Mechanical & Materials Engineering for Particle Accelerators and Detectors, 2-15 June 2024, Sint-Michielsgestel, Netherlands

02–15 giu 2024
Netherlands
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Additive Manufacturing: Fundamentals and Applications

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DIPARTIMENTO DI ECCELLENZA 2023-2027

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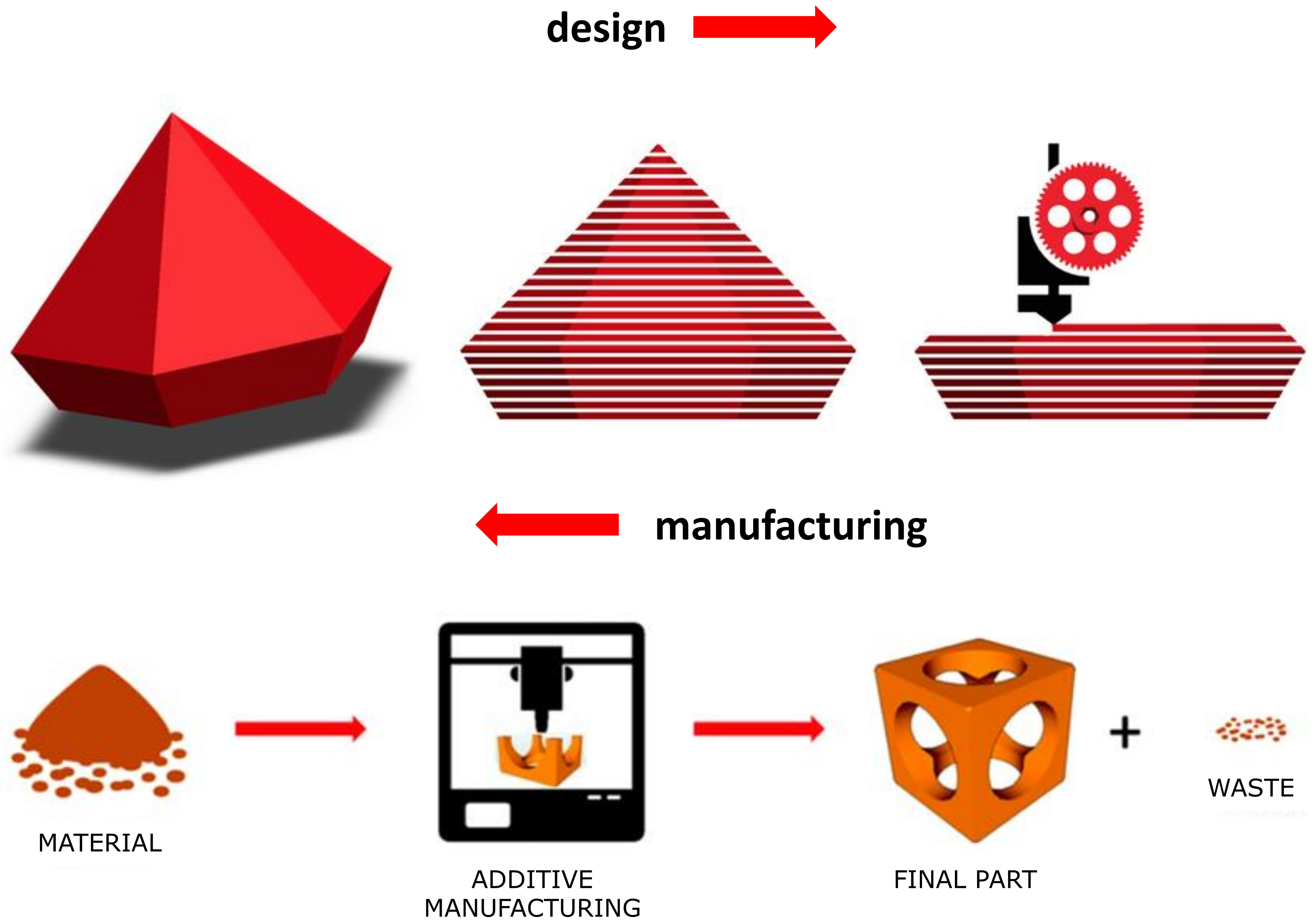
Università degli Studi di Napoli Federico II

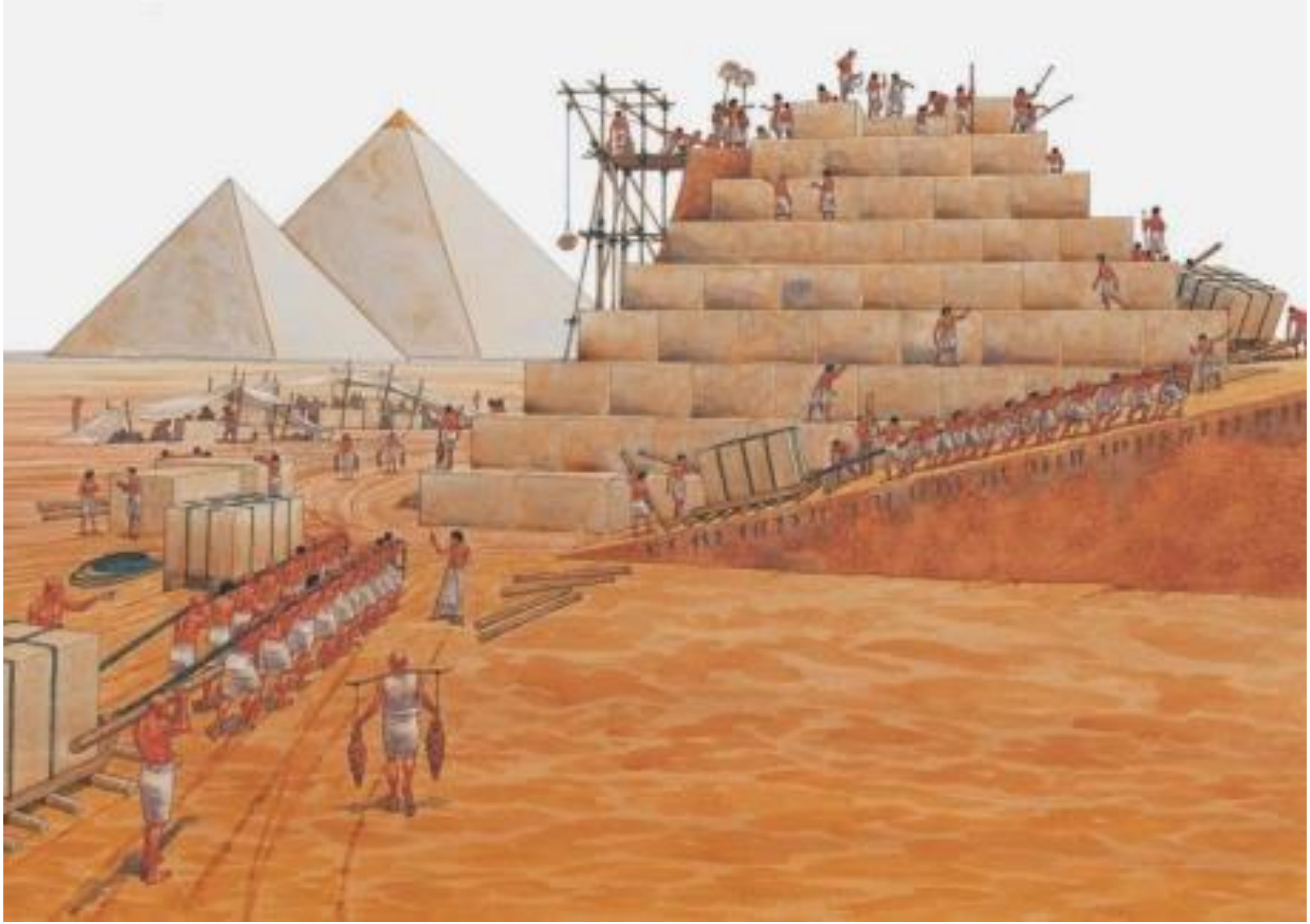
What is Additive Manufacturing?

Additive manufacturing is defined by the ASTM society as:

“a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies”




design
manufacturing
MATERIAL
ADDITIVE
MANUFACTURING
FINAL PART
+
WASTE



Parts are made by adding material in layers; each layer is a thin cross-section of the part derived from the original CAD data
The thinner each layer is, the closer the final part will be to the original.

The major ways they differ are:

- in the materials that can be used,
- how the layers are created,
- how the layers are bonded to each other.

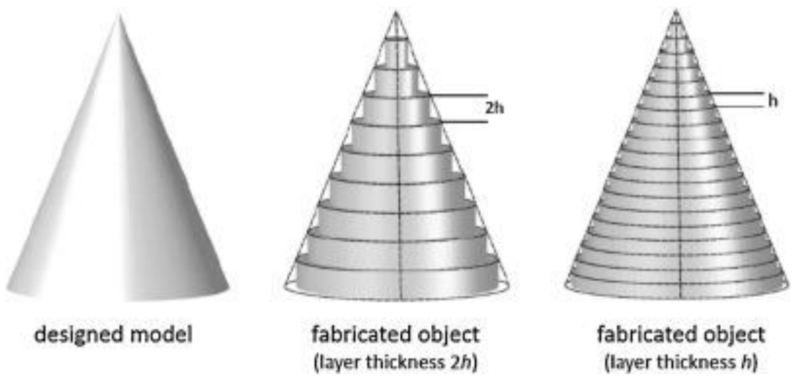
Development of Additive Manufacturing Technology

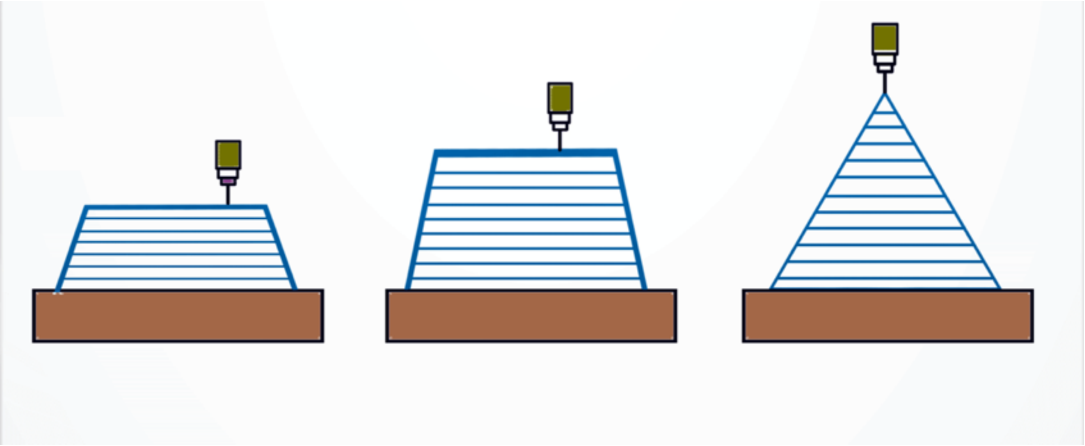
The Use of Layers

A key enabling principle of AM part manufacture is the use of layers as finite 2D cross-sections of the 3D model.

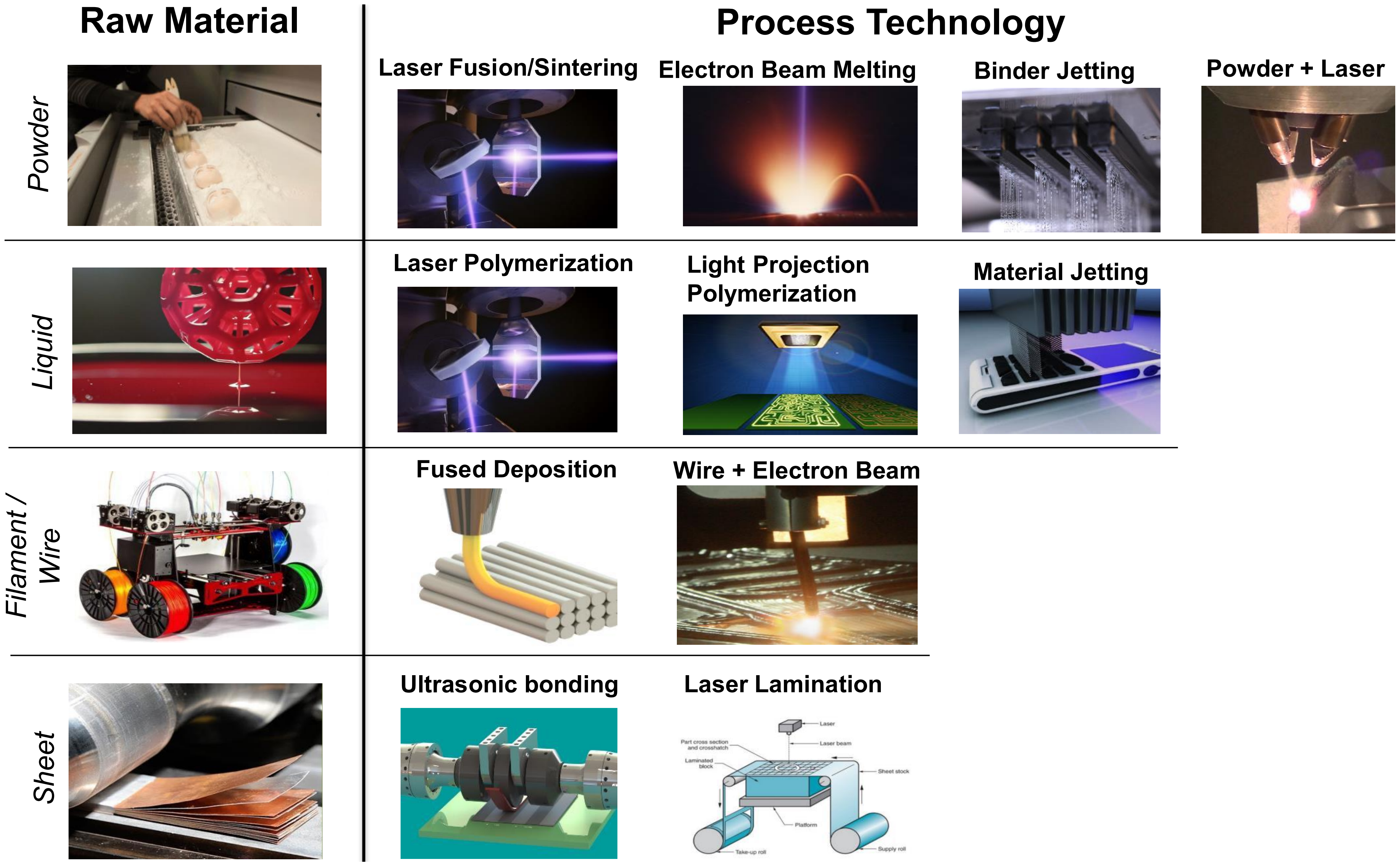
Almost every AM technology builds parts using layers of material added together, primarily due to the simplification of building 3D objects.

Using 2D representations to represent cross-sections of a more complex 3D feature has been common in many applications outside AM.

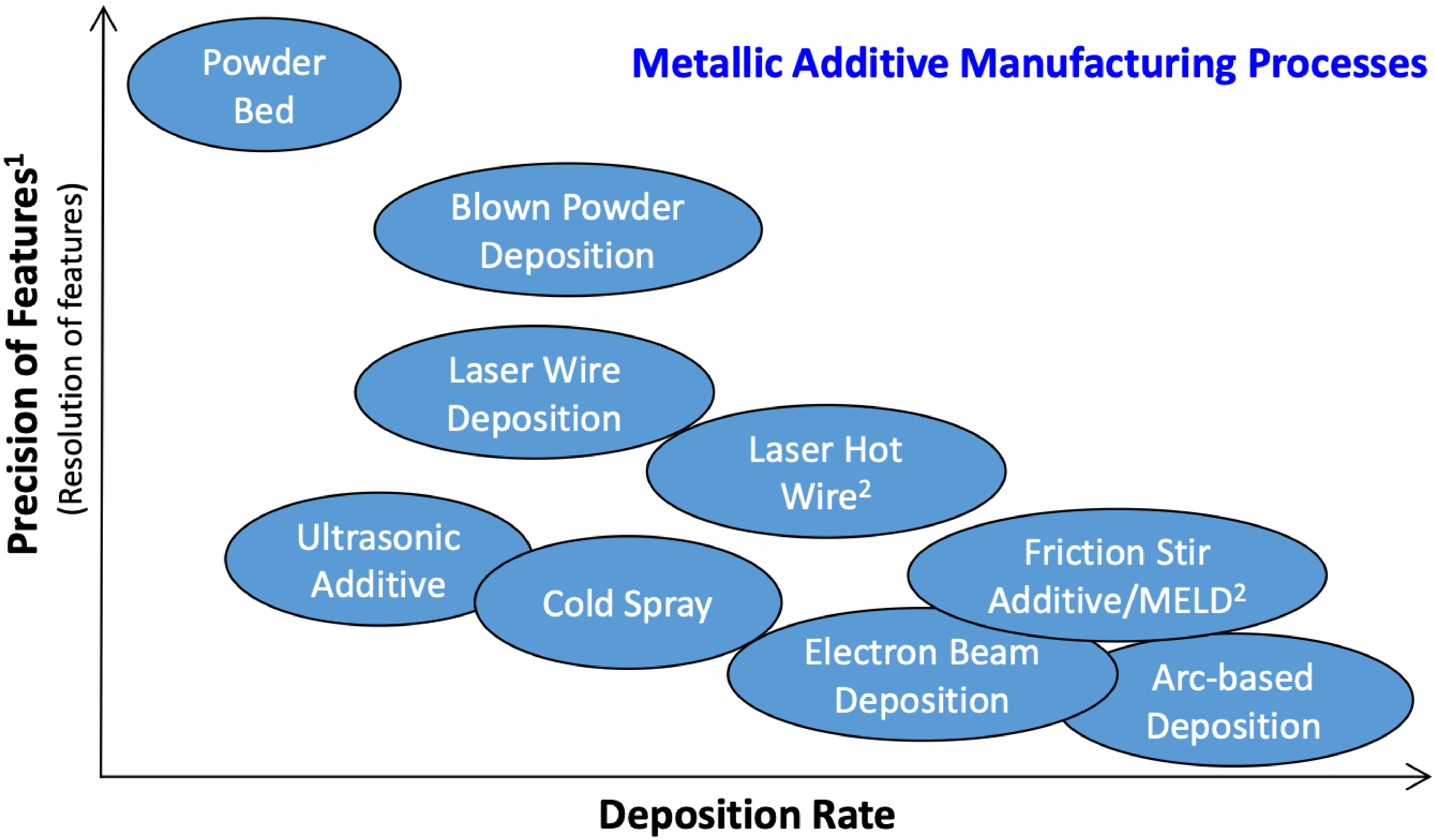




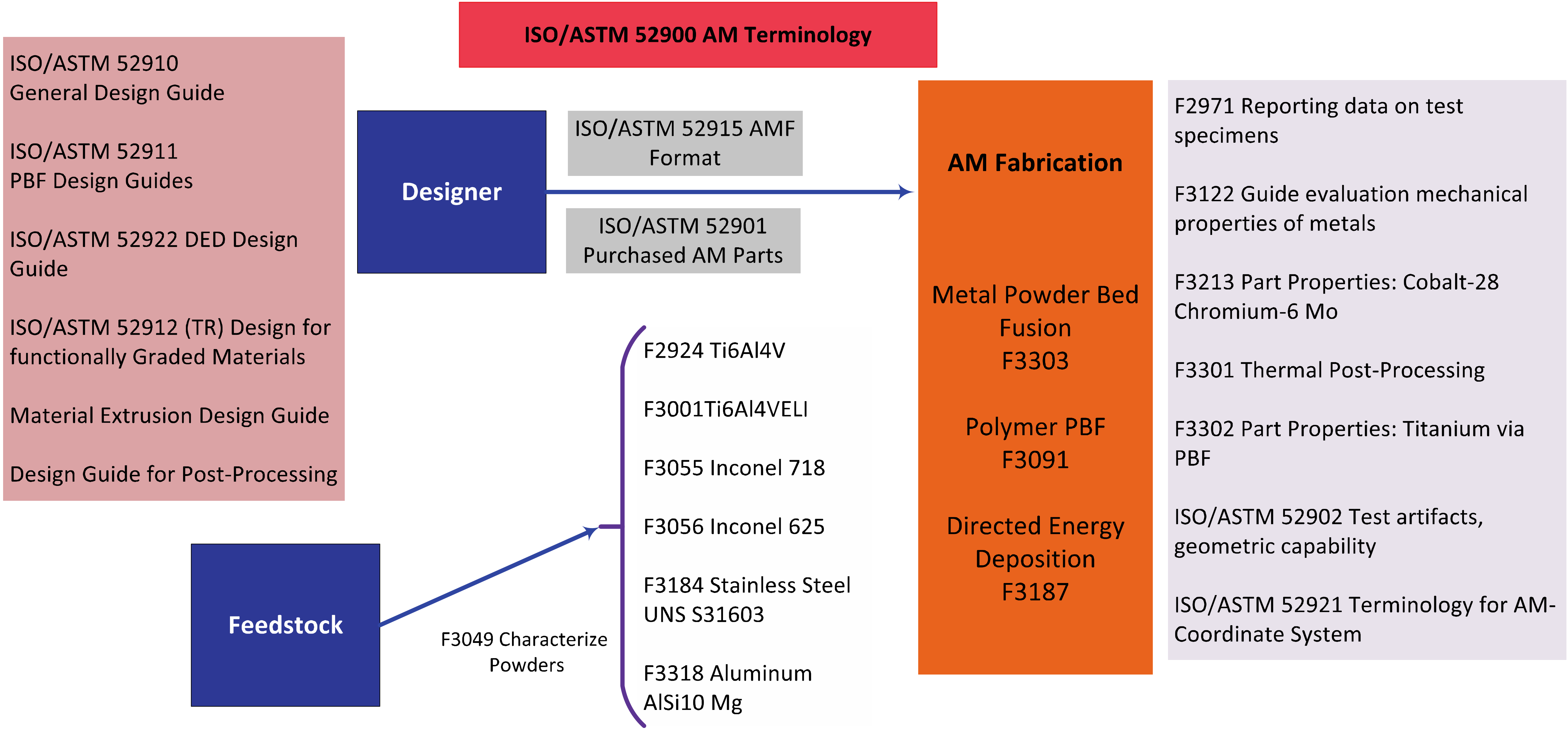
Classification of AM Processes



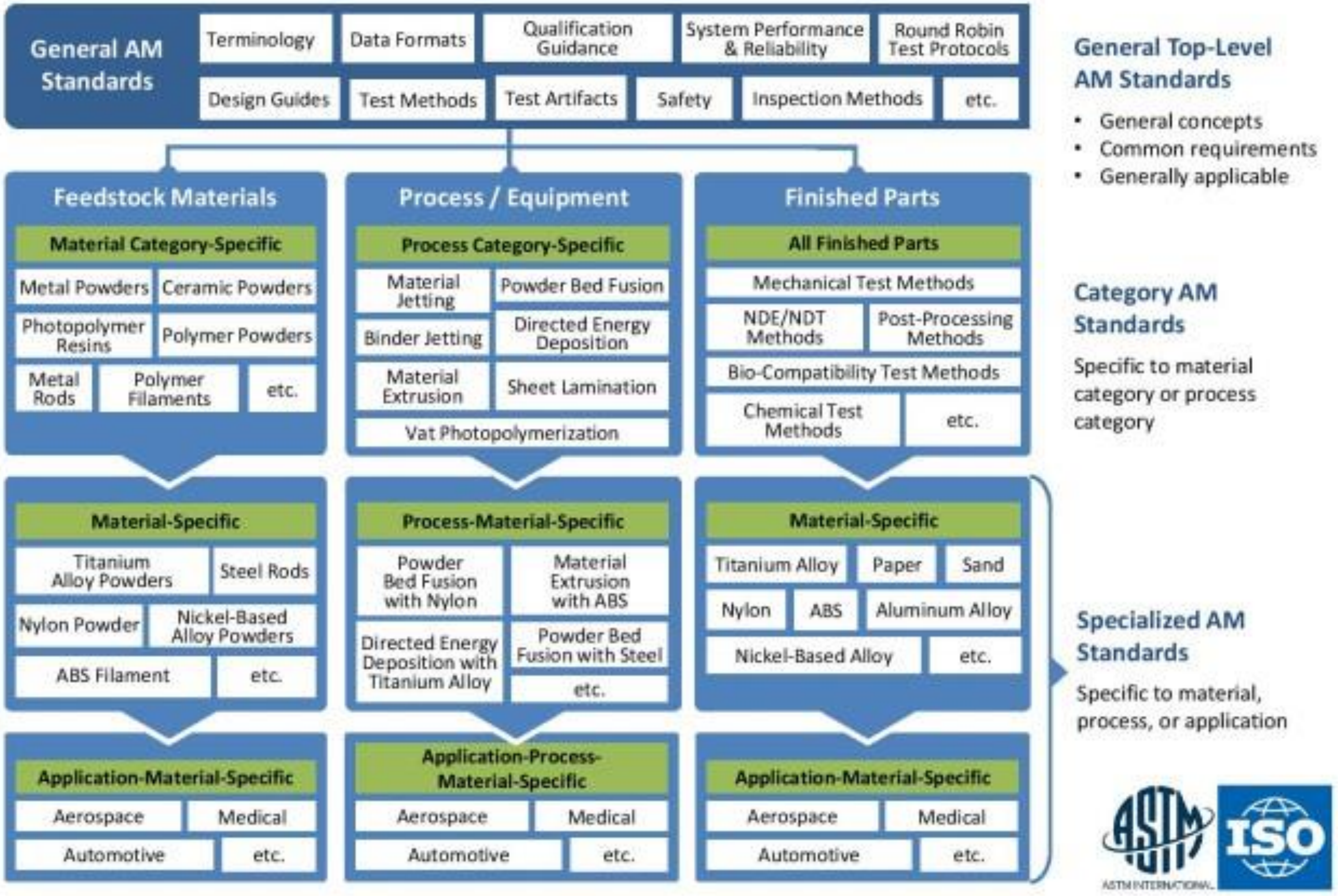
Classification of AM Processes



AM standards



Additive Manufacturing Standards Structure



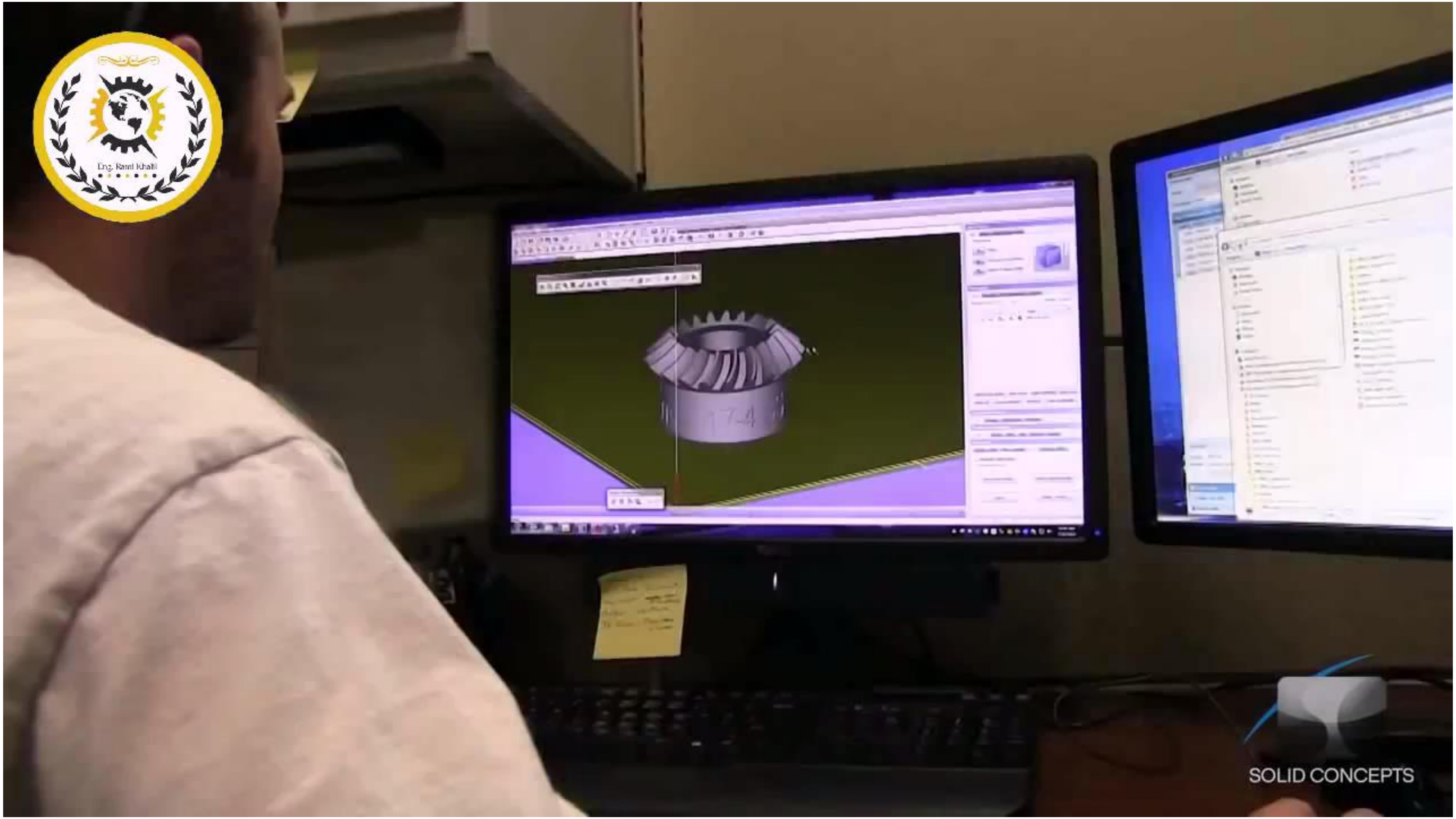
Powder Bed Fusion

All PBF processes share a basic set of characteristics.

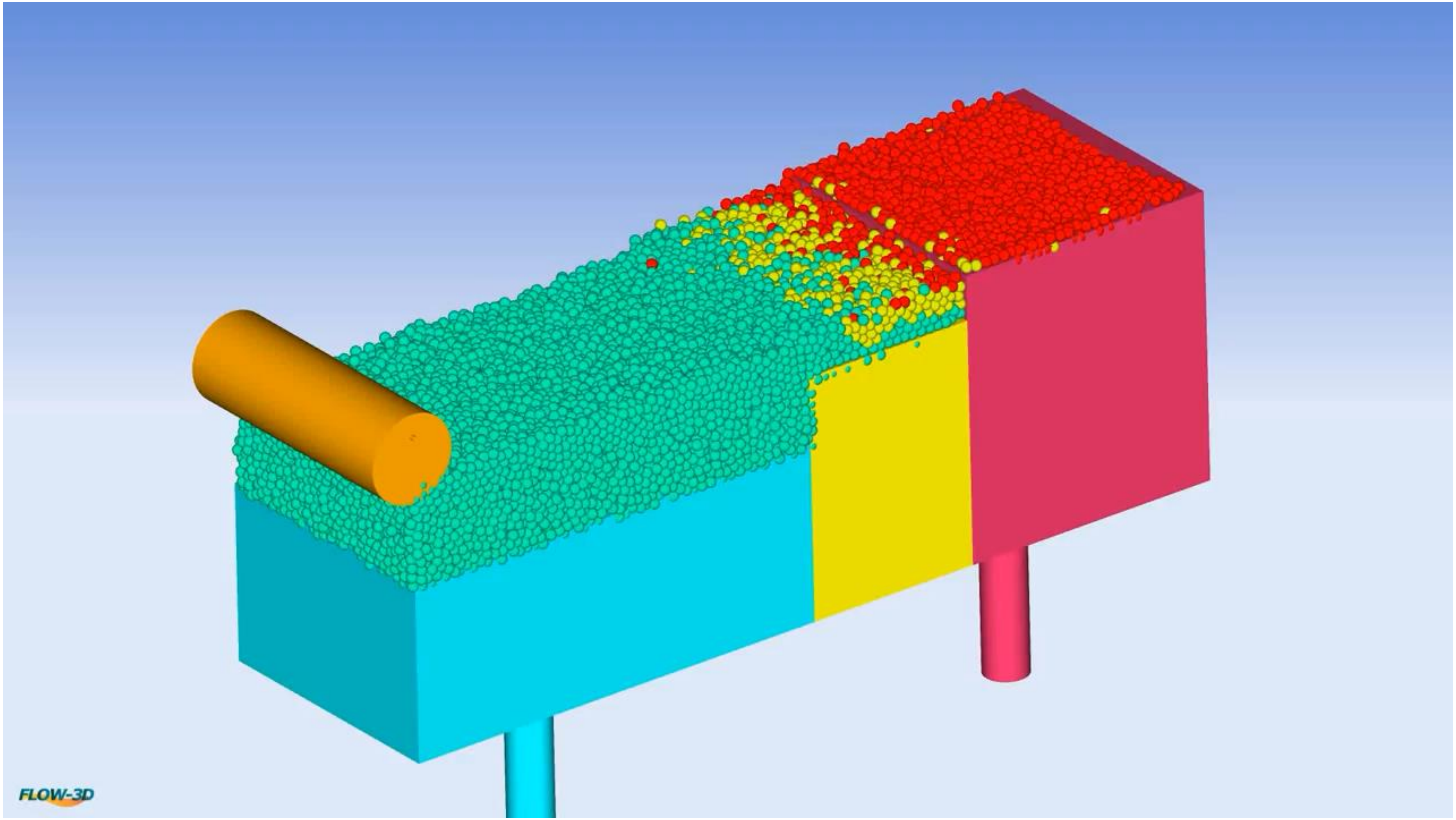
These include one or more thermal sources for inducing:

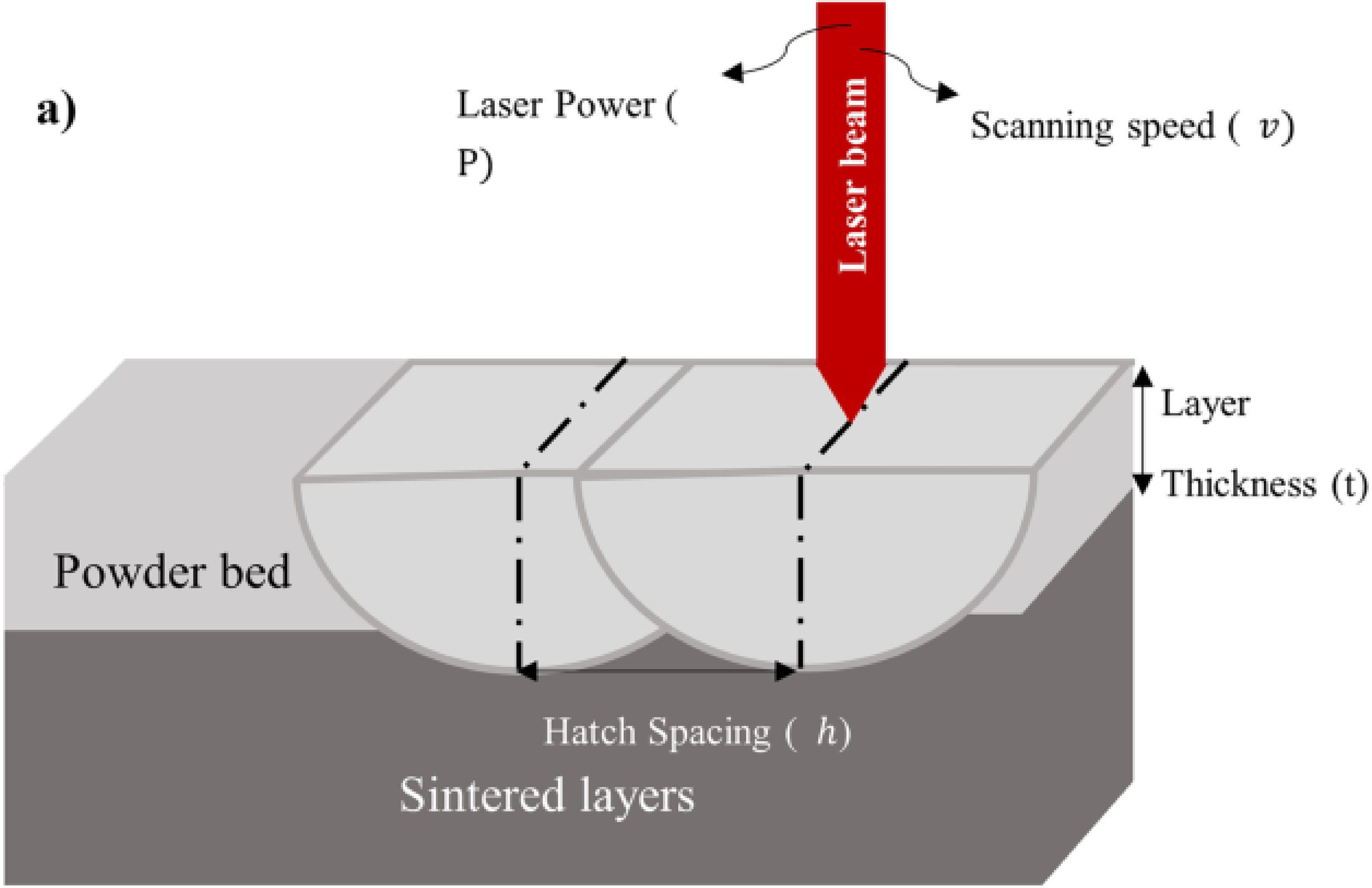
- fusion between powder particles,
- a method for controlling powder fusion to a prescribed region of each layer,
- a mechanisms for adding and smoothing powder layers.

FARSOON
TECHNOLOGIES

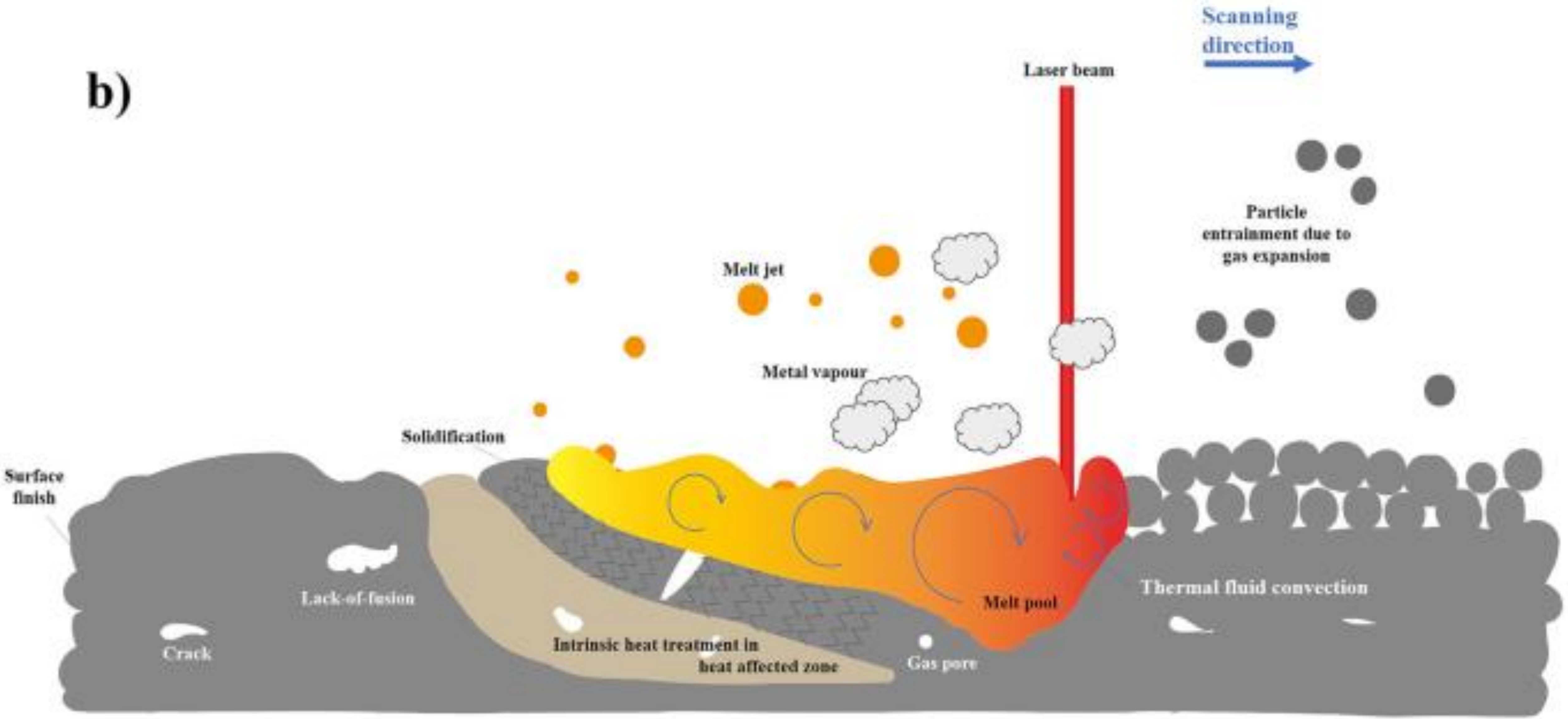

Eng. Rami Khalil
SOLID CONCEPTS


3DnA
new applications

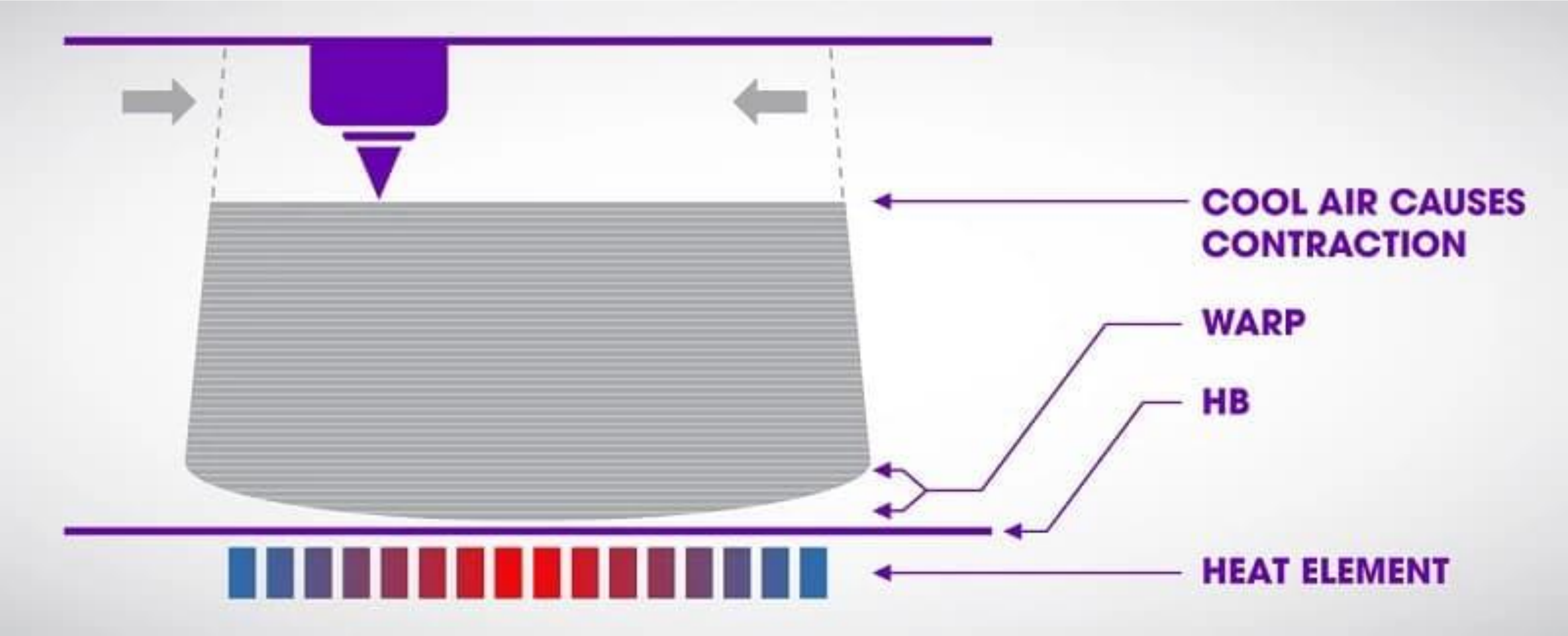

FLOW-3D



a)
Laser Power (
P)
Laser beam
Scanning speed (v)
Layer
Thickness (t)
Powder bed
Hatch Spacing (h)
Sintered layers



b)
Scanning direction
Laser beam
Particle entrainment due to gas expansion
Melt jet
Metal vapour
Solidification
Surface finish
Lack-of-fusion
Crack
Intrinsic heat treatment in heat affected zone
Gas pore
Melt pool
Thermal fluid convection

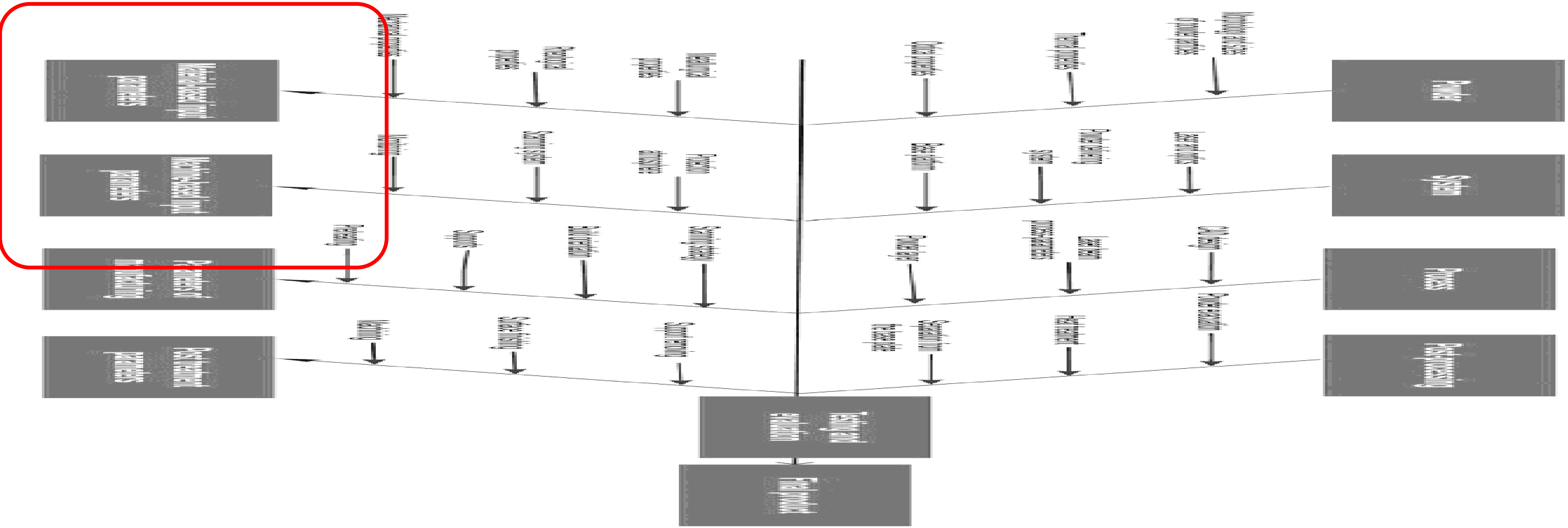


In some cases, the build platform is also heated using resistive heaters around the build platform.

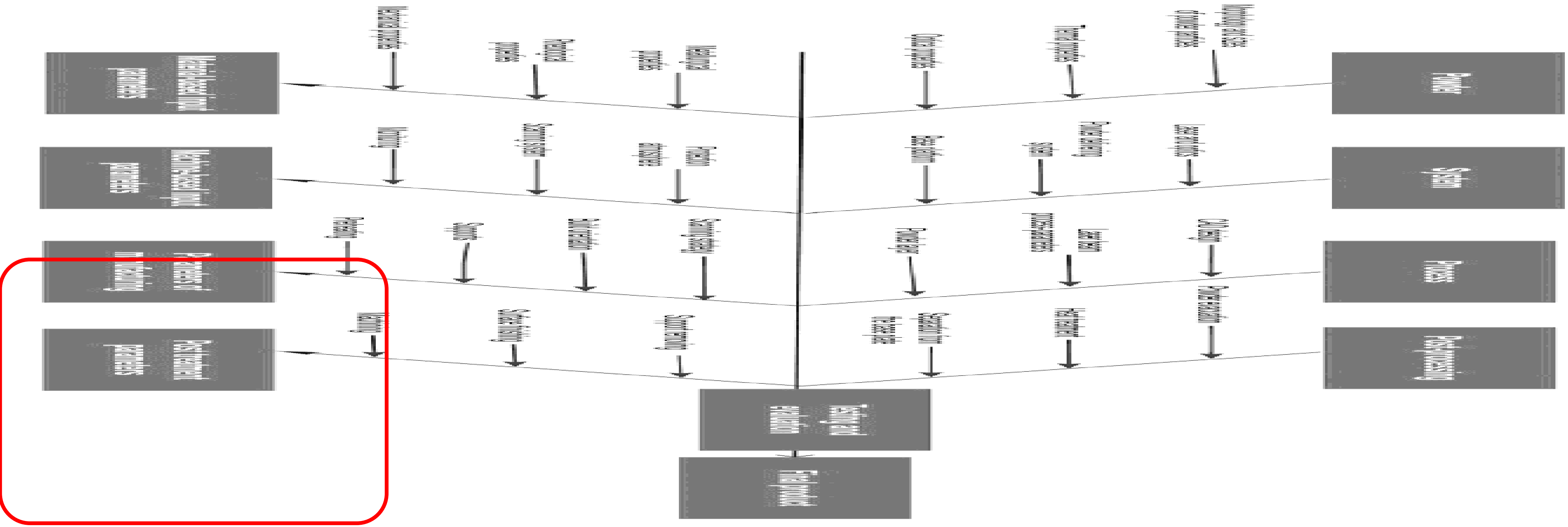
This preheating of powder and maintenance of an elevated and uniform temperature within the build platform are necessary:

- to minimize the laser power requirements of the process (with preheating, less laser energy is required for fusion);
- to prevent warping of the part during the build due to non-uniform thermal expansion and contraction (resulting in curling).

