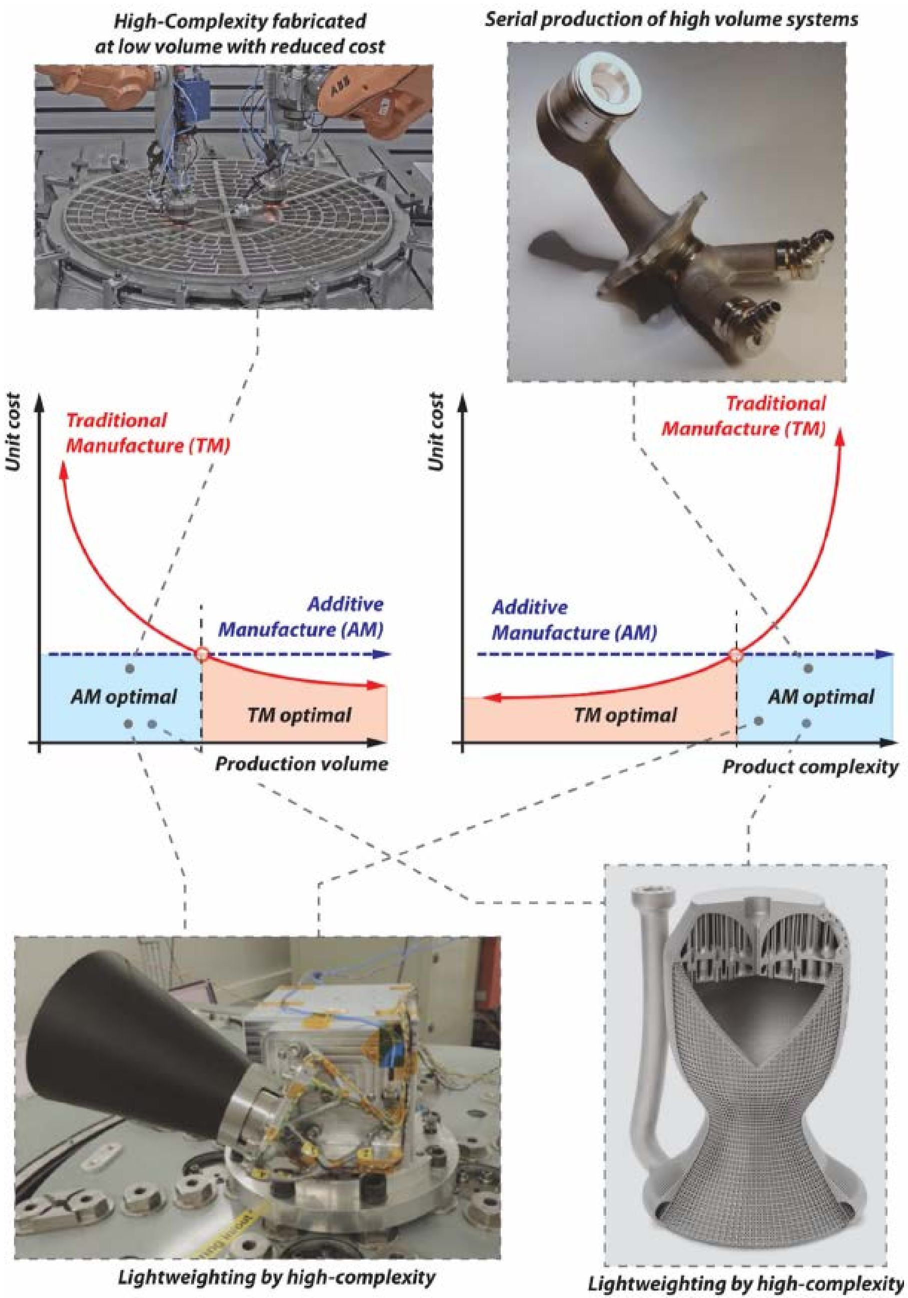
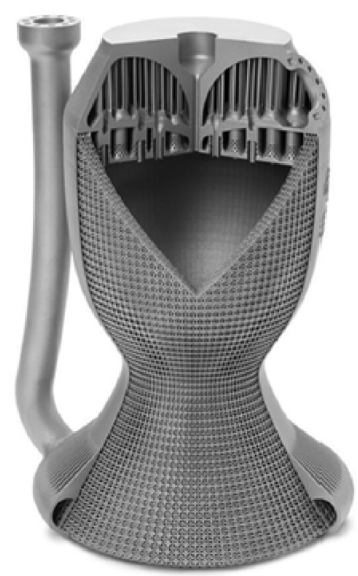



