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SAM
SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

Contents

- SAM Project
- Course Background
- Attendee Feedback Commitments
- Introduction to LB PBF

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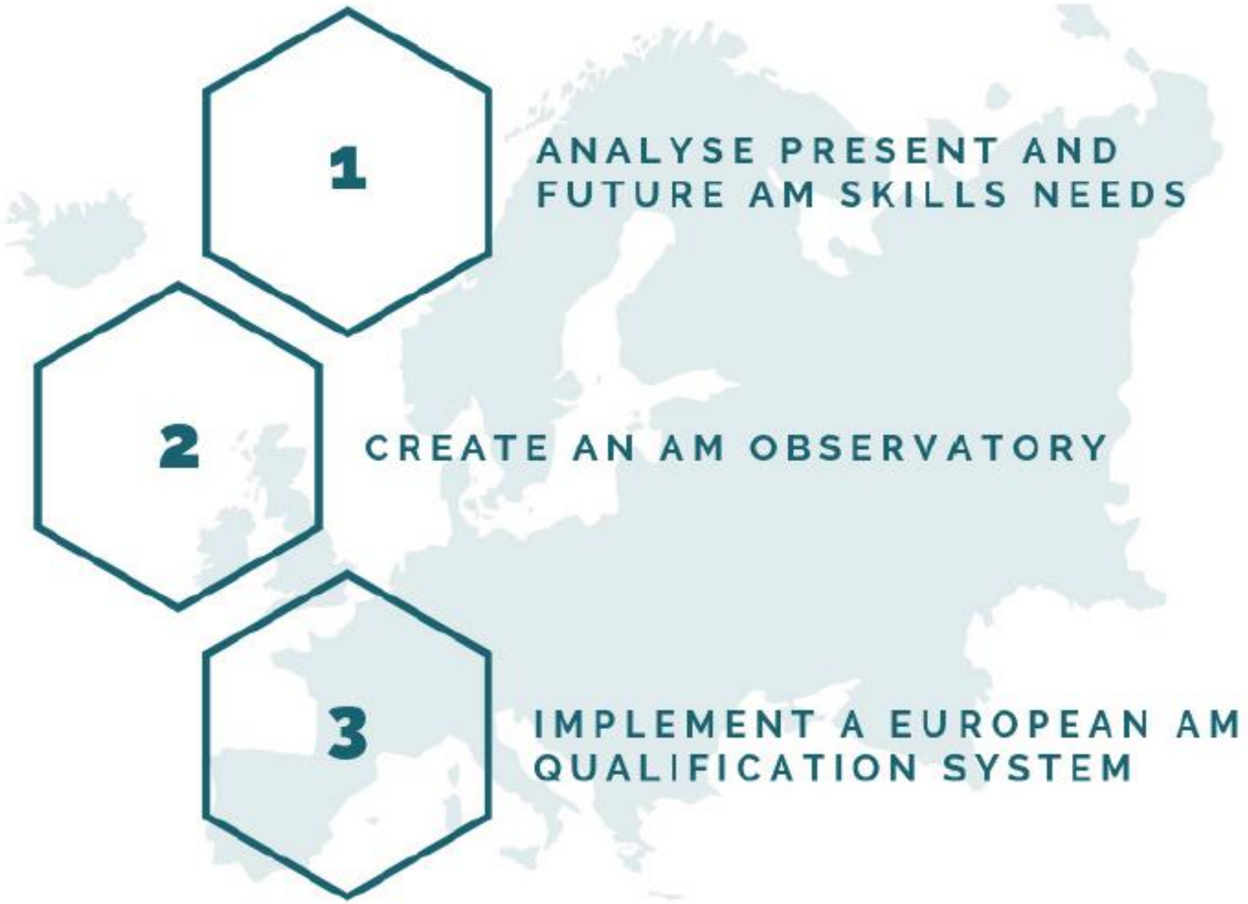
OBJECTIVES



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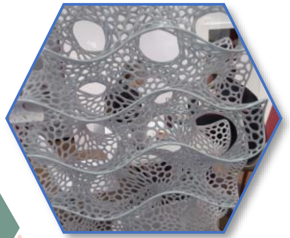
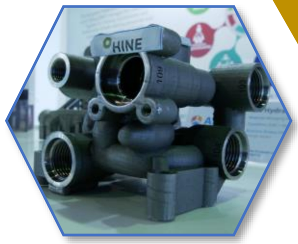
EXPECTED RESULTS



- Methodology assessment current & future skills
- Skills strategy in AM
- Methodology design & review professional profiles
- Observatory in AM
- Promotion of attractiveness AM sector & stakeholders' engagement
- Development of qualifications /competence units & Online Catalogue
- Action plan exploitation of results & roll-out at National, Regional levels



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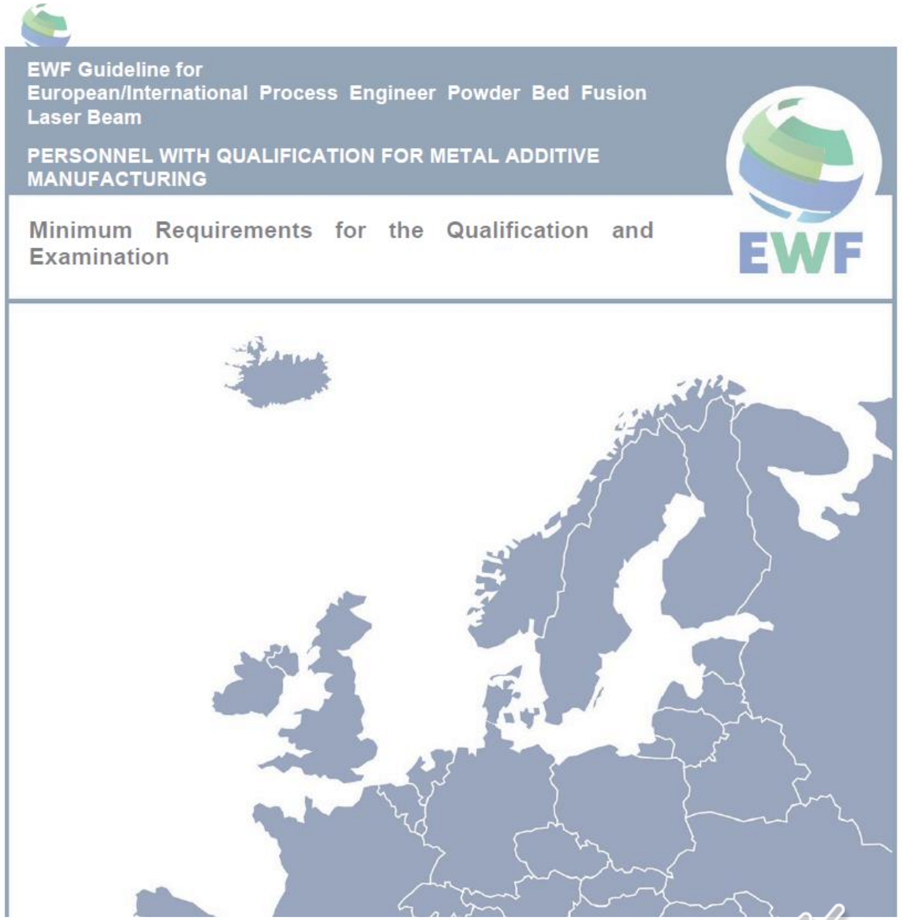
Course Background

- European/International Process Engineer Powder Bed Fusion Laser Beam
- Evaluated and formulated by the EWF International Additive Manufacturing Qualification Council (IAMQC)
- Full qualification equivalent to Level 8 Degree


EWF Guideline for
European/International Process Engineer Powder Bed Fusion Laser Beam

PERSONNEL WITH QUALIFICATION FOR METAL ADDITIVE MANUFACTURING

Minimum Requirements for the Qualification and Examination

EWF

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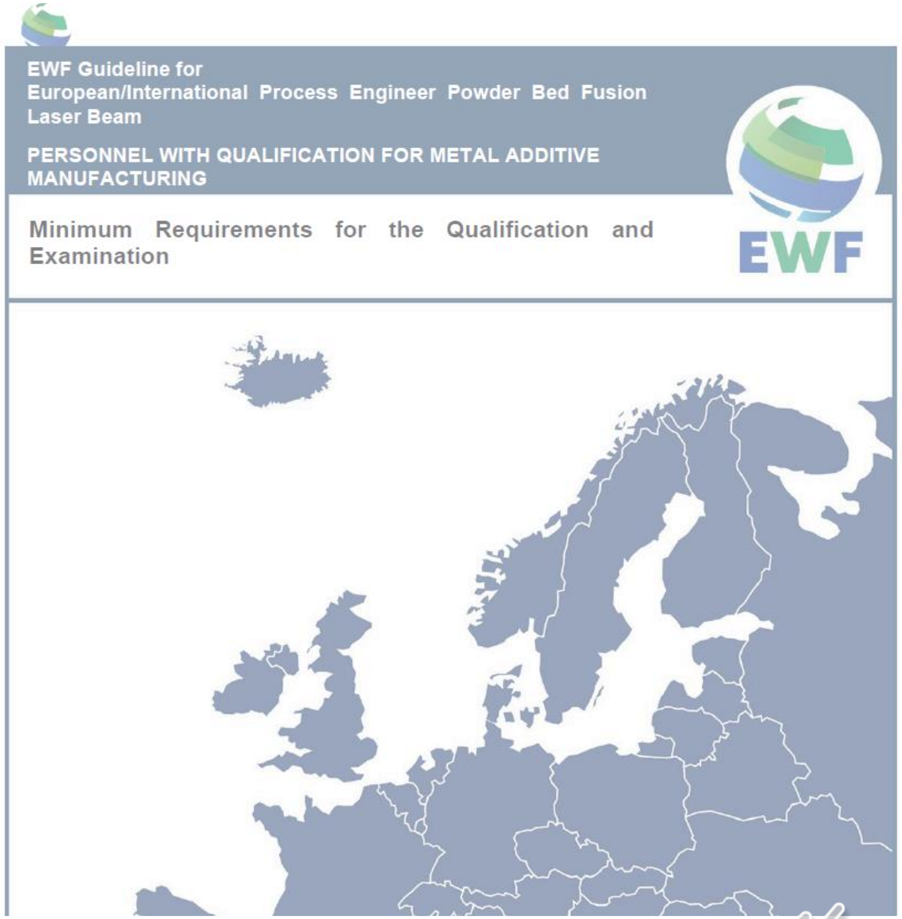
Course Background

COMPETENCE UNITS PBF-LB
CU 00: Additive manufacturing Process Overview
CU 01: DED-Arc Process
CU 08: DED-LB Process
CU 15: PBF-LB Process
CU 25: Post Processing
CU 34: Process selection
CU 35: Metal AM integration
CU 36: Coordination activities
CU 43: Production of PBF-LB parts
CU 44: Conformity of PBF-LB parts
CU 45: Conformity of facilities featuring PBF-LB
OPTIONAL
CU 26: Introduction to materials
MATERIALS (2 REQUIRED)
CU 27: AM with steels feedstock (excluding Stainless Steel)
CU 28: AM with Stainless Steel feedstock
CU 29: AM with Aluminium feedstock
CU 30: AM with Nickel feedstock
CU 31: AM with Titanium feedstock
CU 32: AM with Tungsten feedstock
CU 33: Biomedical metallic materials



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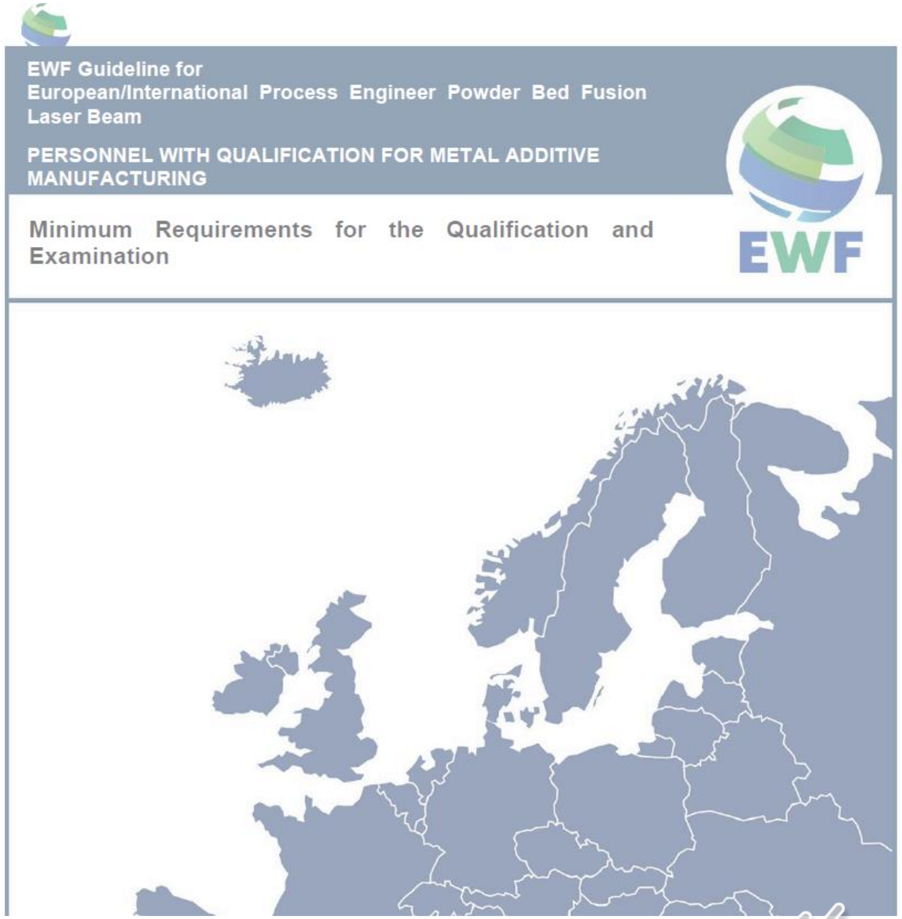
CU 15: PBF-LB Process

COMPETENCE UNITS PBF-LB	LEVEL
PBF-LB Process Principles	Operator
PBF-LB System – Hardware and Software	Operator
PBF-LB Parameters	Operator
PBF-LB Feedstock	Operator
PBF-LB Consumables	Operator
Post Processing	Operator
PBF-LB Processes	Engineer
PBF-LB Build substrate, feedstock and other consumables	Engineer
PBF-LB Equipment and accessories	Engineer
PBF-LB Manufacturing strategy	Engineer



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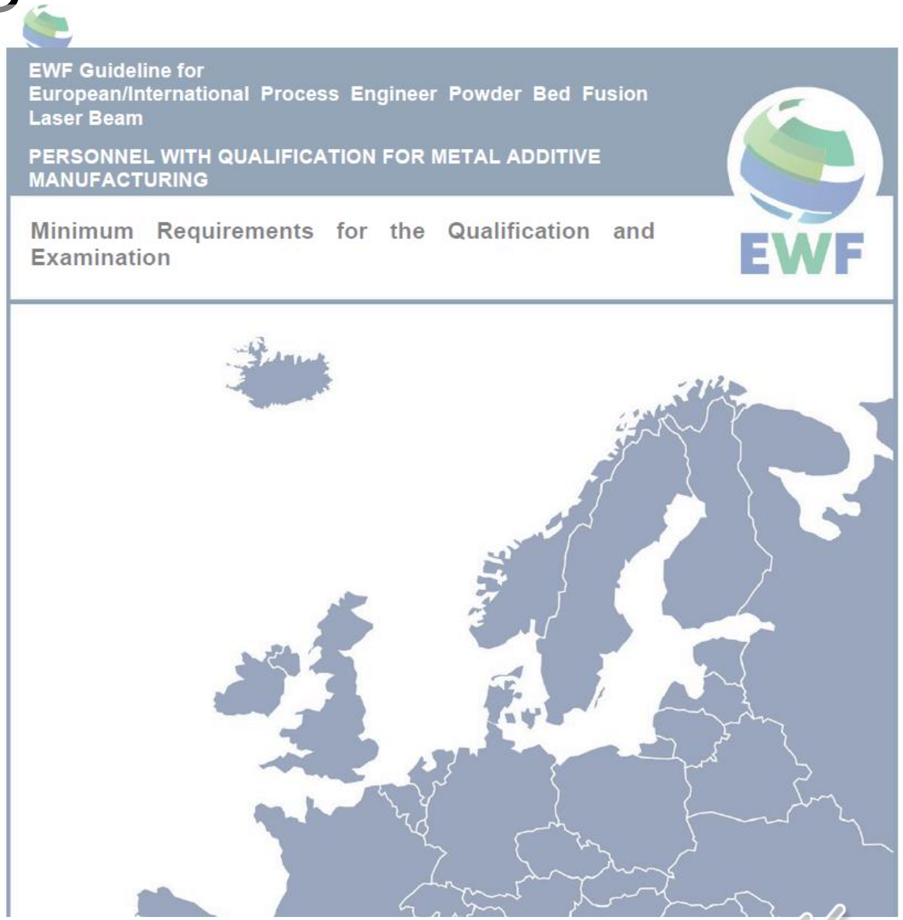
CU 15: PBF-LB Process Learning Outcomes

- Advanced Knowledge of:
  - PBF-LB equipment etc.
  - PBF-LB process parameters etc.
- Advanced Skills:
  - PBF-LB process
  - Process parameters effect on part
  - Influence of consumables on part
  - Areas needing thermal compensation
  - Defect causation & mitigation
  - Regimes and processes of failure
  - Materials selection
  - Metallurgical aspects of PBF-LB parts
  - PBF-LB manufacturing strategy


EWF Guideline for
European/International Process Engineer Powder Bed Fusion Laser Beam

PERSONNEL WITH QUALIFICATION FOR METAL ADDITIVE MANUFACTURING

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Competence Unit 15: PBF-LB Process IMR PILOT

Module	Release Date
System Hardware	*Launch*
System Software	*Launch*
Parameters	*Launch*
Feedstock	17/12/2021
Consumables	17/12/2021
Equipment & Accessories	08/01/2021
Processes	10/01/2021
Manufacturing Strategy	10/01/2021
Post Processing	10/01/2021

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Commitments from Attendees for Pilot

- Survey Link - https://freeonlinesurveys.com/s/mhu1wzpx
- Feedback
- Assessment:
  - End of January 2021 (exact date TBD)
  - EWF will run online
  - Circa 30 minutes
  - Once completed EWF will issue a Certificate

- Creation of new standard for AM qualifications

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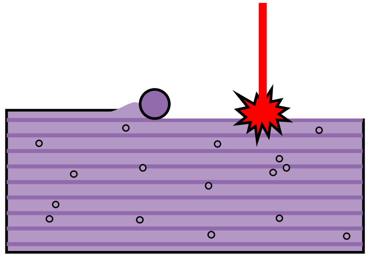
Introduction to Laser Based Powder Bed Fusion

IRISH MANUFACTURING RESEARCH

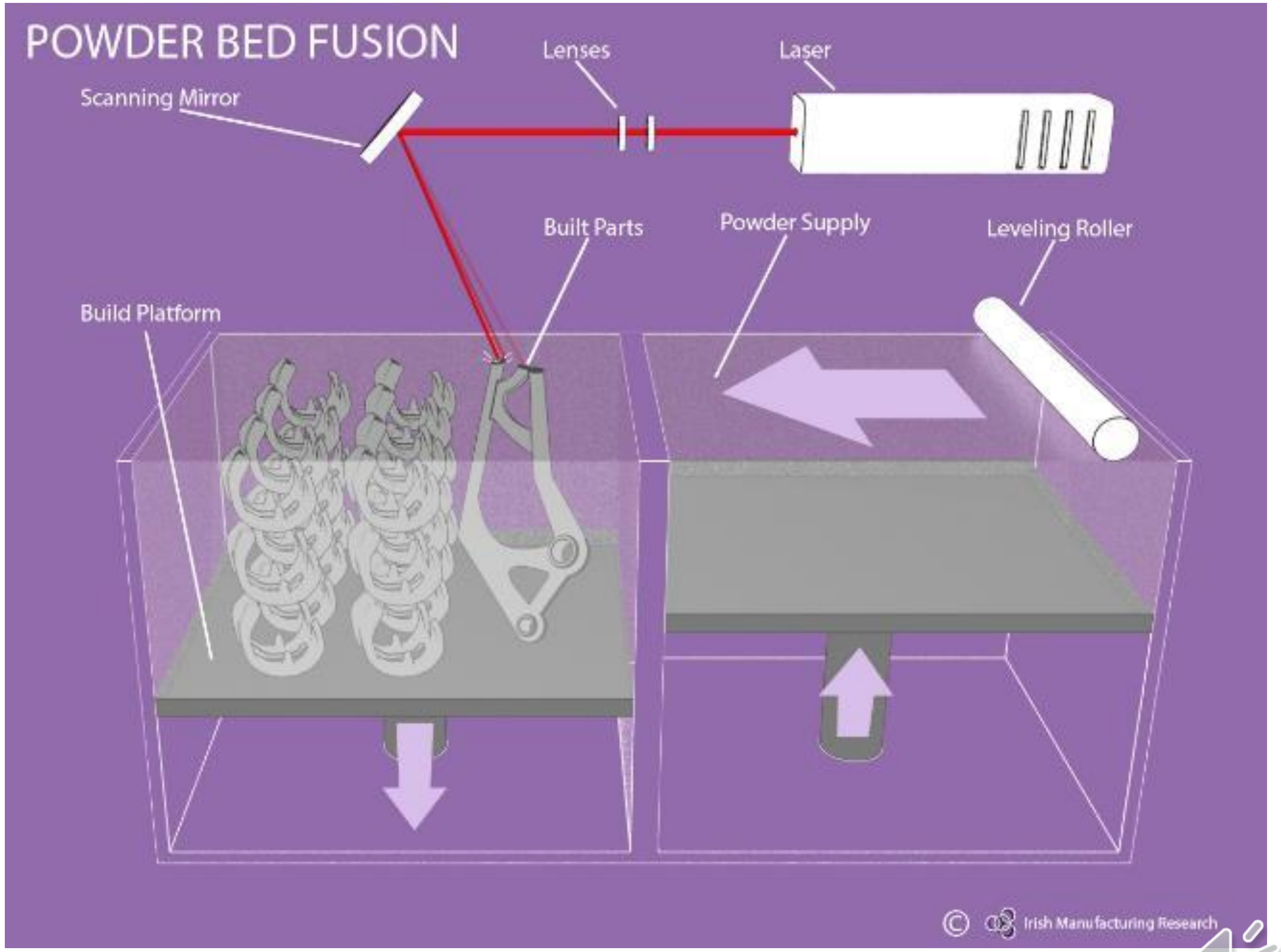
TECHNOLOGY CENTRE
ENTERPRISE IRELAND
IDA IRELAND SUPPORTED



Powder Bed Fusion Laser Beam: Process

Abbrev. **PBF-LB**

- Powder is spread across the build plate
- The laser scans the shape of the first layer
- The build platform moves down one layer height.
- The process repeats until the part is built.



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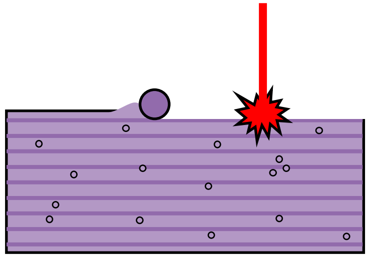

Powder Bed Fusion: Overview


Courtesy of EOS


Courtesy of Joimaxx


Courtesy of Arcam

- Highly accurate
- Great Mechanical properties
- High cost
- Limited part size

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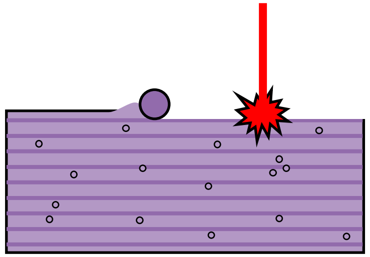


Powder Bed Fusion: Feedstock

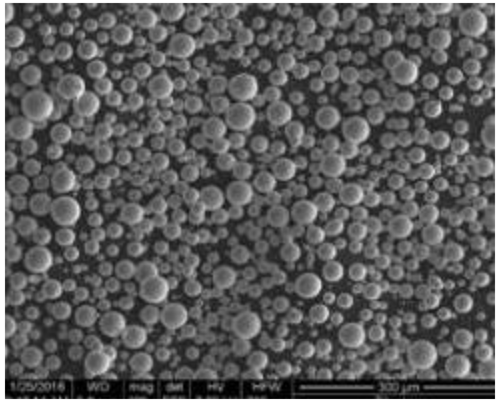
Aluminum
- AlSi10 Mg
- AlSi12
- AlSi7Mg

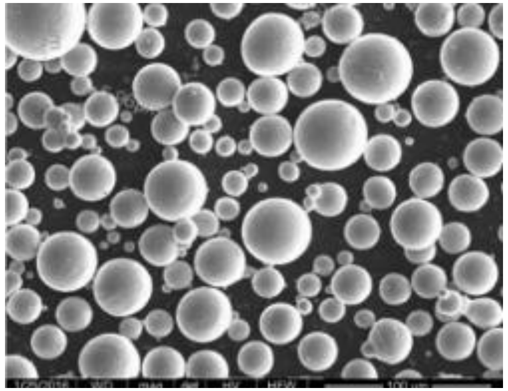
Stainless Steel
- 1.2344/H13
- 1.4313
- 1.4404
- 1.441
- 1.4540

Titanium
- Ti6Al4V
- Ti6Al7Nb

Cobalt Chromium
- CoCr ASTM F75
- CoCr MP1
- CoCr28Mo6 ASTM F799

Others
- Copper Based Alloys
- Gold
- Heavy metals
- Hot work steel
- Nickel based alloys
- Silver
- Tool steel





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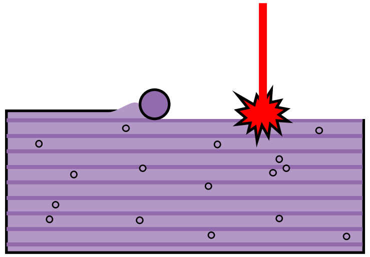

Powder Bed Fusion: Post Processing

- Compulsory
  - Heat Treatment
  - Support Removal
  - Loose Powder Removal
- Functional
  - Machining
- Surface Finish
  - Media Blasting
  - Metal Etching
  - Polishing
  - Micro-machining

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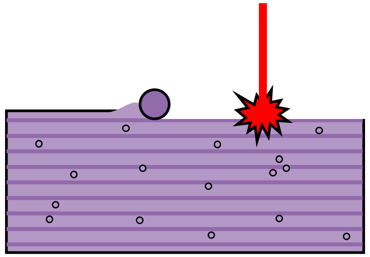
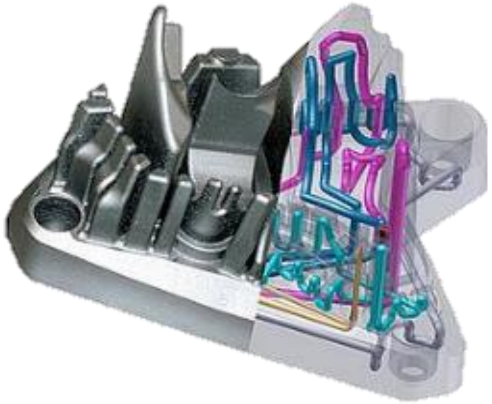


Powder Bed Fusion: Applications



Conformally Cooled Mould Insert
IQ Temp

Spinal Cage
Betatype

Optimised HX
EOS

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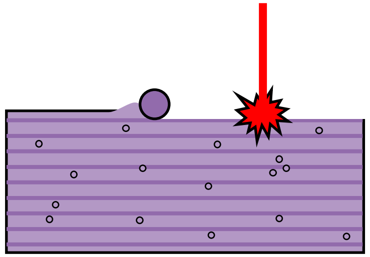
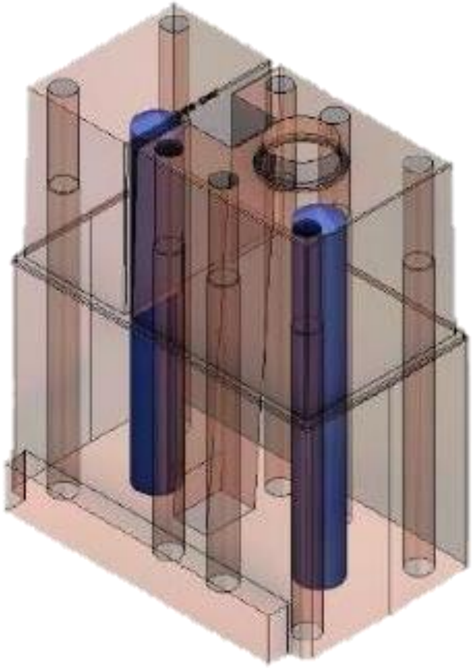
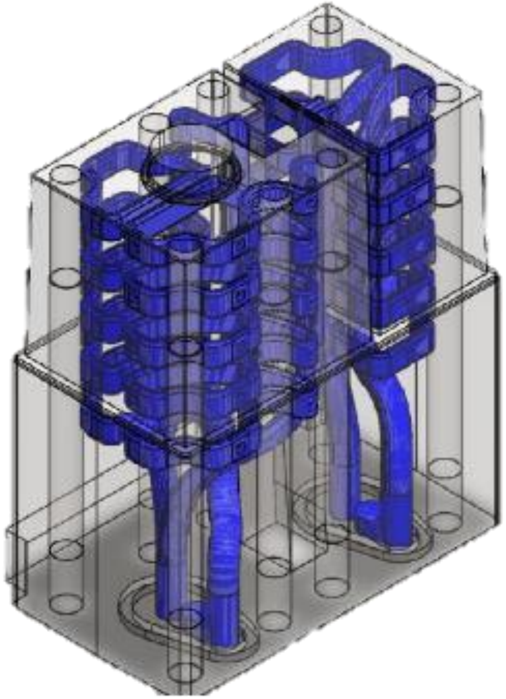


Powder Bed Fusion: Applications

Mold tool in BeCu



Original ‘Bubbler’



Optimised Conformal Cooling

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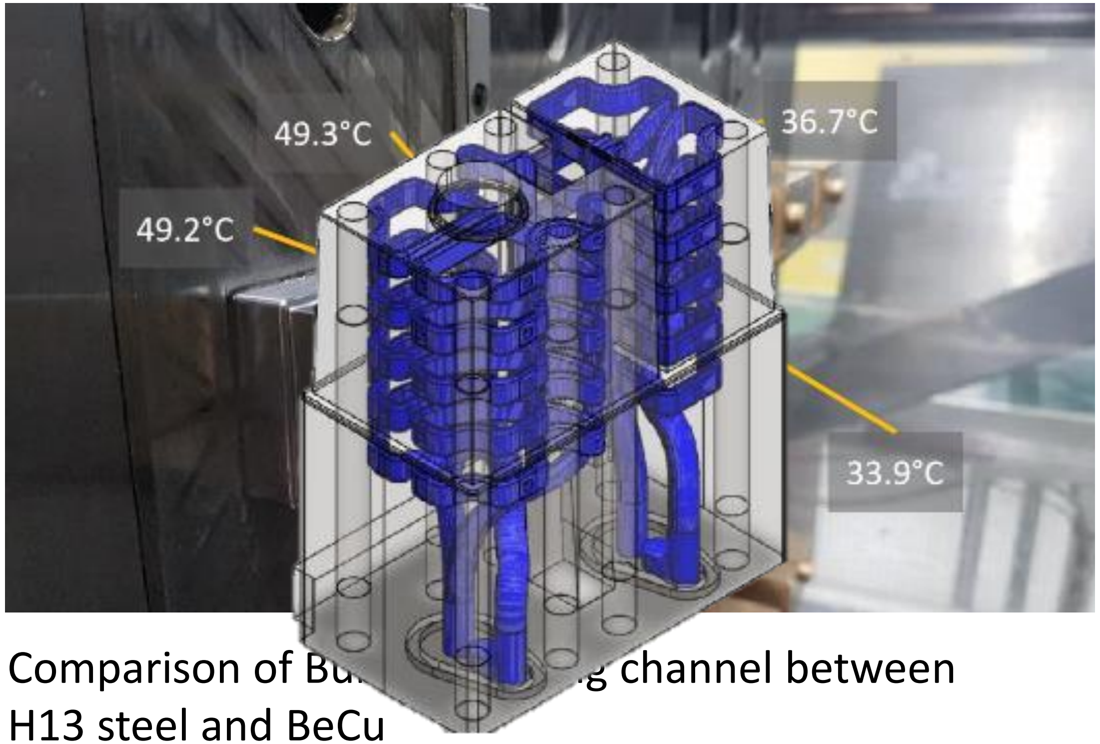
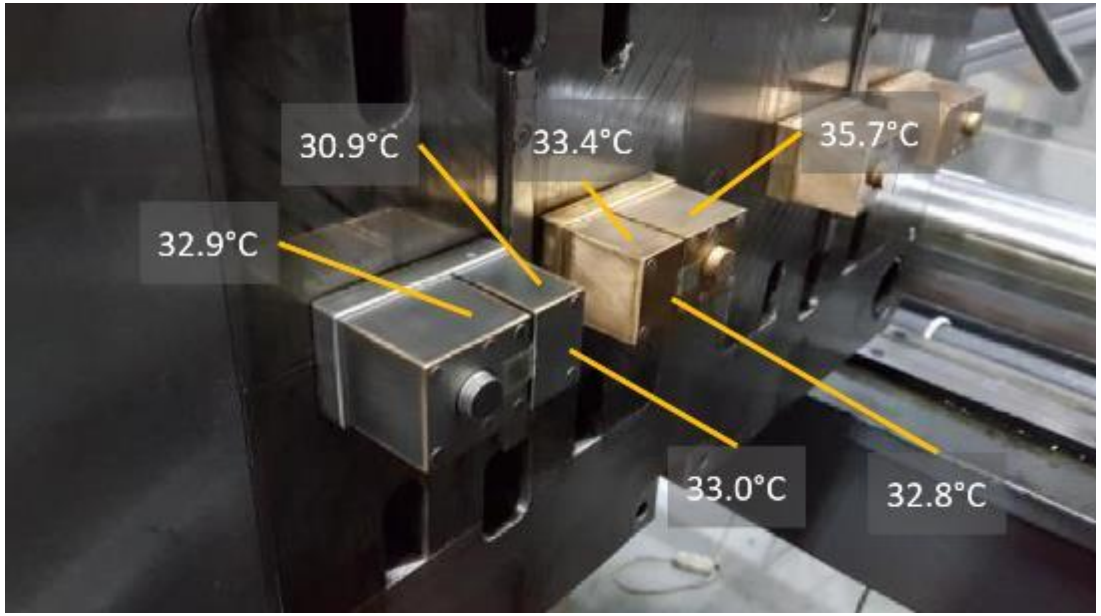
Powder Bed Fusion: Applications



Comparison of Bu… …g channel between H13 steel and BeCu



Comparison of conformal cooling channel in maraging steel and Bubbler cooling channel in BeCu

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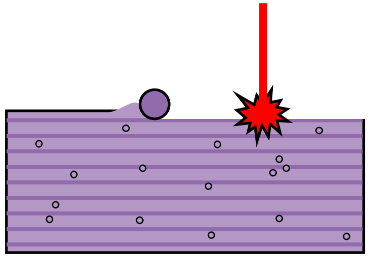

Powder Bed Fusion: Platforms

OR Laser – Creator
$95,000
ϕ100x100mm

Renishaw – AM500
€650,000
250x250x300mm

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Thank you

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Process

CU15-1: PBF-LB Processes

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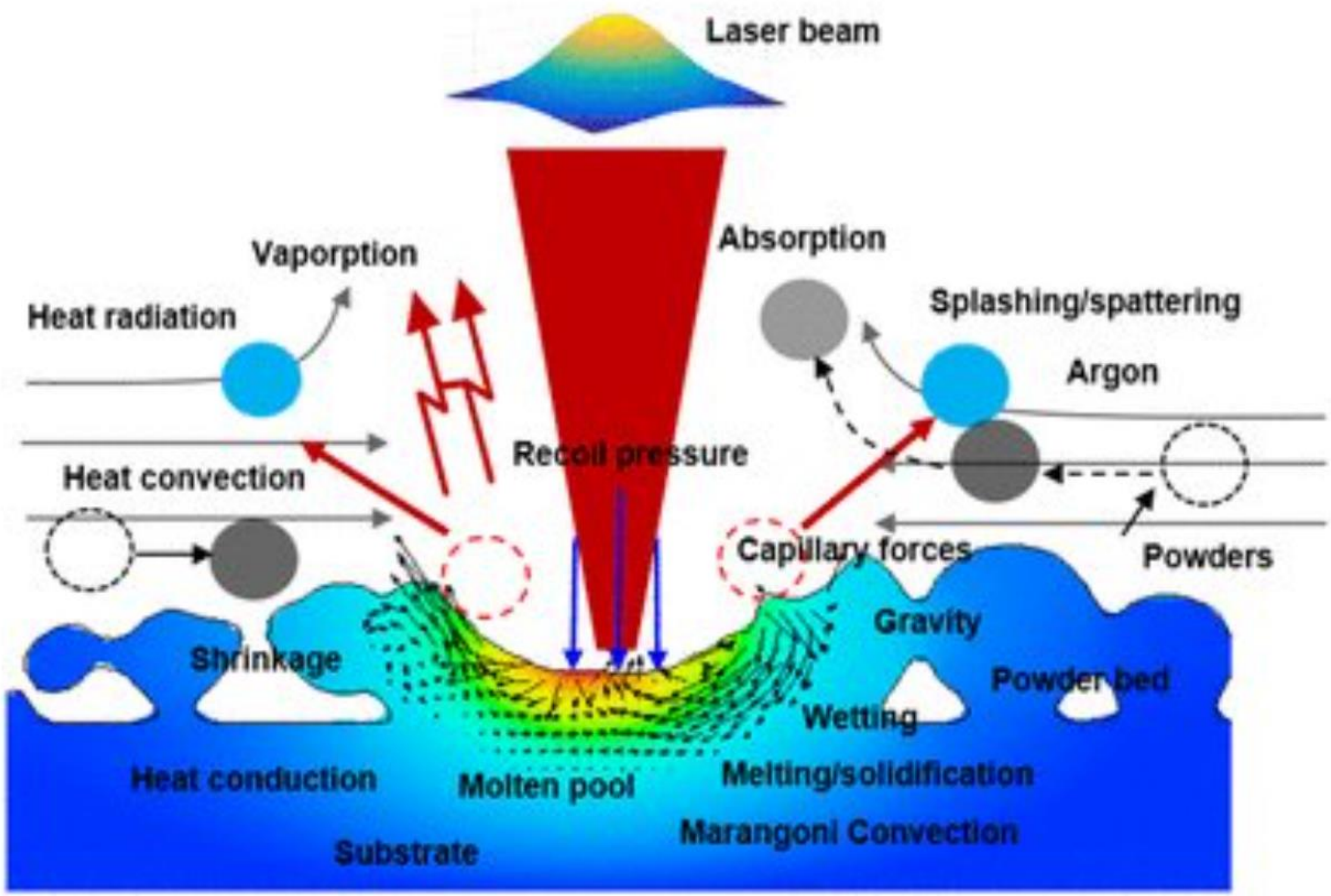
Introduction to Physical processes of LBPBF

- Heat transfer to and from the meltpool
- Meltpool hydrodynamics, welding stability, and porosity
- Solidification, grain growth, and cracking



Chen et al 2018
- 10.1007/s00339-018-1737-8

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Heat transfer to and from a finite volume under a laser spot

$$\rho c_v \Delta T = Q_{radiation} - Q_{convection} - Q_{conduction} + W$$

Change in amount of energy inside the volume

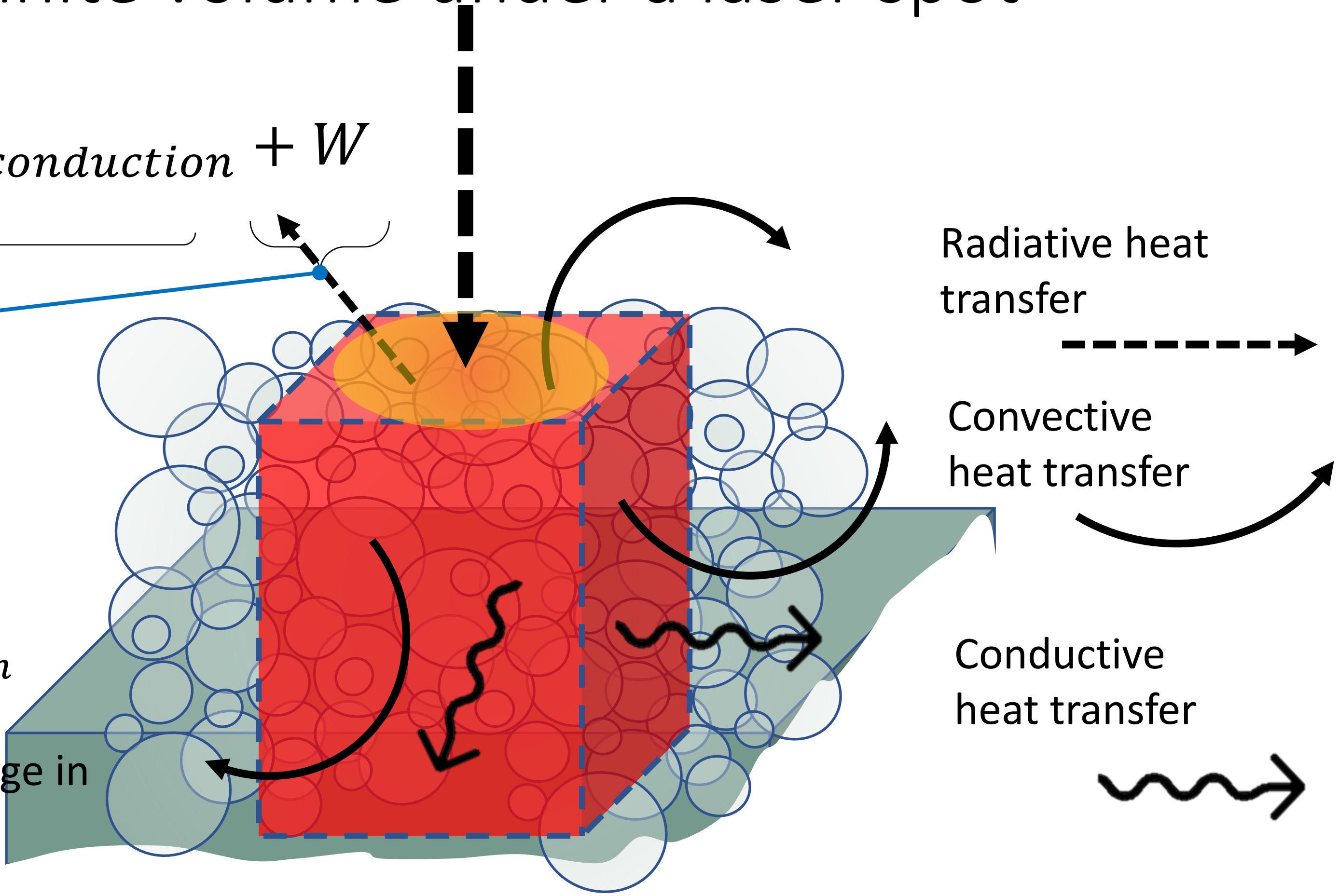
$$\Delta U = Q + W$$

Change in internal energy – proportional to change in temperature

$$Q_{total} = Q_{radiation} - Q_{convection} - Q_{conduction}$$

Sum of work energy – solidification, melting, change in microstructure, etc.