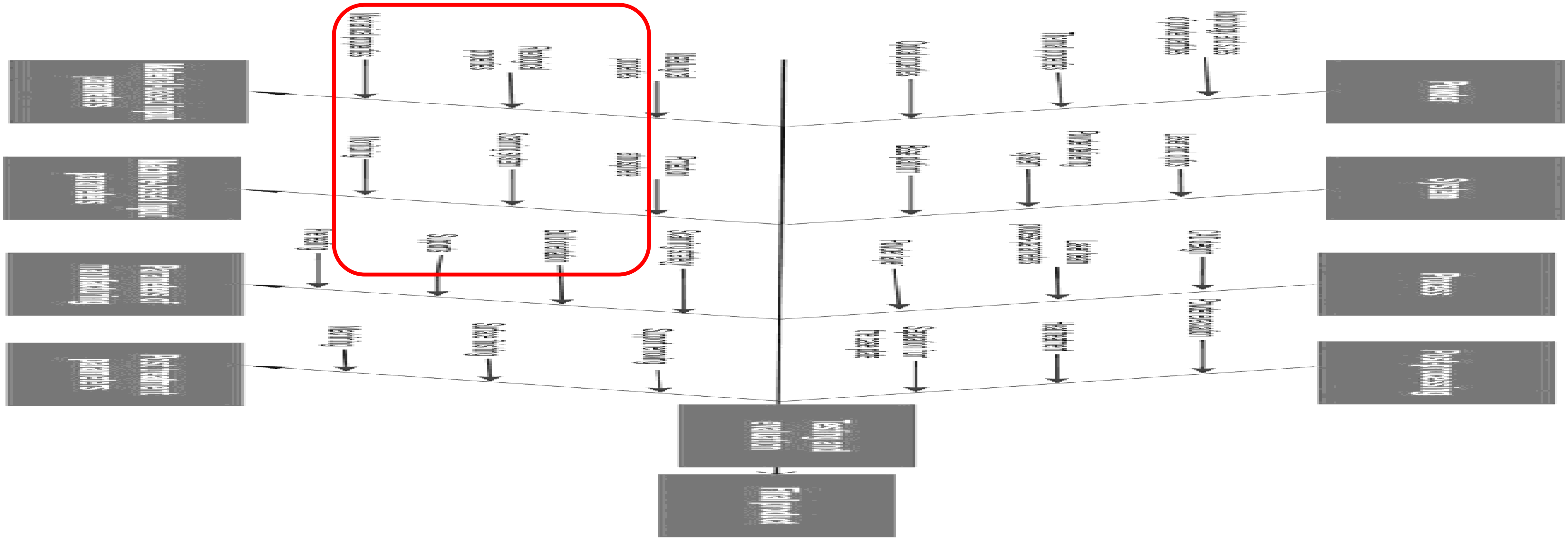
Main parameters influencing the quality of L-PBF components



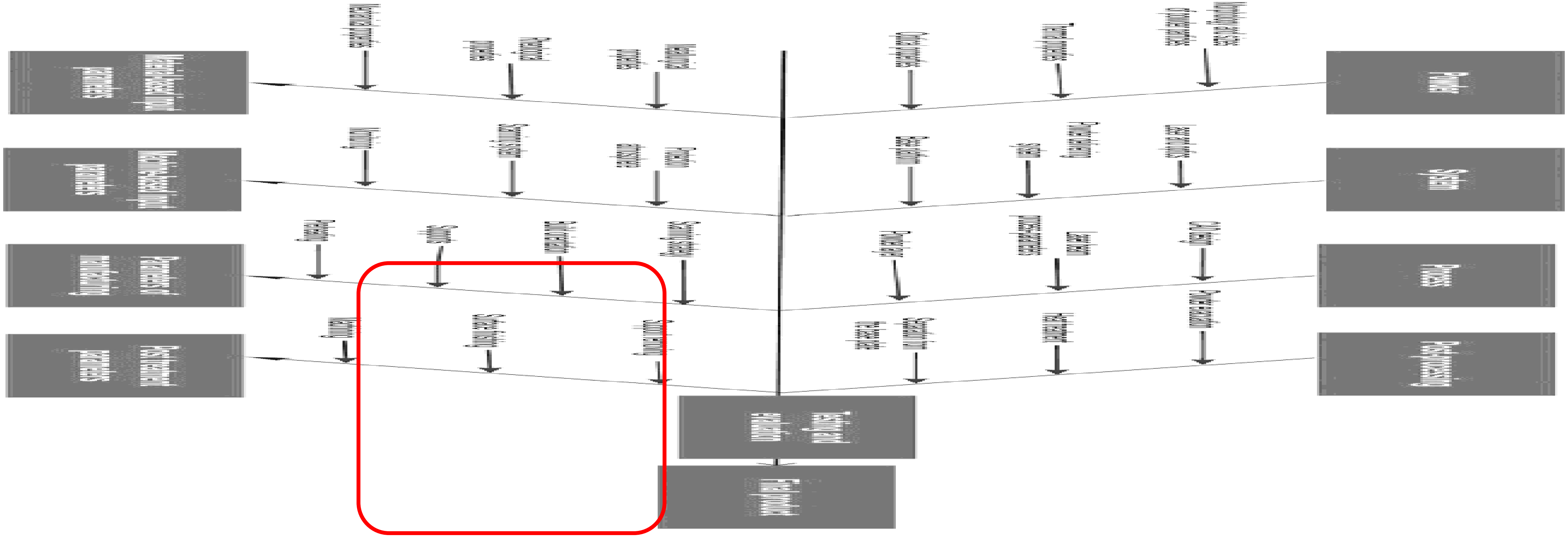
Main parameters influencing the quality of L-PBF components



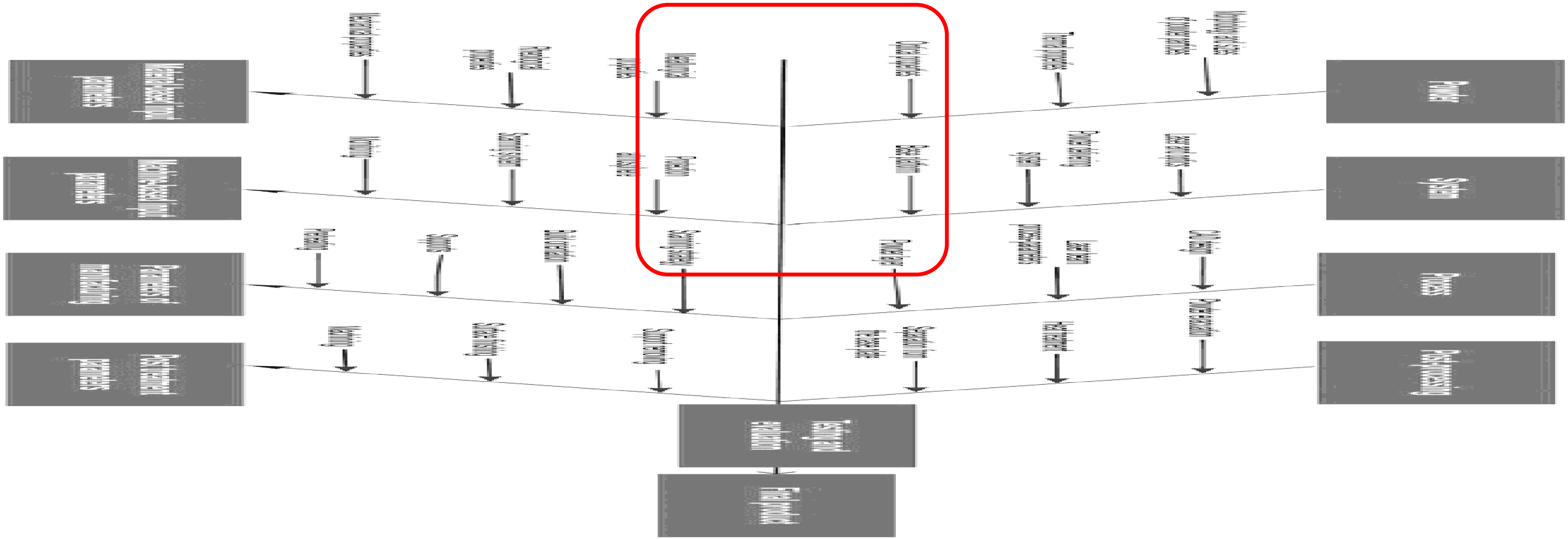
Main parameters influencing the quality of L-PBF components



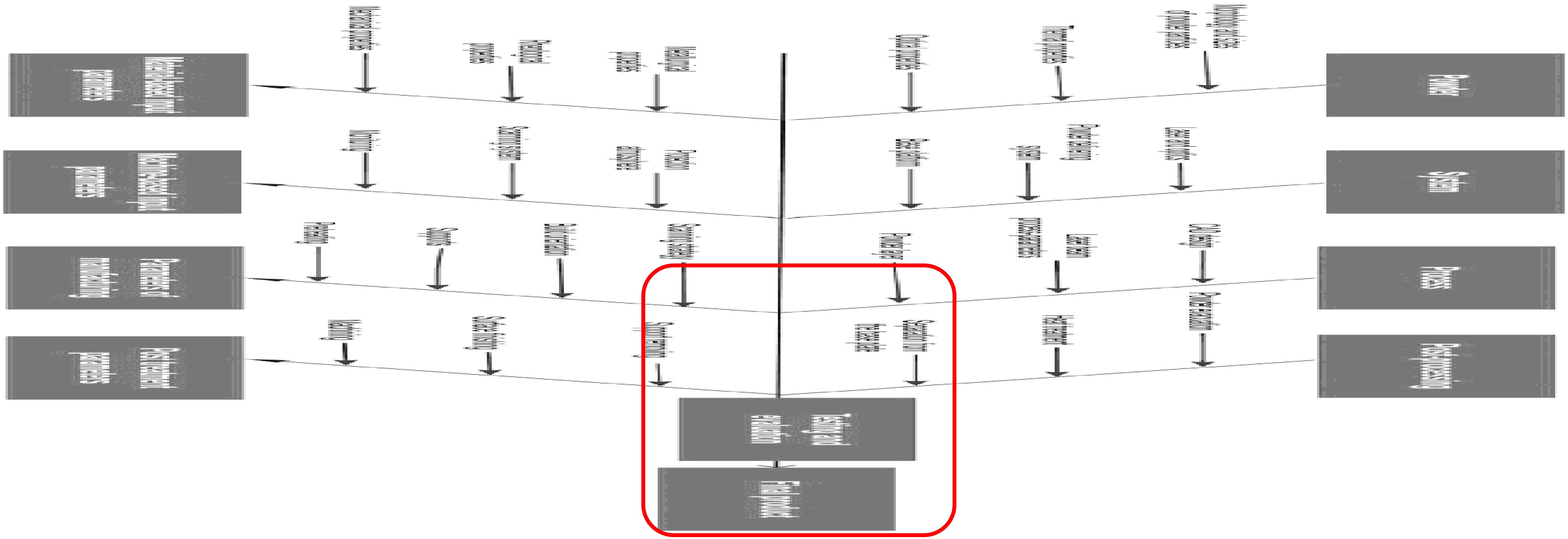
Main parameters influencing the quality of L-PBF components



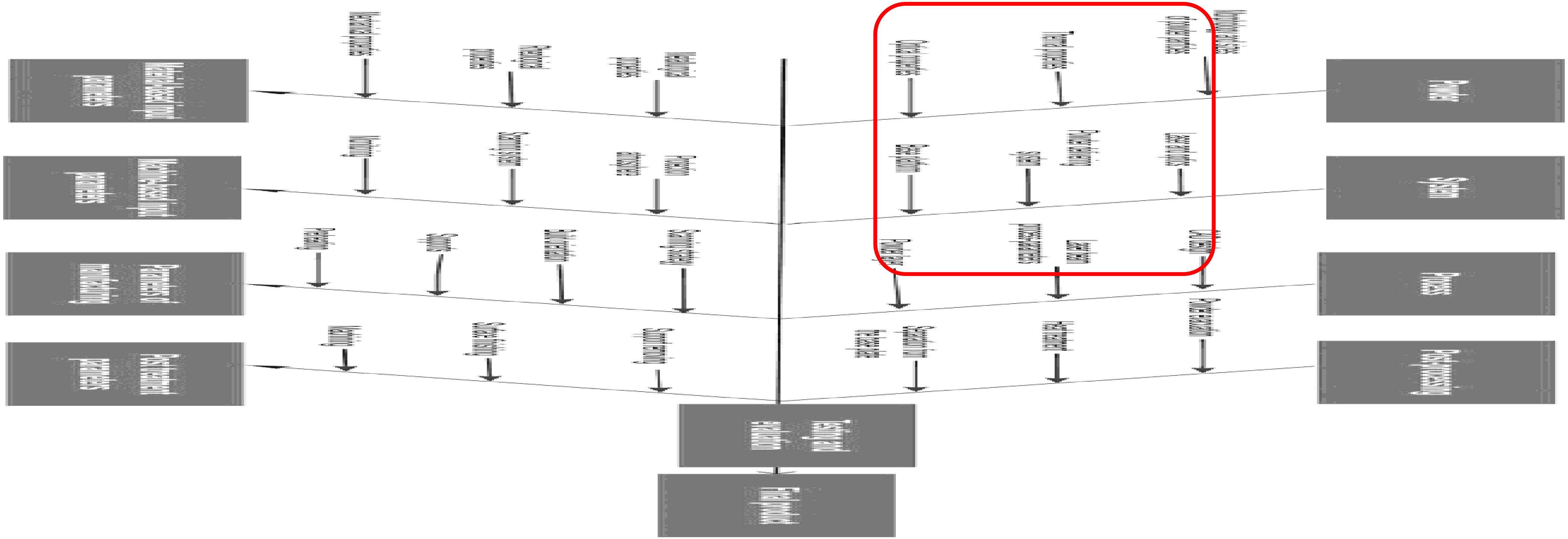
Main parameters influencing the quality of L-PBF components



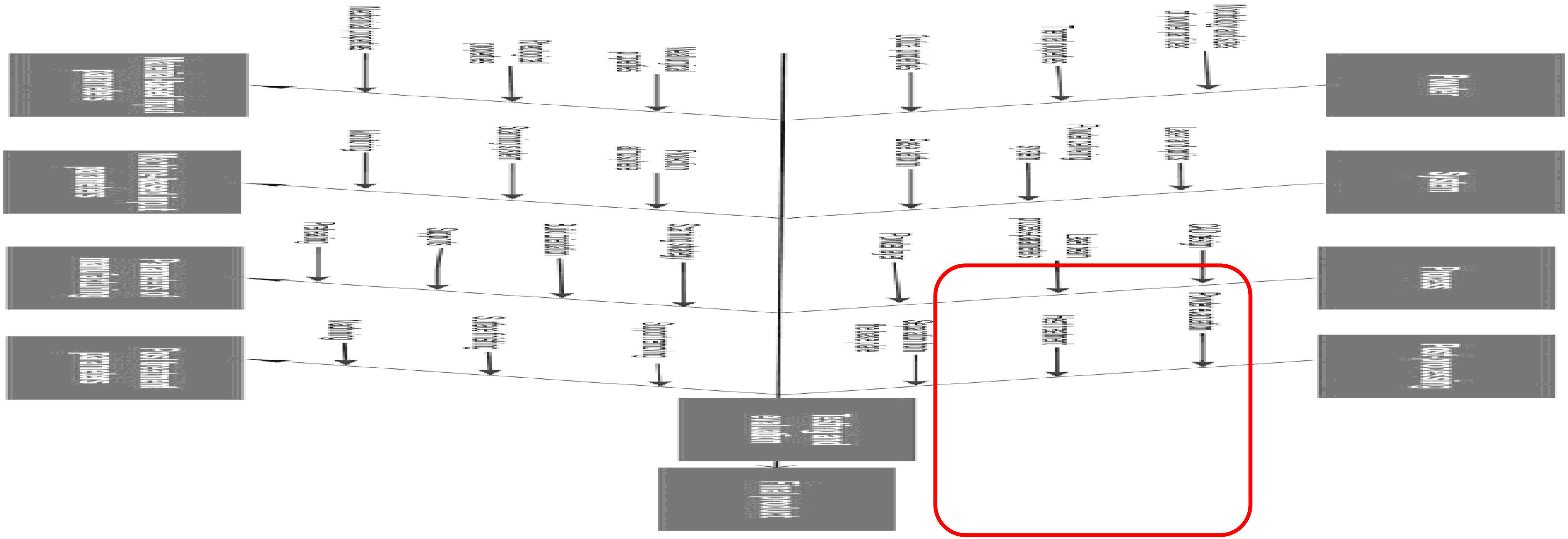
Main parameters influencing the quality of L-PBF components



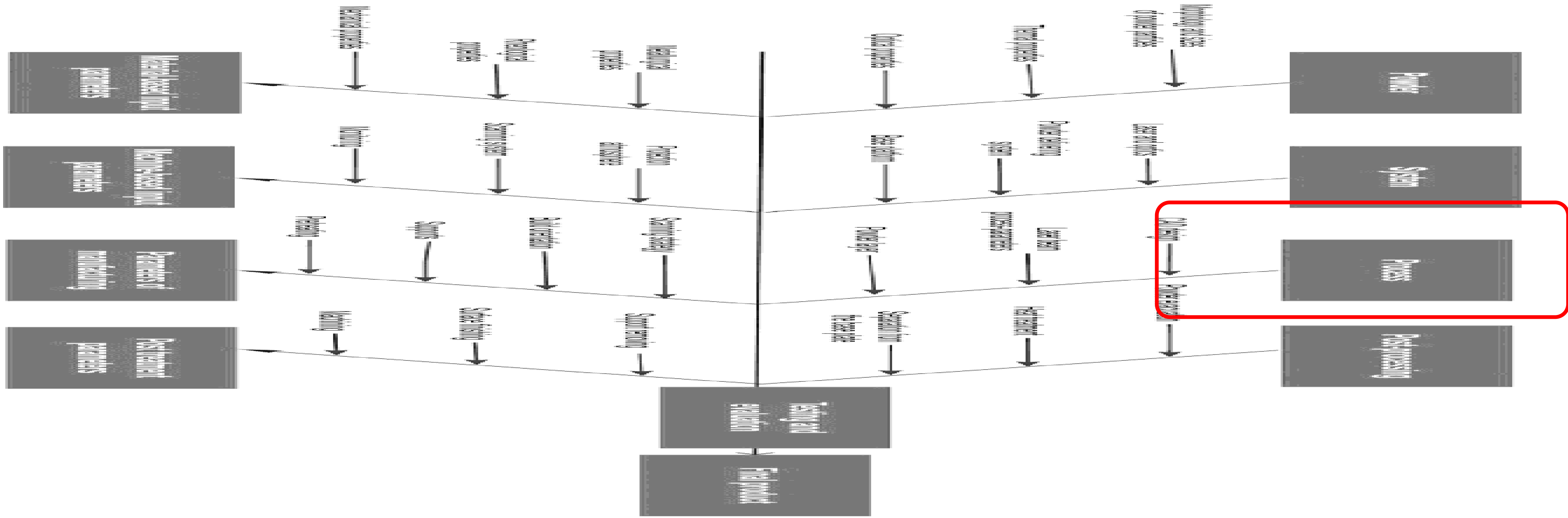
Main parameters influencing the quality of L-PBF components



Main parameters influencing the quality of L-PBF components

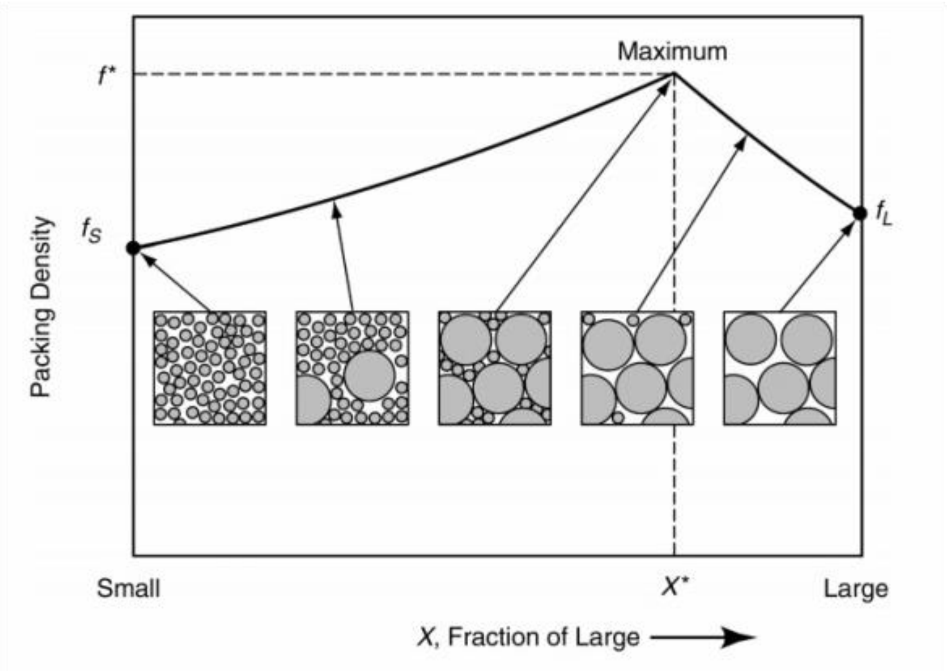


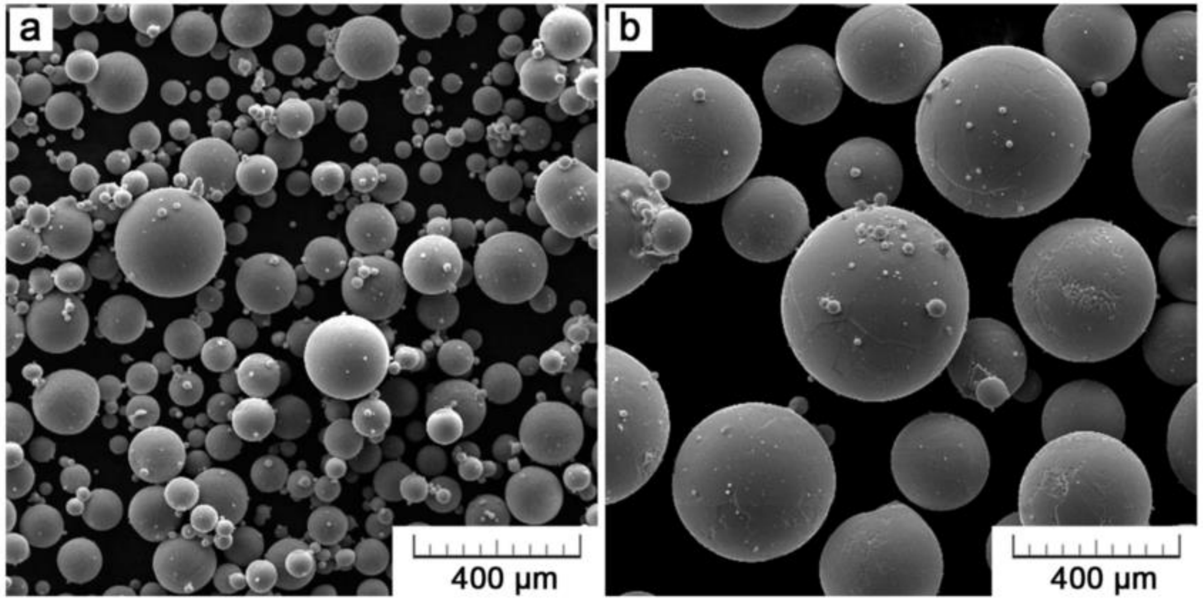
Main parameters influencing the quality of L-PBF components



Powders

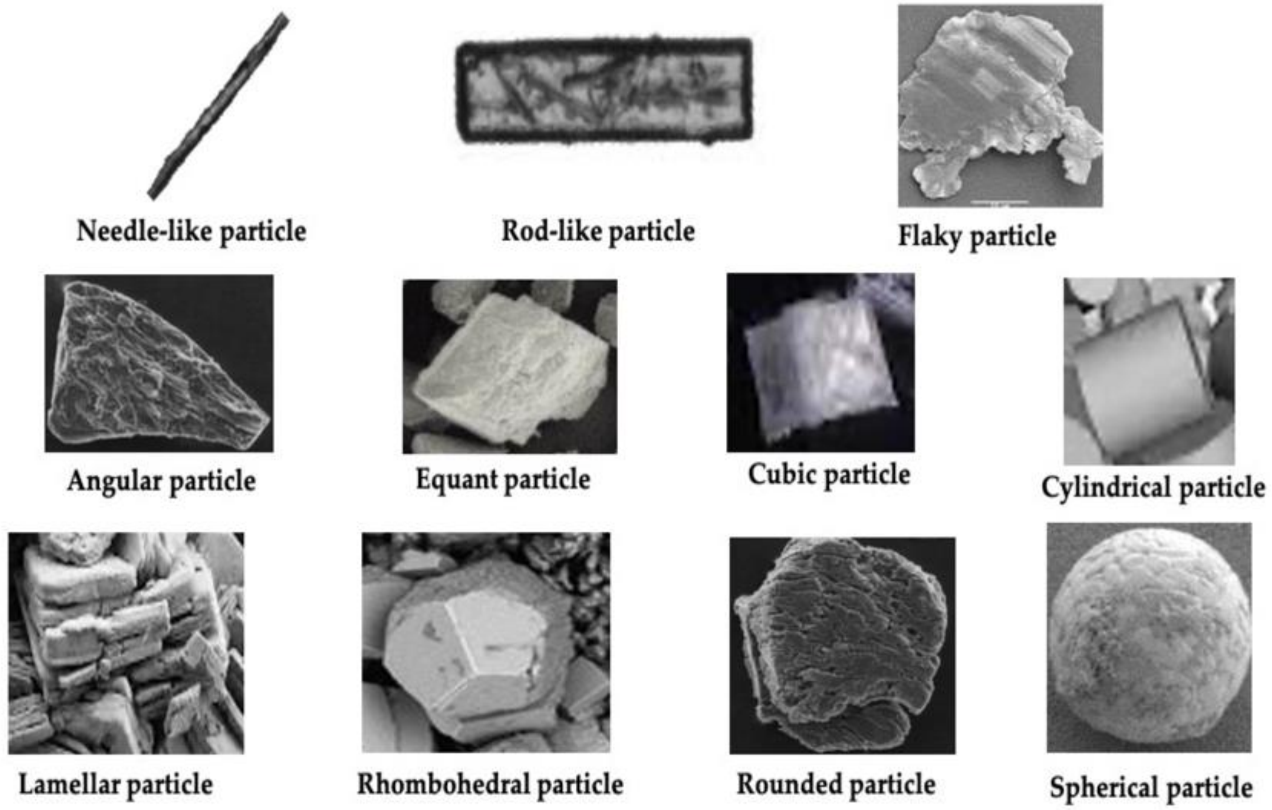
- The powder material properties affect the further selection of all other process parameters;
- The chemical composition, thermal, optical, metallurgical, mechanical, and rheological characteristics of the material play a key role in L-PBF.
- Typically, L-PBF systems use metal powders ranging in size from 5 to 60 μm;
- Granulo-morphometric properties, such as the particle size, particle shape, elongation, roundness, specific surface area, particle size distribution (PSD), etc., affect the delivery of the powder layer, its homogeneity, and the absorption coefficient of laser radiation;

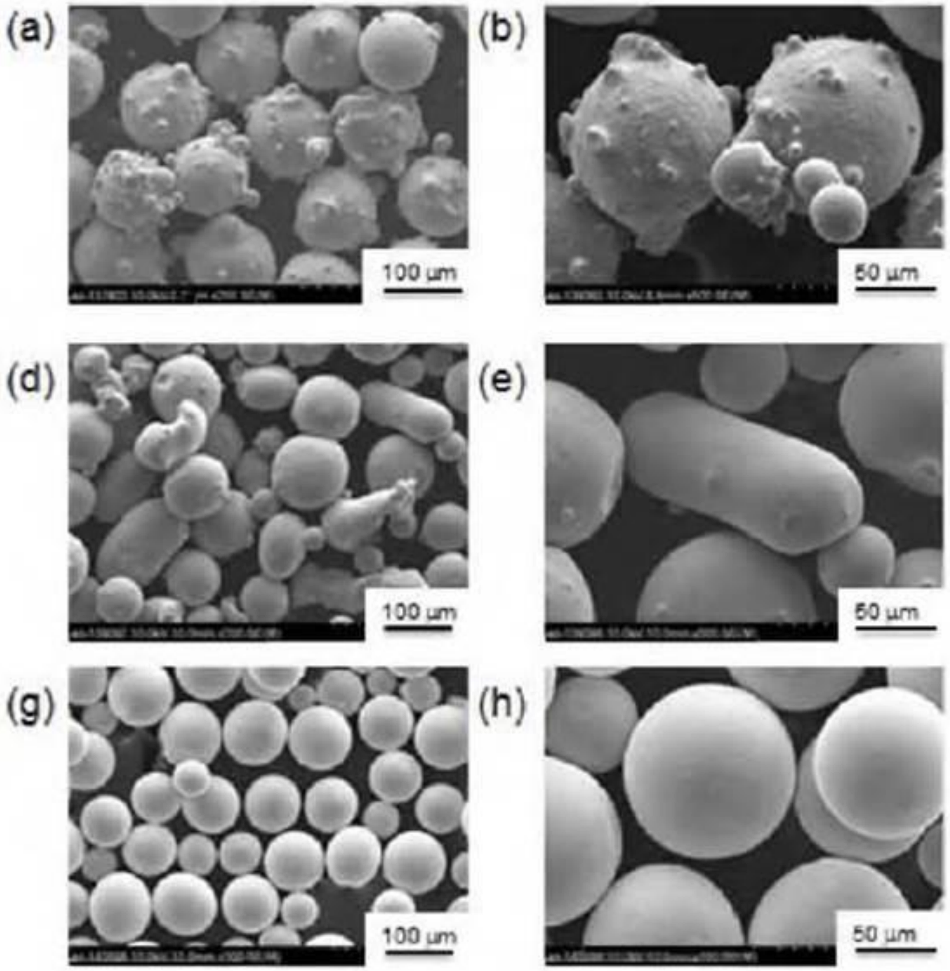




Powders

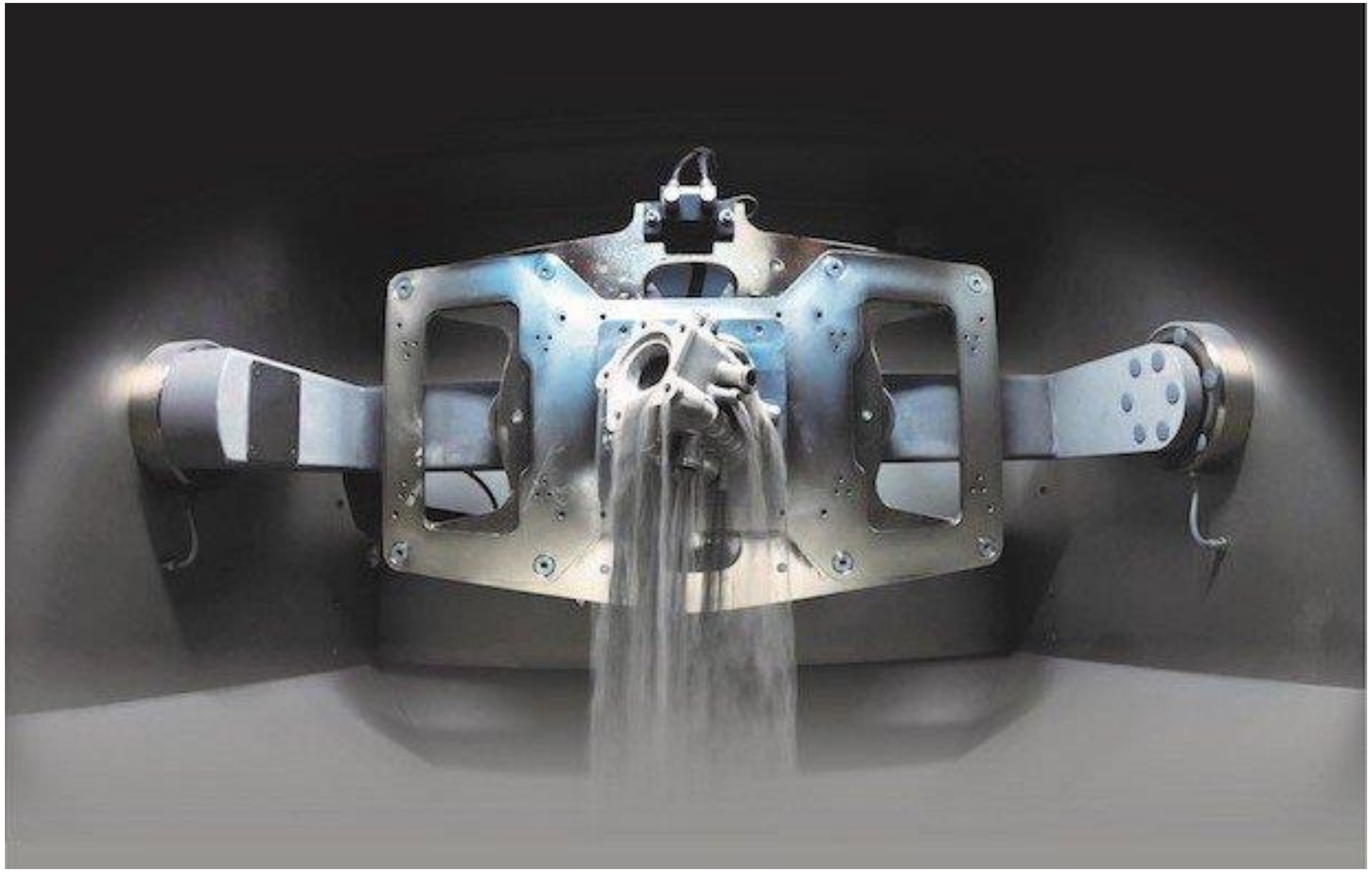
- The most suitable powders for L-PBF are those with spherical particle morphology that has a high packing density, good flowability, and are evenly deposited to the substrate;
- Powders containing a significant fraction of small particles of 1-2 μm in size are easily agglomerated and cannot be properly deposited to the substrate.

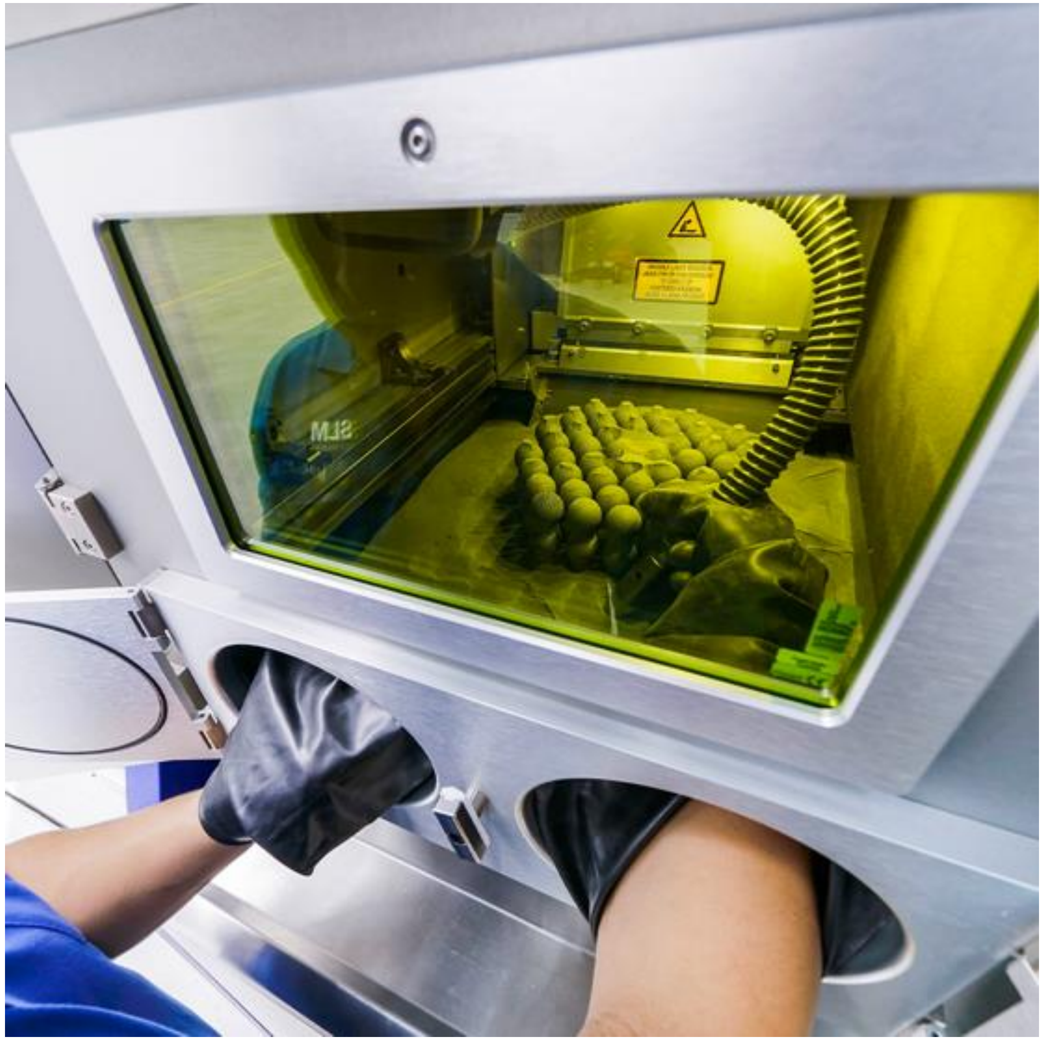


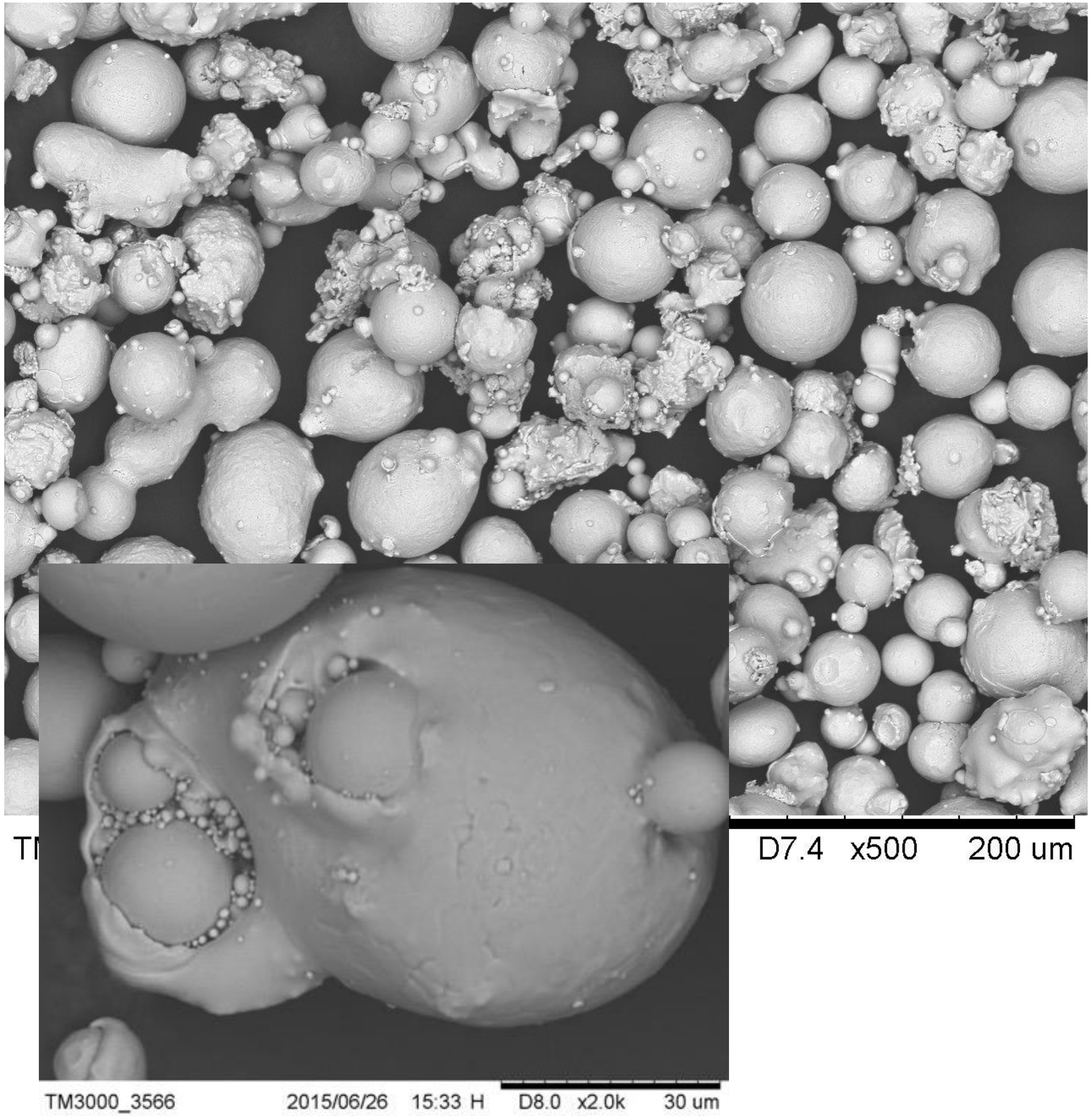


Al-based alloys	**AlSi10Mg, AlSi7Mg0.6, AlSi9Cu3**
Ni-based alloys	Nickel alloy HX, IN625, IN718, IN939
Ti-based alloys	TiAl6V4, TiAl6V4 ELI, TA15, CP (commercially pure) Ti
Co-based alloys	CoCr28Mo6, CoCr28W9
Fe-based alloys	304L, 316L, 15-5PH, 17-4PH, Maraging Steel 1.2709, Maraging Steel M300, H13, Invar 36, 20MnCr5 steel, Stainless Steel CX
Cu-based alloys	CuNi2SiCr, CuSn10, CP Cu, CuCr1Zr
Precious metals	Gold (Au), Silver (Ag), Platinum (Pt), Palladium (Pd)
Refractory metals	Tungsten (W), Molybdenum (Mo)

POWDER REMOVAL



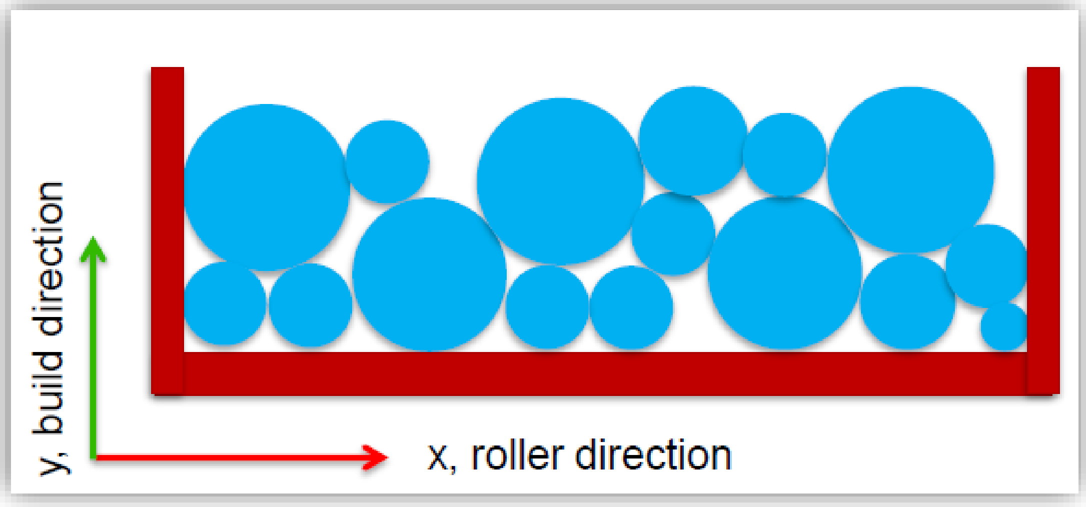



D7.4 x500 200 um
TM3000_3566 2015/06/26 15:33 H D8.0 x2.0k 30 um

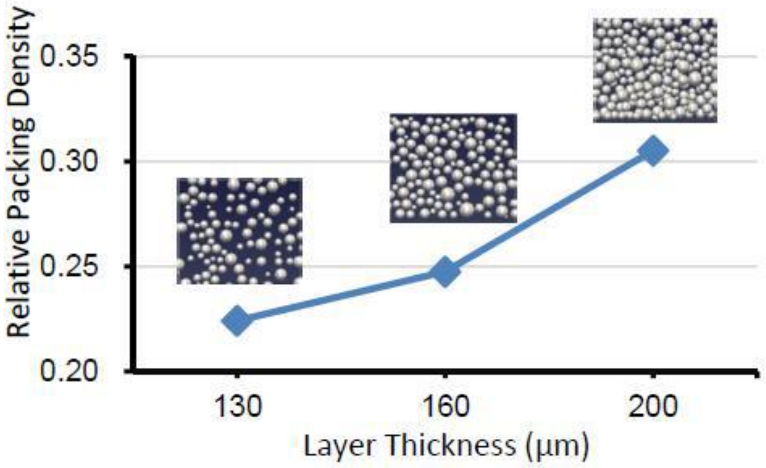

VIKYFLON

| *Focus: the powder bed*

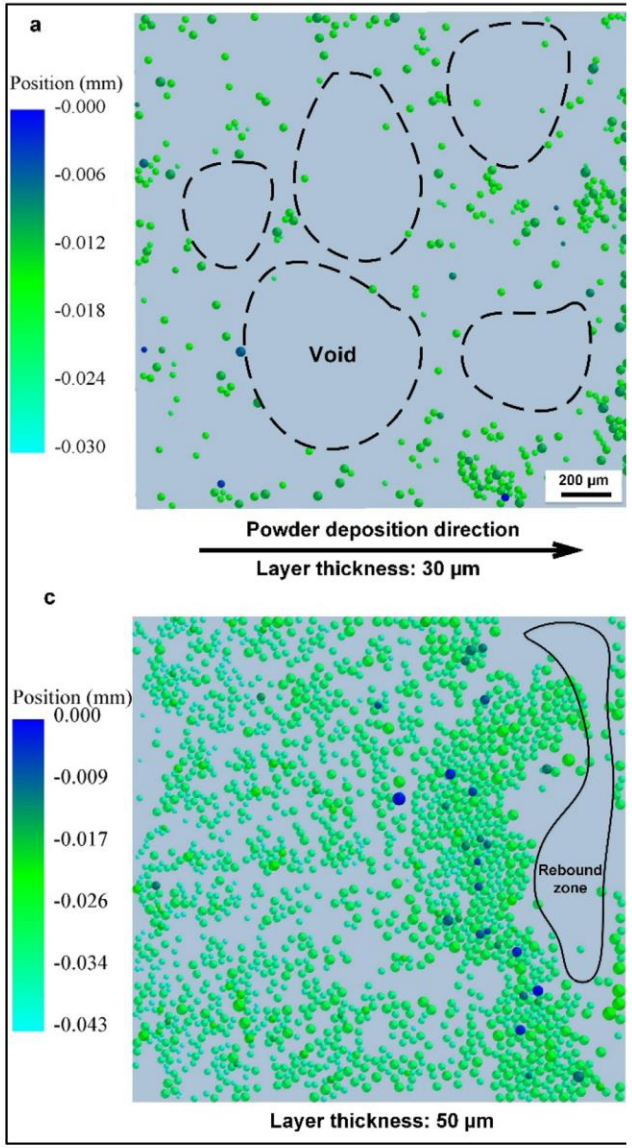
- Speed of the recoating device.
- Layer thickness.
- Shape of the recoating device.



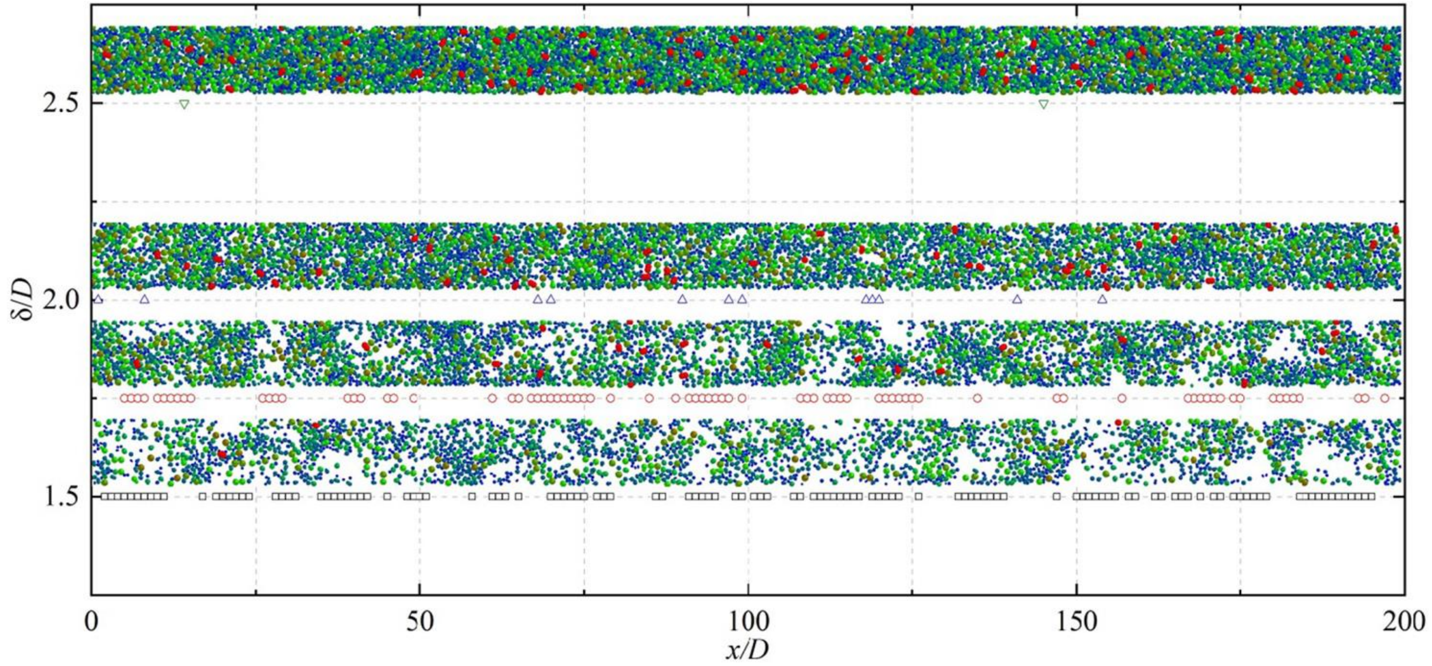
- Powder bed solid volume fraction.
- Effective layer thickness.
- Material/shape segregation.



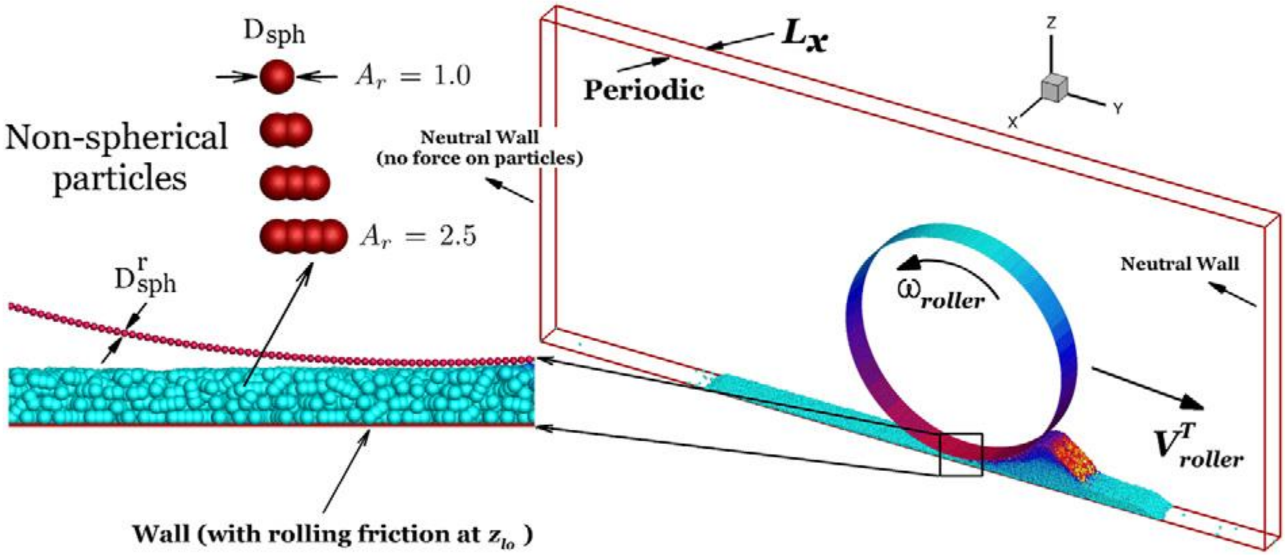
Relative Packing Density
0.35
0.30
0.25
0.20
130
160
200
Layer Thickness (μm)



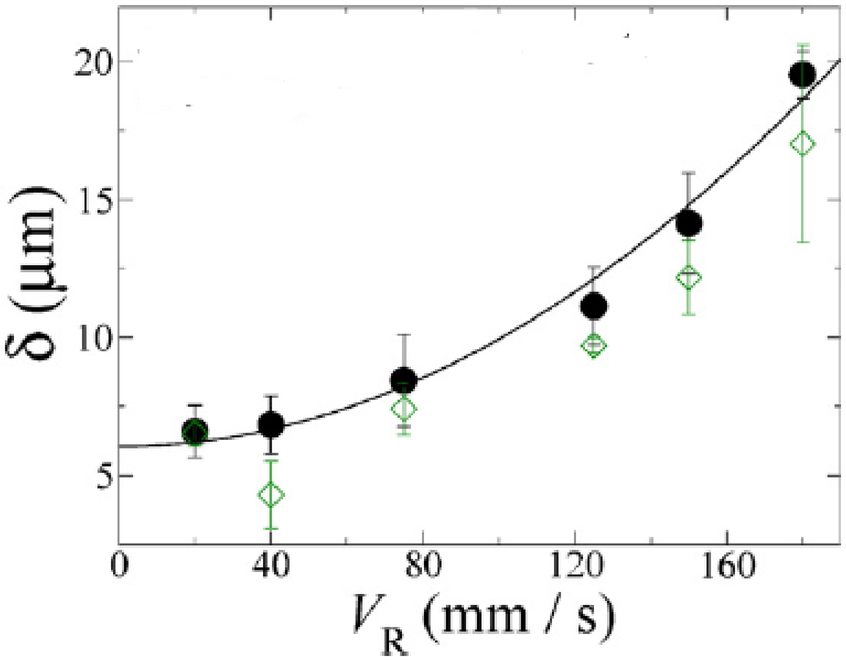
a
Position (mm)
-0.000
-0.006
-0.012
-0.018
-0.024
-0.030
Void
200 μm
Powder deposition direction
Layer thickness: 30 μm
c
Position (mm)
0.000
-0.009
-0.017
-0.026
-0.034
-0.043
Rebound zone
Layer thickness: 50 μm



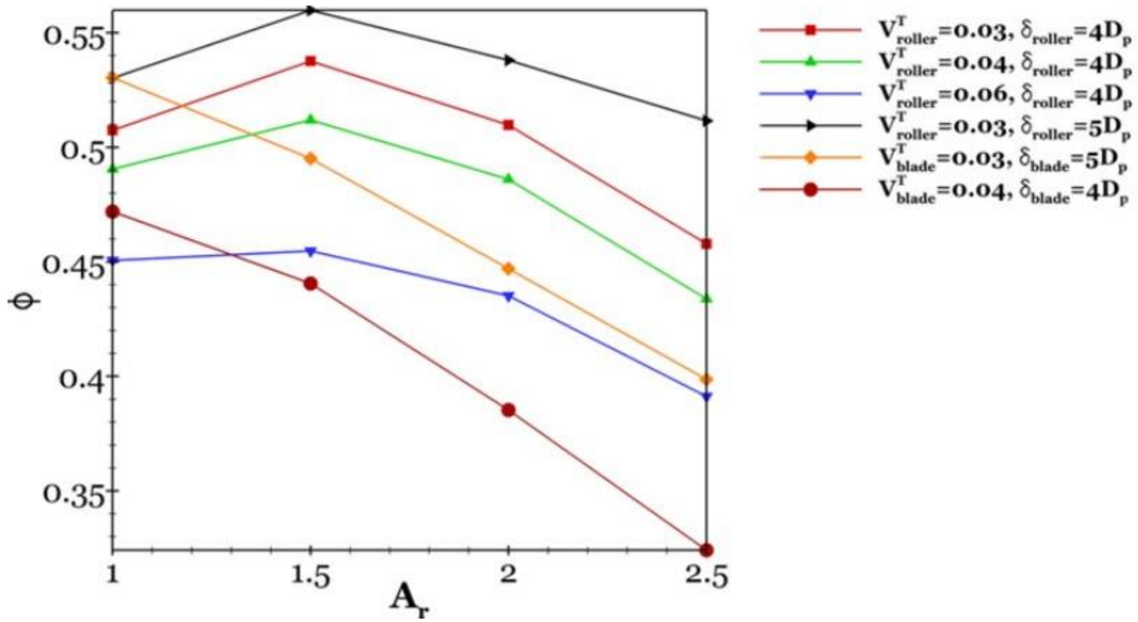
2.5
2.0
1.5
δ/D
0
50
100
150
200
x/D



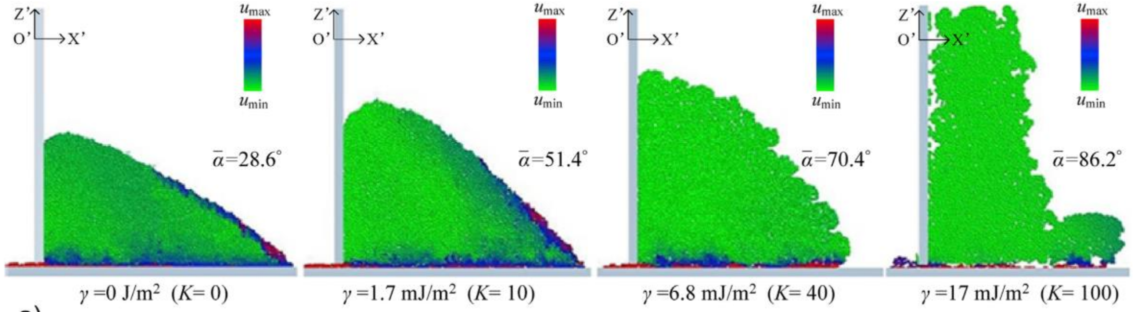
Dsph
Ar = 1.0
Non-spherical
particles
Ar = 2.5
Dr sph
Wall (with rolling friction at zlo)
Lx
Periodic
Neutral Wall
(no force on particles)
Z
X
Y
ωroller
Neutral Wall
VT roller

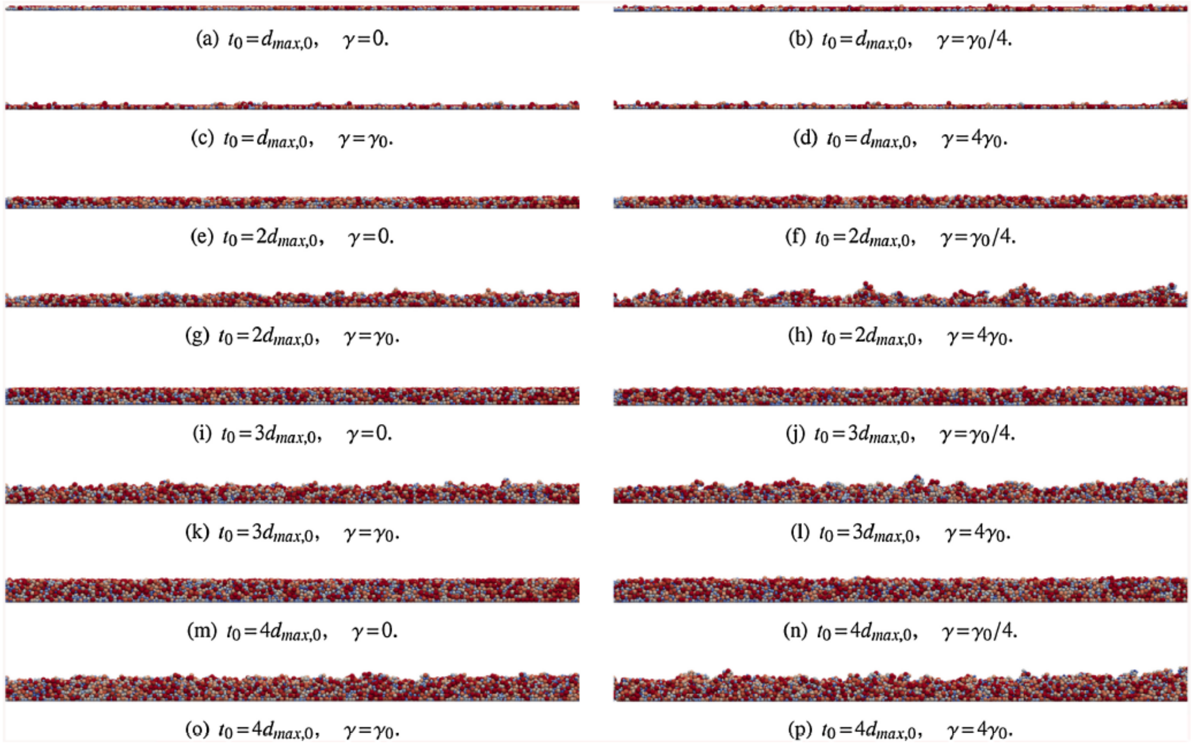


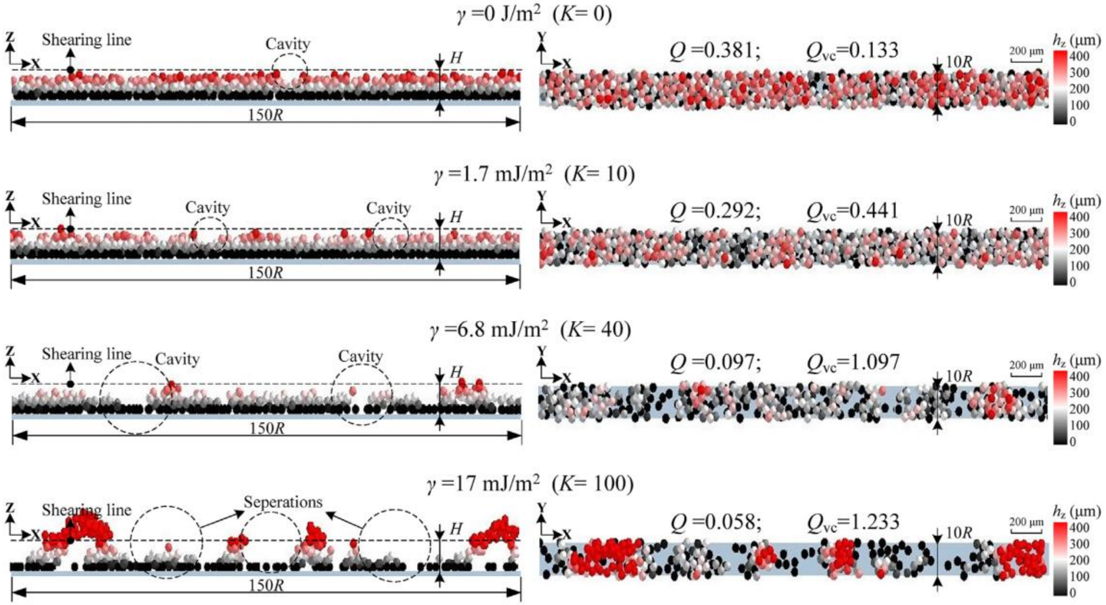
δ (μm)
VR (mm / s)
20
15
10
5
0
40
80
120
160



φ
Ar
0.55
0.5
0.45
0.4
0.35
1
1.5
2
2.5
VTroller=0.03, δroller=4Dp
VTroller=0.04, δroller=4Dp
VTroller=0.06, δroller=4Dp
VTroller=0.03, δroller=5Dp
VTblade=0.03, δblade=5Dp
VTblade=0.04, δblade=4Dp


Z'
O'
X'
u_{max}
u_{min}
$\bar{\alpha}$=28.6°
$\bar{\alpha}$=51.4°
$\bar{\alpha}$=70.4°
$\bar{\alpha}$=86.2°
γ =0 J/m² (K= 0)
γ =1.7 mJ/m² (K= 10)
γ =6.8 mJ/m² (K= 40)
γ =17 mJ/m² (K= 100)
a)


(a) $t_0 = d_{max,0}$, $\gamma = 0$.
(b) $t_0 = d_{max,0}$, $\gamma = \gamma_0/4$.
(c) $t_0 = d_{max,0}$, $\gamma = \gamma_0$.
(d) $t_0 = d_{max,0}$, $\gamma = 4\gamma_0$.
(e) $t_0 = 2d_{max,0}$, $\gamma = 0$.
(f) $t_0 = 2d_{max,0}$, $\gamma = \gamma_0/4$.
(g) $t_0 = 2d_{max,0}$, $\gamma = \gamma_0$.
(h) $t_0 = 2d_{max,0}$, $\gamma = 4\gamma_0$.
(i) $t_0 = 3d_{max,0}$, $\gamma = 0$.
(j) $t_0 = 3d_{max,0}$, $\gamma = \gamma_0/4$.
(k) $t_0 = 3d_{max,0}$, $\gamma = \gamma_0$.
(l) $t_0 = 3d_{max,0}$, $\gamma = 4\gamma_0$.
(m) $t_0 = 4d_{max,0}$, $\gamma = 0$.
(n) $t_0 = 4d_{max,0}$, $\gamma = \gamma_0/4$.
(o) $t_0 = 4d_{max,0}$, $\gamma = \gamma_0$.
(p) $t_0 = 4d_{max,0}$, $\gamma = 4\gamma_0$.