TO and AM of Airbus A320 nacelle hinge bracket.
Left: TO design process. Right: Original bracket (top) and final TO optimized design (bottom).
Original steel bracket = 918 g; TO and AM bracket in Ti6Al4V = 326 g. Copyright: Airbus

Additive Manufacturing Demonstrator Engine Liquid Oxygen (LOX) Turbopump Stator. Courtesy: NASA



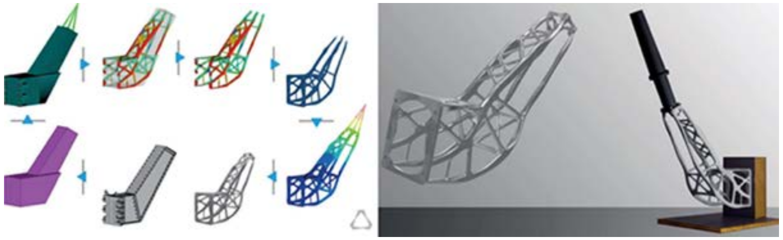
Cellcore prototype rocket nozzle featuring internal cooling channels. Copyright: SLM Solutions/ CellCore

# Lecture 23: Case study – AM applications in aerospace

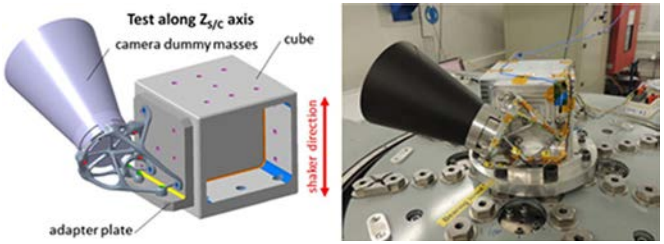
## Aerospace-domain related AM applications:

## 1. Structure and brackets: Aviation, spacecraft and lattice infill structures

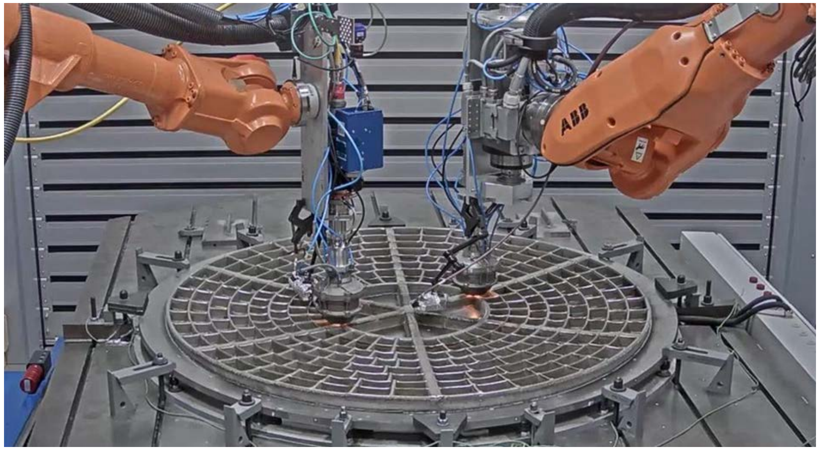
TO and AM of Airbus A350 XWB cabin bracket connector, by LPBF of Ti6Al4V. Copyright Airbus.