$$\Delta U = \rho c_v \Delta T$$



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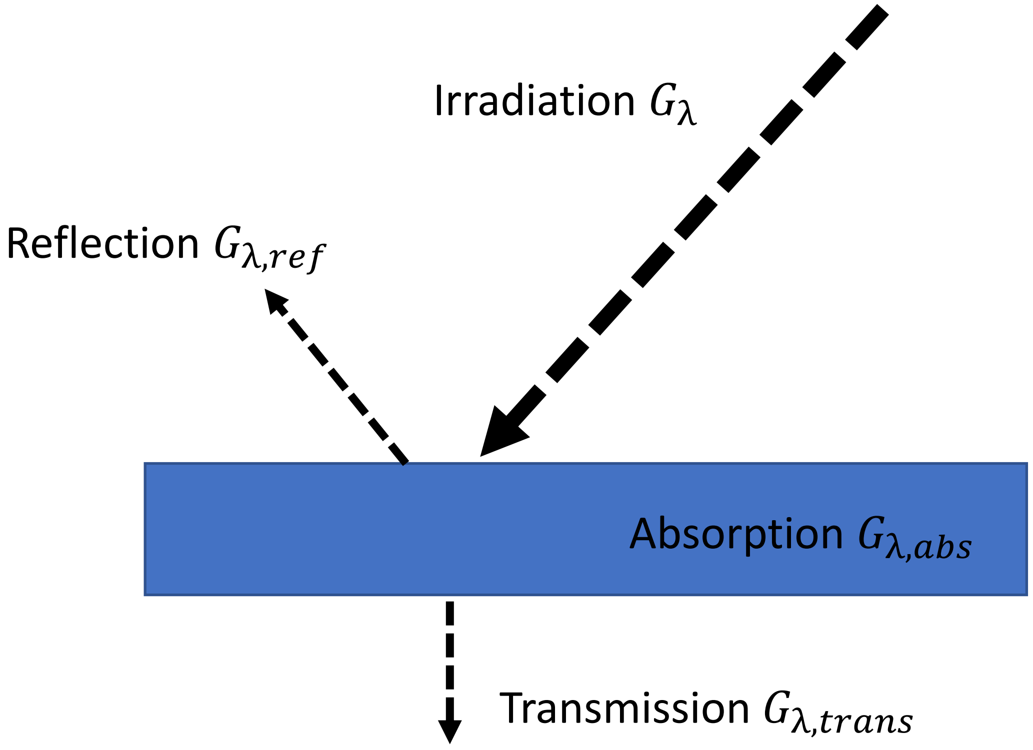
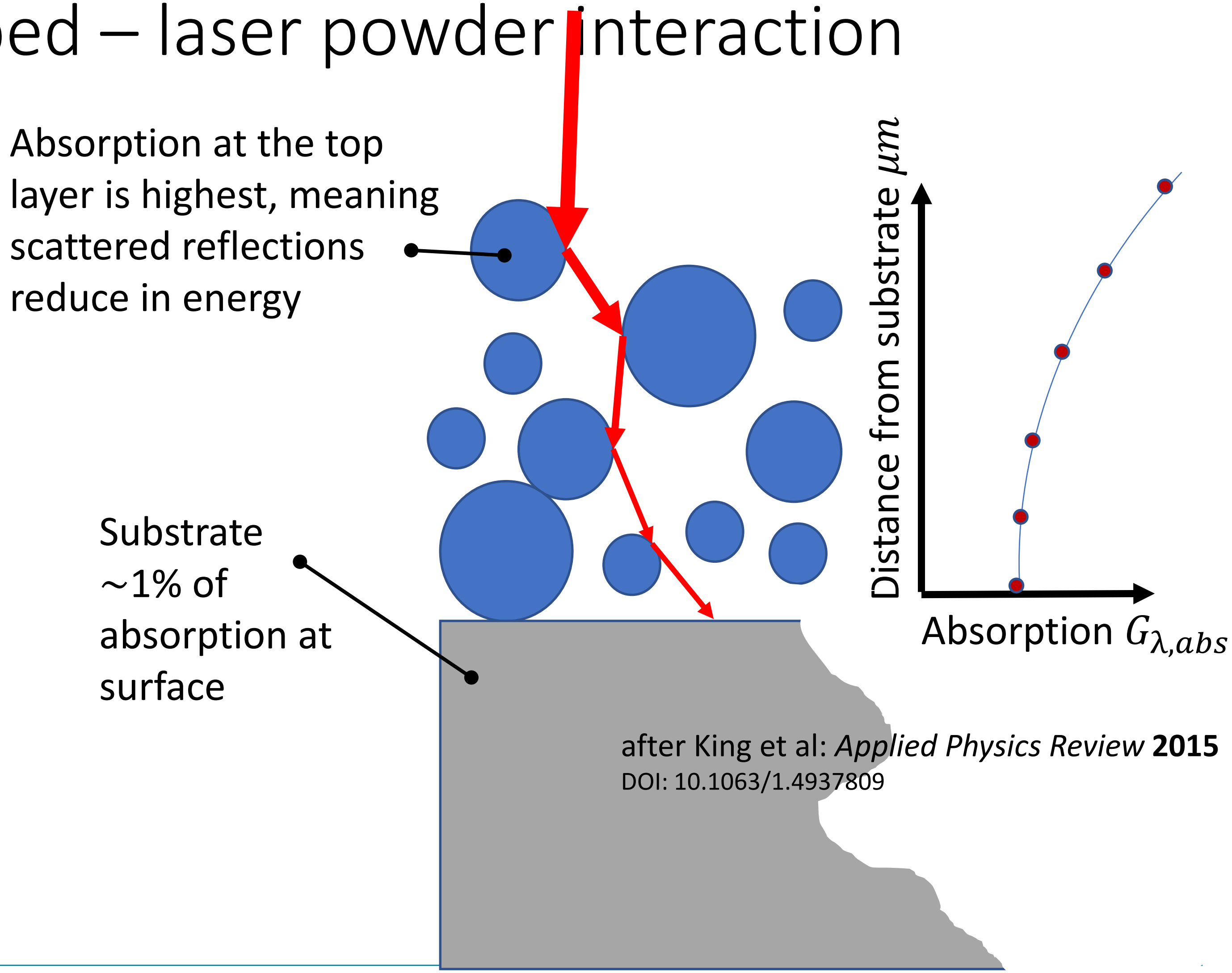
Irradiation of a virgin powder bed – laser powder interaction



$$G_\lambda = G_{\lambda,ref} + G_{\lambda,abs} + G_{\lambda,trans}$$



after King et al: *Applied Physics Review* **2015**
DOI: 10.1063/1.4937809

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Irradiation of a meltpool

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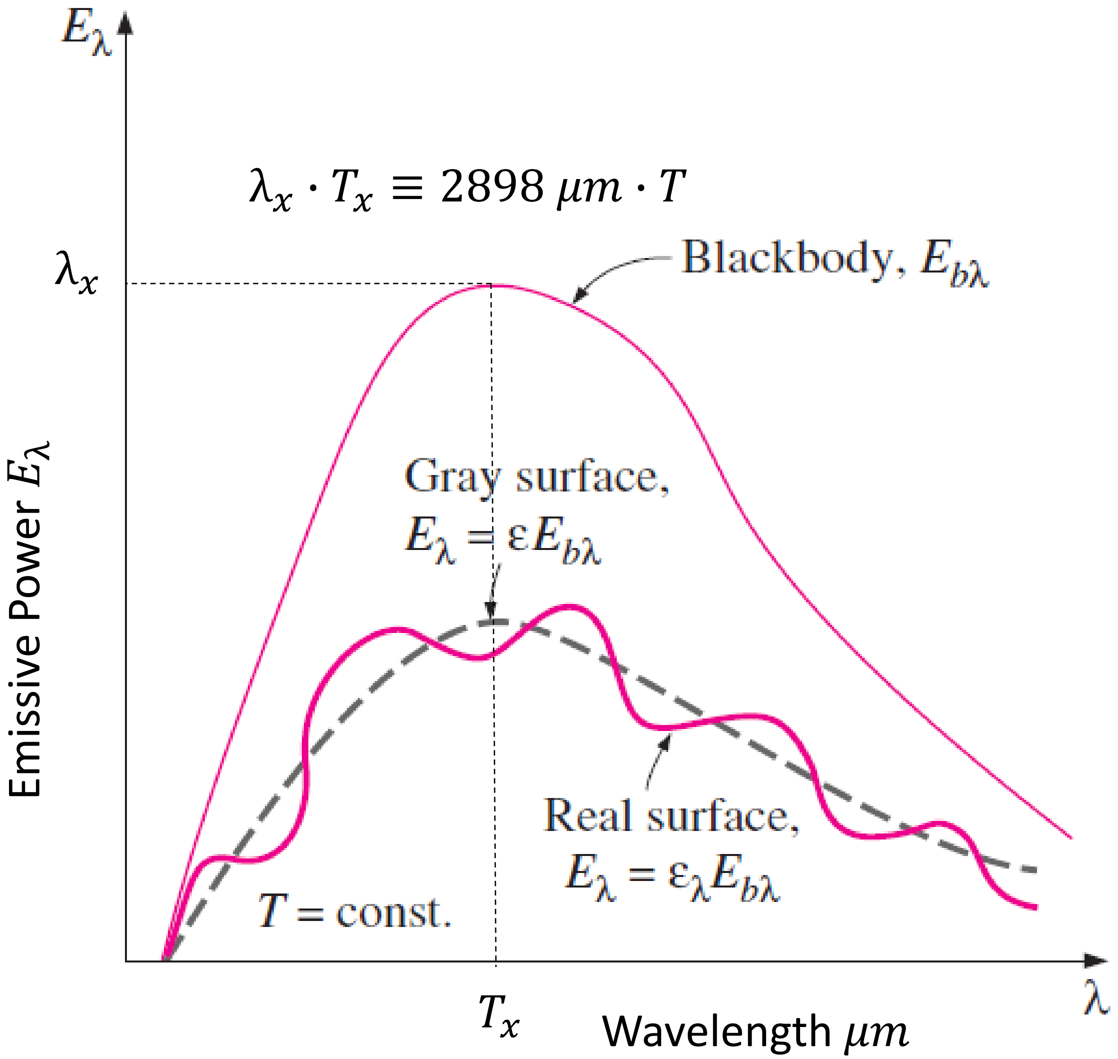


$$E_{blackbody} = \sigma T^4$$

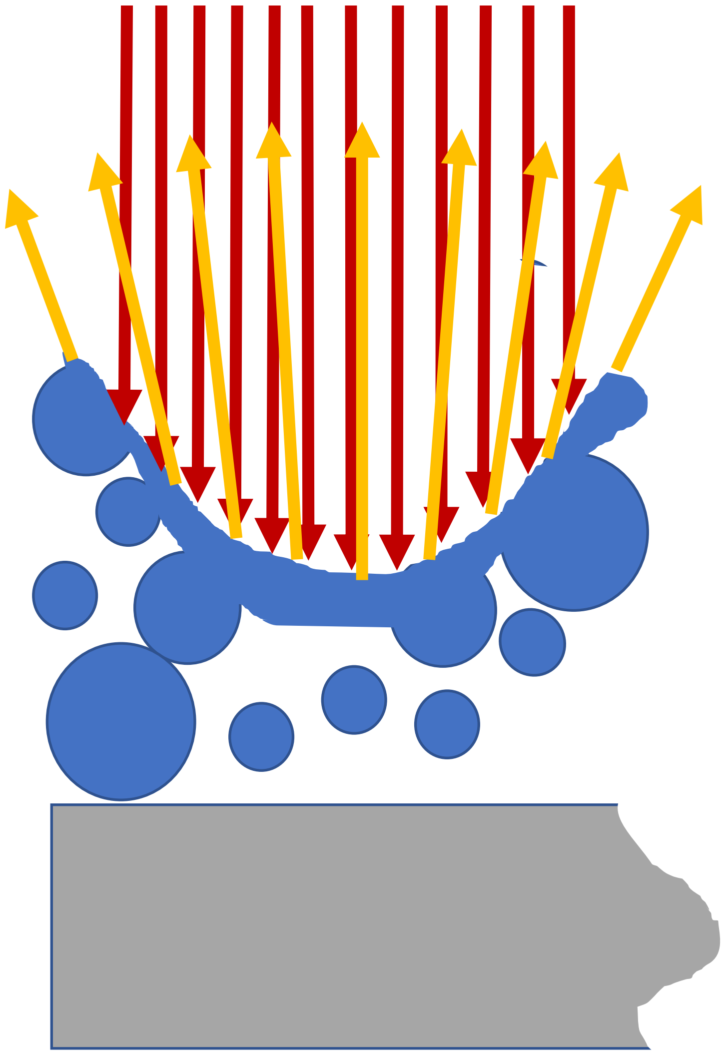
$$E_{graybody} = \varepsilon\sigma T^4$$

$$\varepsilon \approx \alpha$$

$$\frac{Q}{A} = I - E$$

$$= \alpha\sigma T_I^4 - \varepsilon\sigma T_E^4$$

$$\approx \varepsilon\sigma(T_H^4 - T_C^4)$$



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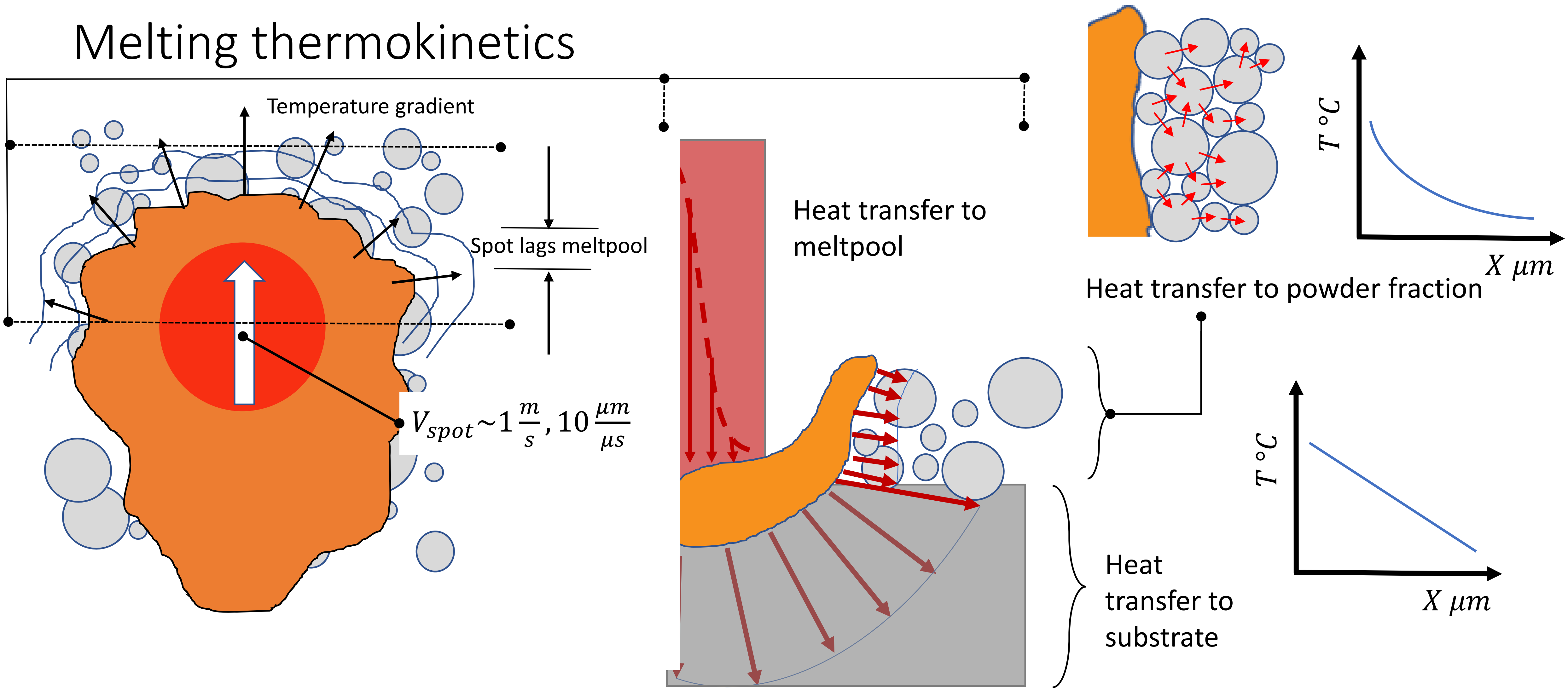
Melting thermokinetics



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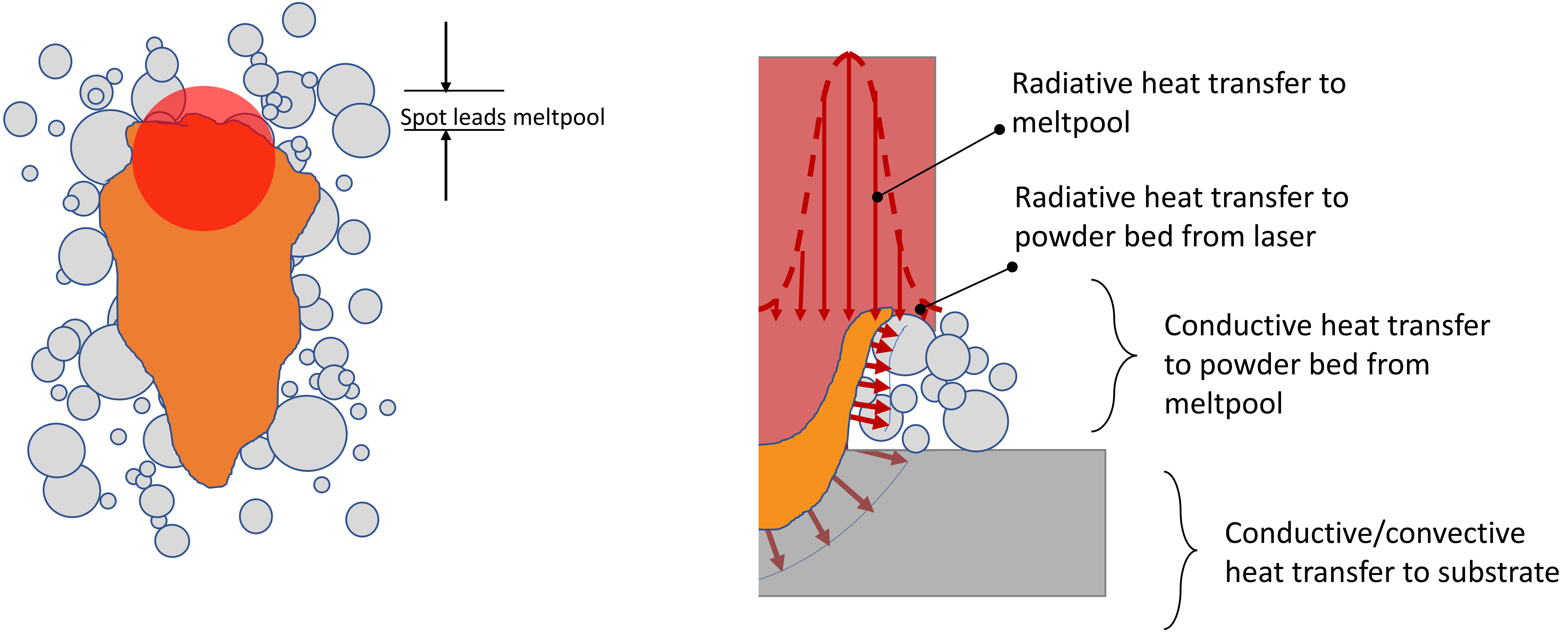
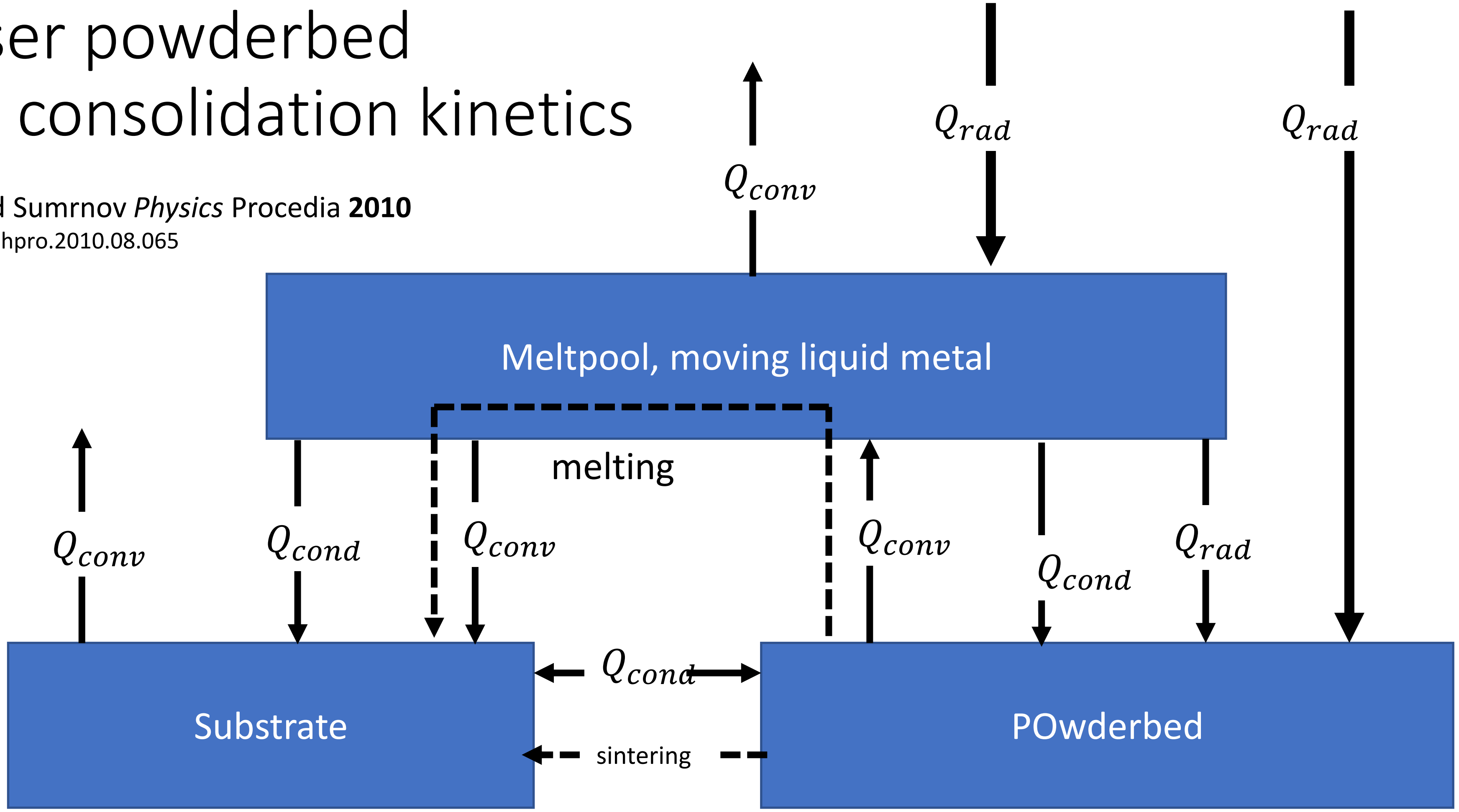


Summary of laser powderbed interaction and consolidation kinetics

Gusarov and Sumrnov *Physics* Procedia **2010**
doi:10.1016/j.phpro.2010.08.065



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Overview of hydrodynamics

- Hydrodynamics
- Balance of hydrodynamic properties and welding regimes
- Impact on weld stability
- Impact on defects

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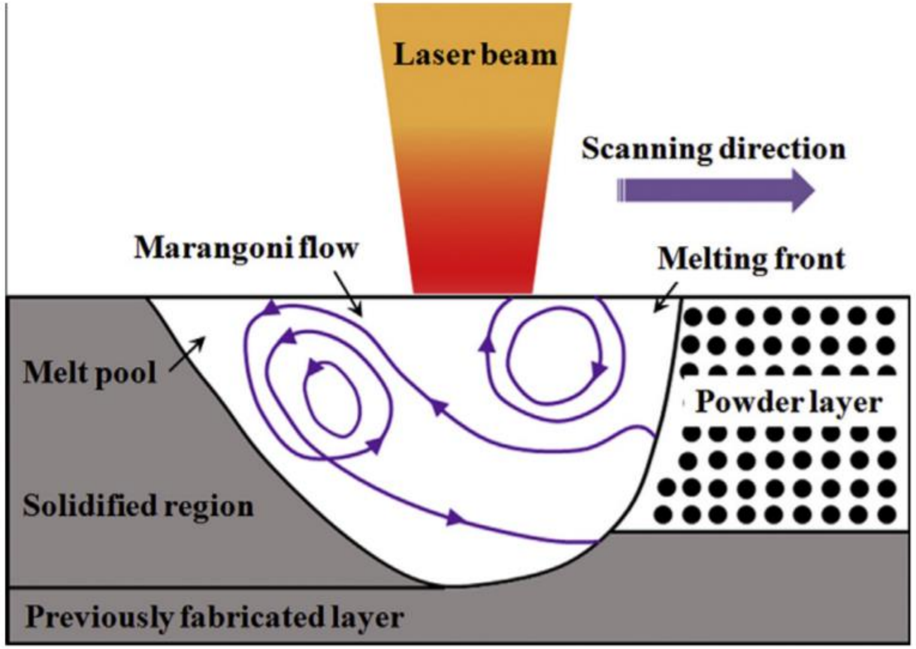
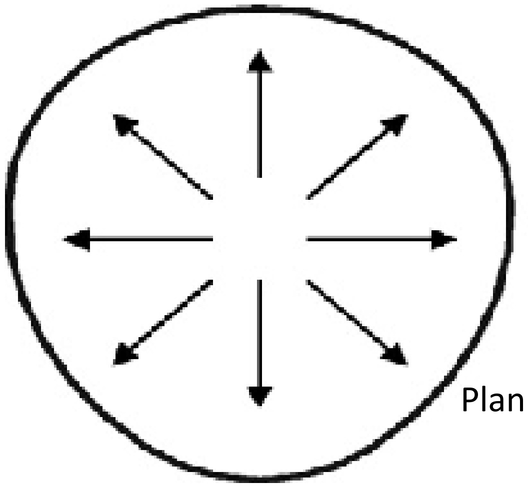
Marangoni flow



Yuan et al 2015
http://dx.doi.org/10.1016/j.matdes.2015.05.041 0261-3069/



Plan view of meltpool

Section view of meltpool

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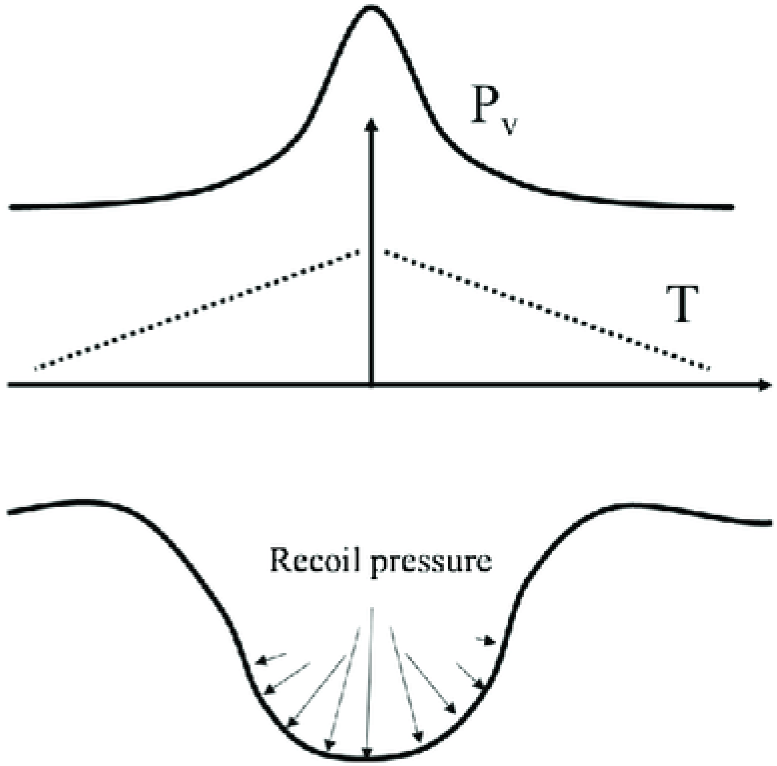
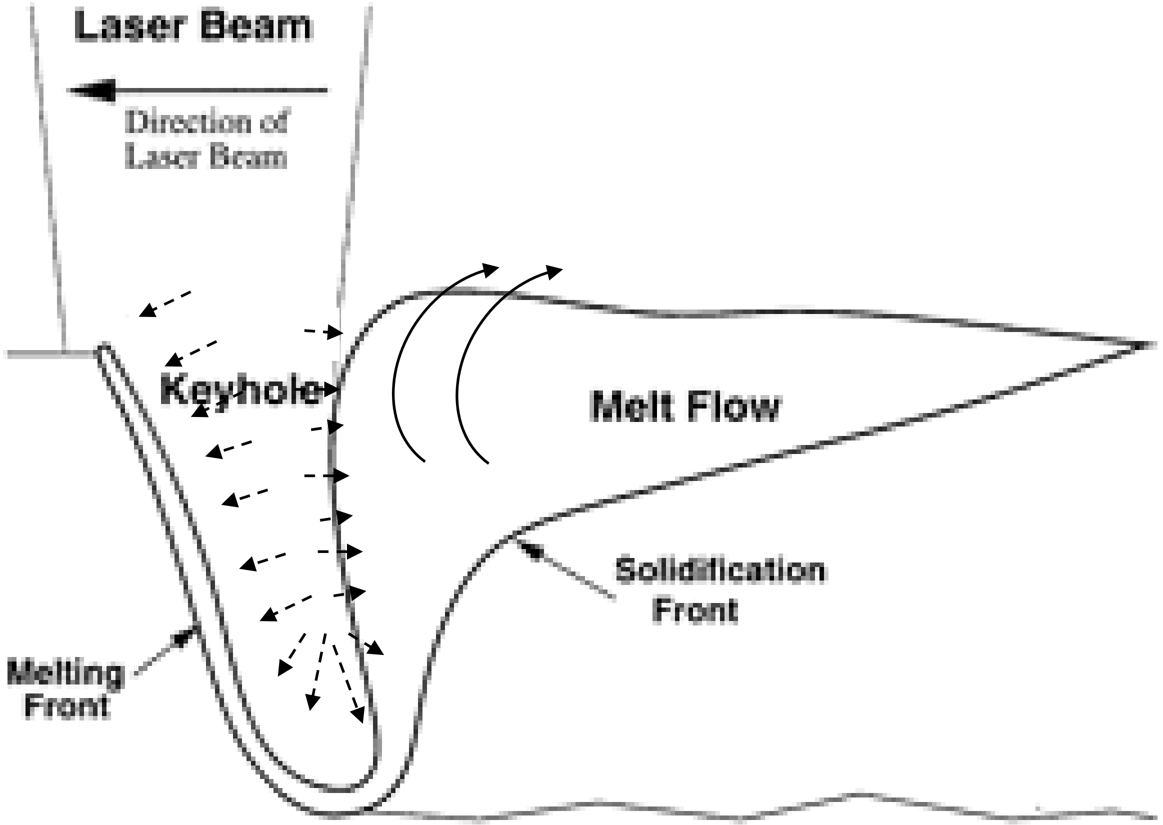
Recoil Pressure and Combined Flow





Variation of recoil pressure with temperature

Modeling of solidification microstructure evolution in laser powder bed fusion fabricated 316L stainless steel using combined computational fluid dynamics and cellular automata – Zhang et al 2019 *Additive Manufacturing*

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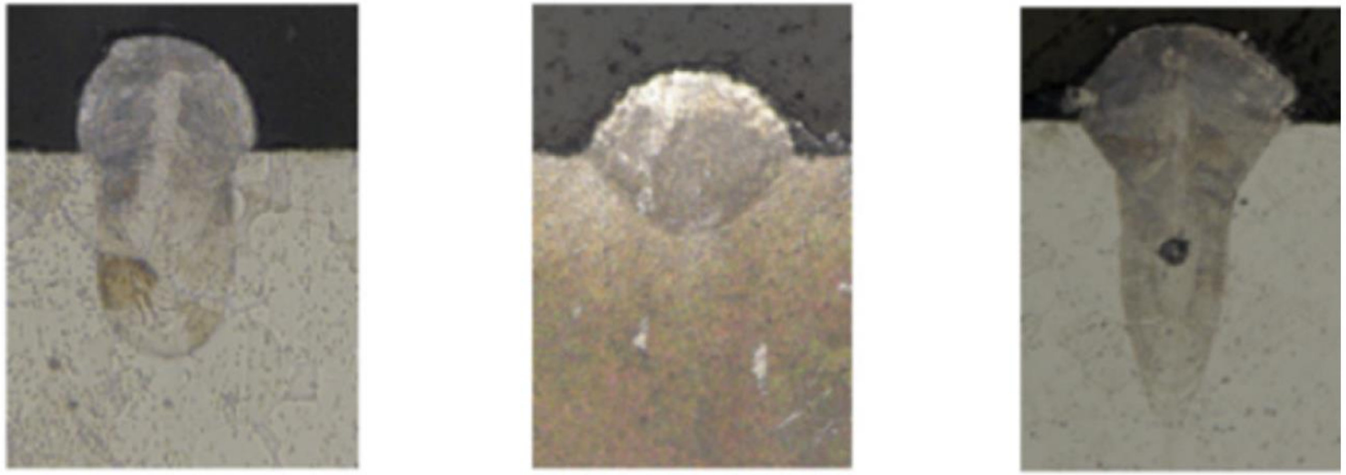
Melting modes

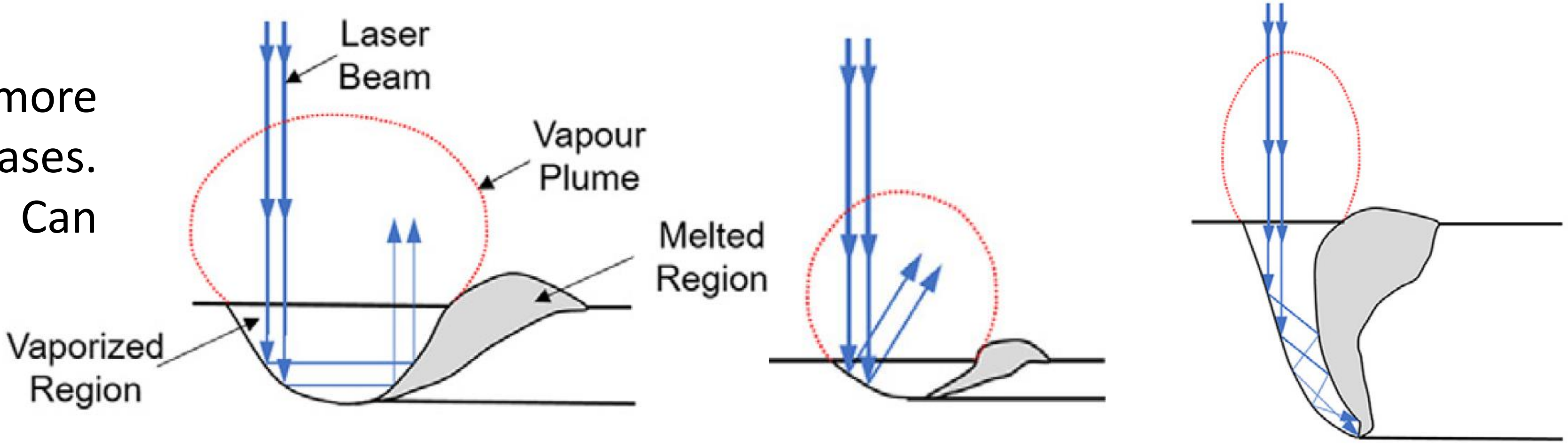
- Transient - Stable formation and good penetration, and a smooth, even weld.

- Conduction – at higher power penetration is sufficient, becomes progressively more unstable as thermal power decreases. Low penetration, uneven weld.

- Keyhole – becomes progressively more unstable as thermal power increases. High penetration, uneven weld. Can have ssociated cracking and voids.



Transient   Conduction   Keyhole



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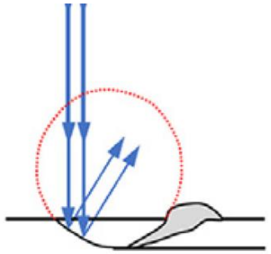
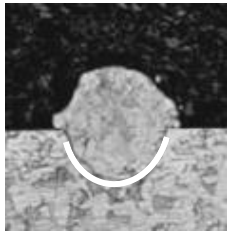
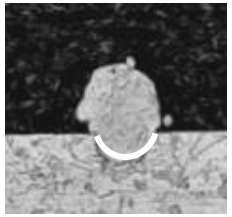
Undermelting and lack of fusion

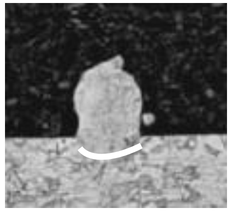




Moderate power allows conductive melting and penetration on the order of 1-2 layers



As power decreases, the weld sits higher and there is less penetration



At very low power levels, the powder beads on the surface.

Bertoli *Materials and Design* **2017**
http://dx.doi.org/10.1016/j.matdes.2016.10.037

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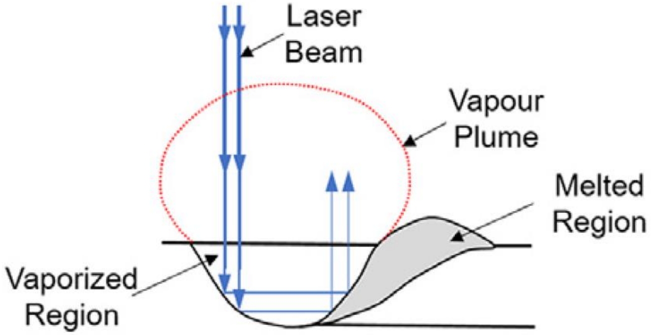
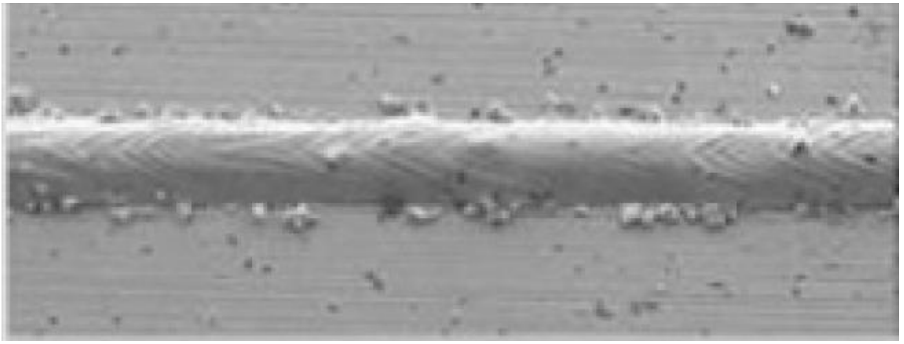
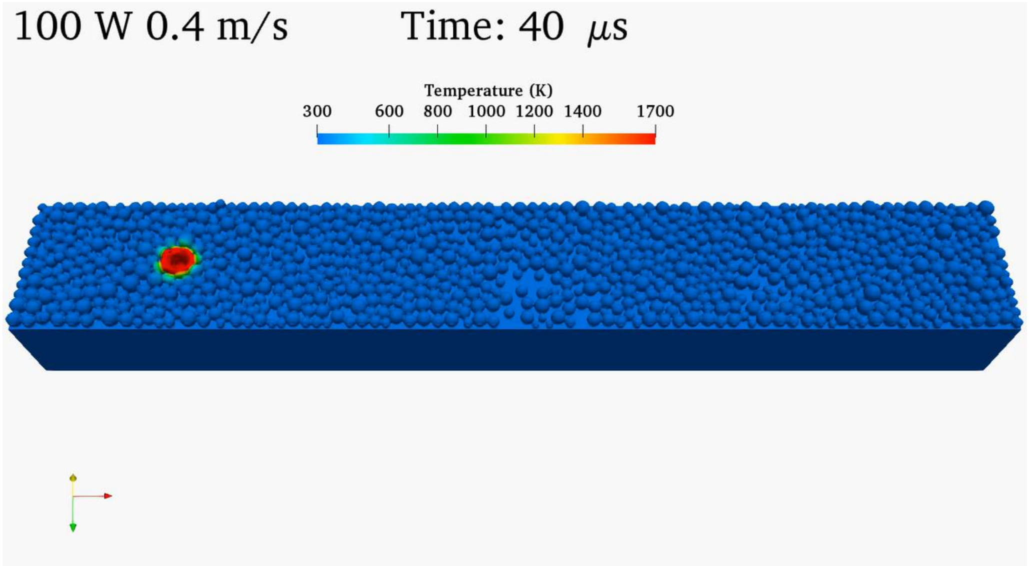
Ideal welding







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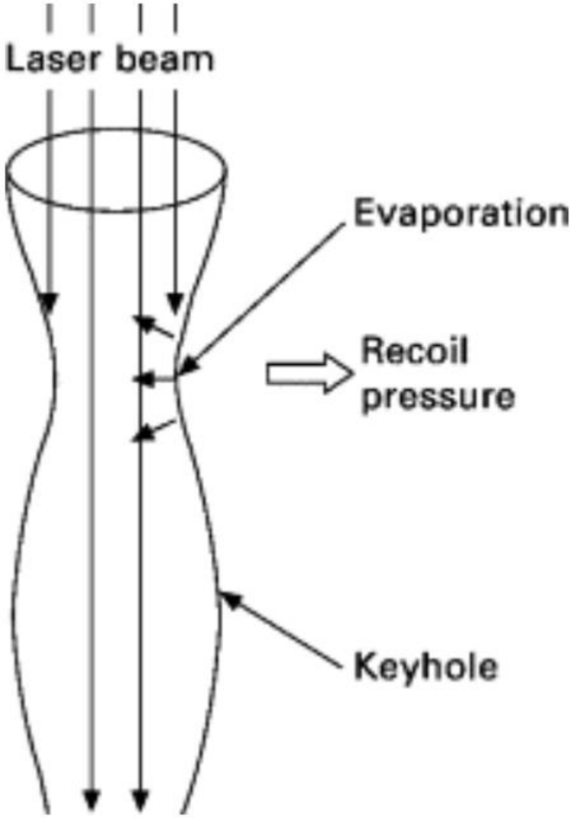
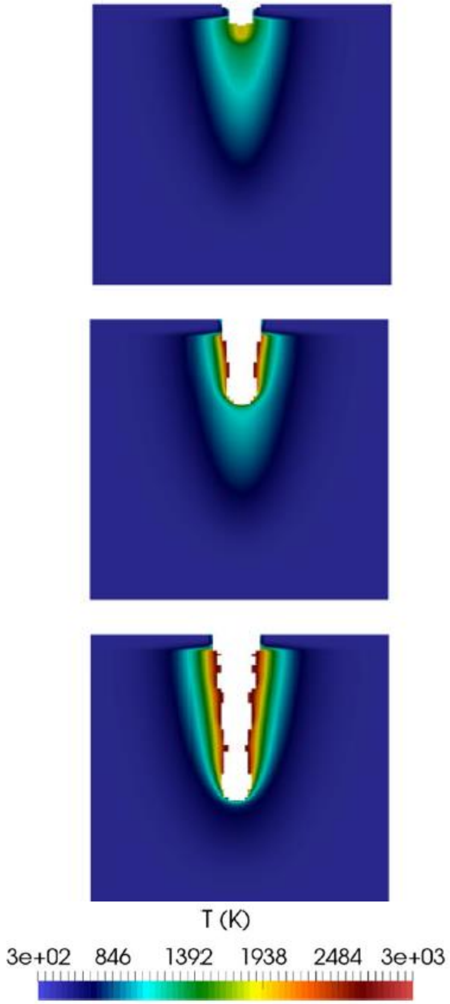
Keyhole stability and porosity

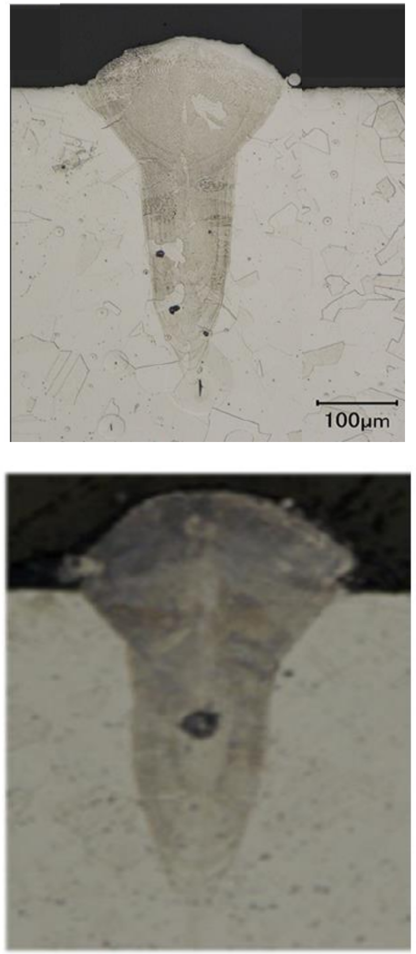
King et al *Journal of Materials Processing Technology* **2014**
http://dx.doi.org/10.1016/j.jmatprotec.2014.06.005

Rayleigh threshold:
$L < \pi D$



https://www.sciencedirect.com/topics/engineering/recoil-pressure





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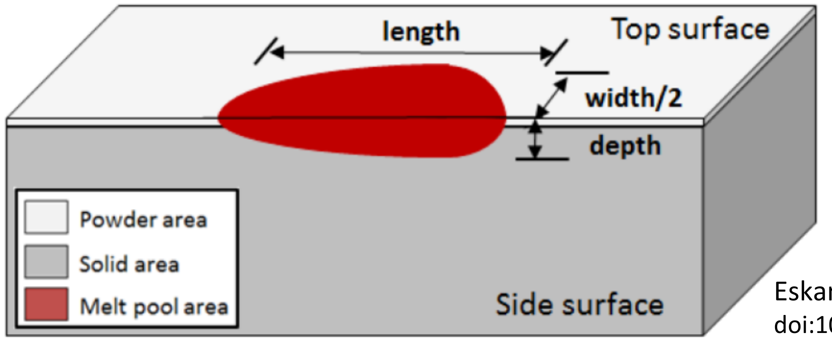
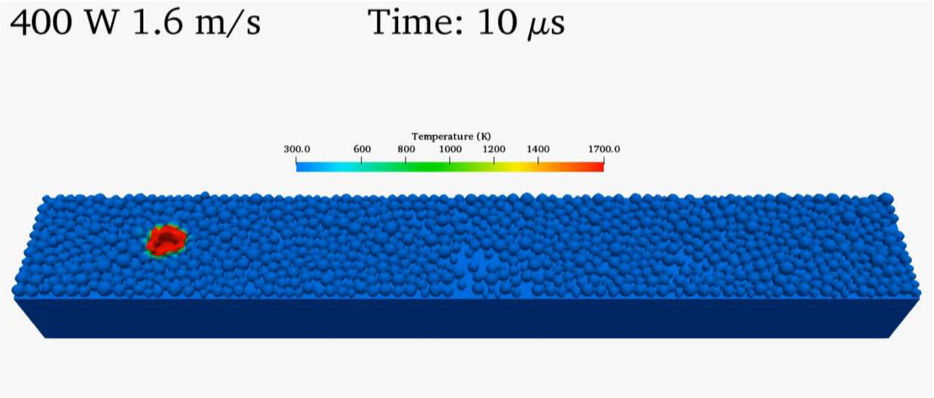
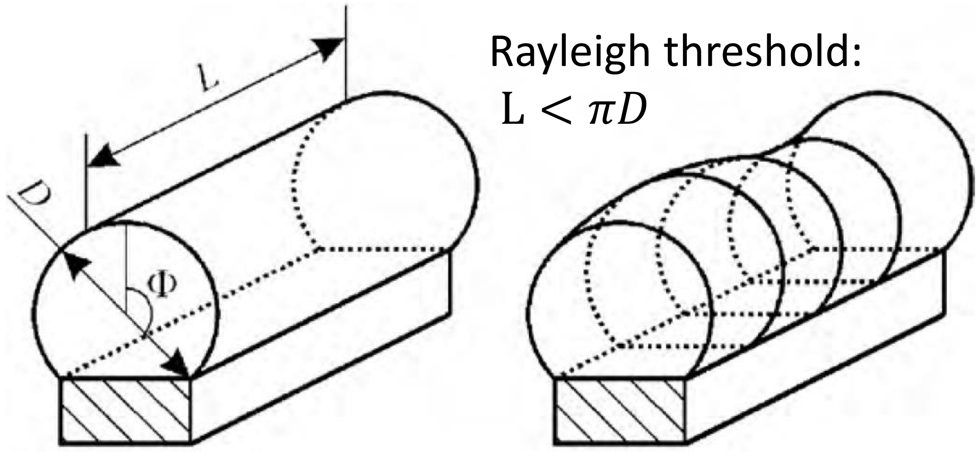
Humping – the Plateau Raleigh Instability



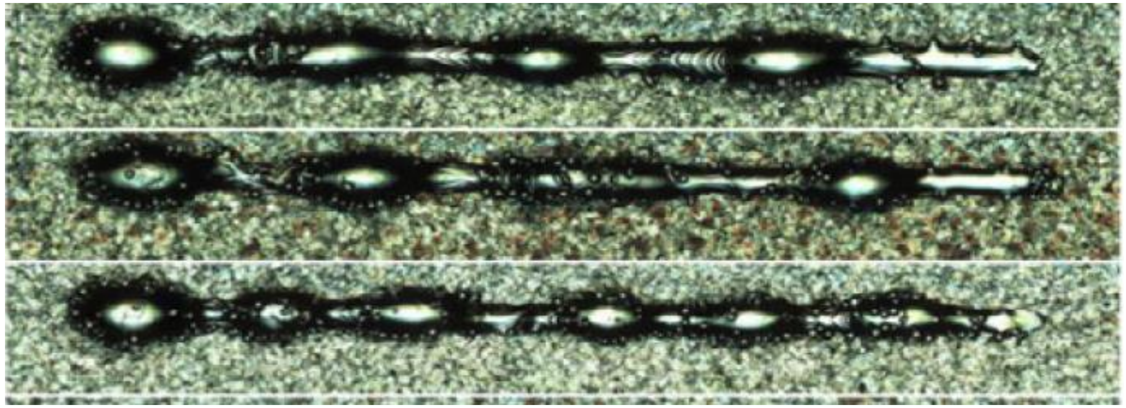
Eskandari et al *Materials* **2019**
doi:10.3390/ma12223791



