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Additive manufacturing in the automotive industry

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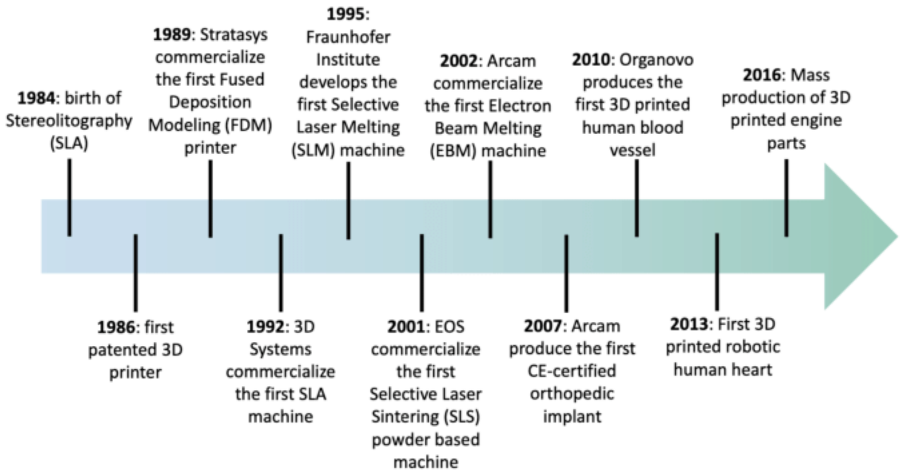
History and evolution of AM



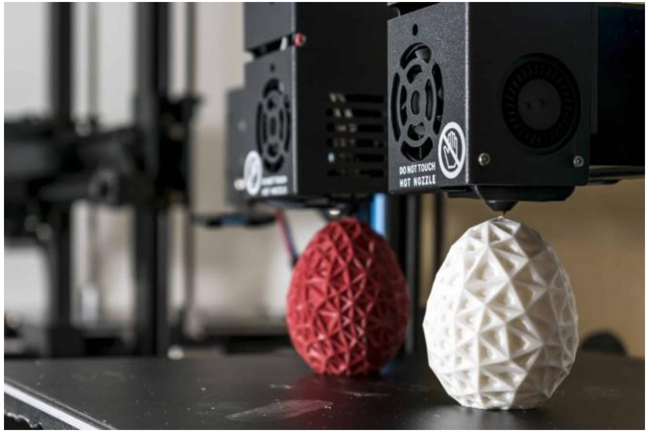
- 1980s: first 3D printing patents (SLA, SLS, FDM)
- 1990s–2000s: mainly used for prototyping
- 2010s: metals join, aerospace & automotive adopt
- 2020s: production-grade materials and precision
- From prototypes → industrial manufacturing

Importance of AM in the automotive industry

- Enables lighter, optimized vehicle parts
- Combines multiple parts into one component
- Reduces waste and tooling costs
- Accelerates prototyping and customization
- Supports sustainable, local production

Main AM process families

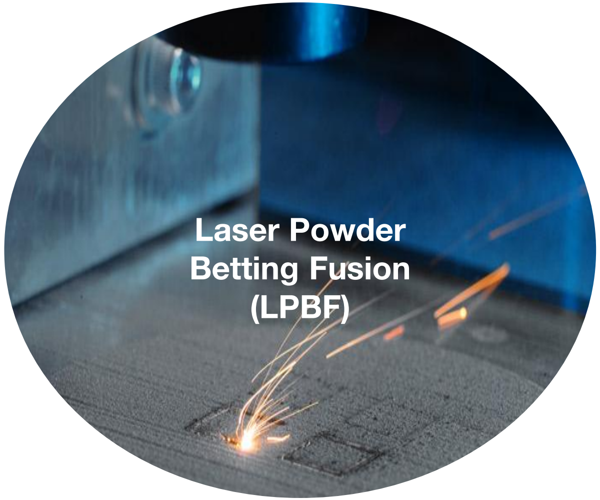
Polymer AM: fast, low-cost, ideal for prototyping

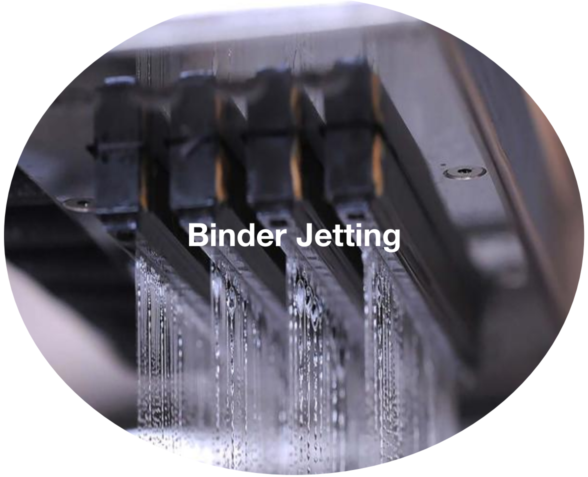


Metal AM: dense, strong, for structural parts

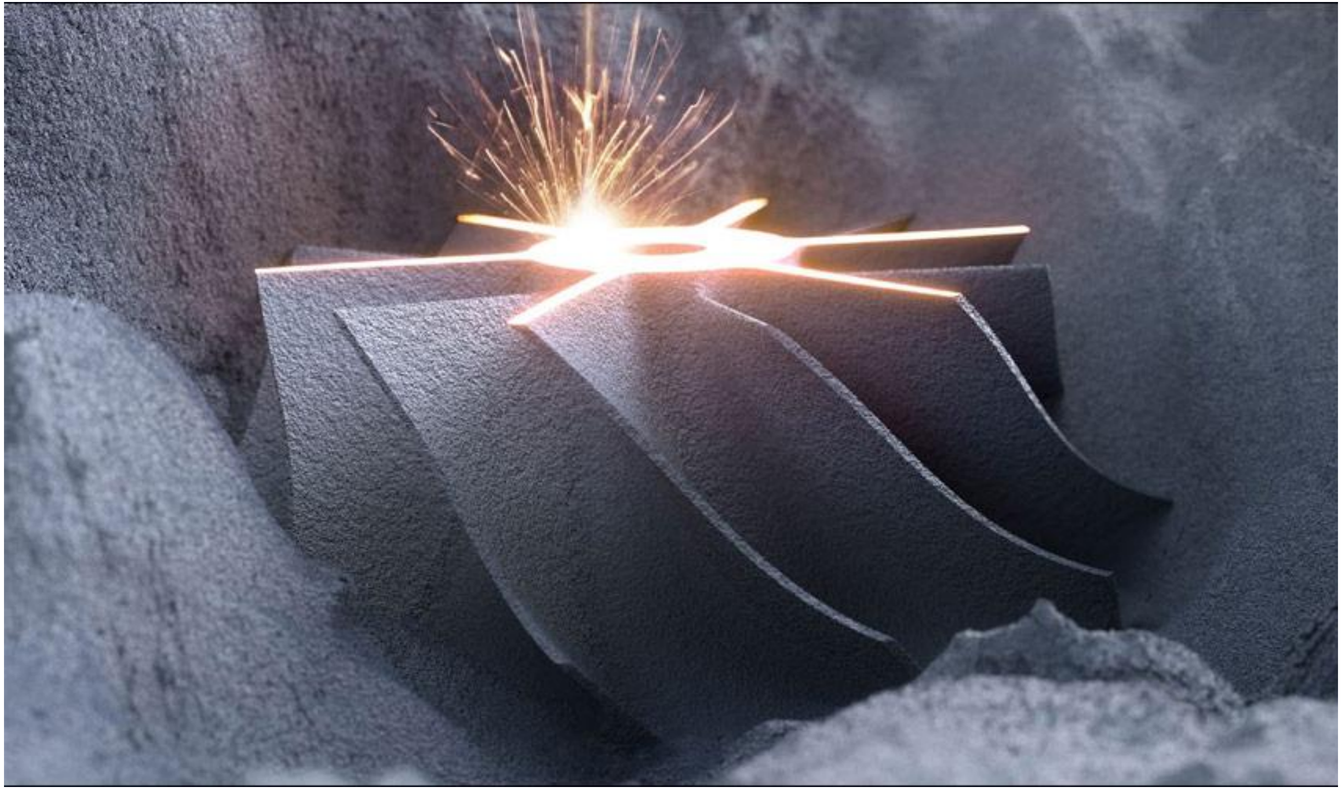
Each family complements the other !