TO process of an antenna bracket for the Sentinel-1C and Sentinel-1D. Photo courtesy of Altair Engineering




Test configuration of the bracket with adaptor plate and dummy masses. Copyright: The American Institute of Aeronautics and Astronautics (AIAA), Inc



Example of 1.5 m mirror support being manufactured as technology demonstrator (image courtesy of Fraunhofer and European Space Agency)


nTopology and AFIT lattice CubeSat bus structure. Credit: nTopology

A CubeSat is a square-shaped miniature satellite (10 cm x 10 cm x 10 cm —roughly the size of a Rubik's cube), weighing about 1 kg .


Thales Alenia Space examples including AM lattice structure usage: (a) satellite solar panel deployment mechanism – ‘‘Adel’light hinges for solar arrays of satellites” and (b) satellite sandwich panel ‘‘Diphasic heat spreader”. Courtesy of Thales Alenia Space

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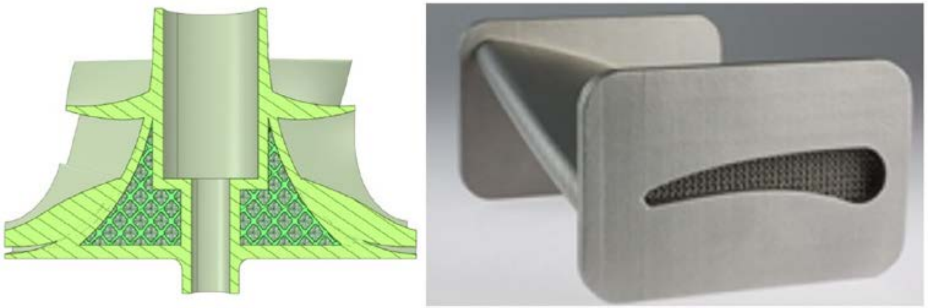
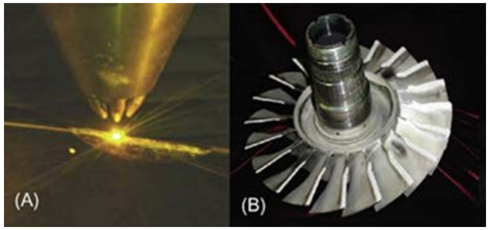
## 2. Static and dynamic engine components



AM built impeller with internal lattice – design concept and a similar manufactured physical part with internal lattice from a different study [Courtesy: SLM Solutions].

The GE LEAP Fuel Nozzle. Courtesy of GE Additive




Blisk repair solution using LENS AM.
Photo Courtesy of Optomec

## 3. Thermal devices

Conflux sectioned F1 heat exchanger application.
Picture Courtesy of Conflux Technology