Khairallah et al *Acta Materiala* **2016**
https://doi.org/10.1016/j.actamat.2016.02.014



Rayleigh threshold:
$\mathrm{L} < \pi D$



Yadroitsev et al *Journal of Materials Processing Technology* **2010**
doi:10.1016/j.jmatprotec.2010.05.010

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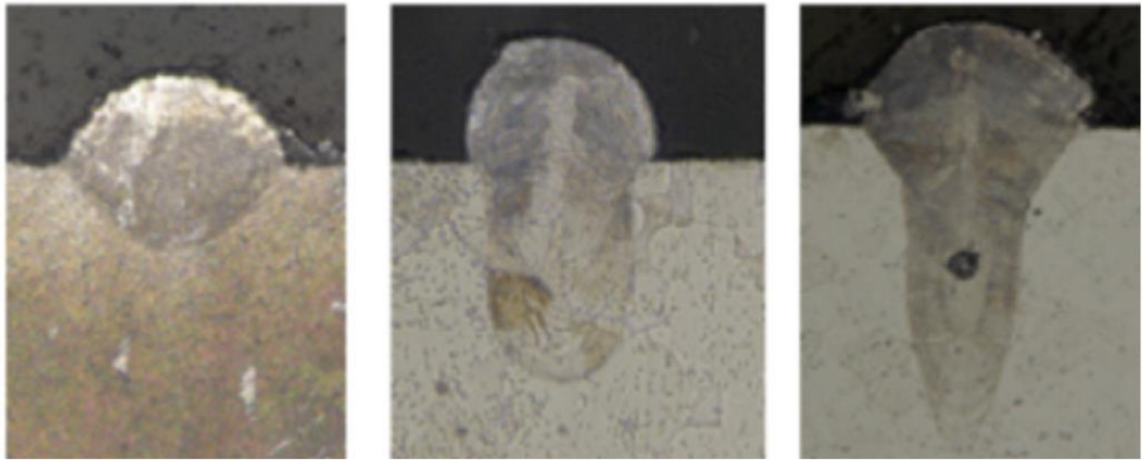
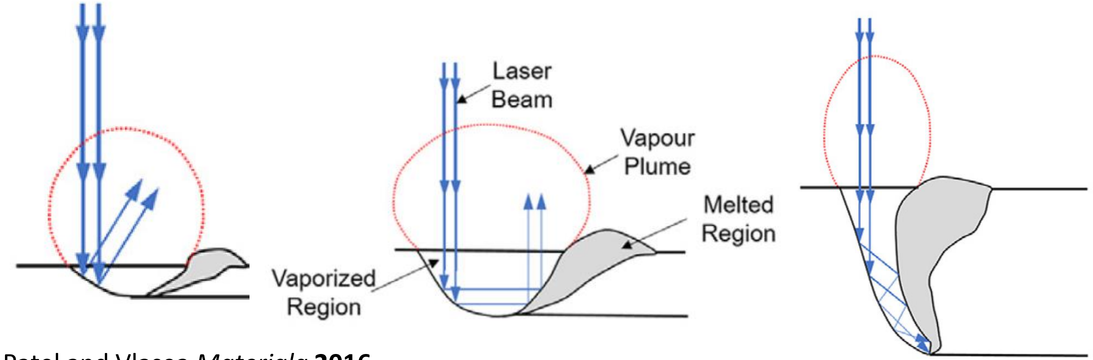
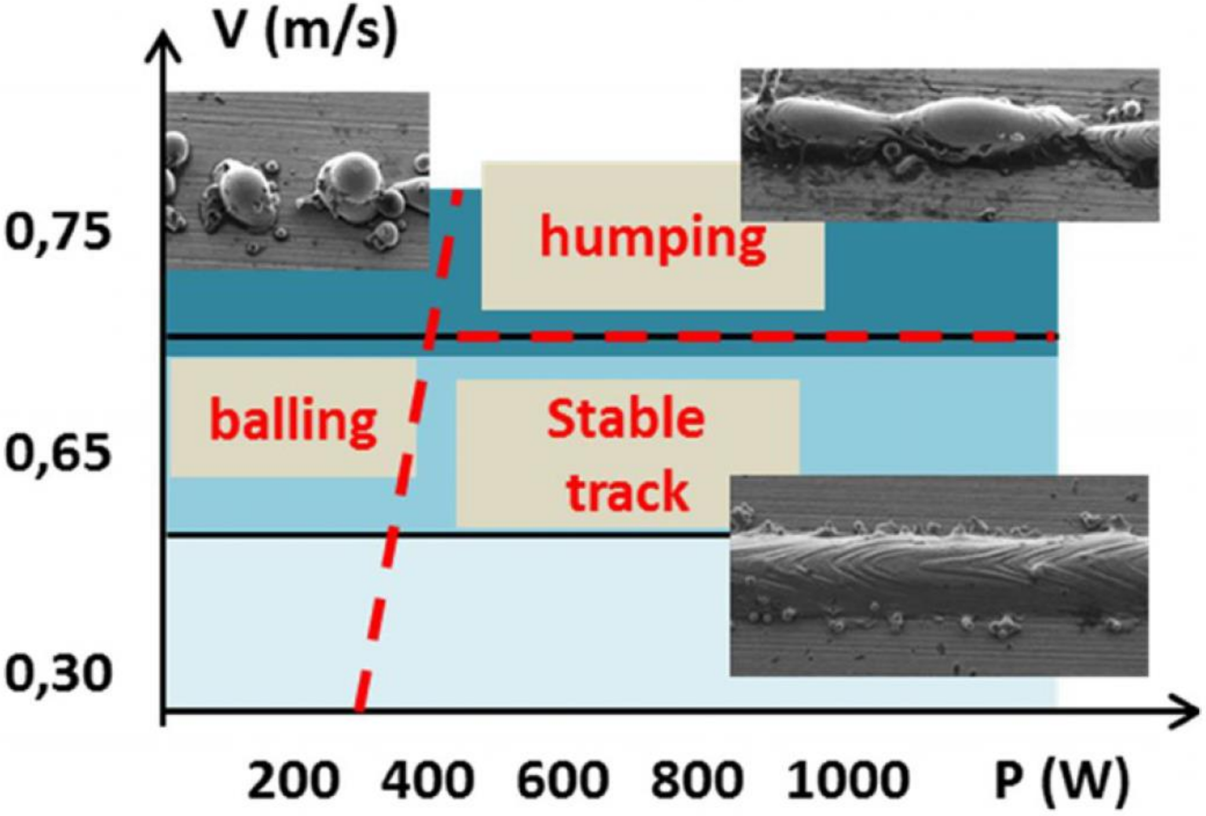
Single track parameter tests



King et al *Journal of Materials Processing Technology* **2014**
http://dx.doi.org/10.1016/j.jmatprotec.2014.06.005



Patel and Vlasea *Materiala* **2016**
https://doi.org/10.1016/j.mtla.2020.100591



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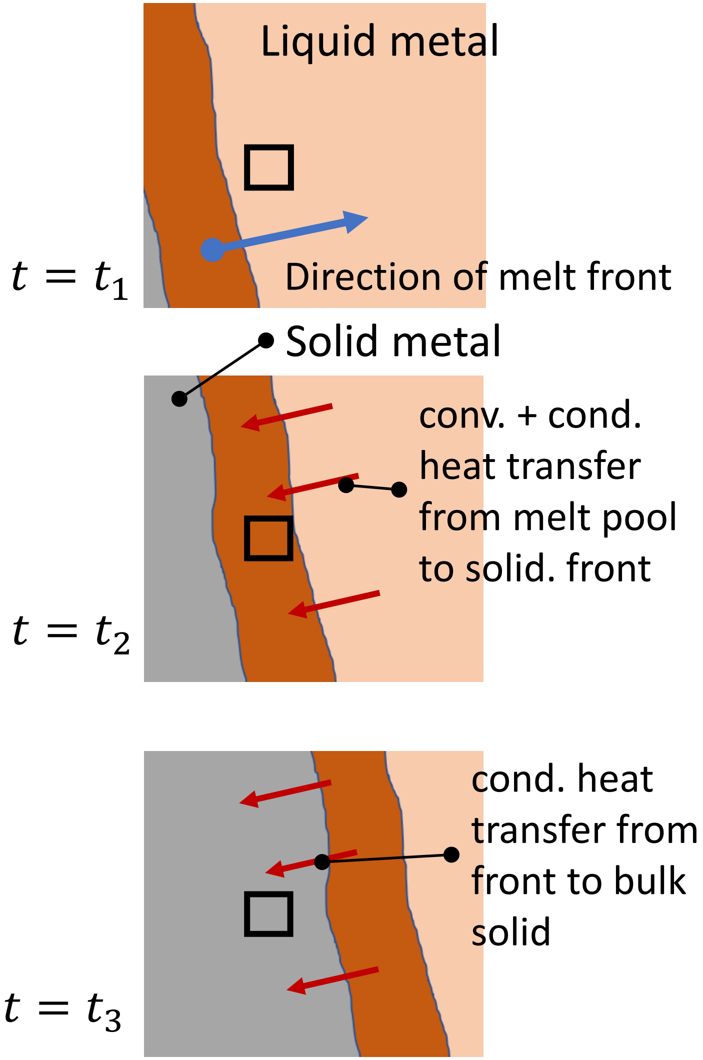
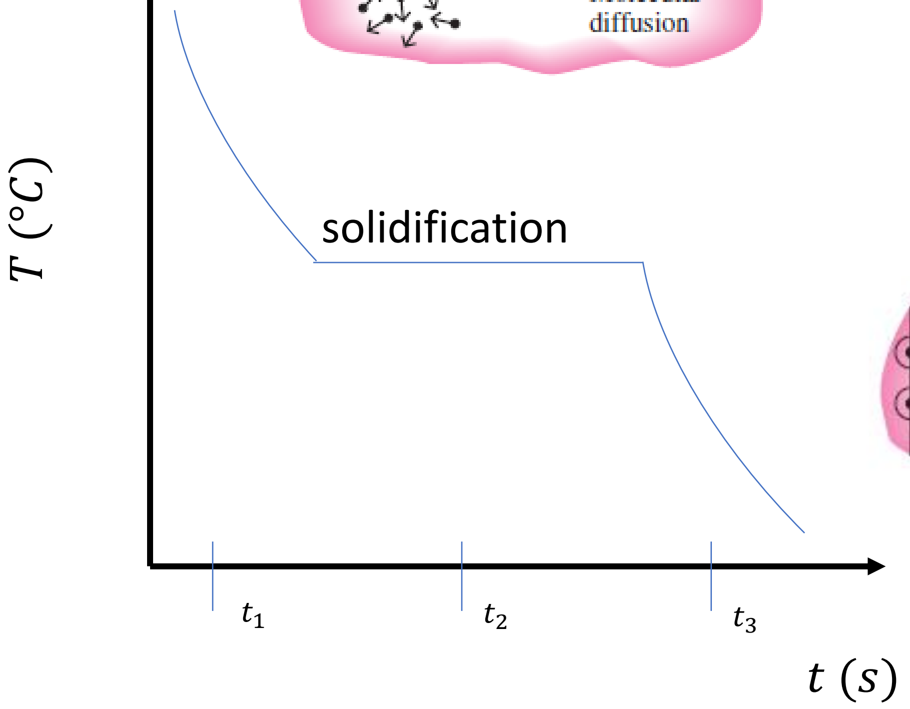
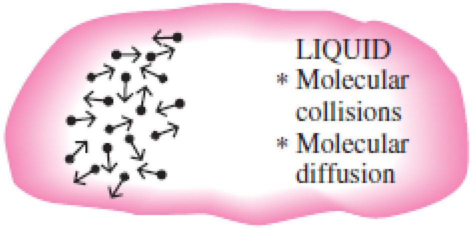
Solidification – Cooling

‘slush’ metal, liquid with solid bits

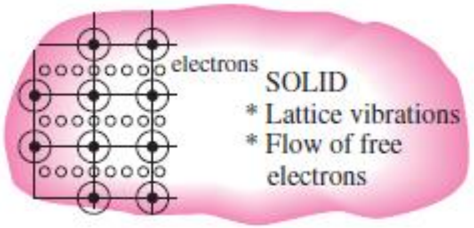






Governing heat transfer mechanism is conductive

$$\dot{Q} = -kA\frac{dT}{dx}$$



Cengel, Y *Introduction to Thermodynamics and Heat Transfer* 4th ed.

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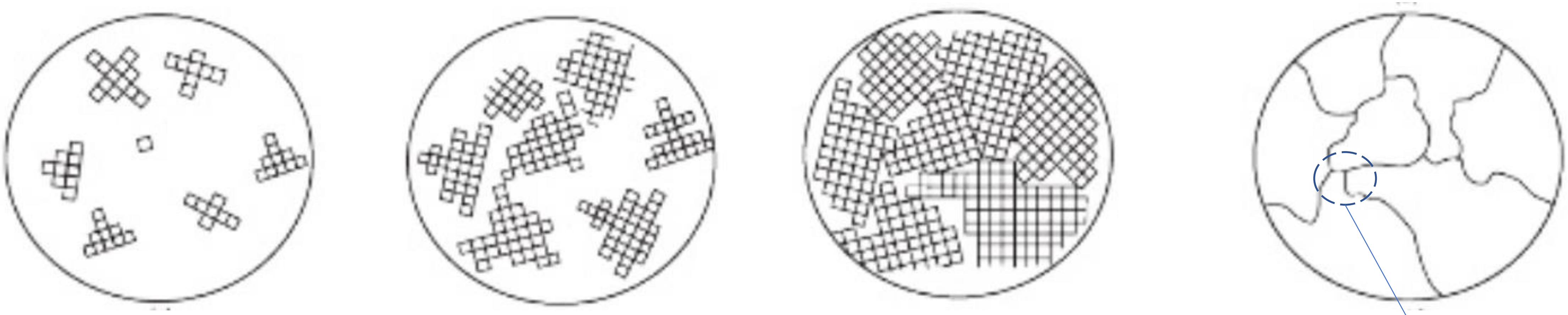
Solidification – Nucleation

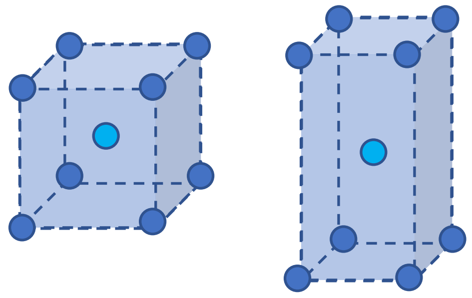
https://www.aub.edu.lb/msfea/research/Documents/CFD-Nucleation.pdf



Nucleation

Growth

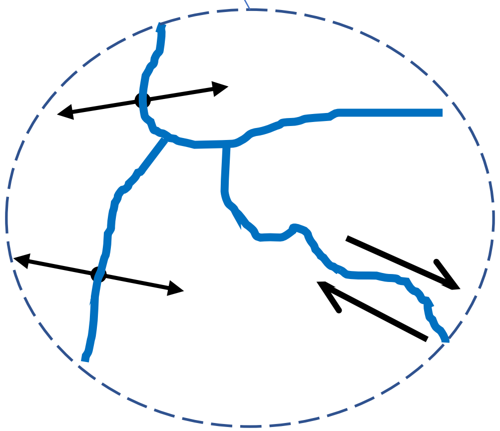
Crystal formation



Different rates of cooling create different lattice organisations

Crystals grow and impinge each other as nucleation continues

Unstable lattice arrangements exert force inside crystals, which sets up tensile and shear stresses at crystal boundaries.



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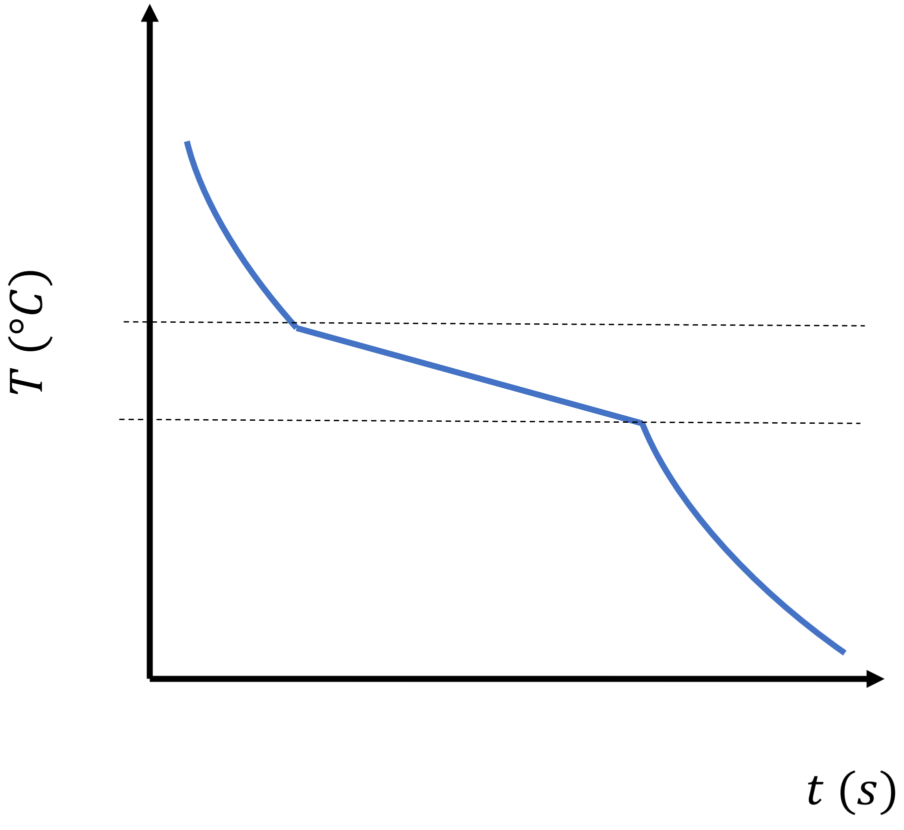
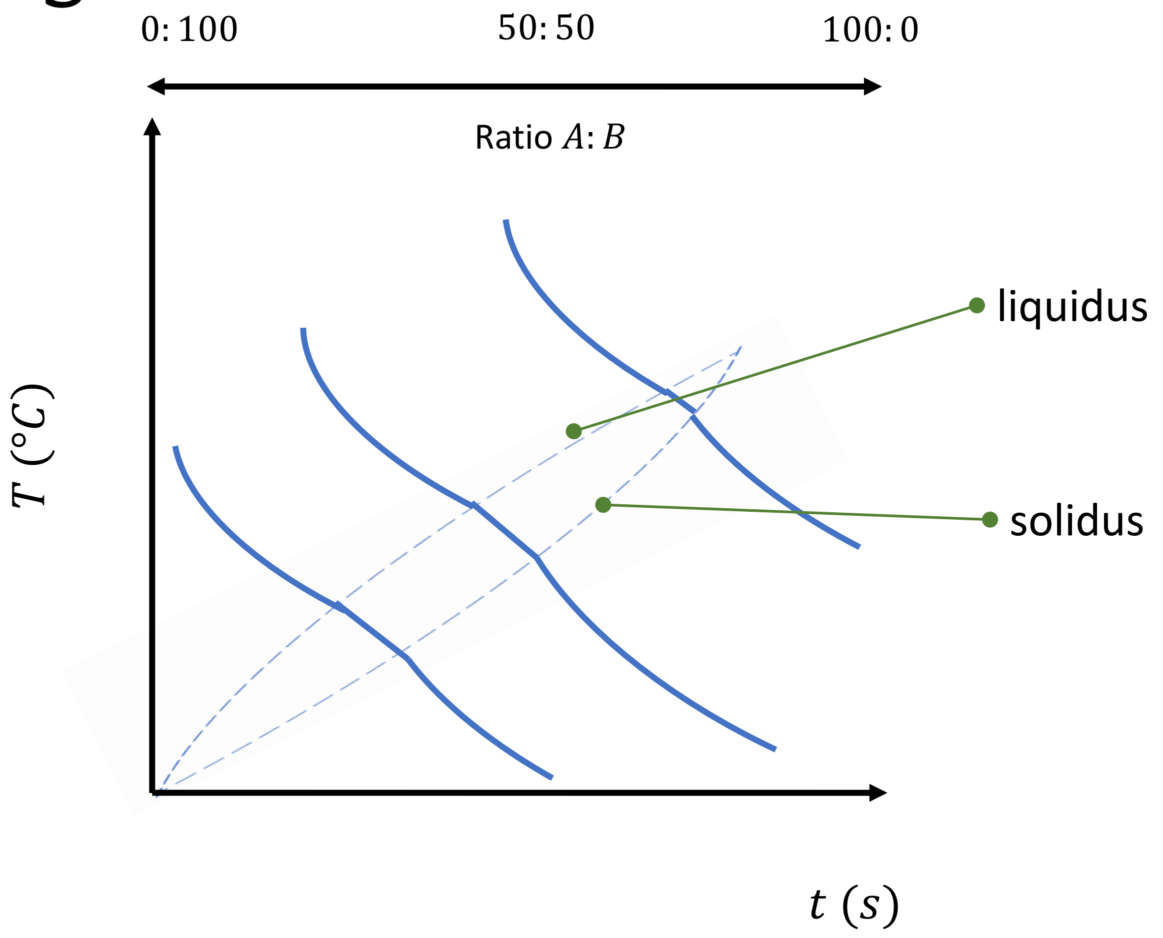
Solidification – Cooling





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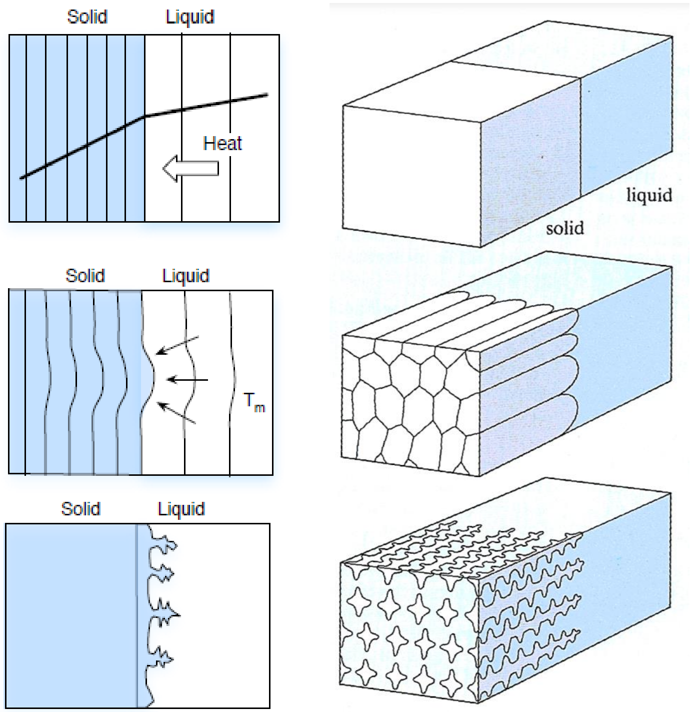
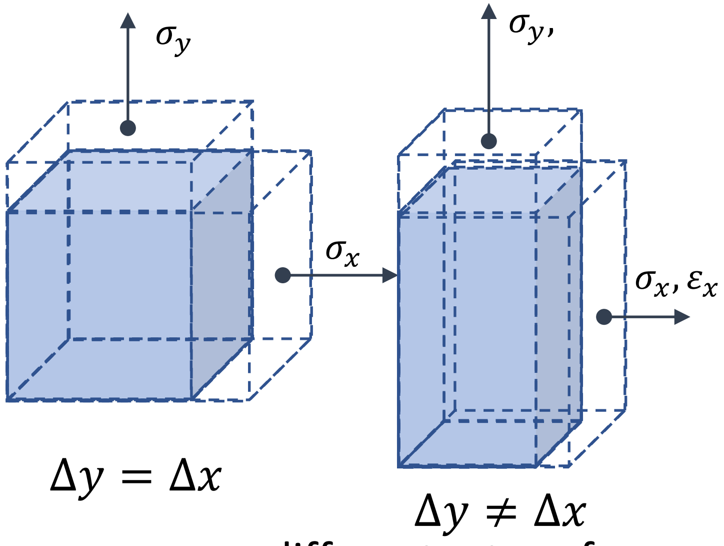
Solidification – Anisotropic microstructures



Internal stress

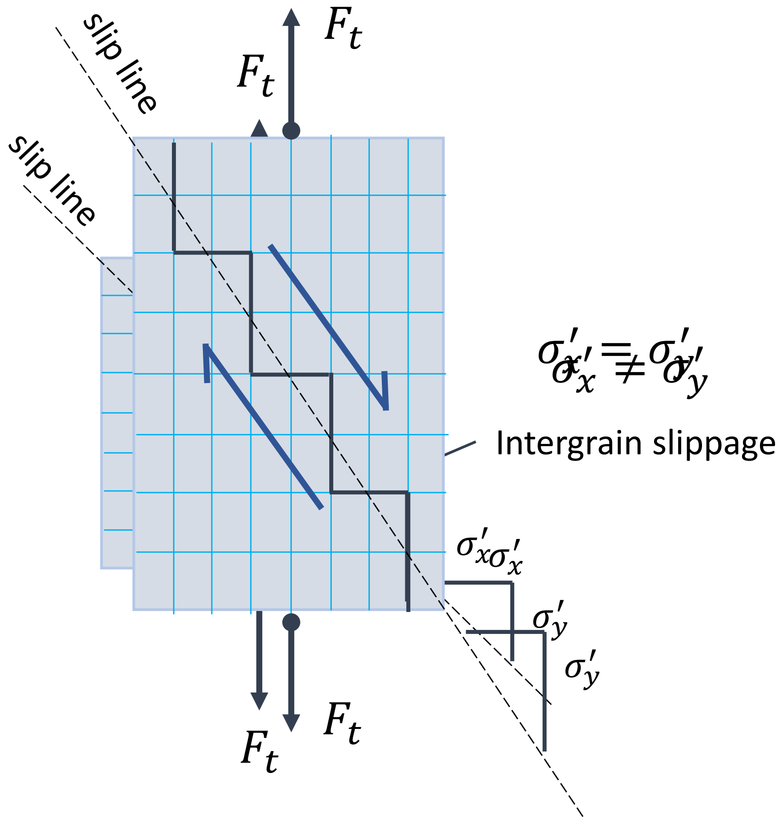
For elastic deformation, stress is proportional to strain

$$\sigma \propto \varepsilon \ \& \ \varepsilon_x = \frac{\Delta x}{x}$$



Anisotropy can cause different rates of displacement within grains

External loading



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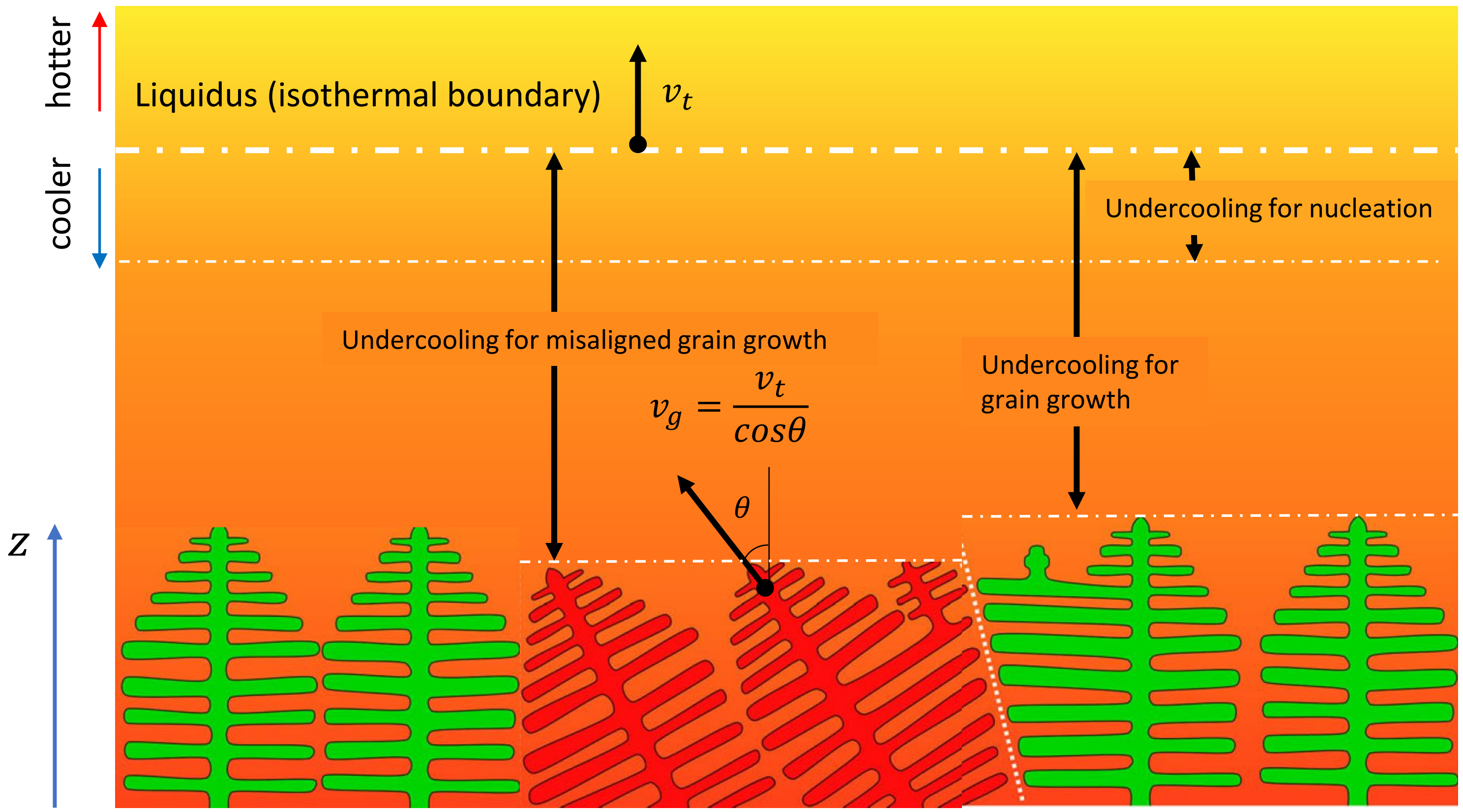
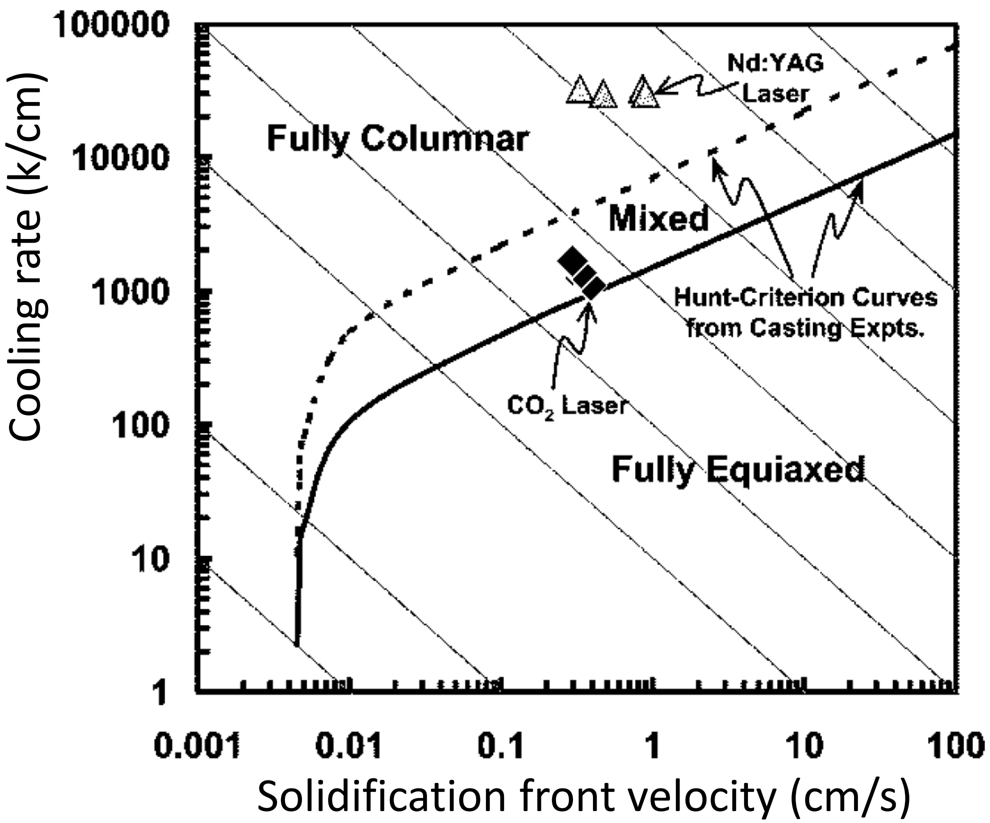
Solidification – in AM



Korner et al; *Metallurgical and Materials Transactions A* **2020**
doi.org/10.1007/s11661-020-05946-3



P.A. Kobryn and S.L. Semiatin; *The Journal of The Minerals, Metals & Materials Society* **2001** https://doi.org/10.1007/s11837-001-0068-x

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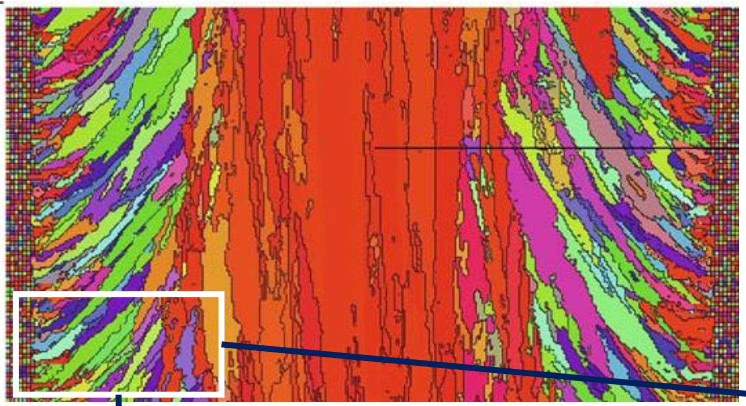
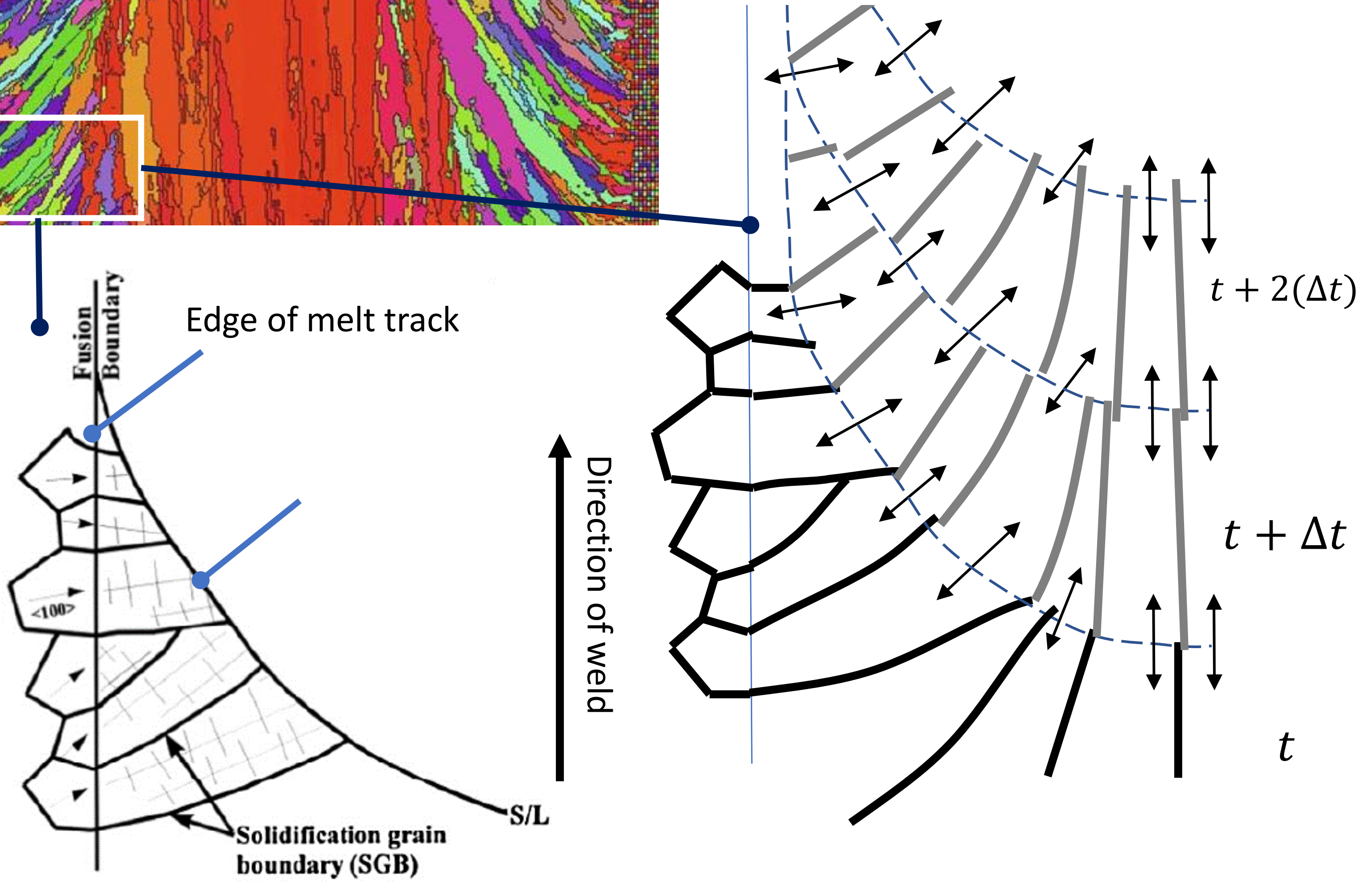
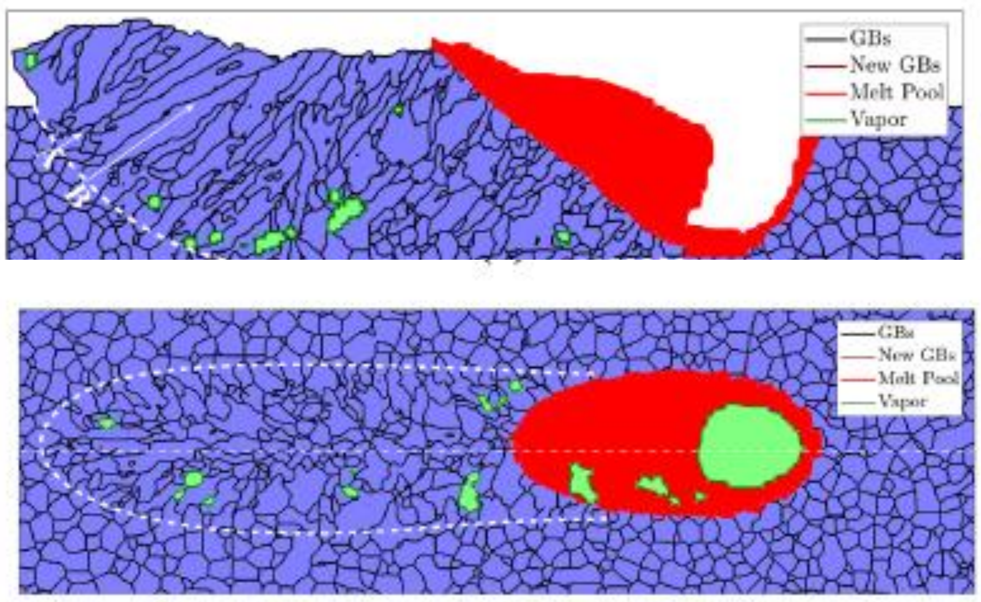
Epitaxial growth within a melt-track





Korner et al; *Metallurgical and Materials Transactions A* **2020**
doi.org/10.1007/s11661-020-05946-3



Shi et al; *The Journal of The Minerals, Metals & Materials Society* **2019**
https://doi.org/10.1007/s11837-019-03618-1

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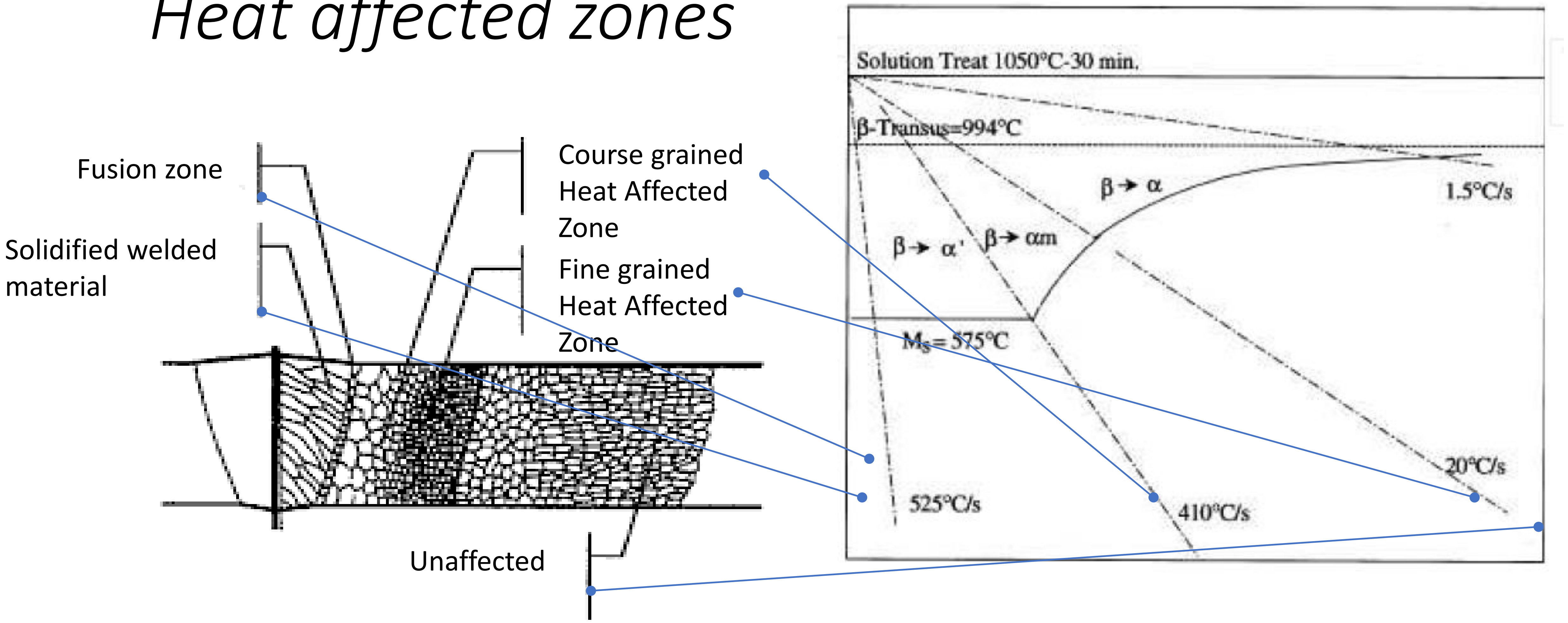
Heat affected zones