Structure of the presentation

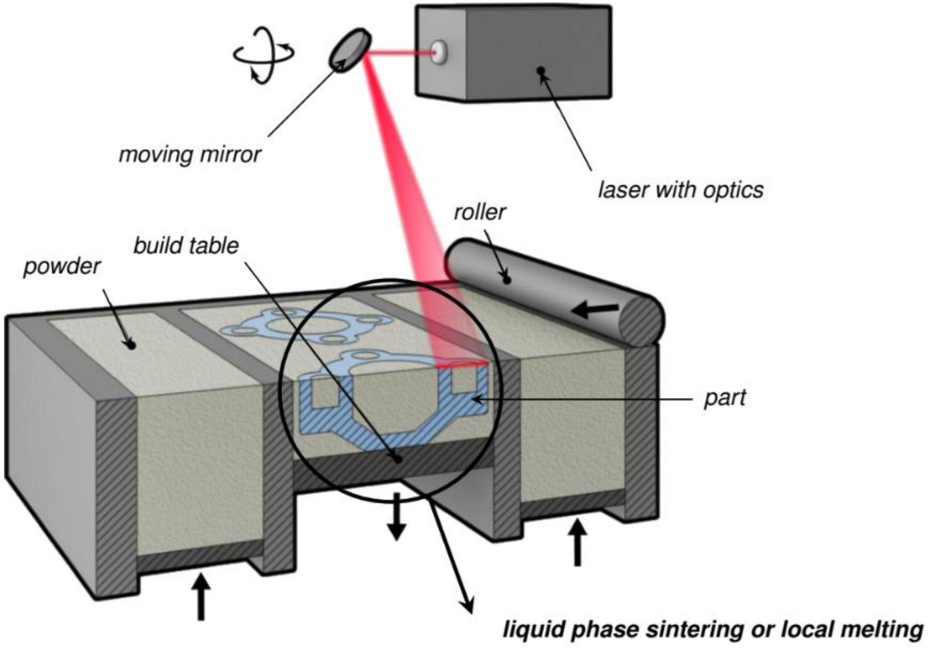




Laser Powder Betting Fusion (LPBF) State of the art



Process principle



- Additive manufacturing process building parts layer by layer from fine powder (metal, polymer, or ceramic).
- High-energy laser selectively melts powder particles in targeted regions.
- Creates a molten pool that solidifies rapidly as the laser moves.
- Enables complex geometries only required material is fused; loose powder acts as natural support.
- Operates in a controlled inert gas atmosphere (argon or nitrogen) to prevent oxidation.
- Laser scanning precisely follows the CAD model, ensuring high dimensional accuracy.

Example of Machine

- Chamber size: from 125 × 125 × 125 mm^3 to 500 × 280 × 850 mm^3
- Number of lasers: from 1 to 4
- Laser power range: 100 W – 1000 W
- Beam diameter: from 70 μm to 115 μm
- Minimum feature size: around 150 μm
- Prices: from €150,000 to several million euros

SLM 500

Physics

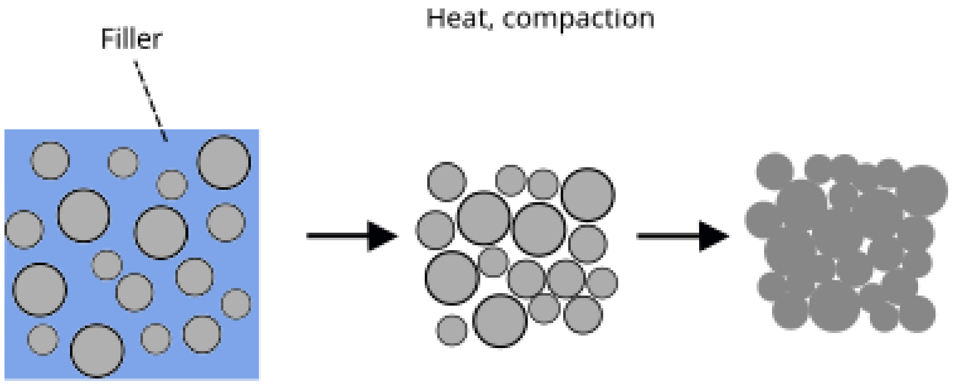
Local Melting

- Used to produce fully dense, high-performance parts
- Standard process in metal LPBF

Liquid Phase Sintering

- Applied when materials cannot be fully melted easily (e.g. ceramics)
- Helps reduce thermal stresses and distortion
- Results in partially dense structures suitable for non-critical components

Liquid Phase Sintering



Sintering Définition [Wikipédia] : Process of compacting and forming a solid mass of material by pressure or heat without melting it to the point of liquefaction.

Liquid Phase Sintering Définition [Wikipédia] : Liquid phase sintering is the process of adding an additive to the powder which will melt before the matrix phase.

Advantages of LPBF

- Applicable to a wide range of materials : metals, polymers, and ceramics
- Powders (especially Metal) are recyclable and can be reused
- Loose powder acts as natural support, allowing complex geometries and overhangs
- Reduced need for additional supports, minimizing post-processing
- When supports are used, they control heat flow and reduce warpage, overheating, and balling
- Uses spherical powders for uniform spreading and consistent layer quality
- Powders produced by gas/water atomization (metals) or chemical precipitation (polymers) ensure good flowability and packing density

Materials

3 main type of material powder

- Metal (L-(M)PBF)
- Ceramic (L-(C)PBF)
- Polymer (L (P)PBF)

Metal Powder

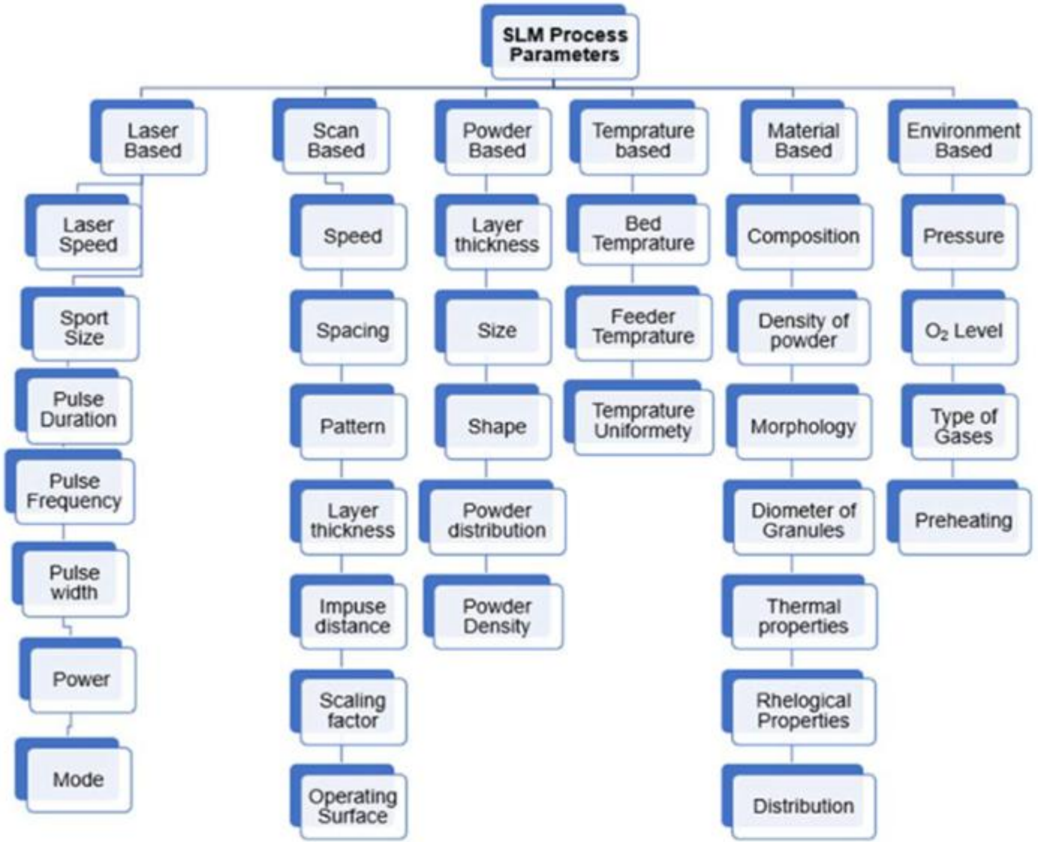
Material	E (GPa)	Rm (MPa)	ε_{rup} (%)
Metals (L-(M)PBF)			
Ti6Al4V	110	1150	11
Inconel 718	170	980	31
Maraging Steel	180	1100	8
Polymers (L-(P)PBF)			
Peek HP3	4.2	90	2.8
PA2201	1.7	48	15
PrimeCast101	1.6	5.5	0.4

Mechanical properties (order of magnitude)

Process parameters in LPBF

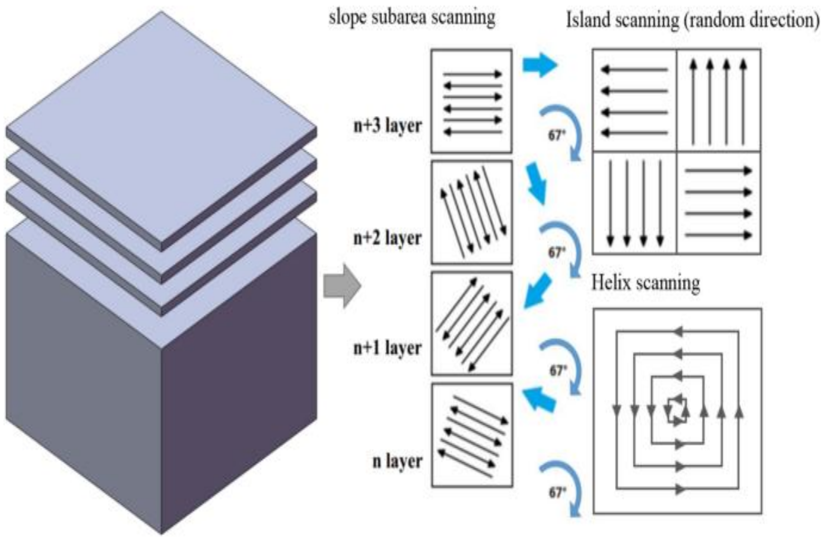
The quality, density, and surface finish of LPBF-produced parts are strongly influenced by several interrelated process parameters. These parameters can be grouped into five main categories: laser-based, scan-based, powder-based, temperature-based, material-based, and environment-based.