γ =0 J/m² (K= 0)
Shearing line
Cavity
H
150R
Q =0.381; Q_{vc}=0.133
10R
200 μm
h_z (μm)
400
300
200
100
0
γ =1.7 mJ/m² (K= 10)
Shearing line
Cavity
Cavity
Q =0.292; Q_{vc}=0.441
γ =6.8 mJ/m² (K= 40)
Shearing line
Cavity
Cavity
Q =0.097; Q_{vc}=1.097
γ =17 mJ/m² (K= 100)
Shearing line
Seperations
Q =0.058; Q_{vc}=1.233
b)

| *Discrete element method*

Contact detection and particle overlap

Overlap δ

Force-displacement law applied to each contact

Force

Apply Newton's second law to calculate the resultant motion of the particle

Update position and velocity

Δt

Force-displacement law:

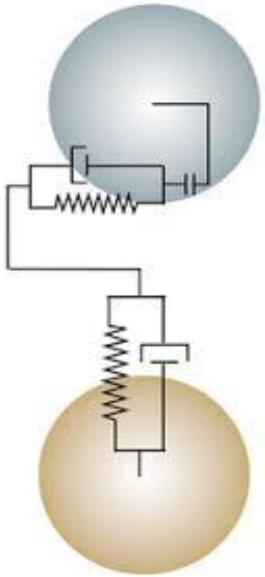
$$F = \left(k_n \delta n_{ij} - y_n v n_{ij}\right) + \left(k_t \delta t_{ij} - y_t v t_{ij}\right)$$

Nonlinear Hertz-Mindlin

$$k_n = \frac{4}{3} E' \sqrt{R' \delta_n}$$

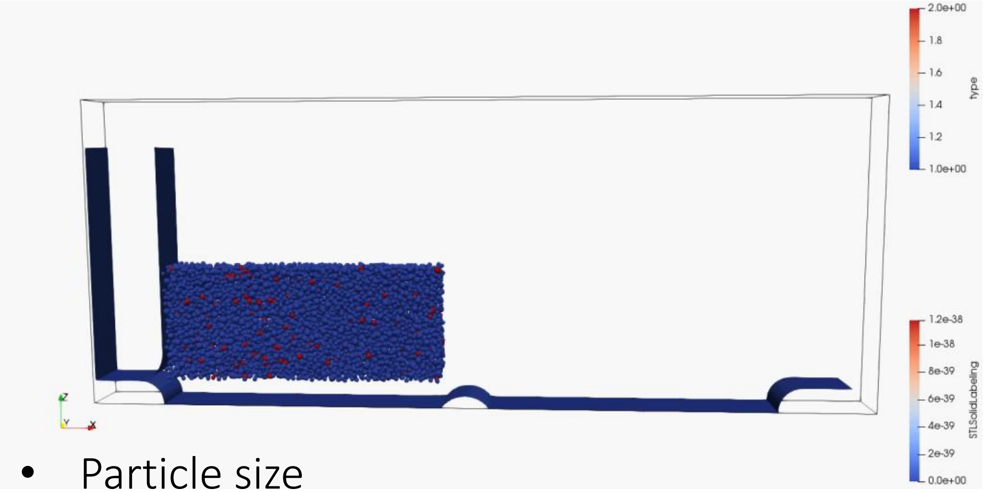
Additional cohesive force simplified Johnson-Kendall-Roberts

$$F = kA$$

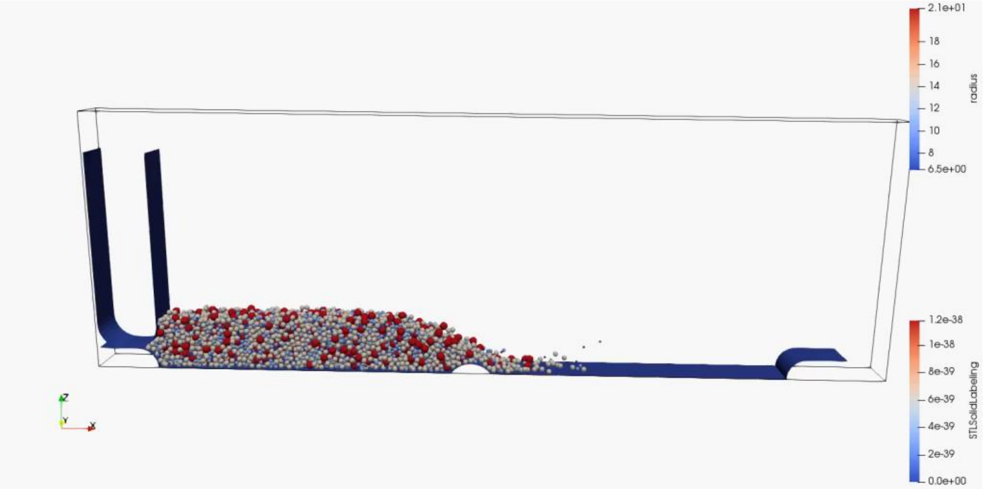


| *Powder Spreading simulation*

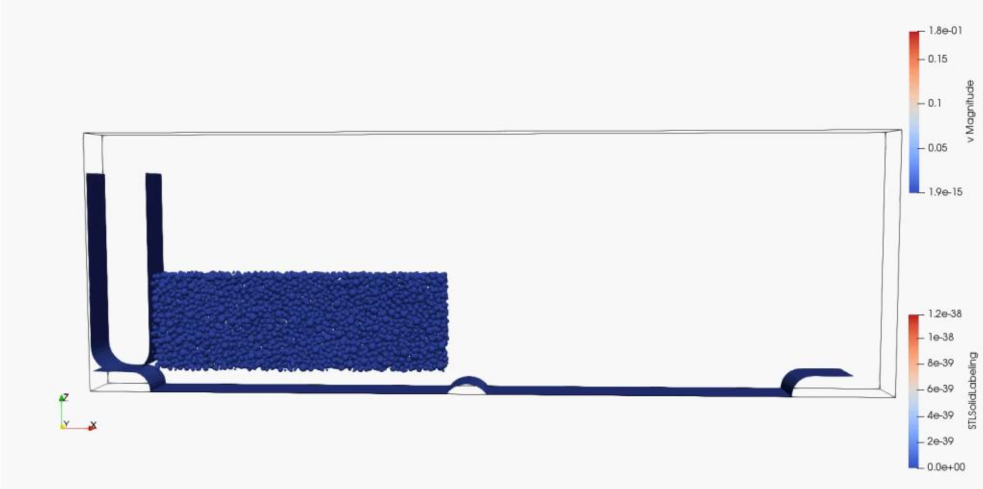
- Material segregation



- Particle size

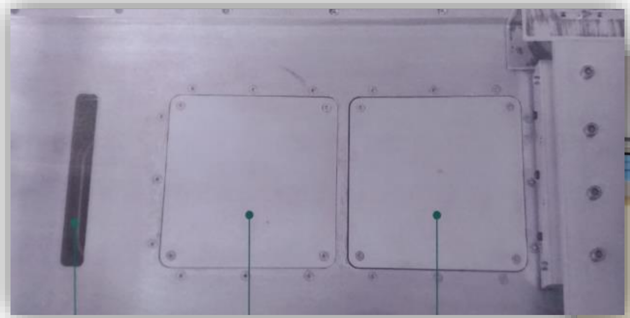


- Velocity profile

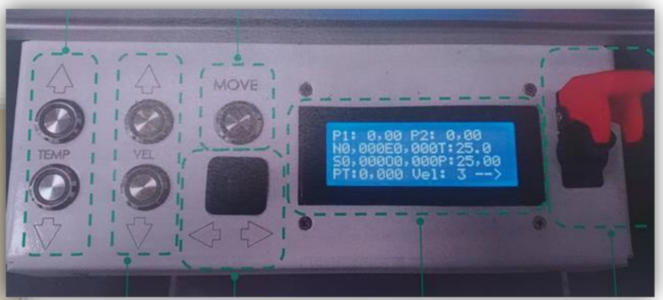


- Local packing factor and density
- Local variation of the PSD
- Effective layer thickness

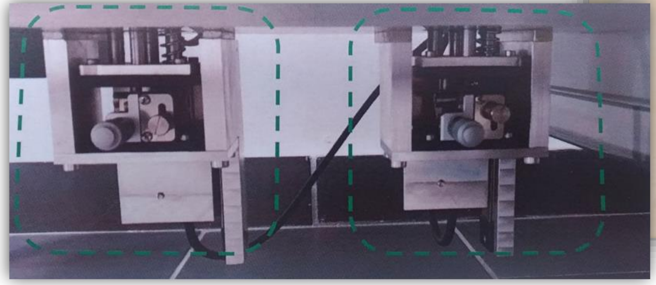
| *Experimental device*



Removable blade



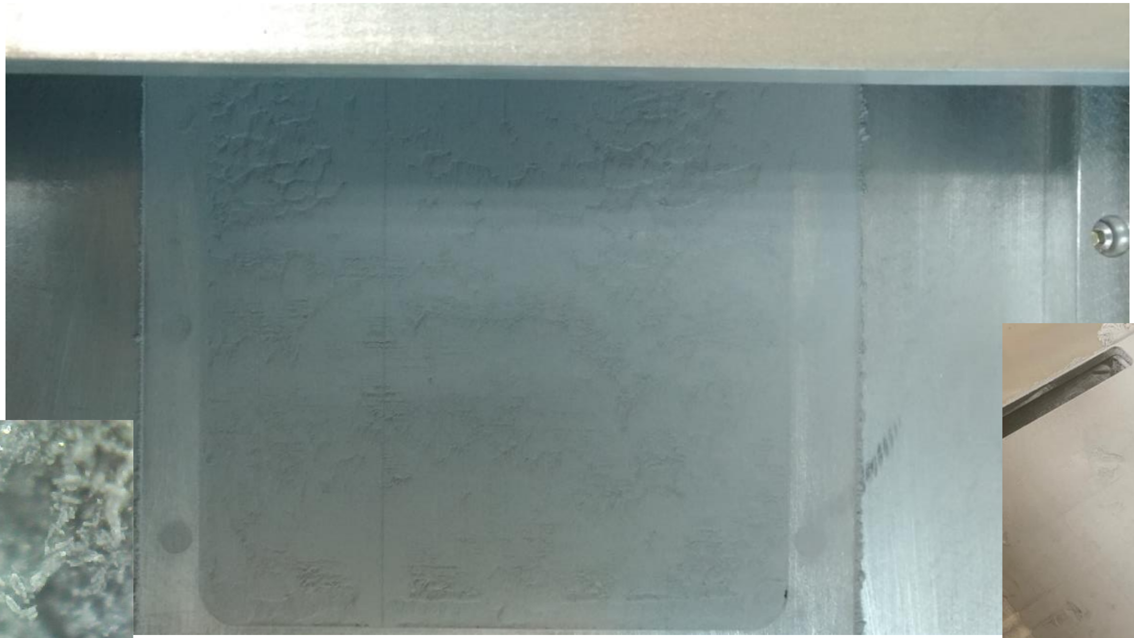
Control panel with 6 different blade's speeds and selectable temperature for the plate

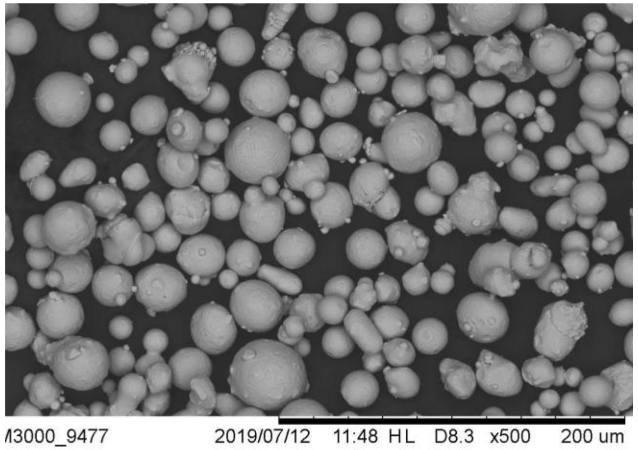


Micrometric screws to adjust the layer thickness and powder feedstock

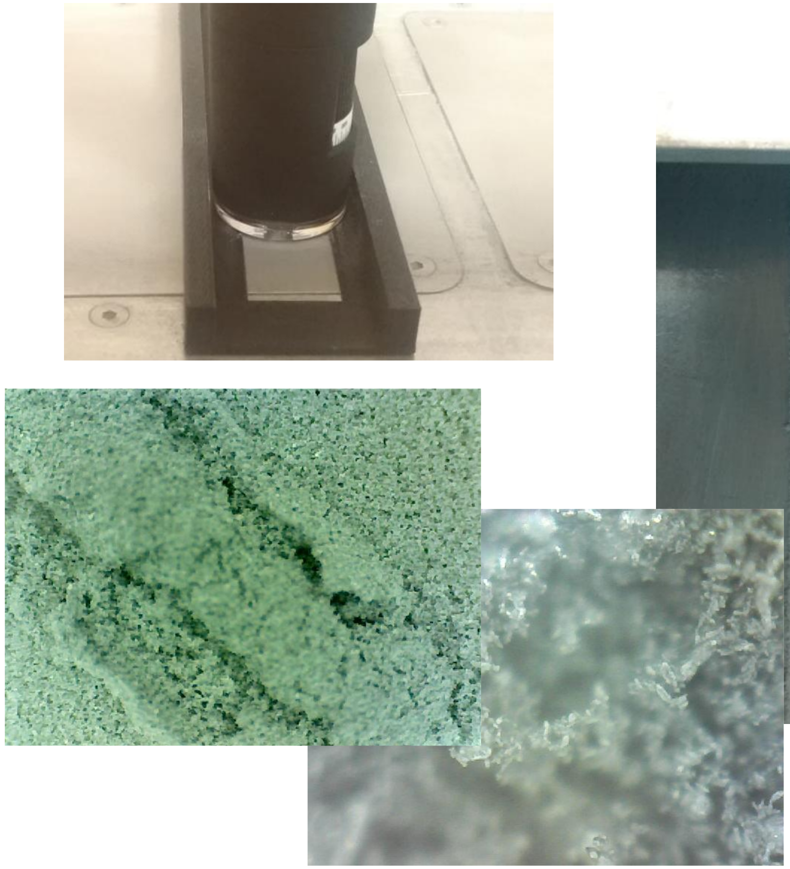
Set of portable microscopes with different leves of magnification

| *Experimental device*

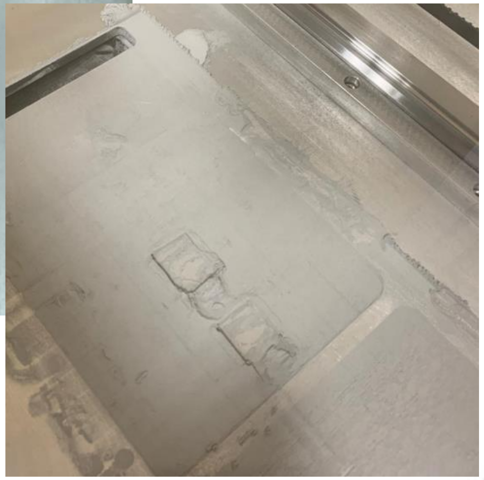




Analysis of Sem images to study variations in the PSD and characteristcs of the powders



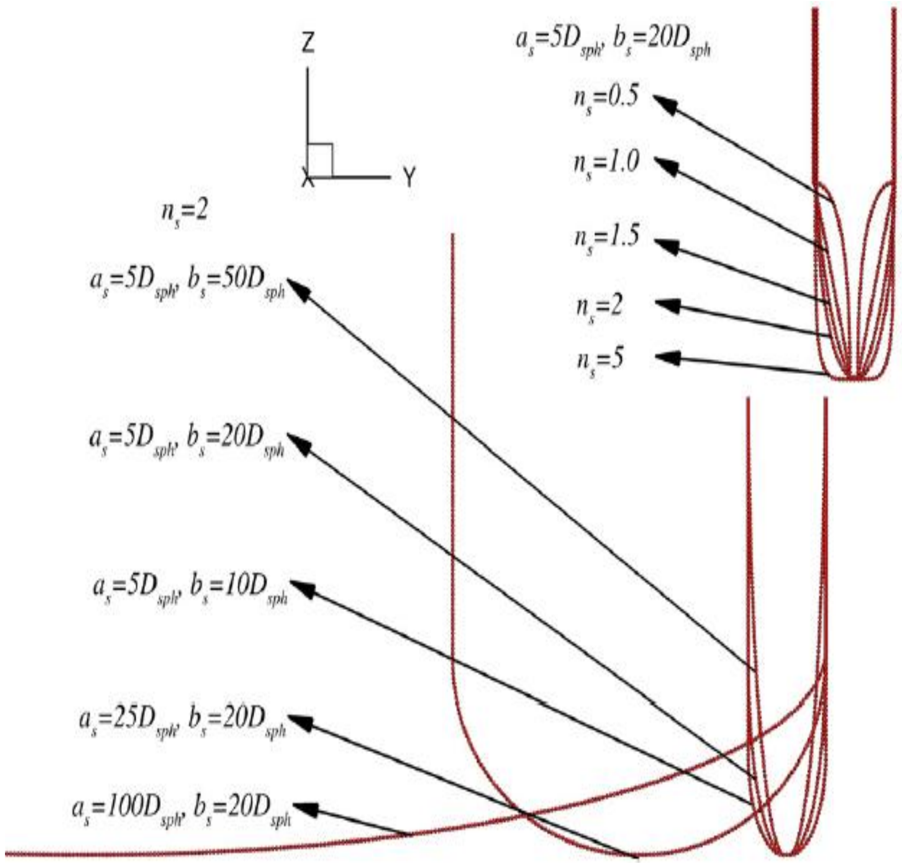
Acquire images on situ at different levels of zoom with a portable microscope to perform analysis of the powder bed

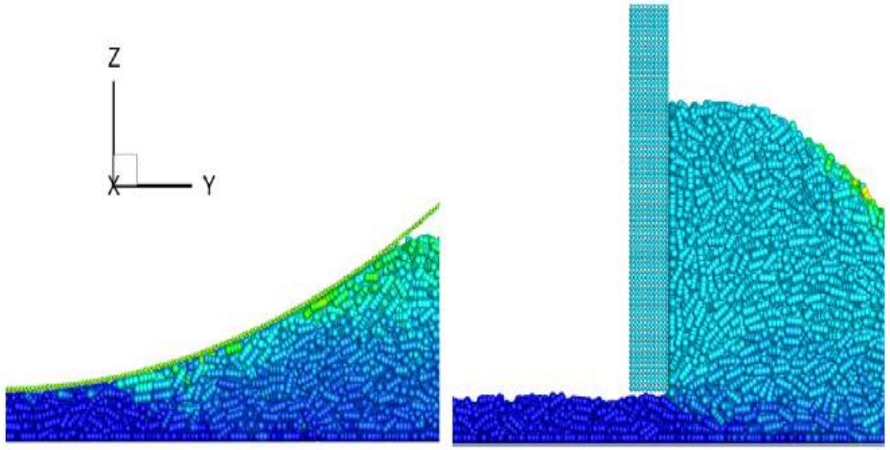


Extract samples of the powder bed to measure the local density

POWDER HANDLING: POWDER BED DEPOSITION

SPREADER GEOMETRY

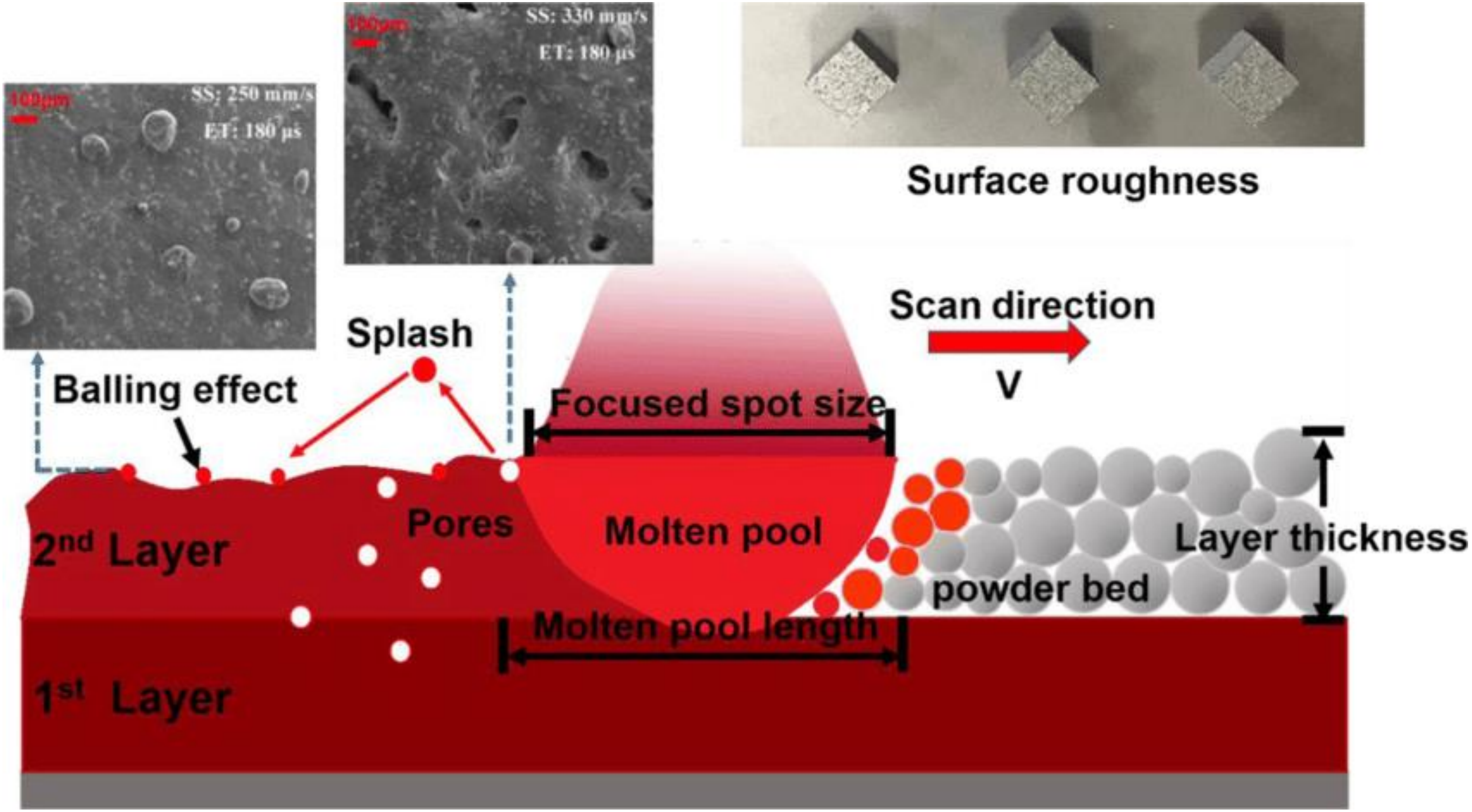




Powder removal, gas supply, and filtration systems

- Since the powder has a large specific surface area, to prevent the metal material from intense oxidation, the L-PBF process takes place in an inert gas atmosphere;
- For more inert (resistant to oxidation) metal alloys (Ni-based, Co-based, Fe-based, etc.), nitrogen is used, and for more active metal alloys (Al-based, Ti-based, etc.), argon is used;
- As a result of the interaction of laser radiation with metal powder, intensive evaporation and ejection of the material occurs.
- Particles entrained by the evaporation-driven protective gas flow are dragged into the melting pool or ejected.
- The spatter ejection depends on protective gas flows, laser plume, and dynamics of the melt pool.

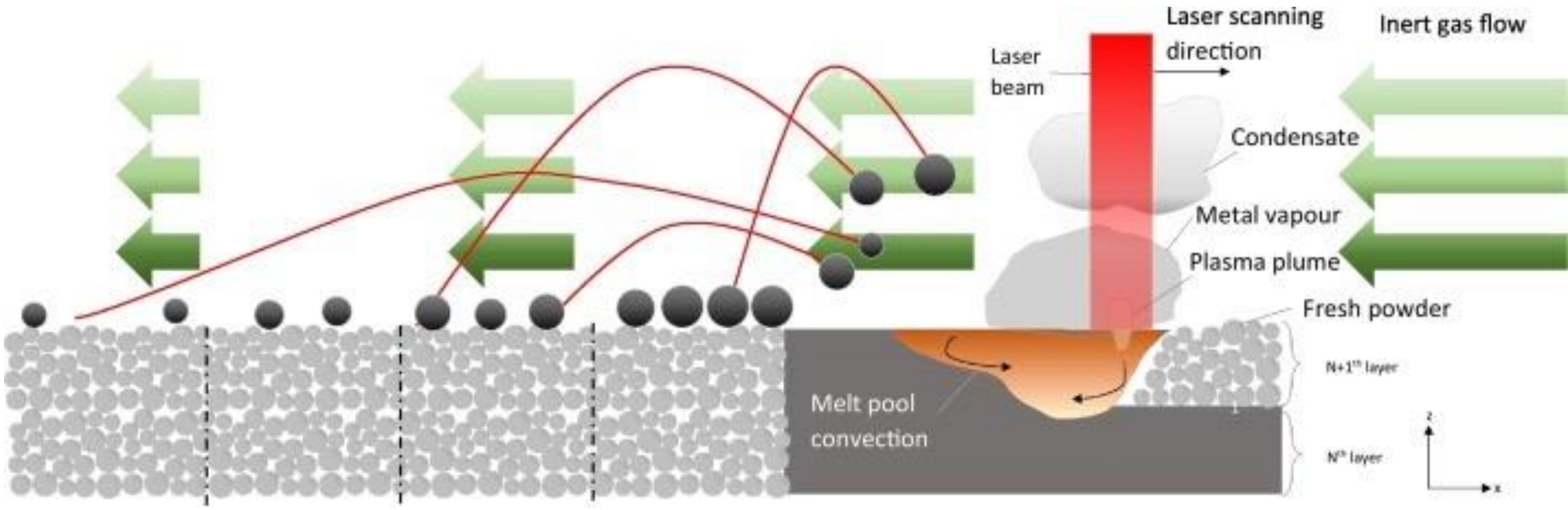
BALLING EFFECT


100μm
SS: 250 mm/s
ET: 180 μs
100μm
SS: 330 mm/s
ET: 180 μs
Surface roughness
Splash
Balling effect
Scan direction
V
Focused spot size
Pores
Molten pool
2nd Layer
Layer thickness
powder bed
Molten pool length
1st Layer

Powder removal, gas supply, and filtration systems

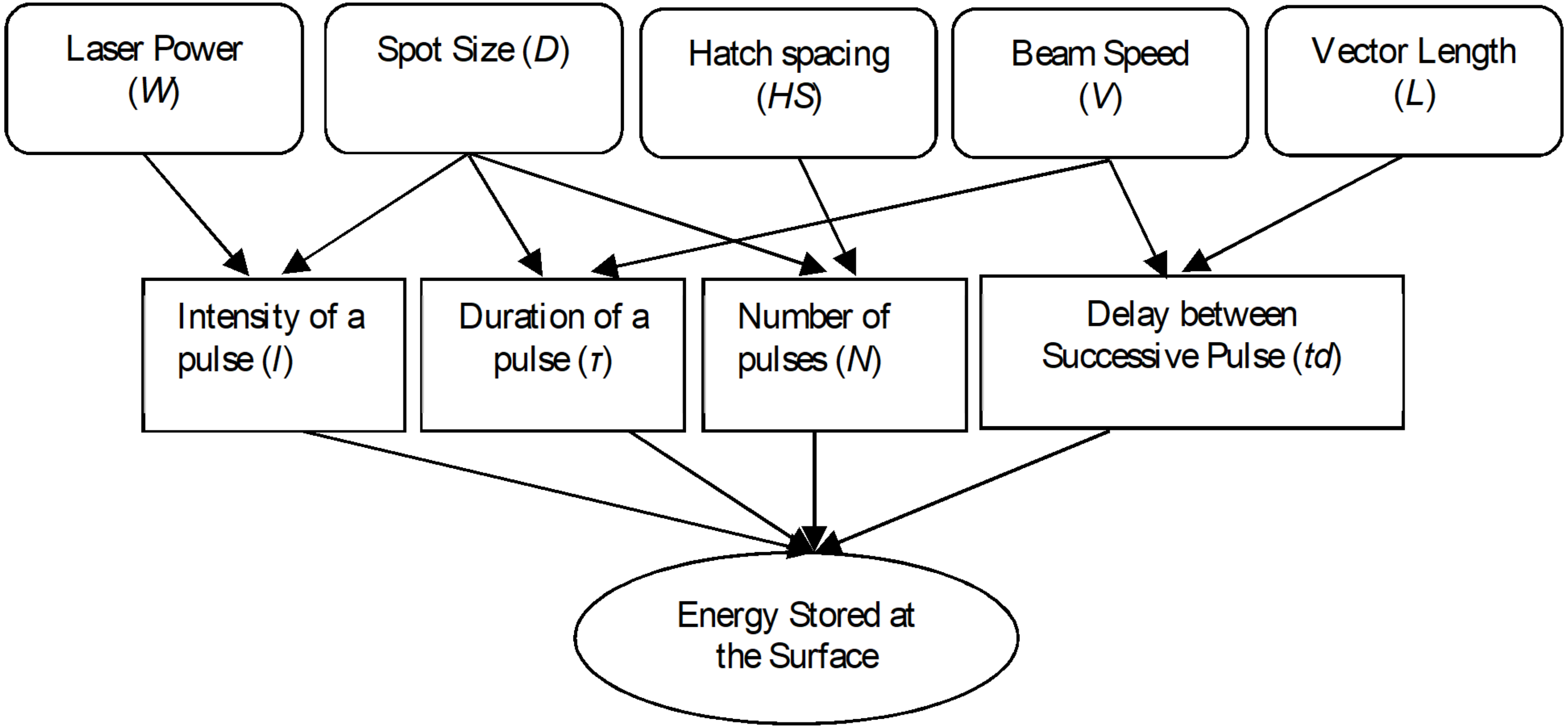
- To prevent contamination of the surface of the powder layer a filtration system is used.
- When changing protective gases, it is imperative to change filters:
    - nitrogen and argon have different physical properties and different gas permeability,
    - various metals deposited on the filters can react chemically, which can cause the filters to ignite and destroy the L-PBF system.
- A directional flow of shielding inert gas, which uniformly flows directly over the surface of the powder layer, removes products of the process (metal condensate and spatter particles) from the laser-powder interaction zone.

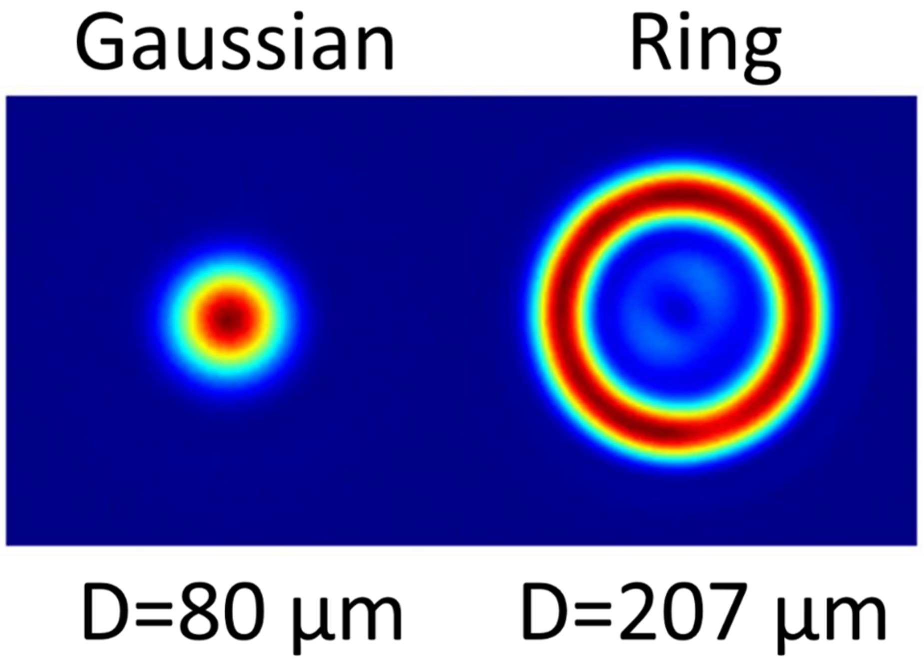
INERT GAS FLOW

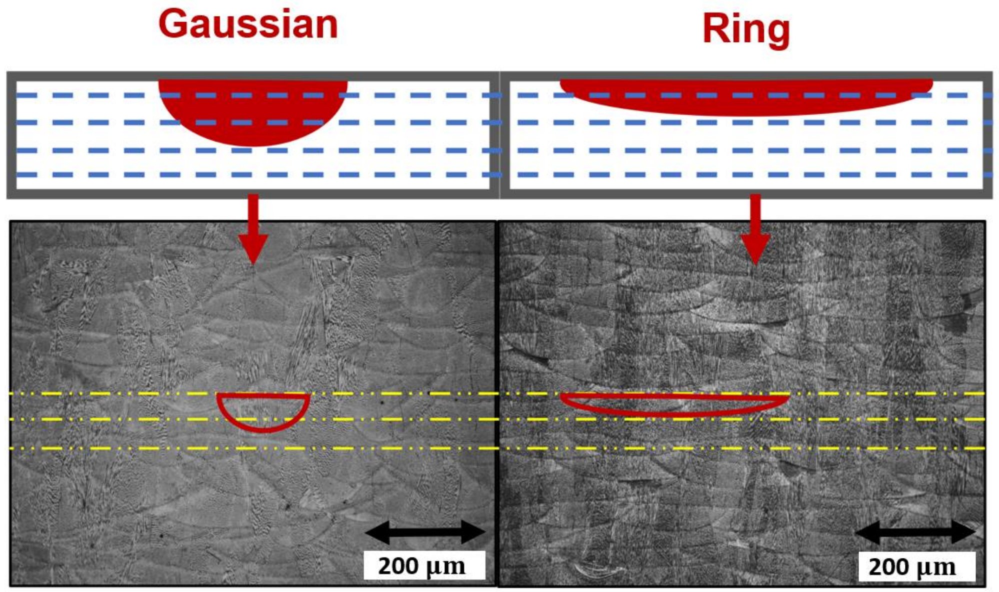


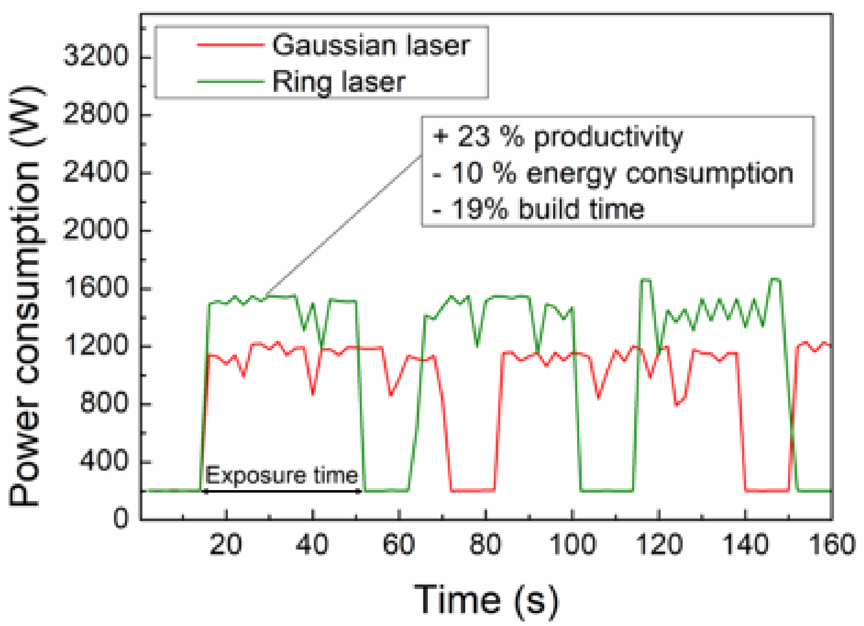
Melt-pool dynamics and track formation

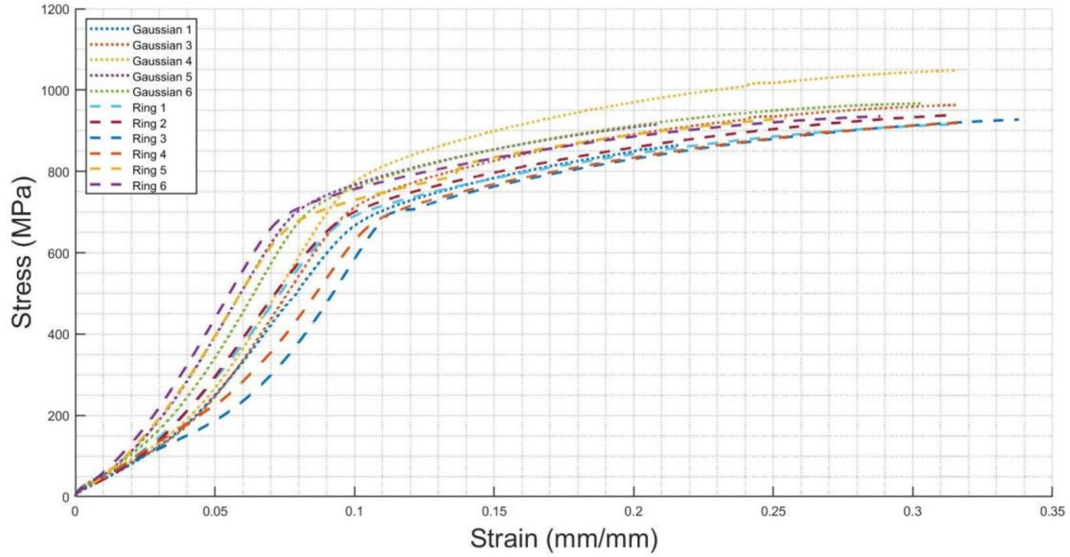
- When the laser beam scans over the surface of a thin powder layer, energy absorbed from the laser beam heats the underlying material;





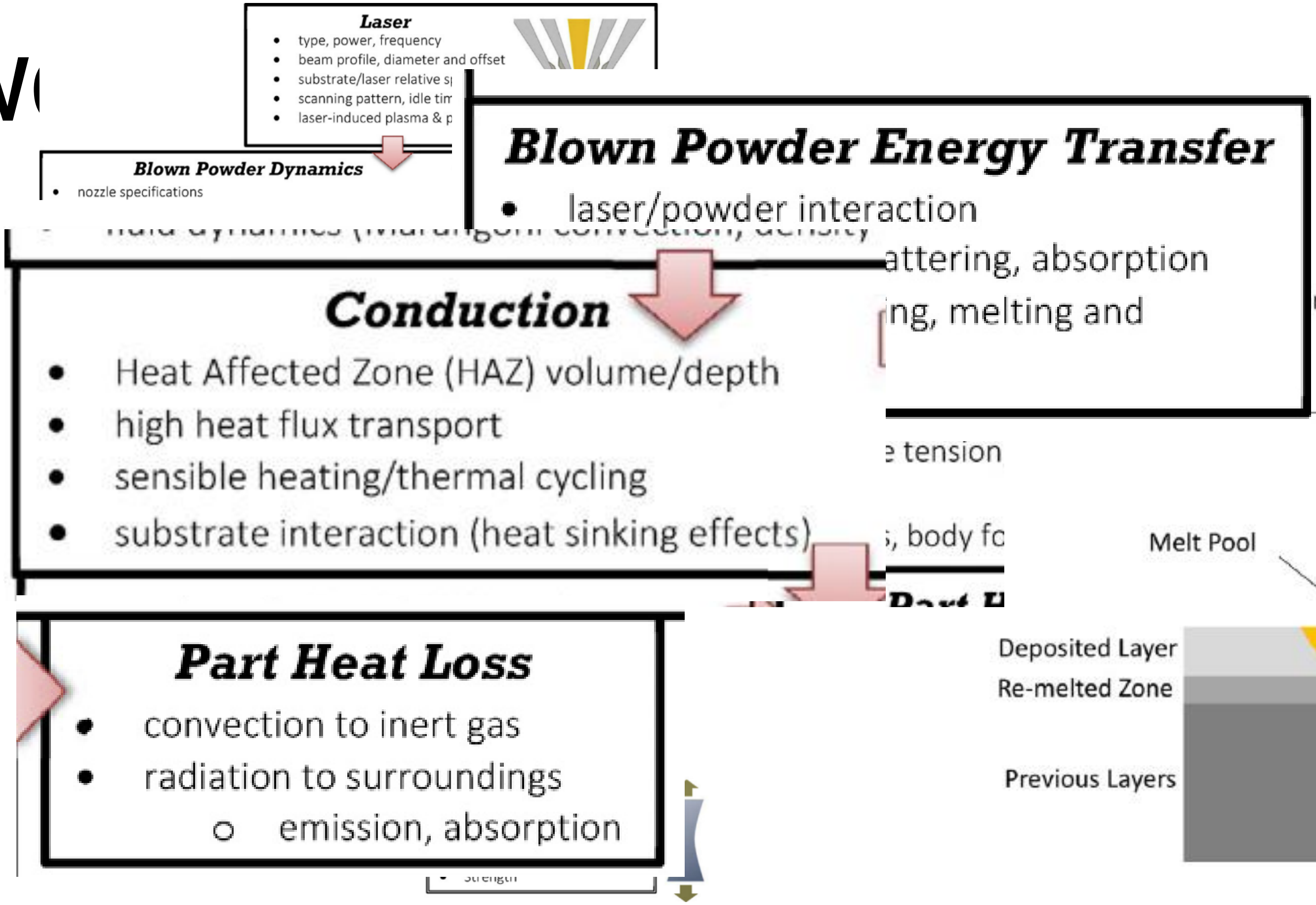


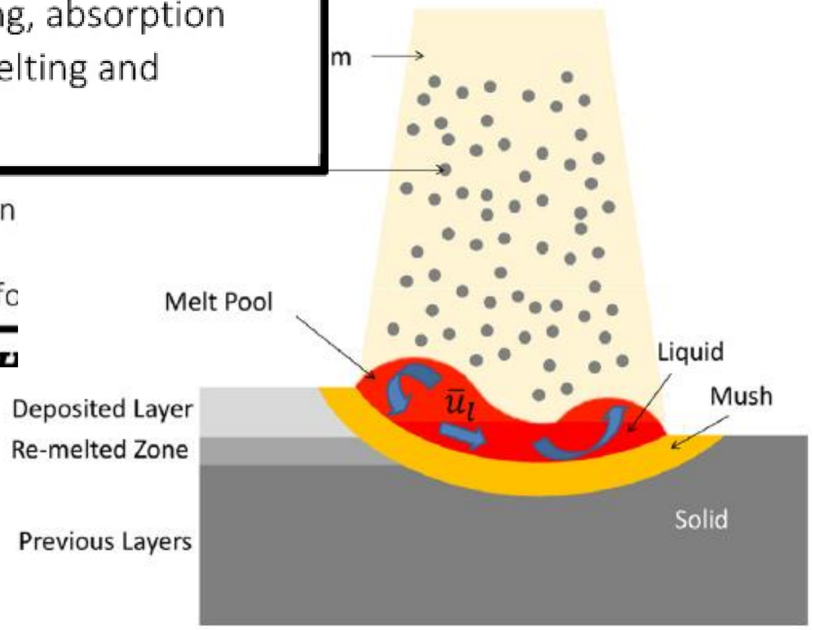




Cozzolino, E., Tiley, A.J., Ramirez, A.J., Astarita A., Herderick E. (2024) Energy efficiency of Gaussian and ring profiles for LPBF of nickel alloy 718. Int J Adv Manuf Technol.
https://doi.org/10.1007/s00170-024-13511-0

Interaction between Laser Beam and Pow





S.M. Thompson et al. An overview of Direct Laser Deposition for additive manufacturing; Part I: Transport phenomena, modeling and diagnostics, Addit. Manuf. 8 (2015) 36-62.

Interaction between Laser Beam and Powders

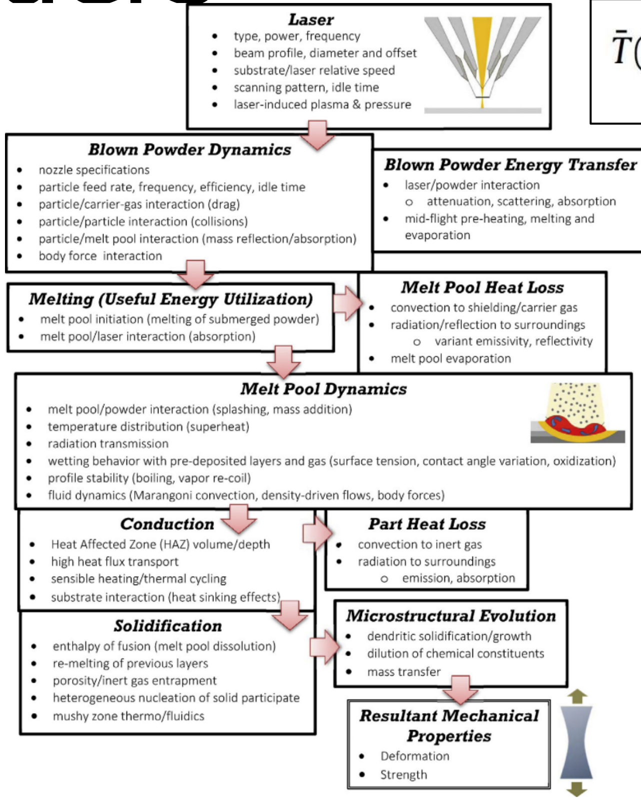
$$q''_{\text{laser}} = \frac{2\alpha_{\text{m}}P}{\pi R^2}\exp\left(-\frac{2r^2}{r^2_{\text{b,i}}}\right)$$

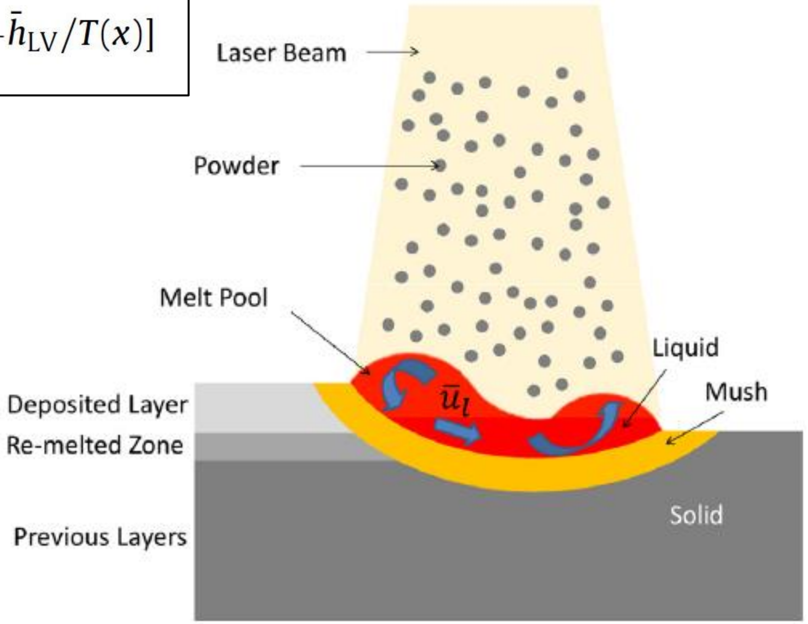
$$q''_{\text{loss}} \cong h_x(T(x)-T_\infty)+\varepsilon\sigma(T^4(x)-T^4_\infty)+\rho_{\text{L}}\left|\frac{\Delta x}{\Delta t}\right|_{\text{e}} h_{\text{LV}}$$

$$\bar{T}(x^*,z^*) = \text{e}^{-x^*}K_{\text{o}}\left(\sqrt{x^{*2}+z^{*2}}\right)$$

$$\left|V_{\text{iso}}\right| = \left|V_{\text{beam}}\right|\cdot\cos\theta$$

$$\left|\frac{\Delta x}{\Delta t}\right|_{\text{e}} = c_{\text{s}}\exp[-\bar{h}_{\text{LV}}/T(x)]$$



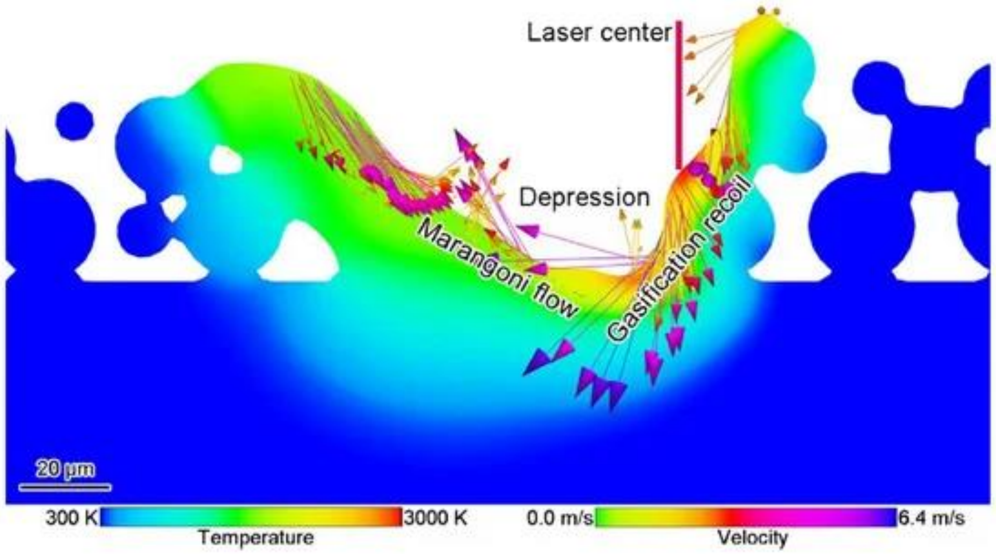


S.M. Thompson et al. An overview of Direct Laser Deposition for additive manufacturing; Part I: Transport phenomena, modeling and diagnostics, Addit. Manuf. 8 (2015) 36-62.

Powder Bed Fusion

Melt-pool dynamics and track formation

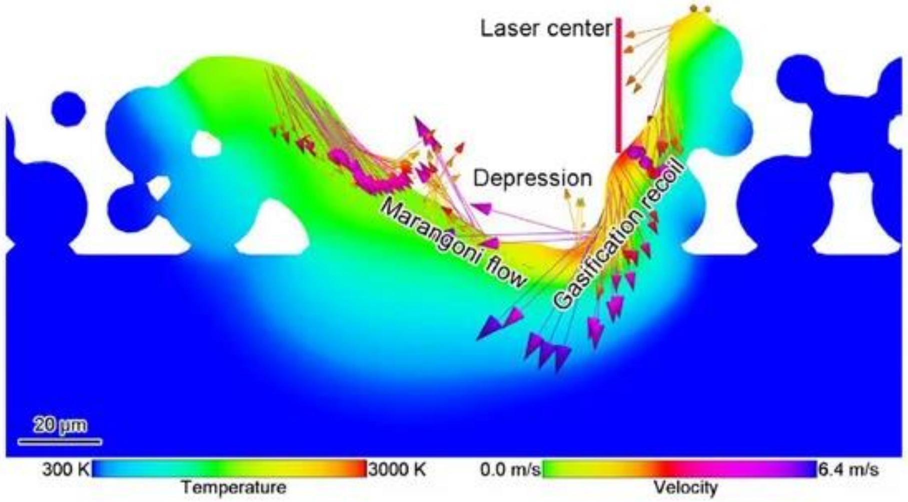
- Molten powder particles and the substrate create a joint melt pool;
- Heating, time-evolution of the melt pool, and the solidification process depend on powder material properties, process parameters, and the build environment;
- The process parameters affect the phases, recoil pressure, surface tension and Marangoni effect, and hydrodynamics that in turn define the evolution of the melt pool, its size, and shape;



Powder Bed Fusion

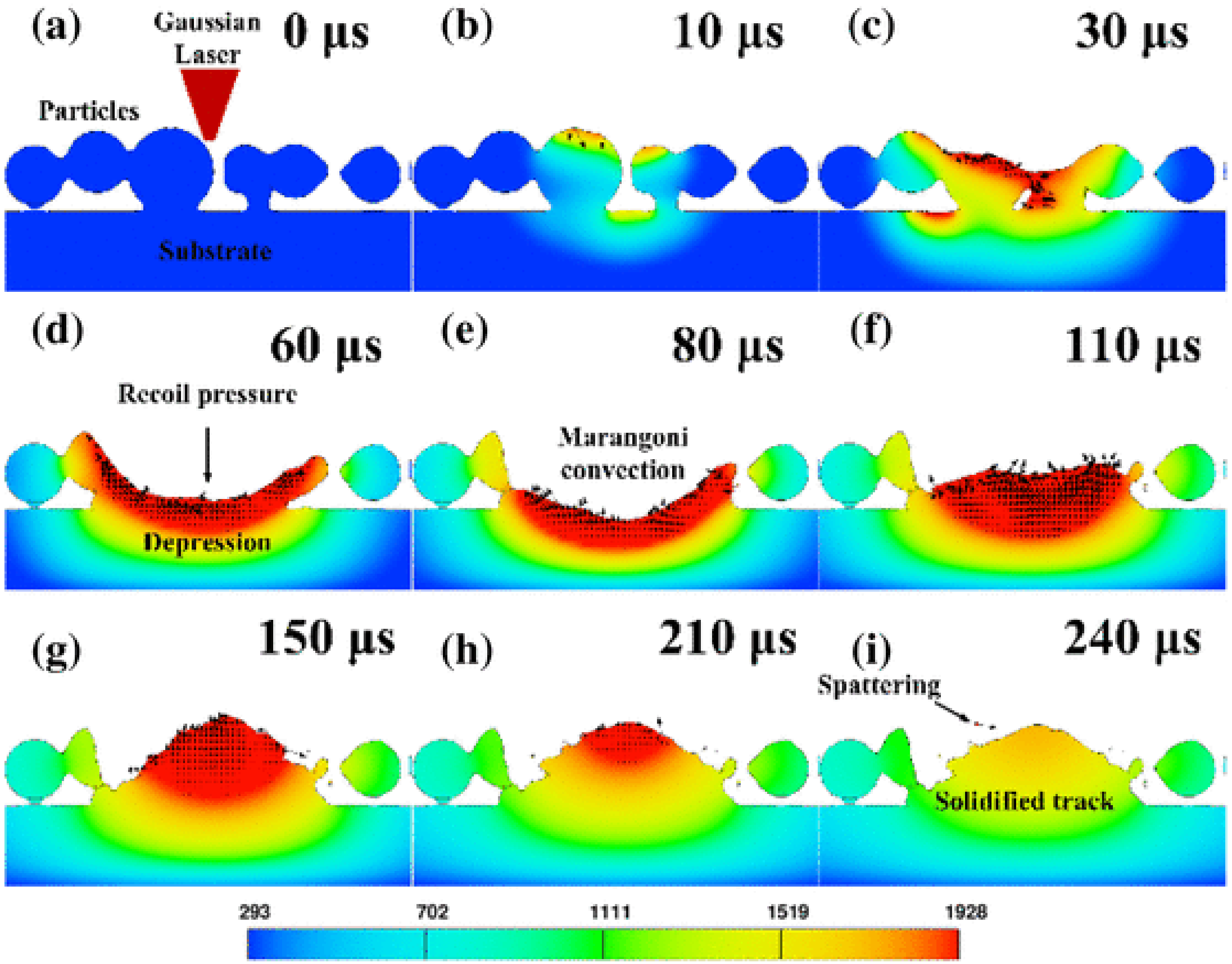
Melt-pool dynamics and track formation

- The Marangoni effect (also called the Gibbs–Marangoni effect) is the mass transfer along an interface between two phases due to a gradient of the surface tension;
- Since a liquid with a high surface tension pulls more strongly on the surrounding liquid than one with a low surface tension, the presence of a gradient in surface tension will naturally cause the liquid to flow away from regions of low surface tension;
- The surface tension gradient can be caused by concentration gradient or by a temperature gradient (surface tension is a function of temperature).