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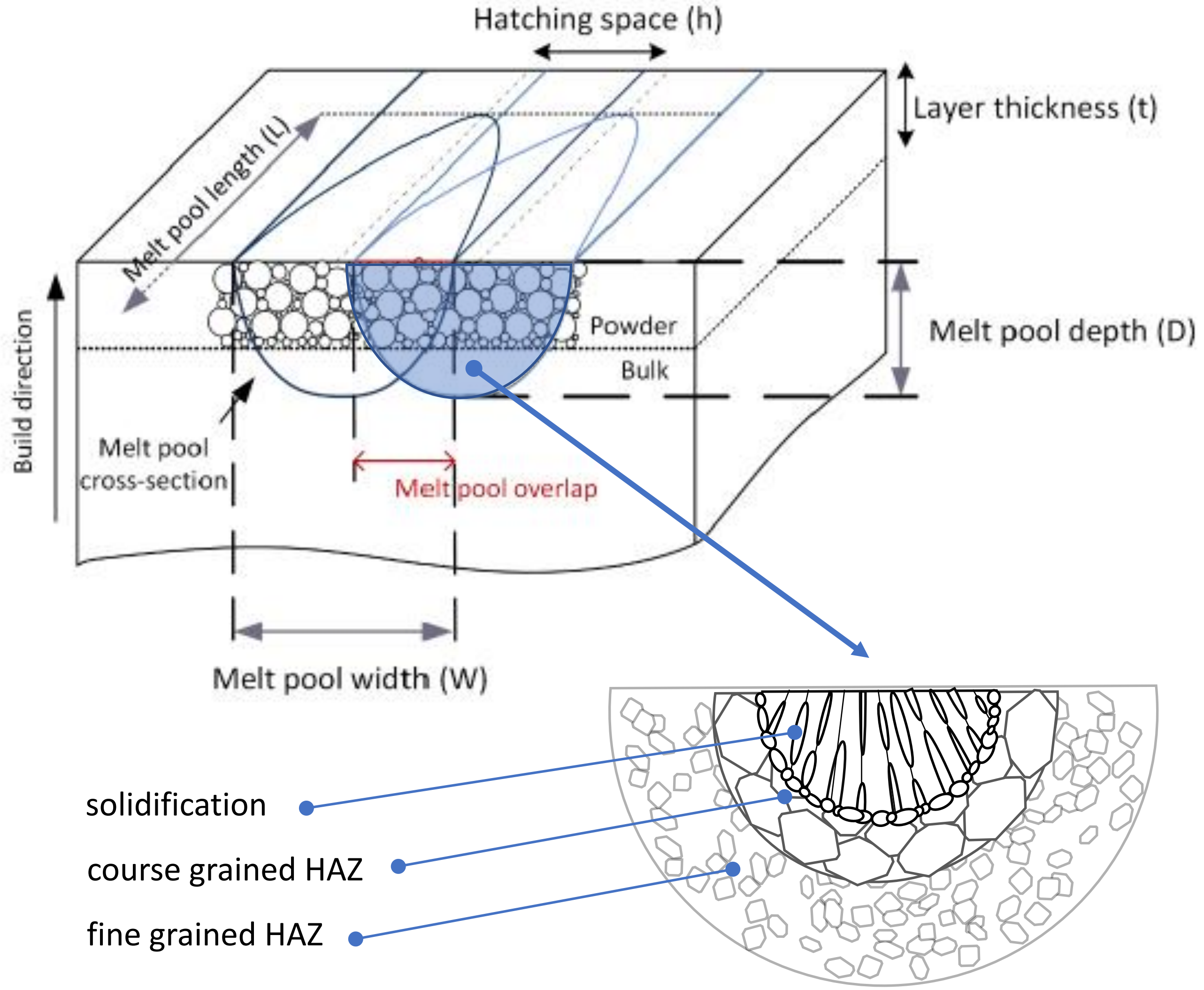
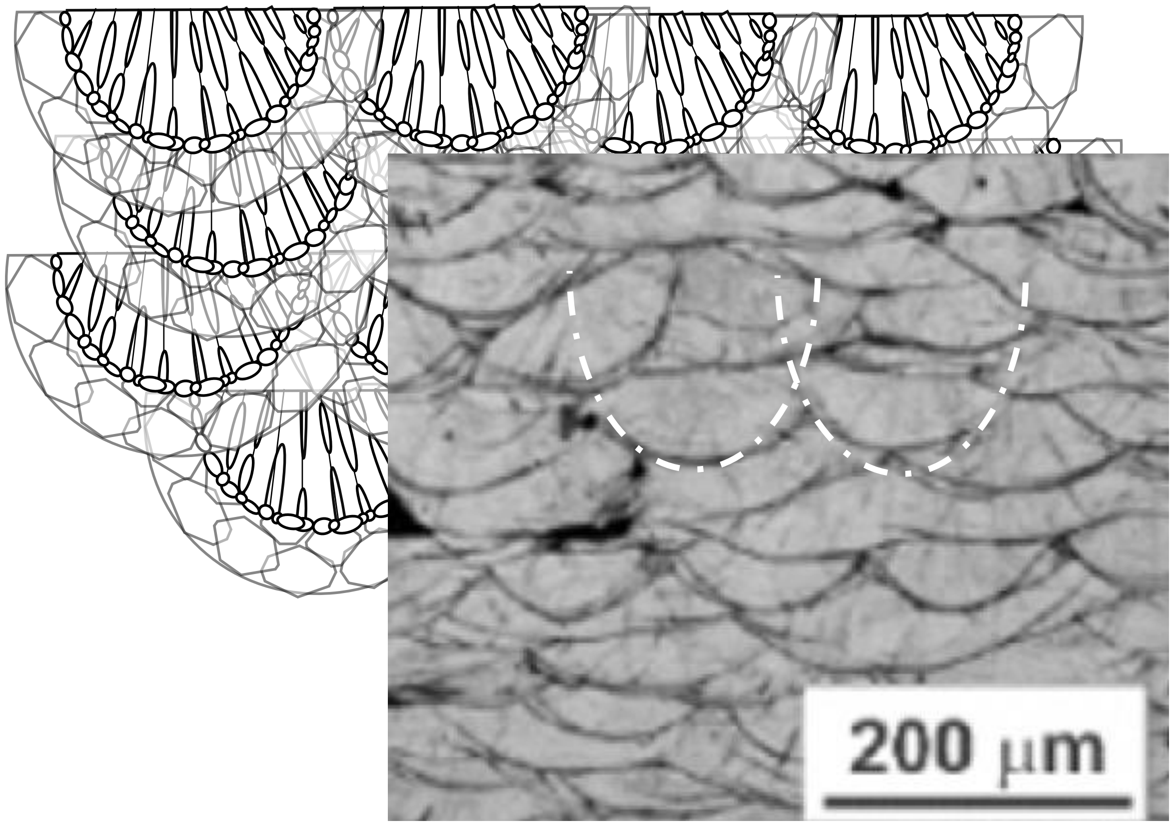
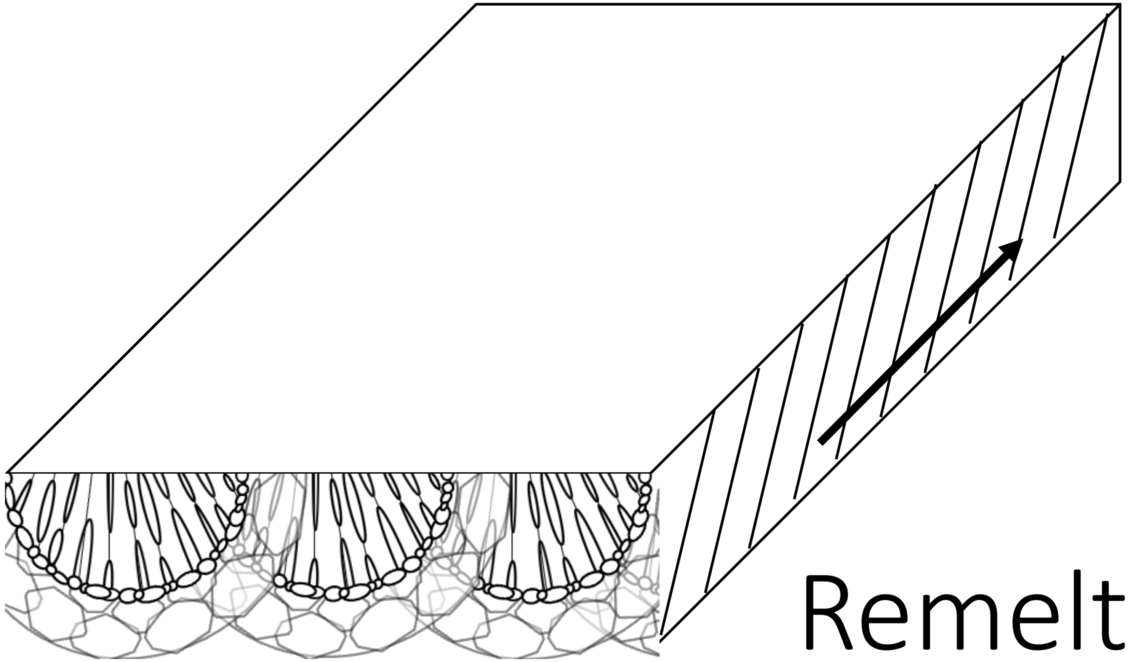
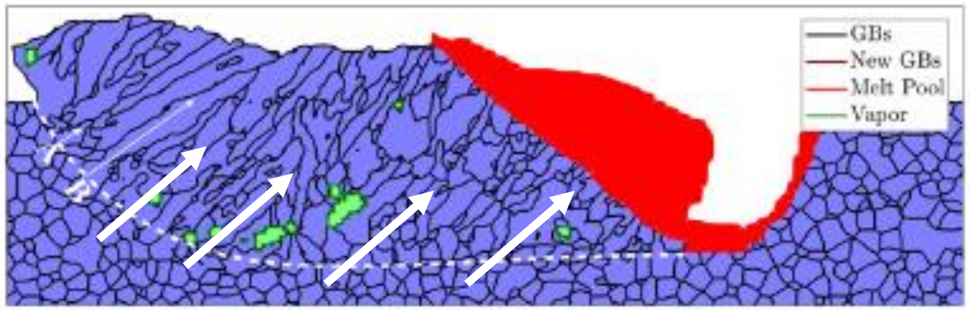
Letenneur et al *Journal of Manufacturing and Materials Processing* **2019**

Remelts in transverse









Remelts in longitudinal section

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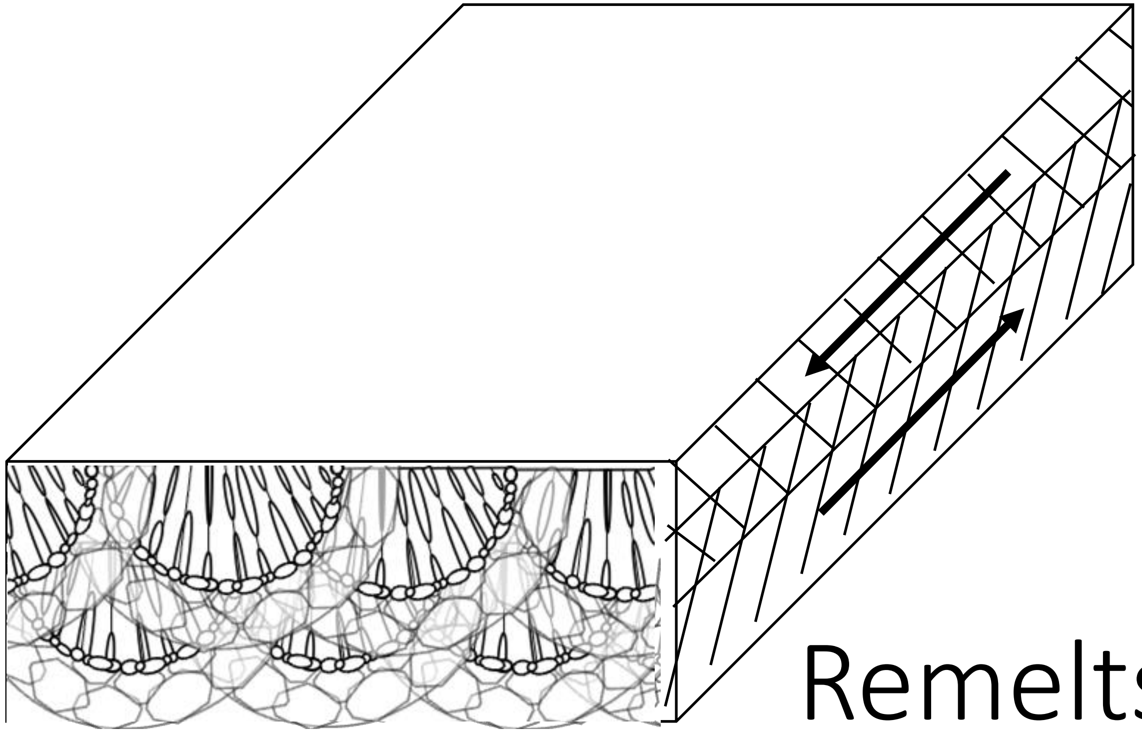

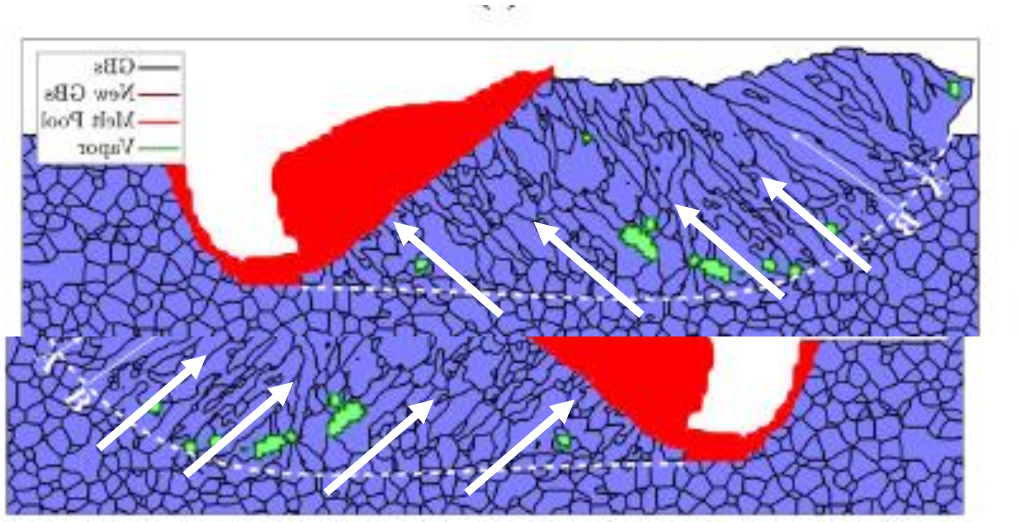

Remelts in longitudinal section

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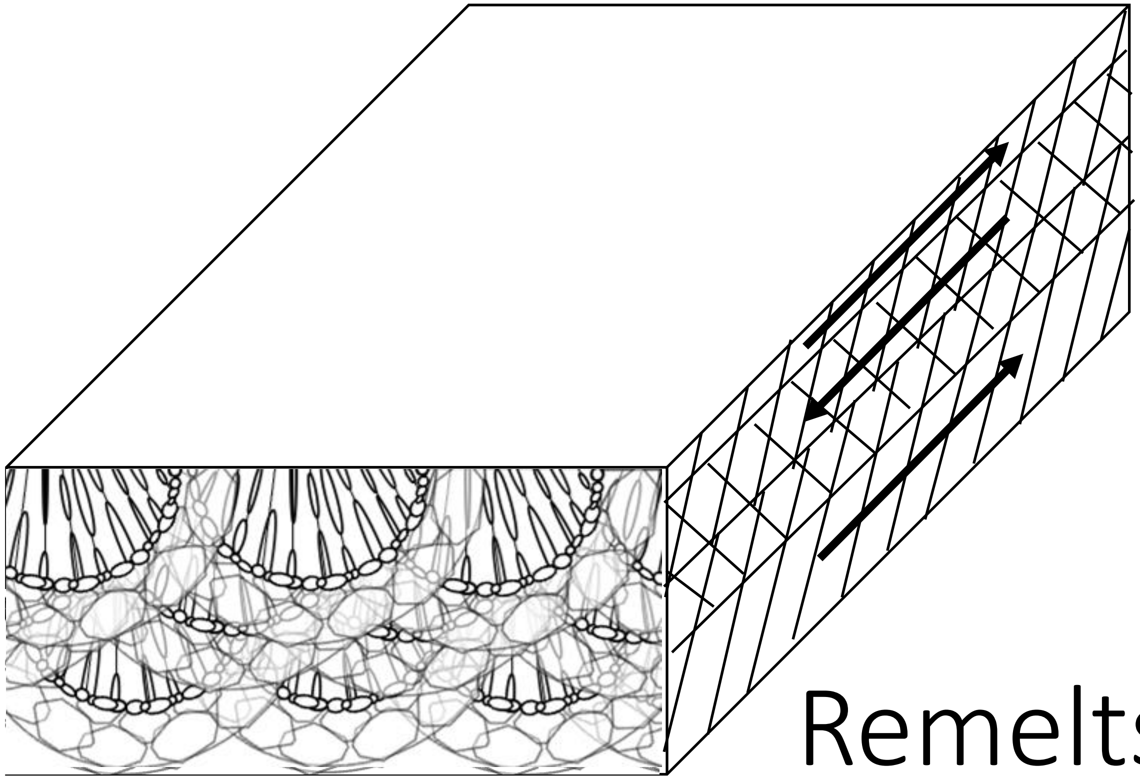

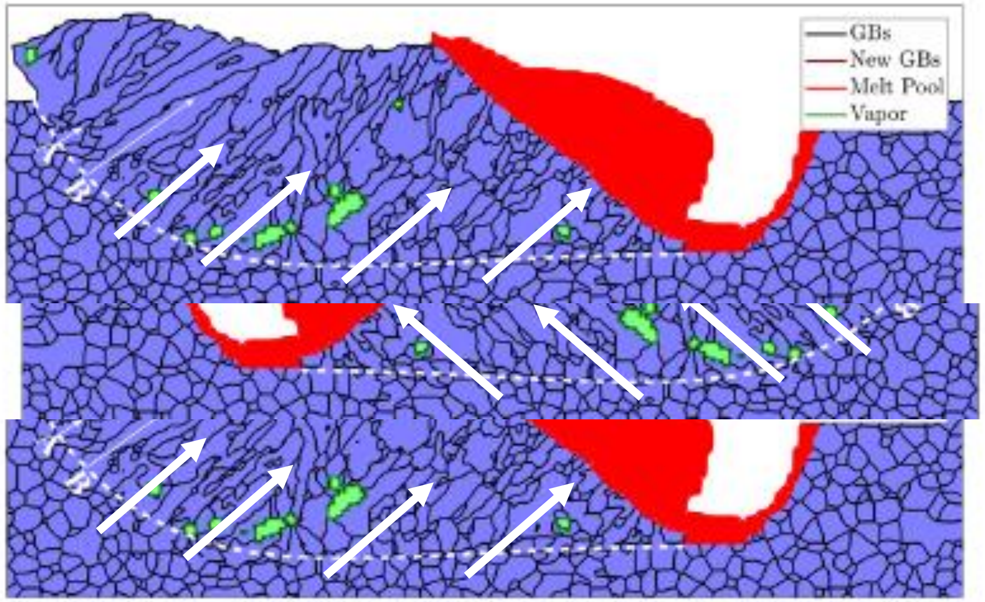

Remelts in longitudinal section

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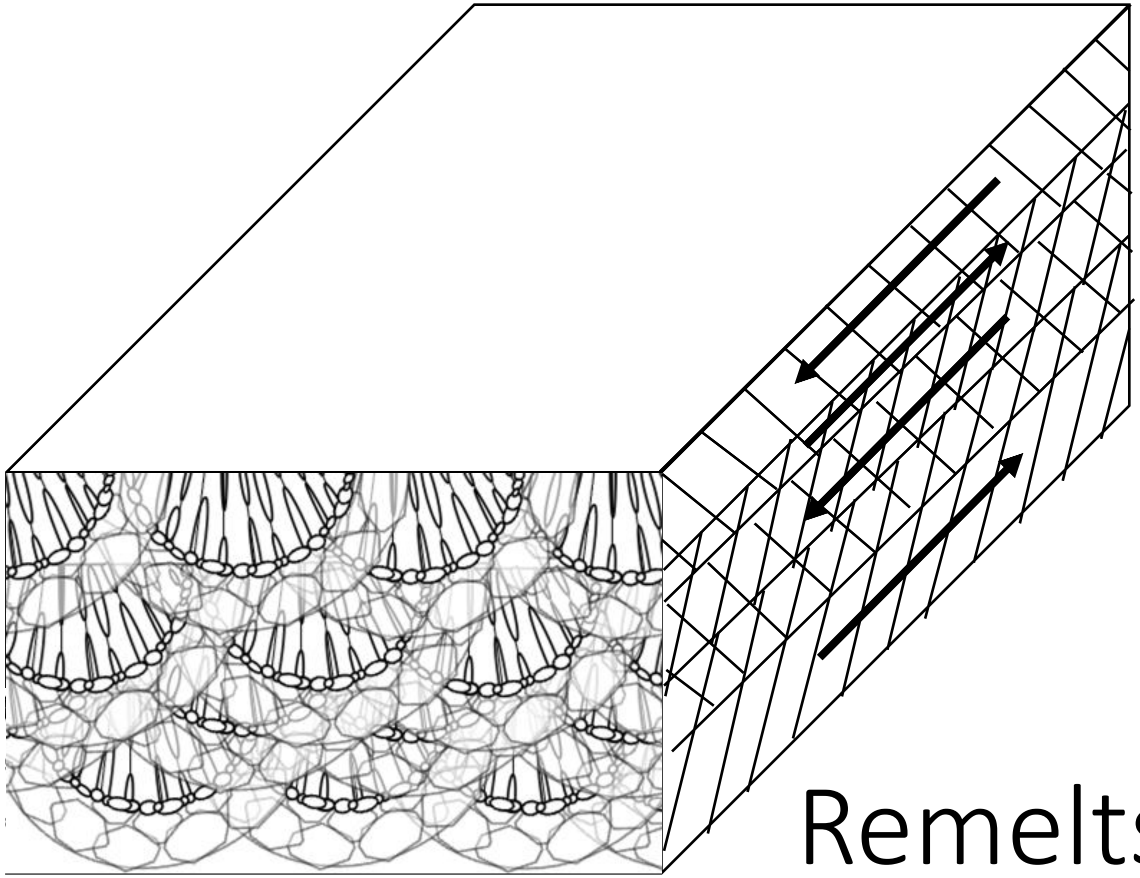

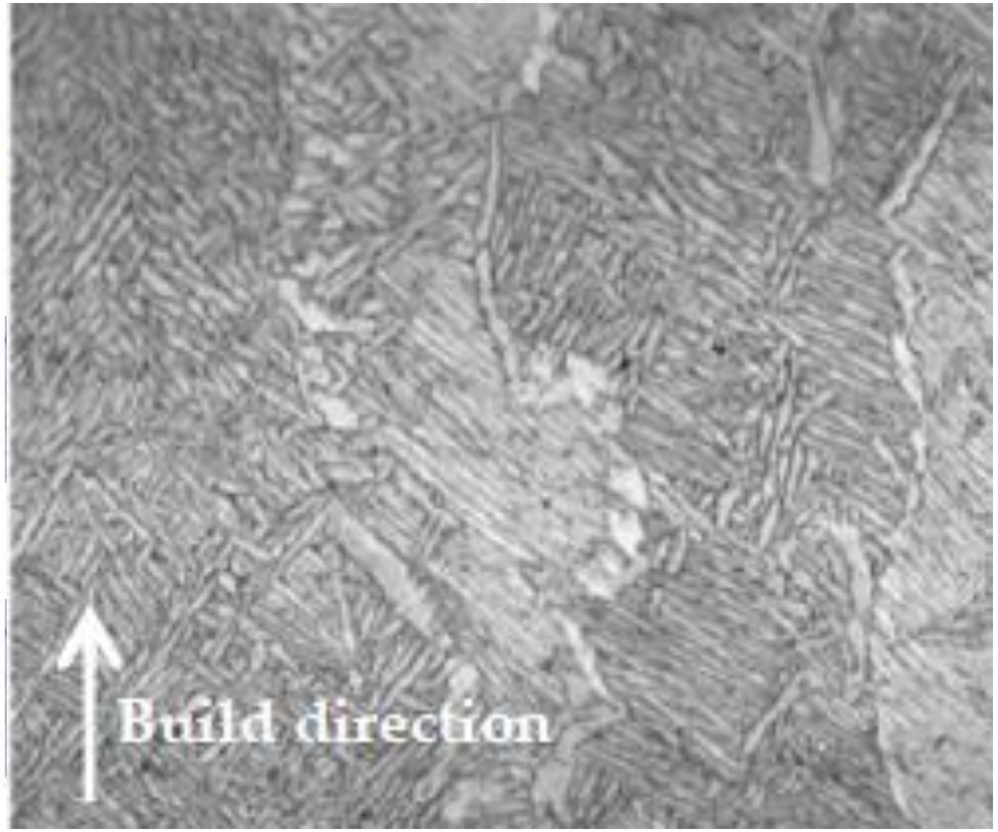

Remelts in longitudinal section

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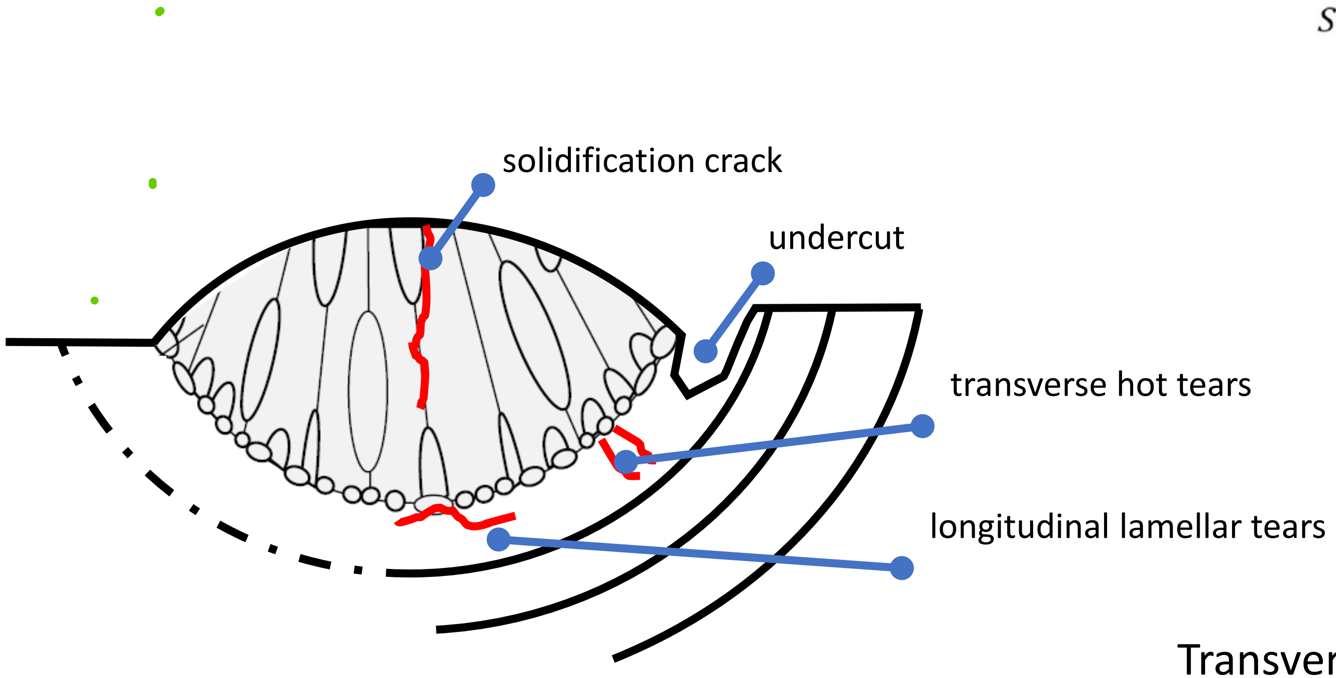
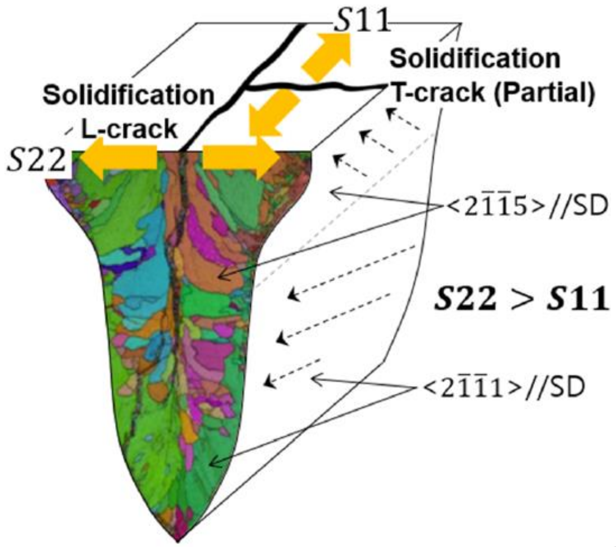
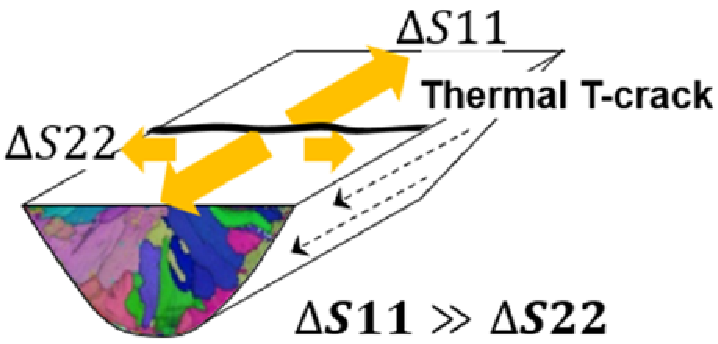
Cracking during solidification



Lee et al *Metals and Materials International* ***2020***
https://doi.org/10.1007/s12540-020-00770-1



Longitudinal and transverse solidification cracks in keyhole welding



Transverse solidification cracks in transient and conduction welding

T-crack frequency sensitive to the laser power and scan speed

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SAM
SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

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CU 15 PBF-LB Process

Hardware

Session Content

- PBF-LB Process review
- PBF-LB System Overview
- Examples of PBF-LB systems

Introduction

- Overview of the PBF-LB system
- Examples of different PBF-LB

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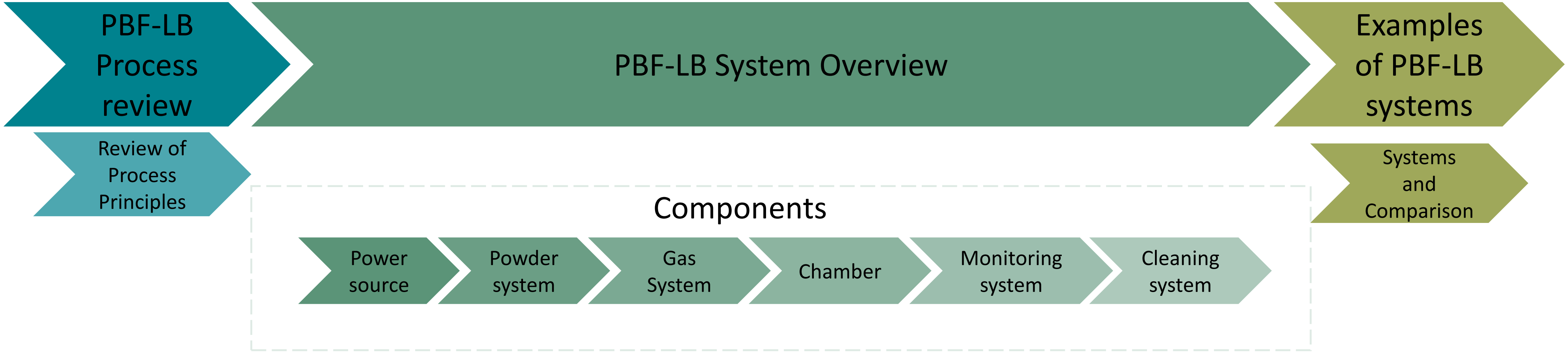
Session Content



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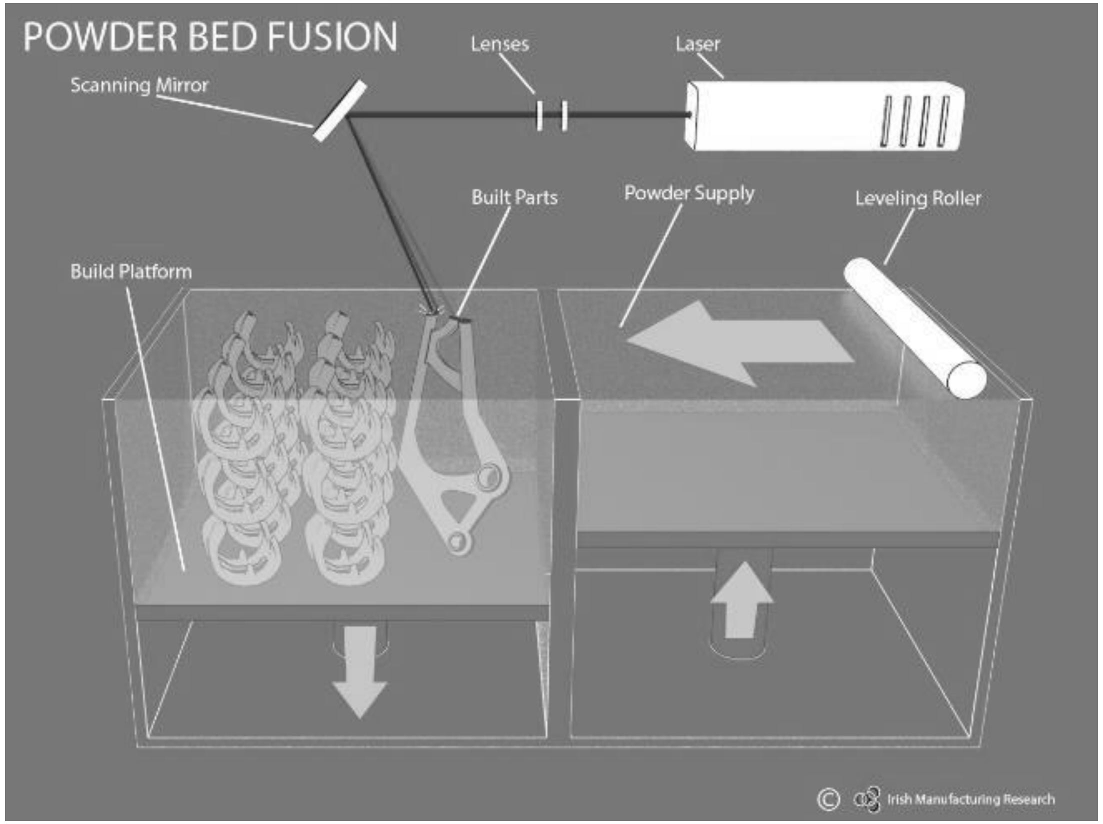
The PBF-LB process follows the sequential steps:

- Inert atmosphere within the build chamber
- Powder is spread across the build plate
- The laser scans the shape of the layer
- The build platform moves down one layer height.



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Session Content

PBF-LB Process review

PBF-LB System Overview

Examples of PBF-LB systems

Power source

Powder system

Gas System

Chamber

Monitoring system

Cleaning system

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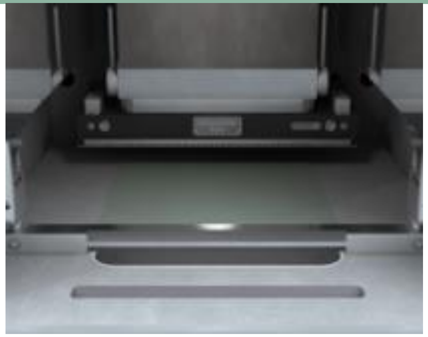
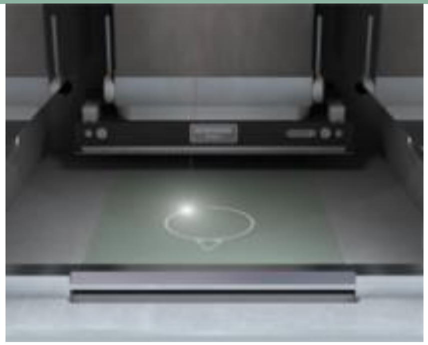
PBF-LB Process review | **PBF-LB System Overview** | Examples of PBF-LB systems

Power source | Powder system | Gas System | Chamber | Monitoring system | Cleaning system

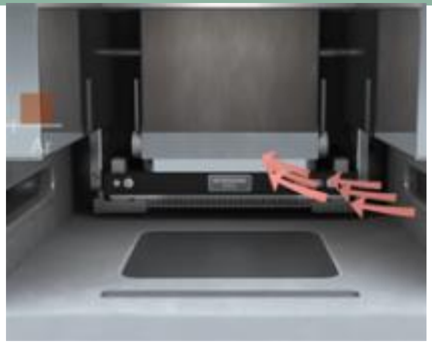
Powder System



Power source



Gas System



Build Chamber

Monitoring

Cleaning System

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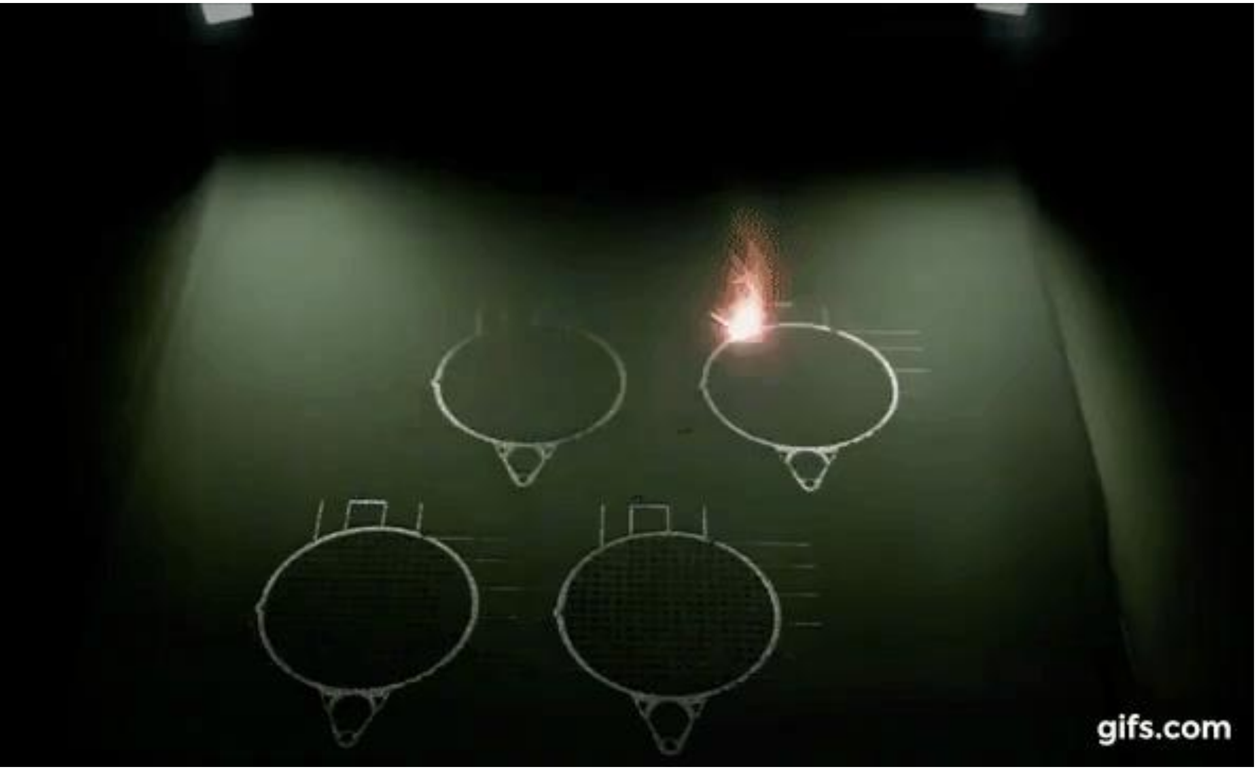

- Fibre laser
- Yb-fibre lasers are the most utilized in LB-PBF machines. Others are CO_2 or Nd:YAG-fibre lasers.
- 1030-1070 nm output wavelength – suitable for metal powder particles due to higher absorptivity at shorter wavelengths
- Typical power 100W – 1kW
- Spot size 30-500 µm

CU 15 PBF-LB - *Process*

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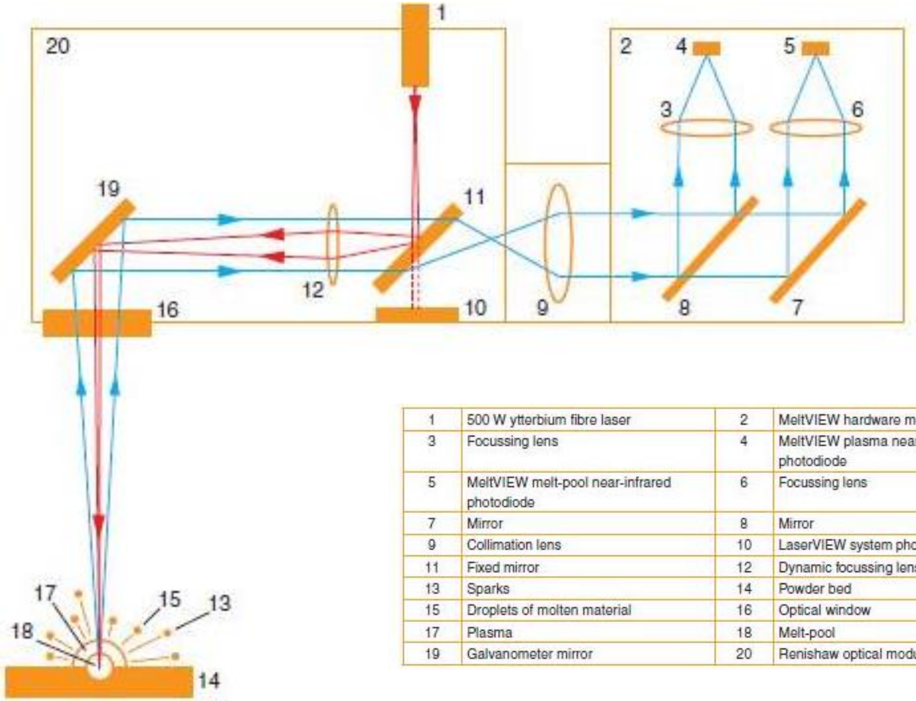
Optical system components:
Laser, focusing lens, high speed scanner, cooling system



1	500 W ytterbium fibre laser	2	MeltVIEW hardware module
3	Focussing lens	4	MeltVIEW plasma near-infrared photodiode
5	MeltVIEW melt-pool near-infrared photodiode	6	Focussing lens
7	Mirror	8	Mirror
9	Collimation lens	10	LaserVIEW system photodiode
11	Fixed mirror	12	Dynamic focussing lens
13	Sparks	14	Powder bed
15	Droplets of molten material	16	Optical window
17	Plasma	18	Melt-pool
19	Galvanometer mirror	20	Renishaw optical module

500W ytterbium fibre laser unit – Renishaw RenAM 500M

Ancillaries

Optical system components:
Laser, focusing lens, high speed scanner, cooling system

Single laser & multi-laser

- Systems are available in single laser format and multi-laser format
- Multi-laser configurations allow increased build rates
- The lasers in multi-laser configurations can cover the **full build area** or **sections of the build area**, depending on the OEM

Choice of laser & parameters according to material

Laser parameters based on the material being processed

⇨ CU 15 PBF-LB *Parameters*

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Power source → **Powder system** → Gas System → Chamber → Monitoring system → Cleaning system

- Supply of raw material to the build area
- Collection of overflow
- Recycling/sieving of unused powder
- Safe handling of metallic powders

Internal powder recycling

External powder recycling

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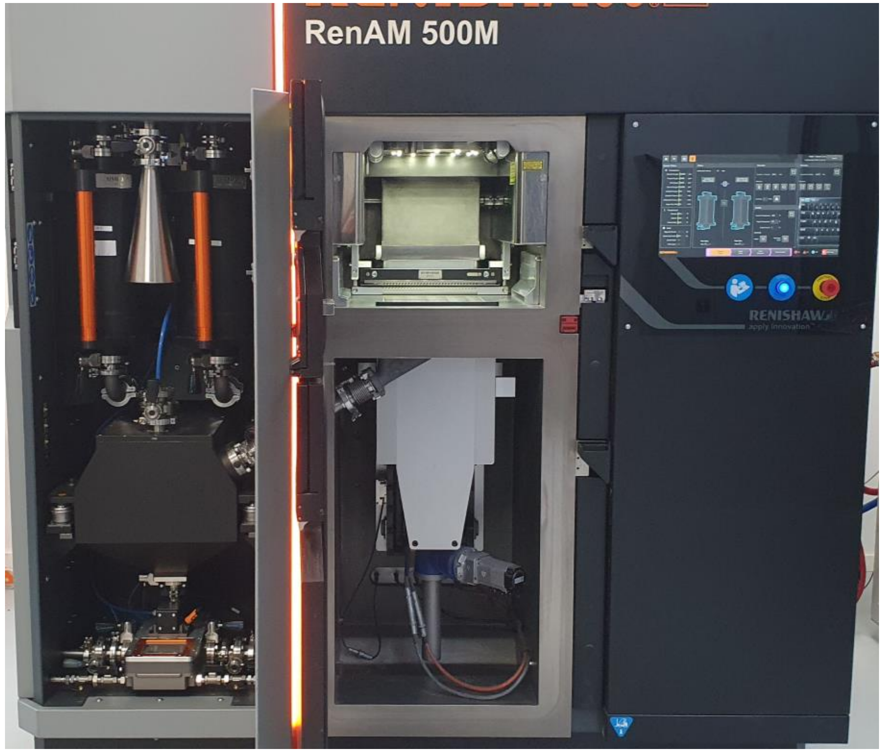
Internal powder recycling



External powder recycling

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Internal powder recycling

Components

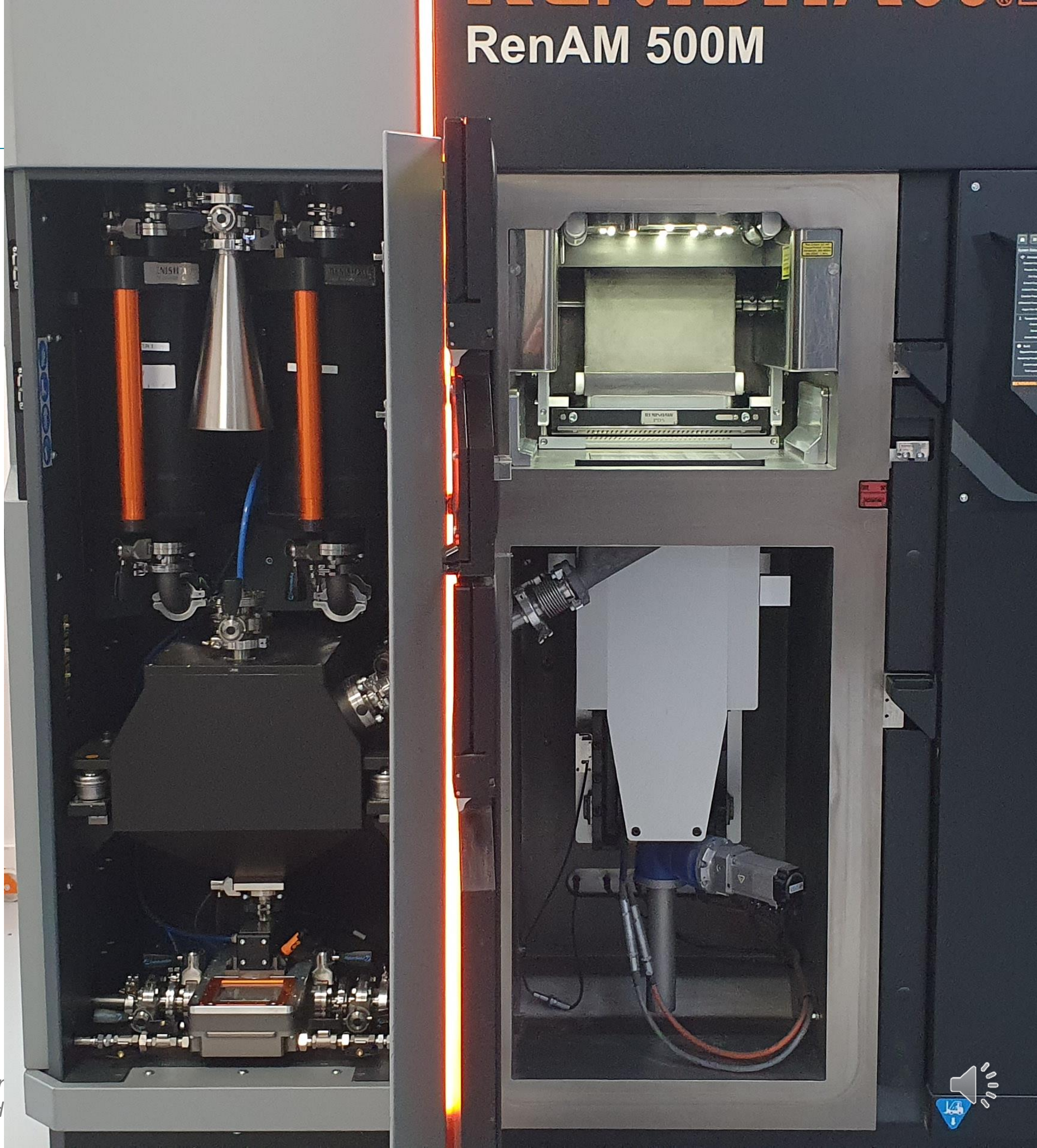
Load hopper

Sieve

Oversized particle storage

Dosing silo

Overflow*



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Internal powder recycling

Components

Load hopper

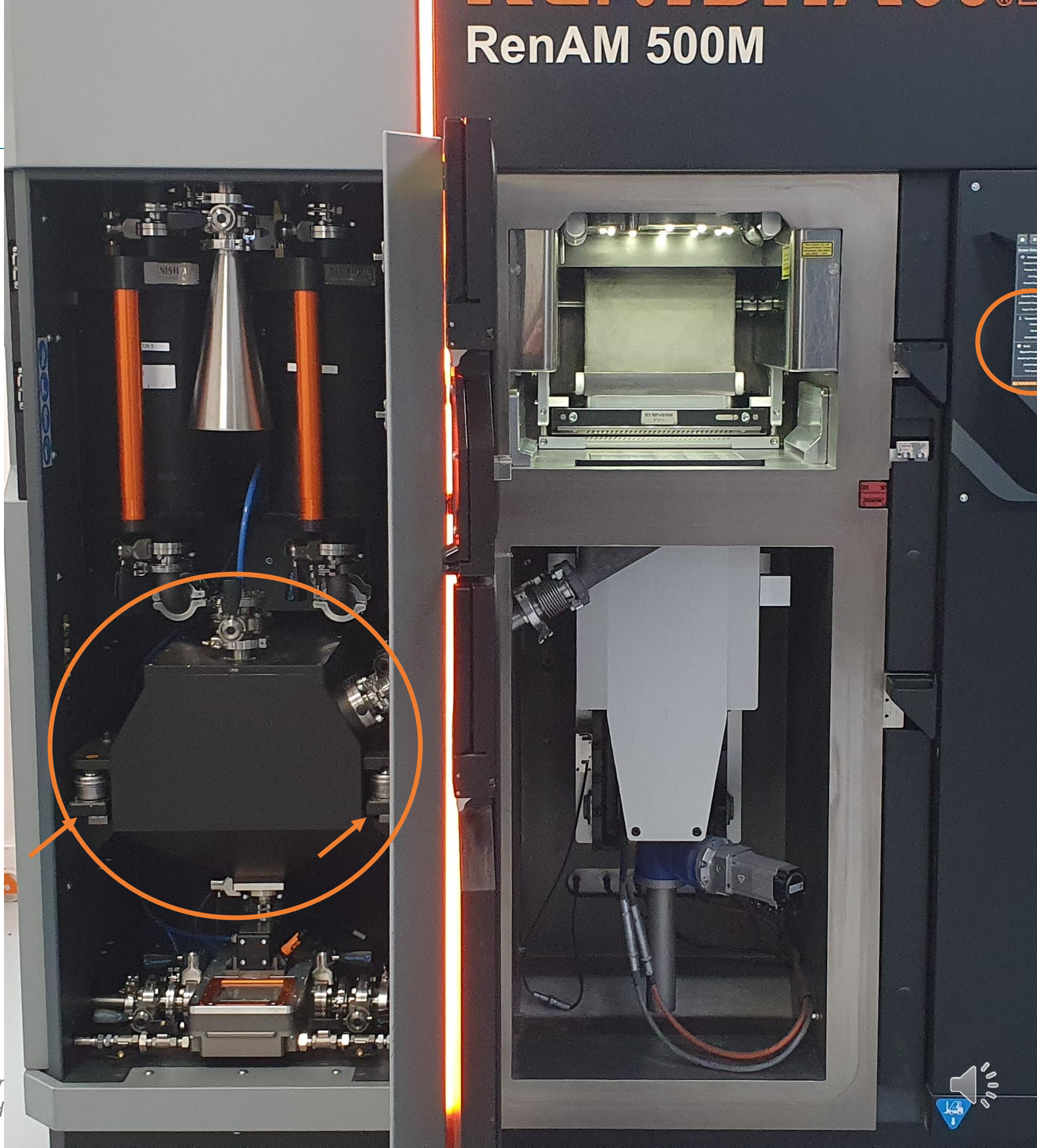
- Stores powder to deliver to the build chamber
- The capacity is usually sufficient for a build equal to the maximum z-axis travel
- Load cells measure the weight of powder in the hopper and this is displayed in the control panel