Table of LPBF Process parameters



Example of process parameters

Scanning strategy



A good scan strategy can for example :

Reduce residual stresses and deformation

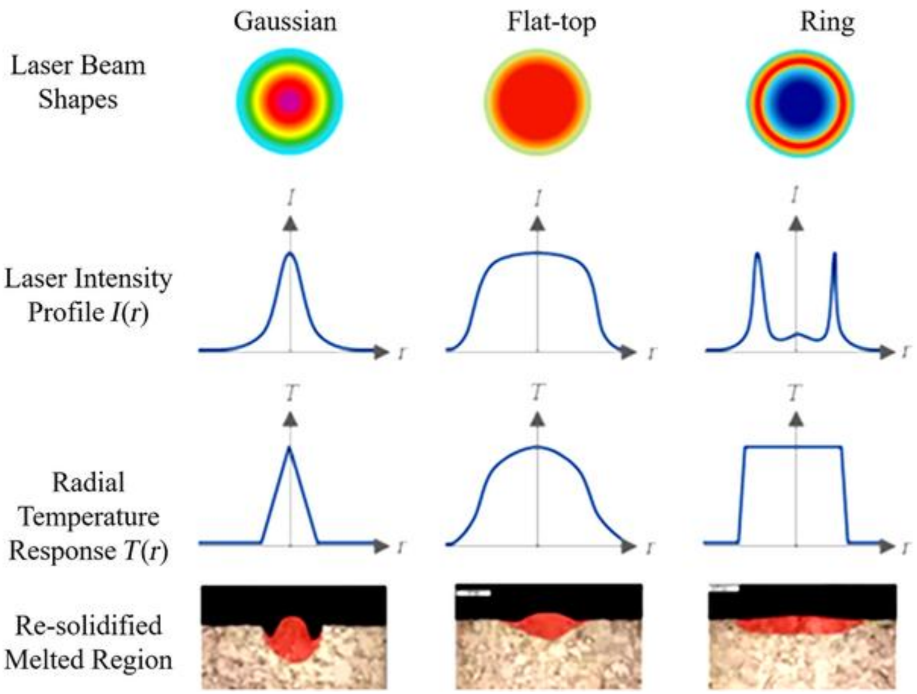
- By varying the scanning direction from one layer to another (e.g., rotation of 67°).
- This limits the accumulation of thermal gradients in a single direction.

Control the microstructure

- The grain orientation and solidification rate depend on the laser path.
- This allows control over anisotropic mechanical properties.

Example of process parameters

Beam type



- Gaussian beam (most used)
- Flat-top beam (advanced system)
- Ring beam (under expérimentation)

Defects in the LPBF

Despite its advantages, the LPBF process is prone to several defects mainly related to complex thermal conditions and process parameters.

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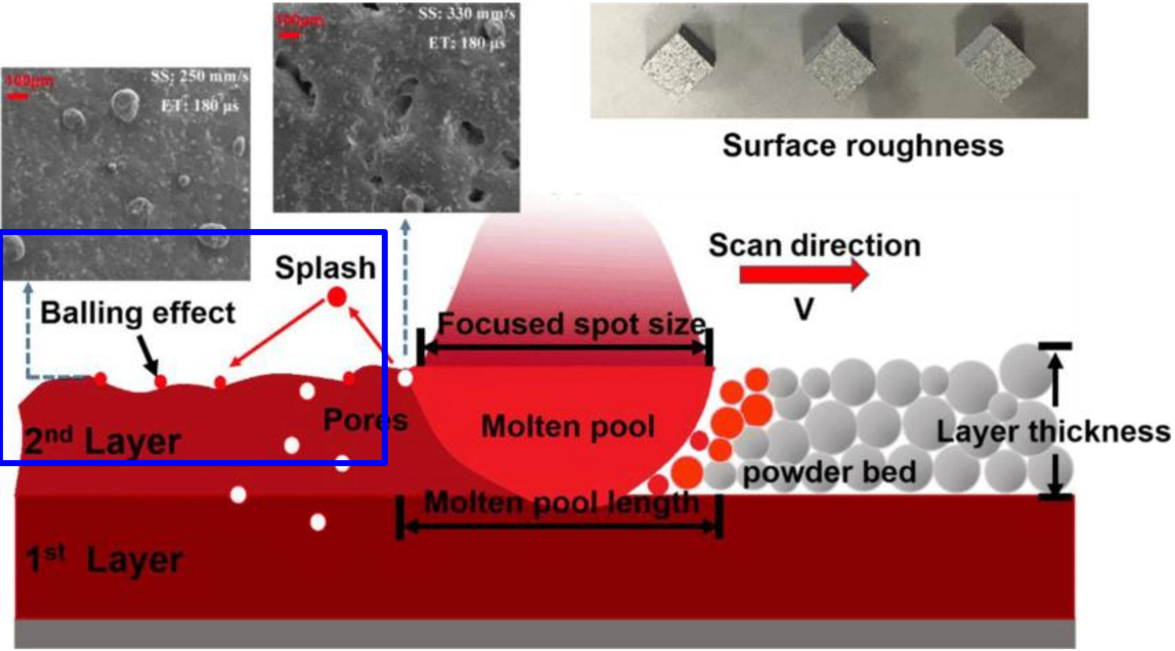
Defects in LPBF



Balling effect

Definition:

Formation of small spherical droplets instead of a continuous melt track during laser scanning.

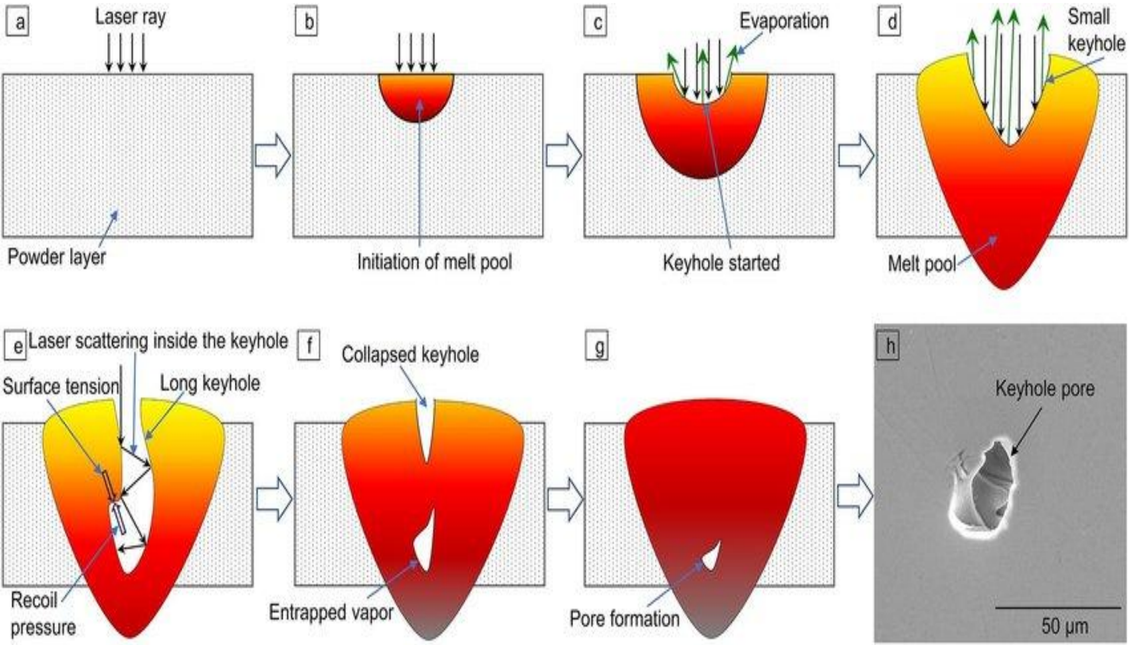
Causes:

- Melt pool instability
- Presence of loose powders in the powder bed
- Improper parameters (low power / high scan speed)
- Large space between two beam line (hatch spacing) or uneven solidification

Prevention:

- Optimize power & speed
- Improve powder quality
- Adjust hatch spacing / layer thickness

Defects in LPBF



Keyhole

Definition:

Formation of a deep, narrow vapor cavity ("keyhole") in the melt pool due to excessive laser energy density.