Powder Bed Fusion

Melt-pool dynamics and track formation



Powder Bed Fusion

Melt-pool dynamics and track formation

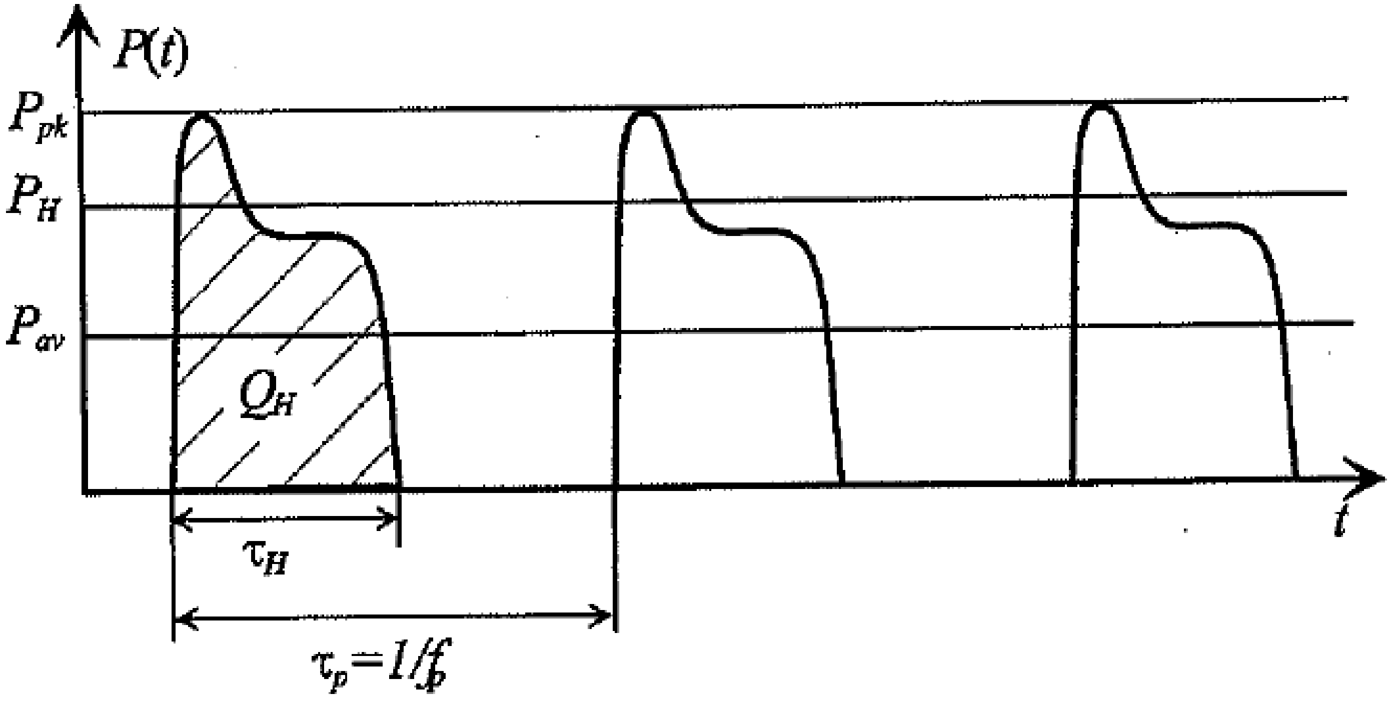
- When the laser beam leaves the melt area, the melt pool starts to cool down and solidifies;
- To create a stable melt pool with a regular shape and geometrical characteristics, several factors have to be consistent with each other;
- Sufficient energy is needed to melt both the powder and the substrate under the laser beam and the interaction time has to be optimized to create a joint stable melt pool.

Powder Bed Fusion

Melt-pool dynamics and track formation

The energy absorbed by material is strictly dependent on laser characteristics such as:

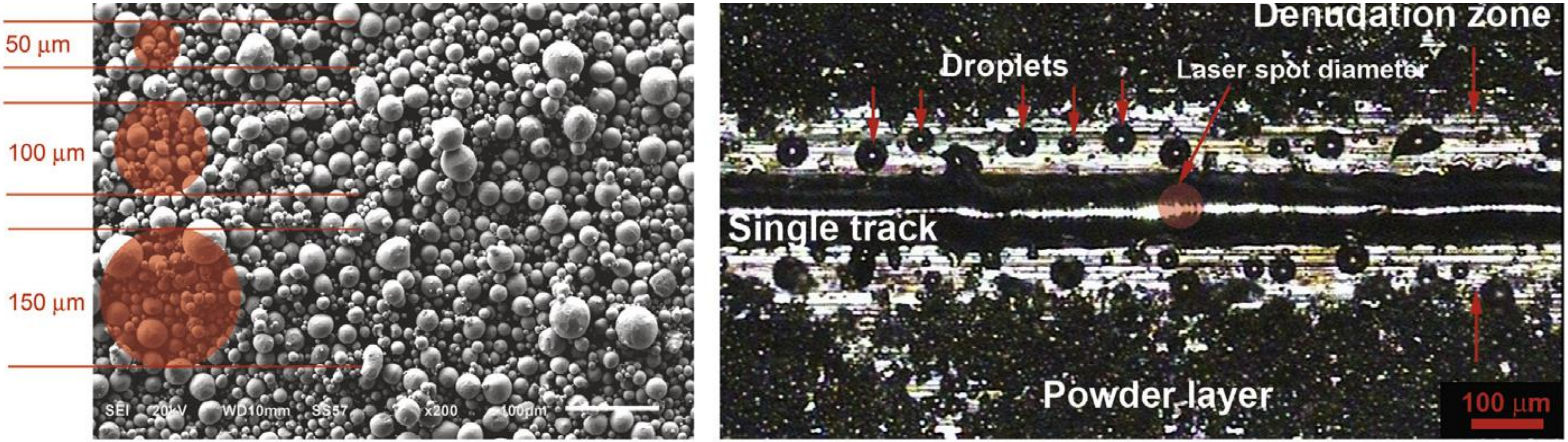
- wavelength,
- pulse width,
- frequency,
- average and maximum power,
- intensity profile,
- laser mode,
- spot size,
- irradiation time,
- etc.



Powder Bed Fusion

Melt-pool dynamics and track formation

- The key energy parameters of L-PBF are laser power and focused beam diameter (spot size);
- The smaller the spot size, the fewer powder particles interact directly with the laser beam:

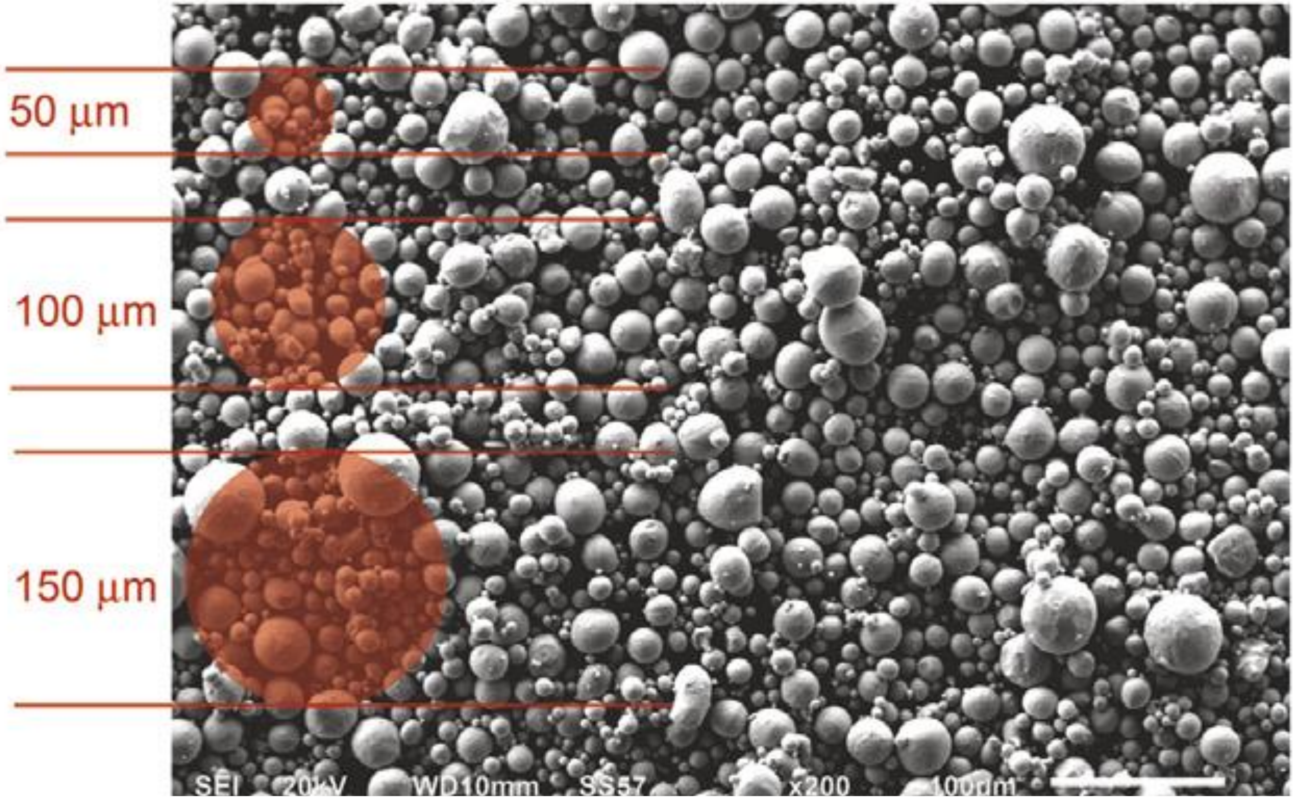


A B

Powder Bed Fusion

Melt-pool dynamics and track formation

- A single track is formed not only from powder placed directly under the laser spot; adjacent particles are involved in the process and a denudation zone forms (Yadroitsev, 2009);
- The powder denudation zone defines the volume of powder involved in the track formation and spattering process.



Powder Bed Fusion

Melt-pool dynamics and track formation

- The dynamics of denudation depend on the geometry of the melt pool, the metal vapor flow that is induced by heating under the laser beam, and ambient gas pressure;
- At a typical pressure of about 1 atm in the L-PBF processing chamber, the dominant factor for the denudation is gas flow caused by pressure drops inside the evaporated jet that entrain powder particles surrounding the melt pool into the process;
- Powder particles from the denudation zone are pulled into the melt pool or ejected away;
- Powder particles, or their agglomerates that were partially melted, can create “satellites” at the edges of the track;
- Satellites can also occur from the spattering effect, when powder particles and melt droplets are ejected during the L-PBF process.

Powder Bed Fusion

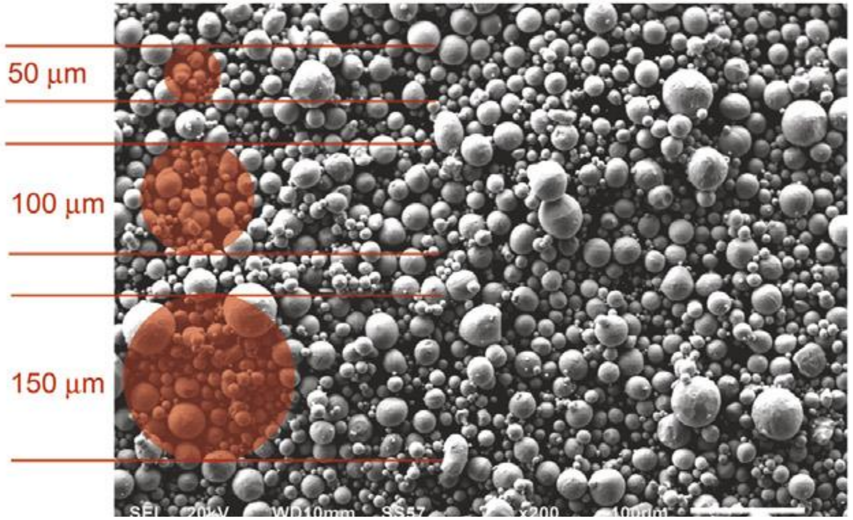
Melt-pool dynamics and track formation

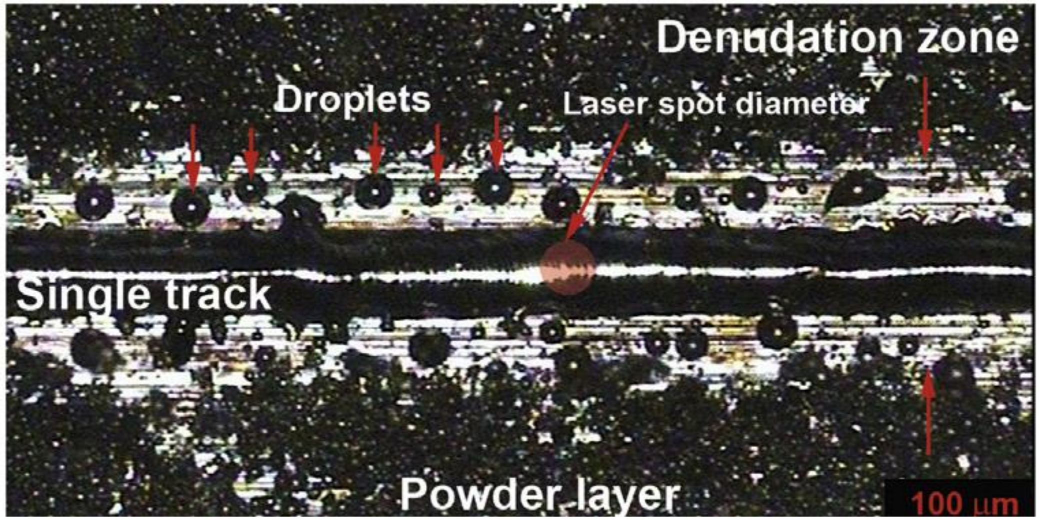
- Spatter particles can be divided into three main classes:
    - particles that travel toward the vapor jet and miss the laser beam, or “cold” spatters;
    - “hot” particles that cross the laser beam;
    - ejections from the melt pool due to melt dynamics and recoil pressure (Ly et al., 2017).
- Energy input affects the size and dynamics of spattering: the general trend is that a higher laser power leads to more intense spatter behavior (Liu et al., 2015).

Powder Bed Fusion

Melt-pool dynamics and track formation

- Hot spatters and melt droplets are visible as bright sparks around the track when the laser beam scans the powder bed;
- The diameters of the melt droplets can be bigger than the original powder particles, thus changing the effective particle size distribution of the feedstock powder.
- When energy from the laser beam is enough to intensively evaporate underlying material, vaporized material solidifies rapidly in the protective gas; this is visible as a “fume” during the laser melting process and creates dark spots on the processed layer;
- These condensates look like a fluffy coating consisting of nano-sized particles.





Powder Bed Fusion

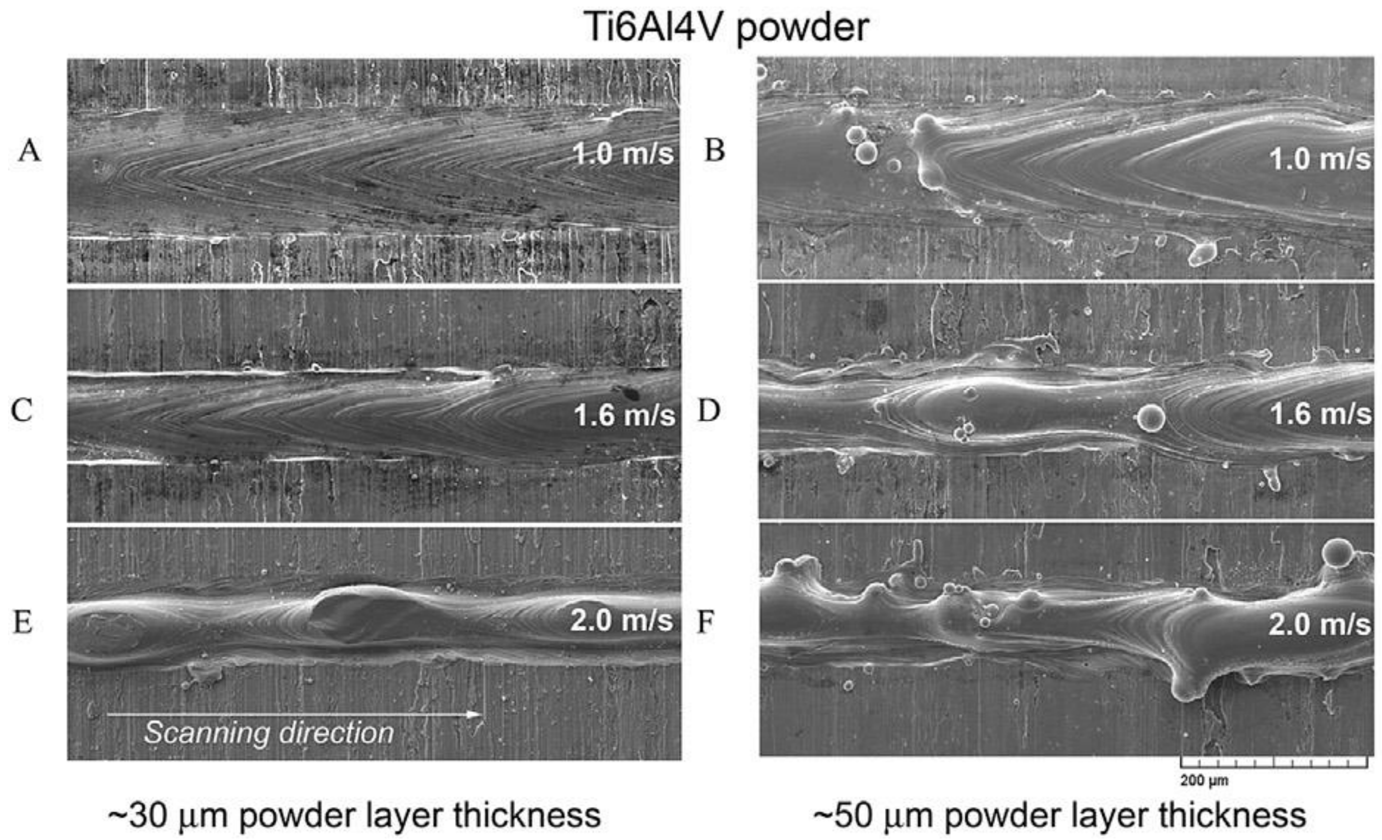
Process stability

- The morphology of single tracks has a complex dependence on process parameters;
- The mechanisms of distortions and irregularities in single tracks are associated with:
    - thermophysical properties of materials,
    - granulomorphometric characteristics of the powder,
    - inhomogeneity in powder layer thickness;
- energy input parameters such as:
    - laser power,
    - spot size,
    - scanning speed;
- build environmental parameters.

Powder Bed Fusion

Process stability

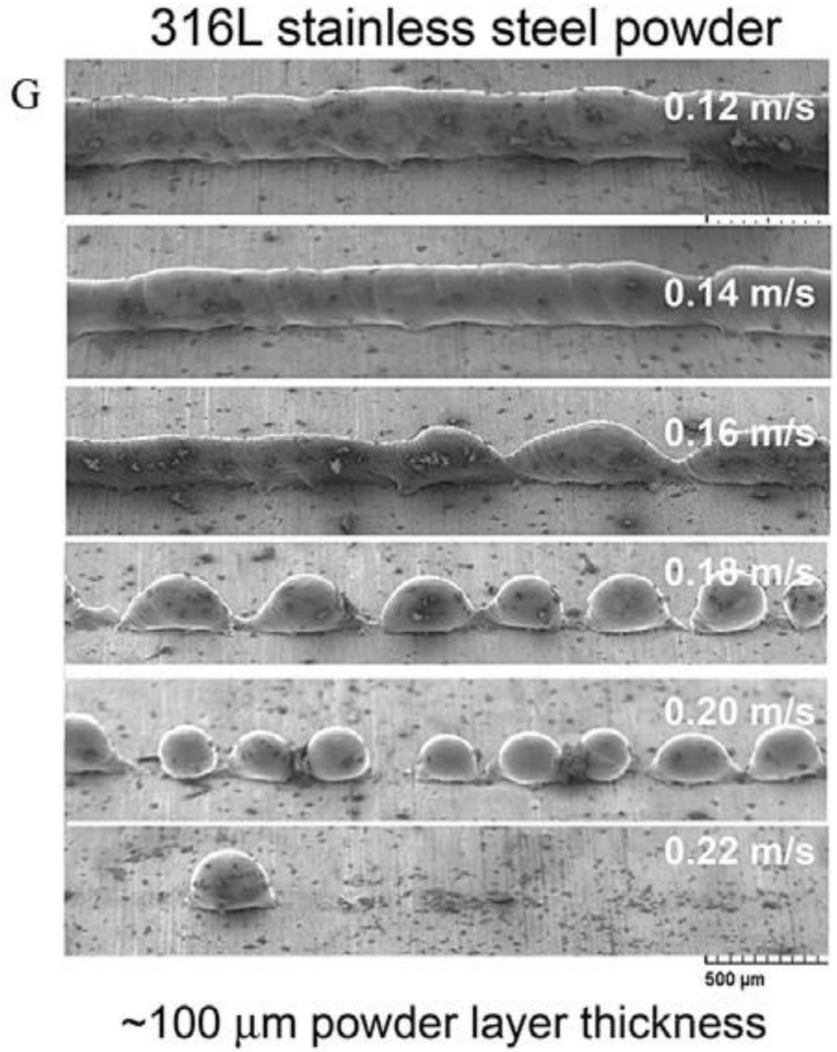
- Analysis of the formation of single tracks from metal powders by L-PBF showed that the process has a threshold character;
- There are continuous tracks with regular sizes and ripples (A and B), continuous tracks having periodic humps and valleys (humping effect, C), tracks with irregular flow front with many satellites (D), and irregular tracks with highly varying widths and heights (E and F) up to a chain of beads, the so-called “balling effect.”



Powder Bed Fusion

Process stability

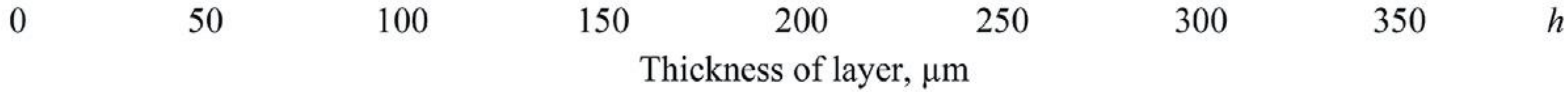
- The evolution of a single track from a regular shape to a chain of beads with increasing scanning speed...

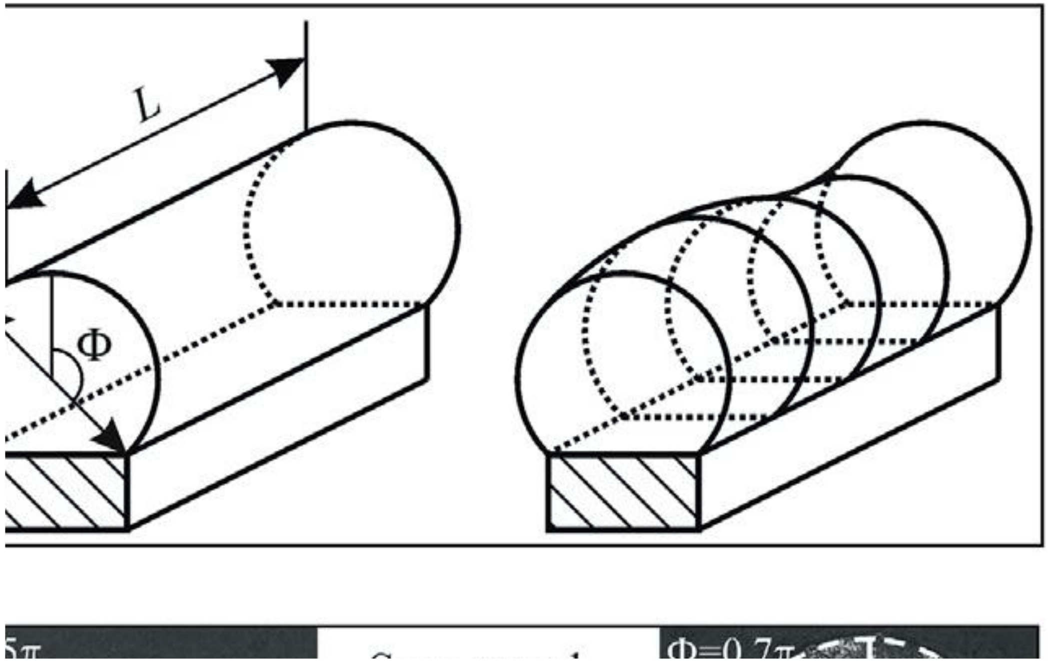


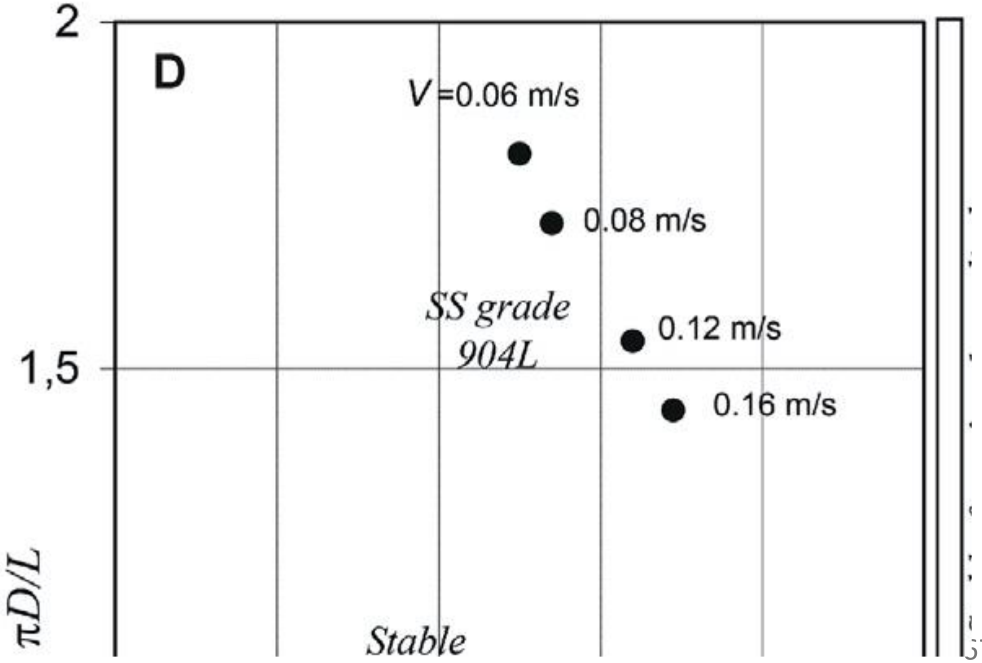
Powder Bed Fusion

Process stability

- The evolution of a single track from a regular shape to a chain of beads with increasing scanning speed as a function of thickness layer at a constant Power level
- Droplets are formed as the result of melt pool disintegration because of a capillary instability. A long cylinder of liquid tends to break up into drops with the same volume but smaller surface. This effect is known as the Plateau-Rayleigh instability.



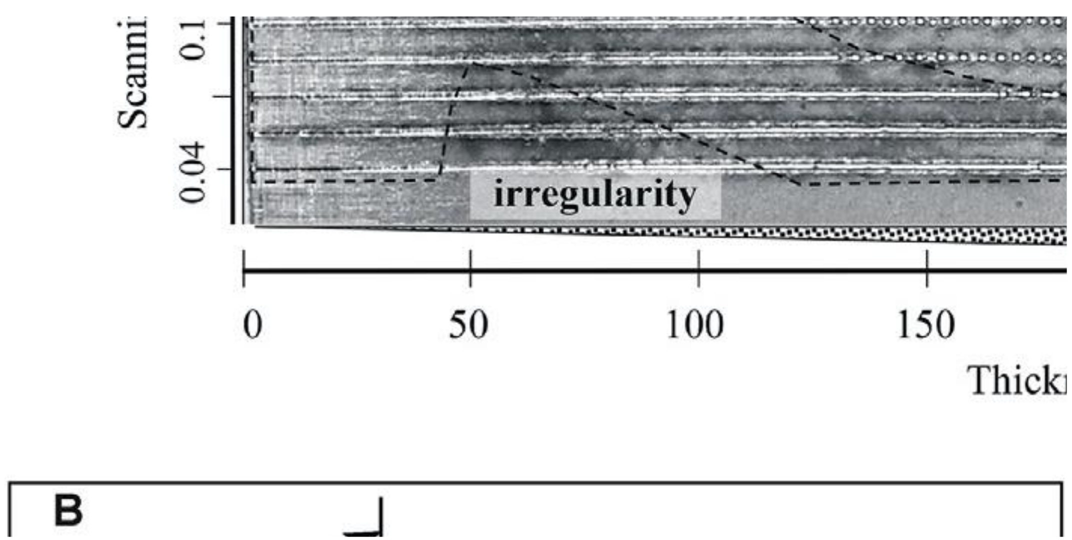


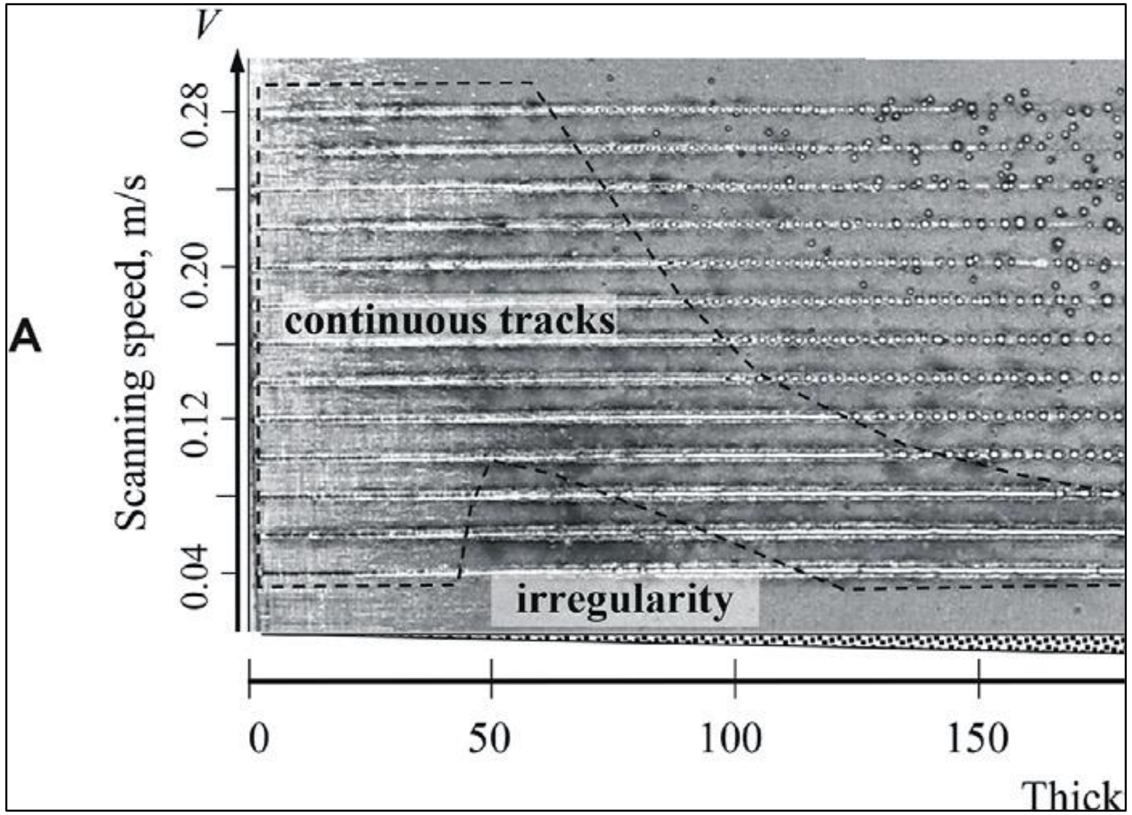


Powder Bed Fusion

Process stability

- One can model the melt pool as a circular cylinder of diameter D and length L. Such a cylinder is stable if its aspect ratio $L/D < \pi$ and unstable otherwise **????**
- The aspect ratio of the melt pool increases with the scan speed
- The Plateau-Rayleigh instability of a circular cylinder explains the loss of stability with increasing the scan speed

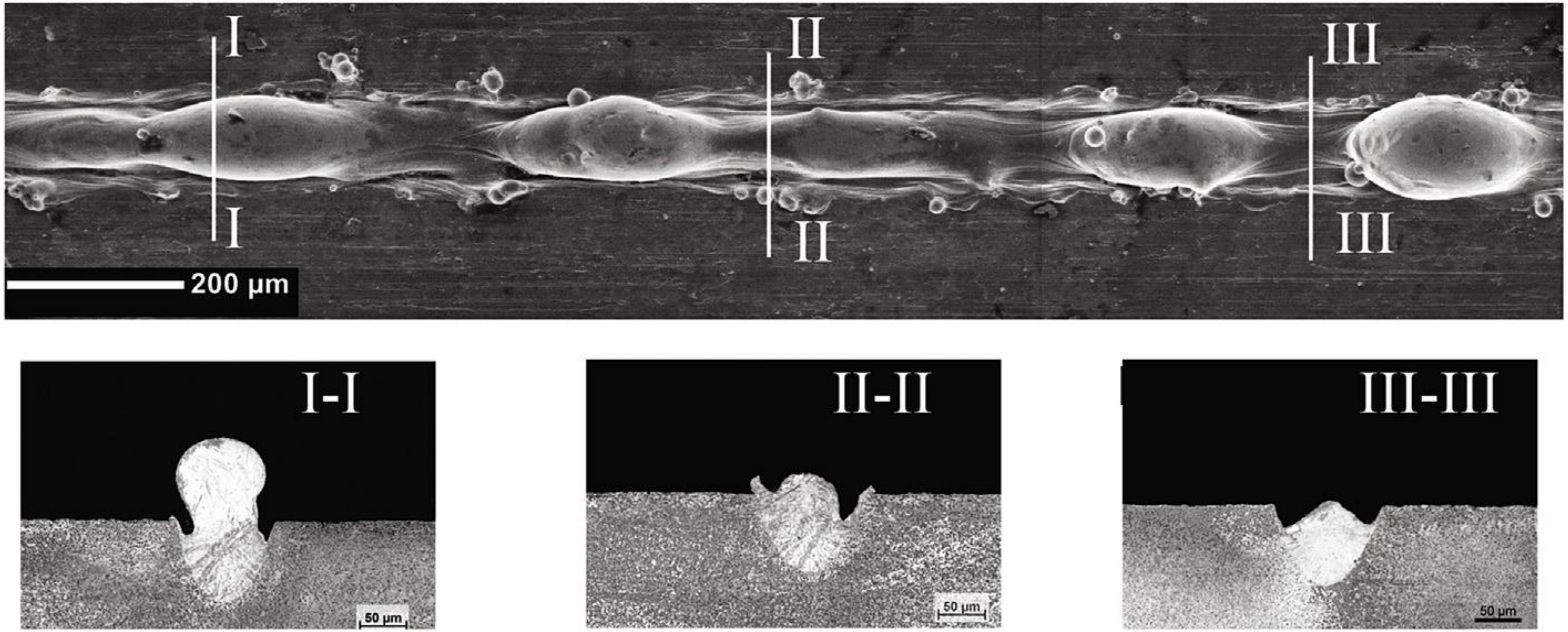




Powder Bed Fusion

Process stability

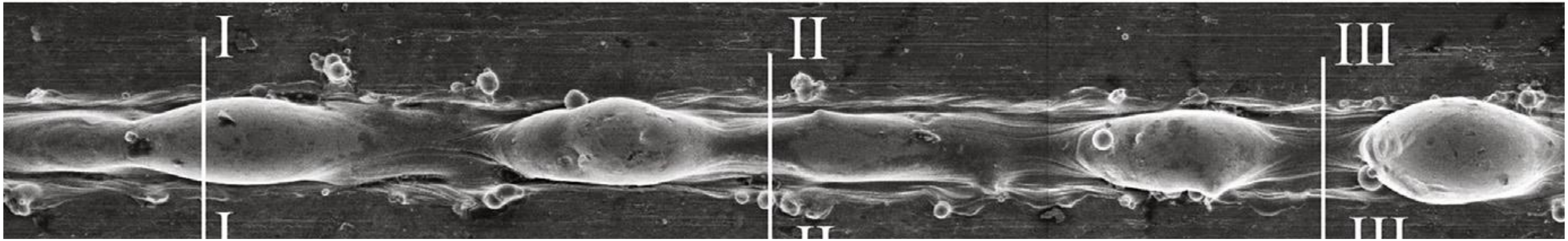
- The morphology of the L-PBF Ti6Al4V track with expressed humping effect is shown in fig;
- It can be seen that the depth of penetration is sufficiently high, and the single track is continuous.



Powder Bed Fusion

Process stability

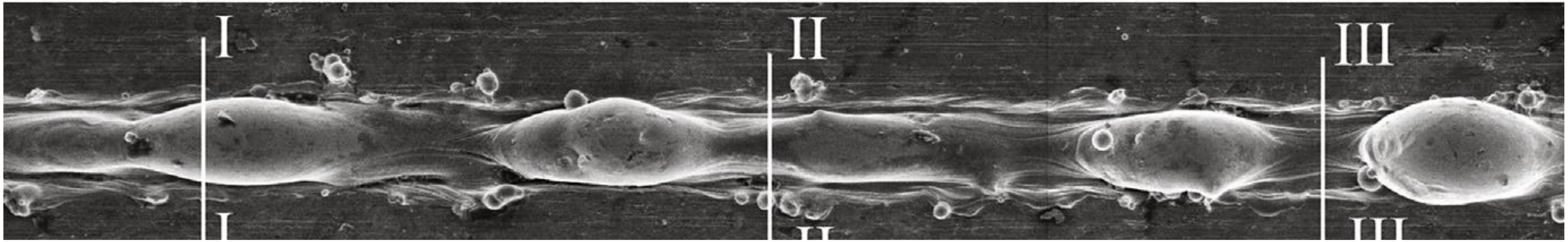
- The Humping effect is a phenomenon which is observed approximately since 50 years in various welding procedures and is characterized by droplets due to a pileup of the melt pool. It occurs within a broad range of process parameters;
- It is necessary to clearly distinguish the balling and humping effects since they have different origins and both influence the final part quality.



Powder Bed Fusion

Process stability

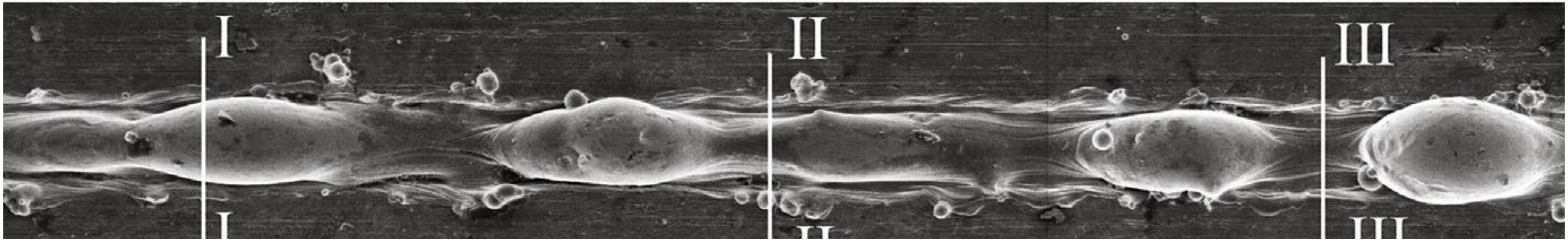
- Similar to welding, the humping effect was found in the L-PBF process and results in continuous tracks which can have periodic waviness of the profile and undercuts.
- It was found that in L-PBF, the humping effect is very pronounced at high laser power and high scanning speed.
- The low surface tension and positive surface tension gradient, recoil pressure, and viscous shear stress contribute to the humping effect.



Powder Bed Fusion

Process stability

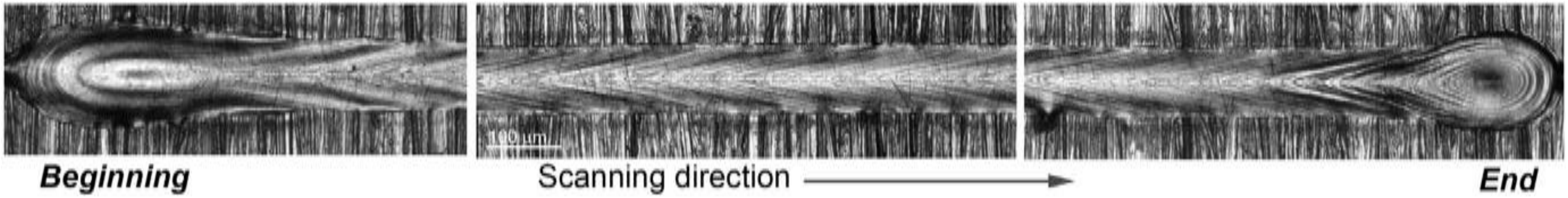
- The deep penetration of the melt pool into the substrate observed during the humping effect can make it possible to build nonporous parts from irregular (humping) tracks by reducing the hatch distance (shift between center of tracks).
- With the balling effect, when the penetration depth is very small, lack of fusion porosity will be very pronounced in 3D objects.
- Humping as well as balling effects are undesirable processes in L-PBF, since they can lead to inhomogeneity of the following powder layer or to collision with the recoater/roller that deposits the powder layer.
- An impact can deform the L-PBF part, recoater, or even the whole system.



Powder Bed Fusion

Process stability: OXYGEN

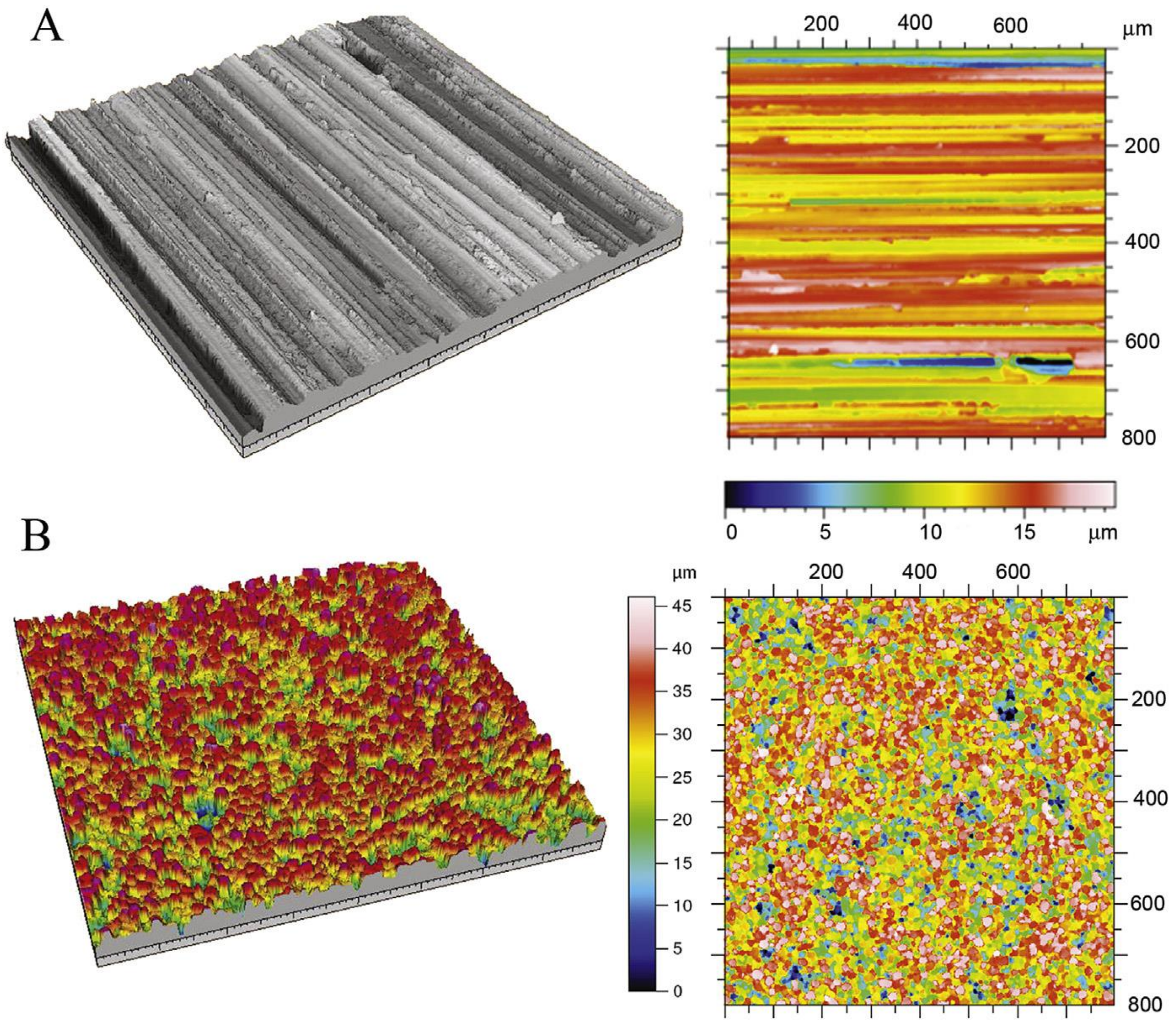
- Different materials show different and sometimes peculiar behavior in the process of single track formation.
- A high content of oxides on the surface of the substrate is undesirable: oxides change the absorption coefficient of laser radiation and increase the melting temperature of the scanned material.
- This affects the wettability of the substrate by molten material, and can lead to the balling effect.
- Oxides also contribute to the formation of cracks.



Powder Bed Fusion

Process stability: ROUGHNESS

- With high roughness it is impossible to deliver a thin homogeneous powder layer.
- Inversely, particles on top of a mirror-polished substrate surface can roll easily and move during deposition leading to an apparently low powder density.
- The roughness of the substrate surface therefore influences the morphology and geometry of single tracks.
- It is recommended to use machined substrates with an average roughness and wavelength of the same order of magnitude as the powder particle size.



Powder Bed Fusion

Process stability: SINGLE TRACK CHARACTERIZATION

- Key features that are used for single tracks' characterization are the shape of the tracks and their geometric dimensions.
- From the top view without cross-sectioning, tracks can be evaluated as having one or more of the following characteristics:

  a) continuous and uniform,

  b) transitional (continuous but with necking or irregularities),

  c) having expressed swelling and depression zones (humping effect),

  d) consisting of a chain of beads (balling effect),

  e) cracks,

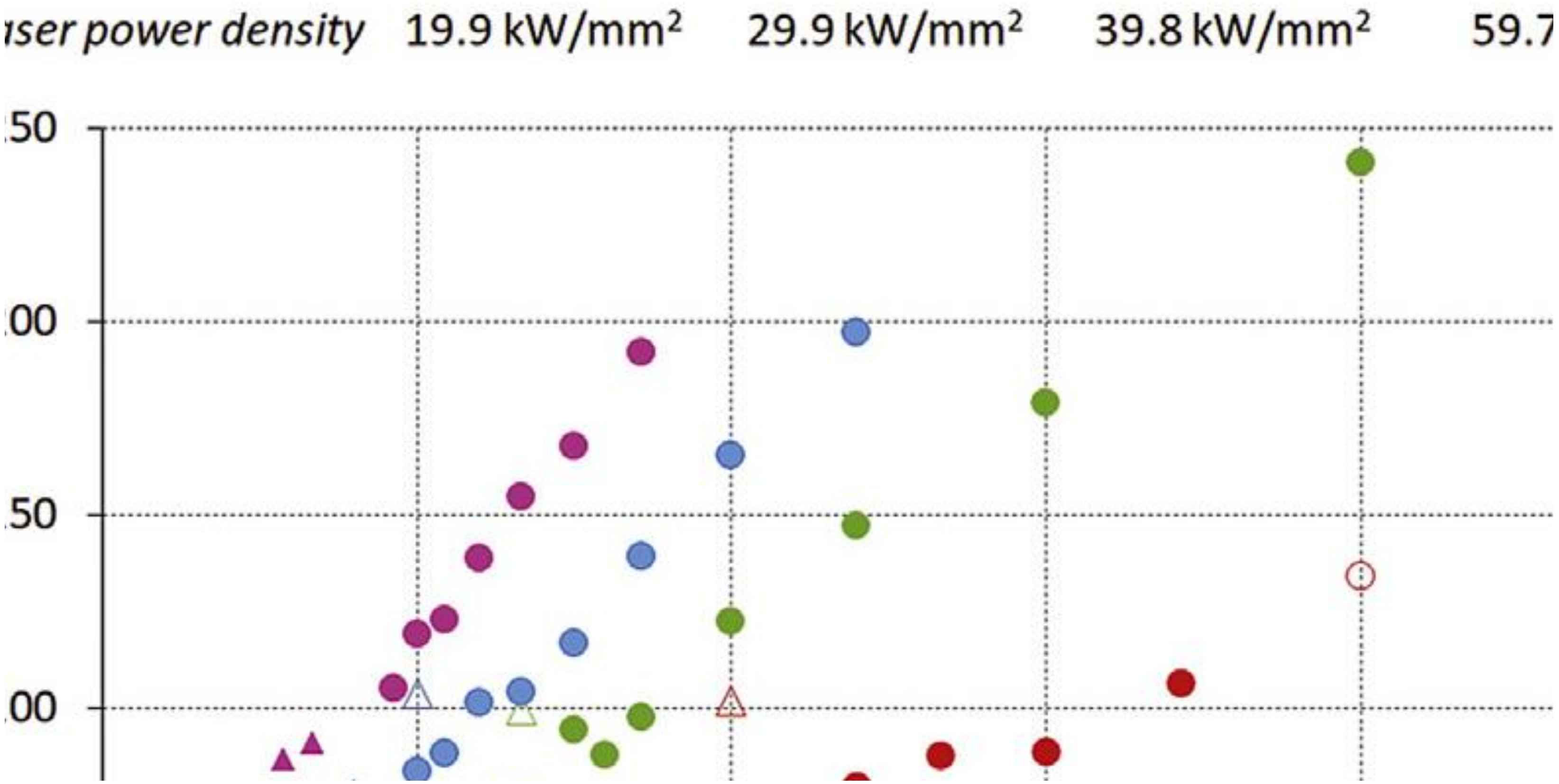
  f) satellites,

  g) droplets near the sintered track.

Powder Bed Fusion

Process stability

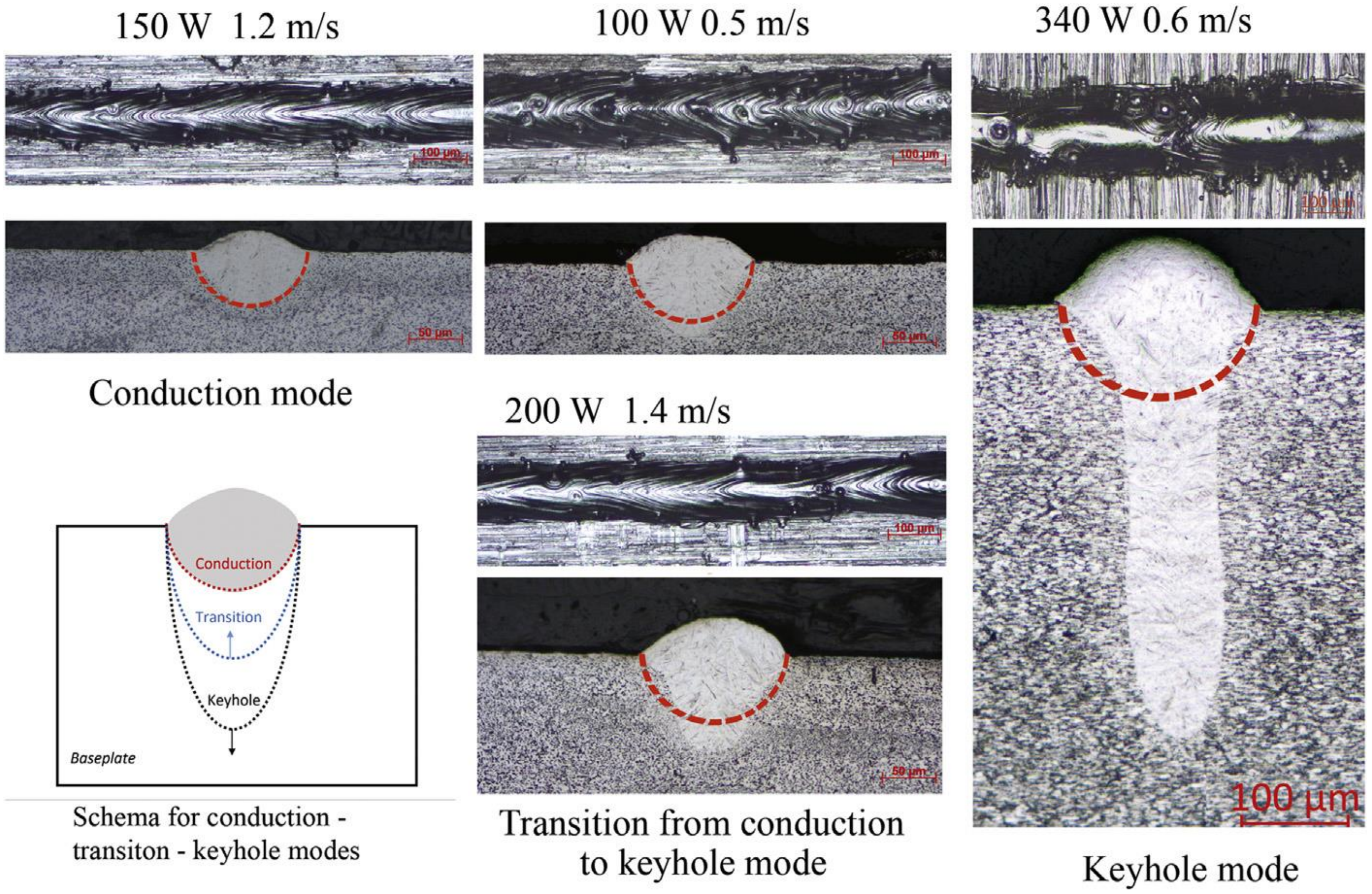
- The main geometrical characteristics of single tracks are:
  - width,
  - remelted depth (or penetration depth),
  - height.



Powder Bed Fusion

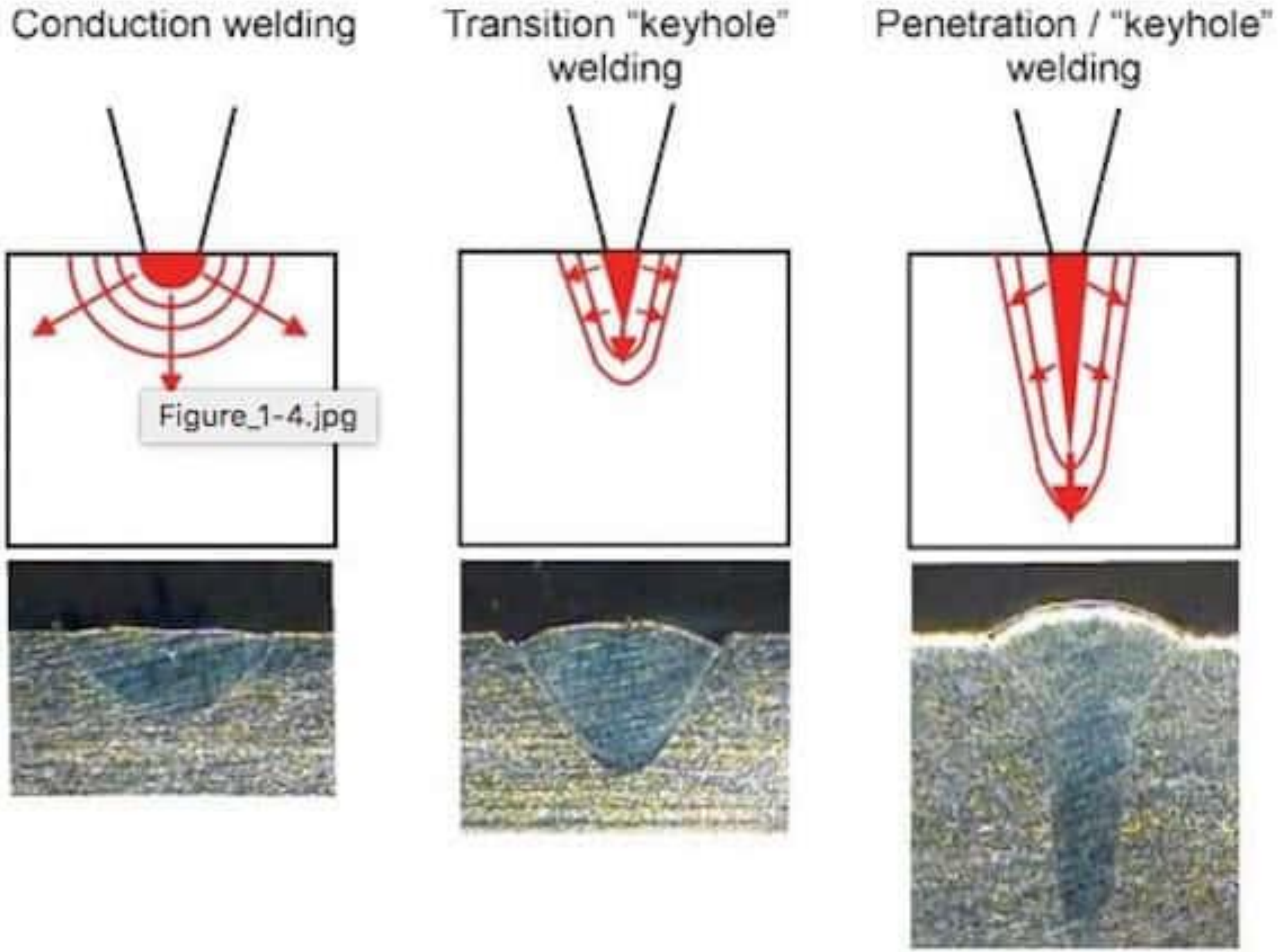
Process stability

- The most influencing factors on the remelted depth of single tracks are laser power density and interaction time.
- With a constant layer thickness, penetration depth increases with laser power density.