Cobra Aero AM and lattice cylinder block design. Courtesy of Cobra AERO

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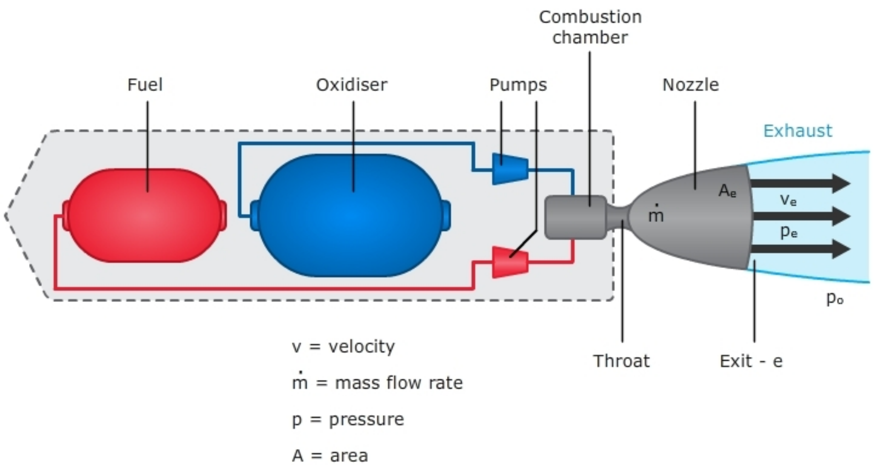
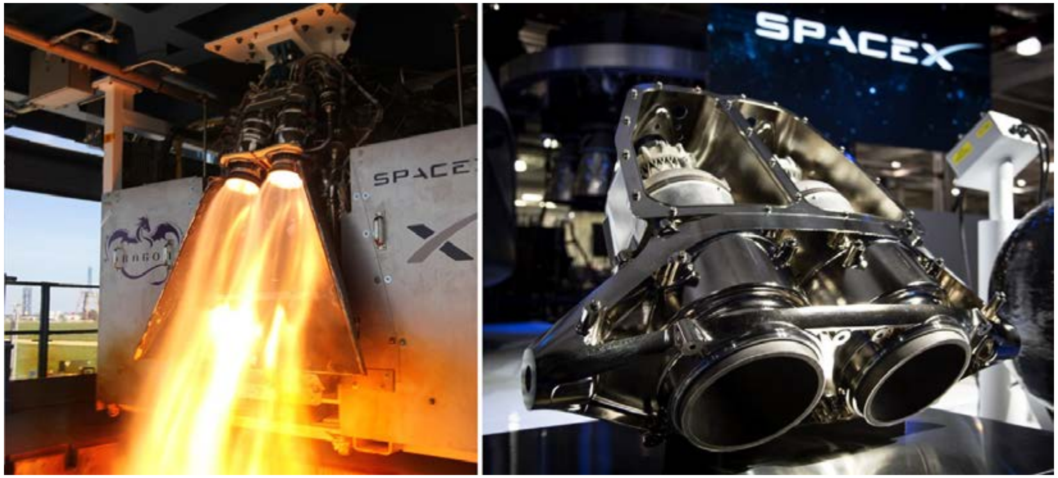
## 4. Liquid fuel rocket components




$$\textbf{Thrust} = F = \dot{m}\, v_e + (p_e - p_o)\, A_e$$

Examples of AM used within liquid hydrogen and liquid oxygen turbopumps at NASA MSFC.

Injector core for the Ariane 6 Rocket. Photo via Ariane Group/EOS




SpaceX AM built Superdraco rocket engine.
Left: SuperDraco Test Fire by SpaceX.
Right: SuperDracos by SpaceX

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a: Bimetallic 7k Coupled Chamber using L-PBF GRCop-42 with HR-1 DED Integrated Nozzle (b: complete with manifolds). c: Bimetallic 40k Chamber built using L-PBF GRCop-42 liner and HR-1 DED Jacket. (Courtesy: NASA)


Examples of Large Scale DED at NASA. A) LP-DED integral channel nozzle 6000 (1.52 m) diameter and 7000 (1.78 m) height with NASA HR-1 alloy deposited in 90 days, B) Powerhead half shell using Inconel 718, and C) LP-DED JBK-75 Nozzle (no channels) that is ½ scale RS-25.

Hyperganic prototype rocket nozzle featuring internal cooling channels and an external lattice. Photo courtesy of Hyperganic

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## Aerospace-domain related AM applications summary