Causes:

- Too high laser power or low scan speed
- Focused Gaussian beam (high center intensity)
  Low powder reflectivity → high absorption
- Repeated melting of same area

Prevention:

- Optimize power and speed (balanced energy input)
- Use beam shaping (top-hat or ring beam)
- Control overlap and scan strategy
- Maintain stable melt pool monitoring

Table of defects in LPBF

Defects	Causes	Solution Methodology
Balling	Presence of loose powders in the powder bed	High power and low scan speed ; Remelting/Reheating
Porosity	Low penetration due to insufficient laser energy density	Reduce laser power ; Increase laser velocity ; Remelting/Reheating
High Surface Roughness	Oxidation from atmospheric gases and adhesion of partially melted powders	Optimize process parameters ; Post processing (Shot blasting, Chemical etching)
Residual Stress, Distortion, Cracking	Uneven heating of local zones ; Rapid heating and cooling	Reduce scan vector length ; Use heated substrate/chamber
Composition Change / Loss of Alloying Element	Vaporization due to overheating	Reduce laser power ; Reduce laser energy ; Increase scan line spacing ; Increase layer thickness
Oxide Inclusion	High affinity to oxygen leading to oxide formation	Provide shielding gas ; Vacuum in processing zone

LPBF for Automotive:

From design discipline to industrialization

Topology Optimization

DfAM

Verification & Qualification

Production Economics & Scalability

The case study

BMW
i8 Roadster 3D Printed Bracket

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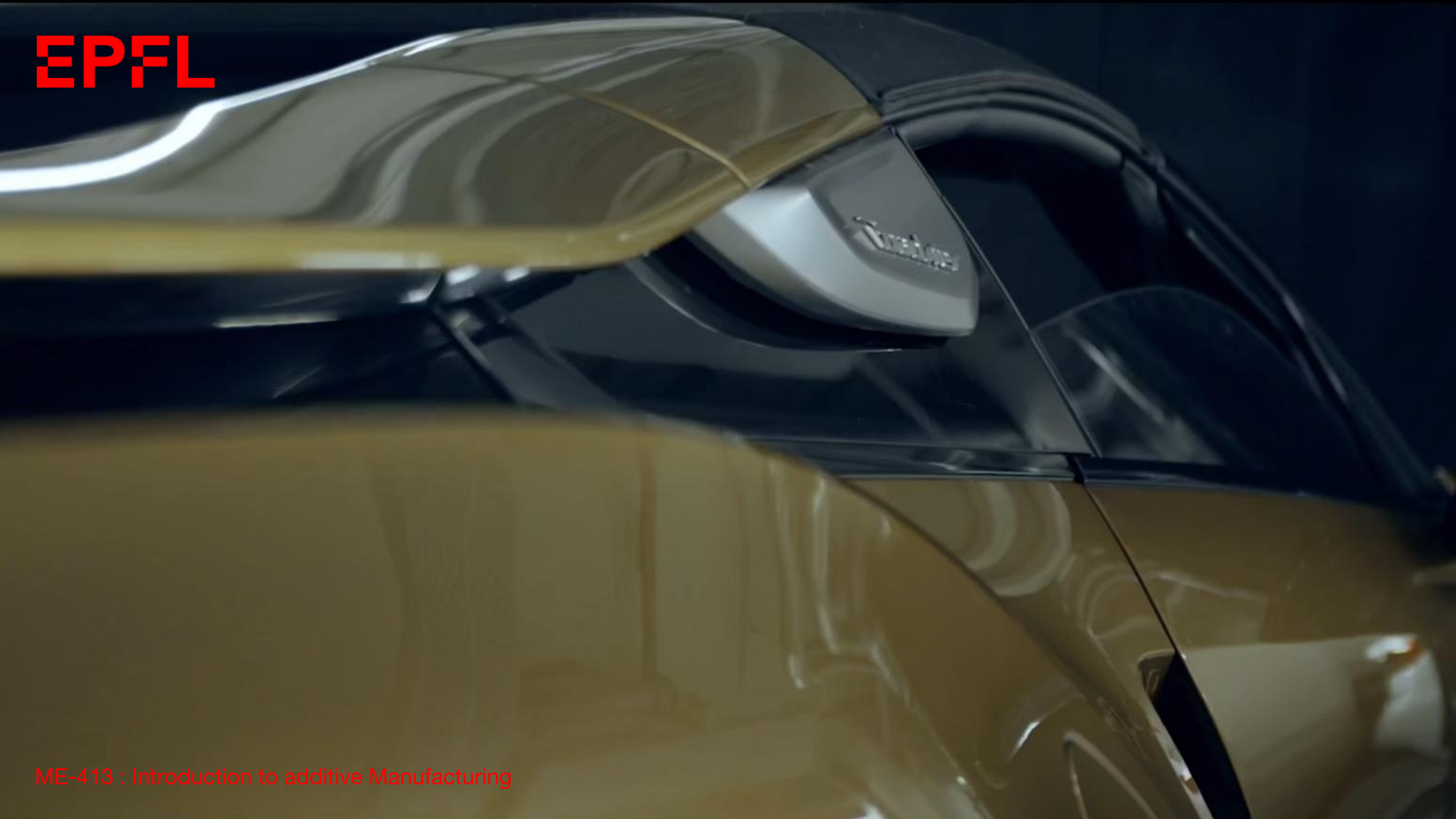
The case study

First metal-AM structural part in a series-production BMW vehicle

44 % weight reduction and 10× faster development

exceeded 1 million printed parts



Topology Optimization Fundamentals

Automotive needs

weight ↓, stiffness ↑, integration ↑

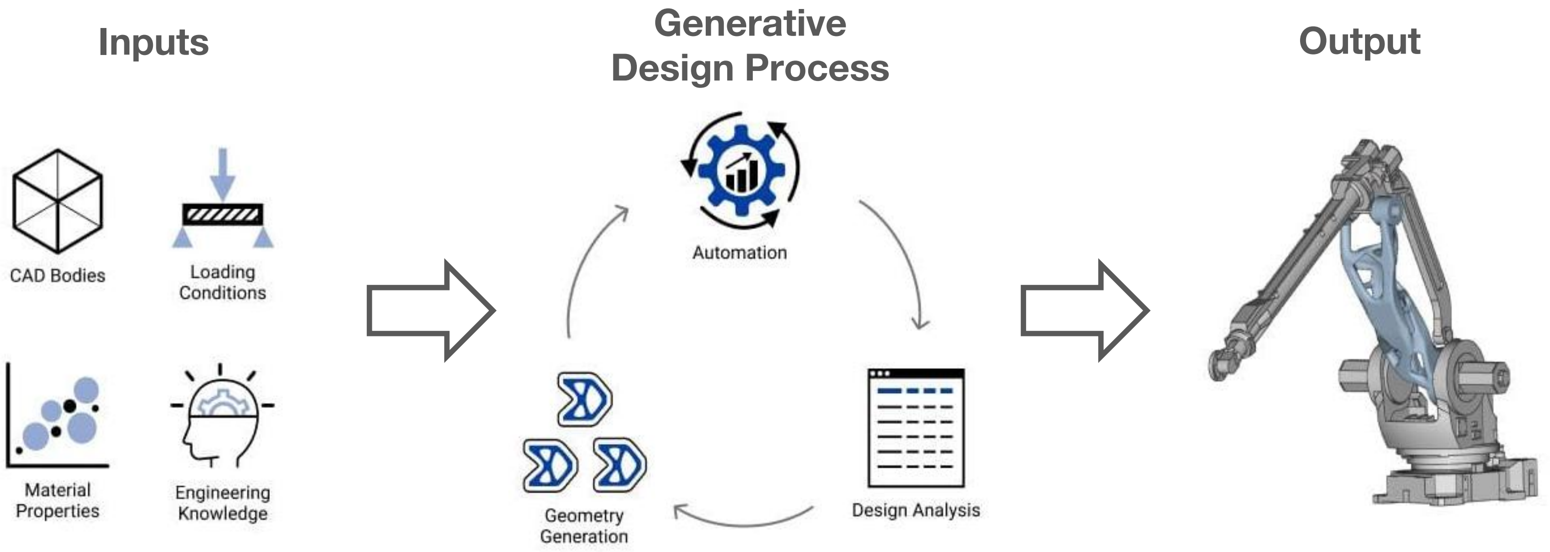
LPBF

Enables organic, optimized geometries.