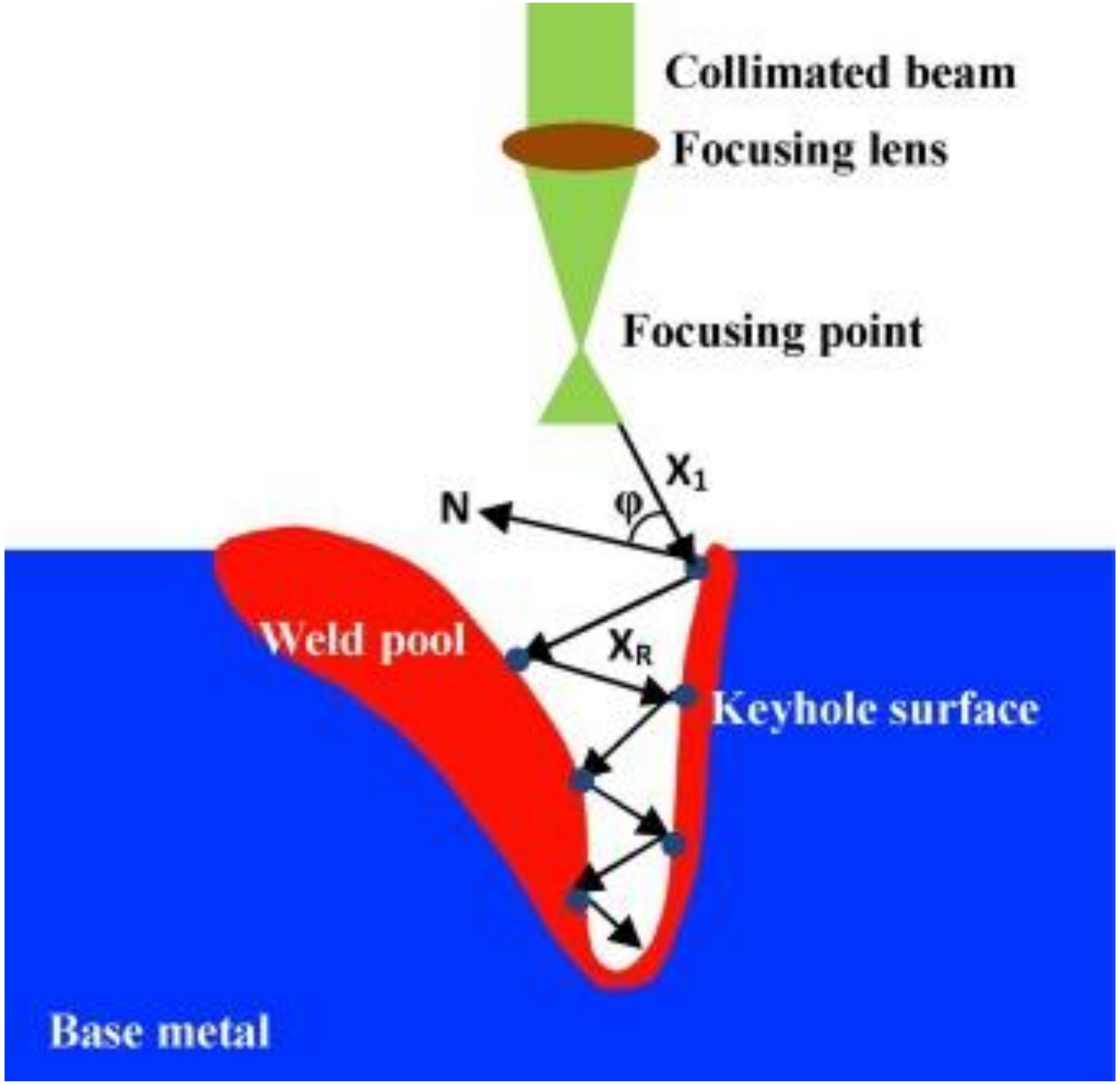
Powder Bed Fusion

Process stability



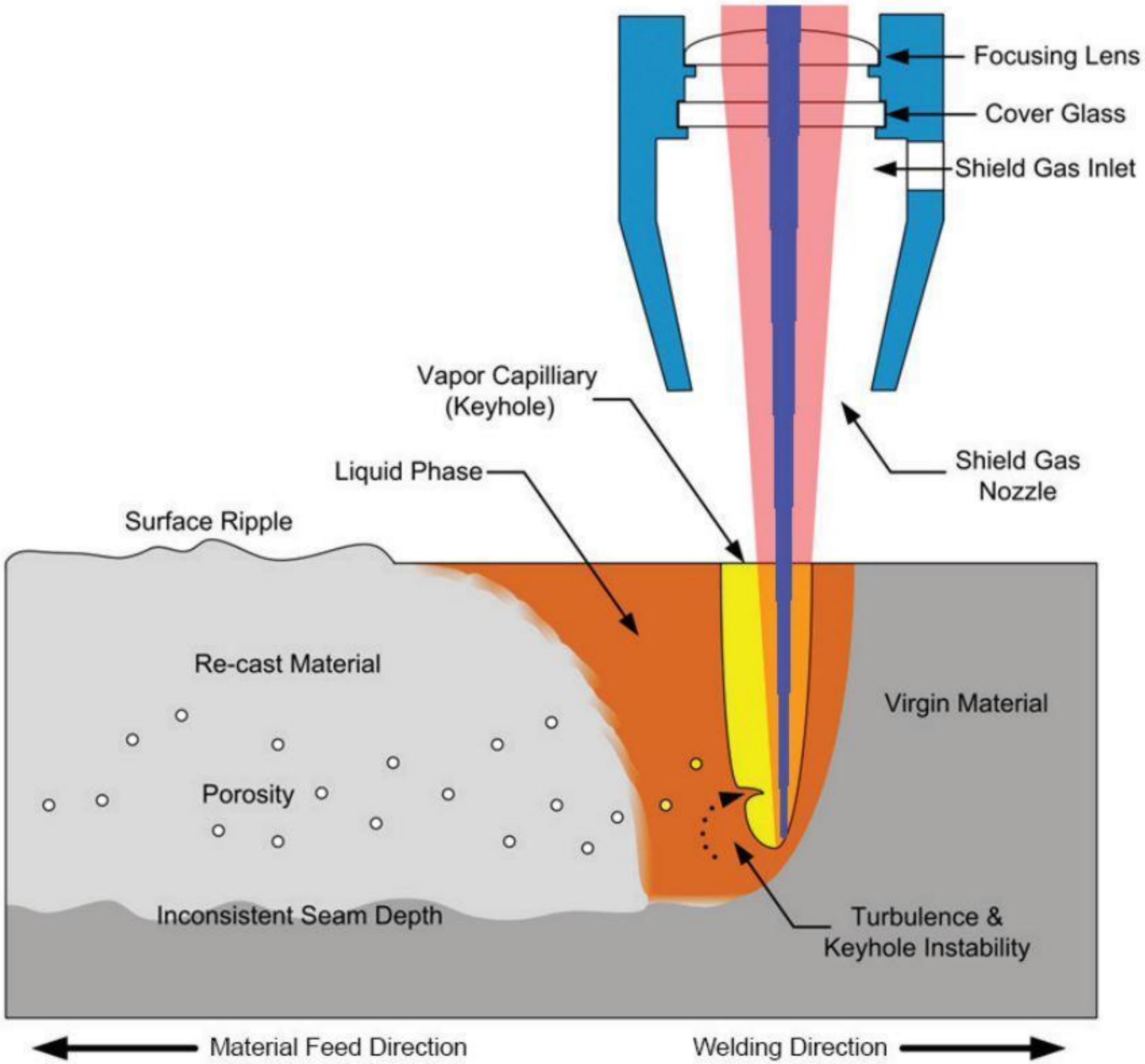
Powder Bed Fusion

Process stability



Powder Bed Fusion

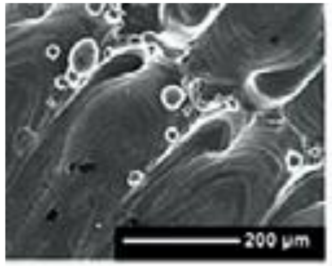
Process stability

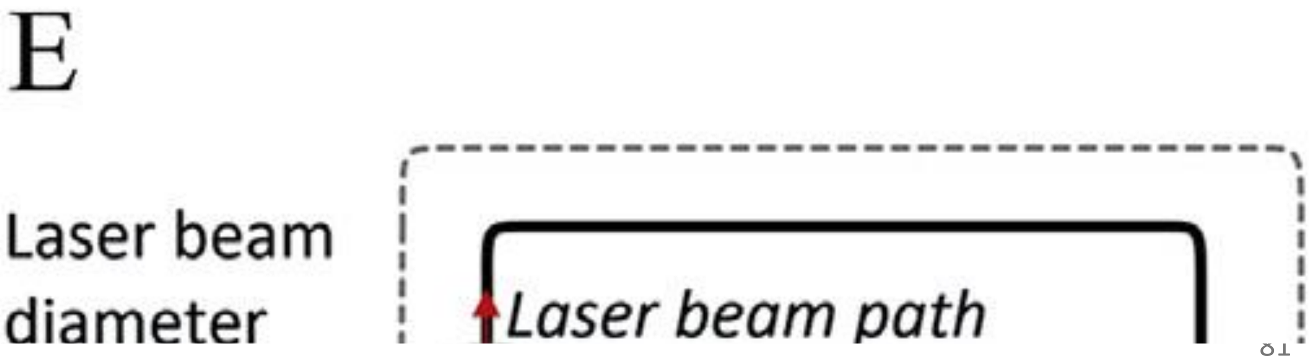


Powder Bed Fusion

Single layer formation

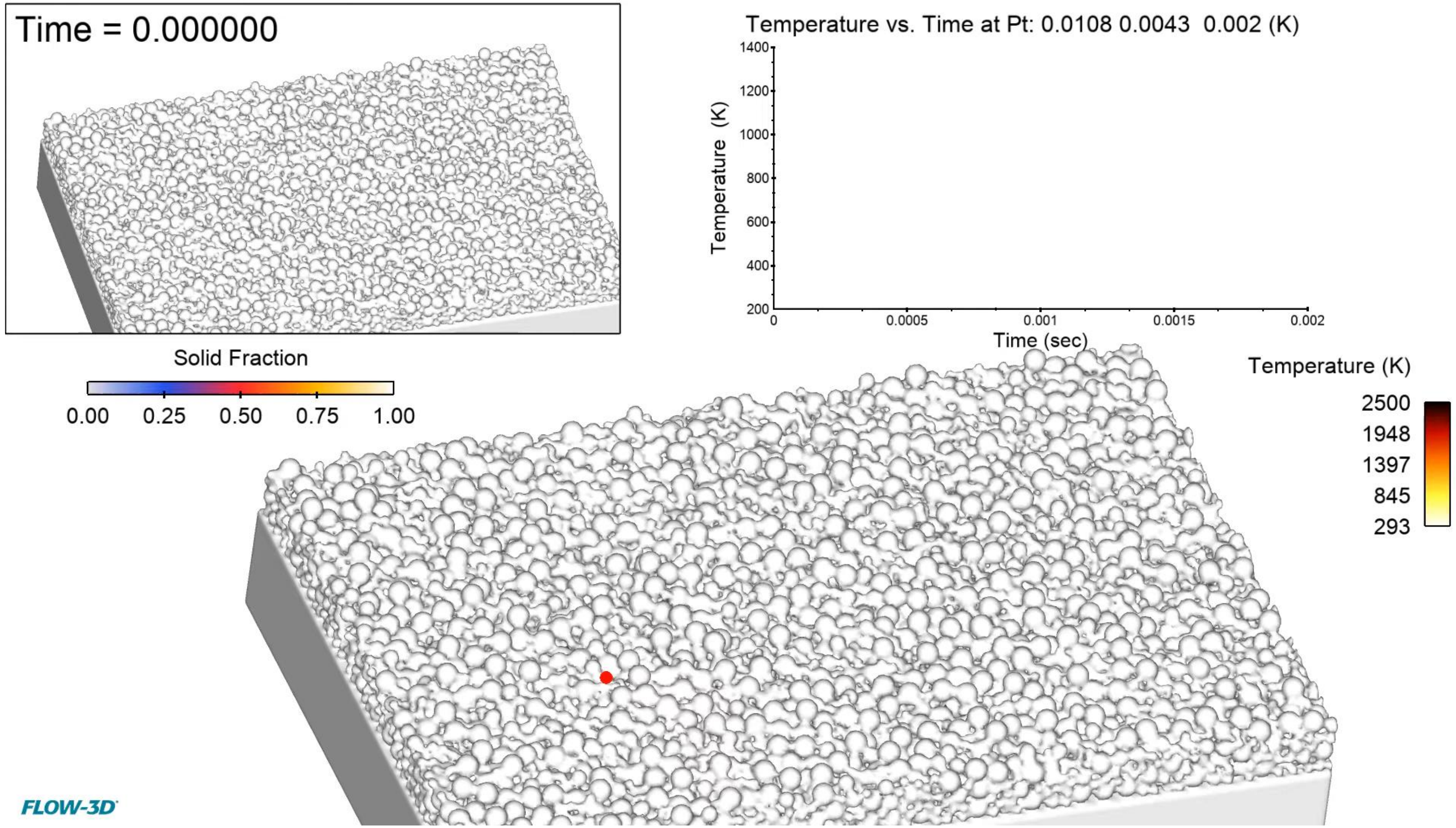
- Each solidified L-PBF layer is a superposition of single tracks.
- Its surface morphology depends on the morphology and the geometrical characteristics of individual single tracks, the scanning strategy, and the hatch distance, which is the shift between tracks in the plane of the laser beam scanning.
- The start-and-stop effect in the hatched area leads to a specific shape of the edge; the attached powder particles and irregularities deteriorate accuracy and surface quality and so contouring is often used.





Powder Bed Fusion

Single layer formation



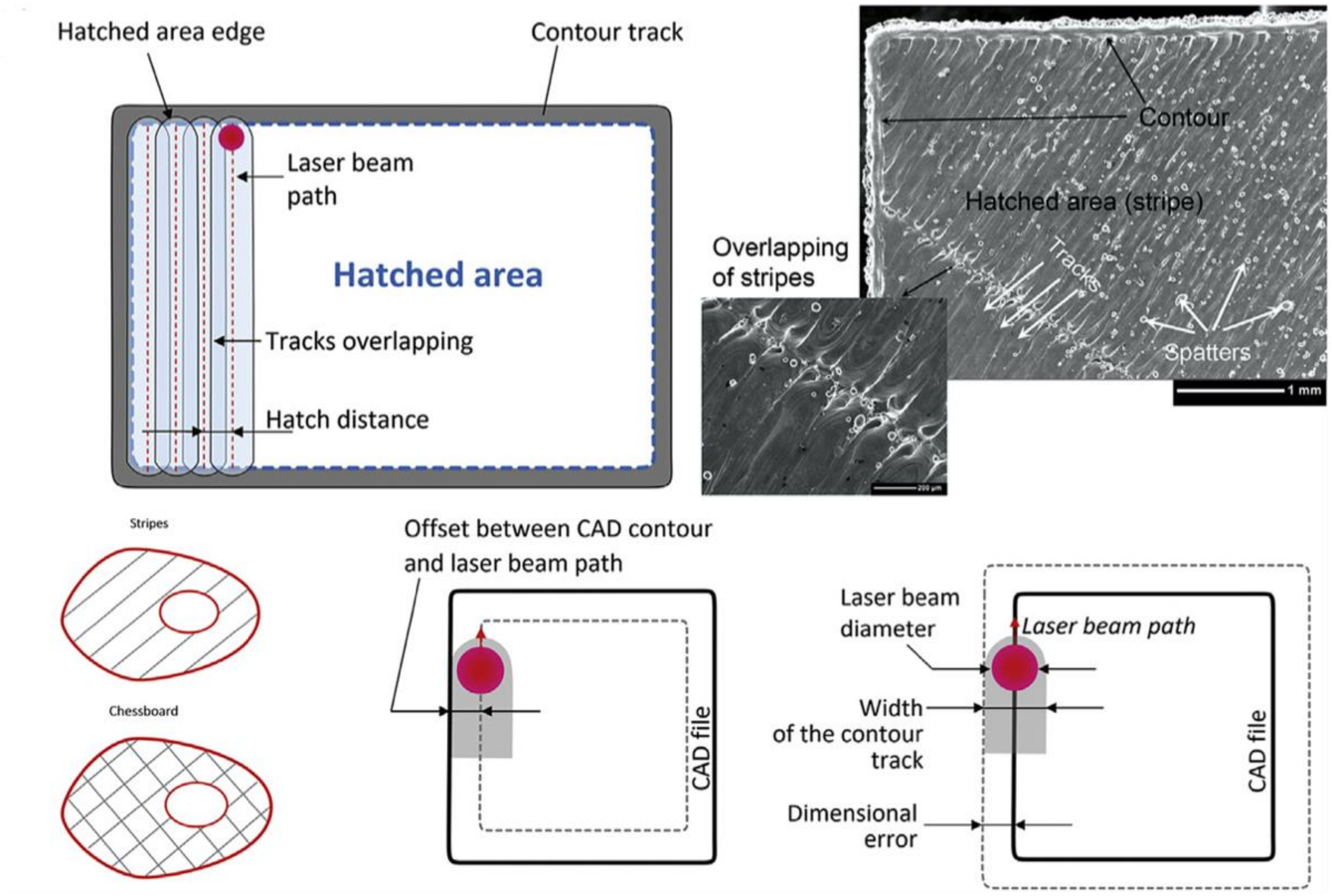
Powder Bed Fusion

Single layer formation

- Different laser power and scanning speeds can be used for hatching and contour areas;
- Scanning strategies represent the manner of scanning of a cross-section;
- In a layer, different hatching patterns can be realized; the more frequently used methods are scanning by stripes, islands (chess-board), or the whole cross-section is scanned without partitioning by elementary hatching patterns;
- In-layer patterns can vary in size and can be done in a different order:
    - Randomly or sequentially,
    - stripe-by-stripe or island-by-island.
- Hatching patterns always overlap to avoid porosity;
- Laser beam scanning inside each pattern can be done in one direction, zigzag (back-and-forth), spiral, or other programmed laser beam movements.

Powder Bed Fusion

Single layer formation



Powder Bed Fusion

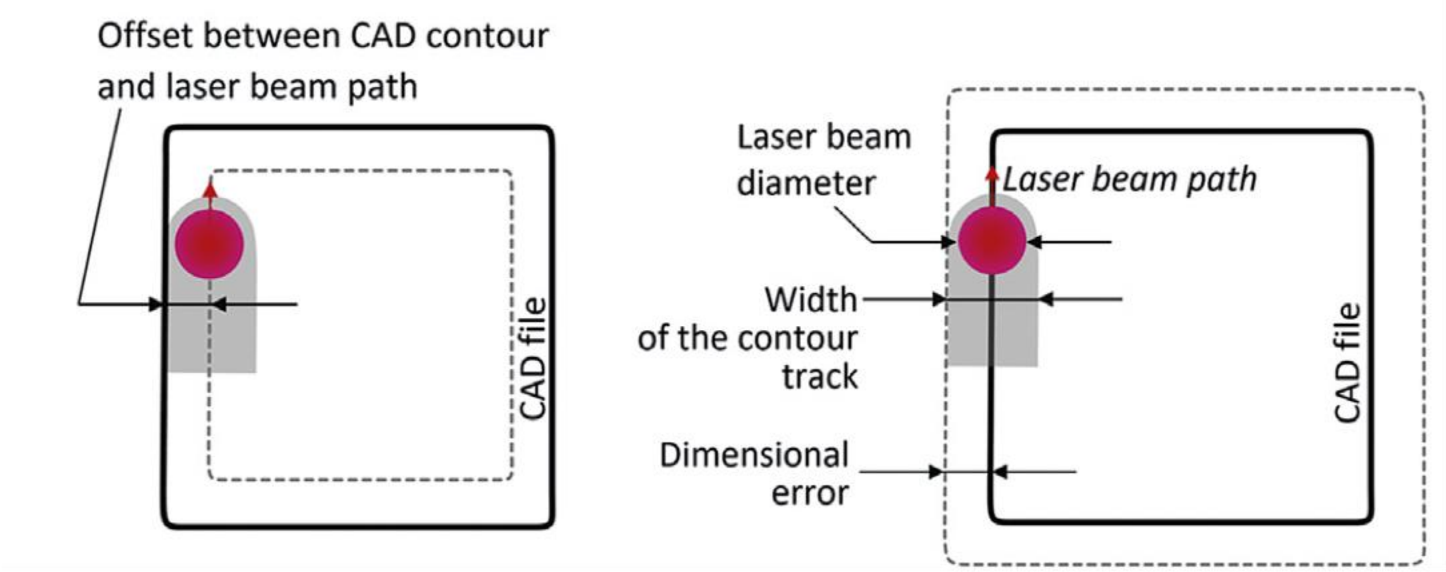
Single layer formation

- The beginning-end effect of single tracks and the changing direction of the laser beam or path (when the laser beam accelerates/decelerates and turns around) has an influence on the melt-pool size and morphology of single tracks.
- In single layers and 3D parts this leads to edge and corner effects where rough and irregular surfaces may occur.
- To decrease edge ridges and corner effects it is recommended optimizing laser power and scanning speed, as well as to scan top layers several times with lower linear energy input.
- In a mirror-based laser scanning system for L-PBF, mirrors accelerate and decelerate in turning points which can be one possible reason for overheating and keyhole porosity.
- A skywriting option, incorporated in L-PBF EOS systems, shuts off the laser beam when the scanner is positioning the beam for scanning so that powder material does not melt during positioning.

Powder Bed Fusion

Single layer formation

- Pre-contouring (scanning the contour of the part before hatching) or post-contouring (after hatching) can be used to improve in-plane (XY) accuracy and surface roughness
- Different scanning parameters can be used for contouring.
- Since the melt pool is bigger than the laser spot size, the laser beam has to be offset from the edges of the scanned cross-section to compensate for this difference and to provide accurate dimensions of the part to be manufactured.



Powder Bed Fusion

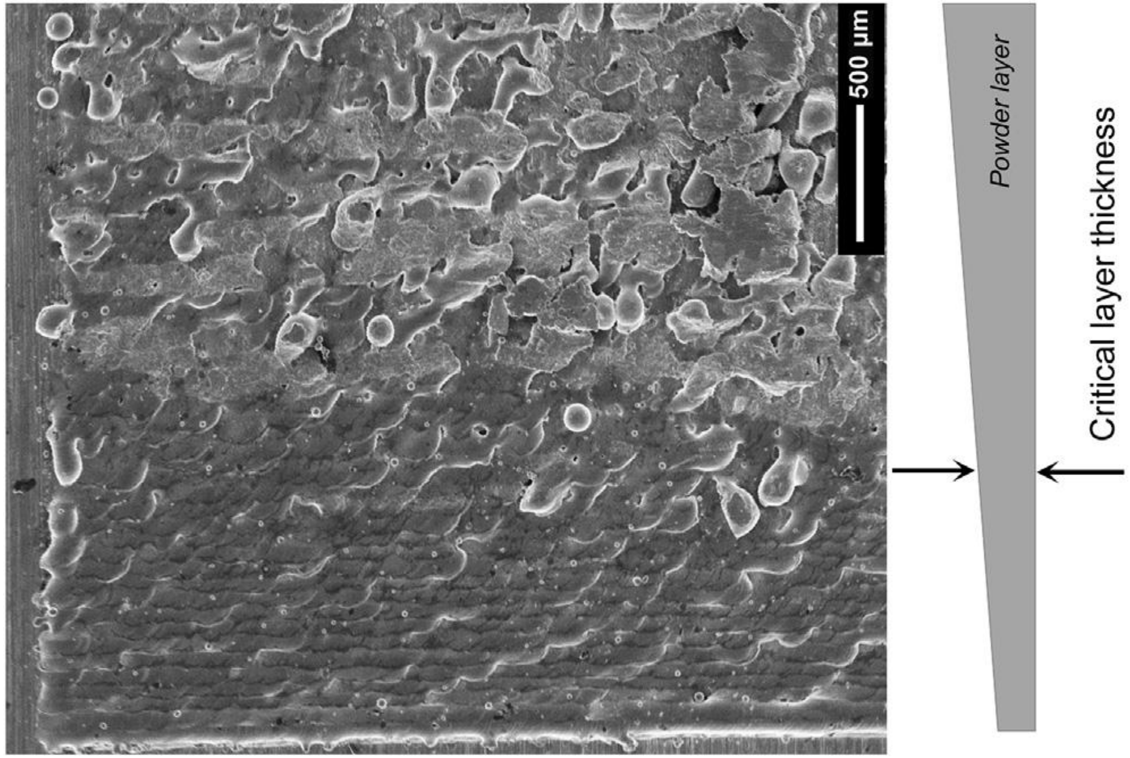
Single layer formation

- A special “power profile strategy” that adjusts the laser power depending on the position of the laser scanning was proposed by Martin et al. (2019) to mitigate keyhole defects near the edges.

Powder Bed Fusion

Characterization of a single layer

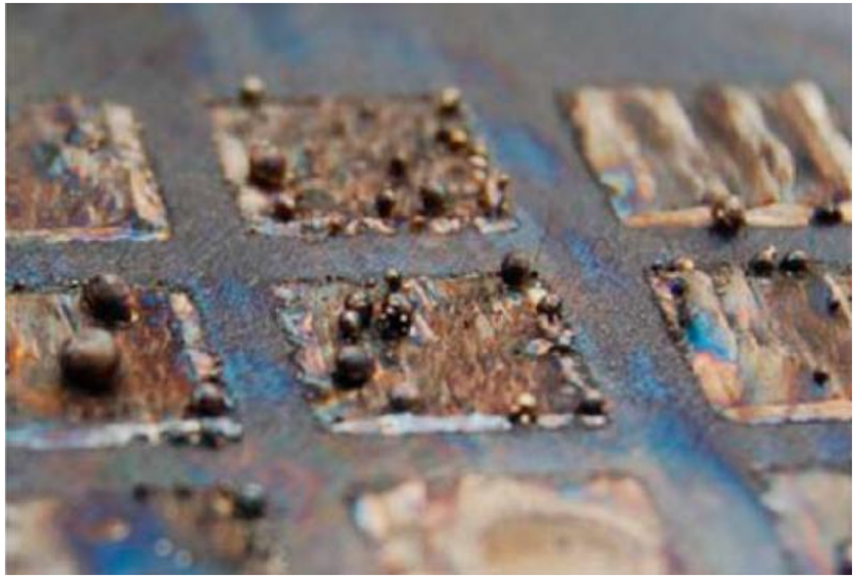
- Nonuniform thickness of the deposited powder layer can also influence the morphology of single tracks and single layers.
- It could be critical for the density of the 3D object: if there is insufficient energy to remelt the thickest powder layer, the balling effect starts, which provokes porosity formation.

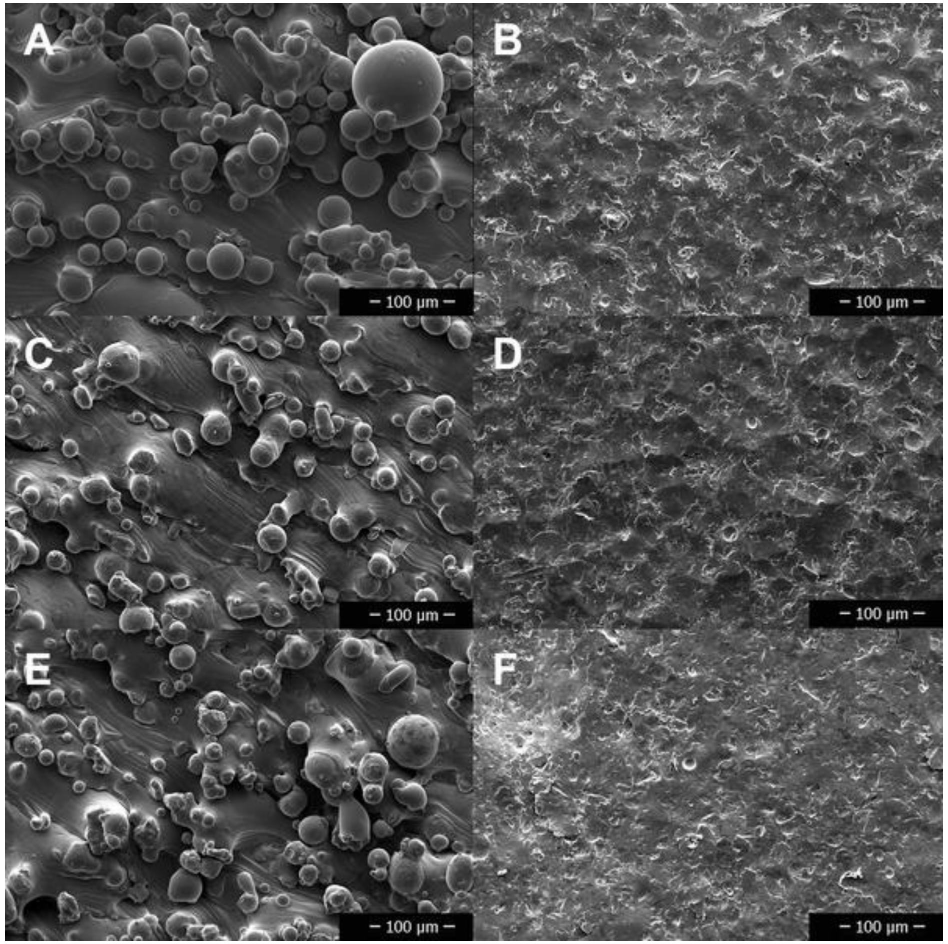


Powder Bed Fusion

Characterization of a single layer

- The surface morphology after laser melting includes peaks and valleys, attached powder particles and droplets, i.e., spatters.

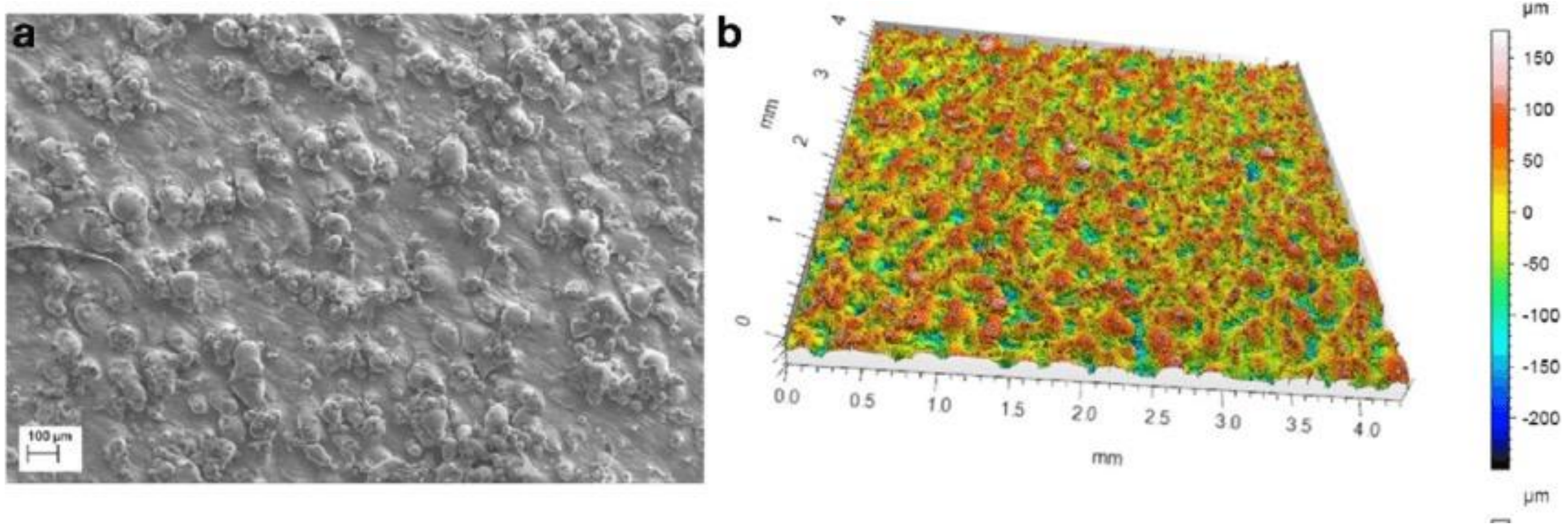




Powder Bed Fusion

Characterization of a single layer

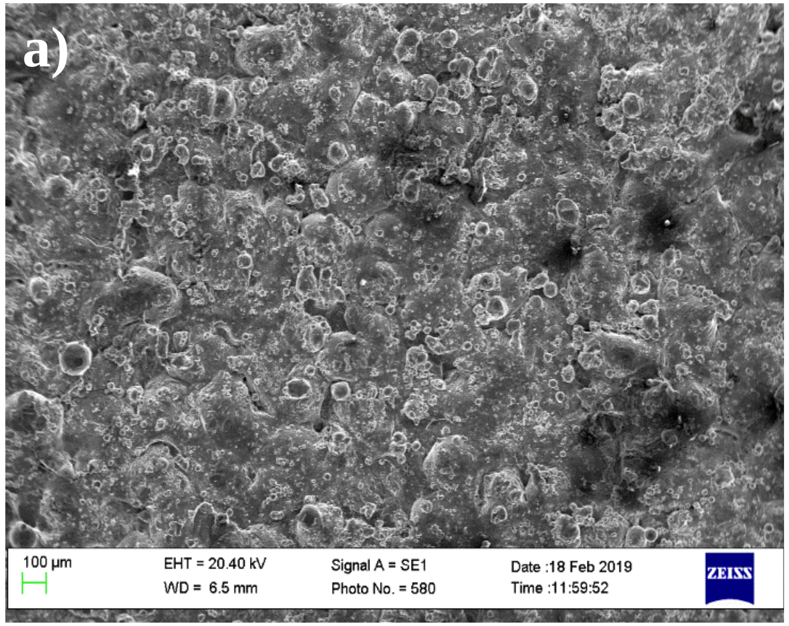
- For the characterization of L-PBF parts, the surface roughness, waviness, deviation from prescribed dimensions, presence of spatters and surface pores have to be analyzed.

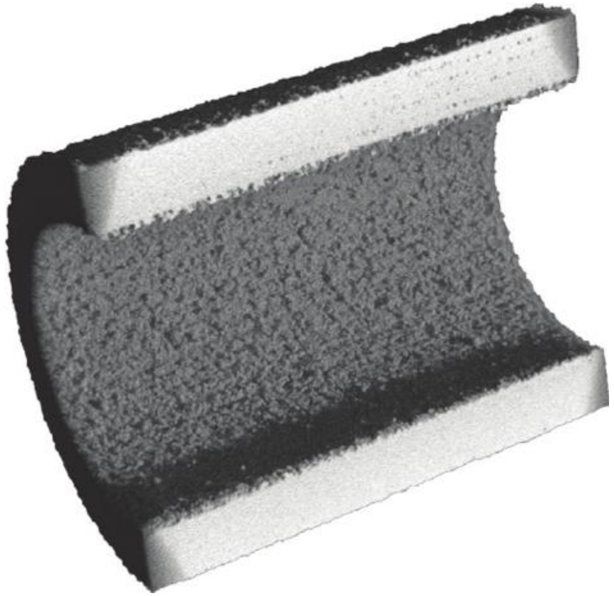


Powder Bed Fusion

Characterization of a single layer

- If a single layer was built with nonregular tracks or with nonoptimal hatch distance, the surface has irregular morphology.
- For characterization of a single layer, SEM images, optical 3D measurement techniques, and CT scans are often used.
- The balling effect, cracks, and overlapping can be identified on the top view; CT scans and cross-sections help to find internal porosity and other defects.





Powder Bed Fusion

Thin wall formation

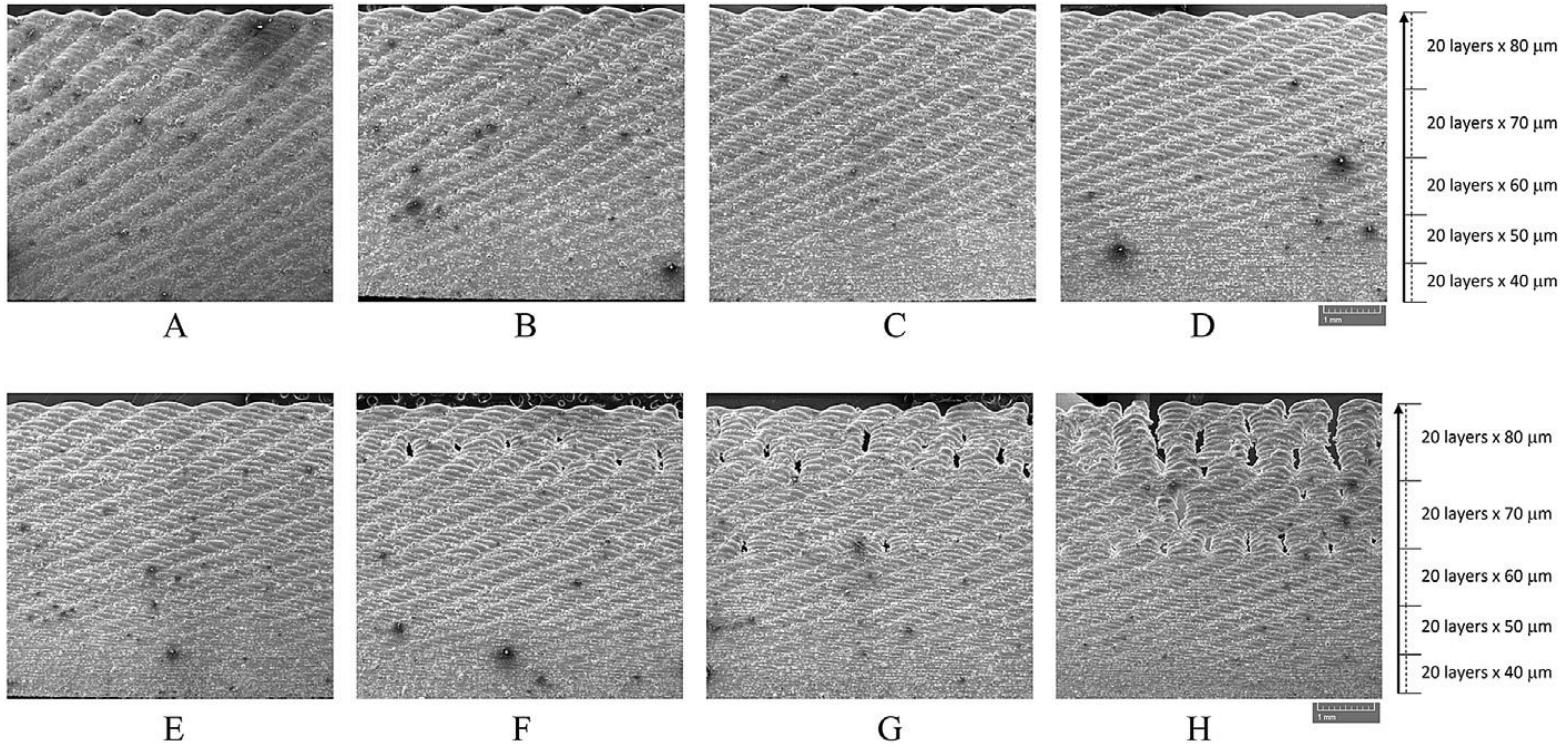
- A thin wall can be defined as an object consisting of single tracks superimposed on each other in the vertical direction (Z-axis).
- A thin wall can be considered as a single layer manufactured in the vertical direction.
- Thin walls may also act as indicators of the manufacturing quality for fine features, for a given set of process parameters.

Powder Bed Fusion

Thin wall formation

- the surface of single-pass thin walls fabricated at a laser power of 50 W and a spot size of 70 μm, with a gradual increase in the layer thickness from 40 to 80 mm with a step of 10 mm for each of 20 layers

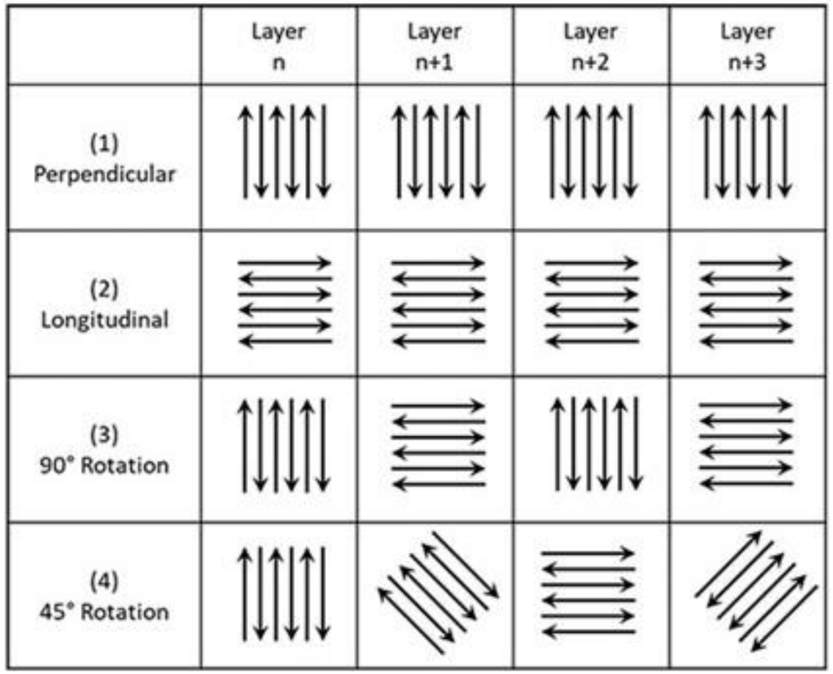
A. 0.04 m/s
B. 0.06 m/s
C. 0.08 m/s
D. 0.1 m/s
E. 0.12 m/s
F. 0.14 m/s
G. 0.16 m/s
H. 0.18 m/s

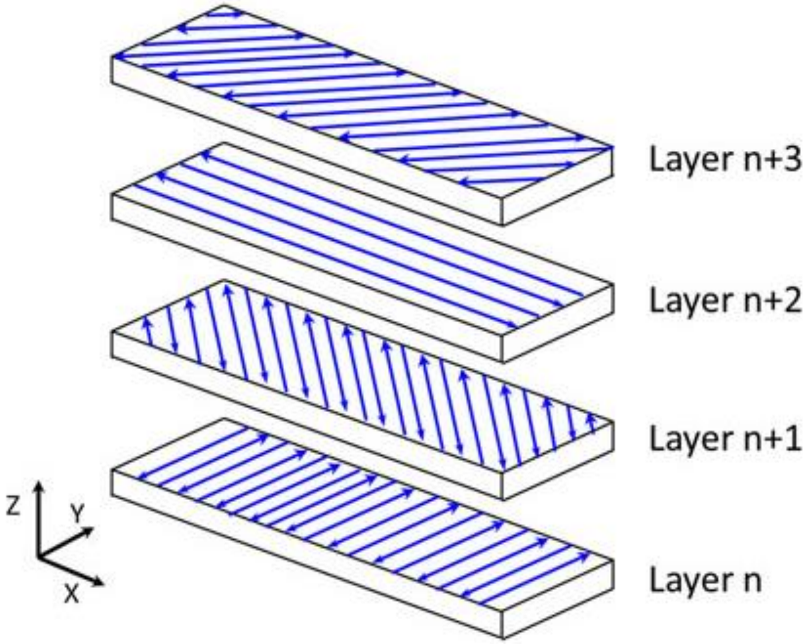


Powder Bed Fusion

Thin wall formation

- Powder particles attached to the surface of thin walls are highly influential on surface roughness and dimensions of the walls.
- Scan length has an influence on the accuracy of thin-wall production. If the thin wall consists of more than one pass, its orientation relative to the scan tracks has an influence on the topology of the thin walls.





Powder Bed Fusion

Thin wall formation

- When a complex specimen consists of thin walls, the surface topology is quite different: there are smooth areas and extremely rough regions: the protective gas flow and turbulence can be responsible for these phenomena.
- When a part has a rough surface, the recoating blade can start to make contact with the specimen that increases the risk of distortion of the specimen, delamination is possible, and this can lead to damage of the powder deposition system.
- There are limitations in accuracy and surface roughness when fine components are produced such as thin walls.
- This has been demonstrated in numerous studies on lattice structures, where fine micro-walls and struts are decisive factors in perfecting L-PBF structures

Powder Bed Fusion

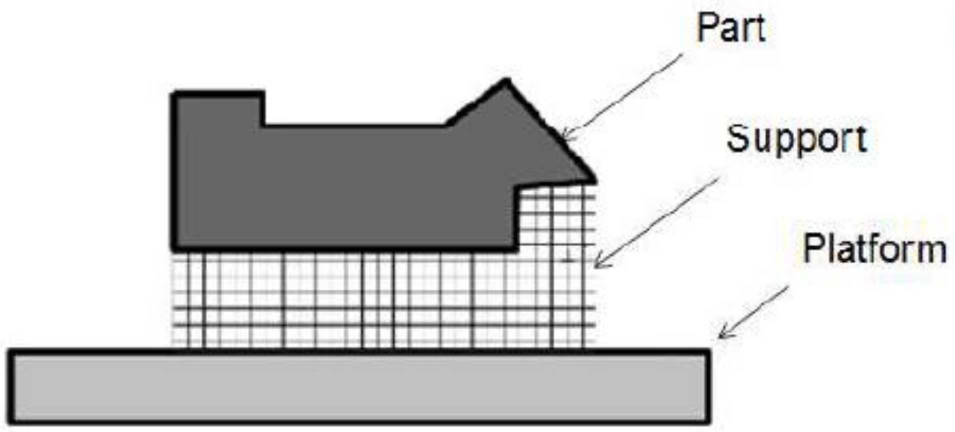
L-PBF object formation

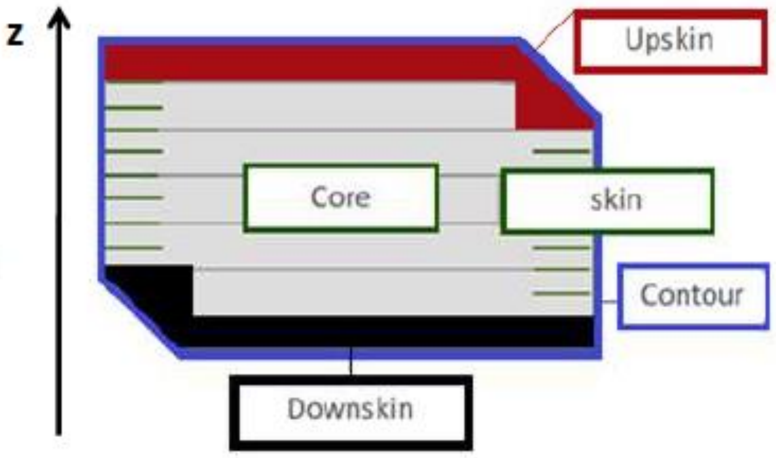
- L-PBF provides freedom of design and allows the manufacturing of complex structures such as lattice structures, topology optimized parts, graded structures, and parts with integrated functions.
- However, there are some limitations and specific features typical of the powder bed fusion process, for example, the dimensional accuracy and surface finishing of the parts.
- Fine structures and minimum feature sizes are limited by powder material and process parameters, such as spot size, laser power, scanning speed, layer thickness, scanning strategy, etc.

Powder Bed Fusion

L-PBF object formation

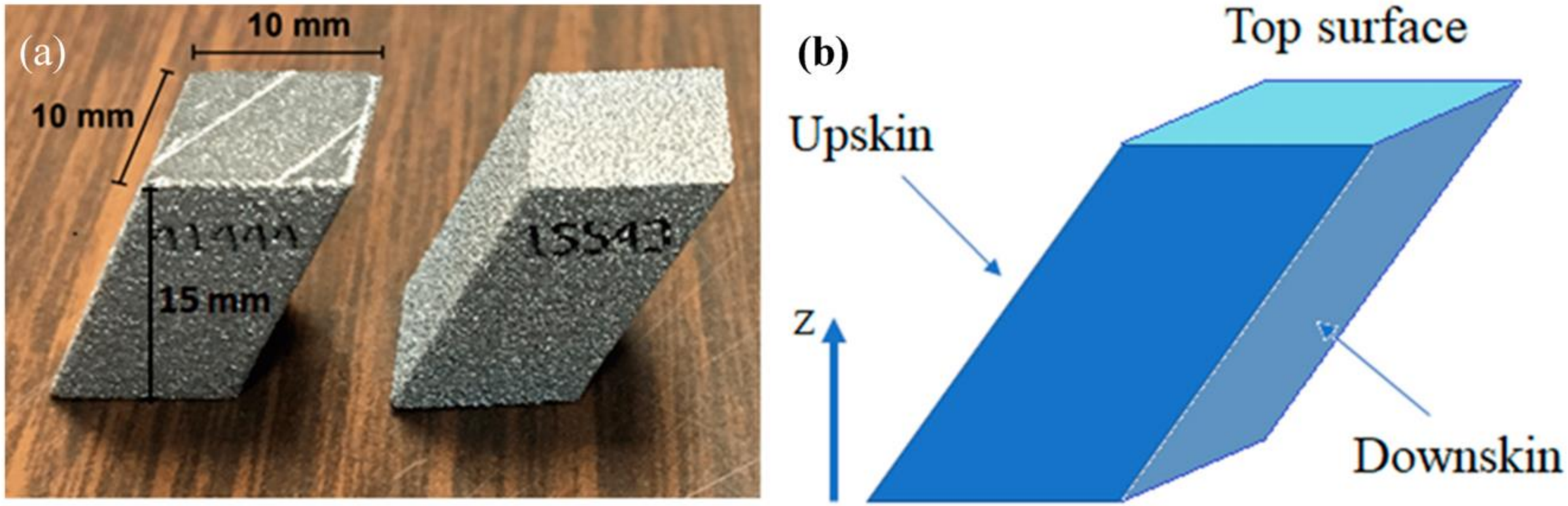
- A 3D component can be divided into three parts: the core part, upskin, and downskin regions.
- Areas that have no upper layers are called upskin; conversely, downskin has no underlying solidified layer.
- The inner region of the component is called the core part.
- For all these areas, the scanning strategy needs to be optimized.





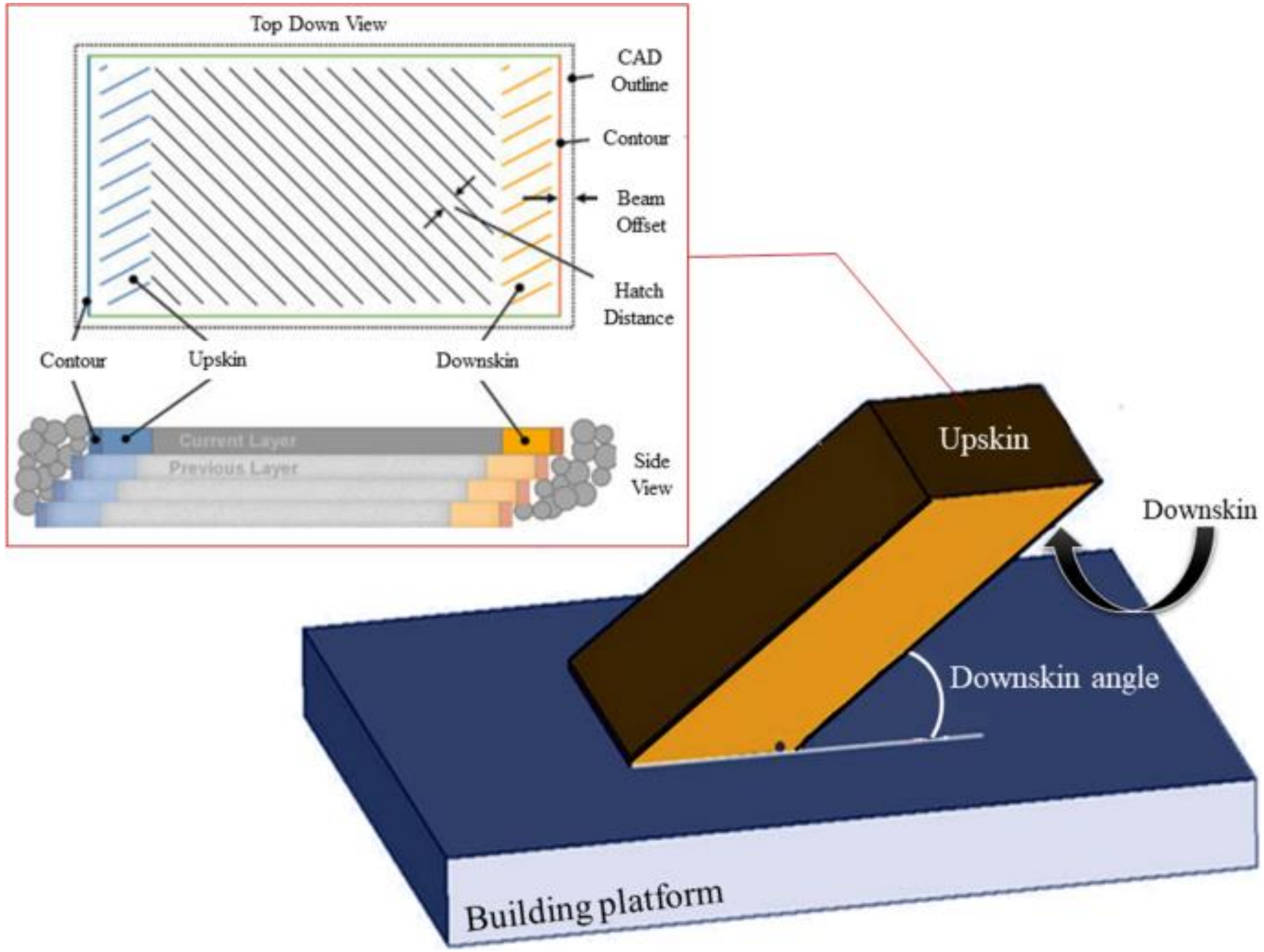
Powder Bed Fusion

L-PBF object formation



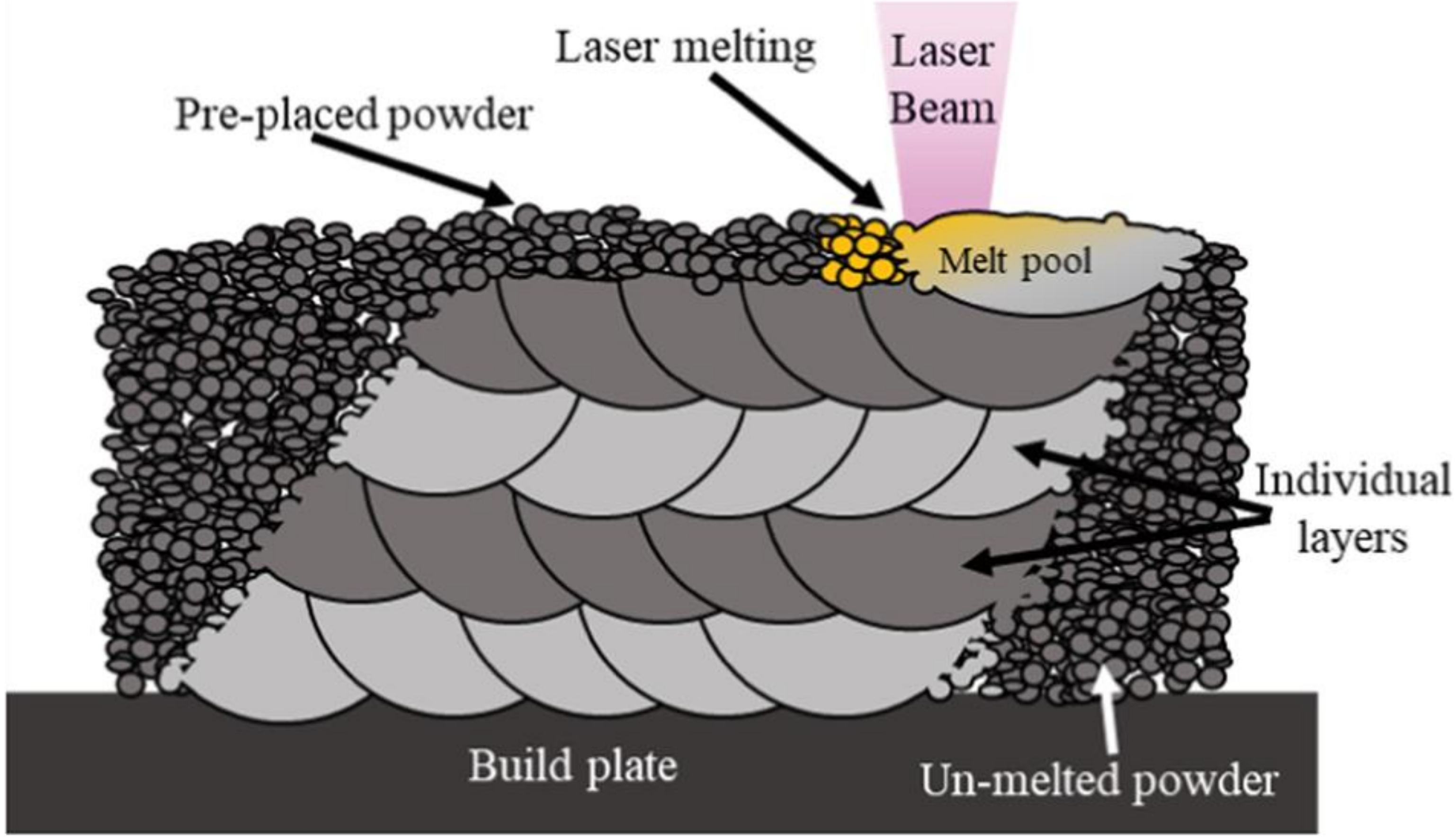
Powder Bed Fusion

L-PBF object formation



Powder Bed Fusion

L-PBF object formation



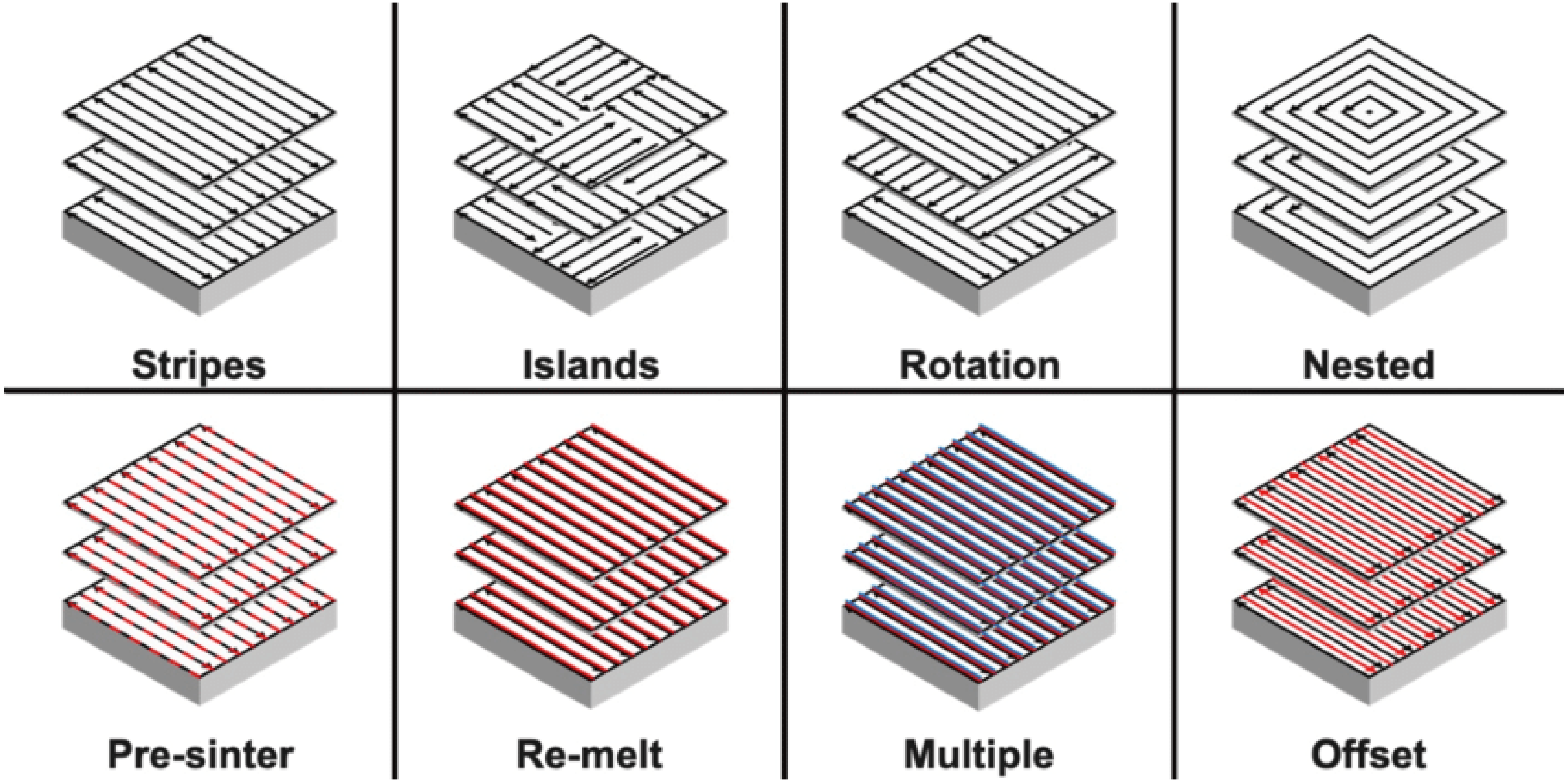
Powder Bed Fusion

L-PBF object formation

- There are many possible ways of scanning:
  - scanning the whole component with similar process parameters or scan by stripes or islands;
  - scanning with different patterns, such as in one direction, zigzag, spiral, etc.;
  - rescanning of the solidified layer;
  - rescanning only specific areas; changing the scanning direction for each subsequent layer, etc.
- Each of the scanning strategies can be applied to achieve specific goals: to improve density, surface quality, and manufacturing accuracy; to decrease residual stress; to achieve a specific microstructure, etc.