Sieve

Oversized particle storage

Dosing silo

Overflow*



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SAM
SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Internal powder recycling

Components

Load hopper

Sieve

Oversized particle storage

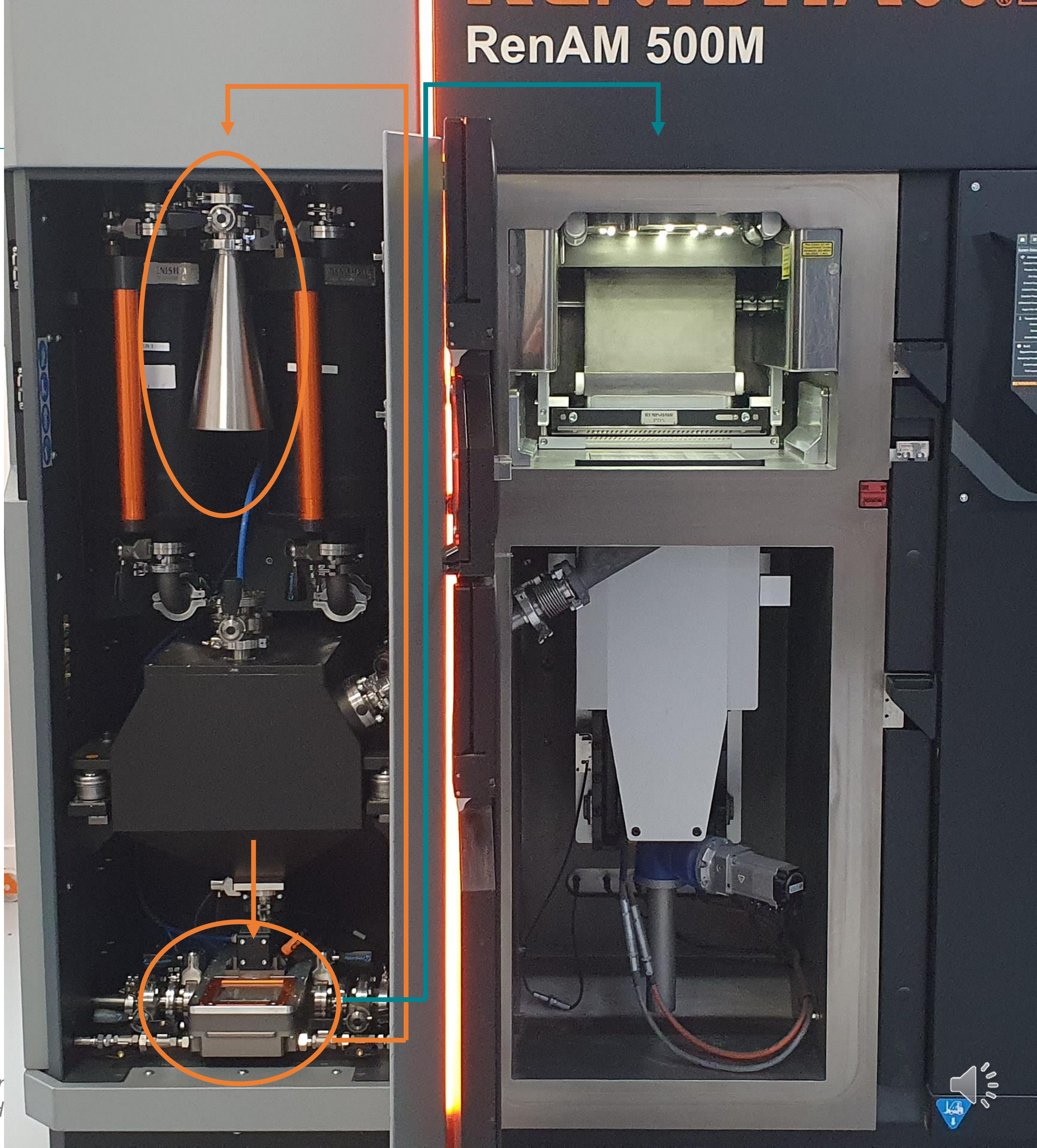
Separation of oversized particles through **sieving**

Oversized powder particles are transferred to the **oversized particles storage**

Usable powder is transferred to the silo

Dosing silo

Overflow*



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Internal powder recycling

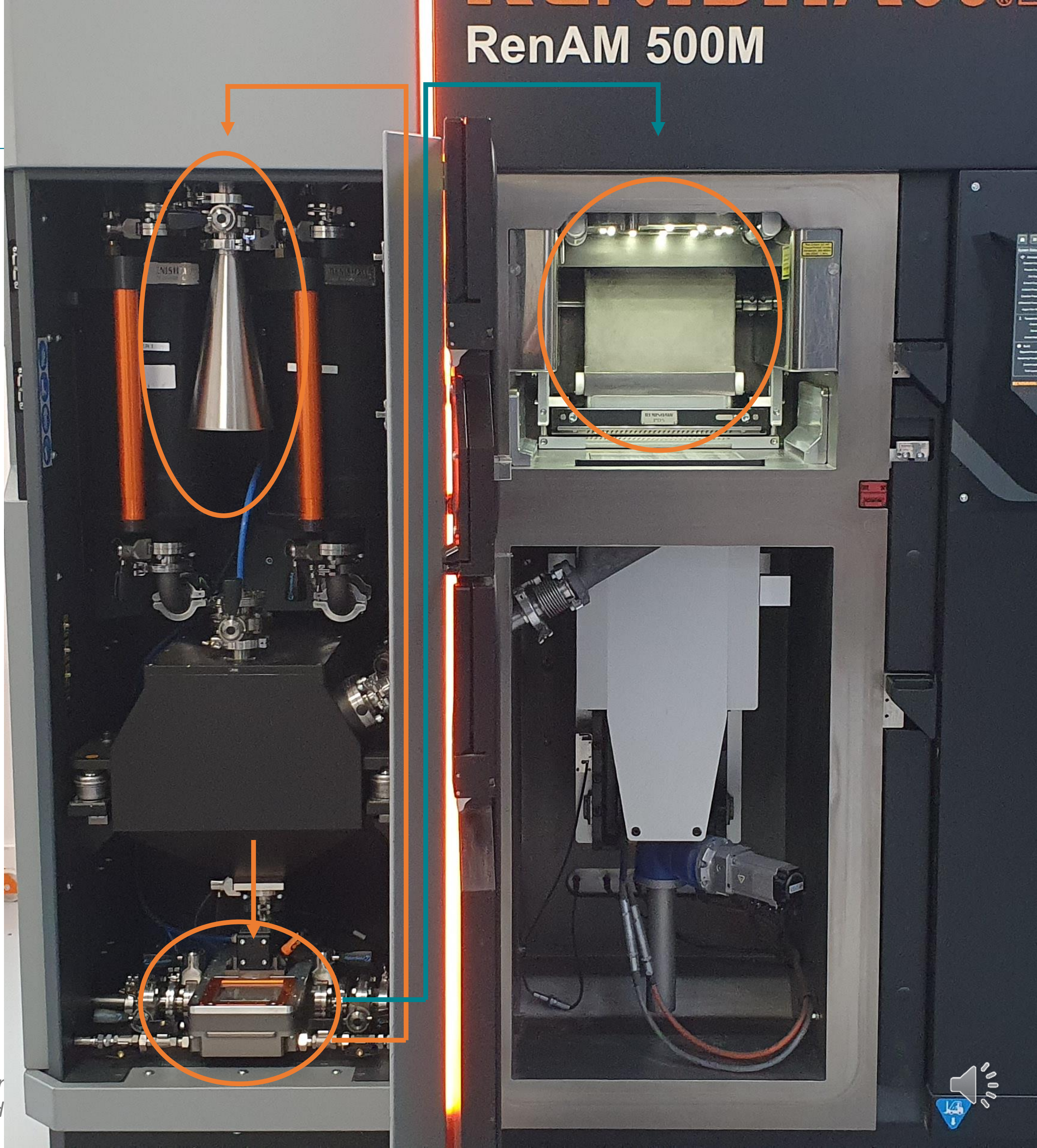
Components

- Load hopper
- Sieve
- Oversized particle storage
- Dosing silo

Located in build chamber

Level of powder is monitored, and powder is transferred from hopper to silo to deliver to build area

- Overflow*



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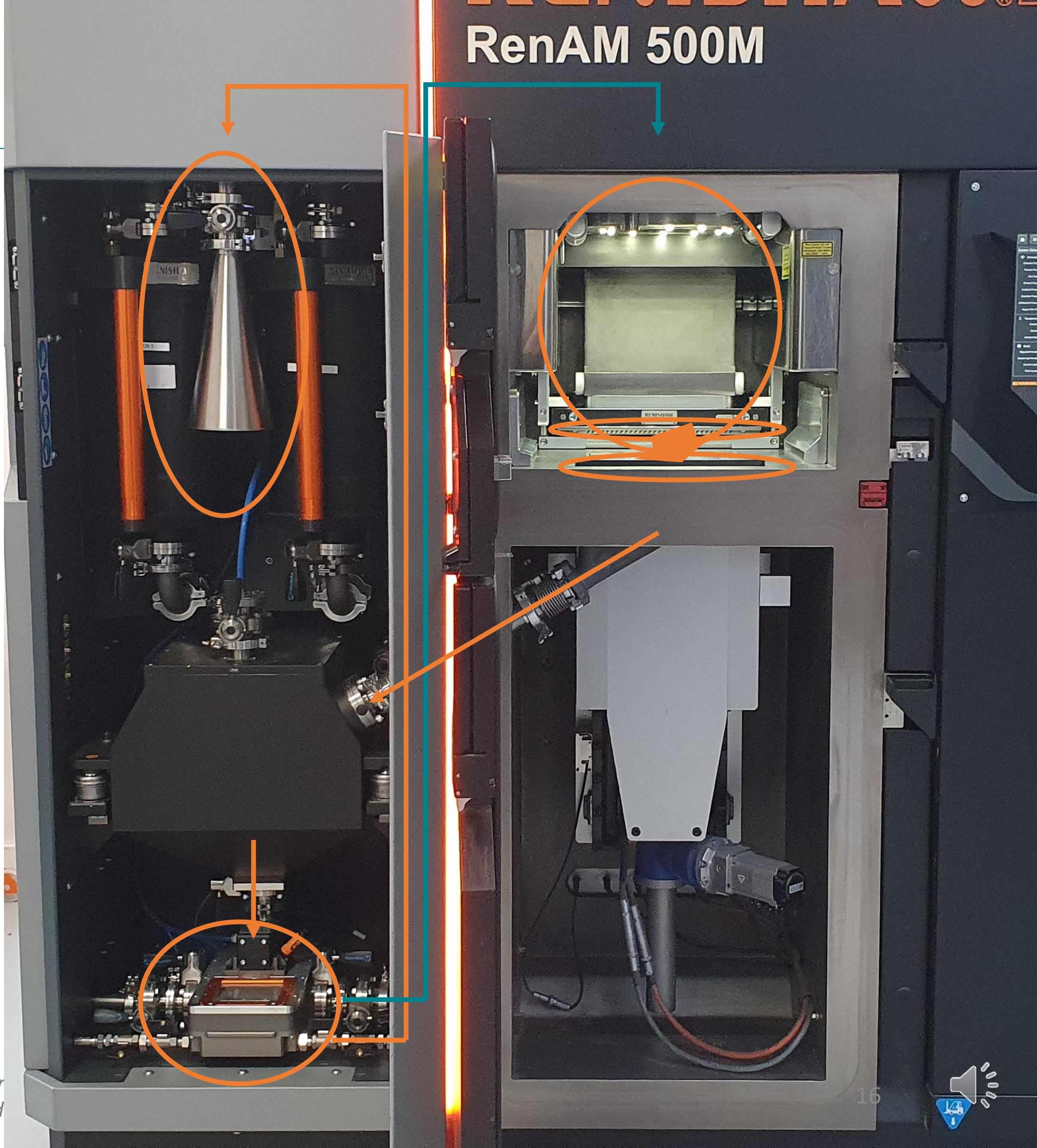
SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Internal powder recycling

Components
Load hopper
Sieve
Oversized particle storage
Dosing silo
Overflow*

Excess powder is collected through overflow system
- Mesh filters within the build chamber

Return to the hopper



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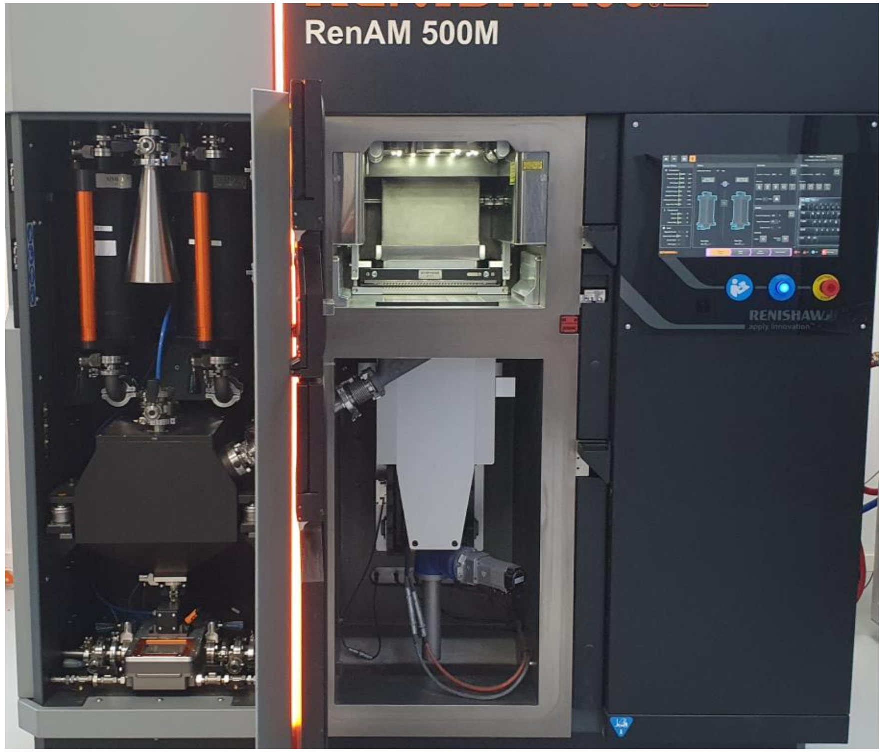
Internal powder recycling



External powder recycling

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External powder recycling

Components

- Powder container/hopper
- Dosing chamber
- Overflow
- Sieve
- Additional powder handling modules

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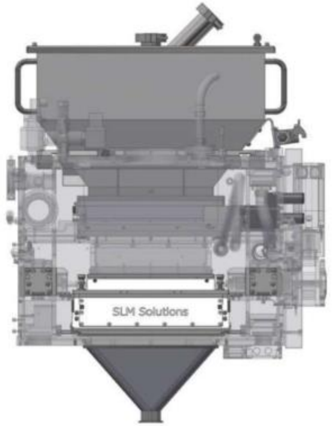

External powder recycling

Components

Powder container or hopper

- Stores powder to feed chamber
- Various capacities to suit build volume and build throughput

Dosing chamber

Overflow

Sieve

Additional powder handling modules

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External powder recycling

Components

Powder container/hopper

Dosing chamber

Stores powder to deliver to the build area

The capacity is usually sufficient for a build equal to the maximum z-axis travel

Overflow

Sieve

Additional powder handling modules

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External powder recycling

Components

- Powder container/hopper
- Dosing chamber
- Overflow

Excess powder is collected in overflow system

Collected powder is sieved for reuse

- Sieve
- Additional powder handling modules

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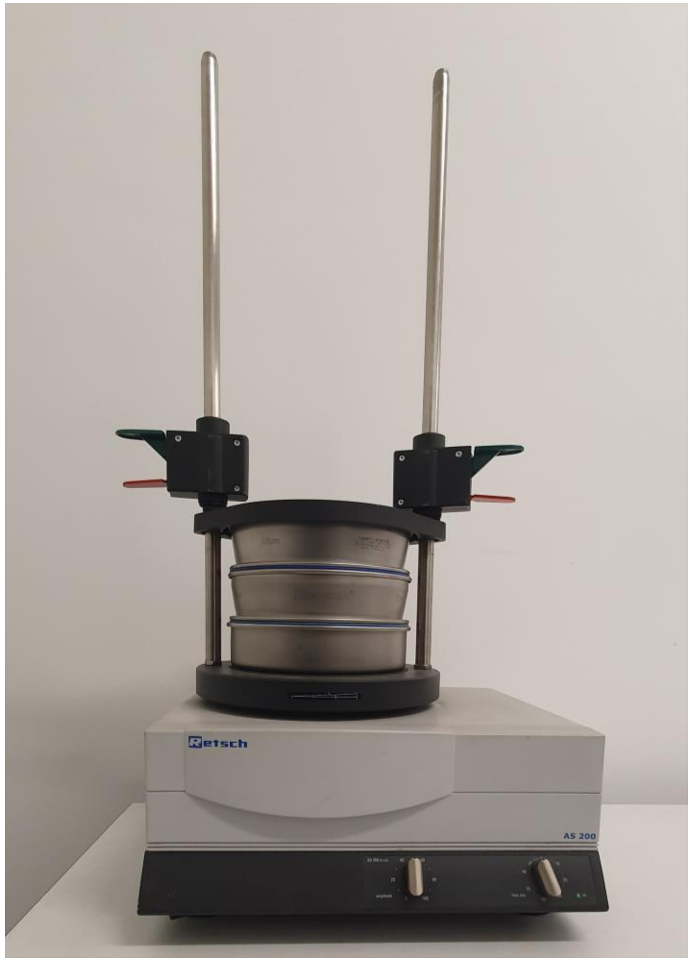

External powder recycling

Components

- Powder container/hopper
- Dosing chamber
- Overflow
- Sieve
  - Separation of oversized particles through **sieving**
  - Powder particles in the desirable size range are collected and reused
- Additional powder handling modules

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External powder recycling

Components
Powder container/hopper
Dosing chamber
Overflow
Sieve
Additional powder handling modules

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Power source | Powder system | **Gas System** | Chamber | Monitoring system | Cleaning system

Inert atmosphere within the build chamber is required

Avoid contamination from reactive gases (such as O_2 and CO_2

Vacuum & fill with inert gas

Fill with inert gas

CU 15 PBF-LB *Consumables*

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Components
Inert gas bottles
Gas circulation system
Filters
Vacuum pump

Inert atmosphere within the build chamber is required

Avoid contamination from reactive gases (such as O_2 and CO_2

Vacuum & fill with inert gas

Fill with inert gas

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Components

Inert gas bottles

- The inert gas is typically supplied by bottles of different capacities - located close to the system or in external areas
- Systems may have nitrogen generation systems

Gas circulation system

Filters

Vacuum pump

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Components

Inert gas bottles

Gas circulation system

- Inert gas circulates through the system to avoid contamination with atmospheric gases
- The gas flow across the build chamber carries out fine metal powder and nanoparticles emitted from the build process
- These are collected by the filters

Filters

Vacuum pump

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Power source | Powder system | **Gas System** | Chamber | Monitoring system | Cleaning system

Components

Inert gas bottles

Gas circulation system

Filters

- The filters capture process by-products for safe disposal
- The filtered gas is then recirculated through the system to maintain a low oxygen content

Vacuum pump

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Power source | Powder system | **Gas System** | Chamber | Monitoring system | Cleaning system

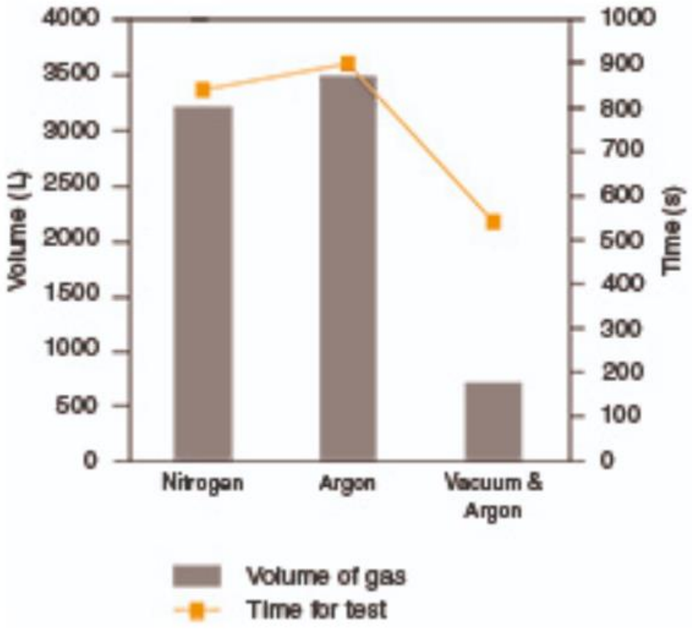
Components
Inert gas bottles
Gas circulation system
Filters

- The filters capture process by-products for safe disposal
- The filtered gas is then recirculated through the system to maintain a low oxygen content
- Water floodable or permanent

Vacuum pump

Components
Inert gas bottles
Gas circulation system
Filters
Vacuum pump

- Vacuum is created within the build chamber before fill with inert gas
- More efficient utilization of gas and faster chamber preparation



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Components

- Beam aperture protective window
- Process gas
- Build platforms
- Powder delivery
- External access
- Viewing window

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Power source | Powder system | Gas System | **Chamber** | Monitoring system | Cleaning system

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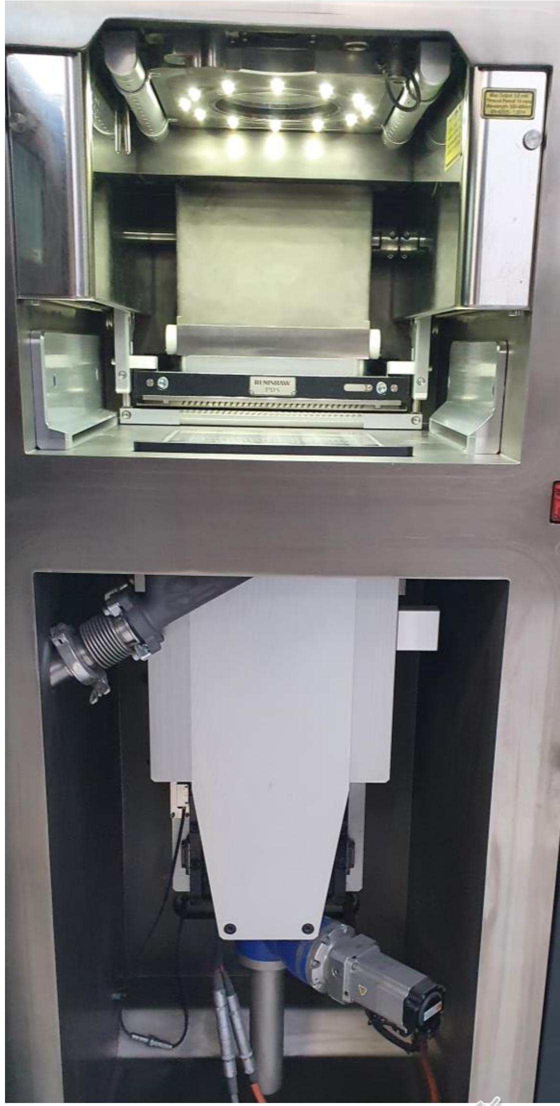

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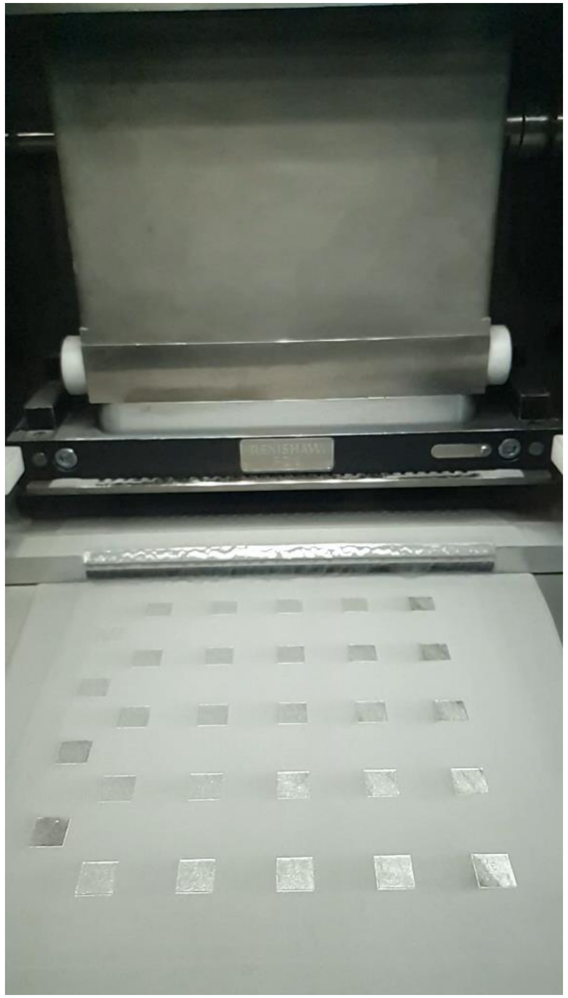

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Power source | Powder system | Gas System | **Chamber** | Monitoring system | Cleaning system

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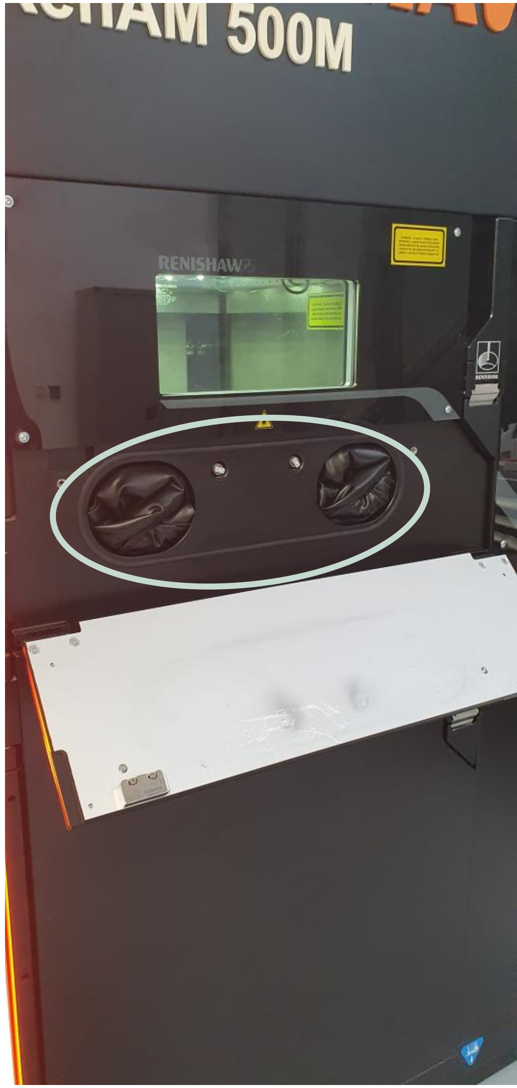

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Power source → Powder system → Gas System → Chamber → **Monitoring system** → Cleaning system

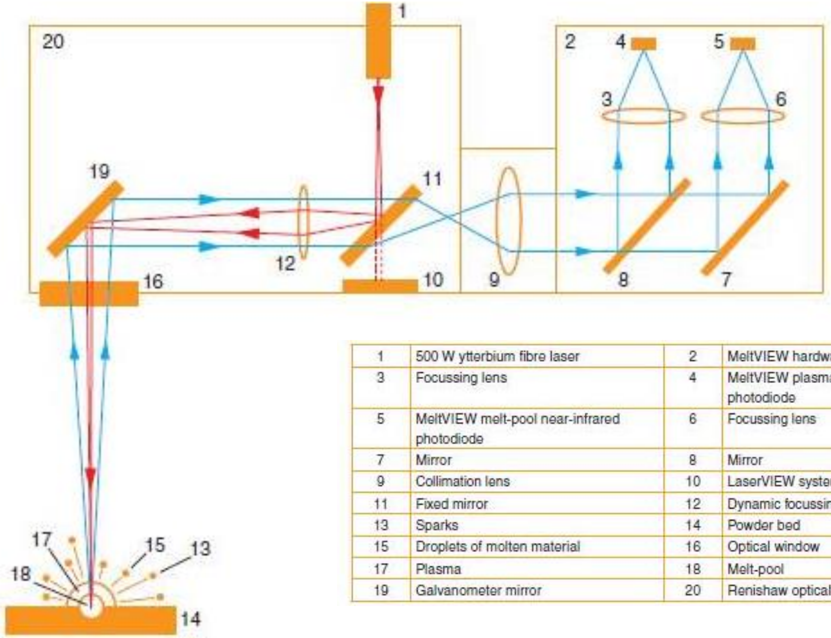
Monitoring systems make possible to analyze the process in real time or subsequently

Quality assurance and process development

Technologies used
- Cameras
- Photodiodes

Monitored
- Melt pool
- Track
- Slice
- Powder bed

Other sensors are utilized to track general process
- Oxygen sensors
- Temperature
- Pressure



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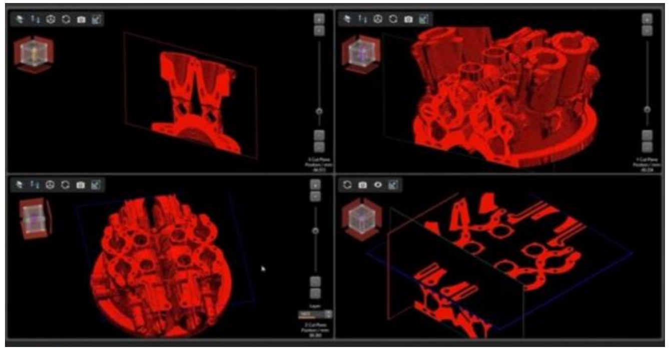
3	Focussing lens	4	MeltVIEW plasma near-infrared photodiode
5	MeltVIEW melt-pool near-infrared photodiode	6	Focussing lens
7	Mirror	8	Mirror
9	Collimation lens	10	LaserVIEW system photodiode
11	Fixed mirror	12	Dynamic focussing lens
13	Sparks	14	Powder bed
15	Droplets of molten material	16	Optical window
17	Plasma	18	Melt-pool
19	Galvanometer mirror	20	Renishaw optical module



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- Removal of residual powder
- Build chamber preparation
- Support safe handling of metal powders
- Internal and/or external

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Session Content

PBF-LB Process review → PBF-LB System Overview → Examples of PBF-LB systems

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Session Content

PBF-LB Process review → PBF-LB System Overview → **Examples of PBF-LB systems**

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Examples of PBF-LB systems

eos
SLM SOLUTIONS
RENISHAW apply innovation™
TRUMPF
VELO3D
GE CONCEPTLASER
3D SYSTEMS
AddUp
Additive Industries
Aurora Labs
FARSOON TECHNOLOGIES
COHERENT. ORLASER
sisma
Matsuura
铂力特

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Commonly seen PBF machines:

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Session Summary

PBF-LB Process review → PBF-LB System Overview → Examples of PBF-LB systems

Power source → Powder system → Chamber → Gas System → Monitoring system → Cleaning system

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SAM
SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

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An Introduction to Software

Used with Laser Based Powder Bed Fusion

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Notes about this course

- The aim of this is to present the basic software packages used within a PBF-LB manufacturing process
- It provides a brief overview of their function within the process
- It provides a brief overview of the specific uses of some of these within the PBF-LB process
- It is not an in-depth course or tutorial on using these software packages

The mention or discussion of any software brand or package does not represent an endorsement

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Introduction

- Additive Manufacturing is a digital manufacturing process
  - It fundamentally relies on software and digital information to operate

- The entire manufacturing chain relies on multiple software packages interacting and transferring data

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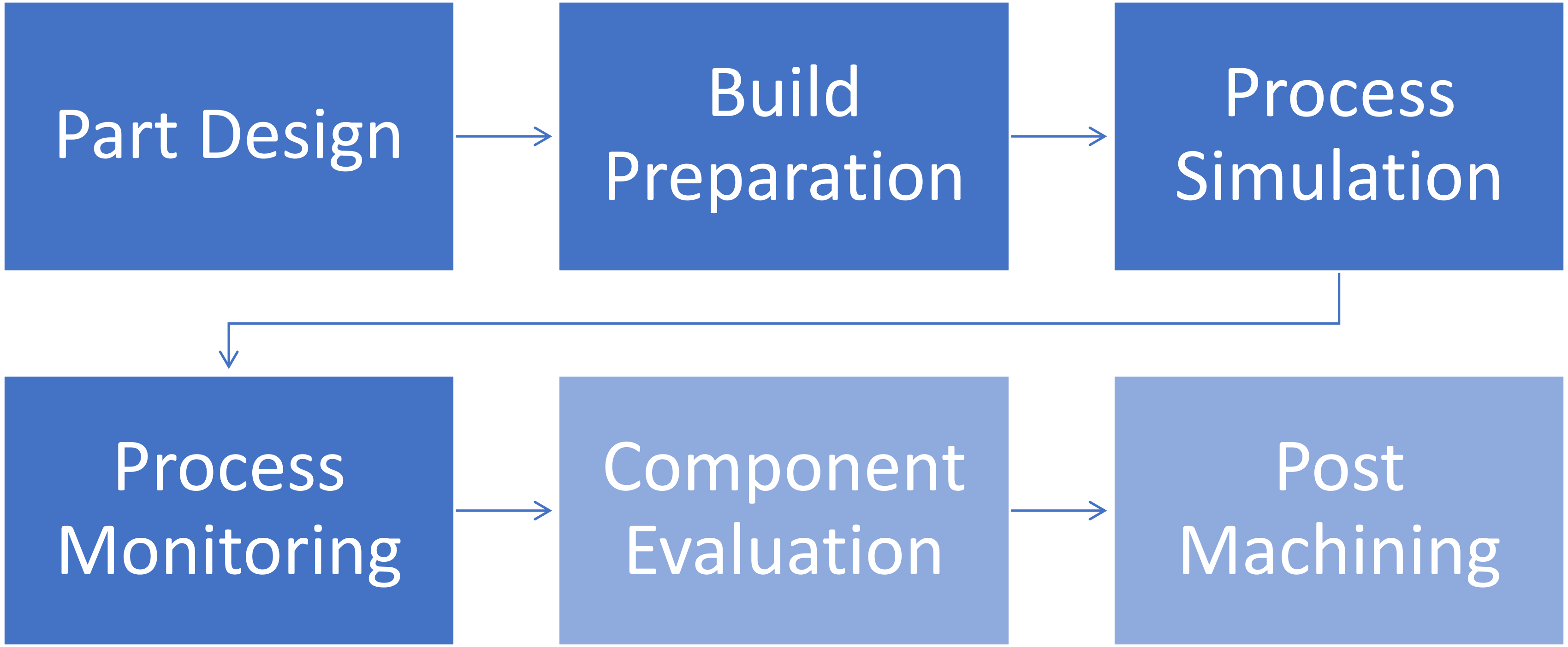
AM Software Chain



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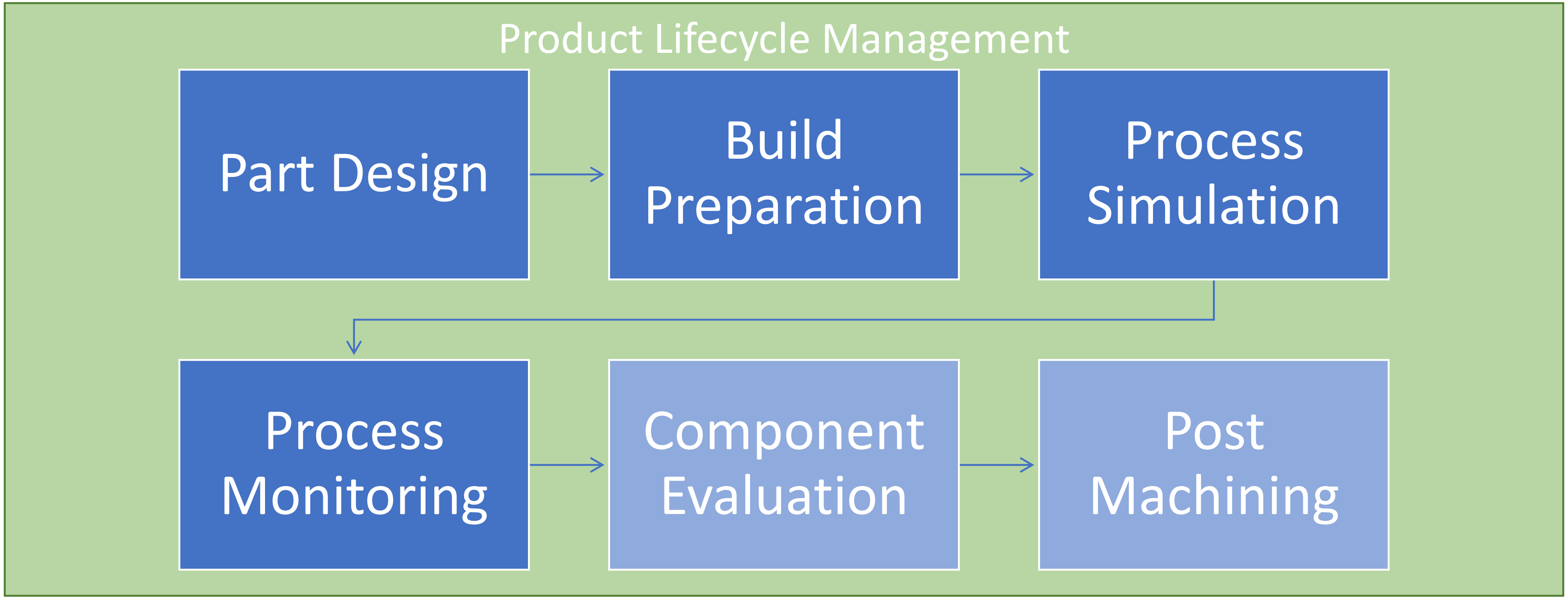
AM Software Chain



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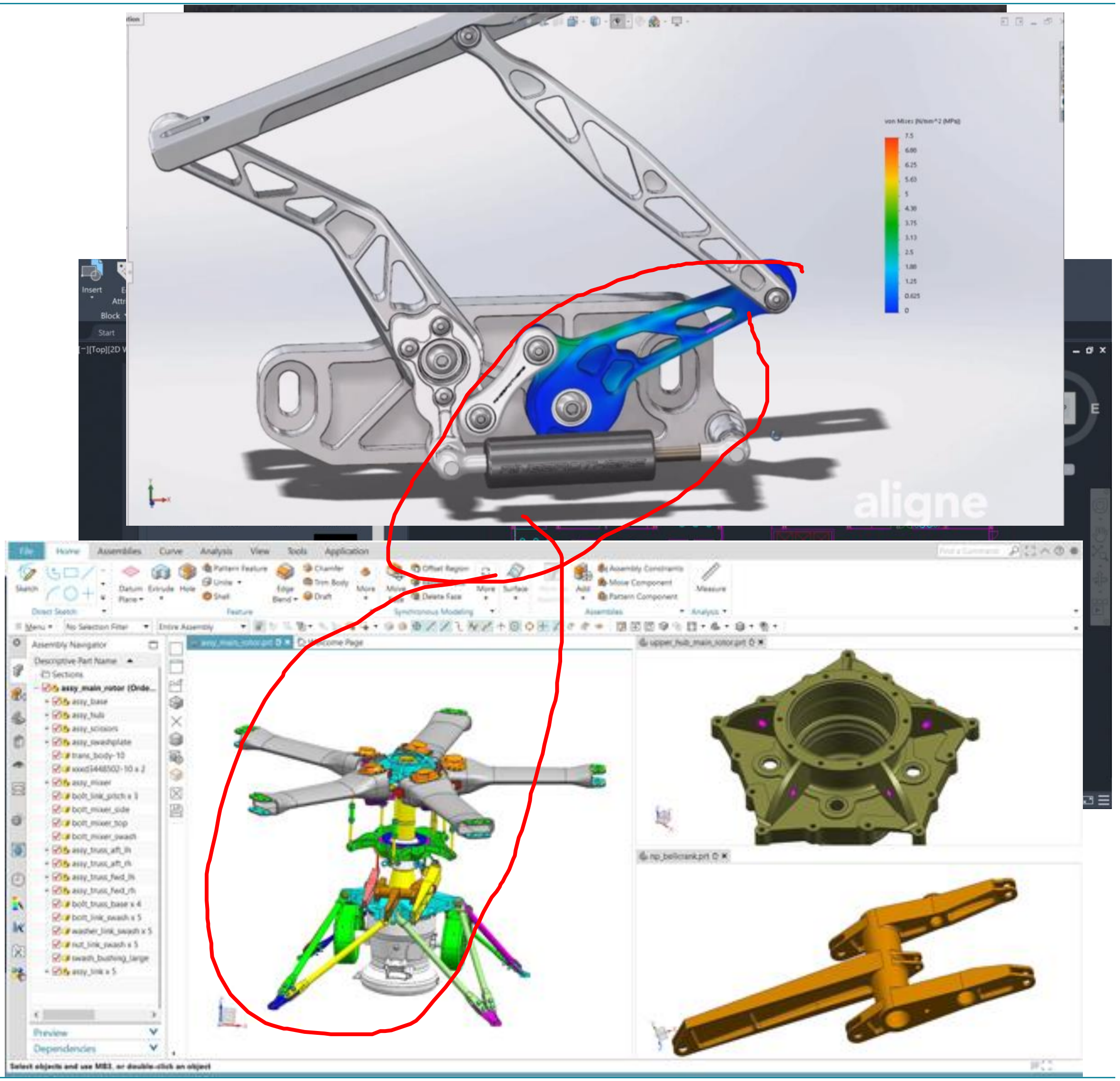
Step 1: Part Design

- Computer Aided Design – CAD
- Design of components using computer software
- 3D CAD – Drawings – Manufacturing Information
- 3D CAD – AM Process



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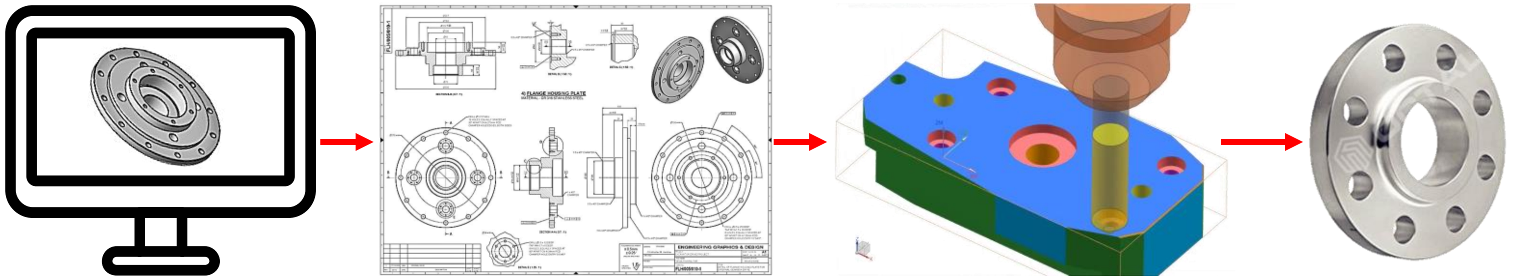
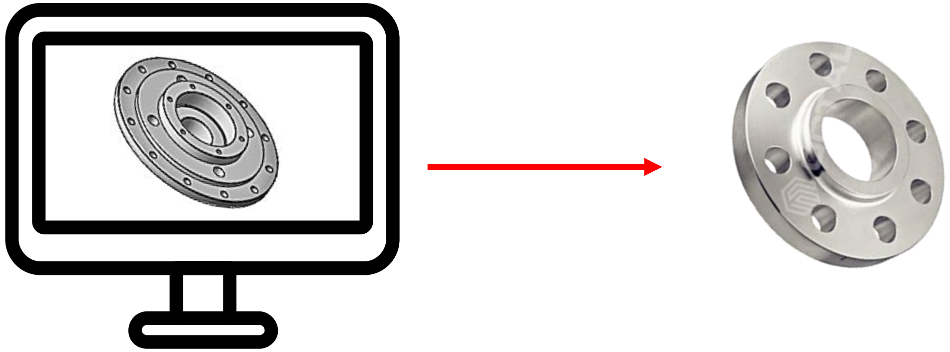
Step 1: Part Design