Fast iteration

systematic method to use freedom of design

Topology Optimization



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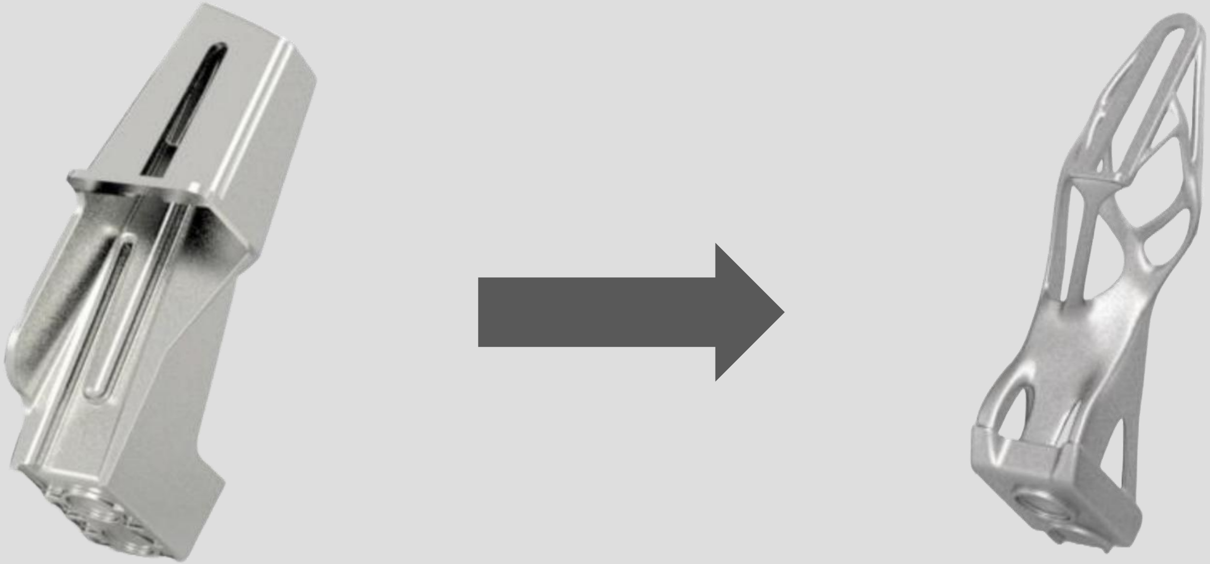
Topology Optimization

Topology Optimization:
BMW i8 Roadster Bracket



"Design freedom is not a license for creativity, it's a responsibility to design within the process."

Common file errors:

Holes
Any holes in a mesh makes it non-manifold and must be closed.

Wrong normals
Normals help the computer understand what is in and out, and what the volume of the model is. All normals must be outward facing.

Non-matching edges
With an unequal number of vertices on two connecting edges/faces, it can be interpreted as a hole in the mesh.

Double corners
The volume of a mesh must be clearly defined, so a vertice, edge or face can only be a part of one shell.

Crossed volumes
Volumes cannot intersect, so when two or more volumes cross into each other they must be combined with a 'boolean operation'.

Color prints:
For multi-color prints it is important that the 3D model is UV unwrapped correctly over the texture file and that the files are linked correctly.

Design tips:

Escape holes
For any cavities there must be sufficient escape holes for support material to escape.

Clearance
To avoid parts fusing when printing, the clearance must be above the minimum clearance*.

Shrinkage
For precision printing it should be taken into account that most materials shrink after printing.

Strength
To avoid breaking, minimum wall and wire thickness* should be obeyed. For parts under more stress extra thickness may be necessary.

Details
To ensure that details such as engravings or embossings show, minimum detail specifications* should be followed.

Resolution
To avoid visible triangles, the mesh resolution must be high enough according to the print size.

*check material specifications at your print service or at the manufacturer of your material.

Ways to save:

Hollowing
The most efficient way to save material and money is, if possible, to hollow the model out.

Intelligent fill
A wire mesh is more than strong enough to do the job of solid fillings with a fraction of the material use.

Size
Scaling down a model can give surprisingly large material savings. A 20 % smaller cube uses only half as much material.

Material
Materials can be expensive, so if the needs of a project can be fulfilled with a cheaper material that is an easy way to save.

3D printing:

Own 3D printer
If you need many 3D prints and want them very fast, it can be a good idea to purchase one.

3D print service
To avoid large investments of money and time and to get the best quality, reliability and largest selection of materials, a professional 3D print service is the way to go.

DfAM:
From Freedom to Discipline

Orientation

surface quality & residual stress.

Support placement

Minimize on loaded faces.

Powder evacuation

Drain holes in closed volumes

Hybrid finishing

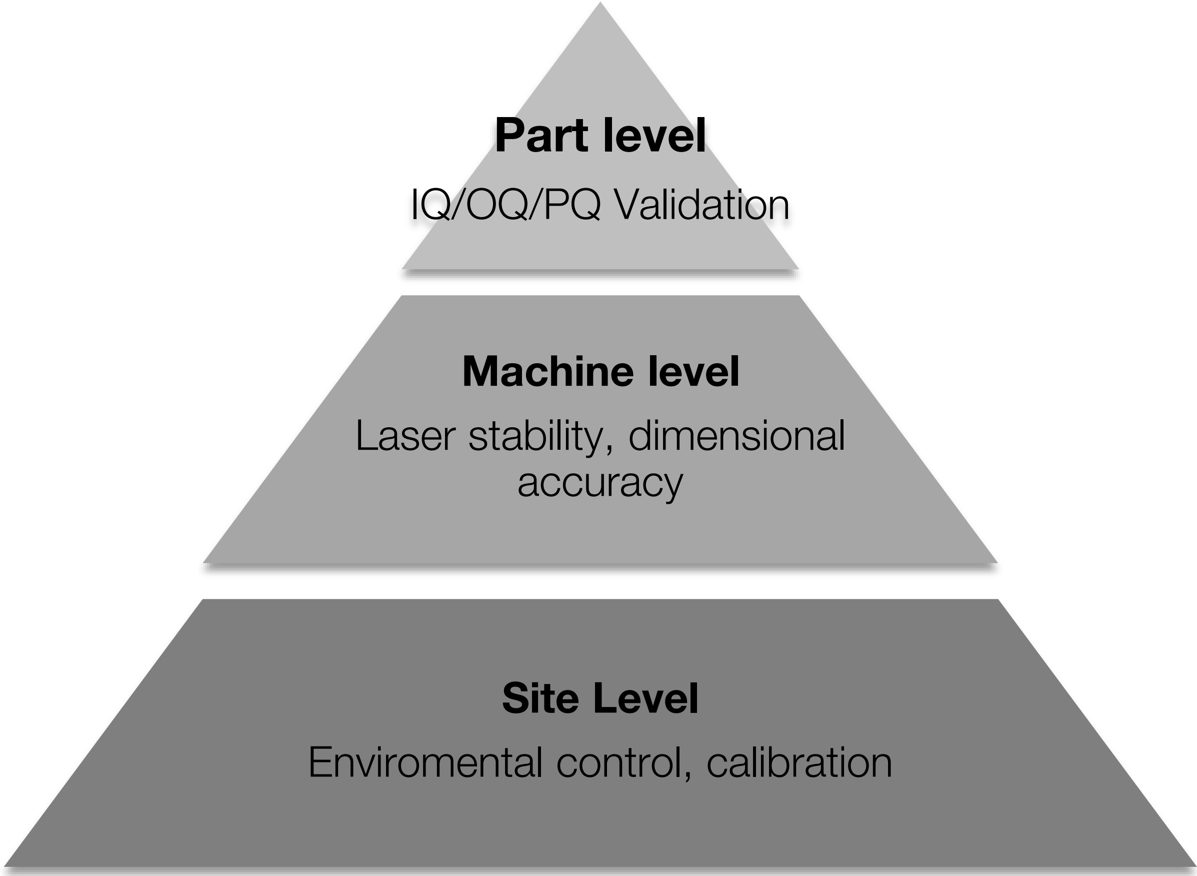
Account for features that need to be machined

DfAM:
BMW i8 Roadster Bracket

The Problems

- **Process variability:** every machine, batch, and orientation can yield slightly different properties.
- **Hidden defects:** porosity, lack of fusion, and residual stress are often internal and undetectable visually.
- **No universal standards:** difficult to certify AM parts to automotive safety requirements.
- **High validation cost:** testing every part is unrealistic.
- **Powder reuse drift:** composition and PSD changes affect repeatability.