| Non-Technical Literature | | | | |
|---|---|---|---|---|
| **Manufacturer or Author** | **Application** | **Design Approach** | **Material used** | **Technologies used** |
| Aerojet Rocketdyne | Thrust Chamber | AM | Copper Alloy | L-PBF |
| Aerojet Rocketdyne | AR1 Preburner | AM | Mondaloy 200™ | L-PBF |
| Airborne Engineering | C18150 copper chamber | AM | Copper Alloy | Not Stated |
| Airbus | Reflector Bracket | AM | Titanium | L-PBF |
| Airbus | A350 Cabin Bracket Connector | AM & TO | Ti-6Al-4V | L-PBF |
| Airbus | A350 XWB Pylon Bracket | AM | Titanium Alloy | L-PBF |
| Airbus & 3D Systems | RF Filter | AM | AlSi10Mg | L-PBF |
| Airbus & EOS | Aircraft Door Locking Shaft | AM | Ti6Al4V | L-PBF |
| Airbus, APWorks, Autodesk | Bionic Partition wall Project | AM, TO, Lattice | AlMgSc | L-PBF |
| Amaero Engineering, Safran | Aero-Engine | AM | Al7SiMg, Hastelloy X, Ti6Al4V | L-PBF, EBM, CS |
| Ariane Group, EOS | Ariane 6 Injector head | AM | Inconel 718 | L-PBF |
| Ariane Group, ESA | Rocket Combustion Chamber | AM | Copper Alloy | L-PBF |
| Autodesk | Lattice Aircraft Seat | AM, TO, Lattice and "lost wax" casting | Magnesium | N/A |
| Betatype | Rocket Nozzle | AM, Lattice | Stainless Steel 316L | L-PBF |
| Blue Origin | BE-7 Engine | AM | Various | Not Stated |
| Blue Origin | BE-4 rocket engine boost pump | AM | Aluminium alloy, Monel | L-PBF |
| Copenhagen Suborbitals | Coaxial Swirl Injectors | AM | Not Stated | Binder Jetting |
| DLR & 3D systems | Liquid Rocket Engine Injector | AM | Ni718 | L-PBF |
| EOS & Airbus | Borescope Bosses | AM | Not Stated | L-PBF |
| EOS & Airbus | Hydraulic spoiler manifold | AM | Titanium | L-PBF |
| EOS & Vectoflow | Flow Measurement Probe | AM | Nickel-Chromium Alloy | L-PBF |
| EOS, Sogeti and Airbus | Vertical tailplane bracket | AM & TO | AlSi10Mg | L-PBF |
| Frustum & 3D Systems | GE Aircraft Bracket | AM & TO | Titanium Alloy | L-PBF |
| General Electric | LEAP engine Fuel nozzle | AM | Cobalt-Chrome Alloy | L-PBF |
| General Electric | GE9X Engine Additive Components | AM | Various | EBM, L-PBF |
| General Electric | Sump Cover | AM | Cobalt-Chrome Alloy | L-PBF |
| General Electric | NACA inlet | AM | Ti-6Al-4V | L-PBF |
| GKN Aerospace | Rocket Engine Turbines | AM | IN718 | DED |
| GKN Aerospace | Turbine exhaust casing | AM | Not stated | L-PBF |
| GKN Aerospace | Bracket | AM | Ti6Al4V | EBM |
| GKN Aerospace | Intermediate compressor case bosses | AM | Ti-6Al-4V | DED |
| GKN Aerospace | Optical ice protection probe | AM | Not stated | Not stated |