- Within conventional manufacturing processes CAD is passed through an intermediatory stage prior to manufacturing
  - Drawings
  - Tool Path Generation
- The way these intermediatory stages were carried out has a significant impact on the final part
  - Parts are made according to drawings – not CAD
- AM removes this intermediatory stage and components are produced according to CAD directly





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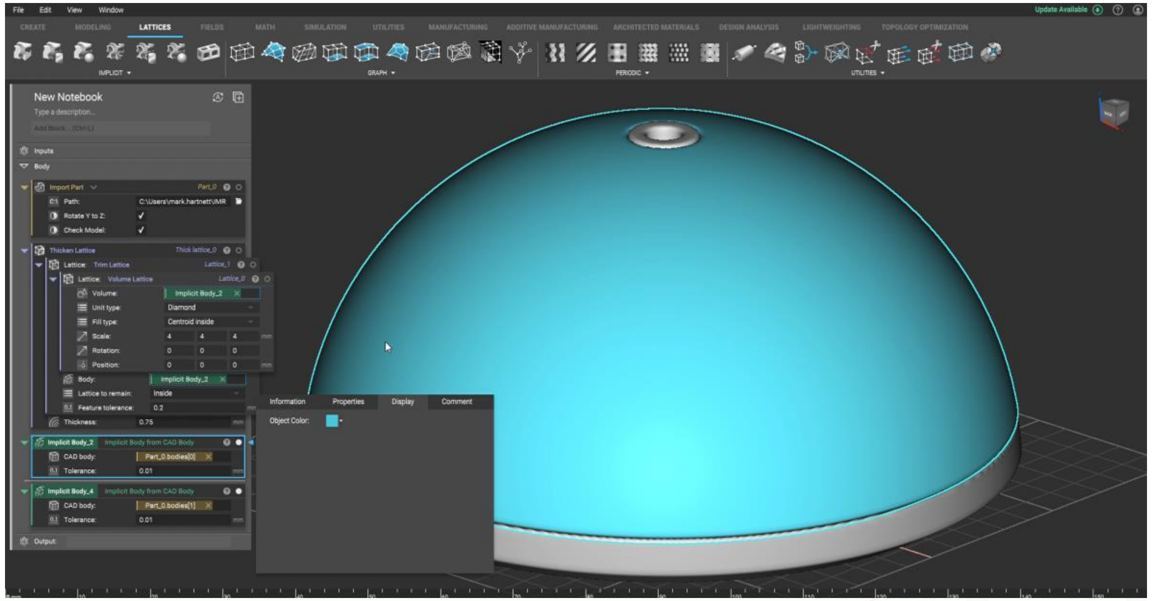
Step 1: Part Design - Advanced

- “Complexity is free”
- PBF-LB allows for the manufacturing of complex components which are difficult or impossible to manufacture through other means
- Specialised design software has been developed to facilitate this
  - Lattice Structure Design
  - Topology Optimisation



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Step 2: Build Preparation

- 3rd Party or Proprietary
- Functions
  - *File Repair*
  - Orientation
  - Supporting
  - Layout
  - Parameter Setting
  - Build Analysis

Materialise Magics
AUTODESK® NETFABB®
SIEMENS NX
RENISHAW apply innovation™
AddUp Manager™
VELO 3D

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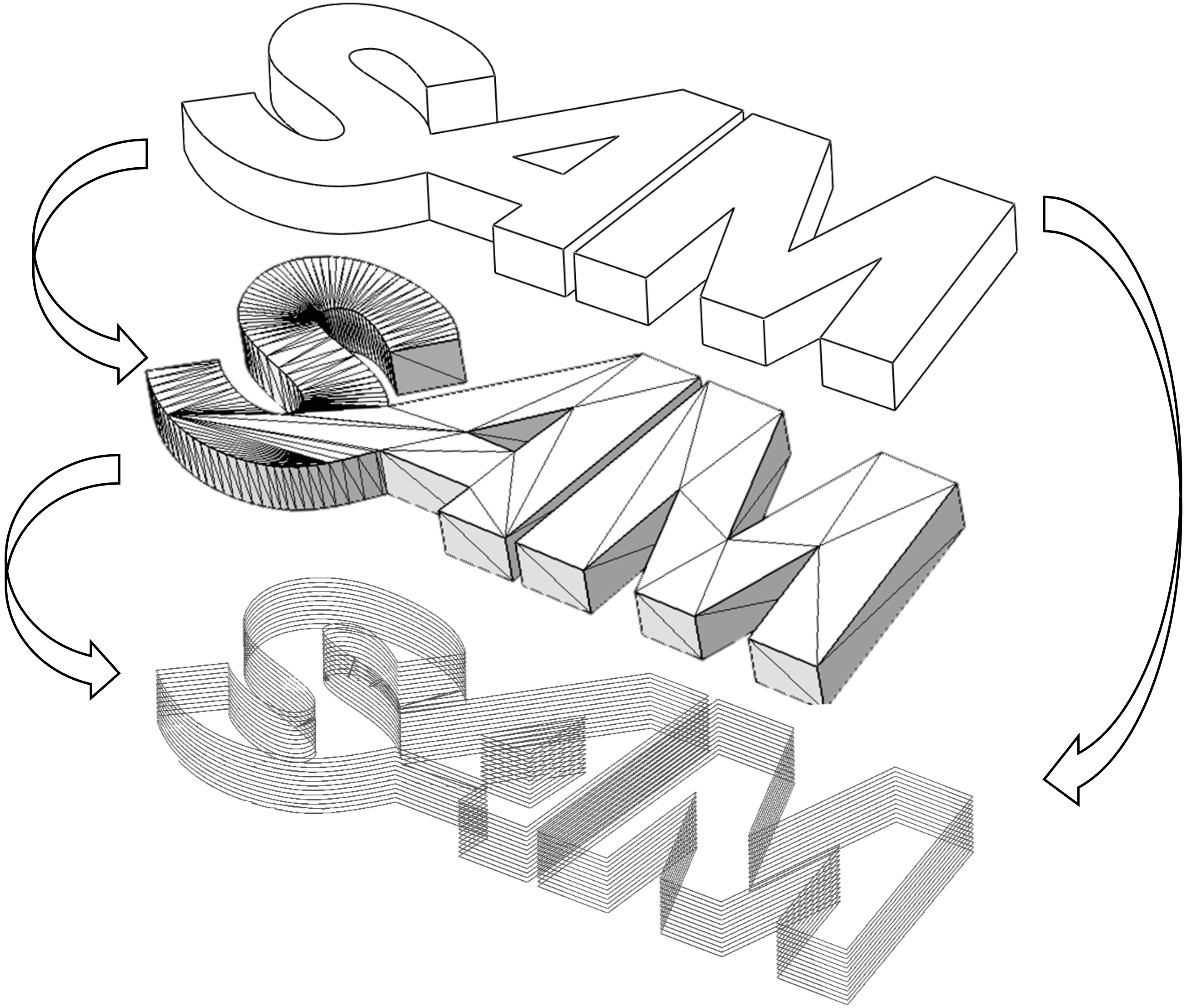
Step 2: Build Preparation

- Surface based - *.STEP, .IGES*
- Tessellated -*.STL, .AMF, .3MF*
- *Slice - .CLI, . SLI*
- Information can be lost or corrupted during file conversions
- Errors:
  - Inverted surfaces
  - Holes
  - Intersecting Geometry



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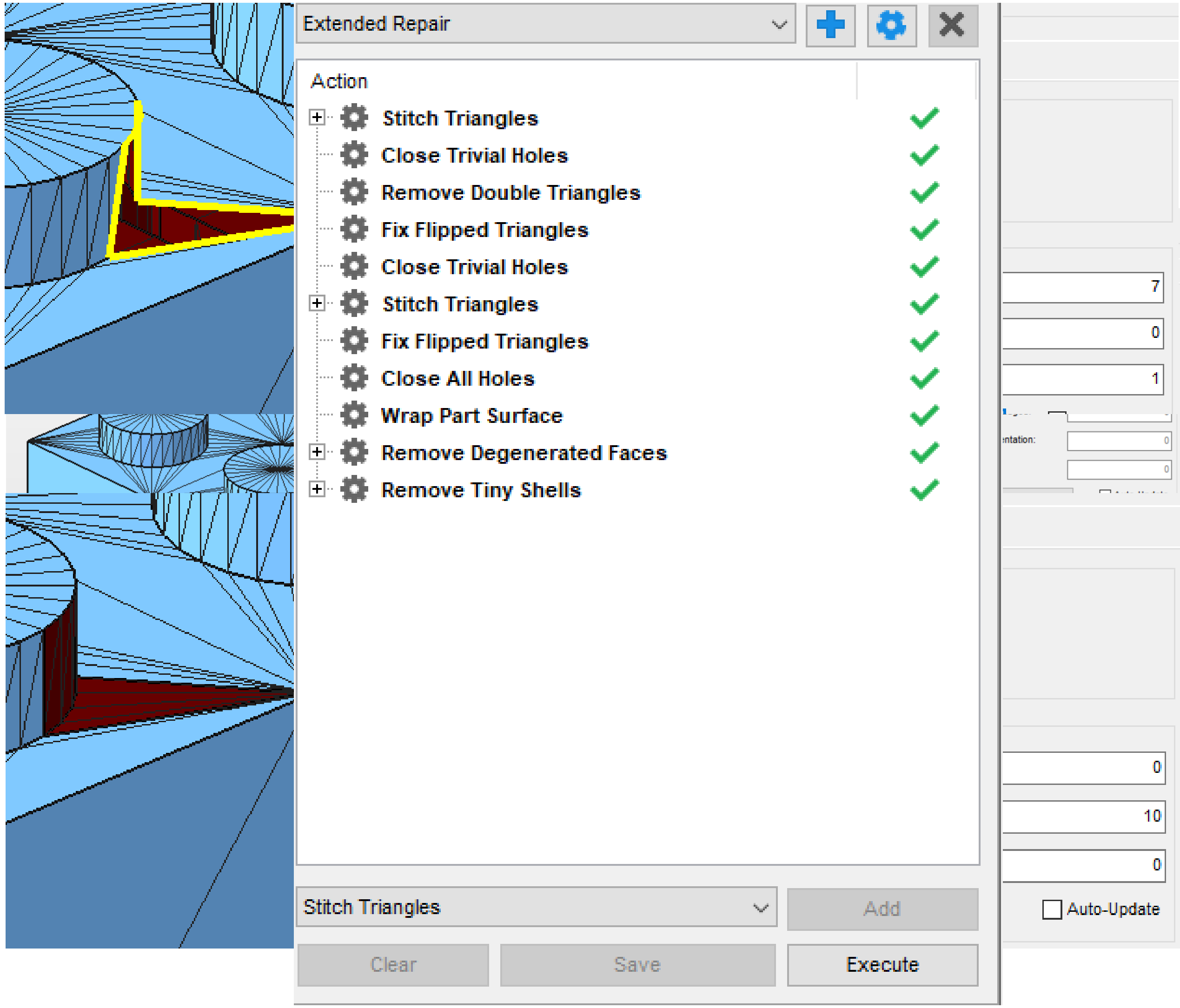

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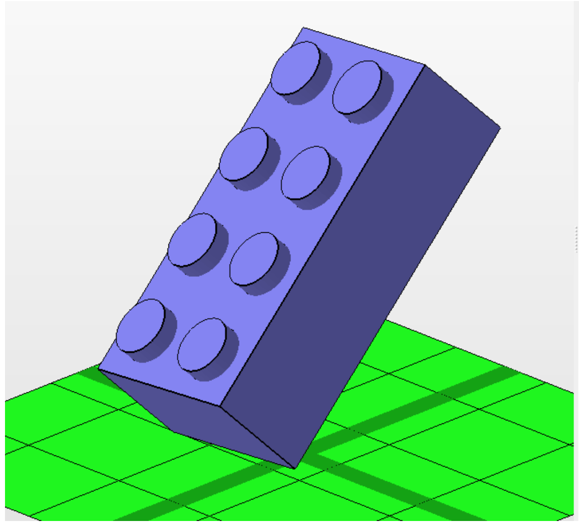
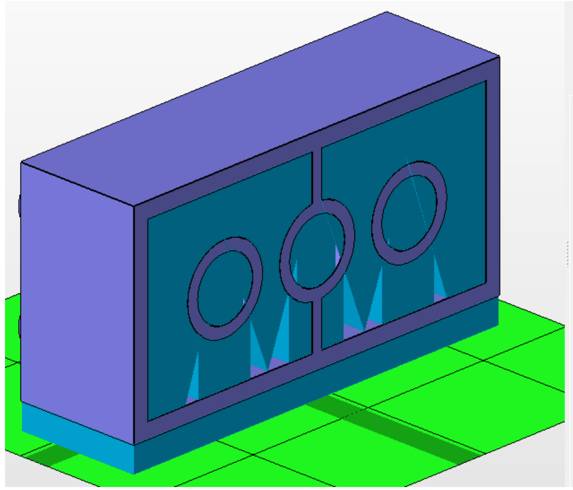
Step 2: Build Preparation

- Orientation
- Parts must be oriented in all 3 dimensions
- Orientation may be manually carried out
- Orientation may be automatically carried out
  - Support Area / Volume
  - Outbox Volume
  - Height



Search Orientations | Choose Orientation

Rank	Supported area (cm²)	Support volume (cm³)	Outbox volume (cm³)	Height (mm)	Center of gravity height (mm)
1	0.000	0.000	16.888	33.0	17.0
2	0.000	0.000	16.889	33.0	18.0
3	0.000	0.000	16.896	33.0	18.0
4	0.047	0.015	20.625	33.7	17.4
5	0.047	0.019	16.522	27.7	15.4
6	0.047	0.019	16.521	27.7	15.4
7	0.275	0.071	12.272	22.5	11.7
8	0.275	0.091	19.581	31.5	16.2
9	5.024	1.529	5.627	13.2	7.7
10	5.024	1.529	5.627	13.2	7.7
11	5.723	2.946	5.627	33.8	17.9
12	5.723	2.946	5.627	33.8	17.9
13	7.920	3.378	5.627	17.8	9.9
14	7.920	3.378	5.627	17.8	9.9
15	5.024	3.622	5.627	13.2	7.5
16	5.024	3.622	5.627	13.2	7.5



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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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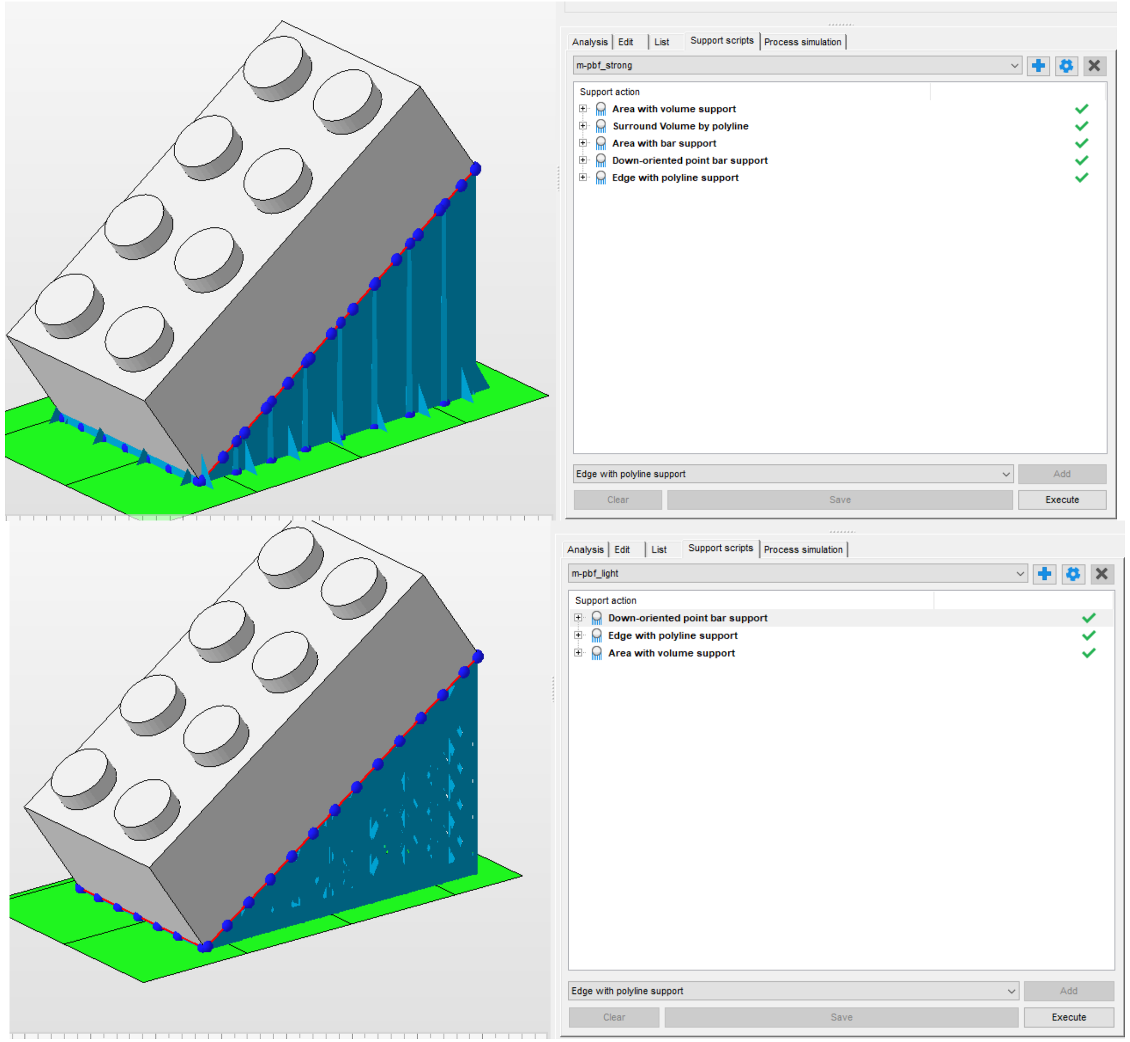
Step 2: Build Preparation

- Supporting
- Sacrificial structures which provide support, fixation or increased heat transfer
- Applied manually or automatically
- Often has options for multiple forms of support structures



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Step 2: Build Preparation

- Layout
- Placing components within the build platform
- Creating duplicates or arrays of components
- Analysing components position with regard to inert gas flow and recoater motion

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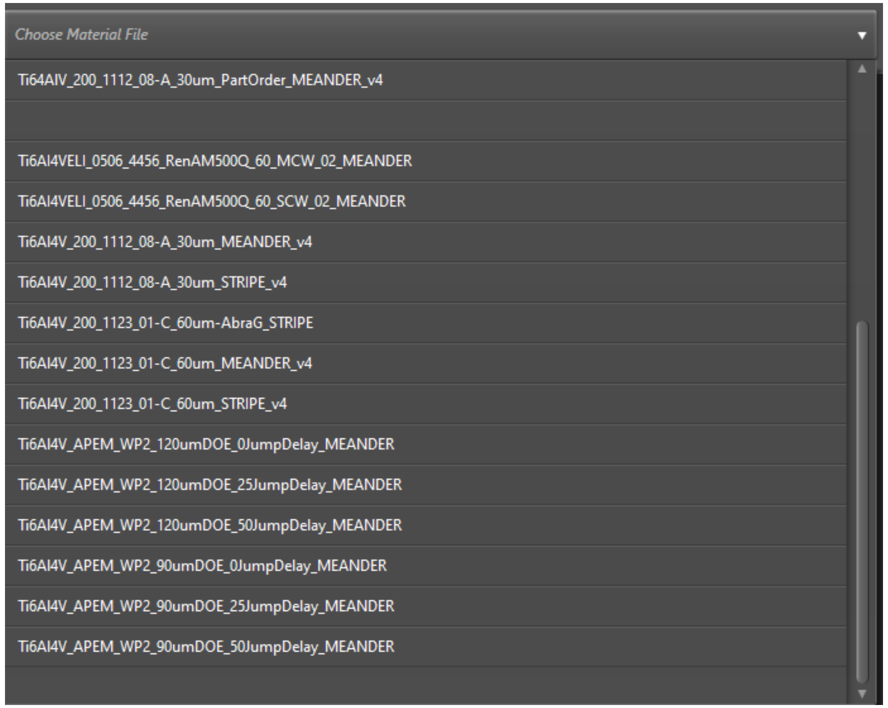
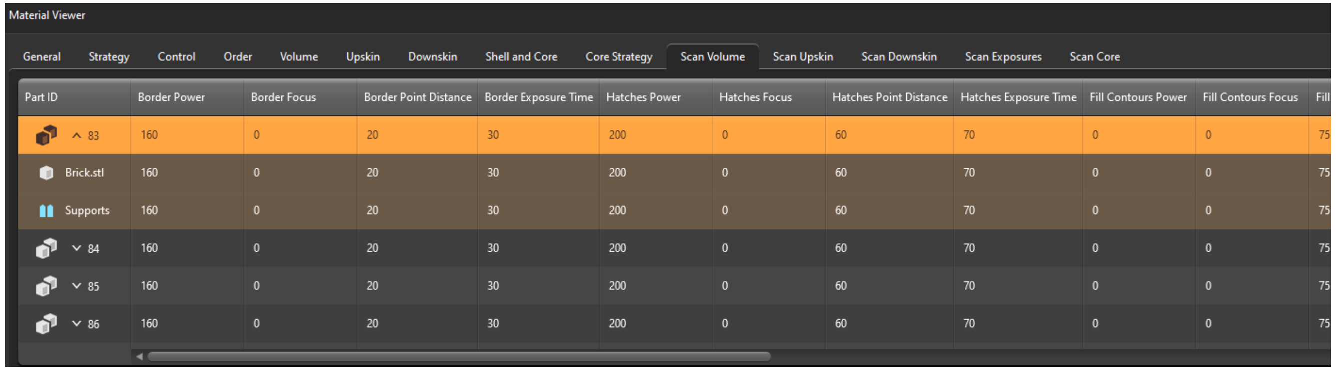
Step 2: Build Preparation

- Parameter Setting
- User applies either blanket or specific build parameters
- Parameters are defined in complete sets, or can be edited individually and on a part by part basis
- Multilaser allocation for certain applications





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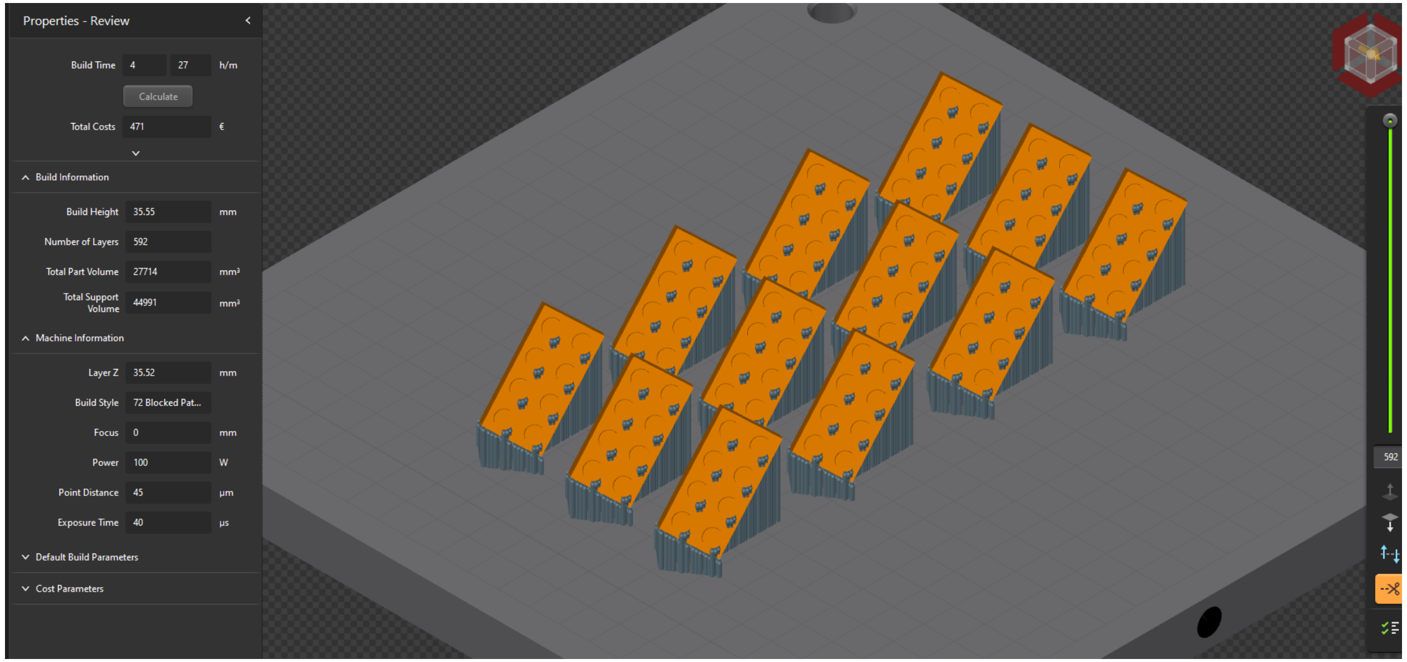
Step 2 – Build Preparation

- Build Analysis
- Provides key insights into the build process
  - Estimated build time
  - Estimated powder usage
  - Number of layers
  - Individual layer times



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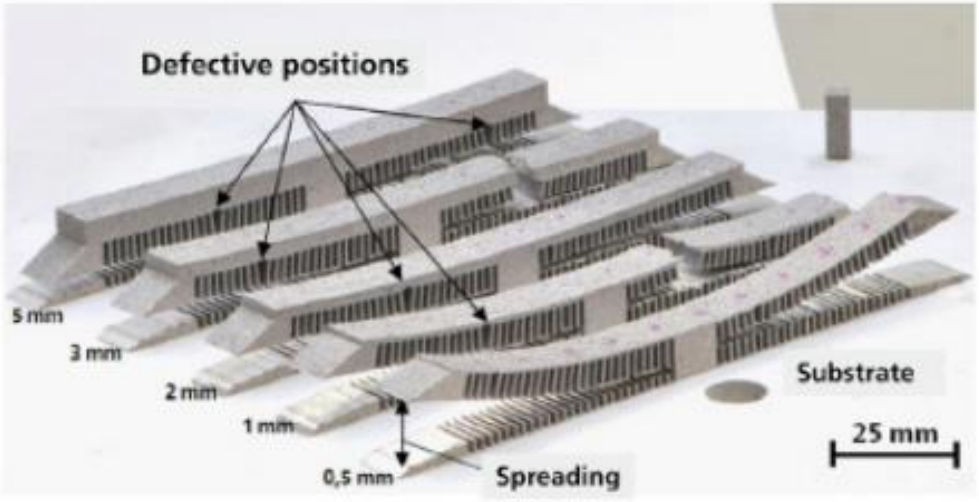
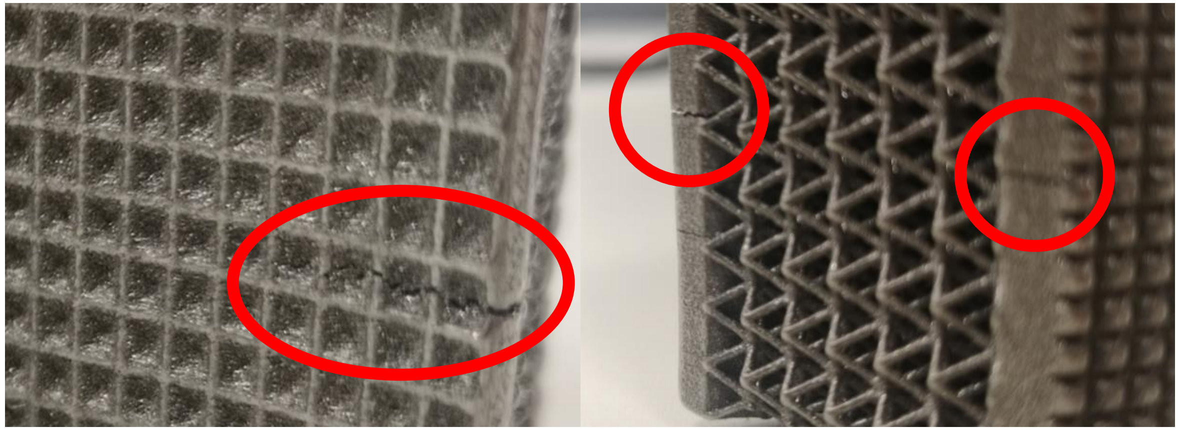
Step 3 – Process Simulation

- PBF-LB is a complex thermo-mechanical process
- Leads to significant internal stress developed in components
- Failure modes
  - deformation
  - support failure
  - cracks
  - recoater crashes





Characterization of part deformations in laser powder bed fusion of stainless steel 316L - Riikonen, Niko, Piili, Heidi – 2020 - Procedia CIRP

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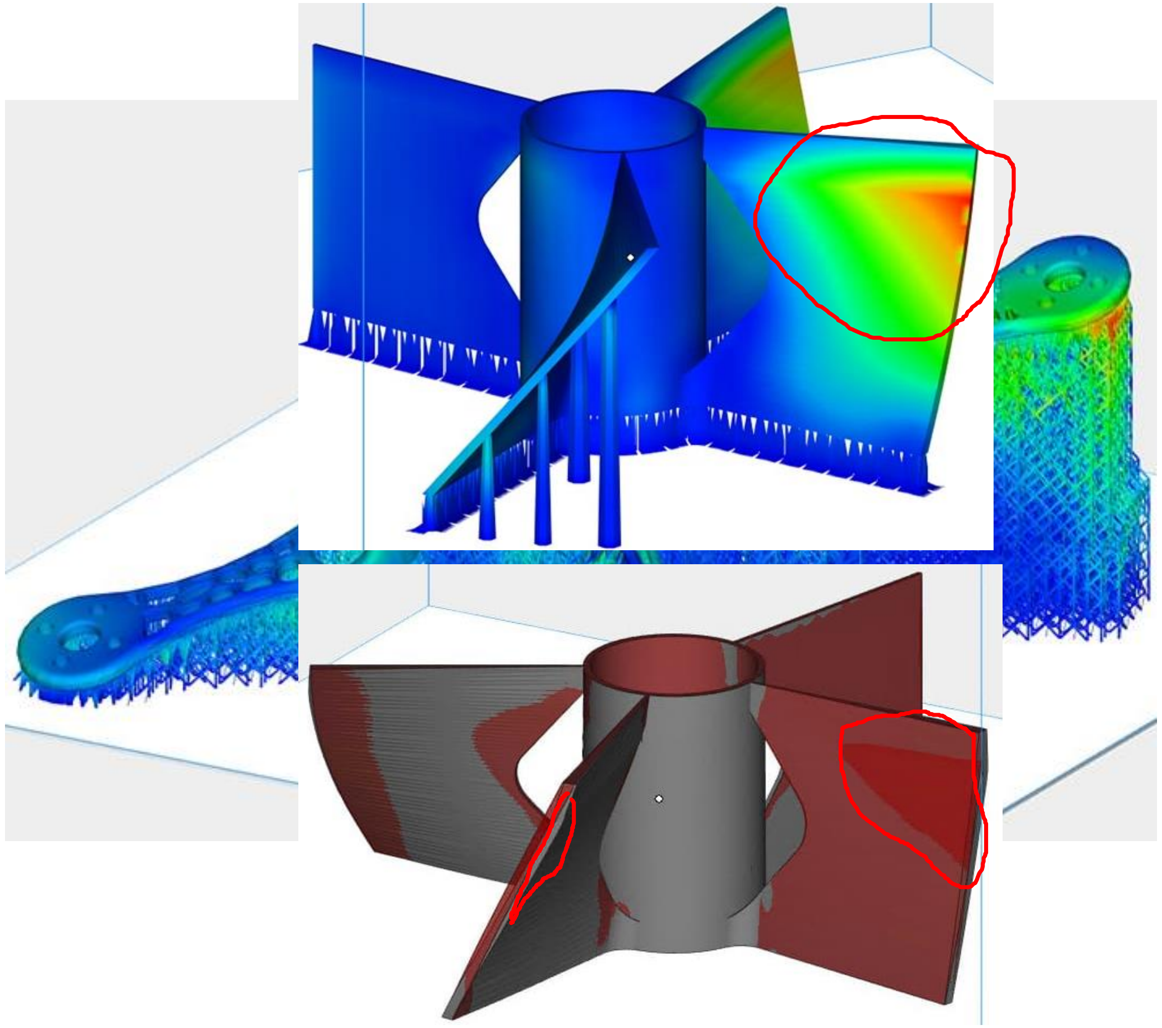
Step 3 – Process Simulation

- Commonly applied within build preparation software
- Allows for improved support structure design
- Allows for pre-deformation of components



materialise.com/en/software/magics/modules/simulation-module

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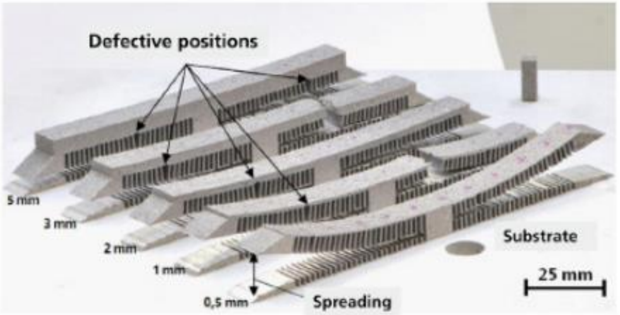
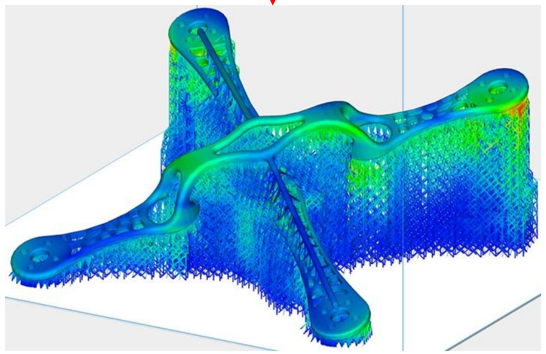
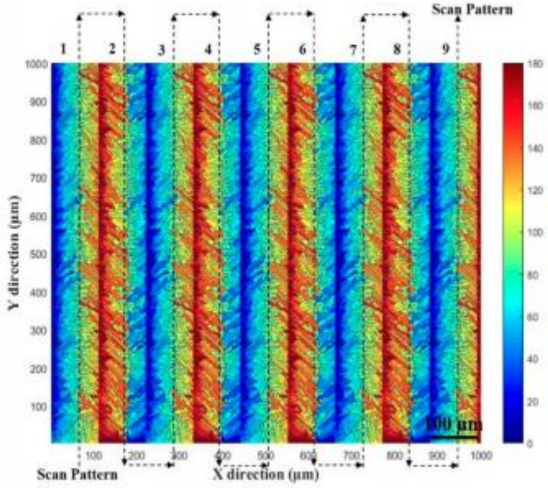
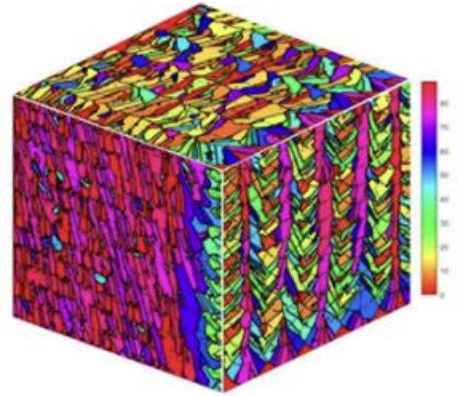
Step 3 – Process Simulation

- Simulation is available at 2 levels
- Process level using inherent strain method
  - Uses strain information obtained from test components
  - Provides fast information on process performance
- Full scale simulation
  - Uses FE method to analyse models down to the microstructure level
  - Expertise and time intensive process









Characterization of part deformations in laser powder bed fusion of stainless steel 316L - Riikonen, Niko, Piili, Heidi – 2020 - Procedia CIRP
www.materialise.com/en/software/magics/modules/simulation-module
https://www.ansys.com/

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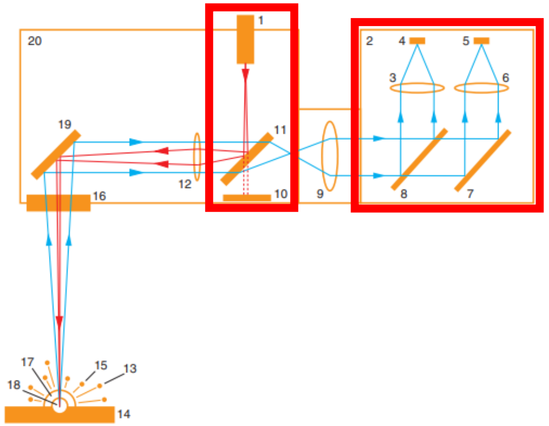
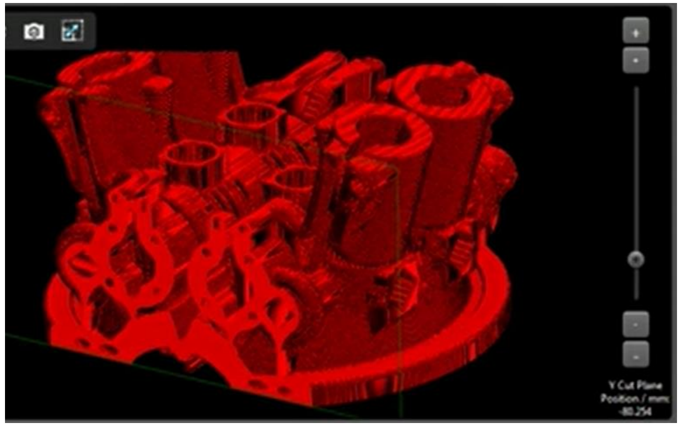
4 – Process Monitoring

- Area of rapidly growing interest
- Instantaneous monitoring of the process
  - Monitoring of process KPI’s
  - Video / Photo monitoring
- Historical monitoring of process
  - Melt pool monitoring
  - Laser output monitoring





https://www.renishaw.com/en/infiniam-spectral--42310

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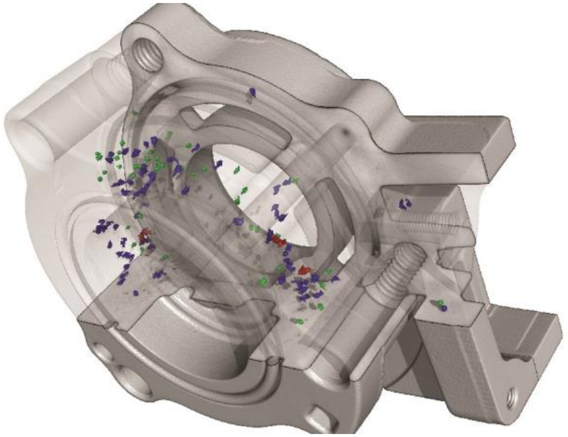
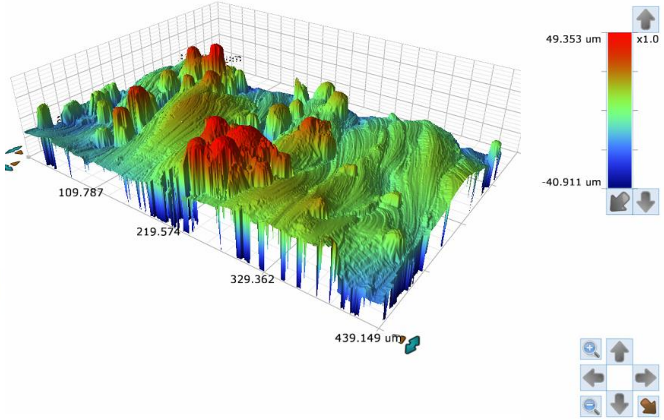
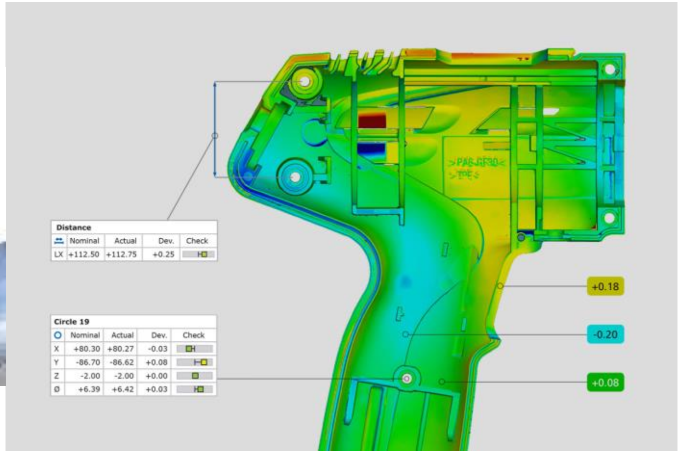
5 – Part Evaluation

- AM is susceptible to several forms of defects
  - Internal porosity
  - Increased surface roughness
  - Distortion
  - Cracking





- Several forms of metrology and inspection are necessary for evaluating components



https://www.volumegraphics.com/en/products/vgstudio-max.html
https://www.gom.com/metrology-systems/atos.html

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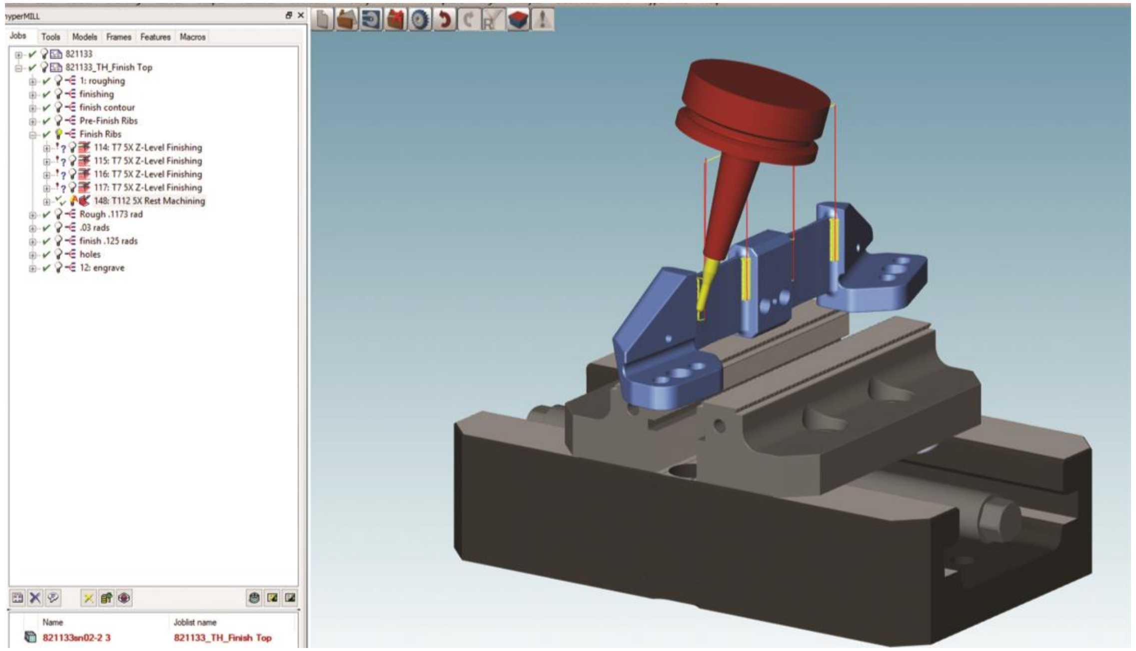
6 – Post Machining

- AM produces near net shape components that typically require machining to hit required tolerances
- Machining requires CAM programming
- Machining AM components can require additional surfaces and reference points to be added



https://www.openmind-tech.com/en.html

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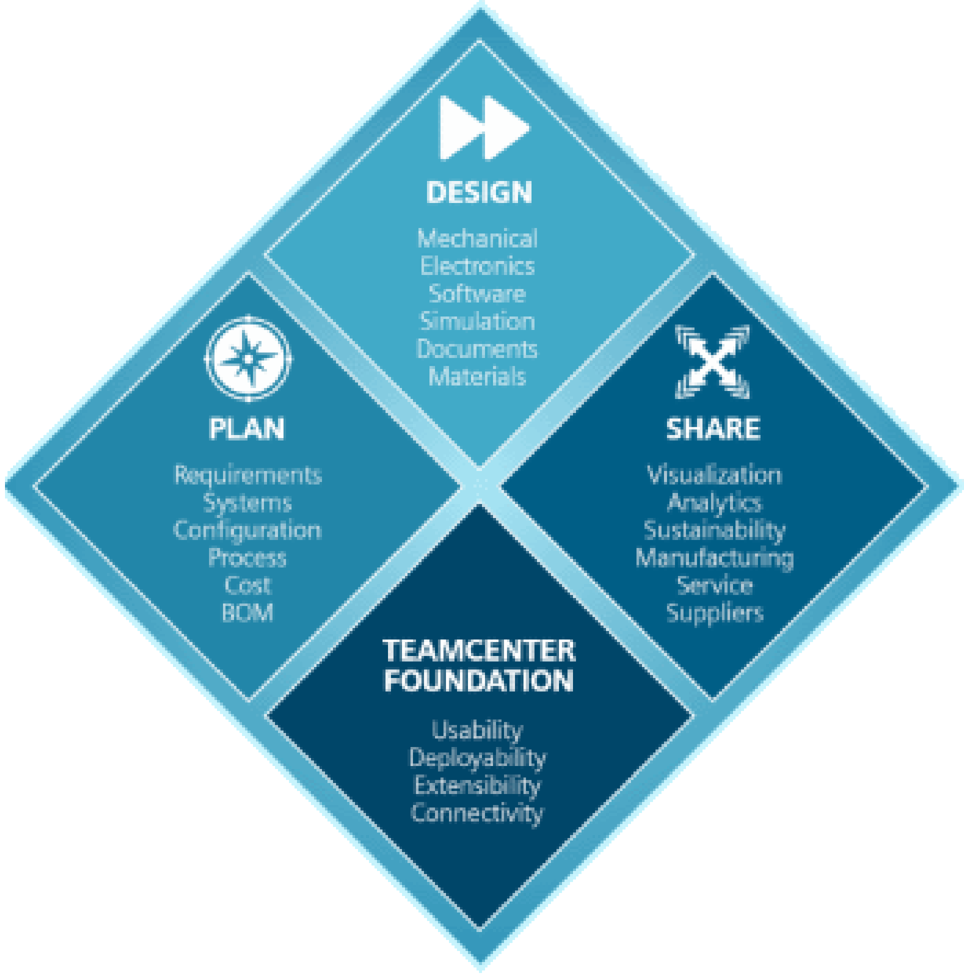
7 – Product Lifecycle Management