The Way Forward



Part-Level Qualification Tools

How do we verify that every printed component performs as designed?

Geometry & Process Verification

Test artifacts

- Benchmark geometries

Material Property Validation

Witness Coupons

- On the same Plate
- Tensile, fatigue and hardness testing

Defect Detection without Destruction

Nondestructive Testing (NDT)

- CT scanning, ultrasonic and dye penetrant

Economics & Scalability — LPBF Cost Drivers

$$C_{part} \approx \frac{(C_m \times T_{build})}{(n \times Y)} + C_{post} + C_{mat}$$

Machine Cost (C_m)

Hourly machine cost

Efficiency (T_{build}, n, Y)

More parts per plate → ↓ cost/part

Post-Processing (C_{post})

Stable process → fewer failures

Material (C_{mat})

Automation ↓ labor cost

Total Cost (C_{part})

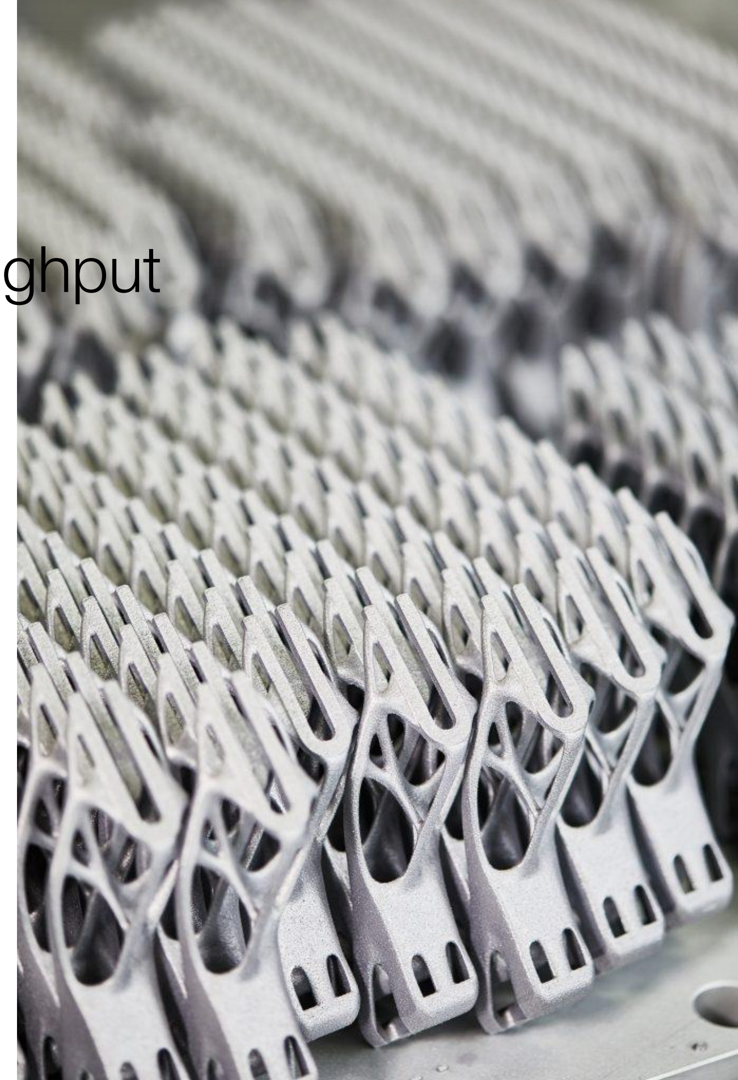
Reuse programs ↓ powder cost

Design and process discipline drive every cost lever

Efficiency:
Maximizing Build Utilization and Throughput

- LPBF cost scales inversely with build occupancy *(Baumers et al., 2017)*.
- Multi-laser systems further increase throughput.
- Fully nested i8 brackets demonstrate near 100% chamber utilization.

High build efficiency = lower cost per part



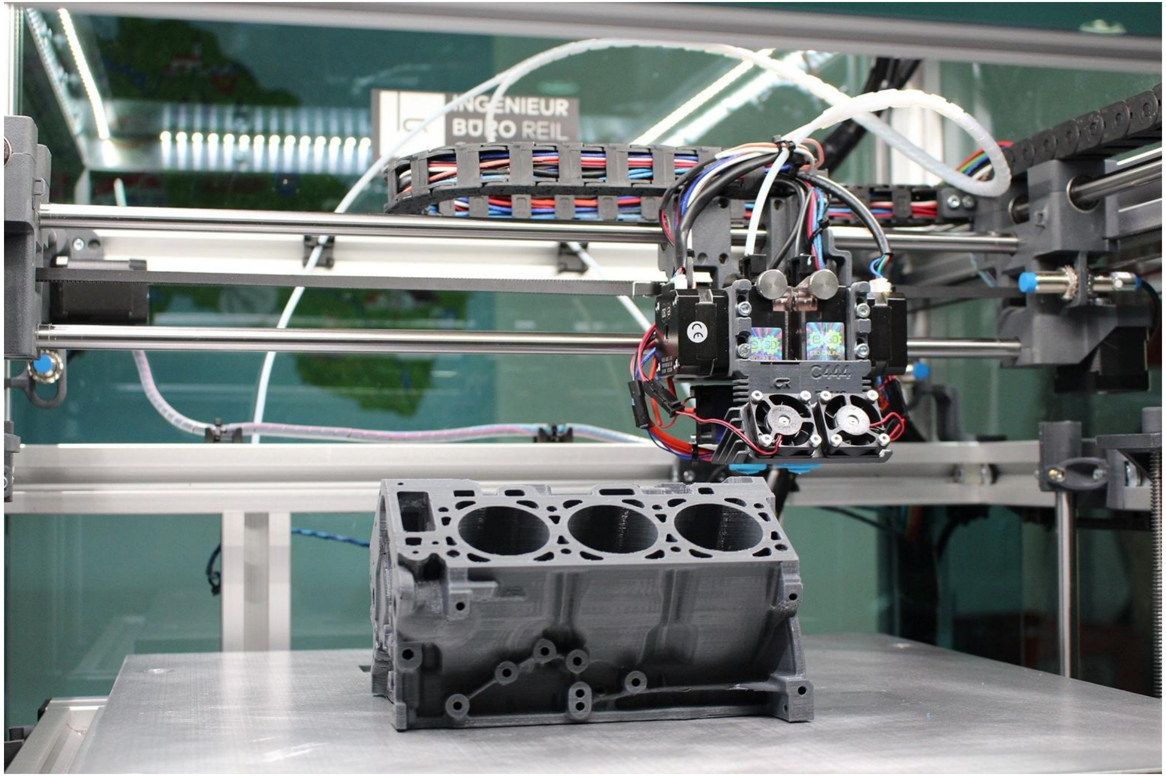
Post-Processing and Automation:
From Print to Ready-to-Use Parts

- Depowdering
- Support removal
- Surface finishing
- Heat treatment

Post-processing is a major cost share (often > 30 % of unit cost).

DfAM:
BMW i8 Roadster Bracket

Fused Deposition Modeling (FDM) State of the art



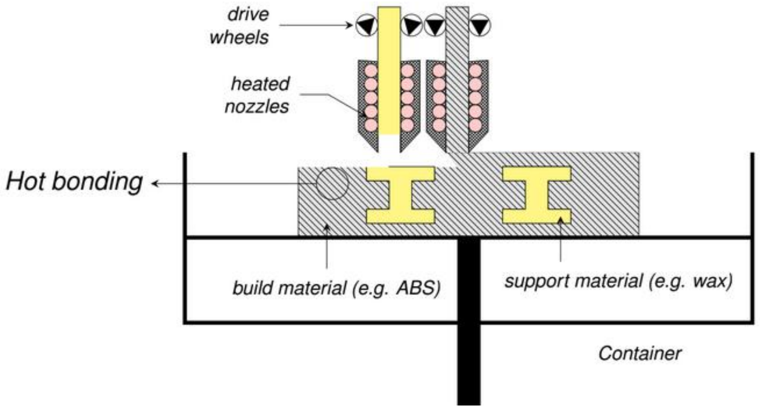
FDM overview for industry

- **Definition:** Material extrusion process depositing molten thermoplastic (180–400 °C) layer by layer.
- **Main applications:** Rapid prototyping, tooling, low-volume parts.
- **Industrial adaptation:** Heated chambers (up to 120 °C), high-temp polymers (Nylon, ULTEM, PEEK), large build volumes (>1 m). Prices from $5000 to $100’000.

Critical parameters:

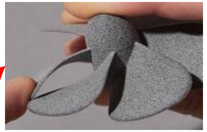
- **Advantages:** Low cost, fast iteration, minimal setup.