# Lecture 23: Case study – AM applications in aerospace

| Non-Technical Literature | | | | |
|---|---|---|---|---|
| **Manufacturer or Author** | **Application** | **Design Approach** | **Material used** | **Technologies used** |
| Hieta | High and Low temperature heat exchangers | AM | Inconel 718/625 or CM247 LC | L-PBF |
| Hyperganic | Rocket Nozzle | AM, Lattice | Inconel 718 | L-PBF |
| Launcher & EOS | E-2 Rocket Engine | AM | C18150 Copper-alloy | L-PBF |
| Lena Space and Oerlikon | Propulsion system Impeller | AM | Not Stated | Not Stated |
| Liebherr-Aerospace & Airbus | Landing Gear Sensor Bracket | AM | Titanium Alloy | L-PBF |
| Lockheed Martin | Satellite Fuel Tank | AM | Titanium Alloy | EB-DED |
| NASA | Rocket Combustion Chamber | AM | GCop-84 | L-PBF |
| NASA | Perseverance Heat Exchangers and structures | AM | Titanium Alloy, Nickel-based superalloy | L-PBF |
| NASA | 7k and 40k coupled chamber and nozzle | AM | GRCop-84, GRCop-42, NASA HR-1, Inconel 625 | L-PBF, EB-DED, DED |
| NASA | Rocket Injector | AM | Inconel 625 | L-PBF |
| NASA | Rocket Engine | AM | Various | Not Stated |
| NASA | LPS Fuel Turbopump | AM | Various | L-PBF |
| NASA | Pogo Accumulator Assembly | AM | Inconel 718 | Not Stated |
| NASA | Maintenance Port Cover | AM | Not Stated | L-PBF |
| NASA | RS-25 Pogo z-baffle | AM | Inconel 718 | L-PBF |
| nTopology & Cobra Aero | Cobra Aero uses multiphysics simulation to optimize UAV engine | AM, Lattice | AlSi10MG | L-PBF |
| nTopology & USAF | Air Force optimizes cubesat using Architected Materials | AM, Lattice | Inconel 718 | L-PBF |
| Oerlikon | Turbine Blade | AM | Not Stated | Not Stated |
| Oerlikon | Double Nozzle | AM | Inconel 625 | L-PBF |
| Optomec | T700 Blisk repair | AM | Stellite® 21 | LENS |
| Orbex | Rocket Engine | AM | Not Stated | L-PBF |
| Orbital ATK | Hypersonic Engine Combustor | AM | Not Stated | L-PBF |
| Parabilis Space Technologies | Multi-Material Nozzle | AM | Copper Alloy, Isomolded Graphite, Inconel 718 | Various |
| Parabilis Space Technologies | RCS Thruster | AM | Not Stated | Not Stated |
| Pratt & Whittney | Compressor Stators | AM | Ti-6Al-4V | L-PBF |
| Relativity Space | Terran 1 Fuel Tank | AM | Not Stated | DED |
| Relativity Space | Aeon Engine | AM | Not Stated | L-PBF |
| RocketLab | Rutherford Engine | AM & Lattice | Not Stated | EBM |

# Lecture 23: Case study – AM applications in aerospace

**Non-Technical Literature**

| Manufacturer or Author | Application | Design Approach | Material used | Technologies used |
|---|---|---|---|---|
| RUAG, EOS, Altair | Sentinel Antenna Bracket | AM & TO | AlSi10Mg | L-PBF |
| RUAG, EOS, Altair | Star Tracker Bracket | AM & TO | AlSi10Mg | L-PBF |
| RUAG, EOS, Altair | LEROS Engine support bracket | AM & TO | AlSi10Mg | L-PBF |
| Siemens | High-Pressure Hydraulic Manifold | AM | Titanium Alloy | L-PBF |
| SLM & Cellcore | Rocket Engine | AM & Lattice | Inconel 718 | L-PBF |
| SpaceX | SuperDraco Engine Chamber | AM, Cert | Inconel Alloy | L-PBF |
| SpaceX | Main Oxidiser Valve Body | AM | Not Stated | Not Stated |
| SpaceX | Raptor Engine Components | AM | Various | Various |
| Spirit AeroSystems & Boeing | Access Door Latch | AM | Titanium Alloy | DED |
| Thales Alenia Space & 3D Systems | Antenna Bracket | AM & TO | Ti Gr5 | L-PBF |
| The Welding Institute | Helicopter combustion chamber | AM | Inconel 718 | DED |
| ULA | Vulcan Bellows Feedline Housing | AM | Inconel 718 | L-PBF |
| Virgin Orbit & NASA | Rocket Combustion Chamber | AM | GRCop-84 | L-PBF |