Powder Bed Fusion

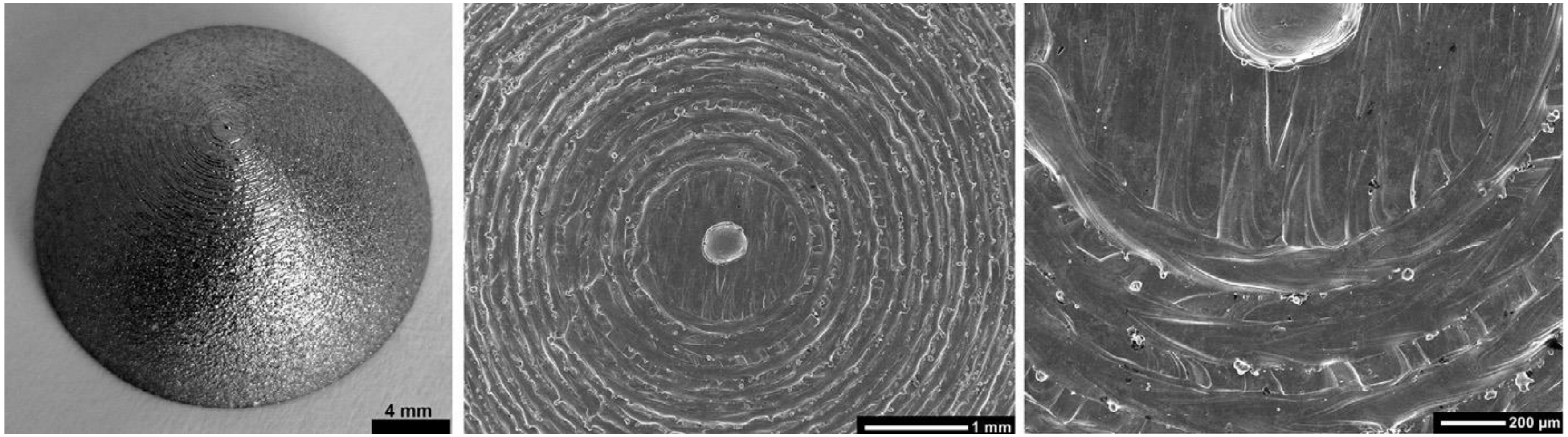
L-PBF object formation



Powder Bed Fusion

L-PBF object formation

- Side surfaces of L-PBF parts always make contact with powder material, so these surfaces often show many attached powder particles and pronounced layered structure.
- The layer-by-layer L-PBF process results in the surface quality being different in the vertical (between layers, Z-direction) and horizontal directions (in-layer, XY direction).
- The powder material and the track-by-track, layerwise nature of L-PBF govern the surface topology of L-PBF parts.



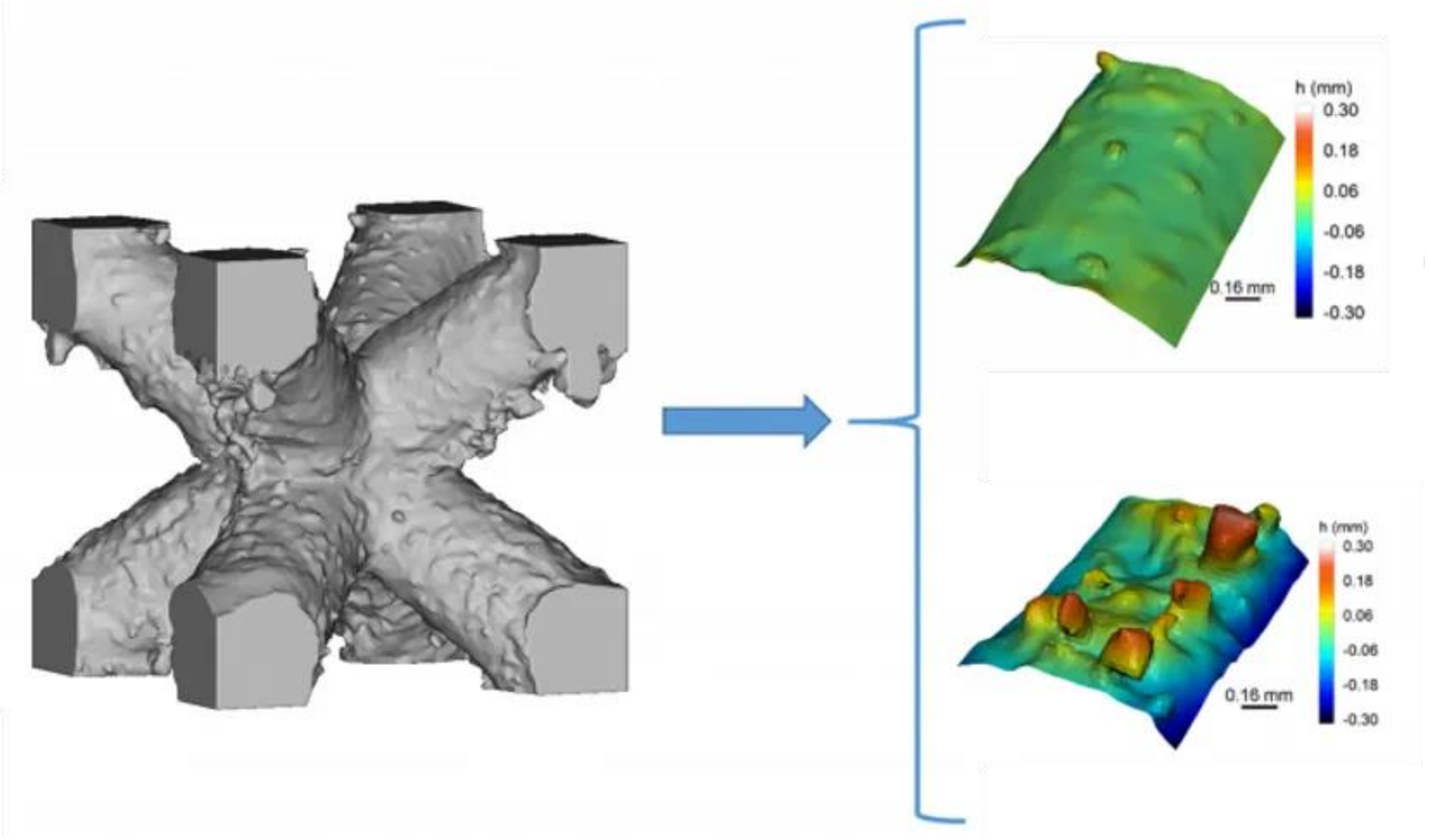
Powder Bed Fusion

L-PBF object formation

- Upward (upskin) and downward (downskin) surfaces are different in L-PBF, and frequently downskin is rougher and has poorer surface quality in comparison with upskin.
- To improve surface quality, upward surfaces can be rescanned several times with a special pattern similar to laser polishing, while side and internal surfaces require special post-processing surface finishing.
- Powder from external surfaces of a 3D object can be removed with compressed air, ultrasonic bathing, mechanically, with chemical reagents, plasma and electrochemical methods, etc.
- However, for lattice structures and parts with small channels with complex shape, powder cleaning presents a real problem that limits applications of powder bed fusion manufacturing.

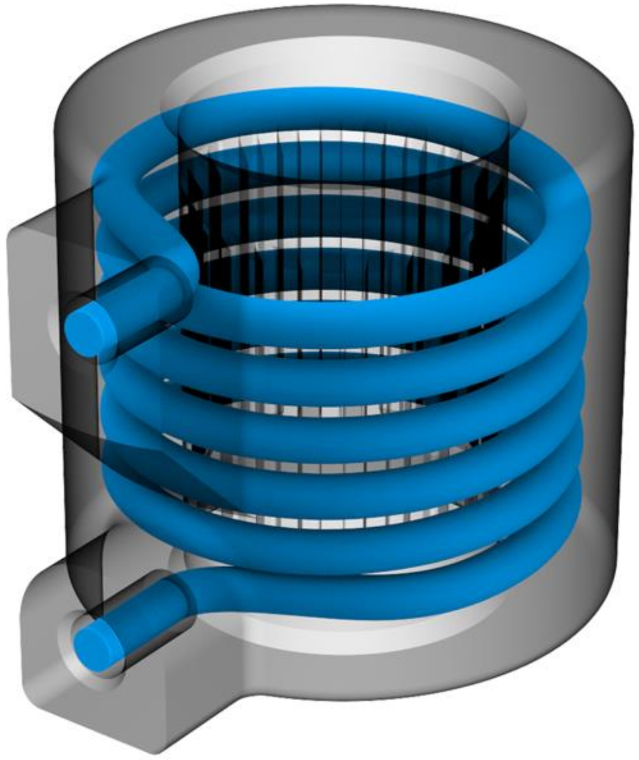
Powder Bed Fusion

L-PBF object formation



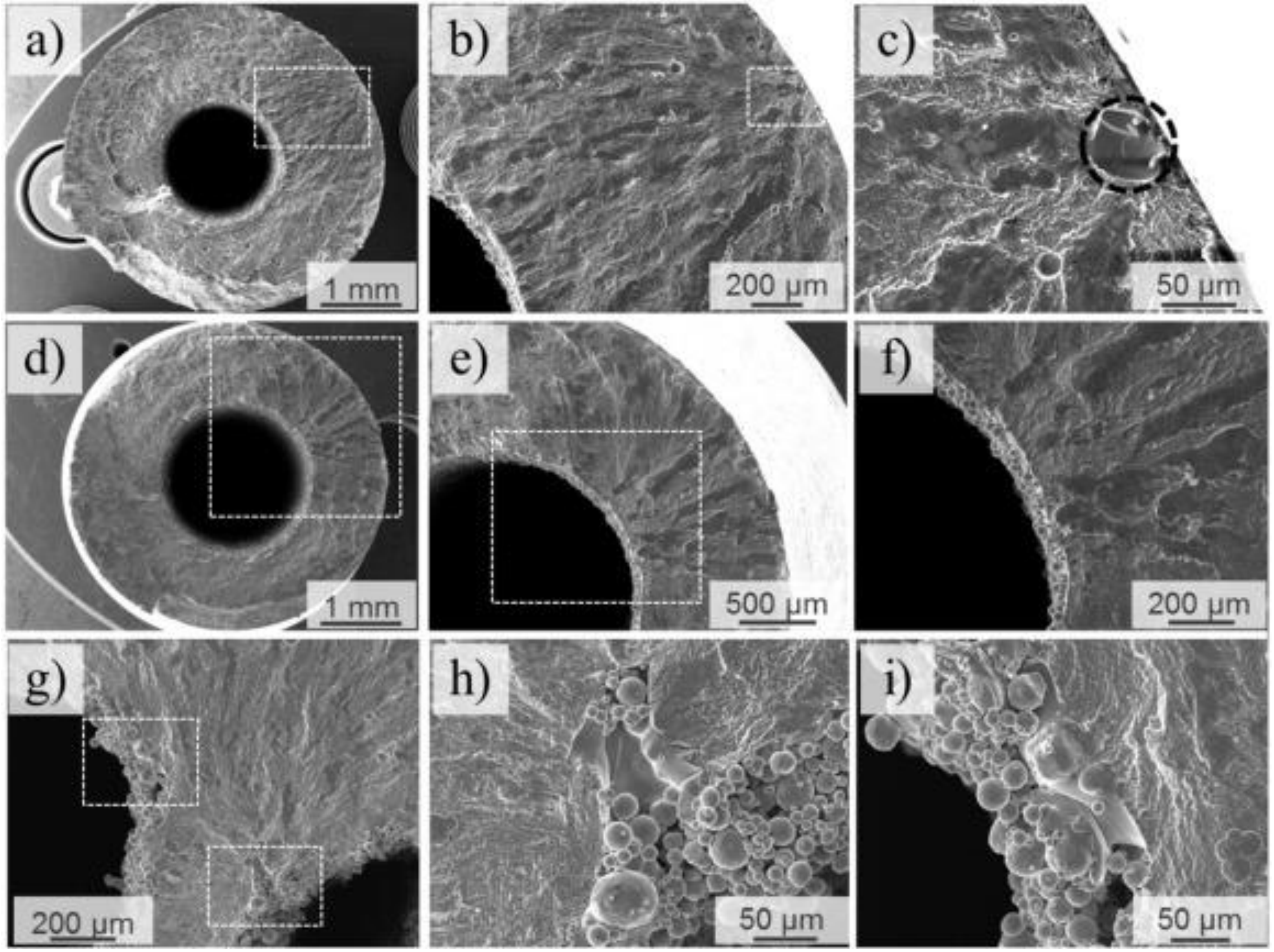
Powder Bed Fusion

L-PBF object formation



Powder Bed Fusion

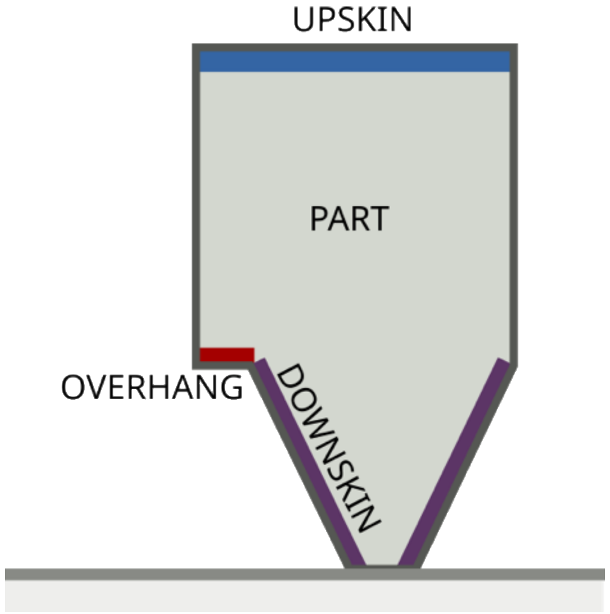
L-PBF object formation



Powder Bed Fusion

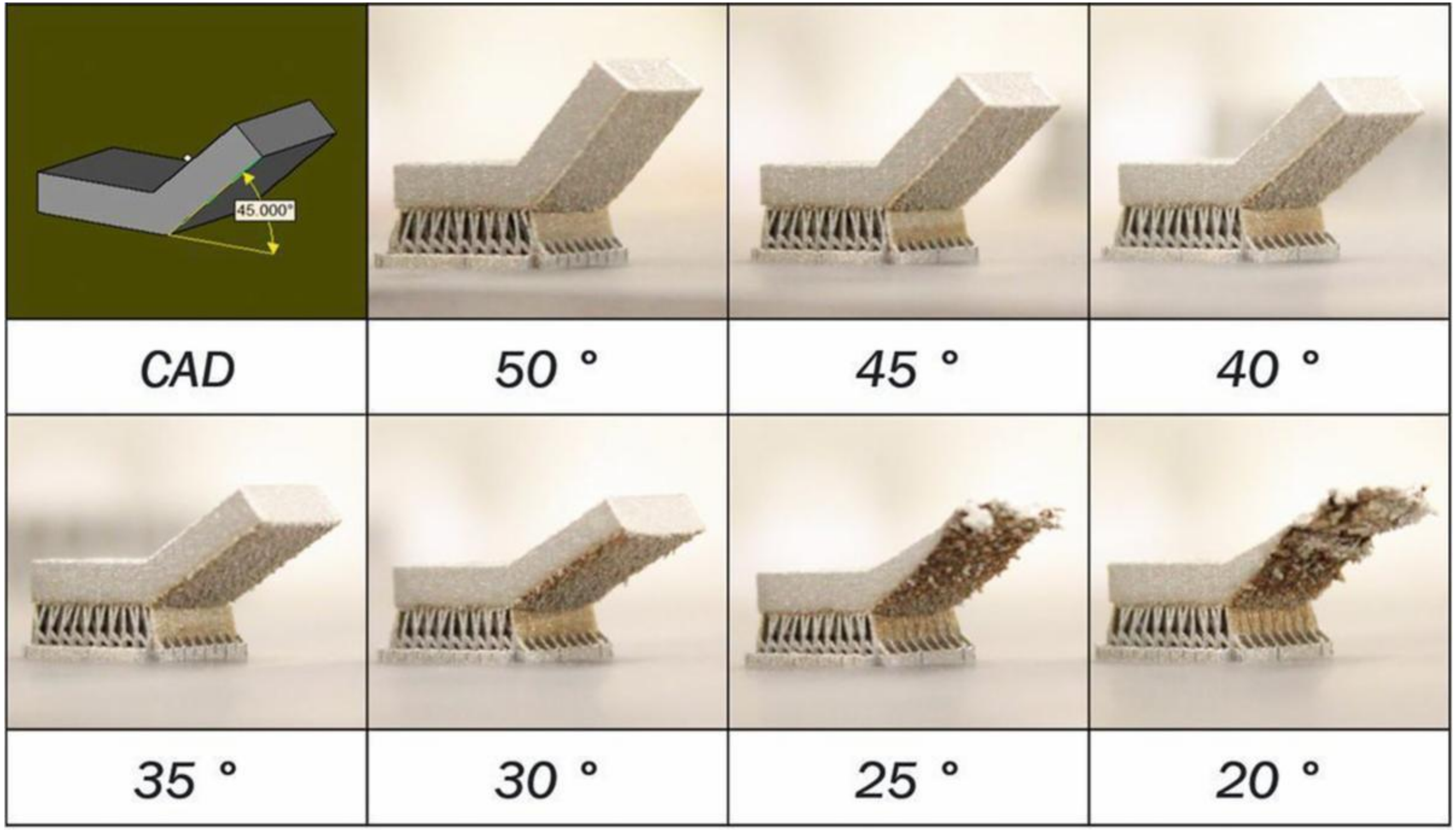
L-PBF object formation

- Objects of complex shapes can contain elements that are at an angle to the base plate, when the critical angle axis exceeds 45 degrees, it needs to be supported.
- During manufacturing, supported overhanging parts have different cooling rates compared with unsupported components; this influences the microstructure and mechanical properties.
- Areas with high residual stress can be determined by simulations of the process and an optimal support type with sufficient strength can be chosen for further manufacturing.



Powder Bed Fusion

L-PBF object formation

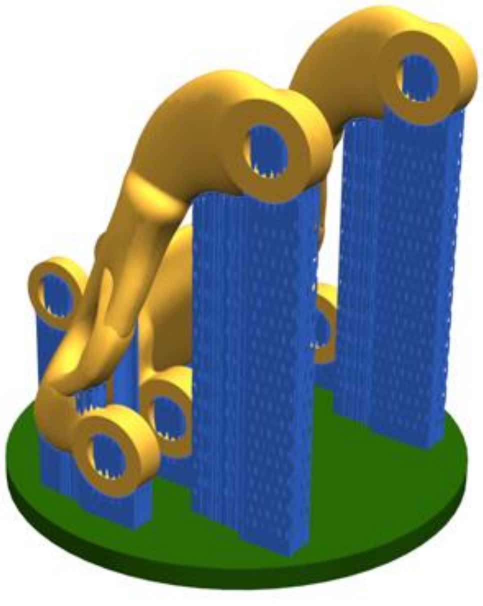


Powder Bed Fusion

Anytime material is deposited in AM needs to be attached to something else by a physical connection.

In addition, in a process which deposits molten material, that material must be supported by something underneath it.

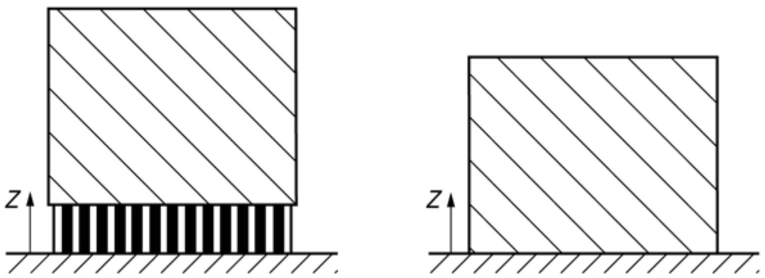
These reasons, plus the need to mitigate the effects of residual-stress-induced and shrinkage-induced warpages means that support structures are needed in many AM processes.



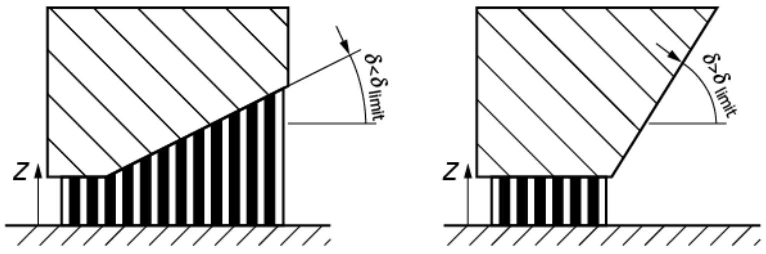
Powder Bed Fusion

Most AM processes need supports if printed surface is less than 45° from the horizontal.

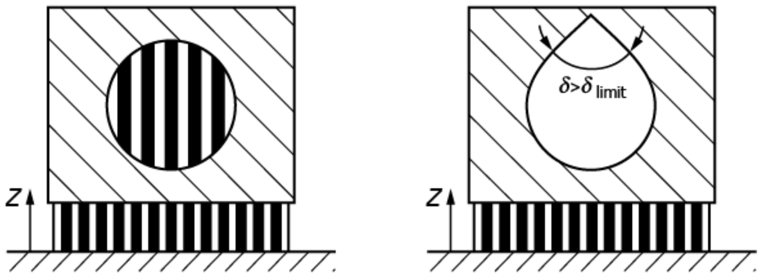
This is particularly true for MEX and for PBF of metals with respect to the interaction of dynamic shear force in the liquid phase and gravity forces in the solid phase.



Left: Support structures connecting the part to the build platform.
Right: Part connected directly to the build platform without support structures.
Comment 1: In order to avoid the risk of cracks, a fillet can be foreseen between the part and the plate (not included in sketch).
Comment 2: When supporting a part directly to the build substrate, removal through wire electrical discharge machining can be complicated due to trapped powder and uneven cutting action.



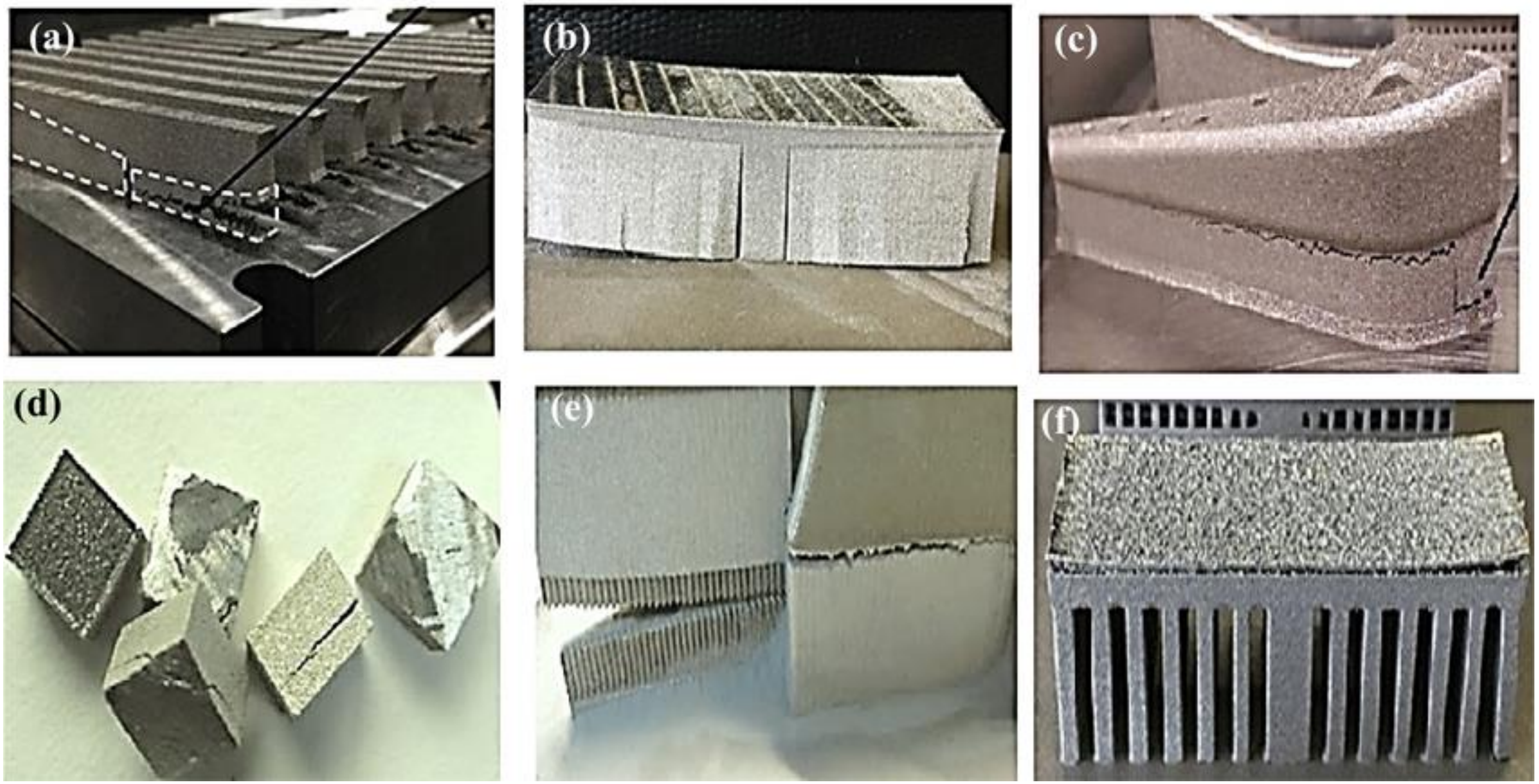
Left: Faces with downskin angle $\delta < \delta_{lim\,it}$ require support structures. Often, $\delta_{lim\,it}$ is between 30° and 45°. $\delta_{lim\,it}$ is dependent on, for example, the material used, the process strategy applied, and also the part characteristic (thickness, shape, etc.) above the regarded face.
Right: Faces with downskin angle $\delta > \delta_{lim\,it}$ do not require support structures. The surface quality may be adversely affected, depending on the angle.



Left: Hole with internal support structure.
Right: Shape of hole modified to avoid use of support structures as per Reference (7).
Comment: If drilling operation is needed after PBF-LB/M, this shape is difficult to machine. Hence, in some cases, it can be better to reduce diameter of hole (often no need for support below diameter of 8 mm) in order to be built without support and drill after or even to not foresee a hole and fully drill instead (e.g. titanium).

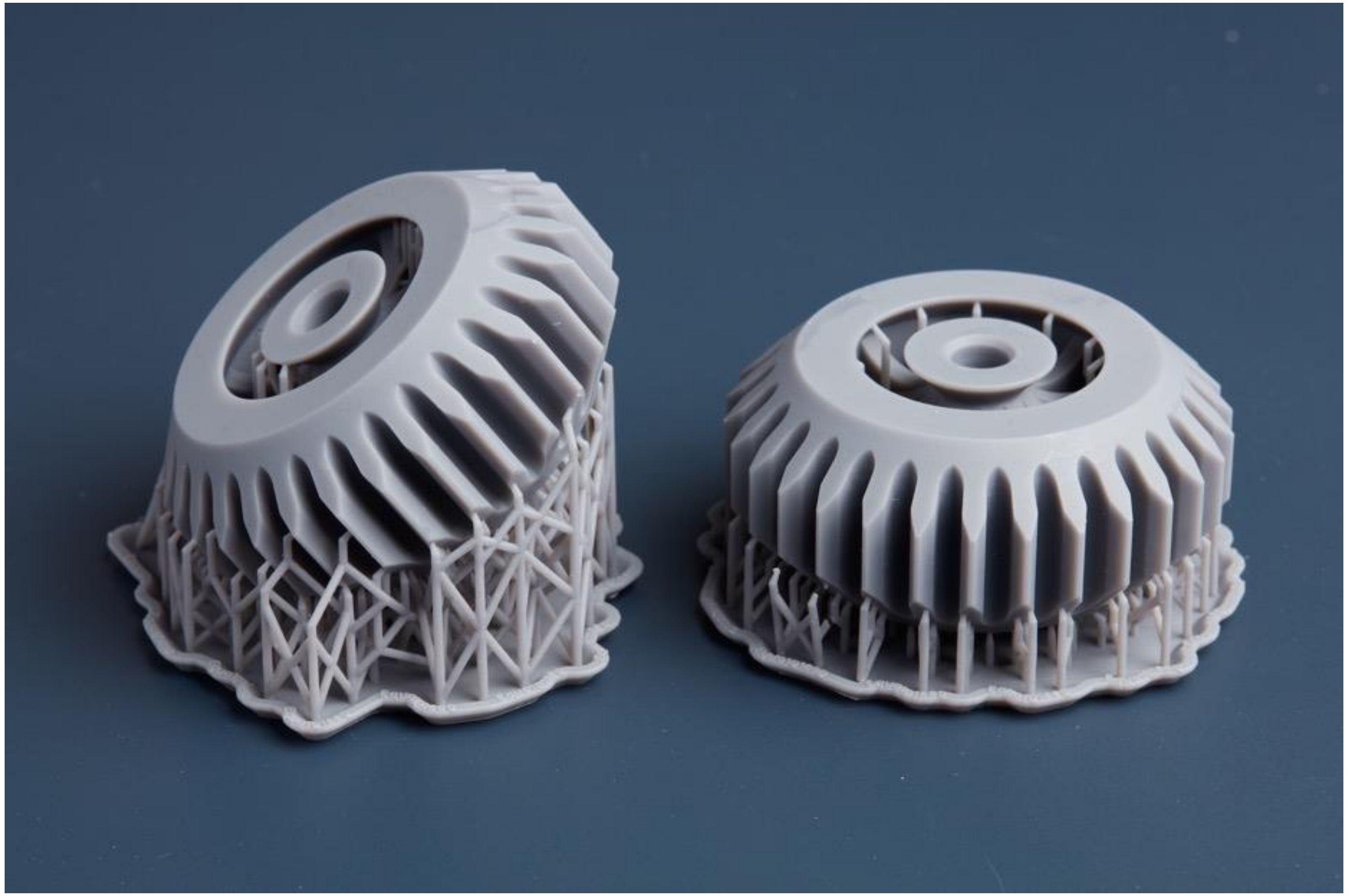
Powder Bed Fusion

When using supports in AM processes, differences in cooling rates between the bulk of the material and contact points with supports increases the risk of the cracks.



Powder Bed Fusion

In addition, supports must be removed after the build process by post-process operations such as machining.



Powder Bed Fusion

L-PBF object formation

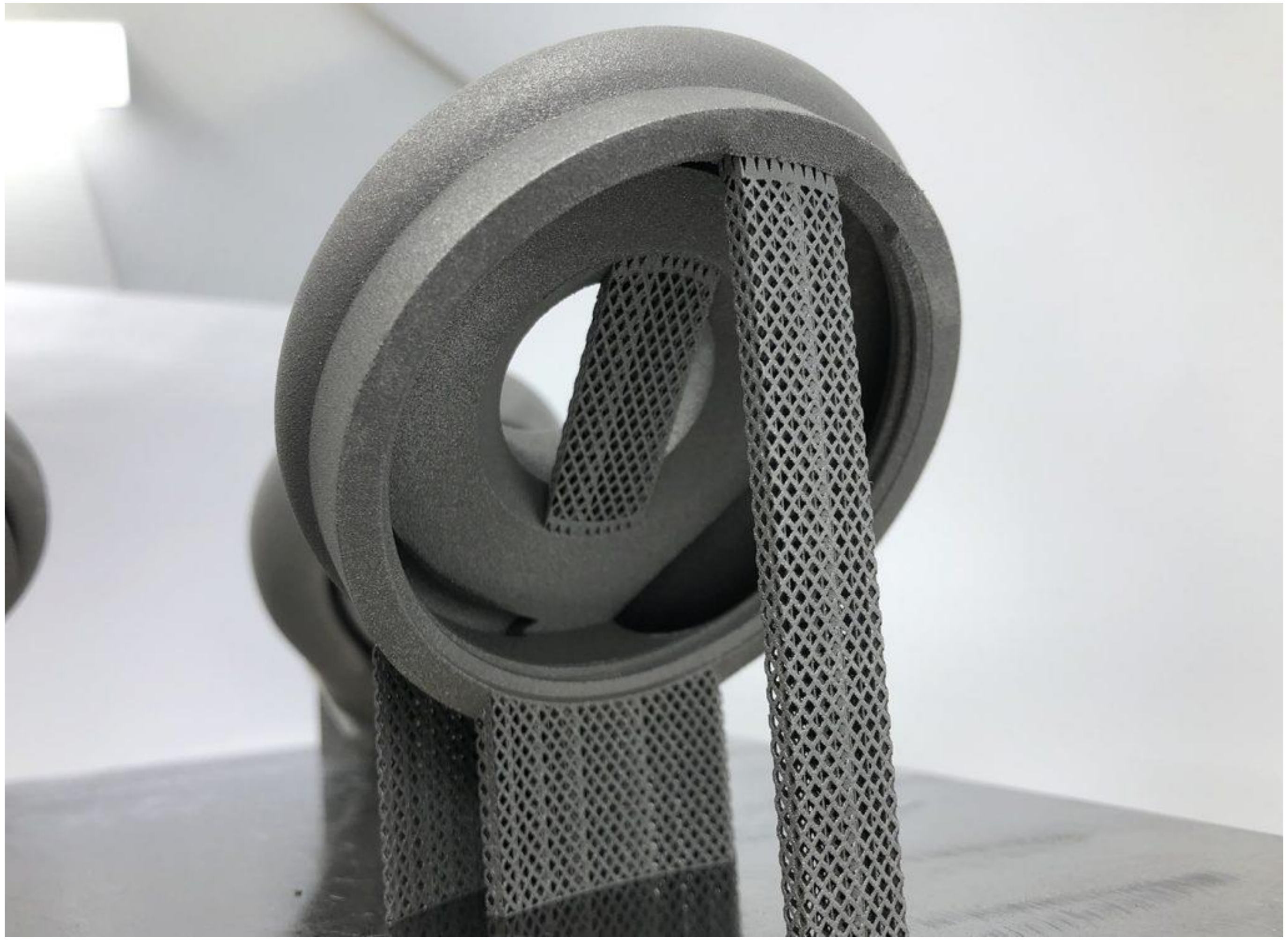
- Optimization and minimization of support structures improve process efficiency, reduce deformation, and improve quality of L-PBF components.
- Supports in L-PBF is a system of thin walls, pins, and cellular structures that serve several purposes:
    - heat dissipation,
    - to fix the part,
    - to stiffen the structure,
    - to resist deformation and bending of the parts during the manufacturing process,
    - to provide a convenient and simple separation of the finished part from the base plate.
- L-PBF makes use of specialized software tools that can generate different types of supports and allows for the selection of certain configurations to change the type of supports and size of their contact zone with the part.

Powder Bed Fusion

L-PBF object formation

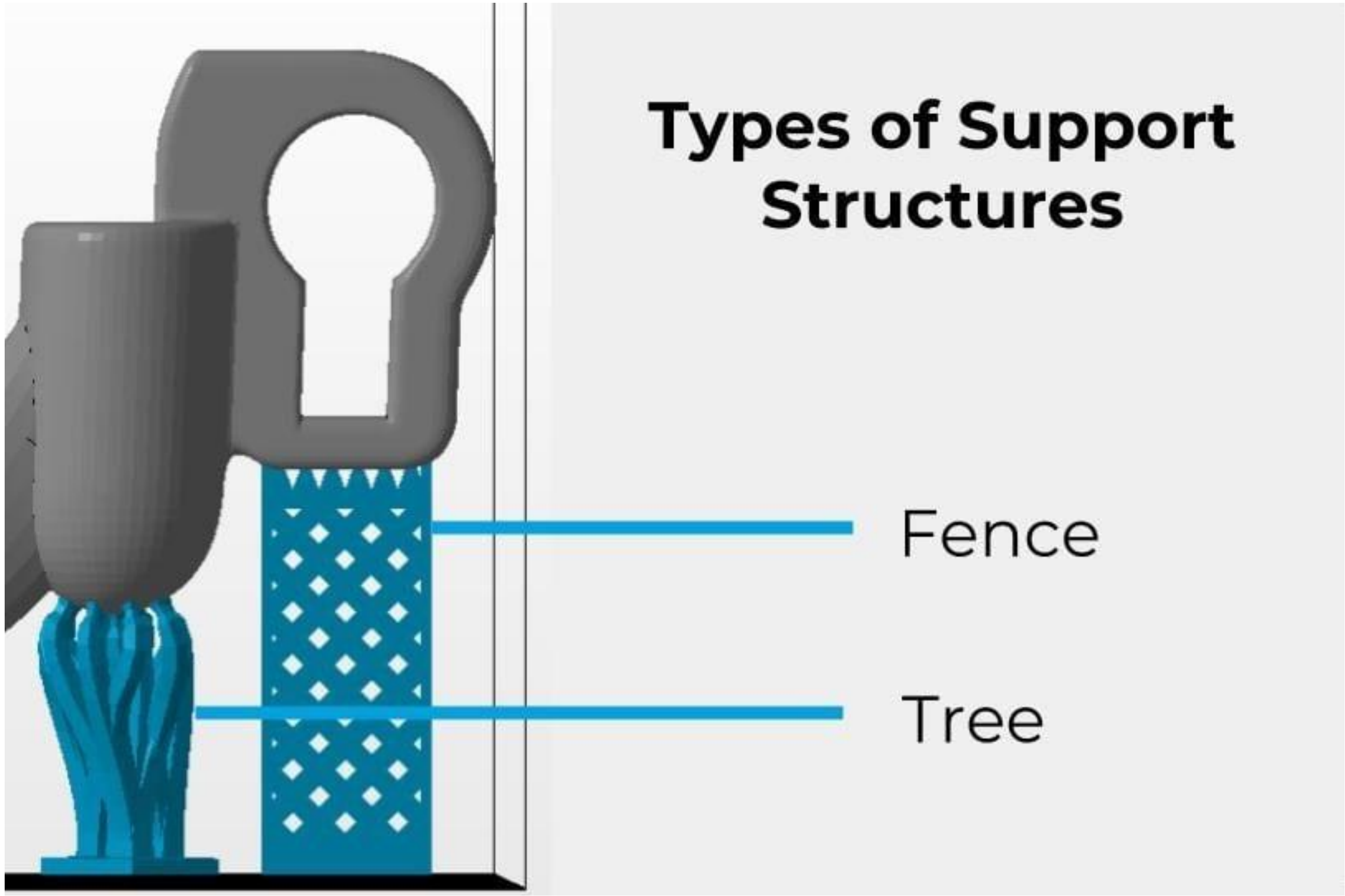
Powder Bed Fusion

L-PBF object formation



Powder Bed Fusion

L-PBF object formation



Porosity in laser powder bed fusion

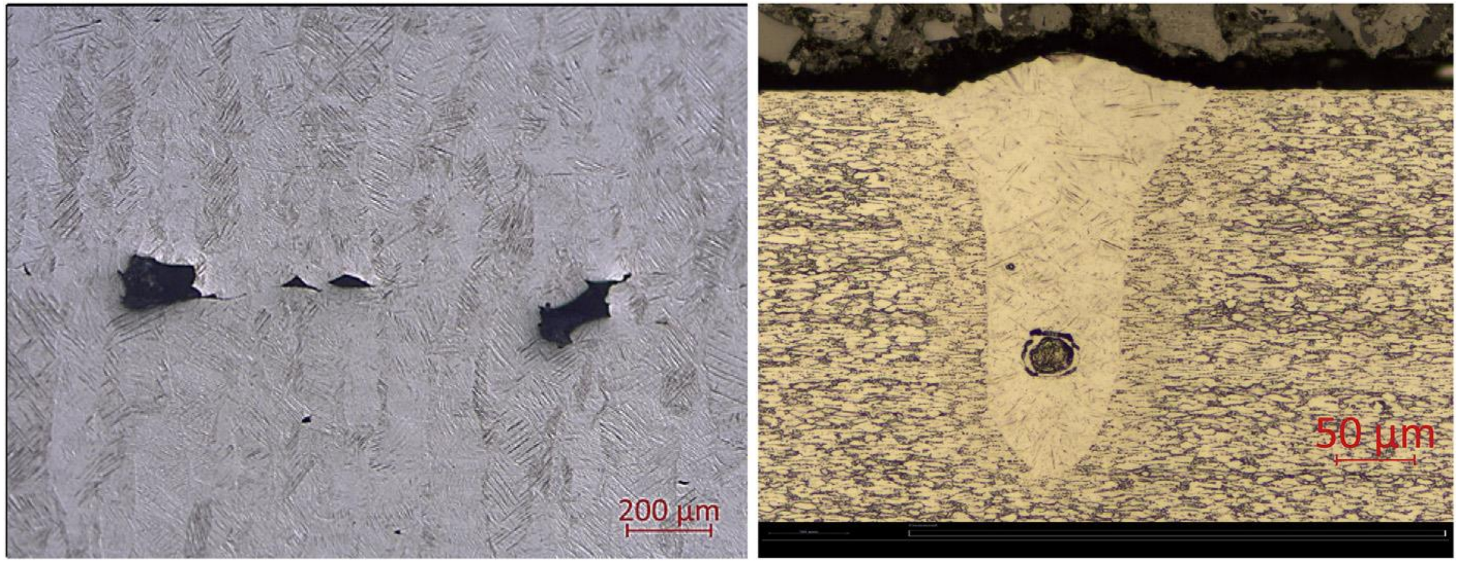
Porosity in AM

Similar to cast metals, porosity in AM occurs in specific forms and these are related to specific mechanisms of the additive process used

In L-PBF there are numerous pore formation mechanisms

The presence of porosity in L-PBF is widely attributed to process parameters

The two most well-known and widely occurring forms of porosity in L-PBF are lack of fusion porosity and keyhole porosity:

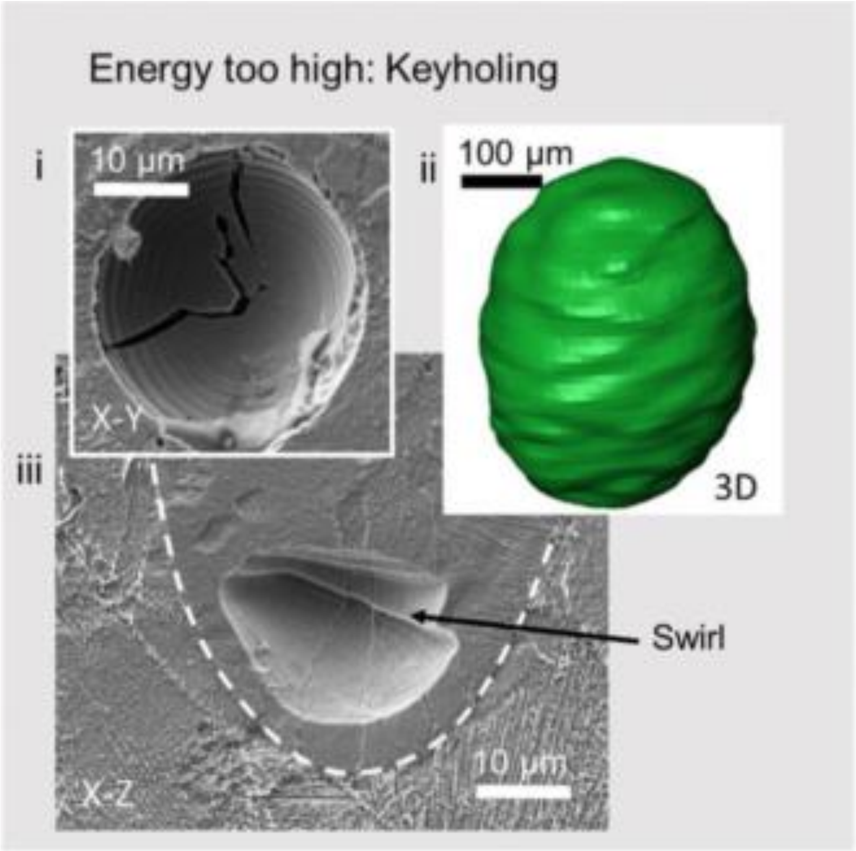


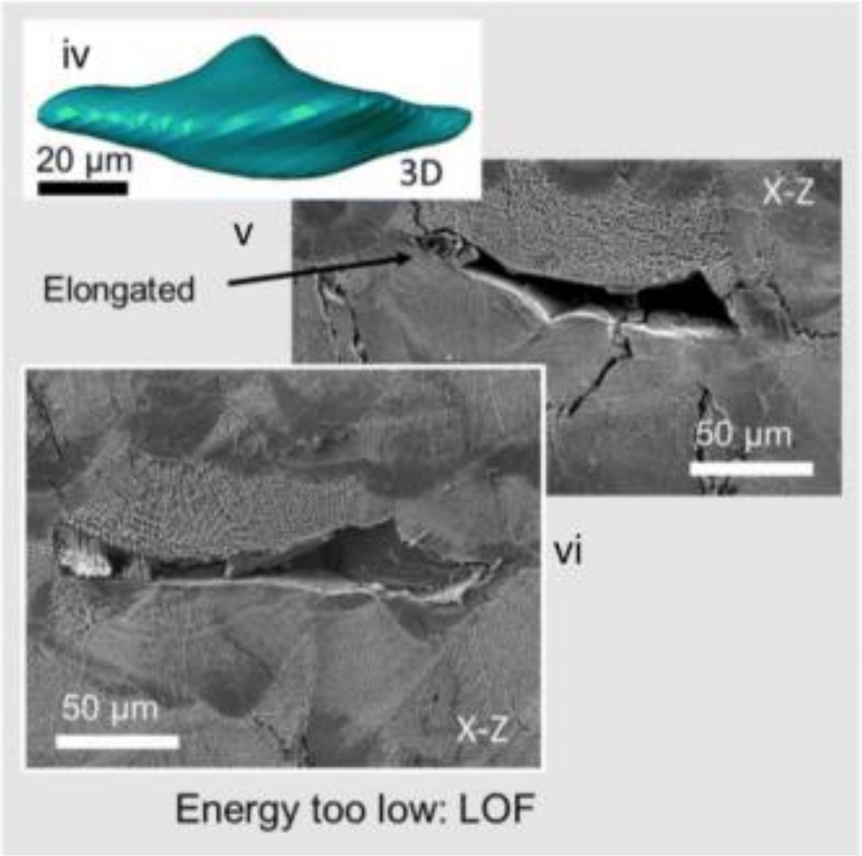
Porosity in laser powder bed fusion

Porosity in AM

lack of fusion porosity

keyhole porosity





Porosity in laser powder bed fusion

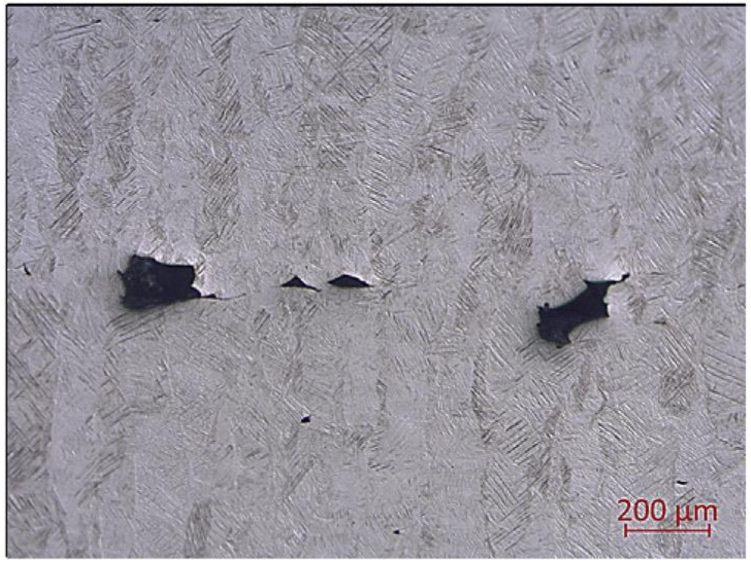
Porosity in AM

Lack of fusion (LoF) porosity occurs when insufficient melting occurs, either due to too high scan speed or too low laser power for the selected powder layer thickness

This type of porosity is irregular in shape and may contain unmelted powder particles

These pores may occur in different sizes and, due to the irregular shape, typically have sharp edges.