- *Extrusion temp (T_e)* → affects layer bonding & viscosity
- *Layer height (h_l)* → surface finish vs. print time
- *Infill density (ρ_i)* → stiffness & mass
- *Raster angle (θ)* → anisotropy control
- *Chamber temp (T_c)* → warping & residual stress



Engineering Polymers and Composites for FDM

Material	E (GPa)	T_m (°C)	Key Traits	Automotive Use
ABS	1.8–2.3	220–250	Tough, machinable	Fixtures, housings
Nylon (PA12)	1.2–1.8	240–270	Wear-resistant, flexible	Jigs, bushings
CF–Nylon	6–8	250–280	High stiffness, stable	Tooling, brackets
ULTEM / PEEK	3.6–4.0	340–400	Chemically + thermally resistant	Under-hood parts



Characteristics of most-used materials :

- **Interlayer adhesion:** Polymer diffusion and re-entanglement depend on T/T_m and deposition time.
- **Fiber reinforcement:** Continuous or chopped fibers : high modulus but low interlayer cohesion.
- **Moisture sensitivity:** Hygroscopic polymers (e.g., PA) degrade during extrusion.
- **Sustainability:** Bio-based PLA blends and recycled PET emerging for tooling.

FDM applications in automotive

1. Prototyping:

- Form, fit, and ergonomic validation (Ford, GM dashboards).

2. Manufacturing Aids:

- Jigs, fixtures, molds.
- Cost ↓ 70 %, lead time ↓ 90 % (Ford, Volkswagen).

3. Low-Volume Parts:

- Custom brackets, ducts, housings, motorsport components (McLaren).

Cost and Sustainability of FDM in Production

- **Economic:**
  - No tooling = geometry-independent cost.
  - Supports on-demand manufacturing → reduced inventory.
  - ROI within months for in-house systems.
- **Environmental:**
  - Additive = near-zero waste.
  - PLA & PETG from renewable/recycled sources.
  - Localized production = fewer logistics emissions.
- **Trade-off:** High energy consumption for chamber heating → mitigated by insulation & optimized infill.

Metric	CNC Machining	FDM
Cost / part	€400–1 500	€20–150
Lead time	2–8 weeks	1–3 days
Waste	High (chips)	Minimal (just filament)

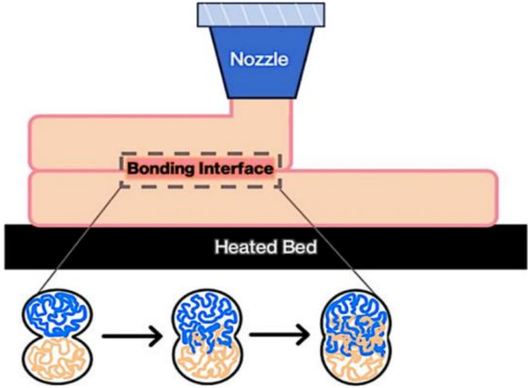
Limitations in FDM process

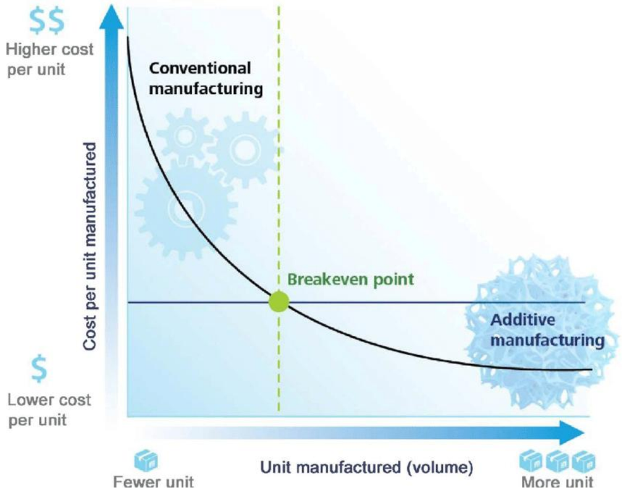
Physical limitations:

- Interlayer bonding → anisotropic properties
- Strength x,y ≫ Strength z
- σ_z limited by poor fusion → 30–50 % of bulk strength
- Thermal gradients: Differential cooling = warping, residual stress.
- Porosity: Voids from under-extrusion or inconsistent flow reduce fatigue life.

Economic Limitations :

- Inconvenient for large-scale production
- Time-consuming for large parts

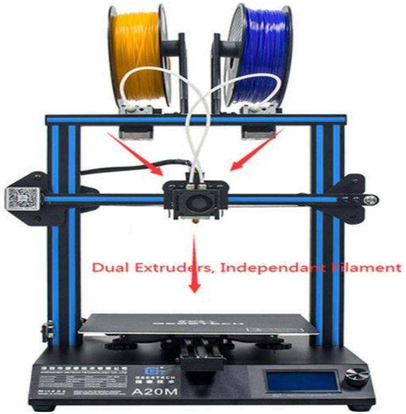


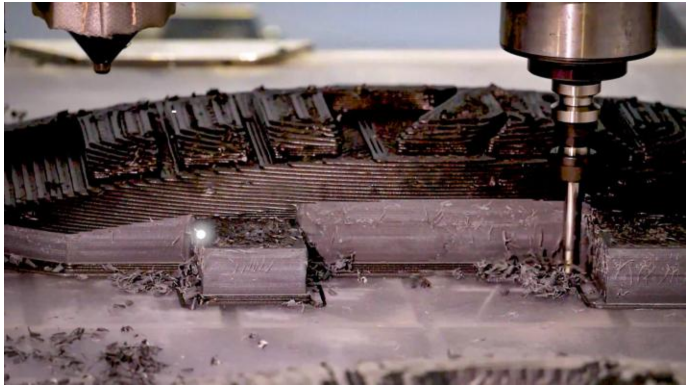


Technological Trends and Future Outlook

Emerging trends:

- **Multi-material printing:** Functionally graded or hybrid parts.
- **Large-format systems:** Tools and molds >1 m.
- **Real-time monitoring & AI-driven control.**
- **Sustainability focus:** Biopolymers, recycled composites.
- **Hybrid manufacturing:** Combining FDM with machining or robotics.





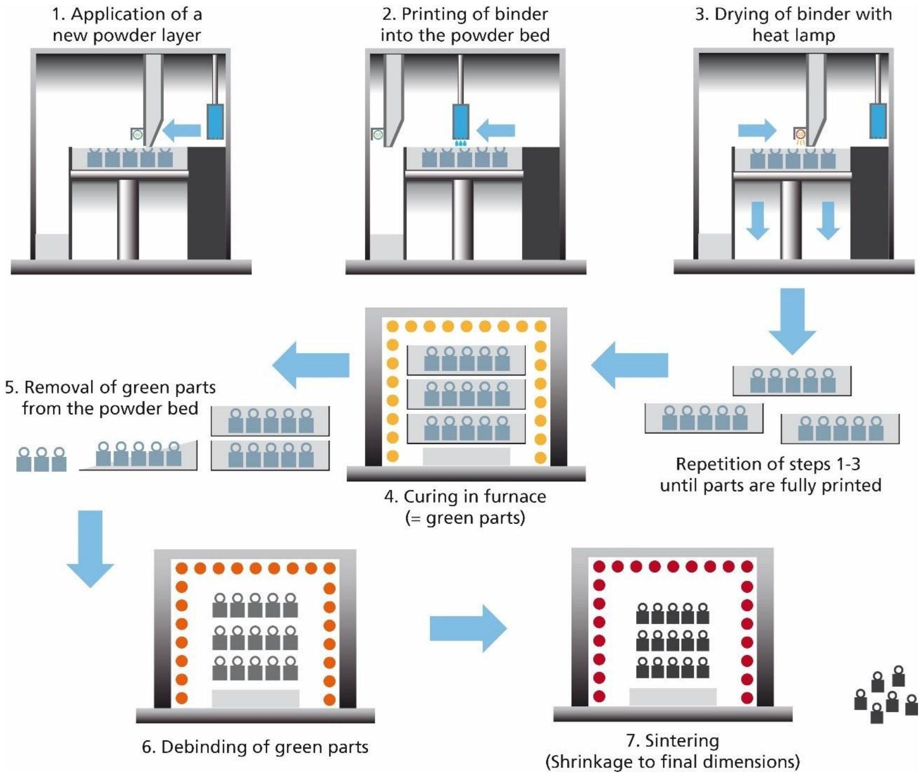
Outlook:

- Key role in rapid tooling and customized low-volume production.
- Enhanced sustainability through biopolymers and recycling.