**Technical Literature**

| Authors | Title | Application Areas | Year |
|---|---|---|---|
| Godec M.,et al. | Hybrid additive manufacturing of Inconel 718 for future space applications | Spacecraft | 2021 |
| Zhan Z., Li H. | A novel approach based on the elastoplastic fatigue damage and machine learning models for life prediction of aerospace alloy parts fabricated by additive manufacturing | Aerospace, Fatigue | 2021 |
| Van Den Berg P, Jyoti B, Hermsen R | Investigation of Thermal Behaviour of Additively Manufactured Green Bi-Propellant Thrusters in CubeSat Applications Using Transient Thermal Modelling | Spacecraft, Engines | 2021 |
| Waugh I., et al. | Additive manufacture of rocket engine combustion chambers from CuCrZr (C18150) using the DMLS process | Rocket, Engines | 2021 |
| Waugh I., et al. | Additive manufacture of rocket engine combustion chambers using the ABD R −900AM nickel Superalloy | Rocket, Engines | 2021 |

# Lecture 23: Case study – AM applications in aerospace

Challenges and opportunities:

1. Certification & standards

Major governing bodies such as the European Union Aviation Safety Agency (EASA), NASA, European Space Agency (ESA), and Federal Aviation Administration (FAA) are imposing increasingly strict testing protocols and certifications that are required for the use of aerospace components in service for both mission-critical and non-critical applications. These certification processes generally involve the repeatability of production processes and consistency in the quality of manufactured components which are both considerable challenges currently in the metal AM industry, especially when producing components in larger quantities. The primary challenge for the certification process of AM built components is the lack of prior knowledge, complete understanding and traceability of the AM process, detailed characterization and AM property databases, and data regarding the failure mechanisms.

2. Structural integrity

However, dynamic mechanical properties such as fatigue and creep have seen relatively less research and there remains a lack of test data reporting among aerospace companies.

The existing AM fatigue literature demonstrates test results that indicate porosity, residual stress and surface roughness are the largest concerns for high cycle fatigue (HCF) and low cycle fatigue (LCF) testing scenarios with overall fatigue properties generally substandard compared to conventional manufacturing processes.

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3. Design for AM

While TO and lattice structures are discussed there are several challenges that exists with these in practical application. Since these techniques often optimize the design based on a known set of inputs and constraints, the load paths for aerospace components must be well understood. These load paths and combined structural, thermal, dynamic, and integrated environments are not always well defined or known for aerospace applications and designs can often include high design margins to account for these uncertainties.

4. Non-Destructive testing (NDT)

Due to the many challenges described before, NDT is prescribed for all critical flight components manufactured by metal AM. NDT is important for identifying flaws such as porosity or cracks in critical components and a variety of methods may be used including radiographic testing (RT), dye penetrant, eddy current, ultrasonic testing, amongst others. one method has proven to be able to overcome many of these challenges: X-ray computed tomography (CT). The major limitations of the technique are the relatively poor resolution for large parts, components with thick walls, challenges with alloys such as copper, and the time and cost involved. For the above reasons, many in-process monitoring tools are being developed to improve the identification of flaws during the process, rather than post-process.

# Lecture 23: Case study – AM applications in aerospace

5. Future opportunity

Many open research questions remain, with opportunities for enhanced understanding and performance and further developments in the near future. The most important areas of current development are listed and discussed below:

- New alloys developed for AM and for aerospace applications
- In situ monitoring for digital twin and accurate flaw Identification
- Build simulation for identification of risks
- In-space and non-terrestrial AM
- Wider usage of architected cellular structures (lattices)
- Usage of optimization techniques such as topology optimization (TO) and hybrid analytical thermal optimization (HAATO)
- Multi-functional components such as integrated electronics and sensors in AM processes

In summary, the main advantages of metal AM in aerospace is cost and lead time reduction. Mass reduction is also a significant opportunity area with optimized design or use of multiple alloys, however these techniques need to be well understood and properties well defined. In addition, part consolidation is a major advantage in this industry. Part complexity capabilities inherent in metal AM allows for high complexity within components, including internal features such as channels and high surface area for heat transfer applications. AM has also been demonstrated in many large-scale applications, so scale is becoming far less of a limitation.

Thank you for your attention