These sharp edges act as stress concentrators under load, causing a significant effect on mechanical properties



Porosity in laser powder bed fusion

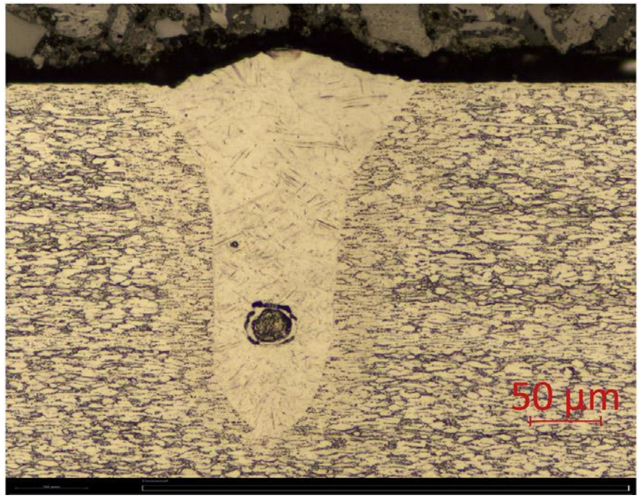
Porosity in AM

The keyhole porosity occurs when the laser power is high and scan speed is low

Keyhole mode melting occurs when the laser causes sufficient material vaporization to create a vapor cavity which creates a depression in the surface

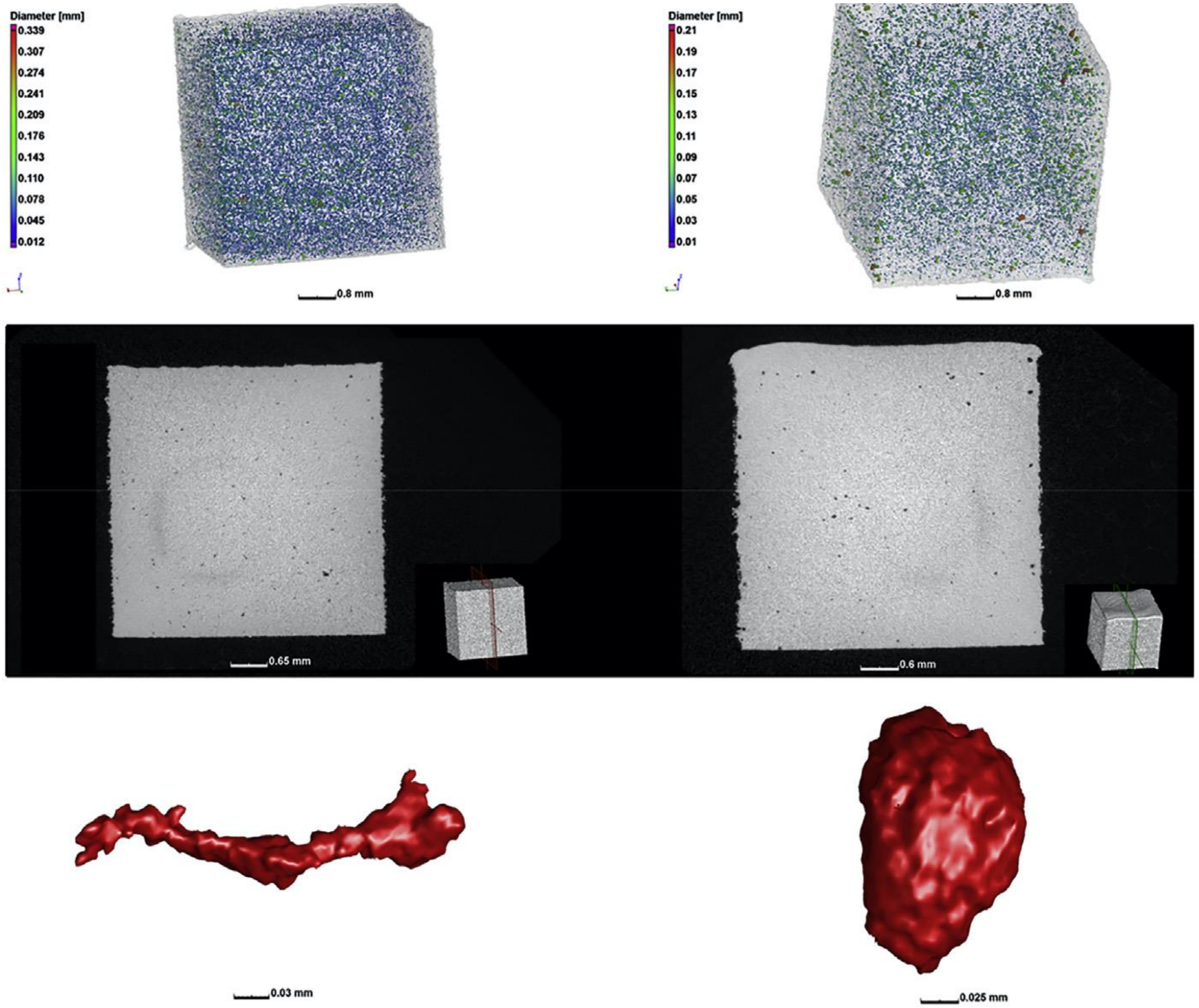
This depression or keyhole cavity may penetrate deeply into the melt pool, and may become unstable and collapse as the melt pool moves, leaving a trapped vapor cavity (or keyhole pore) in the track as it solidifies

This porosity type is more rounded in shape and has a lower influence on mechanical properties if its presence is in low quantities or in small size



Porosity in laser powder bed fusion

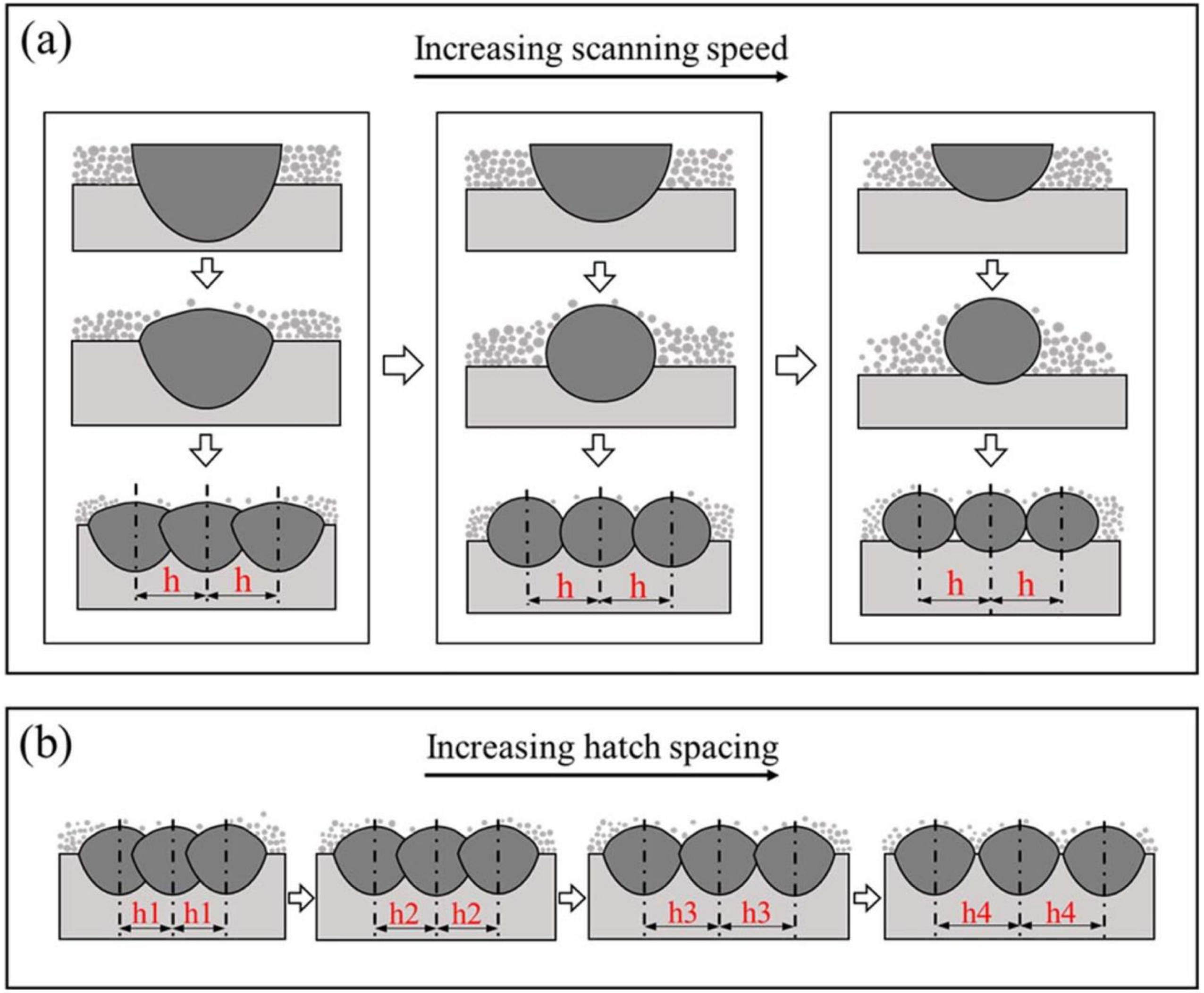
Porosities



Porosity in laser powder bed fusion

Pore formation mechanisms and porosity types

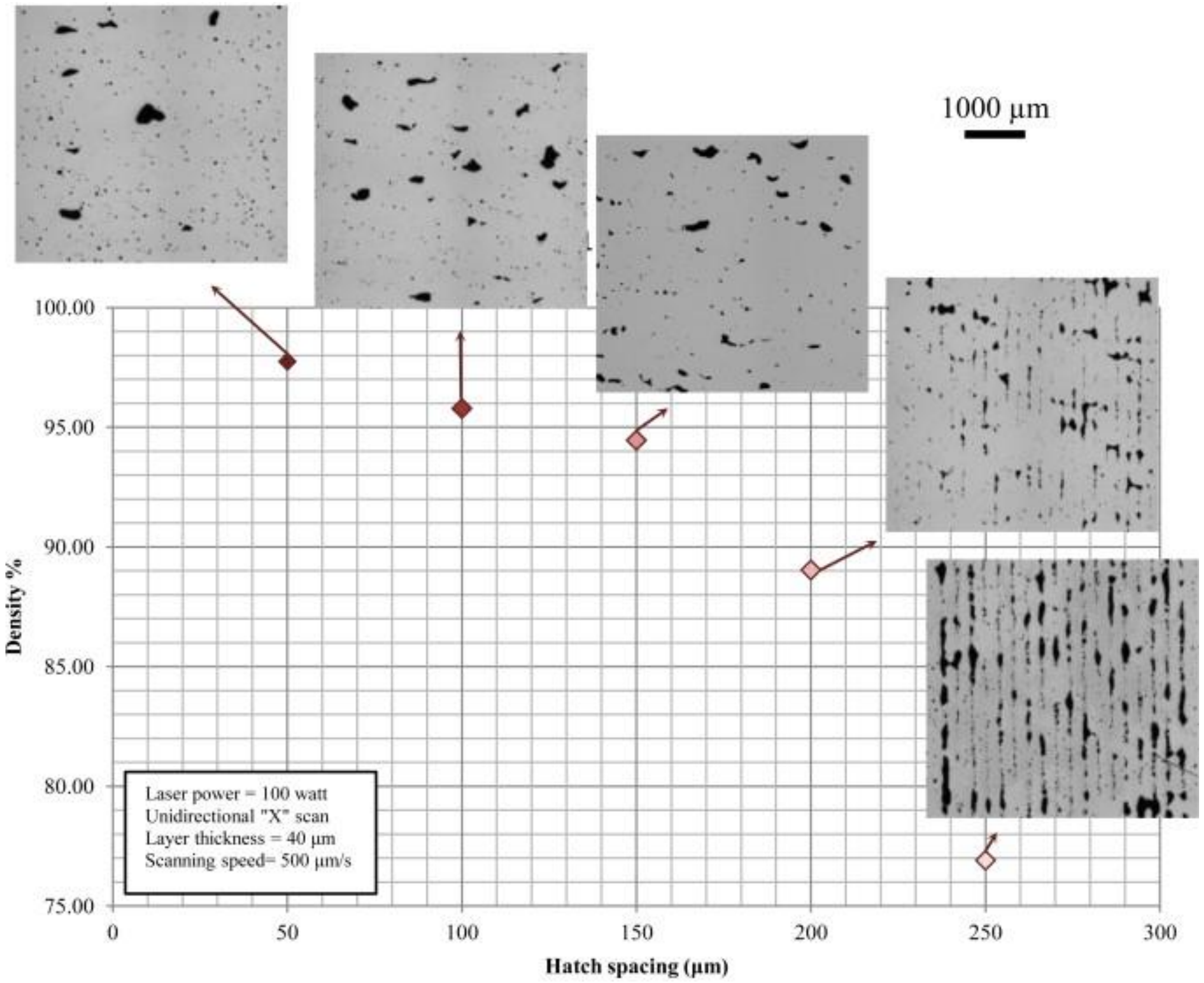
Single layers



Porosity in laser powder bed fusion

Pore formation mechanisms and porosity types

Single layers



Porosity in laser powder bed fusion

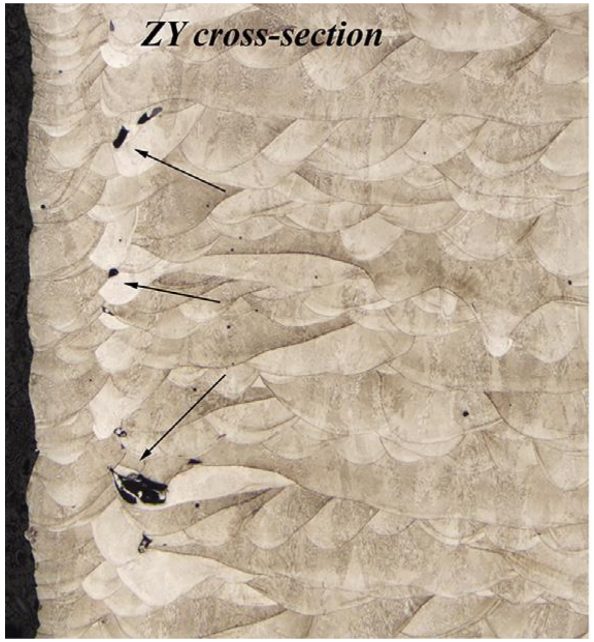
Pore formation mechanisms and porosity types

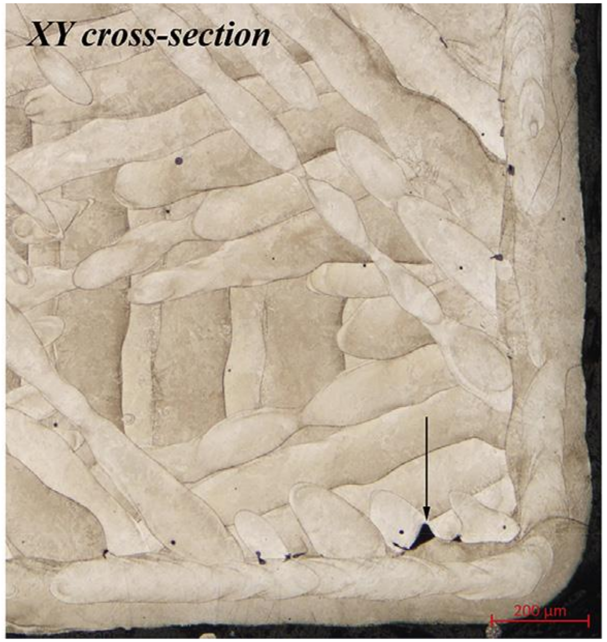
Single layers

The hatch scanning of the core of the part is usually followed by contour scanning

Contour scanning may use different process parameters to improve surface properties

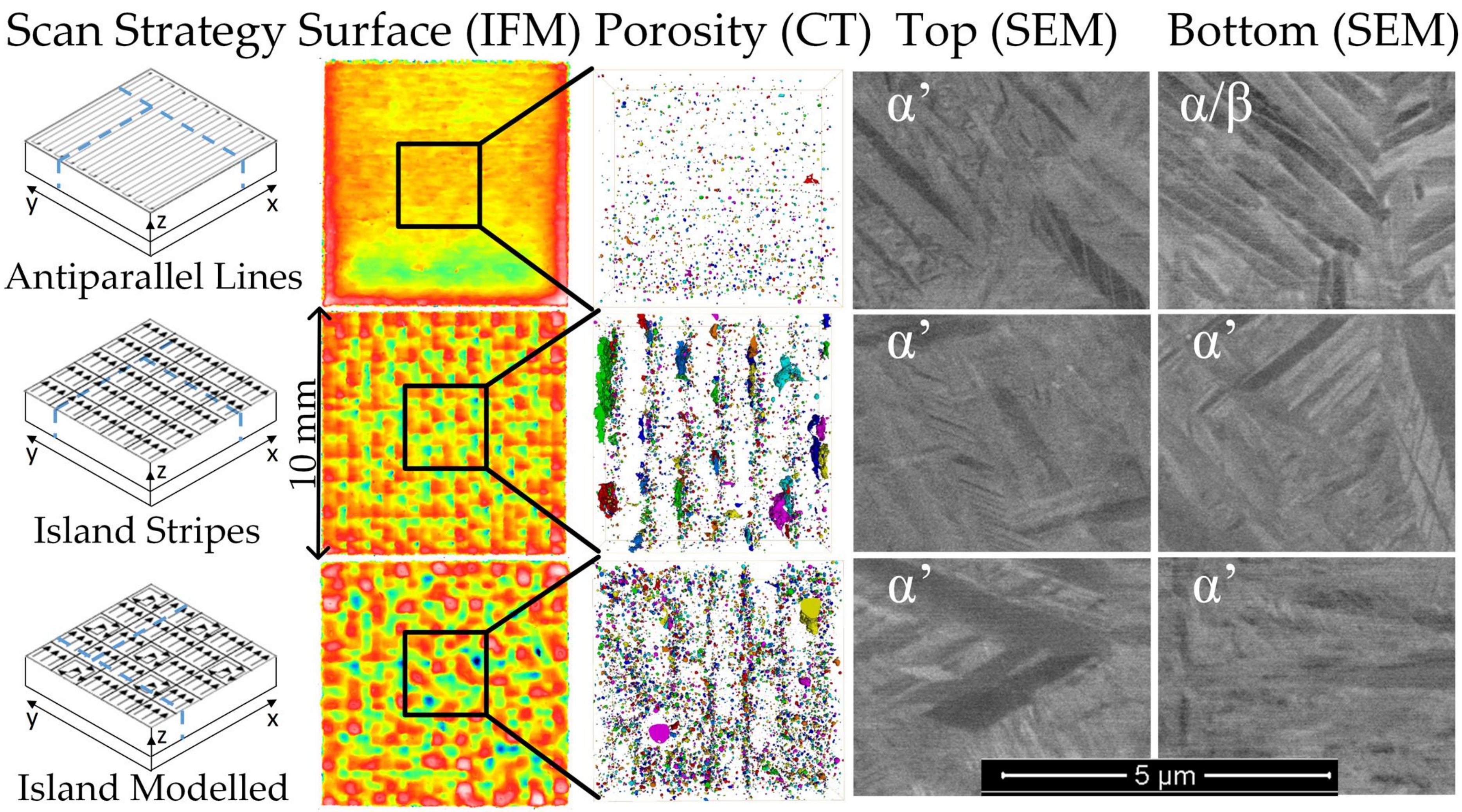
The overlap between the hatch core tracks and contour tracks needs to be sufficient, as this region may be particularly prone to porosity formation





Porosity in laser powder bed fusion

Pore formation mechanisms and porosity types

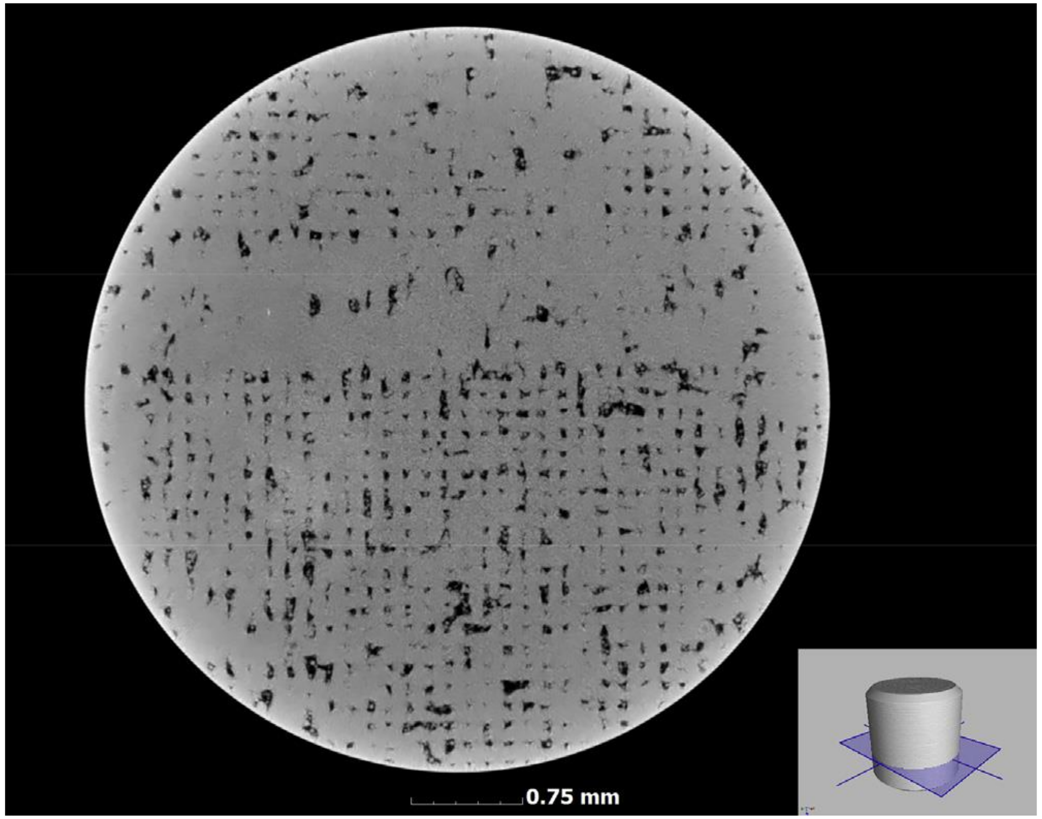


Porosity in laser powder bed fusion

Pore formation mechanisms and porosity types

Multiple layers

This remelting process results in interesting 3D distributions of the remaining pores in different types of checkerboard patterns of porosity



Checkerboard pattern resulting from LoF tracks remelted at 90° layer rotations

LoF regions are between tracks

Porosity in laser powder bed fusion

Pore formation mechanisms and porosity types

Summary of pore types

Porosity name	Mechanism	Shape, distribution, and size
Low energy lack of fusion (LoF)	Insufficient melting, can be due to various reasons: - Low energy causing insufficient penetration to previous layer - Low energy causing insufficient overlap between tracks (or too large hatch spacing) - Insufficient track overlap between hatch and contours near surfaces of material	Irregular shaped pores with sharp edges, can be aligned perpendicular to or parallel to the build direction, depending on the LoF with previous layers or between tracks. Large LoF pores may contain unmelted powder.
Keyhole	Excessive energy creating rounded pores inside the solidified tracks, can occur: - All along the track - Only at turnaround points where laser slows down to turn around or switches off leaving keyhole to collapse - Size of pores depends on keyhole size which scales with laser power and spot size	Rounded pores all along tracks or at end of scan tracks. At intermediate powers this also occurs, the pores are simply smaller.
Track instability LoF	Instability and uneven tracks lead to variations in powder layer thickness on the next layer, and in critical cases balling or humping occurs, creating special forms of LoF on the next layer due to varying thickness of the powder layer	Irregular and sometimes large LoF pores.
Turbulent melt-pool induced LoF	Conditions of melt-pool turbulence creating entrapment of pores, particle and spatter ejection, denudation, and combinations of pore formation mechanisms	Large irregular LoF pores.
Powder porosity	Pores inside powders trapped inside melt pool and do not get time to escape as the solidification is too fast	Rounded and small (smaller than powder particles which are generally about 30 μm).

Porosity in laser powder bed fusion

Pore formation mechanisms and porosity types

Summary of pore types

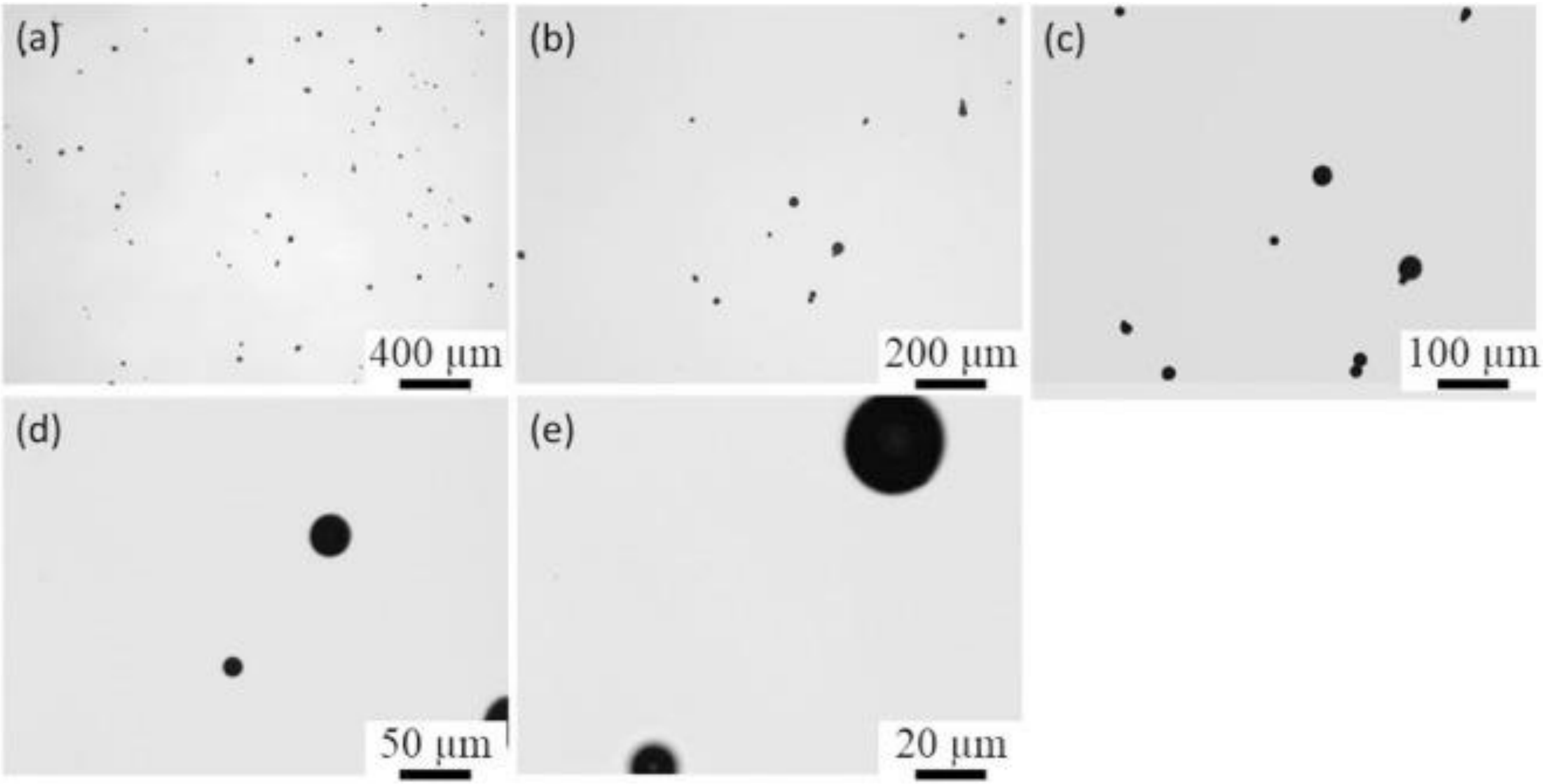
Gas entrapment	Powder packing density or shielding gas related. Pores are entrained into the melt pool and move inside the melt pool but cannot escape before solidification. Entrapment depends on melt-pool conditions as well as shielding gas and powder packing density	Small pores trapped into melt pool, found randomly all over part—typically much smaller than melt pool (also in region of 30 μm).
Uneven powder bed LoF	Uneven powder bed due to scraper damage, local powder clumping, or irregular powders (e.g., re-used powder). Uneven powder bed affects melt-pool stability and indirectly causes pores. In extreme cases, for example, a large particle will not melt sufficiently creating lack of fusion under the region	Elongated pores in build plane (pore tracks), or similar to layered LoF.
Local heating induced keyhole porosity	Local heating creates different melt-pool dynamics creating conditions for pore formation and trapping in solidified material; this can be due to lack of solid material under it (overhang regions) for thermal dissipation - At supported areas but between supports - At solid areas where thermal dissipation is lower, e.g., in corners of parts	Small pores at down-skin regions and at narrow features.
Stop-start pores	When system stops and restarts, part cooling and shrinkage creates a thicker powder layer and insufficient melting of new layer	Layered pores in build plane.
Checkerboard pores	When LoF occurs with some scan strategies, remelting on subsequent layers closes some pores. May occur between tracks or between islands or stripes—regions where porosity often occurs	Small pores in regular grid-patterns.

Porosity in laser powder bed fusion

Porosity measurement

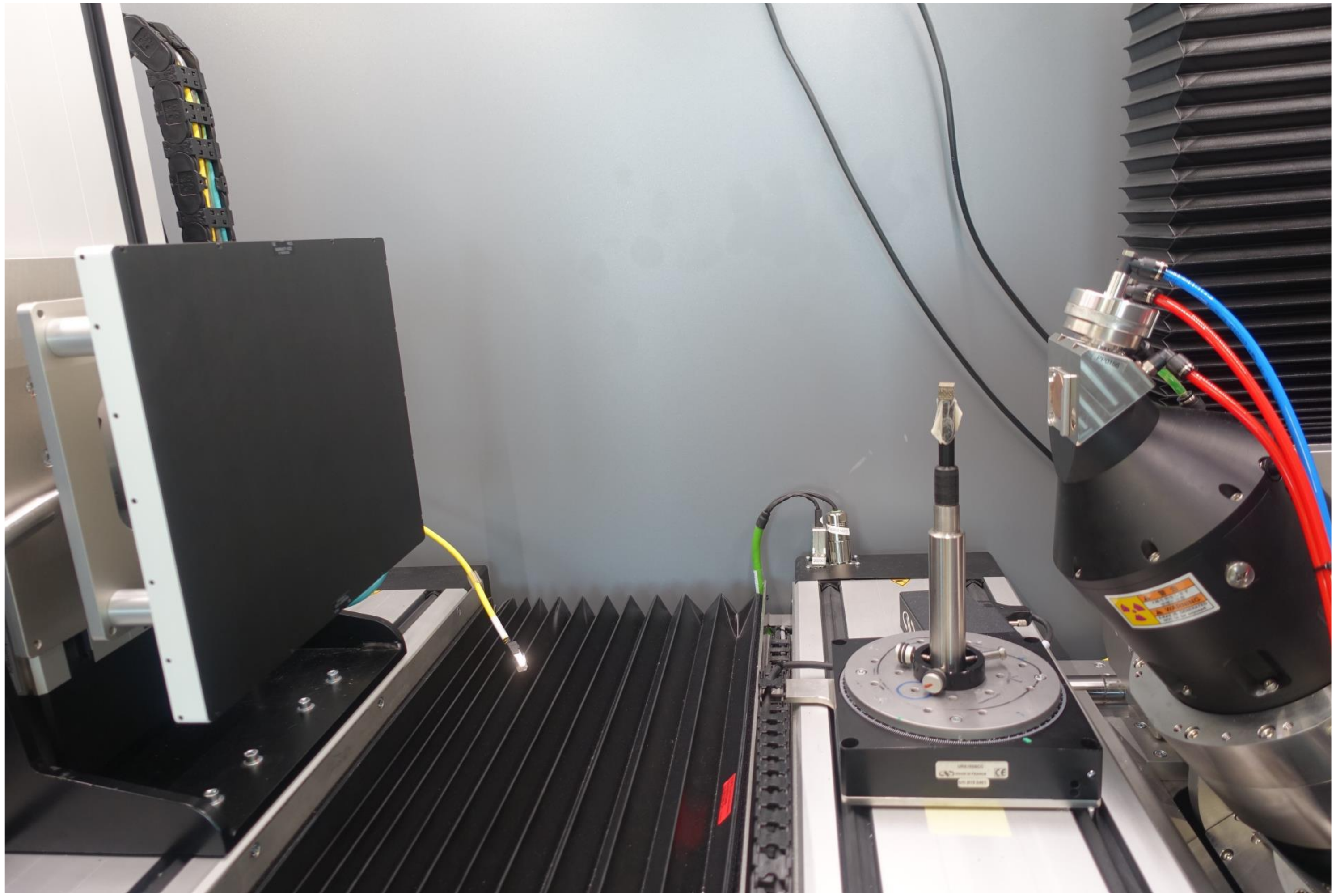
Optical microscopy

The process of sectioning, polishing, and etching parts is already in wide use for microstructural analysis; therefore, the analysis of porosity is often done in tandem.



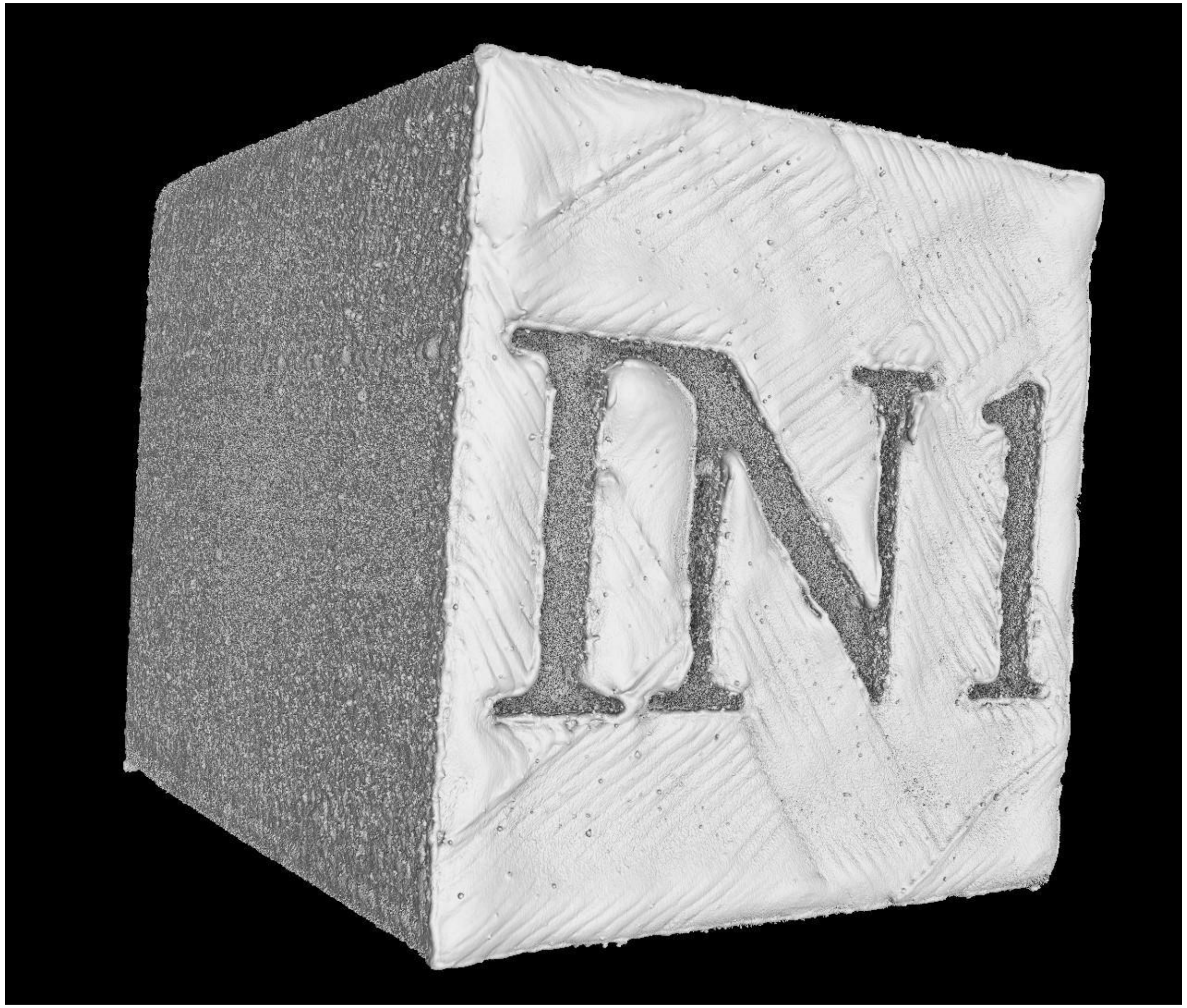
Porosity in laser powder bed fusion

Computed tomography



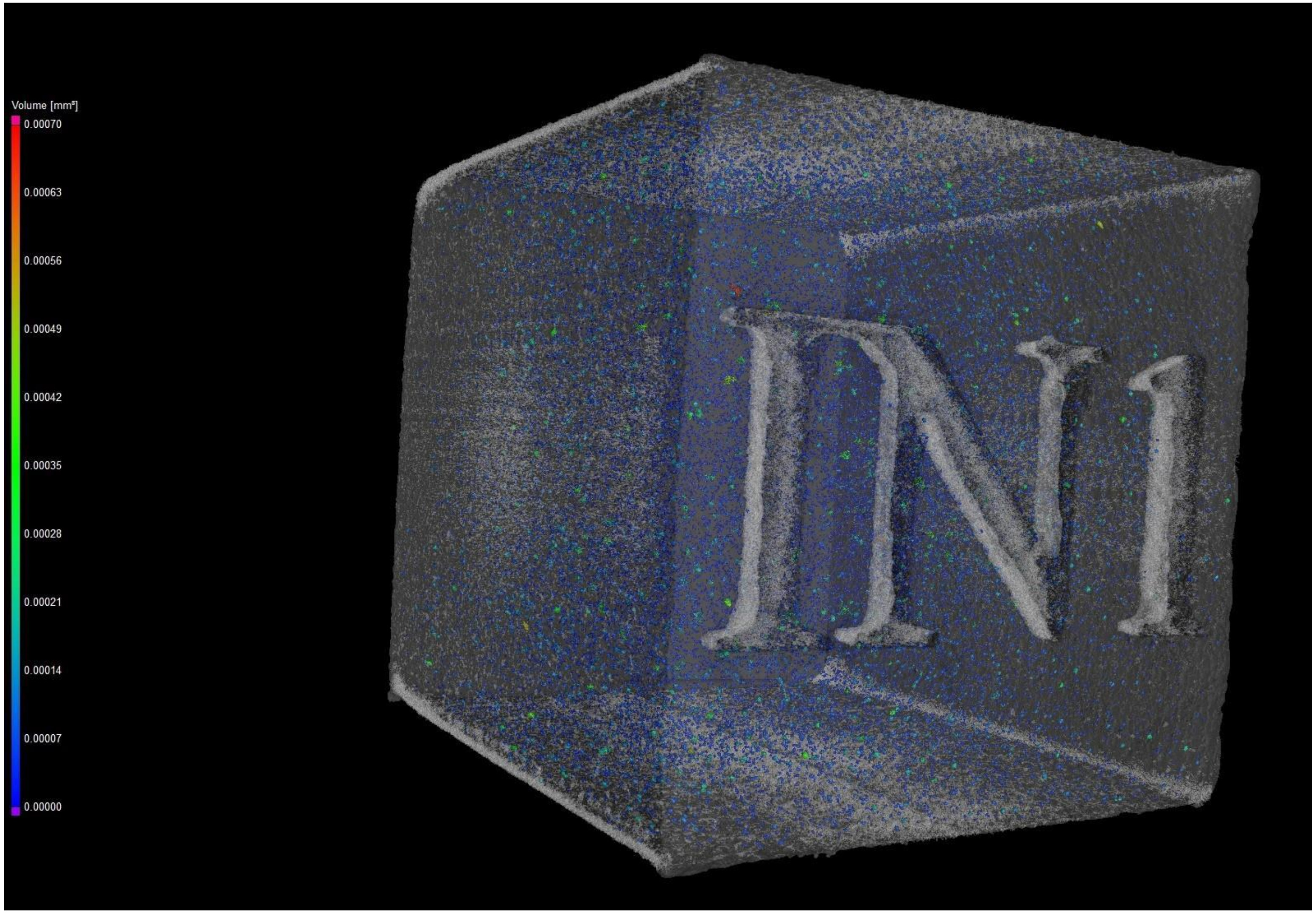
Porosity in laser powder bed fusion

Computed tomography



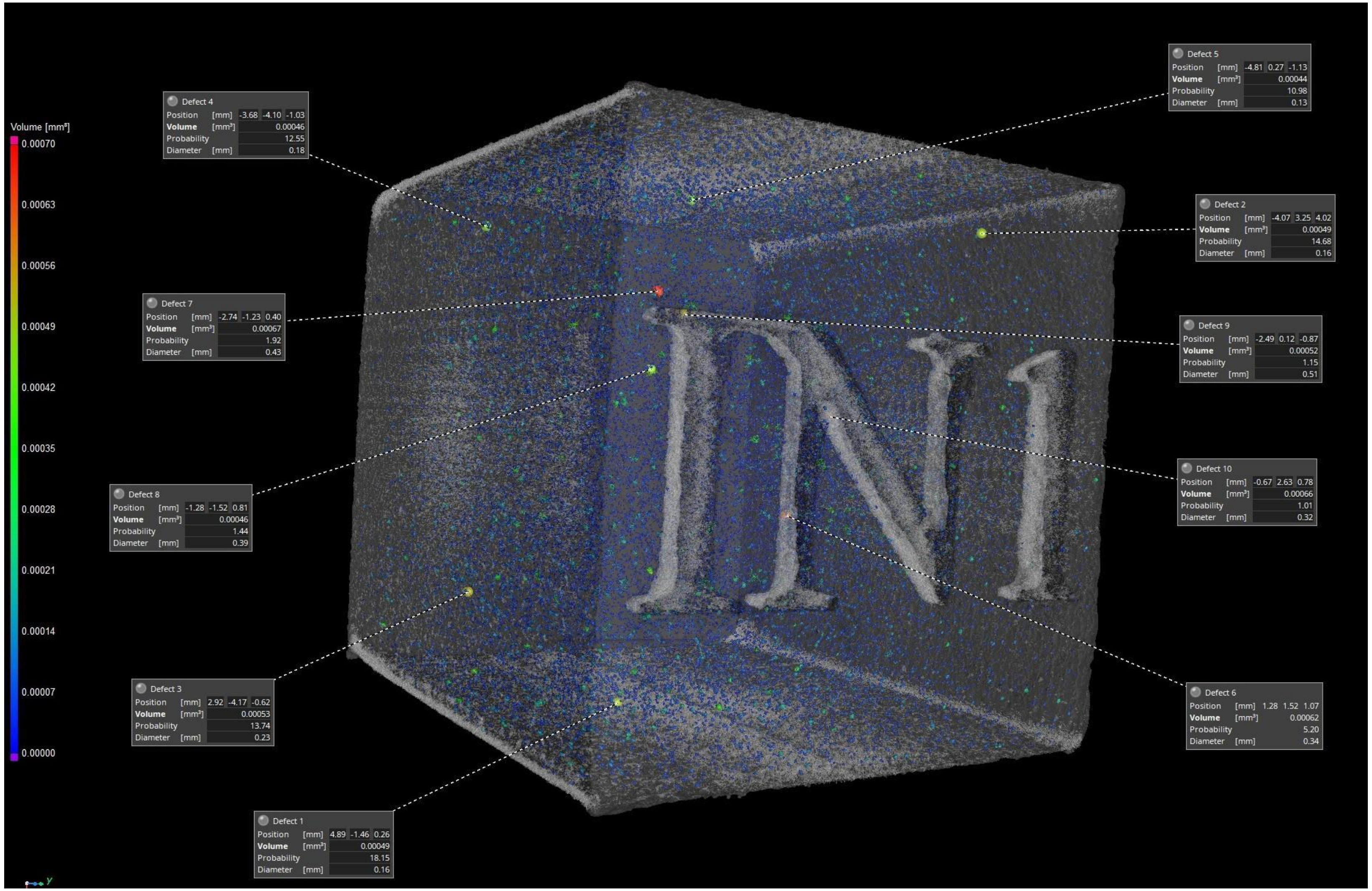
Porosity in laser powder bed fusion

Computed tomography



Porosity in laser powder bed fusion

Computed tomography



Porosity in laser powder bed fusion

Effect of defects

Porosity is widely present in different forms and in different extents.

But at what point is this a problem?

Is there a threshold value that can be defined as being “acceptable”?

Is there a critical pore size?

How does porosity affect the properties of the parts?

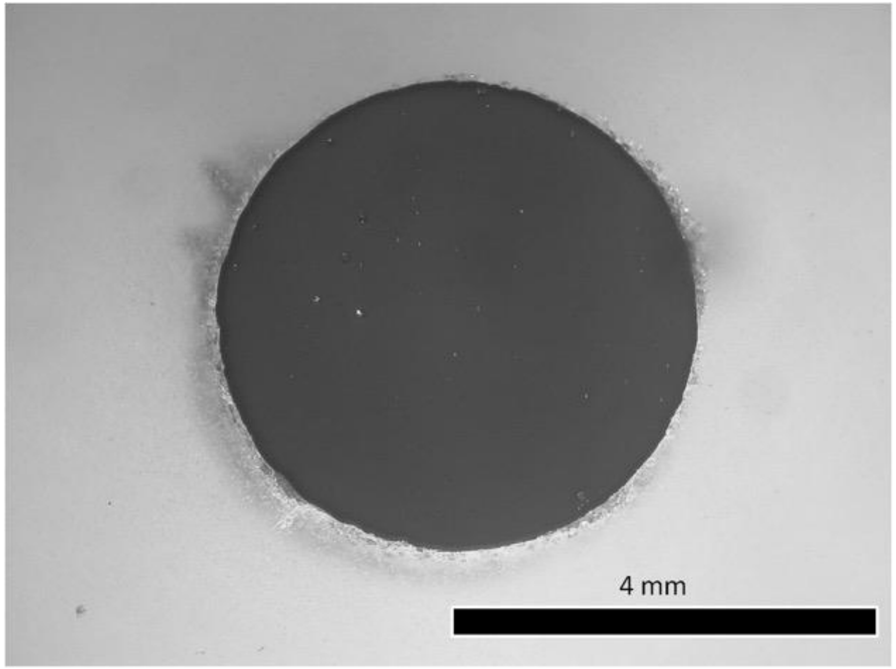
Porosity in laser powder bed fusion

A case study

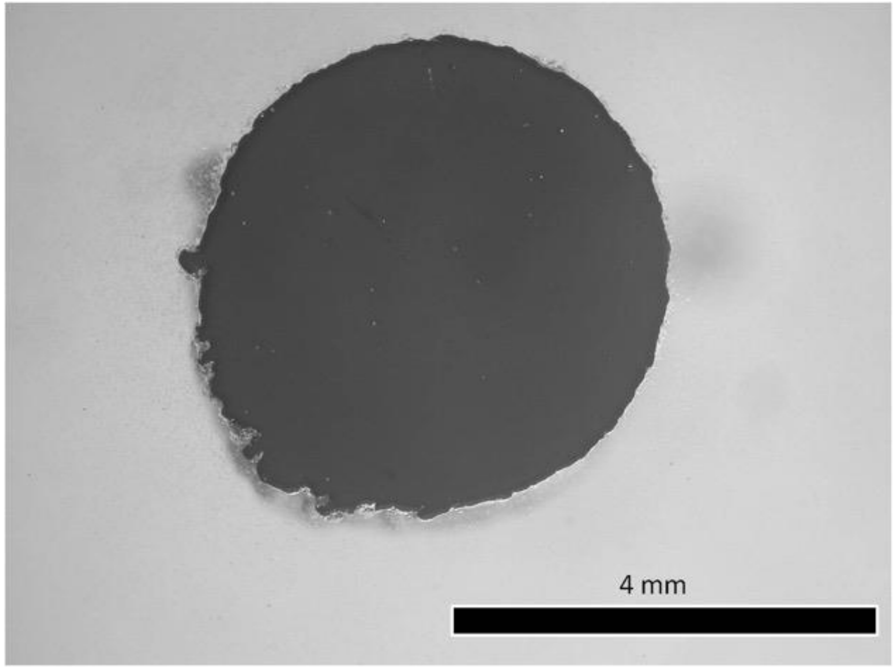
A @ 90°
B @ 0°
C @ 60°

Porosity in laser powder bed fusion

A case study



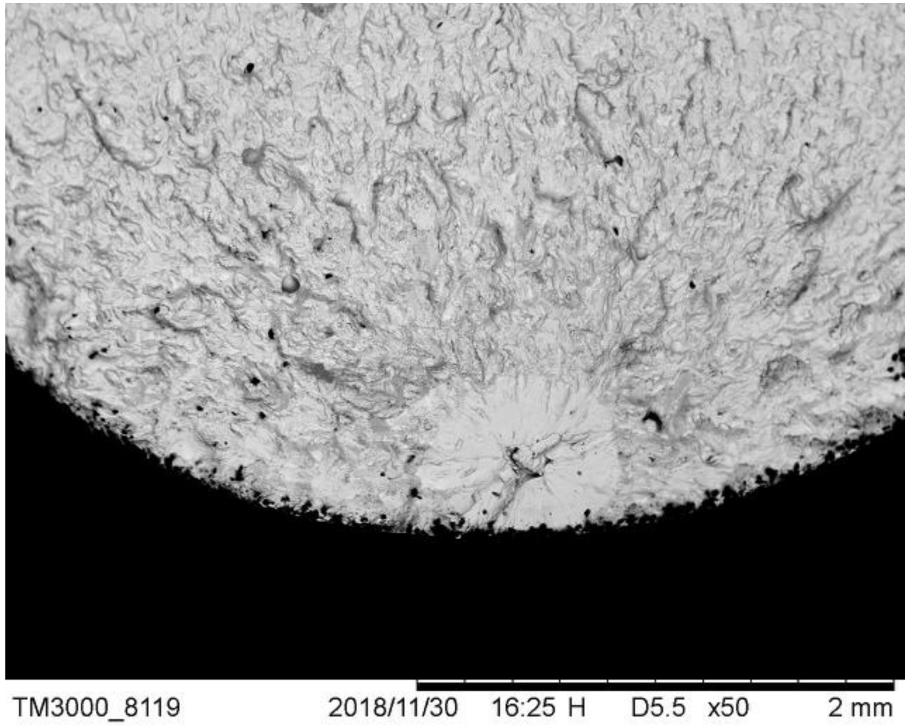
specimen cross section
A = 90°

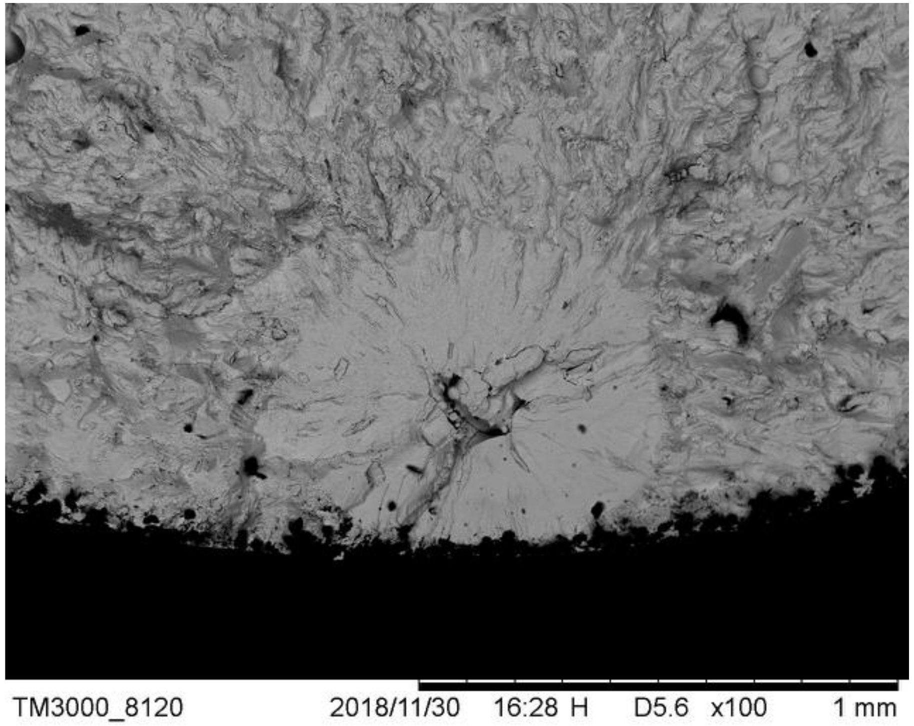


specimen cross section
C = 60°

Porosity in laser powder bed fusion

A case study



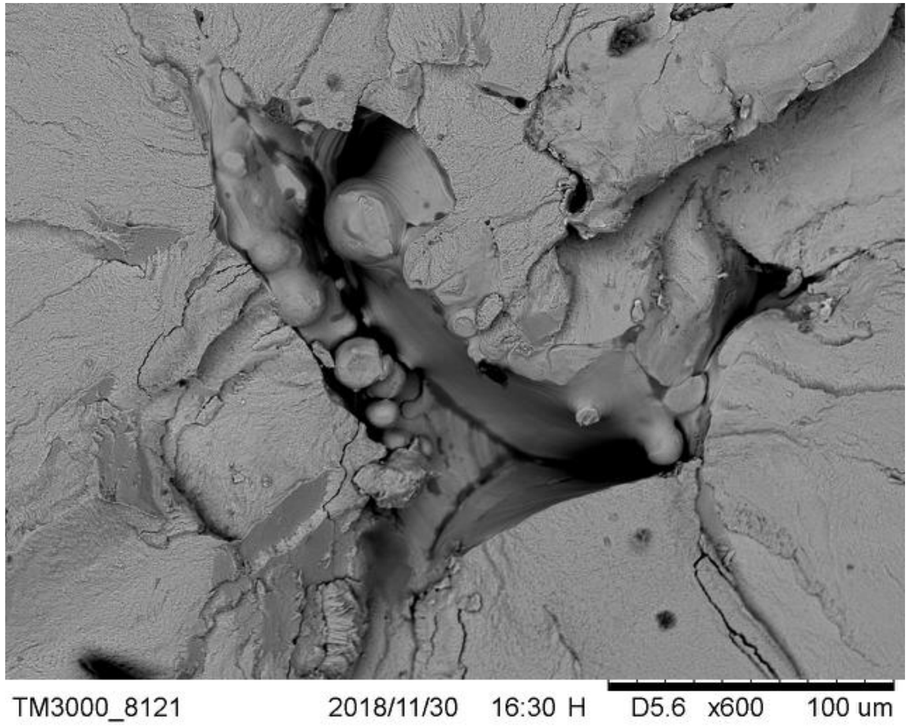


Fracture surface images, at different magnifications, of a type A specimen

*Low stressed and lasted over 1 * 10^6 cycles*

Porosity in laser powder bed fusion

A case study



Fracture surface images, at different magnifications, of a type A specimen

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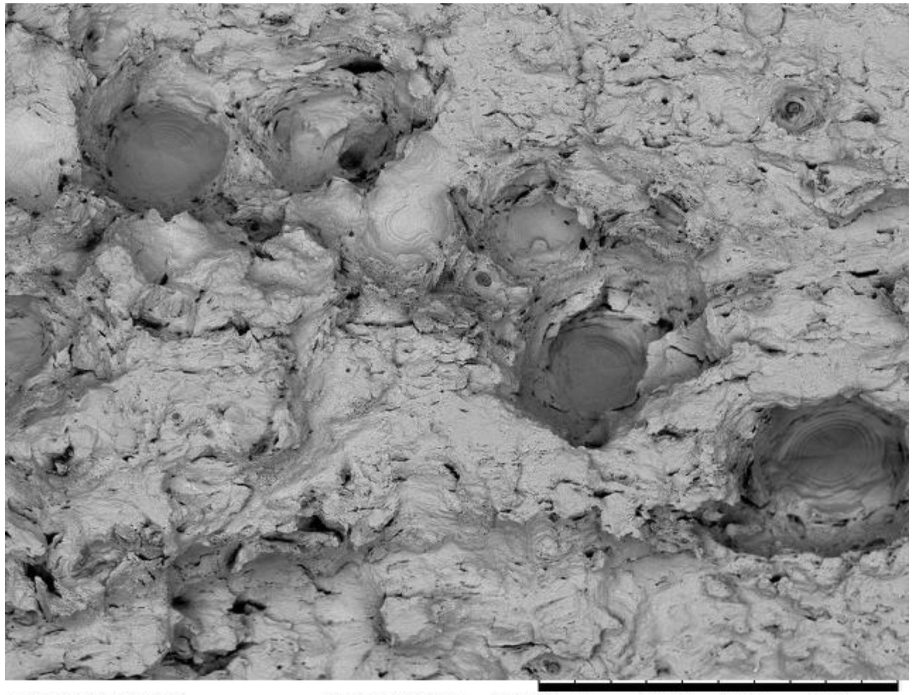
Porosity in laser powder bed fusion

A case study



Fracture surface images, at different magnifications, of a type A specimen

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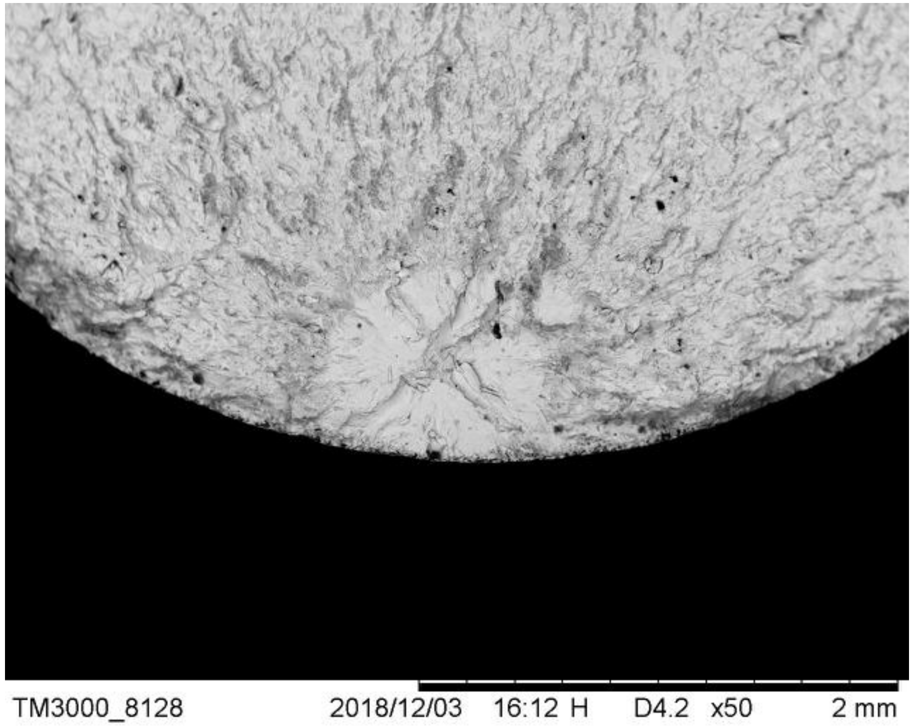
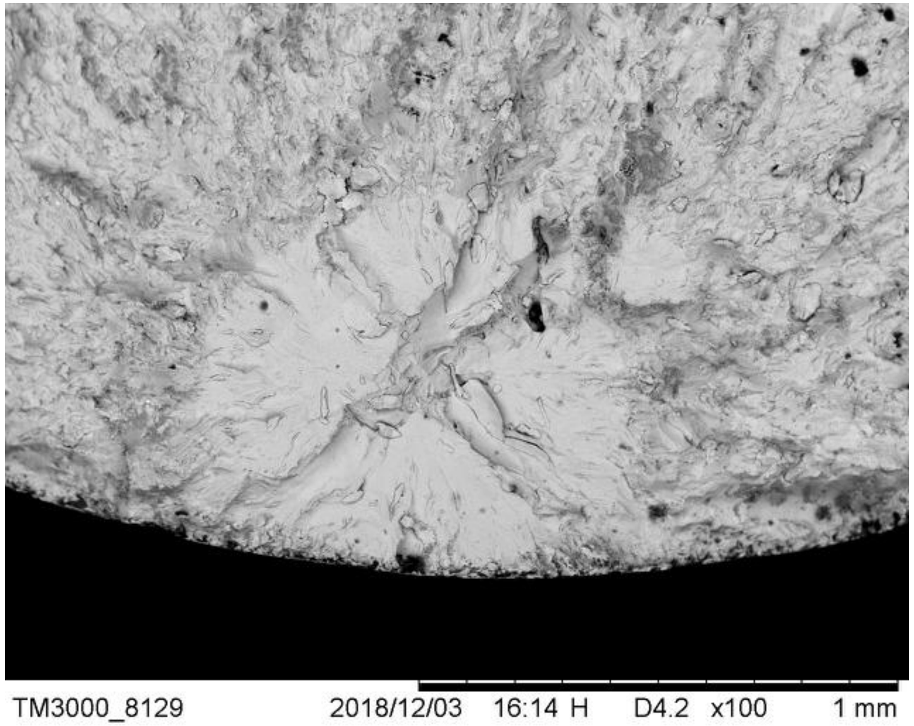
Porosity in laser powder bed fusion