- PBF-LB is a data intensive process
- Multiple file types, from multiple sources must be managed
- High volumes of data can be developed as a result of each stage of the process
- As digital data is fundamentally associated with each stage, strong traceability can be achieved



https://www.plm.automation.siemens.com

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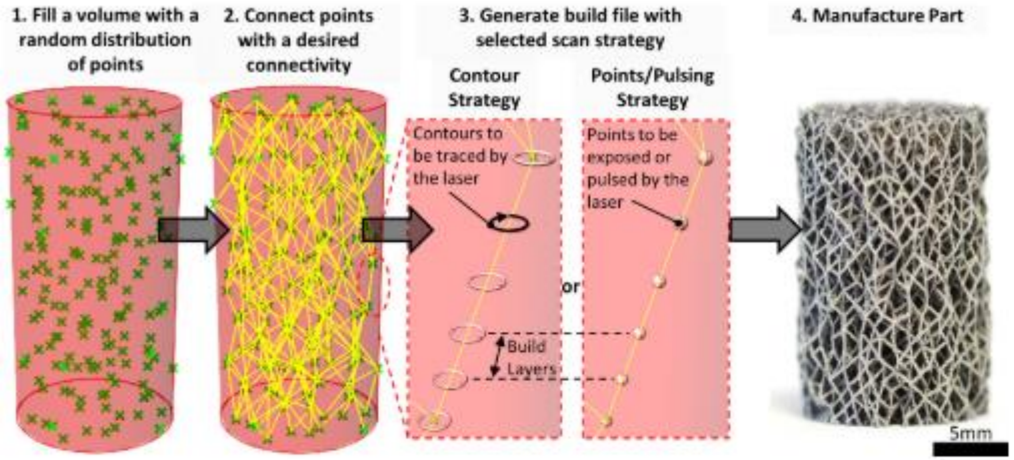
Future Trends

- Encryption
  - File protection from an IP perspective
  - Build enforcement to ensure machine settings and build parameters are obeyed
- Direct to slice
  - Removal of intermediary files
  - Ability to model complex components algorithmically and send directly to slice files
  - Lighter file formats, increased accuracy, increased control



The influence of laser parameters, scanning strategies and material on the fatigue strength of a stochastic porous structure - Ghouse, Shaaz, et. al – 2018 – Additive Manufacturing

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SAM
SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

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Content

- Laser power, focus and optics
- Laser scanning speed
- Hatch spacing
- Layer thickness

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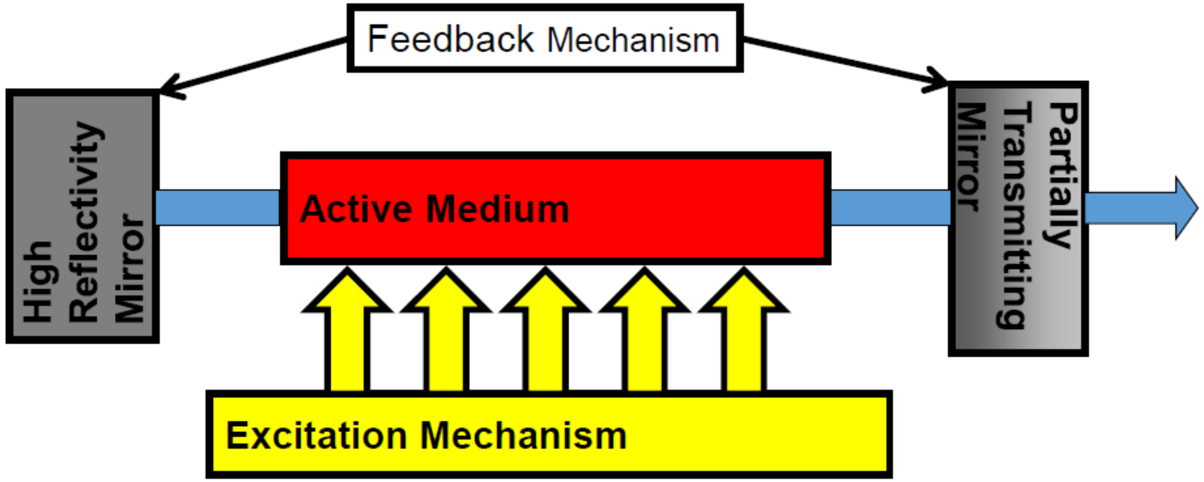
Laser Power

Key Elements

- Active Medium (Gas, liquid or solid)
- Excitation Mechanism (Electrical, optical or chemical)
- Feedback and Output Mechanism



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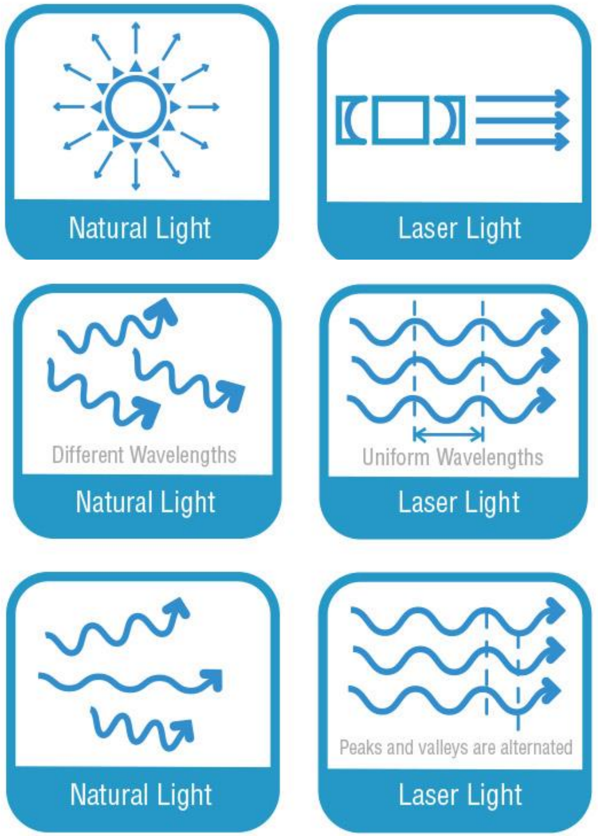
Laser Power

- **Directionality**
  - Most light sources send light in a wide range of directions
  - Lasers have directionality and the light goes primarily in one direction

- **Colour/Wavelength**
  - Most light sources have many wavelengths present
  - Lasers usually are nearly monochromatic – a very precise wavelength

- **Coherence**
  - Most light sources are incoherent
  - Lasers have a high degree of coherence which means they can be focused easily



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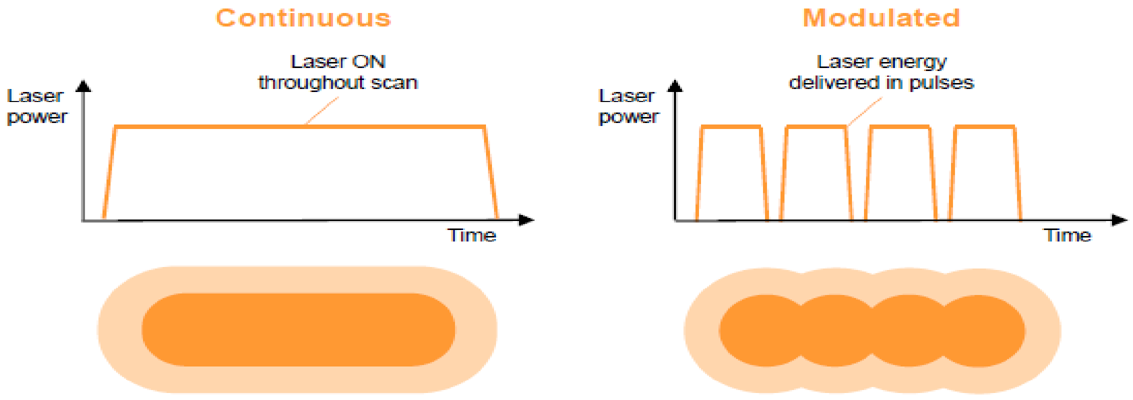
Laser emission types

- Continuous wave lasers
  - Laser is continuously emitting energy
  - **Power** (Watts)
  - **Speed** [mm/s]



Continuous wave and continuous wave in pulsed mode. Diagram from QuantAM version 5 training slides, Renishaw 2019

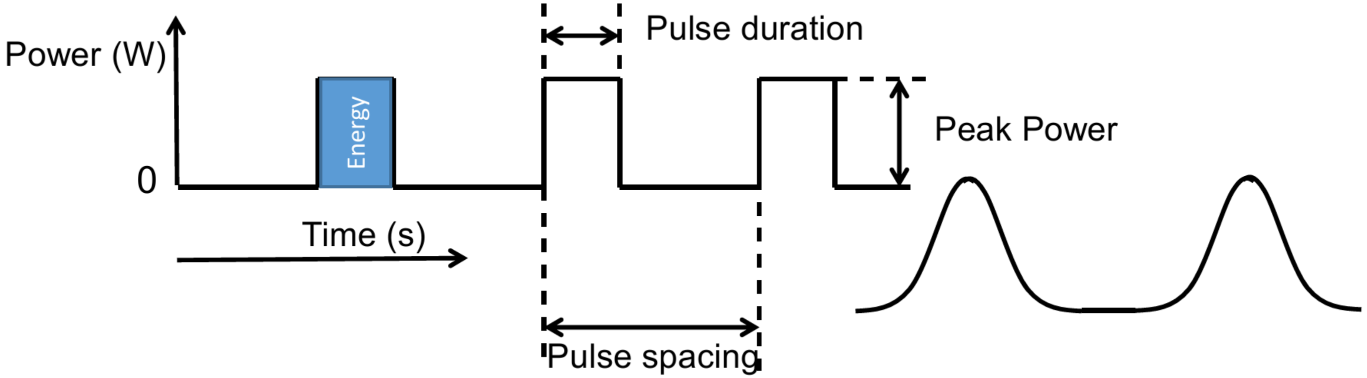
- Continuous wave Modulated mode
  - Continuous wave lasers can also be modulated to imitate pulsed laser characteristics
  - **Power** (Watts)
  - **Speed** $= \frac{(\text{Exposure time(s)} + \text{Jump delay(s)})}{\text{Point distance } mm}$ [mm/s]

Laser emission types

- Pulsed lasers

Pulsed lasers are characterised by

- **Pulse duration** (s)
- **Peak power** of the pulses (W)
- **Energy** of the pulses (=Peak power x Pulse duration) (J)
- Pulse spacing (s)
- **Frequency** of the pulses which is 1/pulse spacing (sometimes called the repetition rate) (Hz)
- **Average power** (= Pulse energy x repetition rate) (W)
- **Pulse shape**



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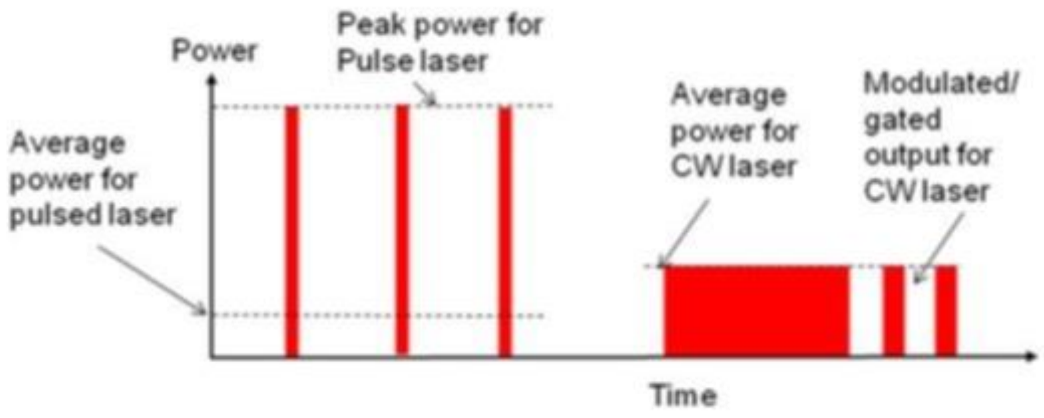
Laser emission types

- Continuous wave lasers Vs Pulsed lasers
- Pulsed lasers tend to have higher peak powers, but continuous wave (CW) lasers emit constant power over time



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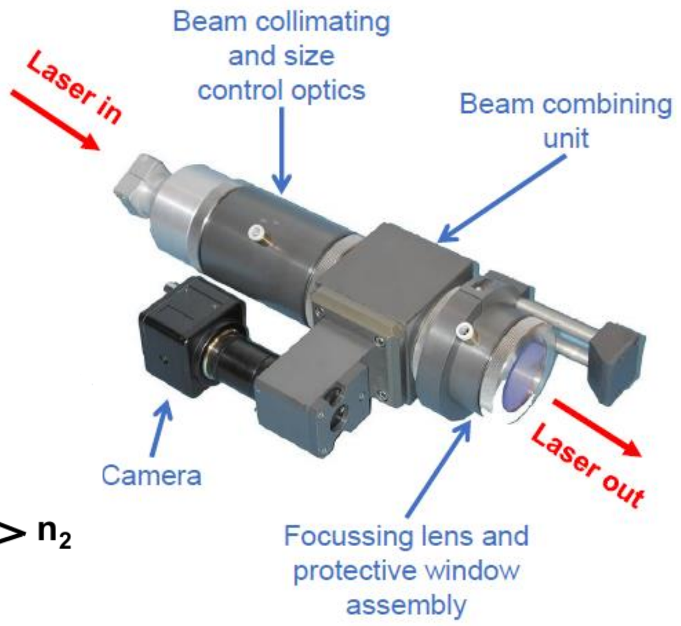
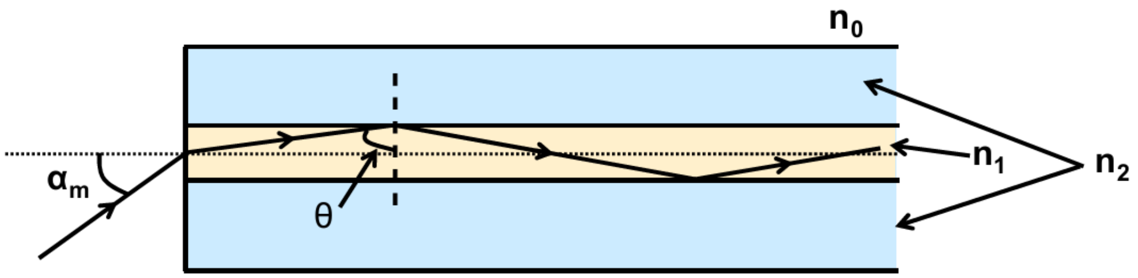
Optics

- Beam Delivery

- Main components of beam delivery and manipulation system:
  - Fibre optic cables
  - Mirrors
  - Lenses
  - Beam splitters
  - Beam combiners
  - Protection windows





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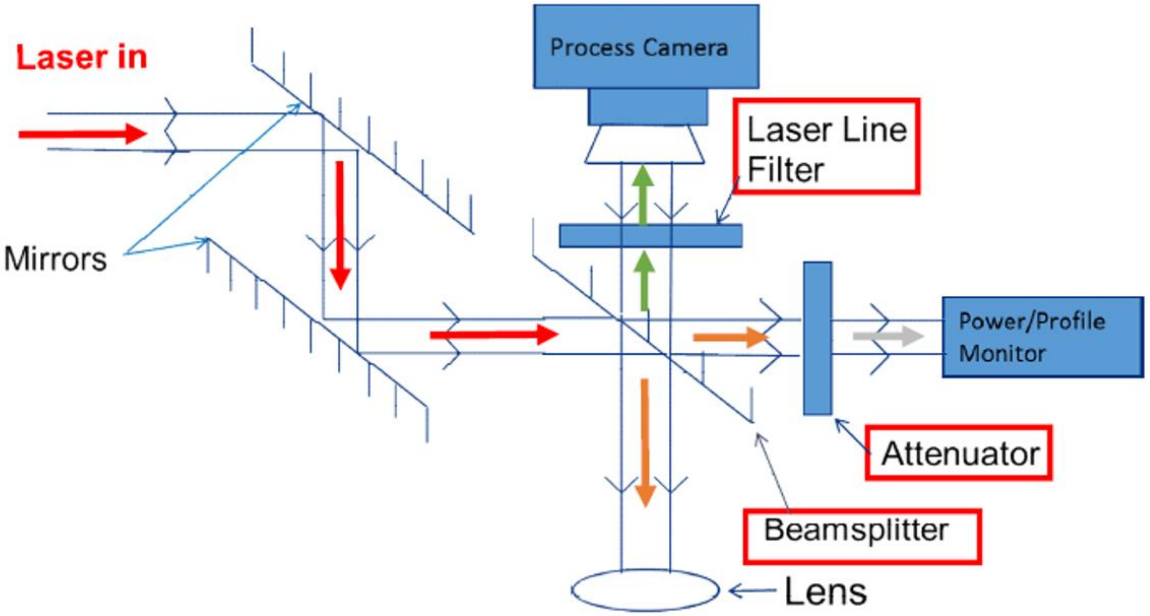
Optics

- Beam Delivery



- **Reflective** (e.g. mirrors)
  - It is all done with mirrors
  - Light is bounced of various surfaces at different angles
- **Refractive** (e.g. focusing lenses)
  - Light is bent at different angles as it passes through a transmissive material such as glass
- **Coated**
  - Very thin coating are added to modify the reflective/refractive properties of a surface
- **Transmissive** (e.g. protective windows)
  - Components designed to pass light without modifying it (usually windows)
- **Absorbing** (e.g. filters)
  - Optics that transmit light but absorb some it
- **Combinations of these**
  - E.g. coated windows

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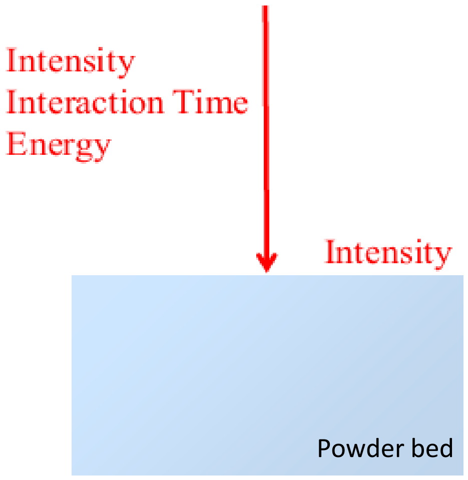
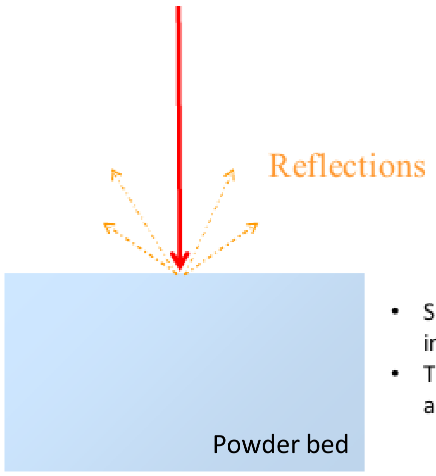
Wavelengths and material interaction

1

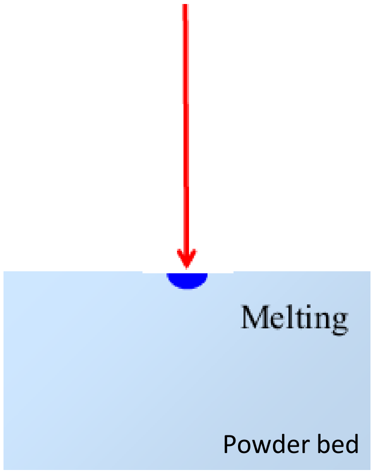


2



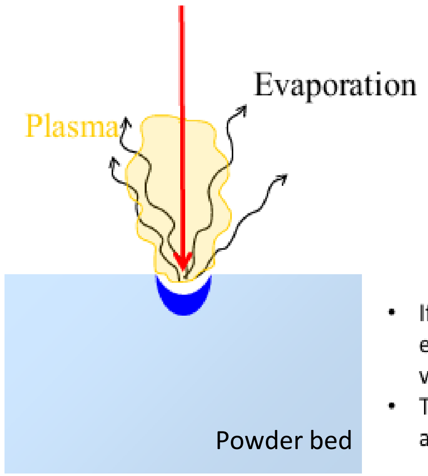
- Surface temperature increases
- This enhances absorptivity

3



- At certain point melting occurs
- Heat is conducted inside of workpiece
- Absorptivity is relatively low
- Weld size depends o material properties

4



- If local temperatures exceeds boiling point – vaporisation starts
- This enhances absorptivity

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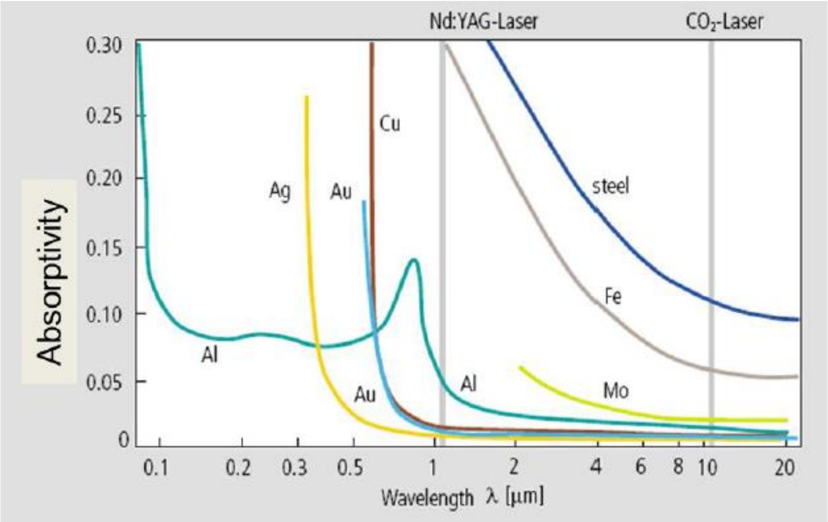
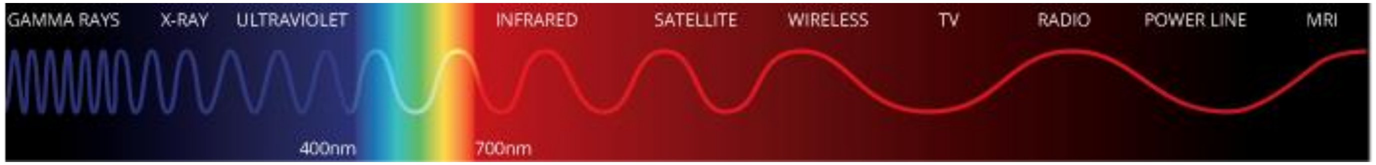
Wavelengths and Material interaction

- In metals, laser energy absorptivity increases as the wavelength is decreased
- Shorter wavelengths can be focused to smaller spot sizes
- Near IR wavelengths can be easily delivered by silica fibre optics, CO_2 lasers have to use expensive lenses or reflective metal optics
- Plasma absorption is less at shorter wavelengths





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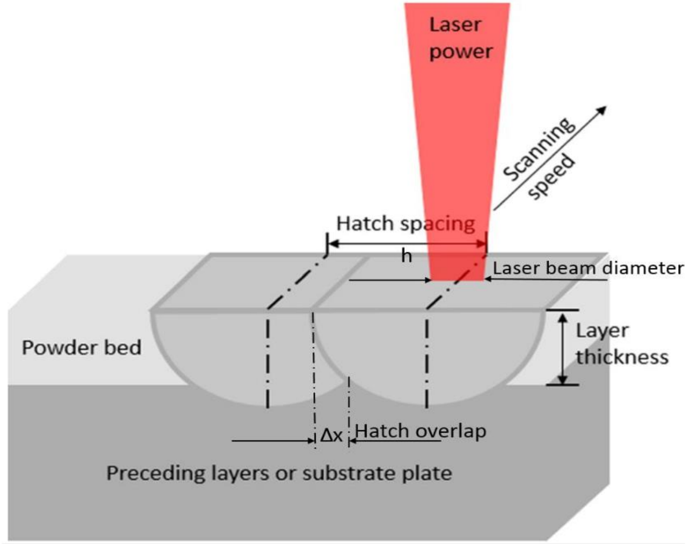
Process Parameters

Energy density of a laser:

Volumetric energy density of a laser power per unit area (J/mm^3)



$$\rho = \frac{P}{\upsilon_s \times h \times d}$$

P = laser power (W)

υ_s = laser scan speed (mm/s)

h = hatch distance(mm)

d = layer thickness (mm)

https://www.semanticscholar.org/paper/On-the-limitations-of-Volumetric-Energy-Density-as-Bertoli-Wolfer/ecf4266eaec643eb56279f3f68d4a5ccea8d8fc9

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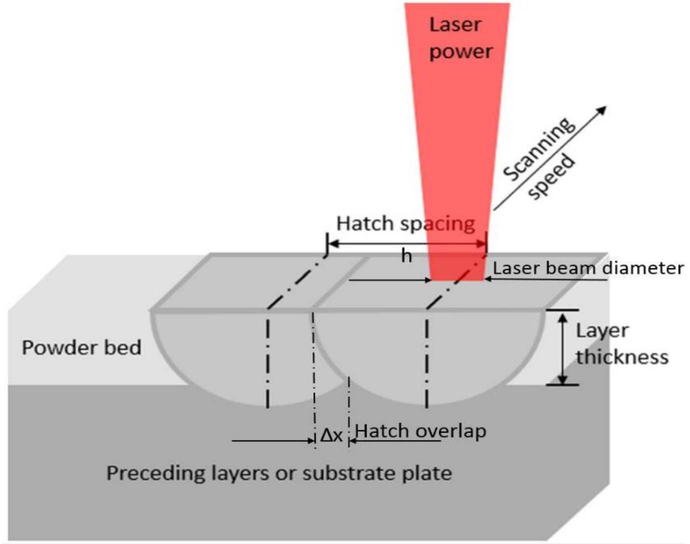
Process Parameters

Energy density of a laser:

Laser Power and laser scan speed



P = laser power (W)

$$\rho = \frac{P}{\upsilon_s \times h \times d}$$

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h = hatch distance(mm)

https://www.semanticscholar.org/paper/On-the-limitations-of-Volumetric-Energy-Density-as-Bertoli-Wolfer/ecf4266eaec643eb56279f3f68d4a5ccea8d8fc9

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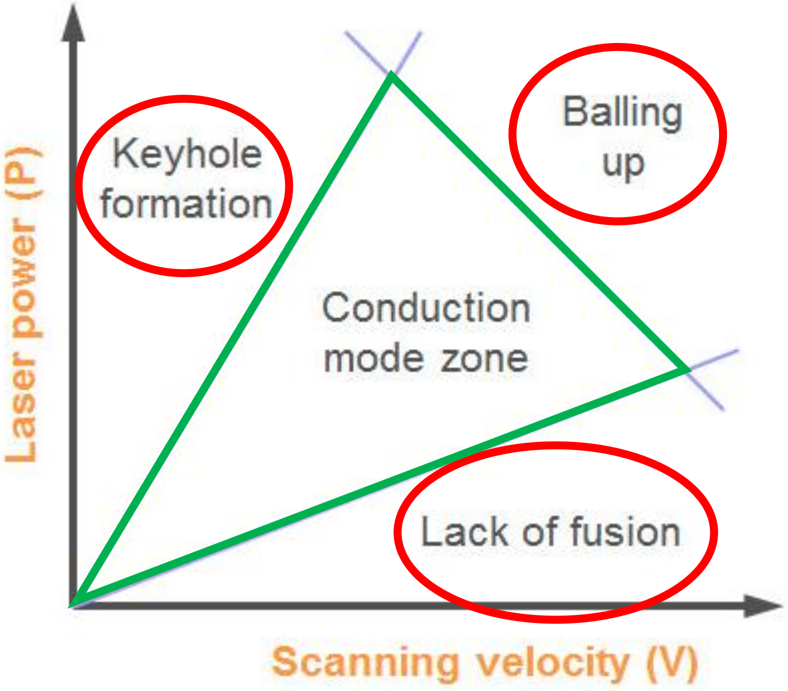
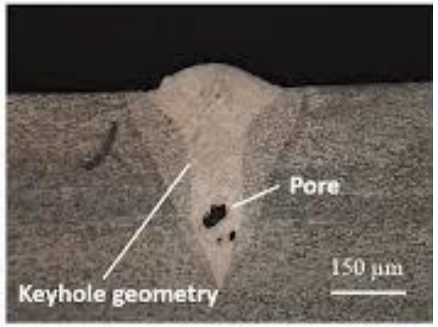
Process Parameters

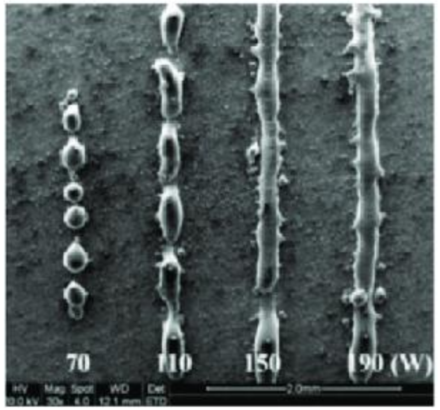
Laser Power and laser scan speed

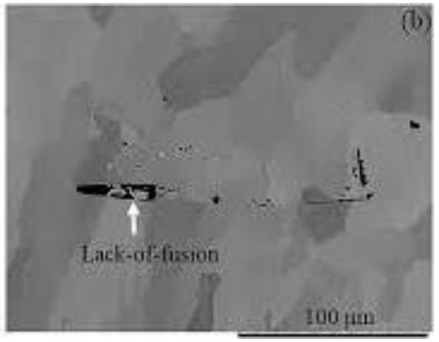
- High power and slow scan speed results in too much energy, often resulting in keyhole formation
- Low power and high scan speed results in insufficient energy and lack of fusion
- Too much of both results in instability in the melt pool formation
- This leaves us with an operation envelope in the 'conduction mode zone'
- However, operating in this envelop doesn't guarantee optimal solidification and material characteristics…



'X marks the spot – find ideal process parameters for your metal AM parts', Marc Saunders 2017







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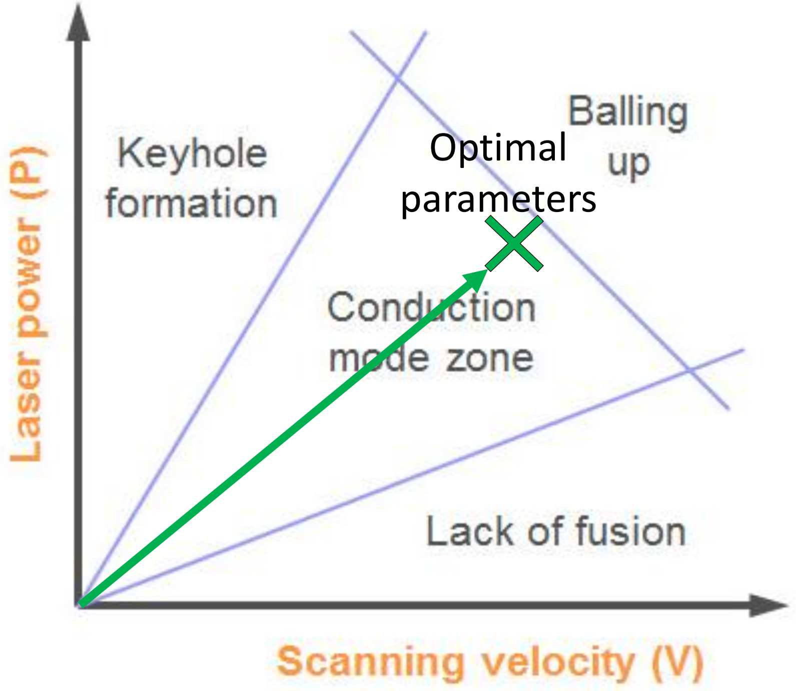
Process Parameters

Laser Power and laser scan speed

- As the molten material cools, solidification occurs unevenly due to different material phases and heat dissipation modes
  - The edges of the melt pool cool more quickly
  - Dendritic crystals form at the cooling edges and grow towards the centre of the molten material, resulting in internal strains
  - These strains can result in part deformation, hot tearing and porosity
  - Size of melt pool will impact molten volume and therefore cooling rate
  - Deeper melt pool will result in more remelting of previous layers and longer columnar grains, leading to more anisotropic material properties



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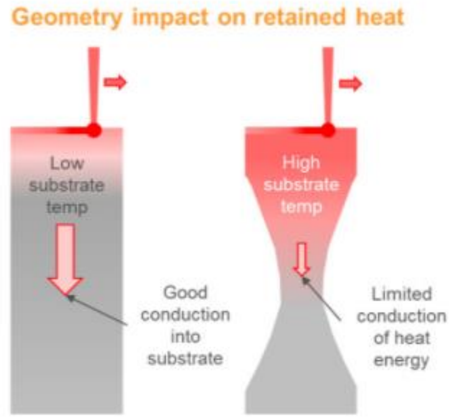
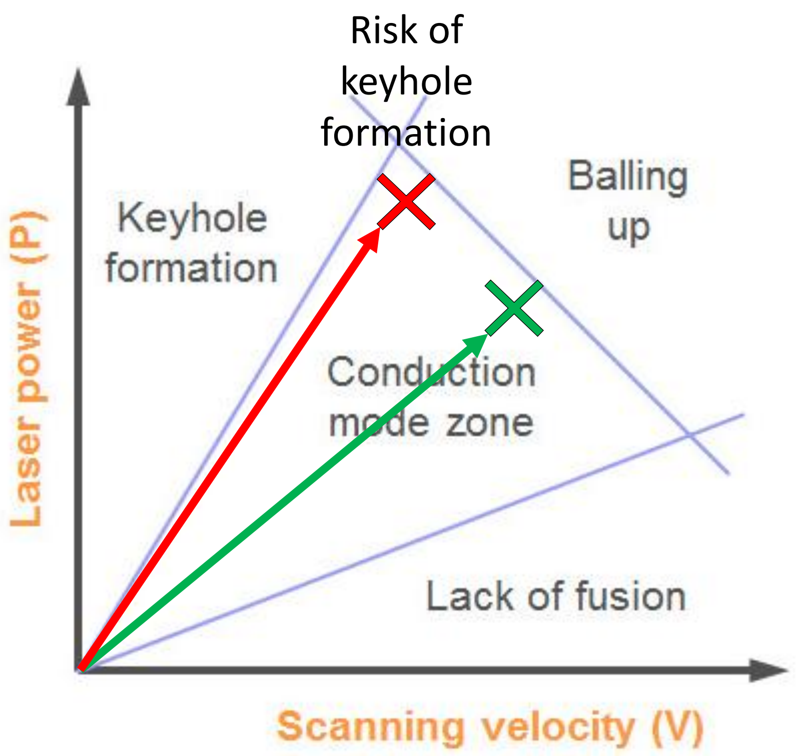
Process Parameters

Laser Power and laser scan speed

- Need to consider a ‘factor or safety’ to account for the impact of the geometry of the part
- Parts with increasing cross-sectional area on the Z- axis will not conduct heat evenly



- Powder and underlying part already at higher temperature, so effectively needing less energy to start keyhole melting



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Process Parameters

Energy density of a laser:

Hatch Spacing

P = laser power (W)

$$\rho = \frac{P}{\upsilon_s \times h \times d}$$

υ_s = laser scan speed (mm/s)

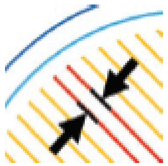
d = layer thickness (mm)

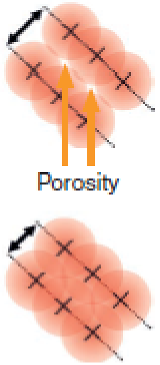
h = hatch distance(mm)

https://www.semanticscholar.org/paper/On-the-limitations-of-Volumetric-Energy-Density-as-Bertoli-Wolfer/ecf4266eaec643eb56279f3f68d4a5ccea8d8fc9

Process Parameters

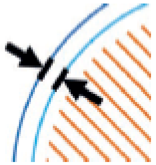
- **Hatch Distance/Spacing**





- Each scan line generated for the laser is called a hatch line. Hatch distance is the spacing between these lines.
- If these lines don't overlap, porosity can occur within the part from gaps between melt pools.
- Hatch spacing is impacted by laser power and scan speed for continuous wave lasers, and energy and point distance for pulsed or modulated lasers.

- **Edge Distance**



- Hatch offset is the distance between the inner boundary scan and the ends of the hatch lines.
- This can also describe the distance between the hatch lines and the edge of the .stl file when printing without boundary scans.
- When building with multiple boundary scans, the boundary distance is the spacing between each successive boundary scan.

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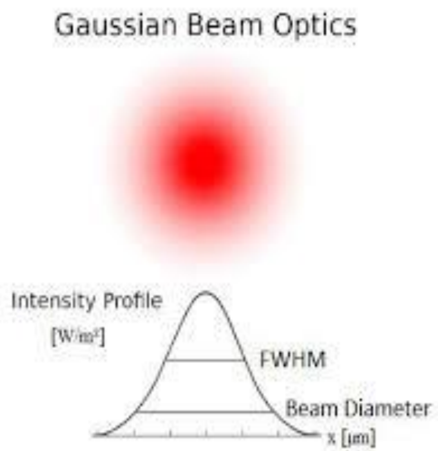
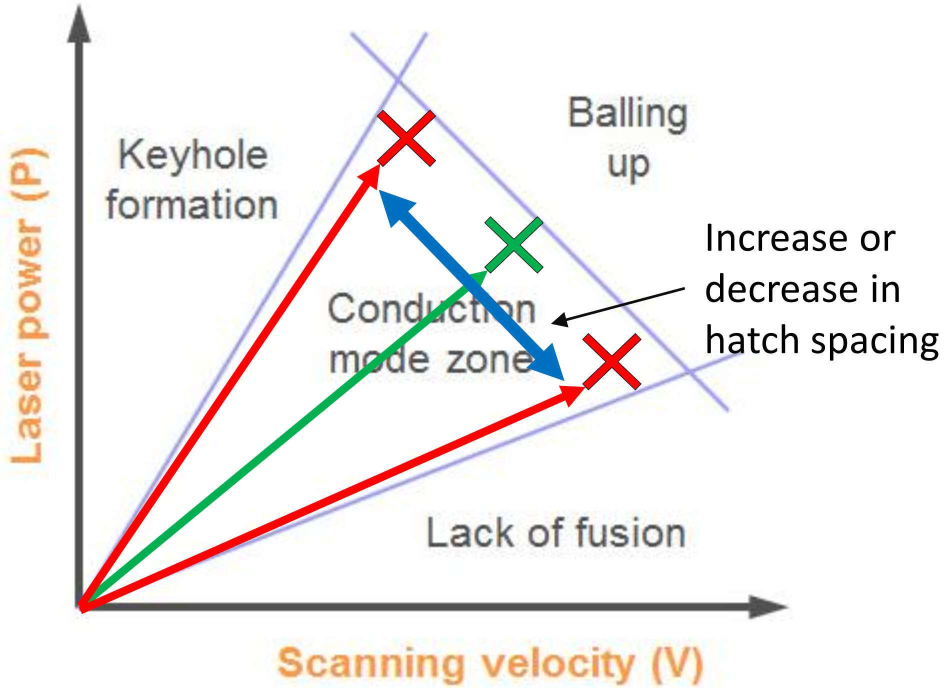
Process Parameters

Hatch distance

- Increasing hatch spacing can allow us to reduce the velocity or inversely, increase the laser power to manipulate the melt pool characteristics
- However, as the power distribution in the laser beam is gaussian, significantly more power is absorbed at the centre of the beam
- Ideally hatch spacing is kept proportional to the laser spot size to reduce anisotropic characteristics



Rasouli, Karwan, 'Laser Beam Pathway Design and Evaluation for Dielectric Laser Acceleration', June 2019, Uppsala University



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Process Parameters

Energy density of a laser:

Layer Thickness

$$\rho = \frac{P}{\upsilon_s \times h \times d}$$

P = laser power (W)

υ_s = laser scan speed (mm/s)

h = hatch distance(mm)

d = layer thickness (mm)

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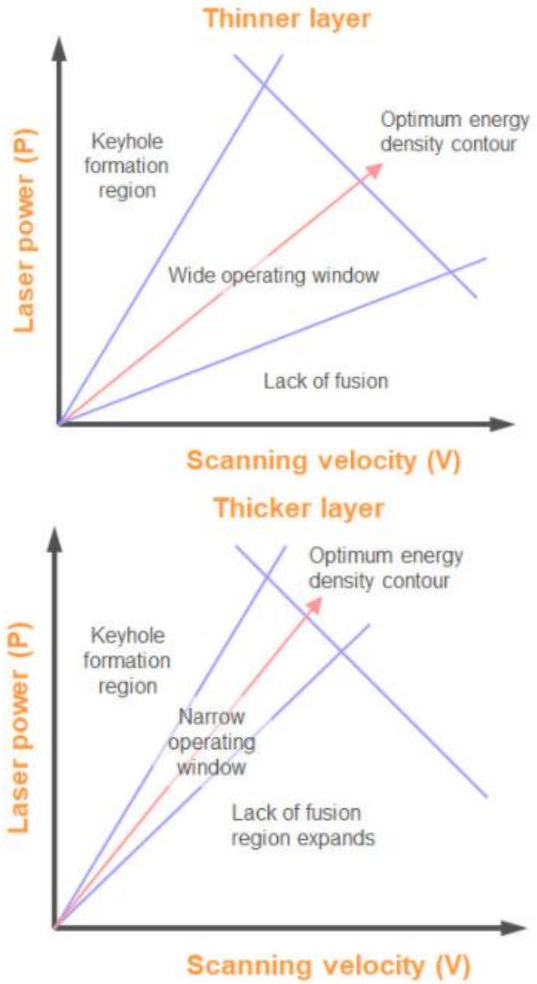
Process Parameters

Layer thickness

- Increasing layer thickness increases the chance of poor fusion
- Increasing laser power and velocity to compensate increases the risk of keyhole formation, effectively narrowing the operating envelop
- Optimal layer thicknesses is related to the laser spot size spot size
- Many SLM machines use lasers with a nominal spot size of 70µm - 100µm and operate will with layer thicknesses between 30µm - 90µm
- Bigger spot sizes can result in reduced geometric accuracy, rougher surface finish, more spatter and melt pool emissions and an impact on material characteristics



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Process Parameters

Energy density of a laser:

Volumetric energy density of a laser power per unit area (J/mm^3)

$$\rho = \frac{P}{\upsilon_s \times \mathrm{h} \times d}$$

P = laser power (W)

υ_s = laser scan speed (mm/s)

h = hatch distance(mm)

d = layer thickness (mm)

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Process Parameters

Energy density of a laser:

Volumetric energy density of a laser power per unit area (J/mm^3)

$$\rho = \frac{P}{\upsilon_s \times f \times d}$$

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υ_s = laser scan speed (mm/s)

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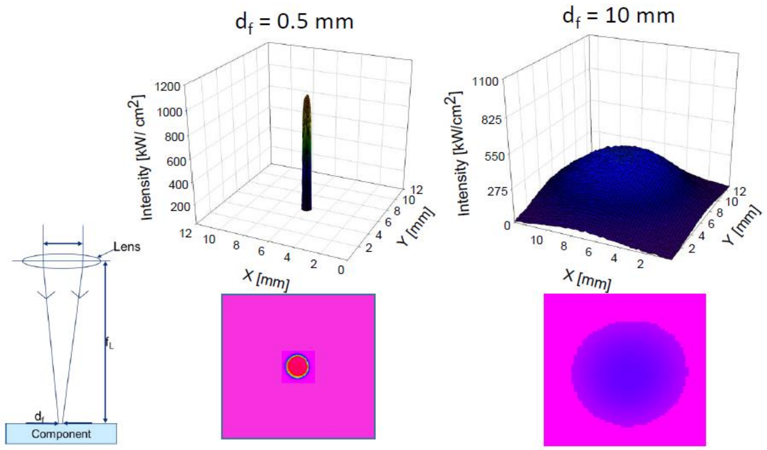
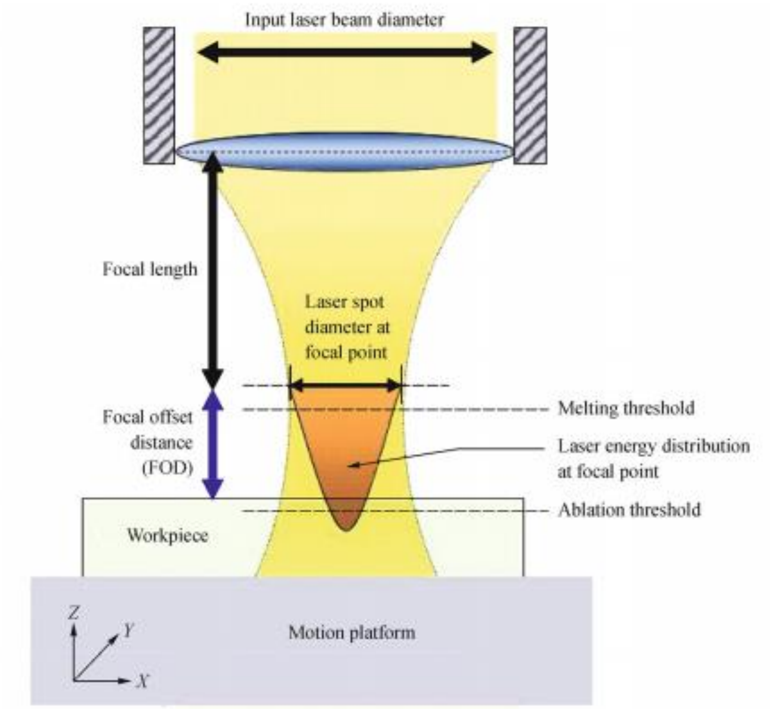
Process Parameters

Energy density of a laser:

- Laser beam profile and focus
  - Most machines have a fixed focal offset
  - Some allow adjustments to this
  - Can allow for wider hatching and thicker layers
  - Decreases energy density, so power or speed needs to be adjusted to compensate





Krishnan, Arun et al. (2019) 'Review on mechanism and process of surface polishing using lasers', Frontiers of Mechanical Engineering. 14,299-319.