Binder Jetting

Principle

- Layer by layer method, linking powder particles with binding agent (particule size between 20 µm to 200 µm)
- Obtention of green parts: with linked particles, not good mechanical properties
- Remove the powder not used
- Put the parts in an over to sinter particles together
- Infiltration do increase the part's density



Materials

Many of the materials used in the automotive industry can be used in binder jetting process

Material	Young's modulus (GPa)	Melting temperature (T°)	Use in the automotive world
Technical ceramics	200-400	1700	Heatshield
Aluminium	70	600	Body components
Stainless steel	200	1400	Mechanical pieces
Nickel alloy	200	1300	Brake system

Advantages and drawbacks

Advantages

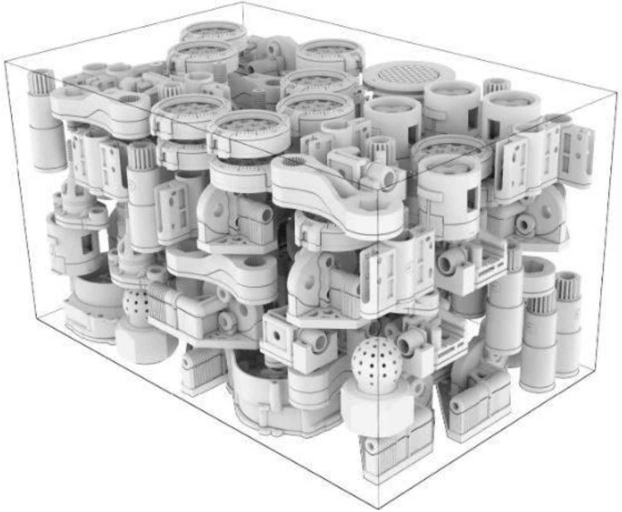
- Fast process: 2s-5s per layer
- Range of materials
- Multiples pieces done at the same time
- Relatively cheap
- Not a lot of losses, possible to reuse the non binded powder
- No supports
- Allow complex geometry

Drawbacks

- Post processing mandatory
- Tolerances and surfaces finish not the best
- Long sintering time and precise step to follow (about 10 hours for medium size steel part)
- Shrinking of the part during sintering process

Implementation in the industry

- Possible to generate complex geometry
- Optimize the whole printing volume/time
- Multiple use:
  - Parts generation
  - Prototyping
  - Restoration of old pieces



Mechanical pieces

Helicoidal gears done by Ford and Desktop metal

Valves generated by HP and Volkswagen

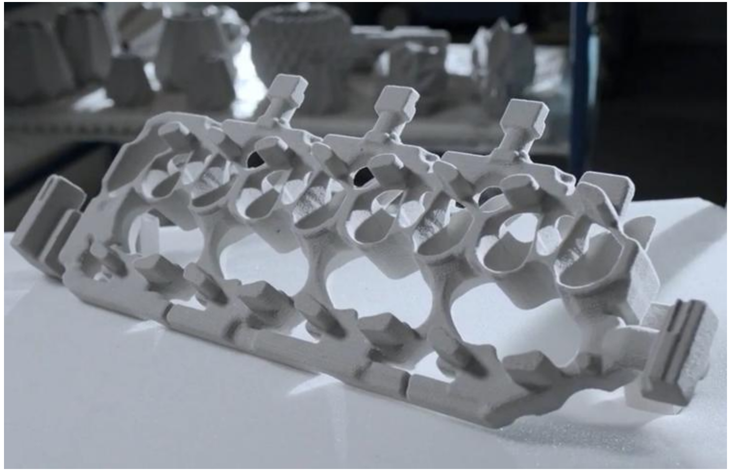
Specific pieces

Aluminium mounting radar plate by Nissan

Gear lever by Volkswagen

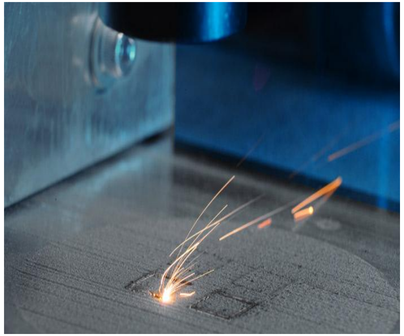
Indirect use through casting

Binder jetting is often closely related to foundry. Core or even sand molds can be generated by sand particles bonded by the chemical agent.



Sand core created by ExOne for a cooling system of an electric car

Summary of the Three Key AM Processes



LPBF

- ➔ dense
- ➔ precise
- ➔ strong
- ➔ costly

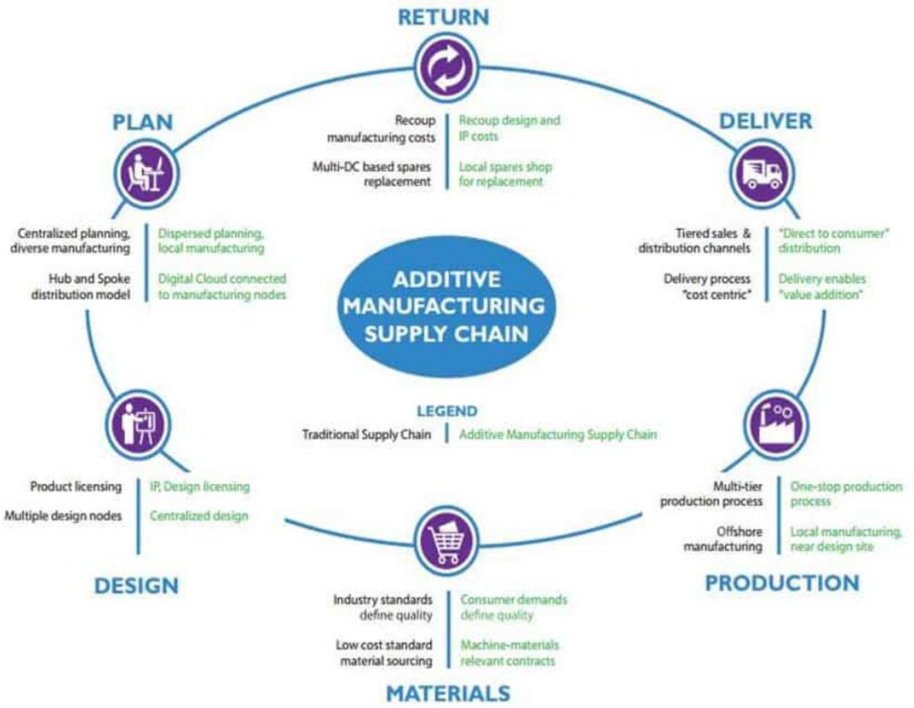
FDM

- ➔ fast
- ➔ ideal for prototypes
- ➔ versatile
- ➔ affordable

Binder Jetting

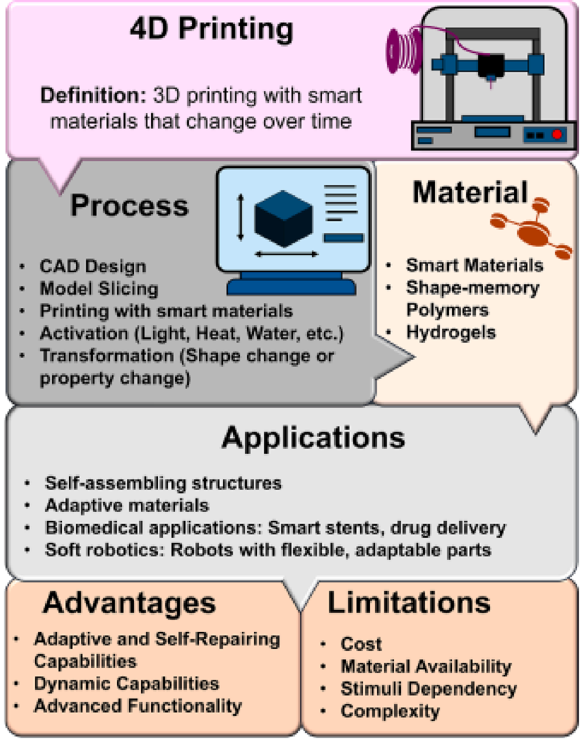
- ➔ compromise between LPBF and FDM
- ➔ scalable
- ➔ attractive costs

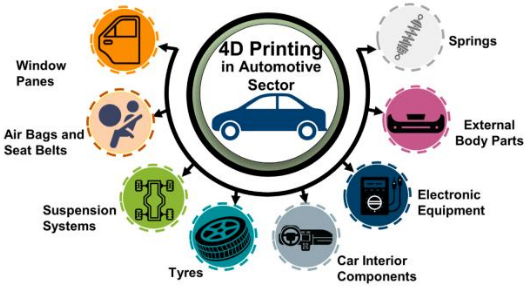
AM's Role in the Automotive Industry



- Drives innovation and lightweight design
- Reduces material waste and energy consumption
- Supports greener manufacturing
- Shortens supply chains and lead times
- Enables on-demand local production
- A pillar for next-gen automotive systems

Future Perspectives





- Multi-material and hybrid AM systems
- 4D printing: adaptive, self-healing parts
- AI and digital twins for process control
- Key enabler for electric & autonomous vehicles
- Towards a fully digital, sustainable industry