A case study



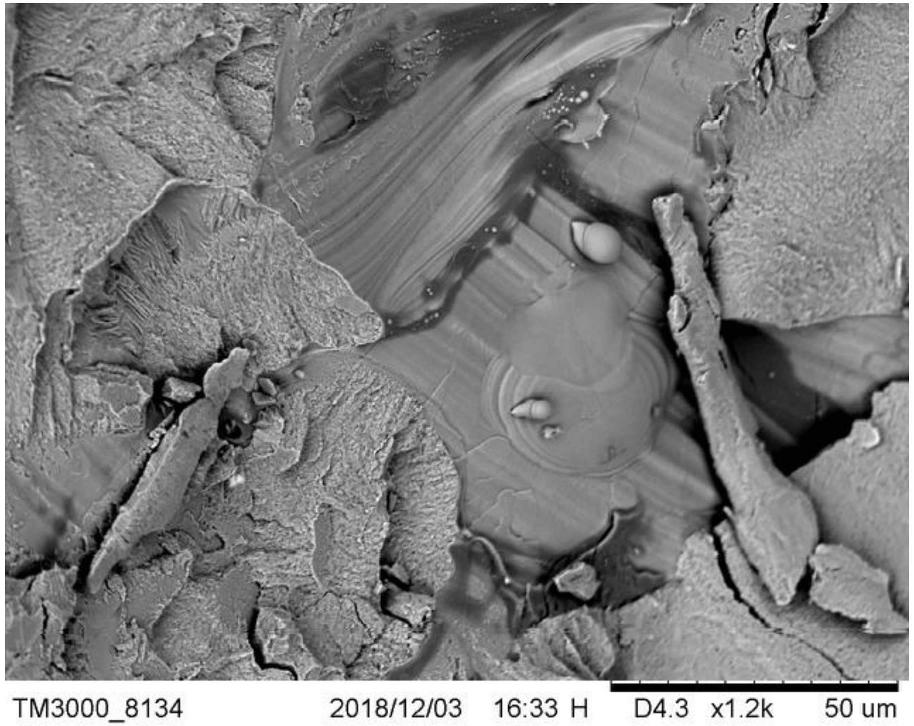


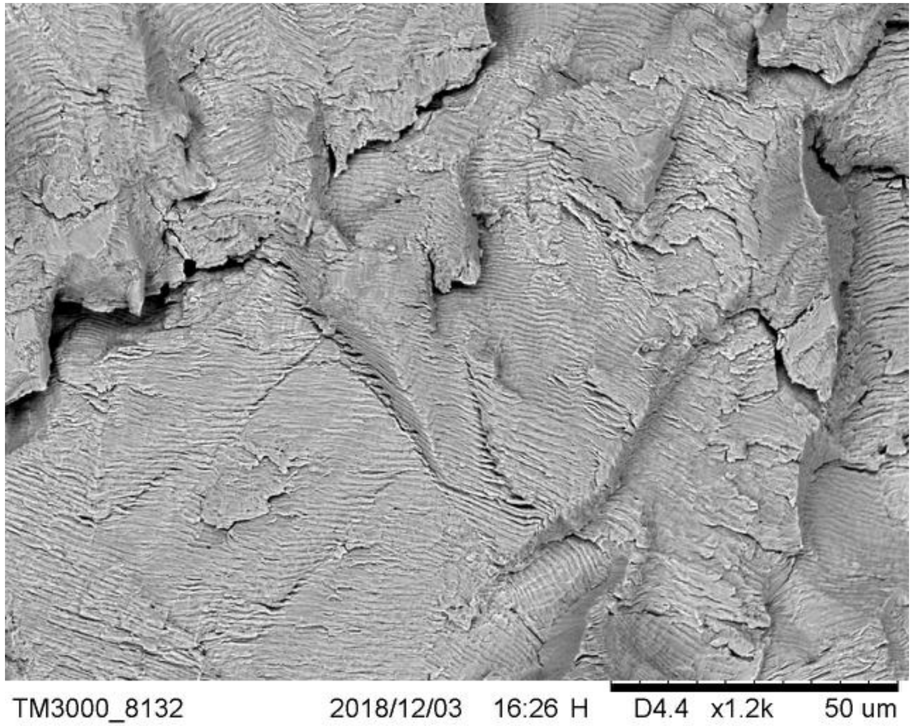
Fracture surface images, at different magnifications, of a type C specimen

*Low stressed and lasted slightly less than 1 * 106 cycles*

Porosity in laser powder bed fusion

A case study





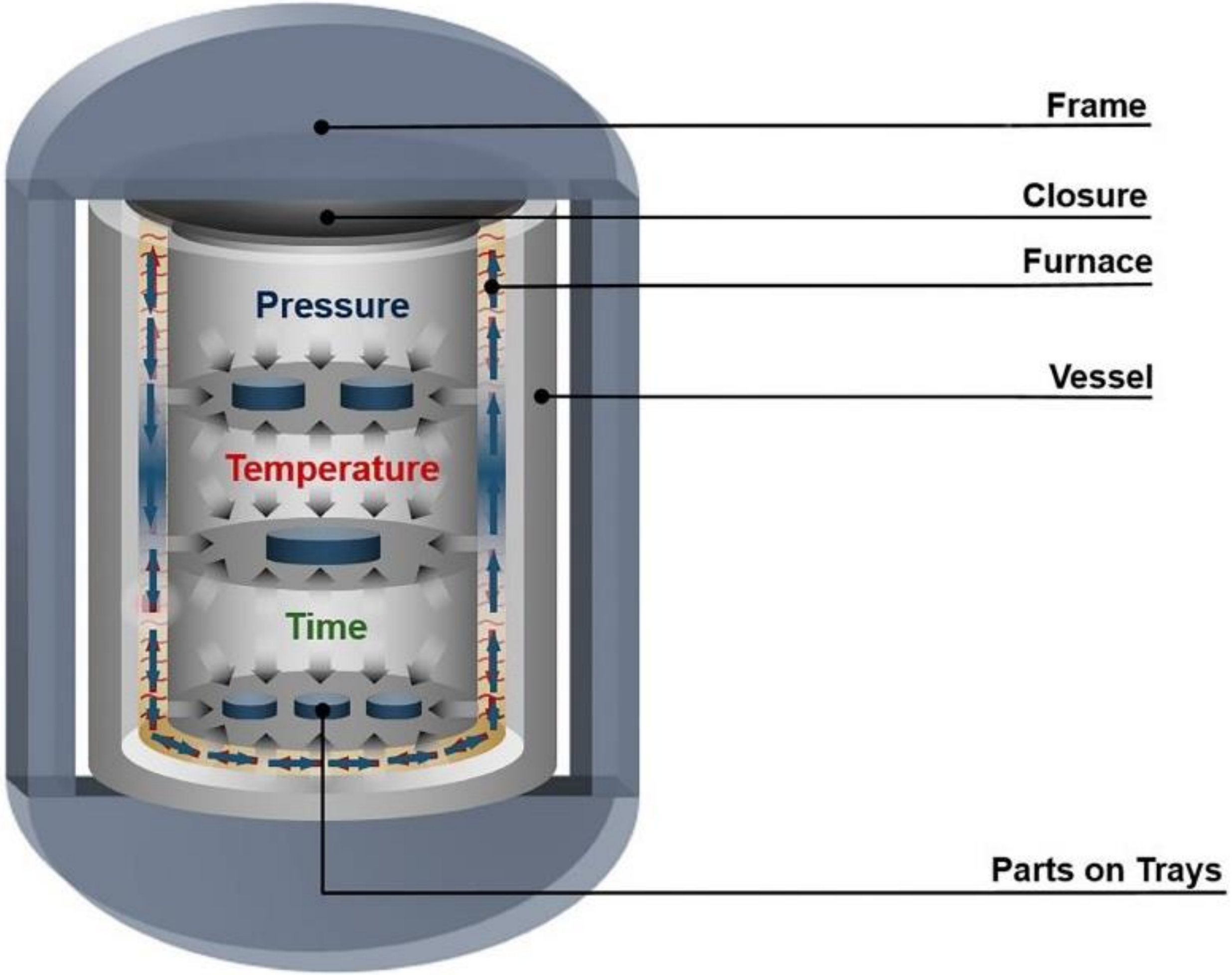
Fracture surface images, at different magnifications, of a type C specimen

*Low stressed and lasted slightly less than 1 * 106 cycles*

Porosity in laser powder bed fusion

Pore closure and mitigation

Hot isostatic pressing



Porosity in laser powder bed fusion

Pore closure and mitigation

Hot isostatic pressing

This high temperature and high pressure process consolidates pores entirely and closes all forms of pores in L-PBF except those very near the surface in isolated cases

Internal pores are easily closed but near-surface pores connected to the surface make the HIP process ineffective and are not closed

Porosity in laser powder bed fusion

Pore closure and mitigation

Hot isostatic pressing

HIP is performed not only for pore closure but it also coarsens the microstructure removing anisotropy and improving the ductility of the material

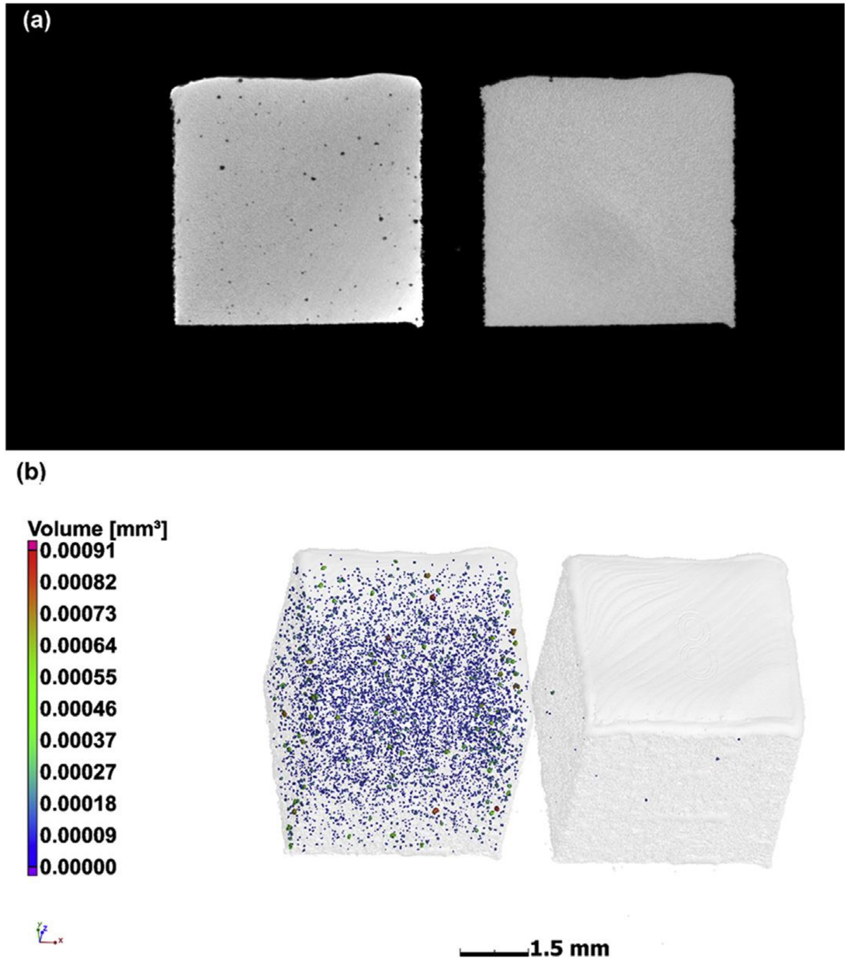
This typically improves the fatigue strength, and a partial role is played by the closure of pores in this improvement

Near-surface pores may remain problematic which also highlights the need for surface processing or strategies to improve the surface finish in the L-PBF process itself

Porosity in laser powder bed fusion

Pore closure and mitigation

Hot isostatic pressing



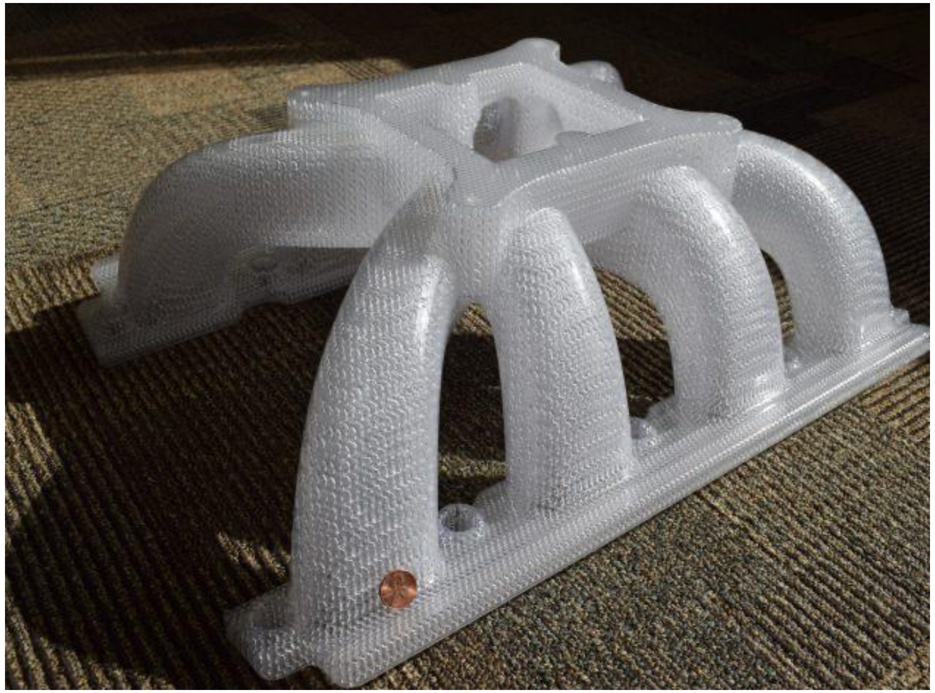
Industrial Drivers for AM Adoption

Rapid Tooling

SL resins expand more than wax and crack the ceramic shell.

The QuickCast™ pattern style was added automatically to hollow part STL files by SL machine pre-processing software.

The QuickCast™ lattice struts were designed to flex, collapse inward, break, but not transfer high loads to the part skins which could crack the shell.



Industrial Drivers for AM Adoption

Rapid Tooling

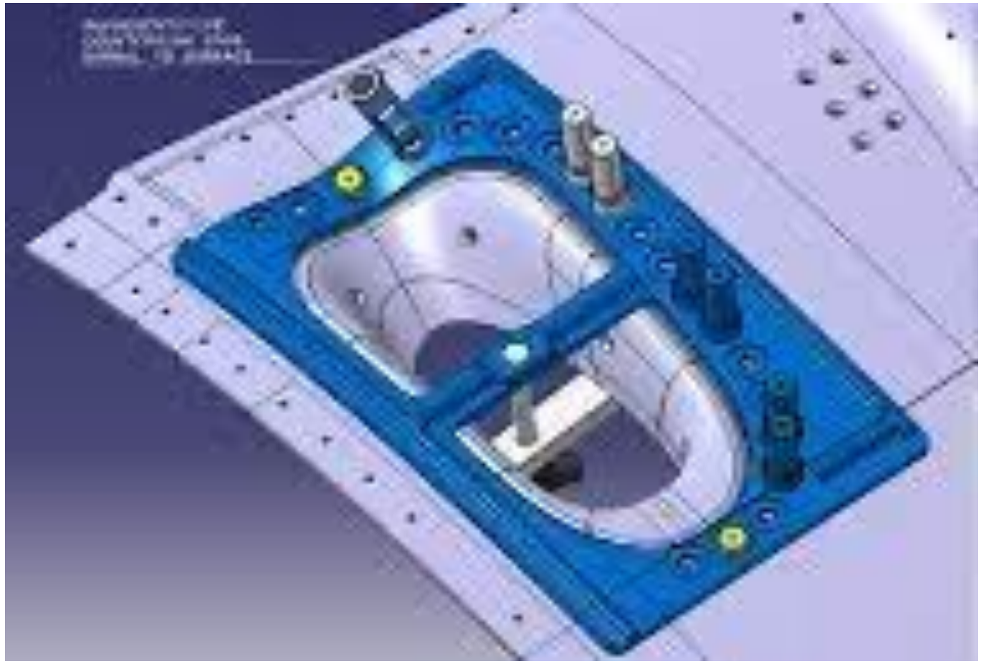
Boeing, Northrop Grumman, and other aerospace companies have used Material Extrusion technology to fabricate tooling.

They developed tooling designs for composite part layup

Industrial Drivers for AM Adoption

Rapid Tooling

Other reported tooling applications included drill guides and various assembly tools.



Industrial Drivers for AM Adoption

The Use of AM to Support Medical Applications

Industrial Drivers for AM Adoption

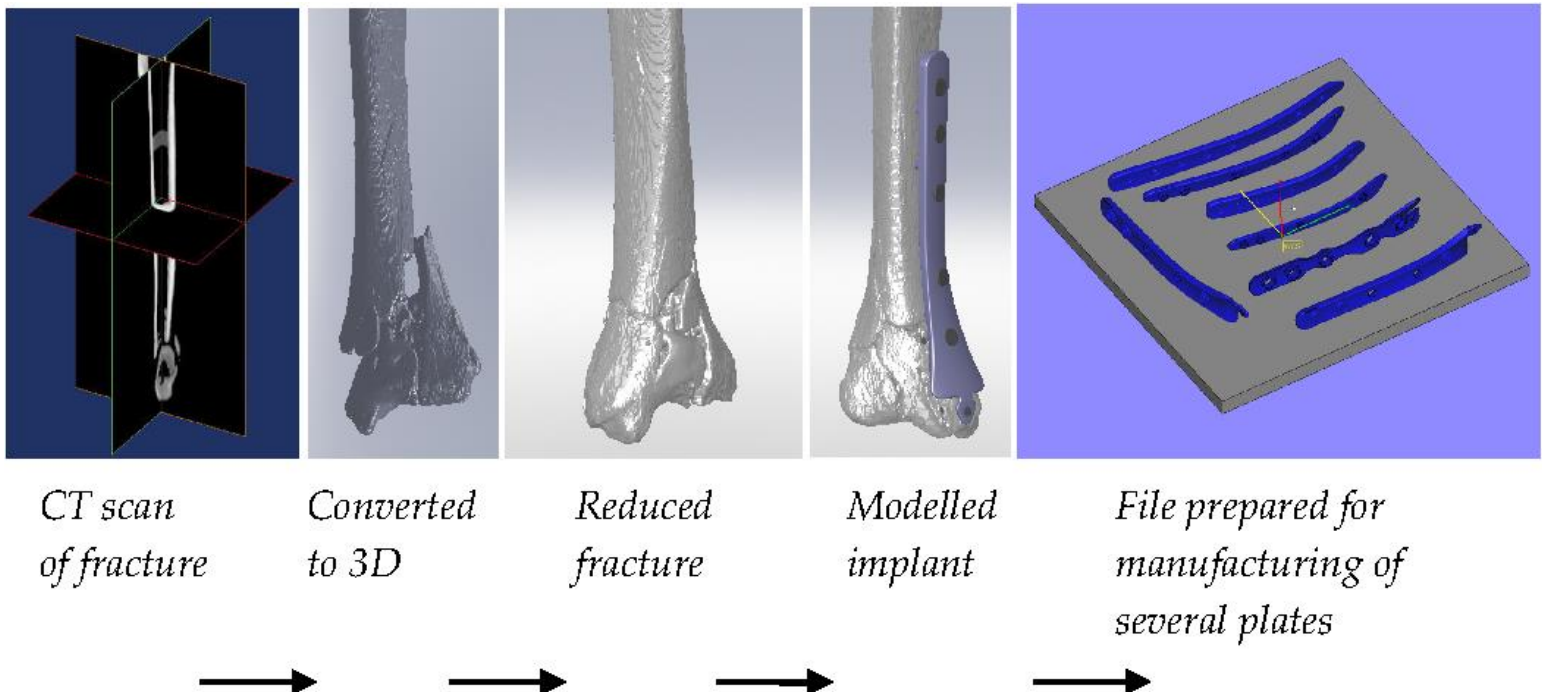
The Use of AM to Support Medical Applications

- Orthopedics
- Surgical and diagnostic aids
- Prosthetics and implants
- Tissue engineering
- Software tools and surgical guides

Industrial Drivers for AM Adoption

The Use of AM to Support Medical Applications

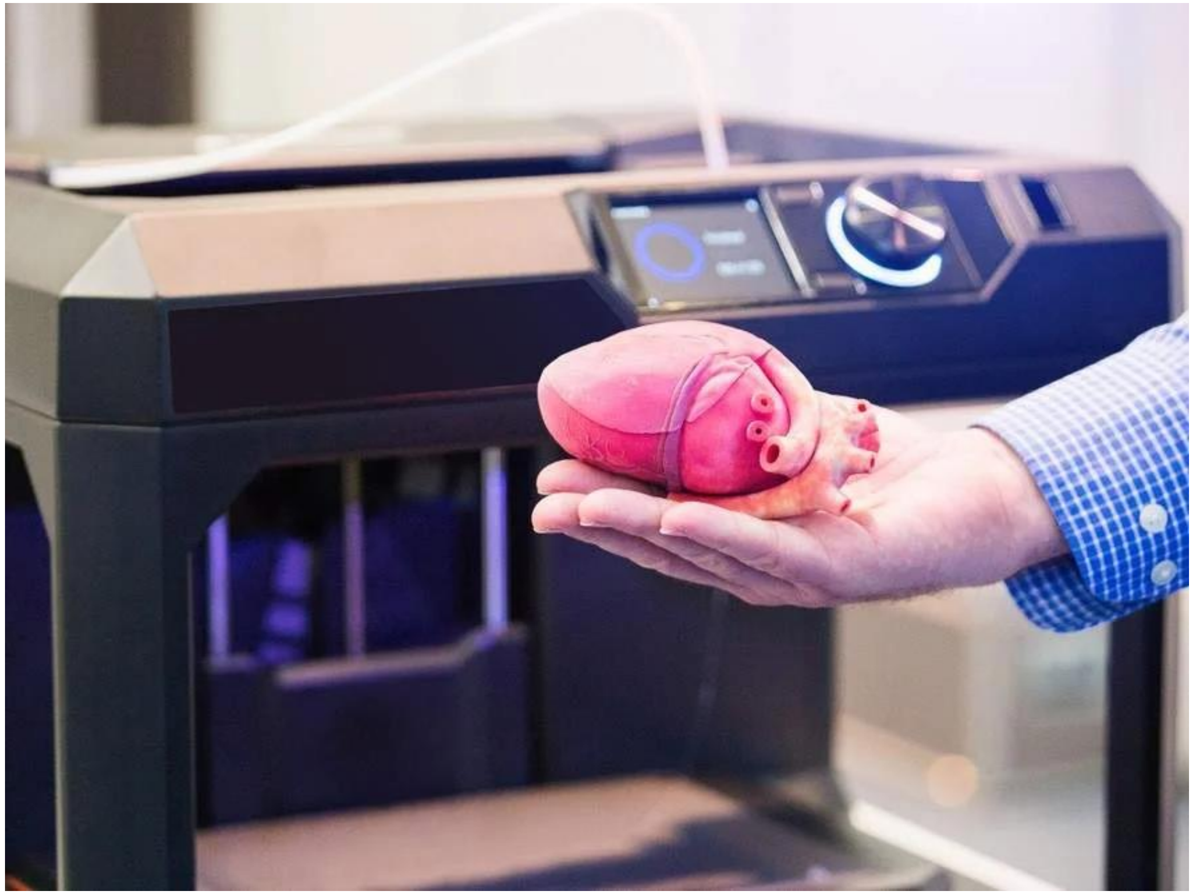
Orthopedics



Industrial Drivers for AM Adoption

The Use of AM to Support Medical Applications

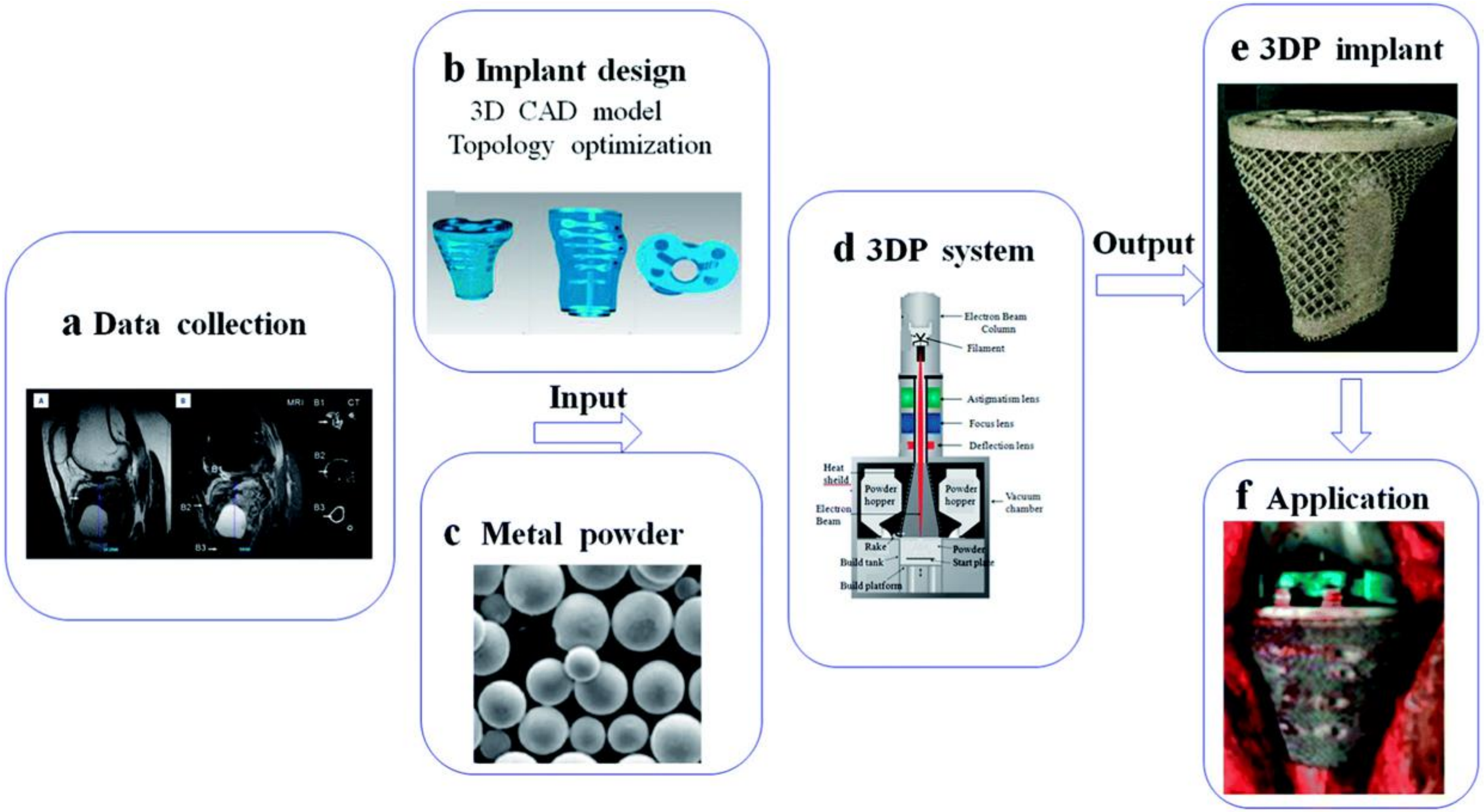
Surgical and diagnostic aids



Industrial Drivers for AM Adoption

The Use of AM to Support Medical Applications

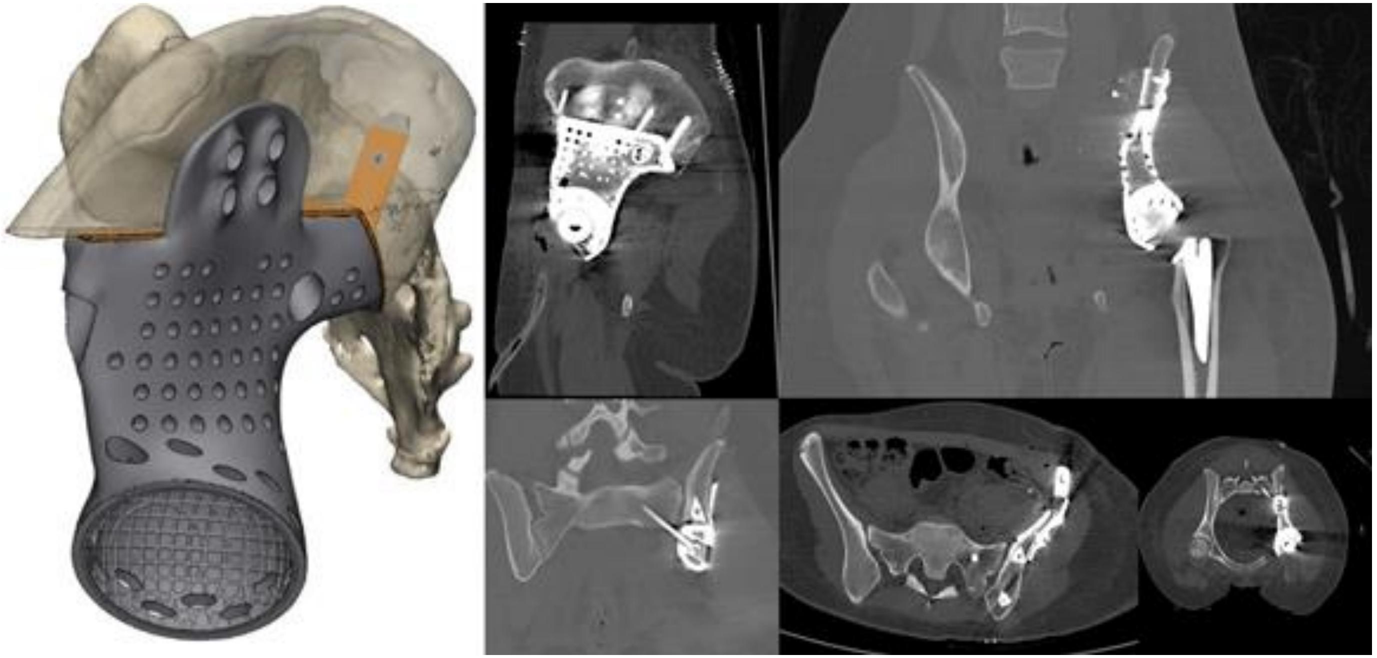
Prosthetics and implants



Industrial Drivers for AM Adoption

The Use of AM to Support Medical Applications

Prosthetics and implants



Industrial Drivers for AM Adoption

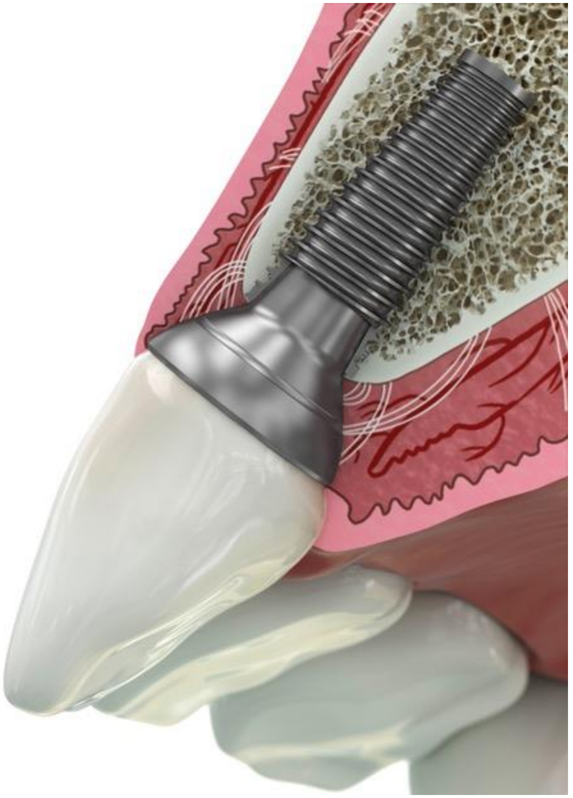
The Use of AM to Support Medical Applications

Prosthetics and implants

Industrial Drivers for AM Adoption

The Use of AM to Support Medical Applications

Prosthetics and implants



Industrial Drivers for AM Adoption

The Use of AM to Support Medical Applications

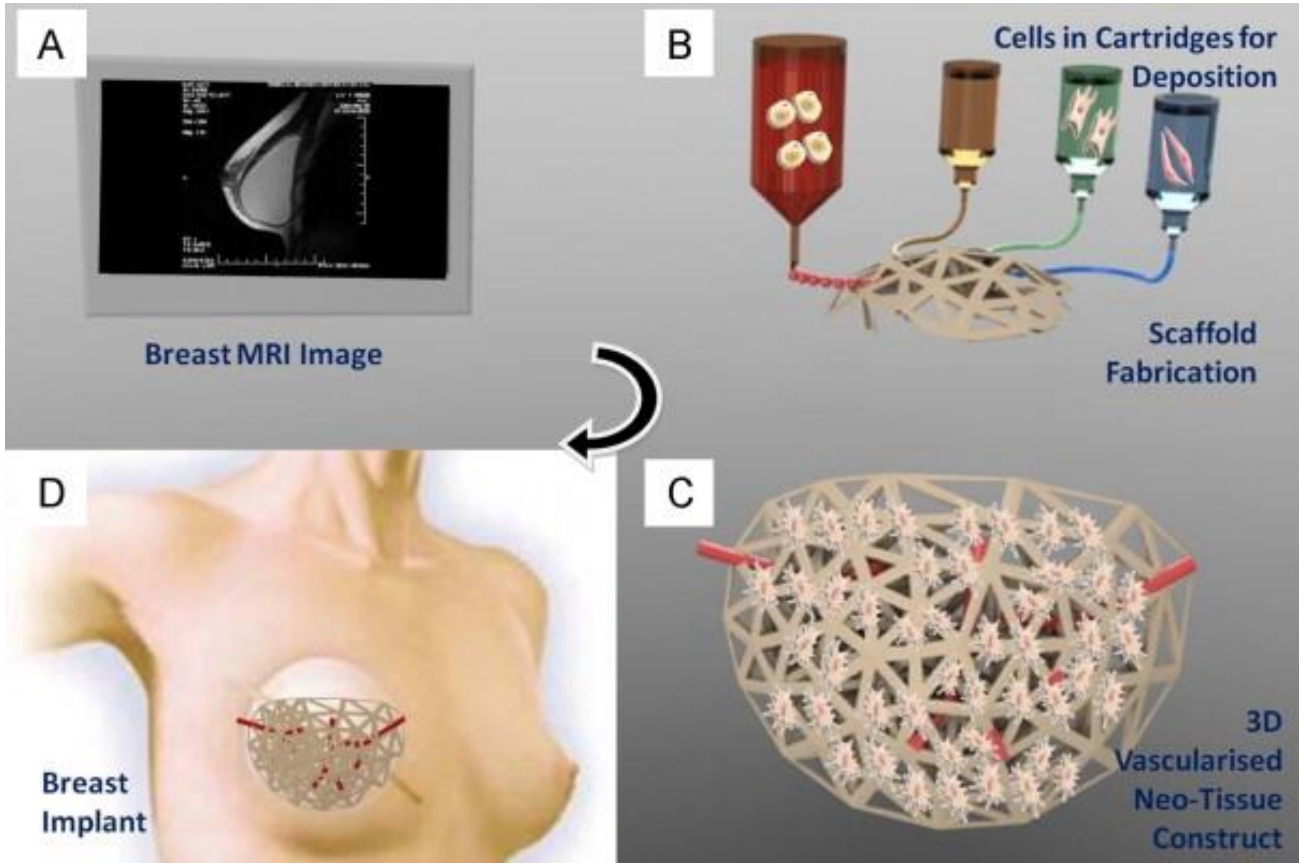
Five Fraunhofer institutes have developed a bespoke additively manufactured joint implant, intended to restore the mobility of fingers with damaged joints

The goal was to create an automated process which would allow personalised finger joint implants to be produced from metal or ceramic in a rapid, safe and certified process.

Industrial Drivers for AM Adoption

The Use of AM to Support Medical Applications

Tissue engineering



Industrial Drivers for AM Adoption

The Use of AM to Support Medical Applications

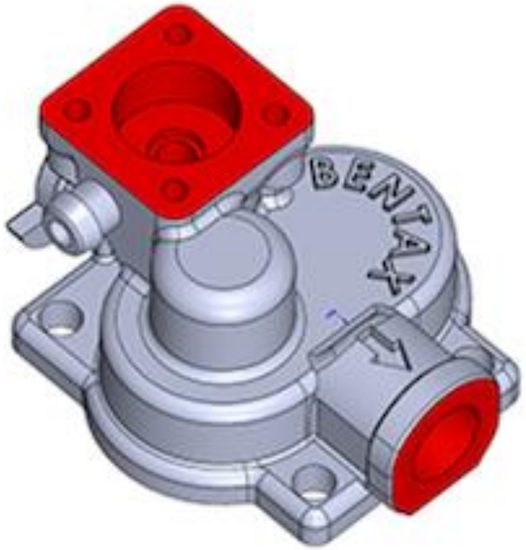
Surgical guides

New applications of AM

New applications of AM

The Danish Technological Institute has partnered with coffee supplier Bentax to showcase the use of Additive Manufacturing in the replacement part sector.

The company replaced the previous, expensive milk pumps with additively manufactured spare parts, reducing production waste and expense



New applications of AM

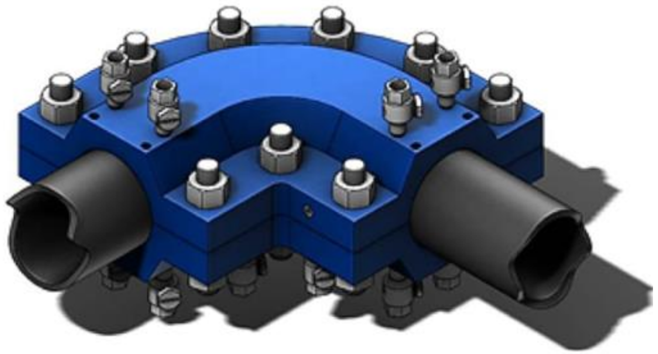
Airflight, a startup aerospace company based in Brønderslev, Denmark, is working to develop multi-rotor aircraft, including large drone-based flying cranes.

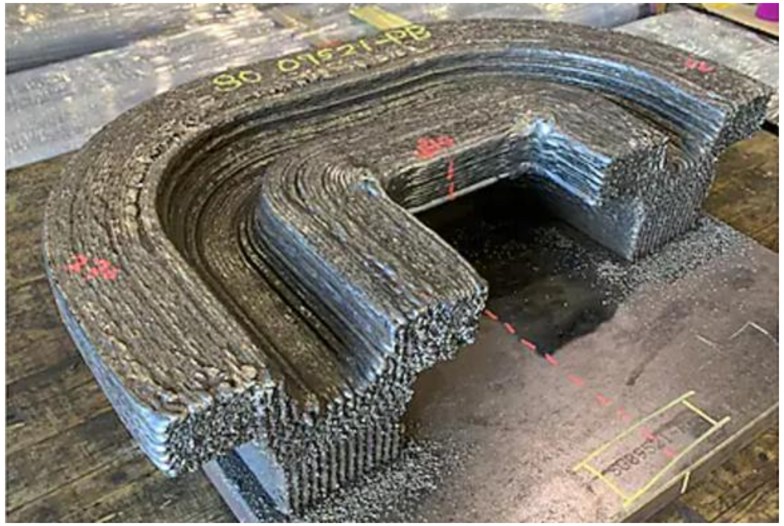
The company is reported to have already benefitted from the technology, reducing the weight of brackets used to hold the arms of the drone by some 67%.

New applications of AM

Shell has successfully installed its first additively manufactured leak repair clamp in service.

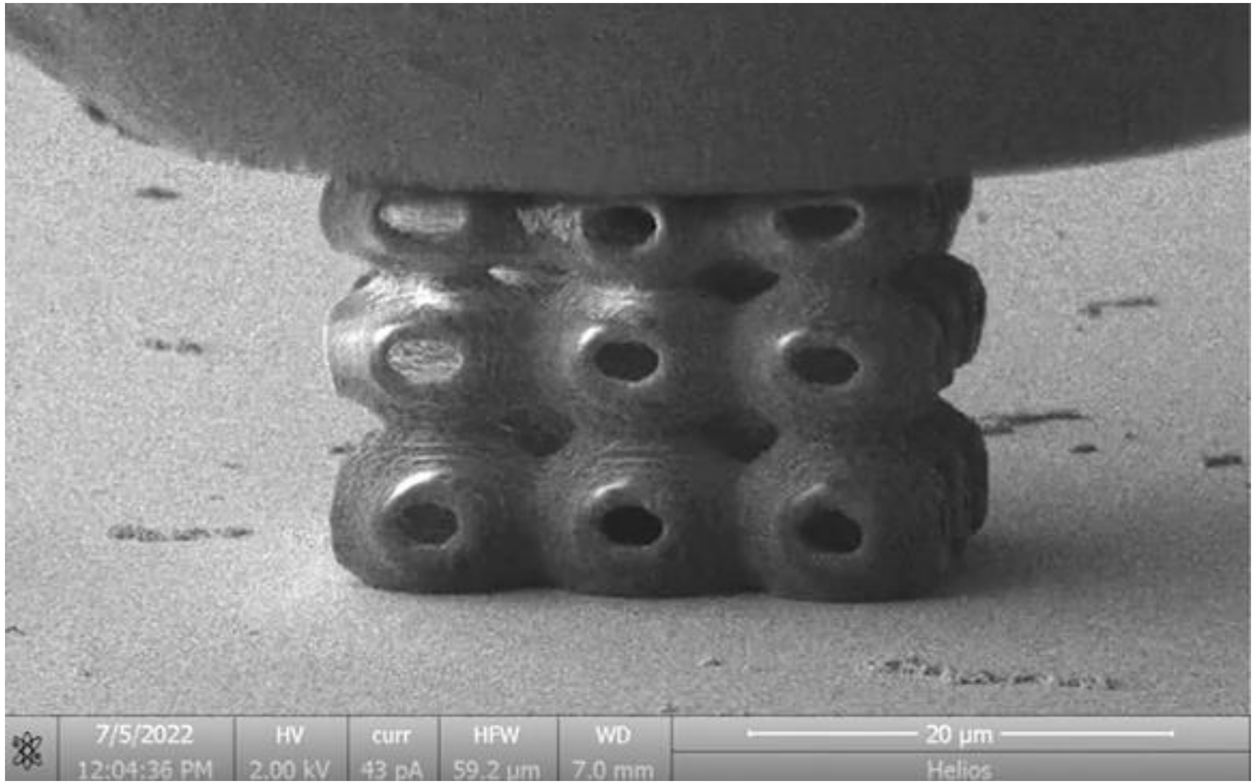
Clamps are engineered solutions used to encapsulate and restore pipelines against pipeline defects or wall thinning arising through erosion and corrosion mechanisms.





New applications of AM

Researchers from Stanford University, California, USA, have designed a new metal/polymer composite for nanoscale Additive Manufacturing capable of absorbing twice the energy of materials with a similar density.



New applications of AM

GE 9X

New applications of AM

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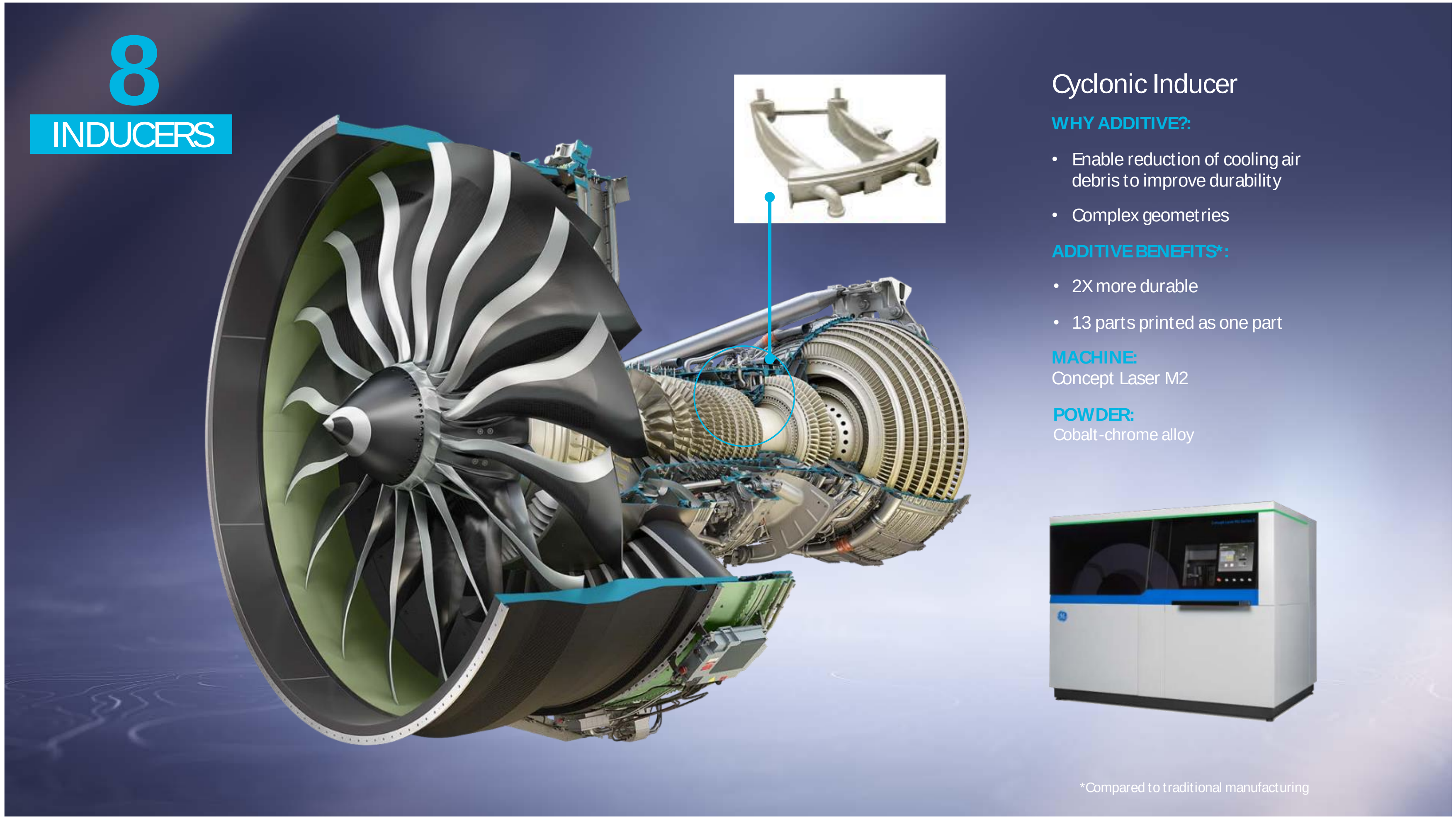
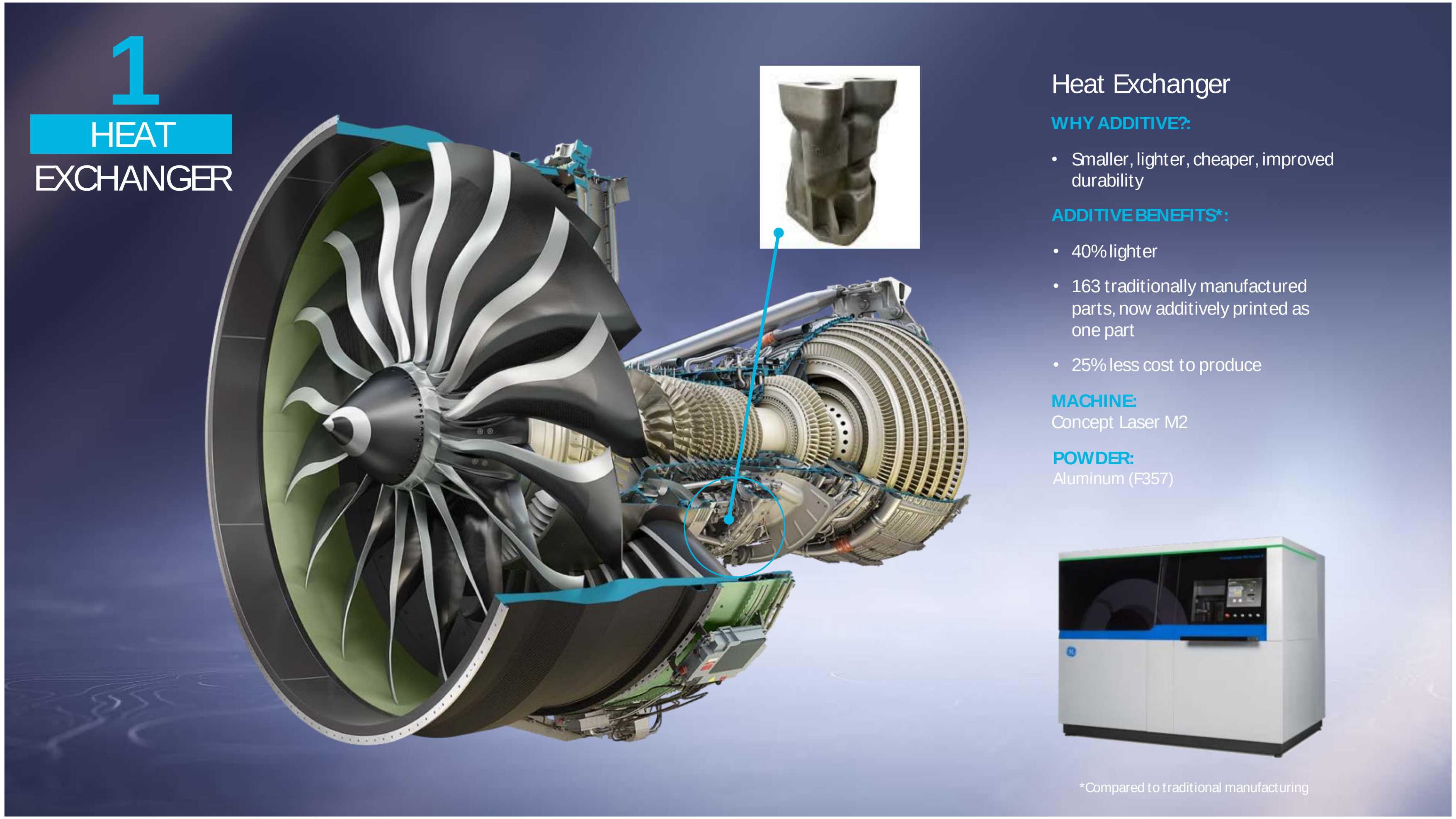
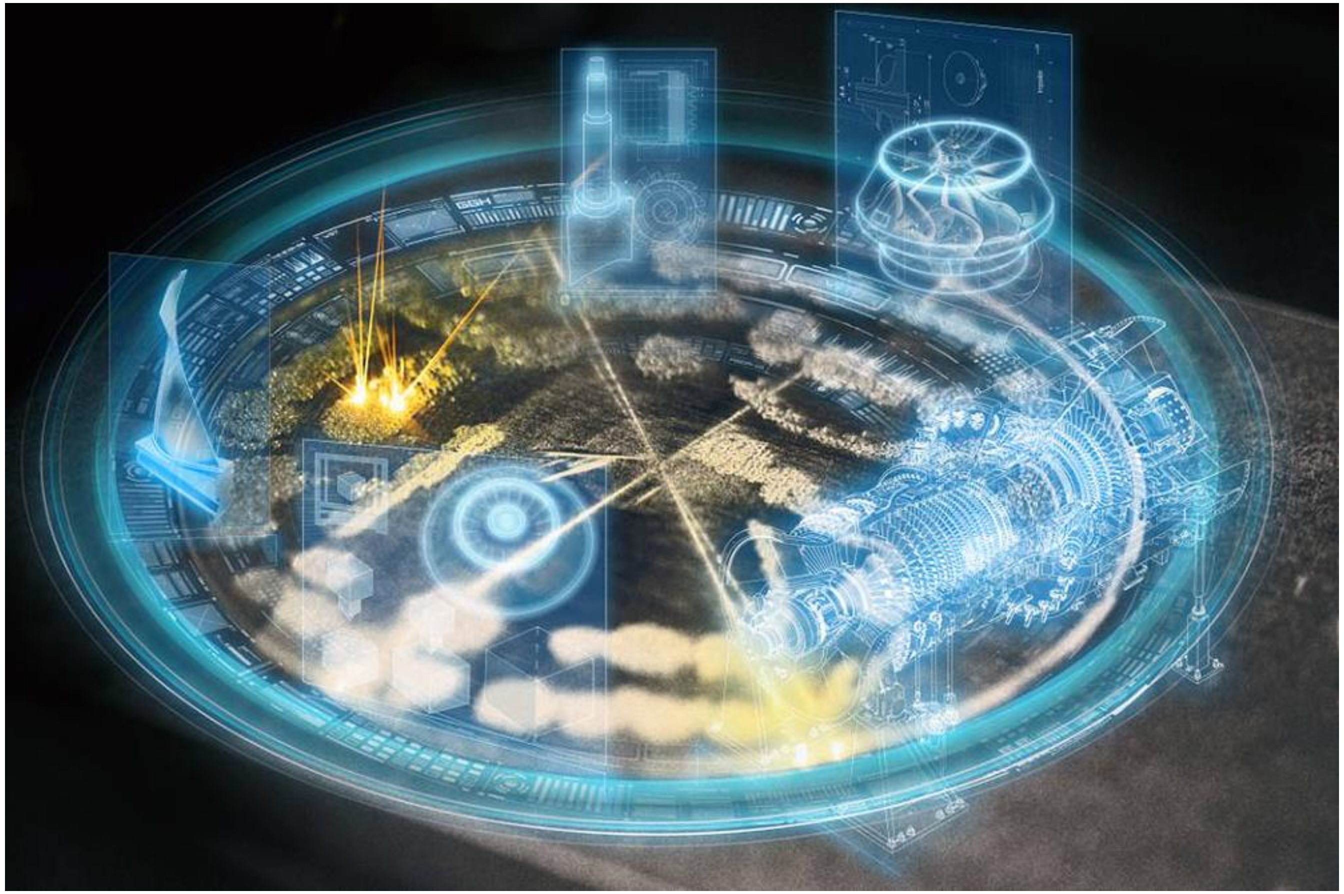


New applications of AM

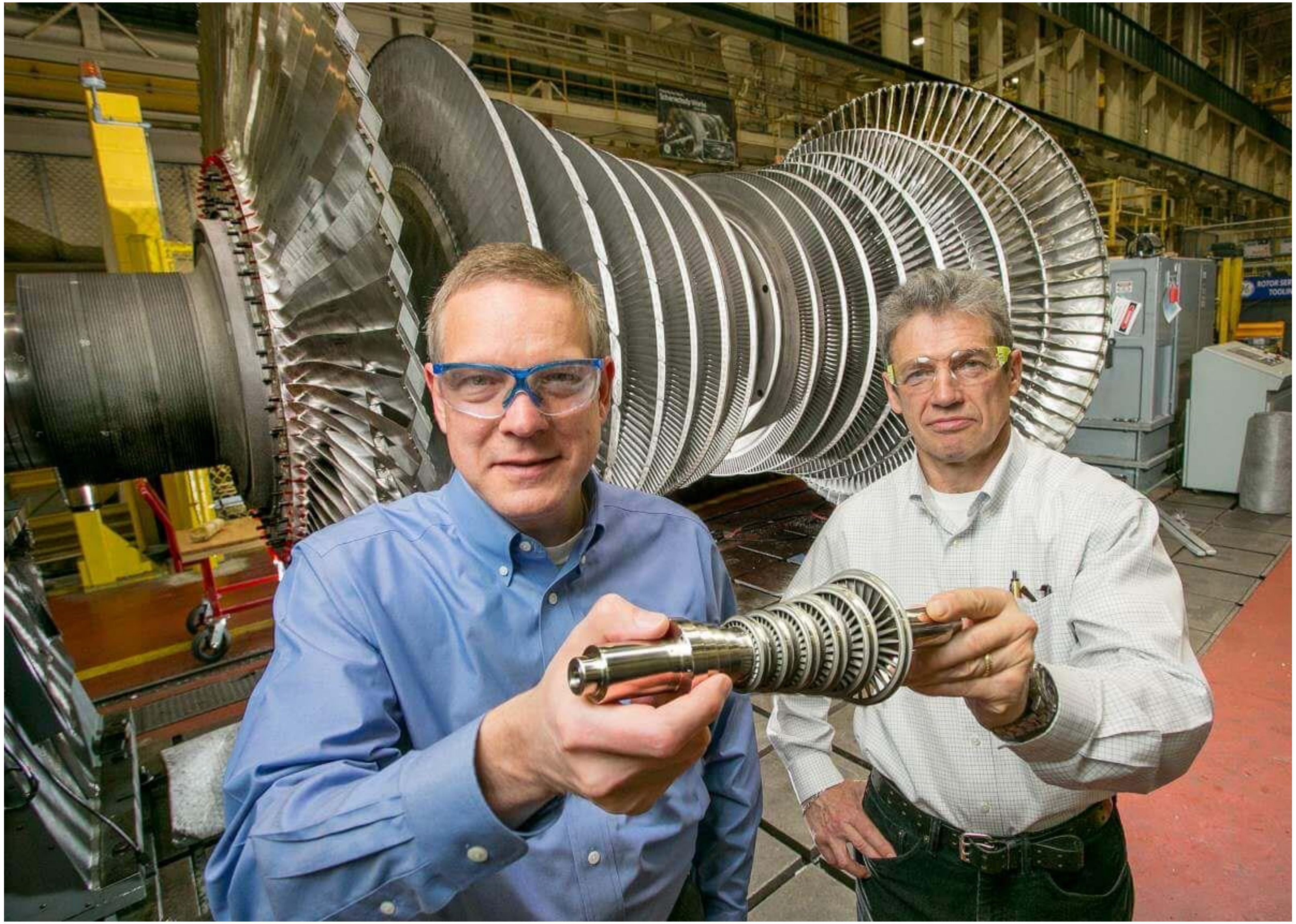
GE 9X



WHAT IS THE FUTURE OF ADDITIVE MANUFACTURING?



WHAT IS THE FUTURE OF ADDITIVE MANUFACTURING?



Q&A (hopefully)

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