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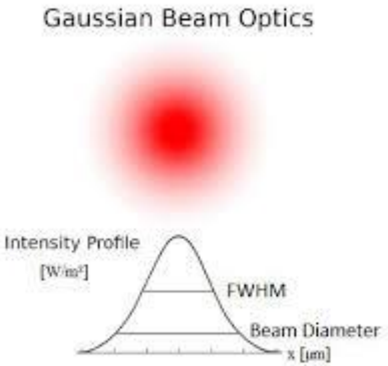
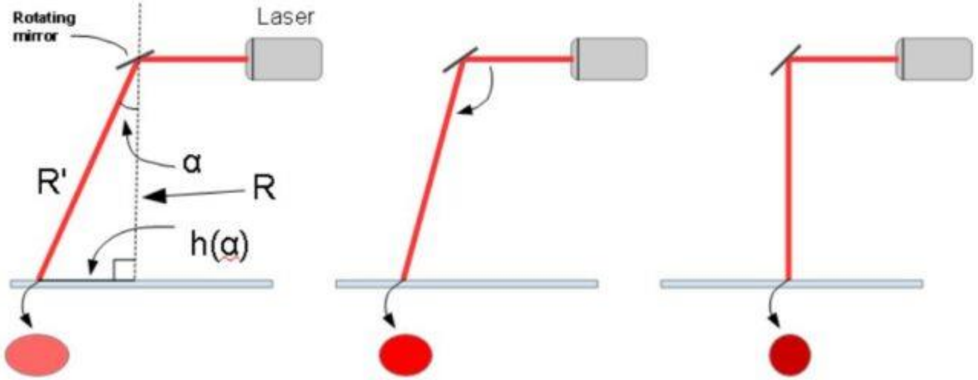
Process Parameters

Energy density of a laser:

- Beam profile and focus
    - The energy distribution is not consistent in the laser beam or across the build plate
    - The shape of the spot can also distort due to the incident angle with the build plate
    - Machines generally compensate for this in either hardware or software



Rasouli, Karwan, 'Laser Beam Pathway Design and Evaluation for Dielectric Laser Acceleration', June 2019, Uppsala University



Charles Bibas , February 2020, 'Traditional SLS/SLM 3D Printing Errors', tecnica.com (Accessed December 2020)

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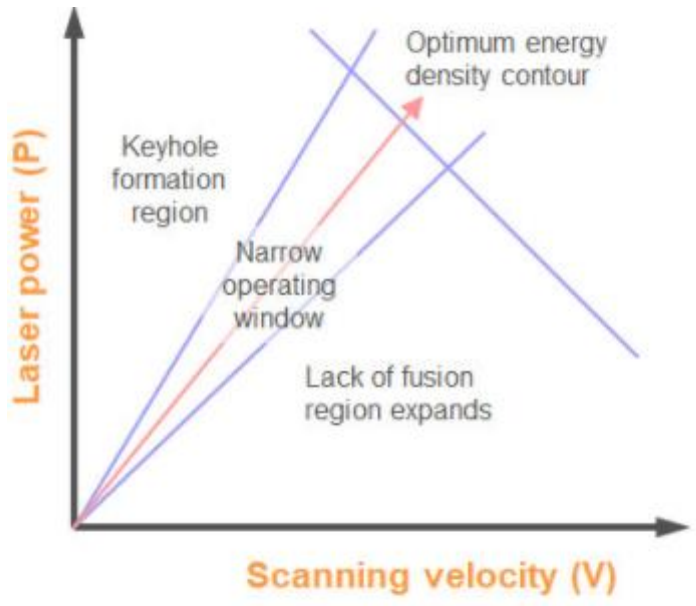
Process Parameters

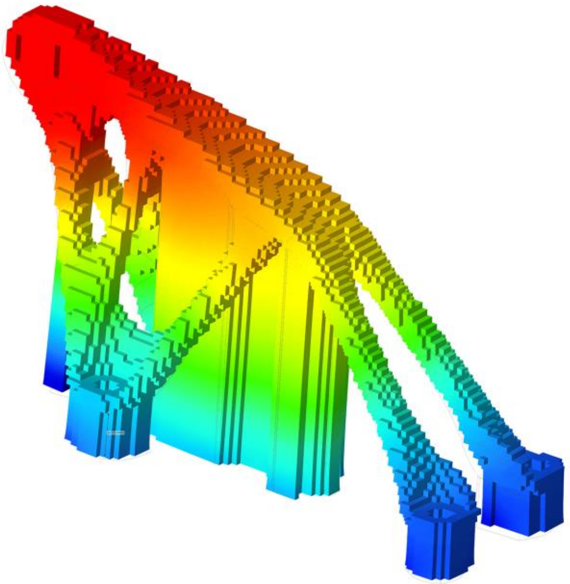
Energy density of a laser:

- Beam profile and focus

- Reducing spot size increases the chance of keyholes forming
- Simultaneously increasing the chance of incomplete fusion
- Compensations need to be made with hatch spacing to ensure good layer fusion, while laser power and speed adjustments need to be made to avoid keyhole formation
- Very similar to what happened with thicker layers, although with a different outcome



Process Parameters



Thermo-mechanical simulation of complex geometry using 'Inspire Print3D' from Altair

- Materials will heat and cool at different rates based the primary mode of heat conduction and influenced by the part geometry
- Complex parts require the development of specific parameter sets for various areas in the part depending on the goal:
  - Bulk material
  - Borders
  - Up-skins and down-skins

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SECTOR SKILLS STRATEGY
IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

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Content

- Melt pool emissions
- Gas flow
- Recoater types and powder dosing
- Process oxygen content
- Process preheating

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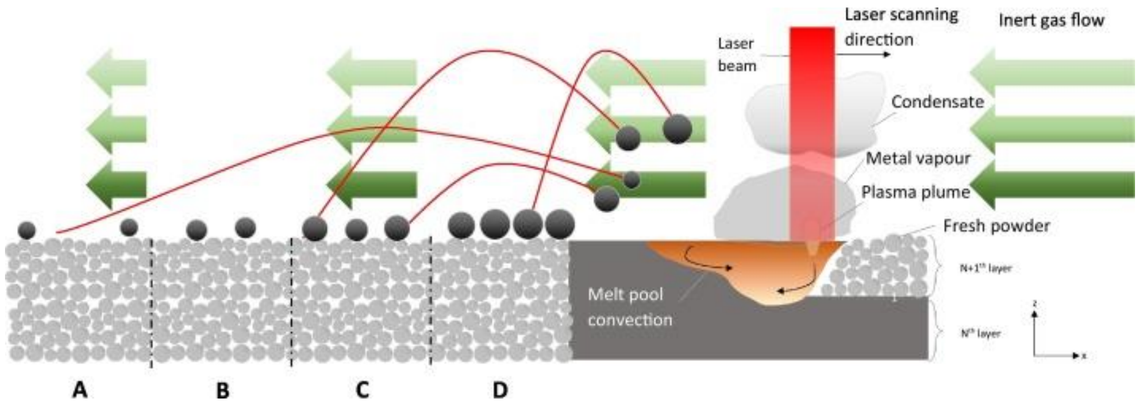
Process Parameters

Gas flow – Main function

Main role of the gas flow - remove emissions from the melt pool from the build area

- Spatter – Large particles can land on the powder bed and cause porosity
- Plume and material condensate – Can absorb and diffract the laser before it reaches the powder bed, reduce the energy density
- Condensate – can build up on the laser glass during a print, absorbing some of the energy from the laser



Ahmad Bin Anwar et Al. (2019) Spatter transport by inert gas flow in selective laser melting: A simulation study. Powder Technology Vol. 352

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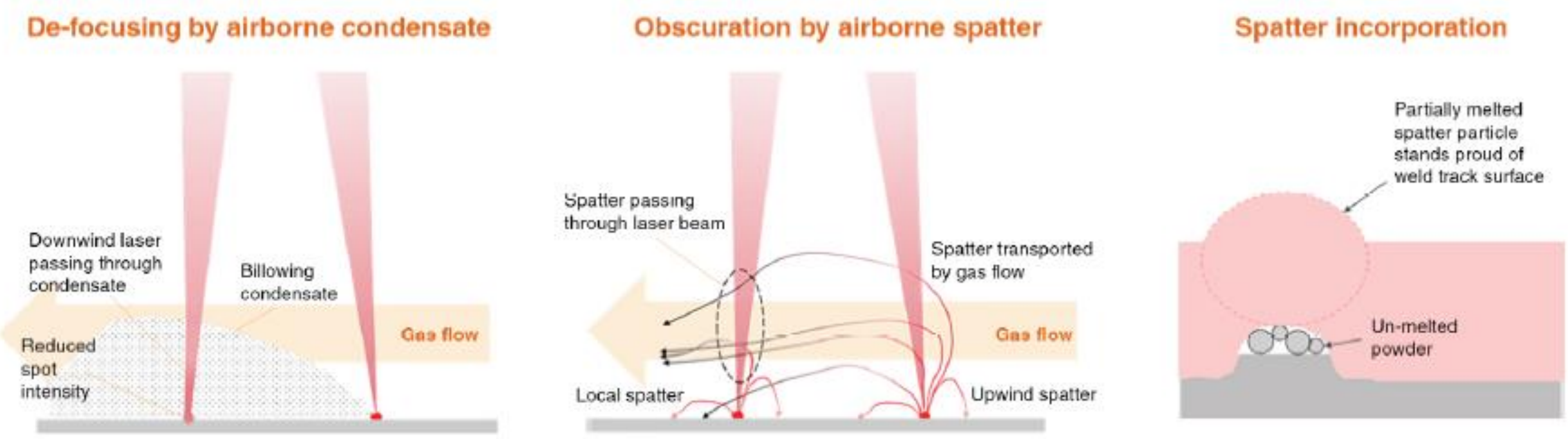
Process Parameters

Gas flow – Multi-laser systems

Multi-laser systems complicate gas flow designs

Single laser systems can print parallel and opposing the gas flow to reduce laser interaction with the laser

More complex gas flows and laser scanning strategies are needed to avoid the emission from one laser interfering with another



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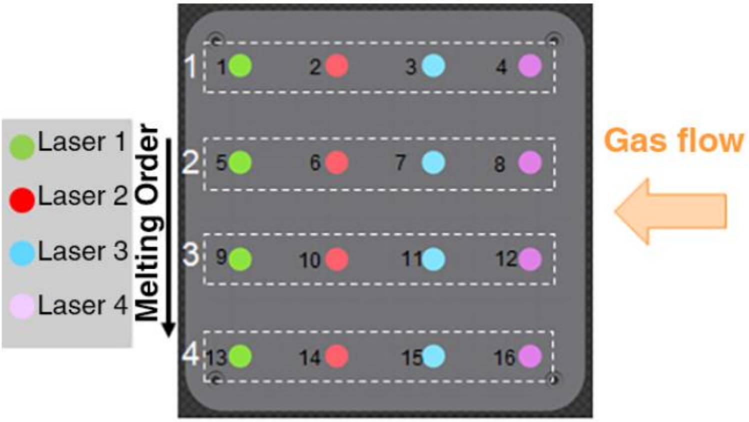
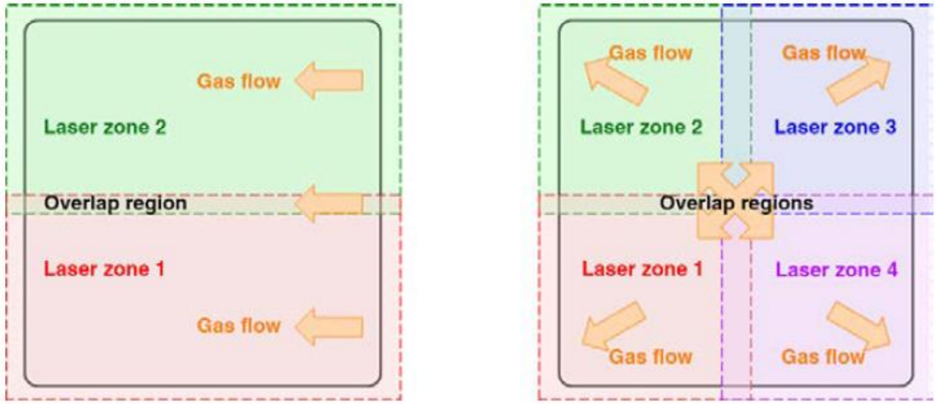
Process Parameters

Gas flow – Multi-laser systems

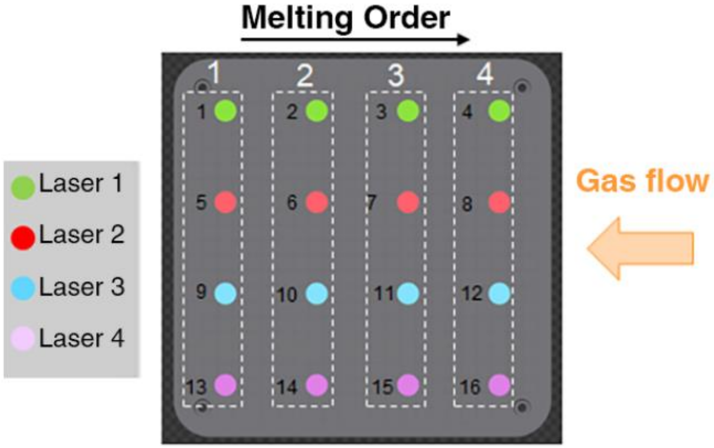
- Some multi-laser systems segment the build plate into zones and limit the lasers to these segments, optimizing the gas flow for this design
- Most machines use a simple gas flow and users design scan strategies to reduce risk of emissions and contaminations



Suboptimal laser scanning strategy for multi-laser system with full build plate coverage for each laser



2- and 4- laser machines with separate laser zones



Optimal laser scanning strategy for multi-laser system with full build plate coverage for each laser

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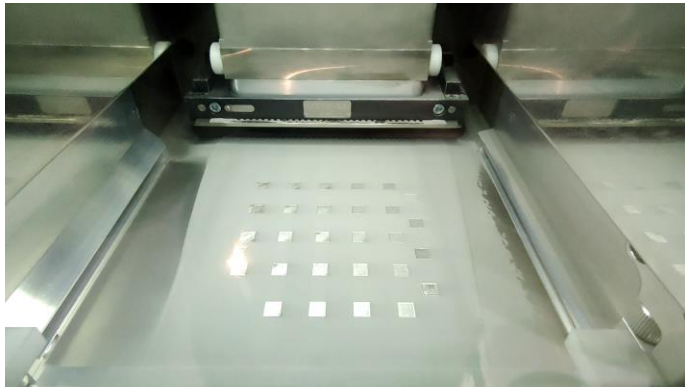
Process Parameters

Recoaters and dosing factor

- Different types of common recoaters:
  - Single blade – Most common
  - Double blade – Front and back blade, traps powder between
  - Roller recoaters – Need to account for compression ratio



Single blade recoater, Renishaw AM 500M

Double blade recoater, Realizer SLM50

Roller recoater, 3D system DMP 300

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Process Parameters

Recoaters and dosing factor

‘Short feeding’ is the term used to describe when there is insufficient powder to recoat the entire build plate.

Causes

- Insufficient powder in machine to complete build
- Insufficient powder dosing at the start of each layer
- Build fault or failure resulting in the recoater sequence being interrupted

- Impacts
  - Porous parts
  - Complete build failure
  - Damage to recoater system

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Process Parameters

Chamber oxygen content

- Part quality
  - Oxidation
  - Increased porosity
  - Brittle parts
  - Poor mechanical properties

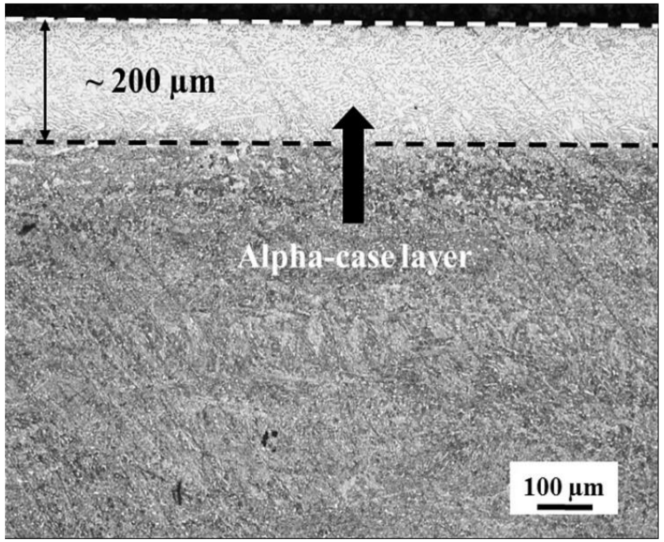

Figure: Alpha-case layer in Ti64 after heat treatment in air.
'EVALUATION OF THE BULK AND ALPHA-CASE LAYER PROPERTIES IN Ti-6Al-4V AT MICROAND NANO-METRIC LENGTH SCALE' Sefer et al. 2015

- Safety factor – oxidation of powder and condensates

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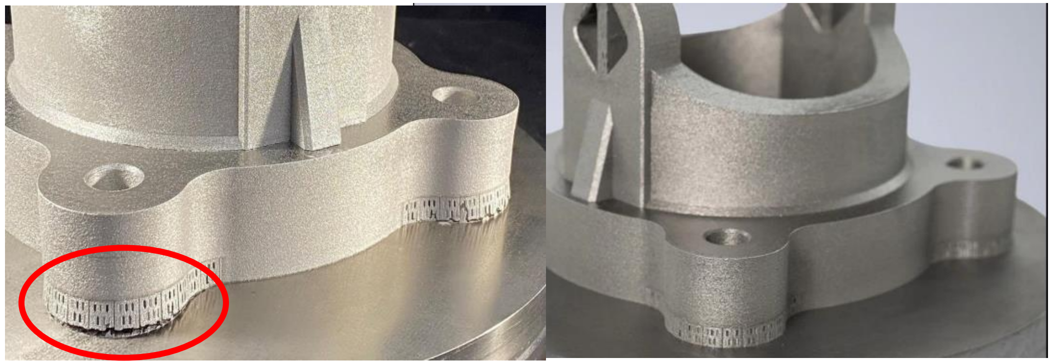
Process Parameters

Pre-heat temperatures

- Many machines can preheat the build plate or build chamber for printing. This can range from 200^{o}C - 800^{o}C or higher, for example;
    - Renishaw, Eos – build plate to 200^{o}C
    - 3D systems – build chamber to 200^{o}C
    - Trumpf TruPrint 5000 – Build plate to 500^{o}C
    - Aconity – Build plate 800^{o}C



Trumpf TruPrint 5000 Web special, accessed 11/12/2020

Increasing the temperature during printing helps to reduce thermal related stresses in parts, especially for poorly conductive materials such as Ti64. It can also impact powder behaviors and increase relative density of the parts

Maly, Martin et al. (March 2019) 'Effect of Procee Parameters and High-Temperature Preheating on Residual Stress and Relative Density of Ti6AL4V Processed by Selective Laser Melting' Materials 12(6):930

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SAM
SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

CU 15 PBF-LB Process

Feedstock

- Content
  - Material for PBF-LB
  - Powder manufacturing processes
  - Powder key characteristics
  - Key performance parameters
  - Effect of powder reuse
  - Standards related with PBF-LB feedstock
  - Feedstock management
  - Traceability
  - Handling and storage
  - Risk

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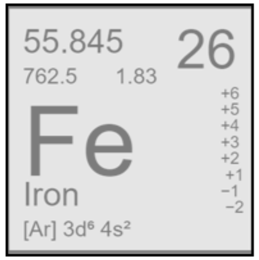
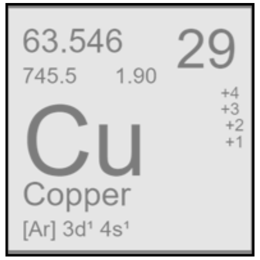
Materials for PBF-LB



Stainless steel alloys & tool steels

- 15-5PH
- 17-4PH
- 316L
- Case hardening steel 20MnCr5
- Maranging steel H13



Copper base alloys

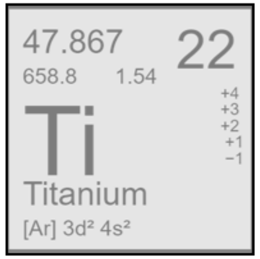
- CuCrZr

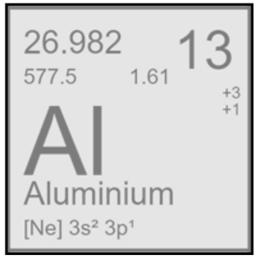
Cobalt base alloys

- CoCr ASTM F75
- CoCr28Mo6 ASTM F799

Titanium alloys

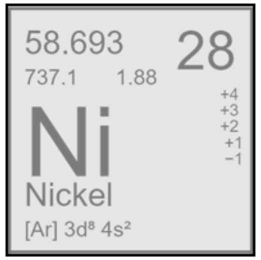
- Ti6Al4V
- Ti6Al4V ELI
- Ti6Al7Nb





Aluminium alloys

- AlSi10 Mg
- AlSi12
- AlSi7Mg0.6



Nickel base alloys

- Nickel Alloy 625/IN625
- Nickel Alloy 718, IN718

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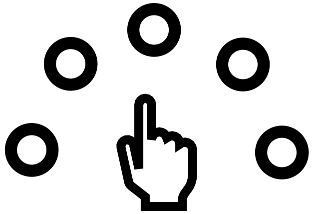
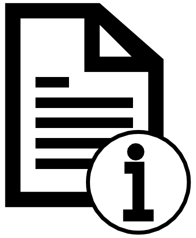
Materials for PBF-LB



- How to chose the feedstock?
  - Based on requirements and user needs
  - Consider the manufacturability of the materials
  - Be conscient that the build plate material and feedstock should be compatible with a similar thermal expansion



- Specific requirements for different materials
  - Aluminium and Titanium are reactive materials, they should be used in the low O2 environments for safety concerns
  - Aluminium and Titanium have a high affinity with O2 an oxidation is likely; they should be processed in low O2 content to limit the oxidation

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Why feedstock performance is important?

?

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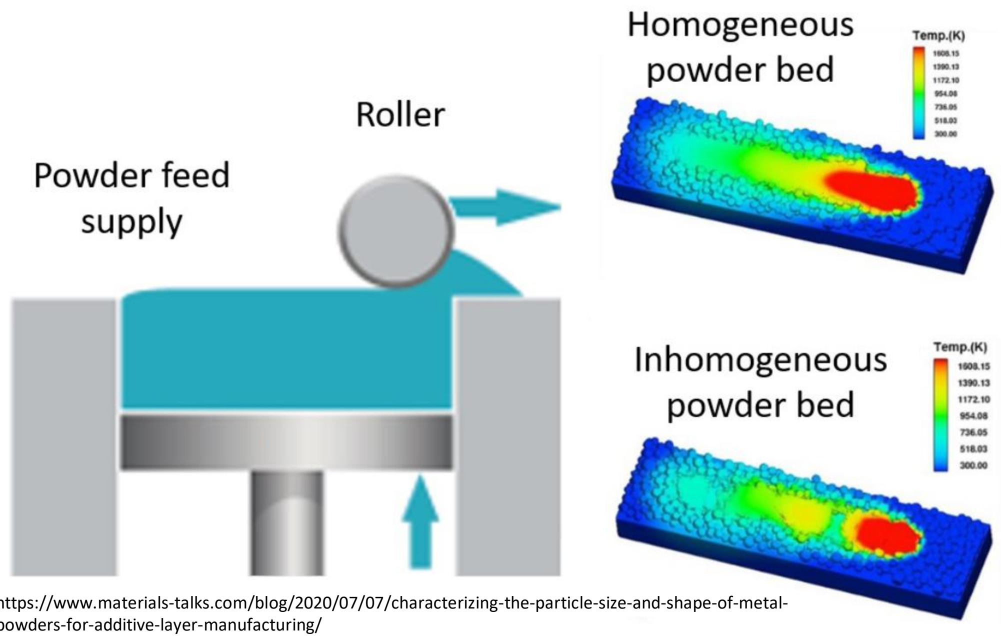
Why feedstock performance is important?

- Homogeneity of the powder bed without gaps
  - Homogeneity translated by the powder bed density
  - Powder bed density is a key factor to heat diffusion for obtaining a good melt-track



https://www.materials-talks.com/blog/2020/07/07/characterizing-the-particle-size-and-shape-of-metal-powders-for-additive-layer-manufacturing/

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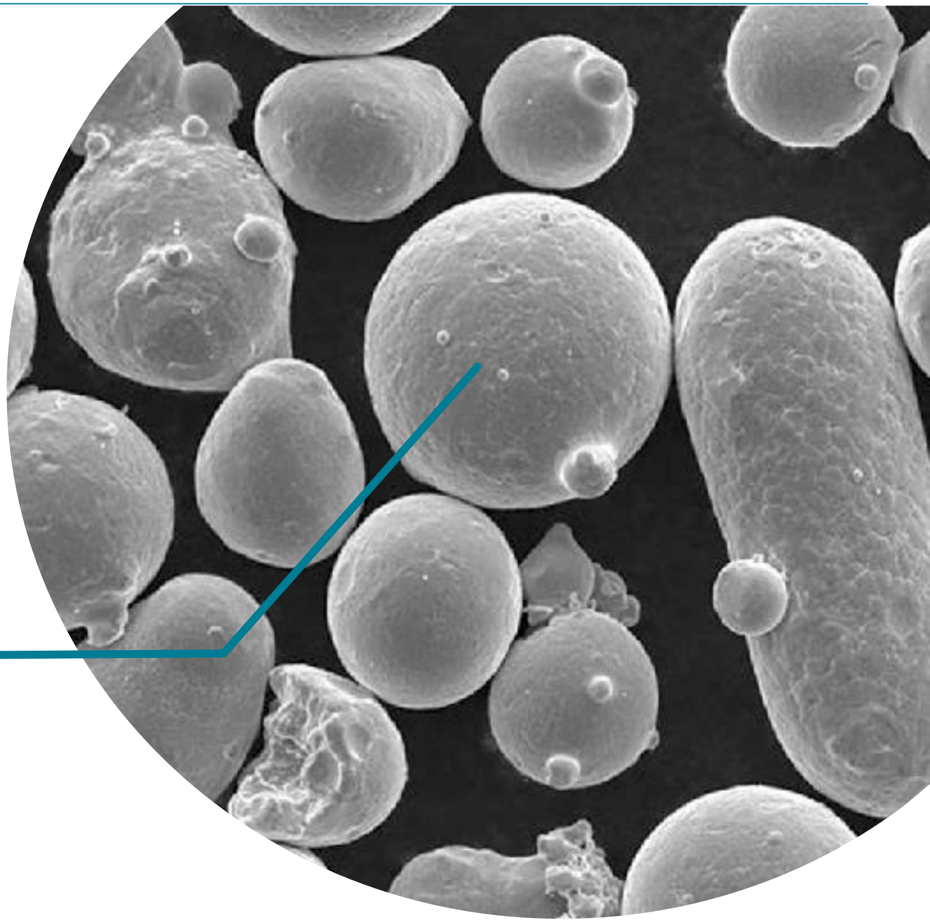
Powder characteristics

- Morphology
- Satellite particles
- Size
- Size distribution
- Microstructure
- Chemical composition
- Porosity
- Density



https://www.researchgate.net/figure/Representative-SEM-image-of-steel-AM-powder-showing-typical-spherical-and-nonspherical_fig1_276259627

- Powder characteristics vary according to the production methods

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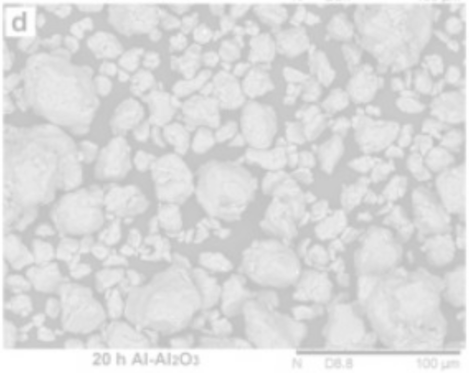
Powder manufacturing processes

Mechanical process

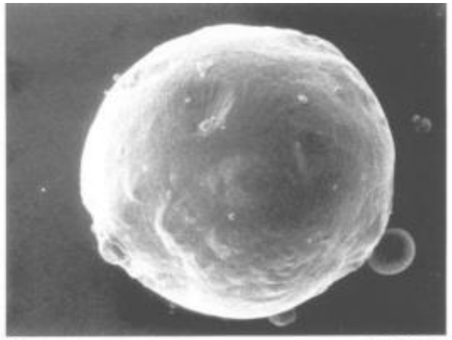


https://www.sciencedirect.com/science/article/pii/S0032591016301747

Reduction process

of Iron Ore 500X

Atomisation process

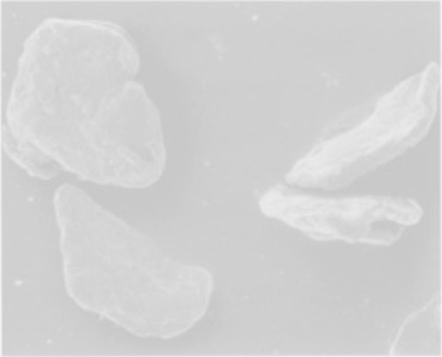


Copper 1,200X

Carbonyl process

Iron 8,000X

Electrolytic process



Iron 390X

https://www.sciencedirect.com/science/article/pii/B9780128035818101419

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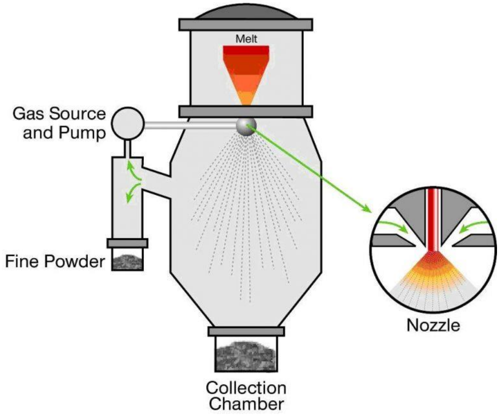
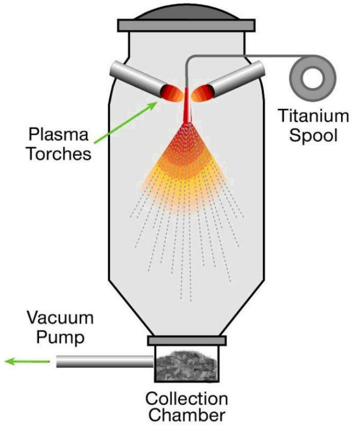
Powder manufacturing processes

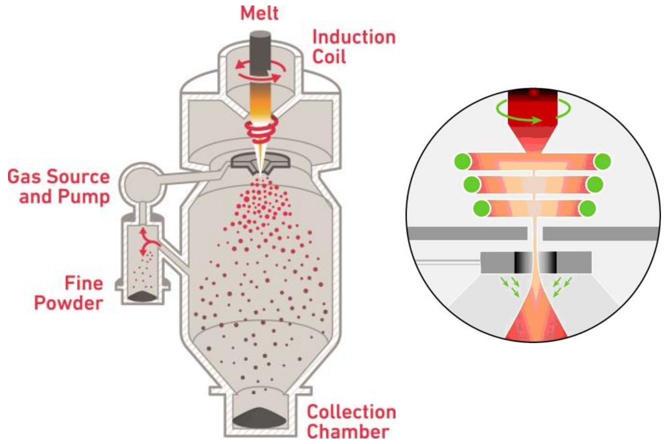
Gas Atomisation



Plasma Atomisation

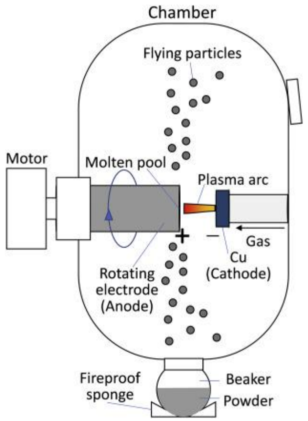


Electrode Induction Gas Atomisation



https://www.bonezonepub.com/2706-titanium-powder-quality-key-to-additive-manufacturing-success

Plasma Rotating Electrode Process (PREP)



https://www.sciencedirect.com/science/article/abs/pii/S0032591020307750

https://www.technology.matthey.com/article/63/3/226-232/

http://maschinetech.com/technical-library/powder-production/

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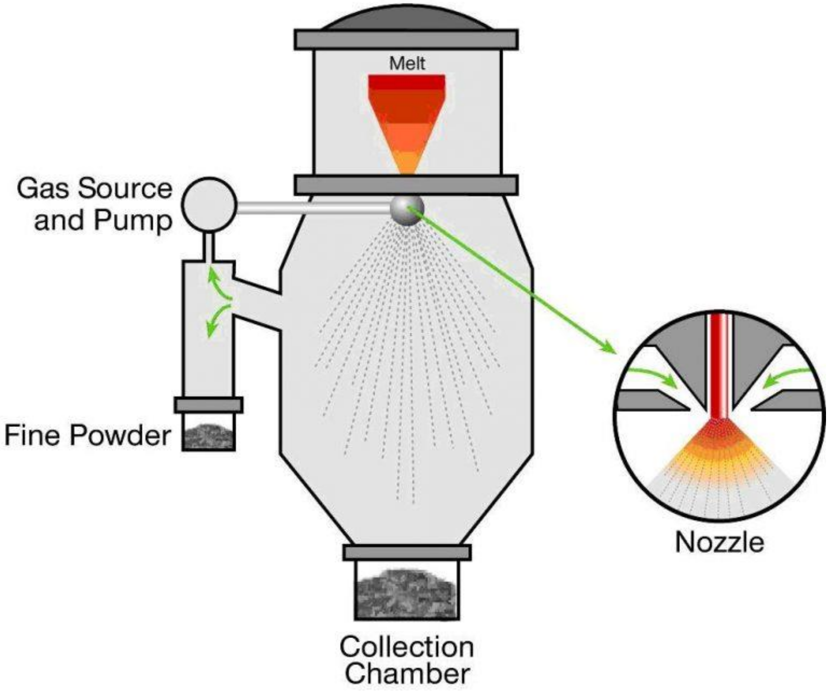
Powder manufacturing processes

Gas Atomisation



https://www.technology.matthey.com/article/63/3/226-232/

http://maschinetech.com/technical-library/powder-production/

- Process:
  - Raw material melted under an inert gas
  - Chamber back filled with gas to force molten alloy to go through nozzle
  - High velocity gas impinges onto the melted material and breaks it up
- Powder:
  - Mostly spherical particles with some asymmetric particles and satellites

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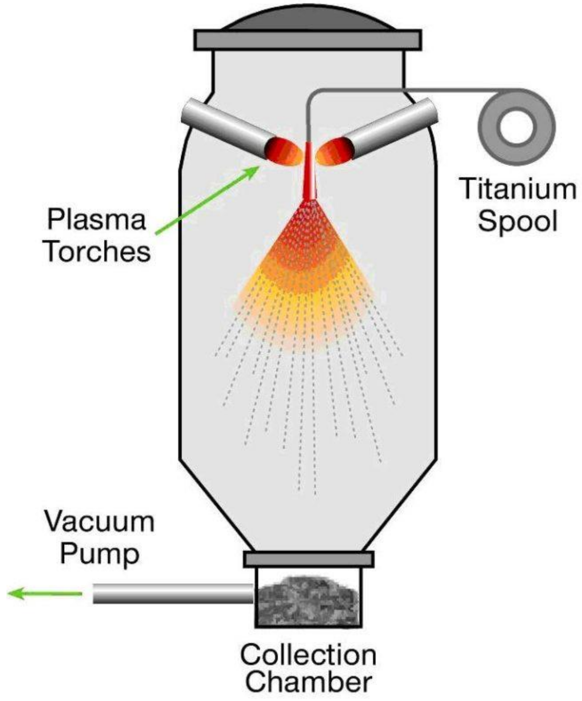
Powder manufacturing processes

Plasma Atomisation



- Process:
  - Wire feedstock is fed into a plasma torch that with the aid of gas atomises the powder
- Powder:
  - Extremely spherical metal powder
  - Size range 0-200um

https://www.technology.matthey.com/article/63/3/226-232/

http://maschinetech.com/technical-library/powder-production/

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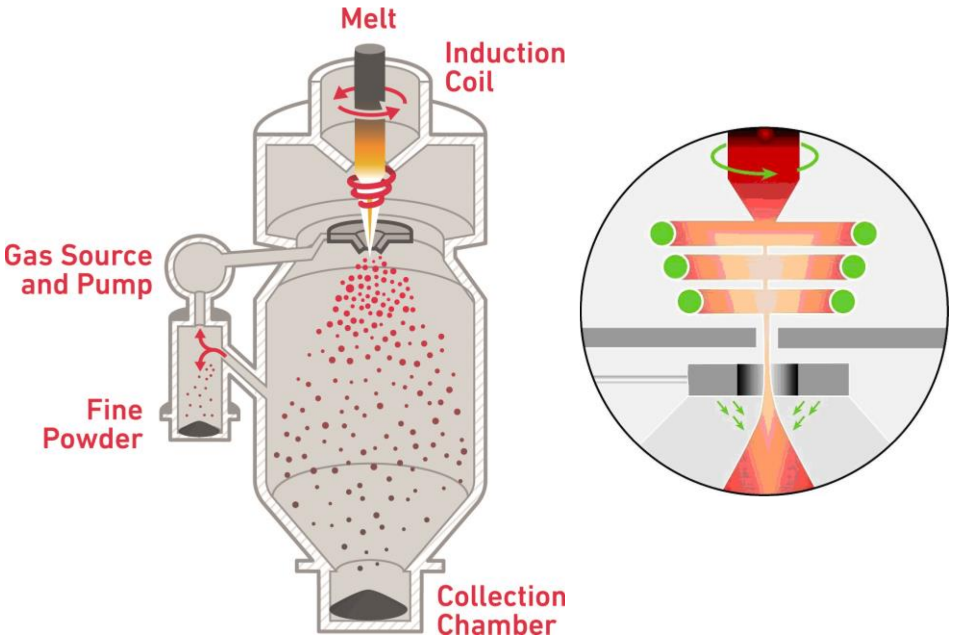
Powder manufacturing processes

Electrode Induction Gas Atomisation



- Process:
  - Feedstock in the form of bar is rotated and melted by an induction coil
  - Motlen metal flows downwards into a gas stream for atomization
- Powder:
  - Similar morphology to gas atomized powder
  - Size range 0-500um

https://www.bonezonepub.com/2706-titanium-powder-quality-key-to-additive-manufacturing-success

https://www.technology.matthey.com/article/63/3/226-232/

http://maschinetech.com/technical-library/powder-production/

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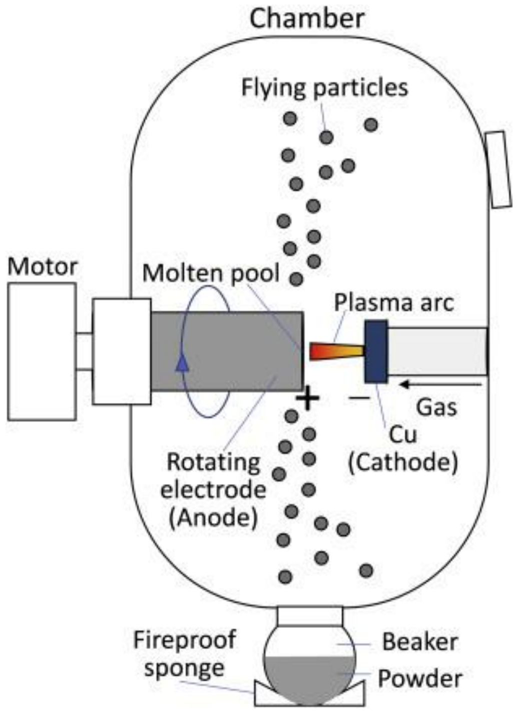
Powder manufacturing processes

Plasma Rotating Electrode Process (PREP)



https://www.sciencedirect.com/science/article/abs/pii/S0032591020307750

- Process:
  - the rotating feedstock bar is melted when it meets with a plasma arc
- Powder:
  - Extremely spherical metal powder
  - Size range 50-500um

https://www.technology.matthey.com/article/63/3/226-232/

http://maschinetech.com/technical-library/powder-production/

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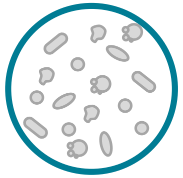
Key parameter/variables affecting powder



Morphology

Particle size distribution

Flowability

Spreadability

Characteristic densities

Chemistry

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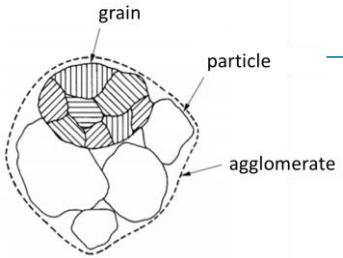
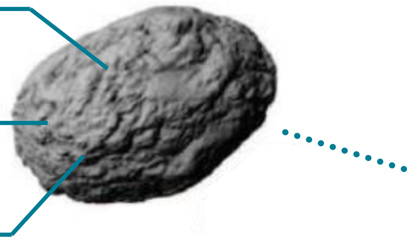
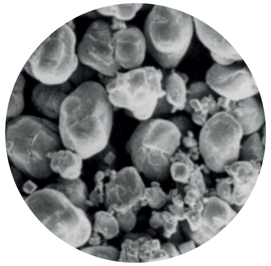
Particle morphology



agglomerate
several particles adhering together

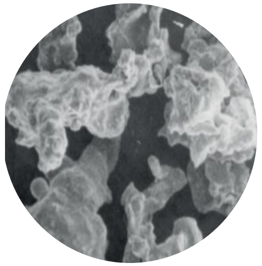
- Sphericity
- Roughness
- Agglomerates



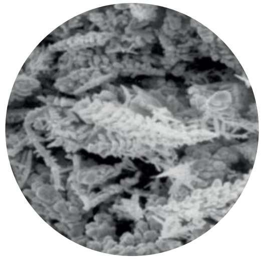


nodular
of rounded irregular shape

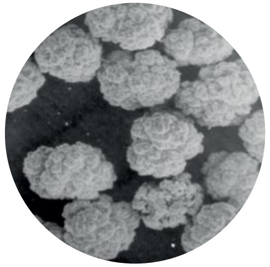
fibrous
having the appearance of regularly or irregularly shaped threads



irregular
lacking any symmetry



dendritic
of branched shape



granular
approximately equidimensional nonspherical shape

spheroidal
roughly spherical

“ ISO/FDIS 3252
Powder metallurgy - Vocabulary

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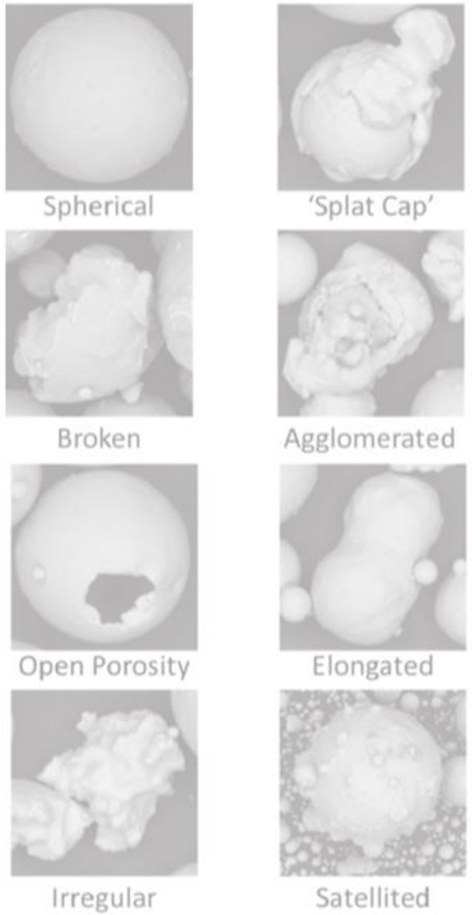
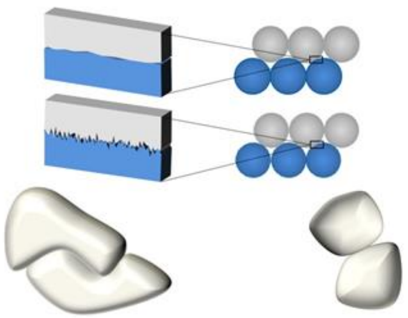
Particle morphology



Picture courtesy: Malvern Instruments Limited

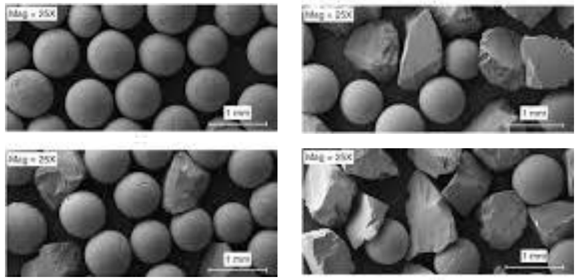
- Powder morphology has a major influence on the processing characteristics:

Flowability



https://www.additivemanufacturing.media/articles/optimizing-metal-powders-for-additive-manufacturing-exploring-the-impact-of-particle-morphology-and-powder-flowability

Packing density

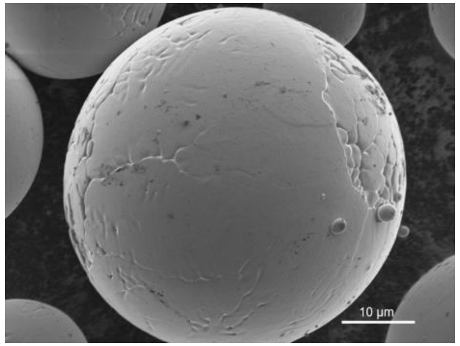


https://ascelibrary.org/doi/10.1061/%28ASCE%29GT.1943-5606.0001994

Particle morphology

- Test methods

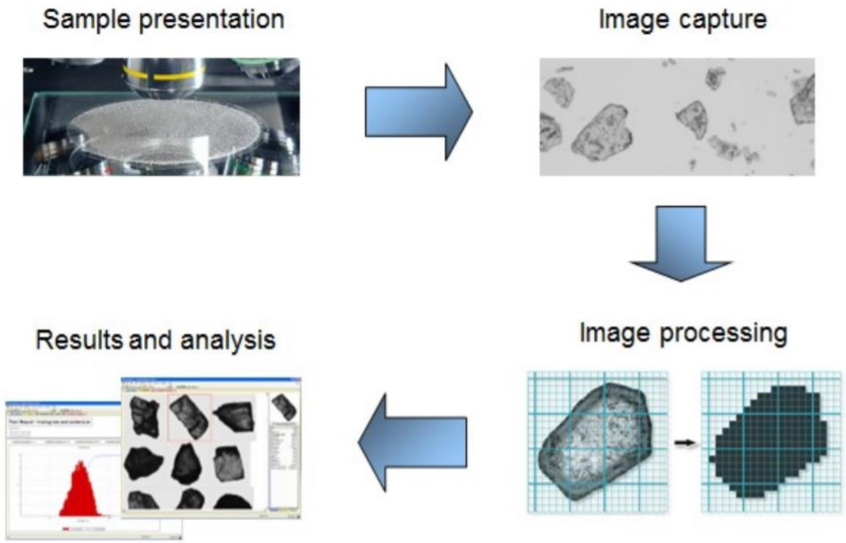
SEM
Scanning electron microscope



https://www.groundai.com/project/modeling-and-characterization-of-cohesion-in-fine-metal-powders-with-a-focus-on-additive-manufacturing-process-simulations/3

Qualitative image comparison and/or quantitative criteria

Automated / semi automated methods



malvern optimizing metal powders for additive manufacturing

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Key parameter/variables affecting powder

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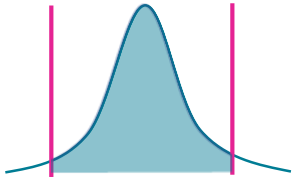
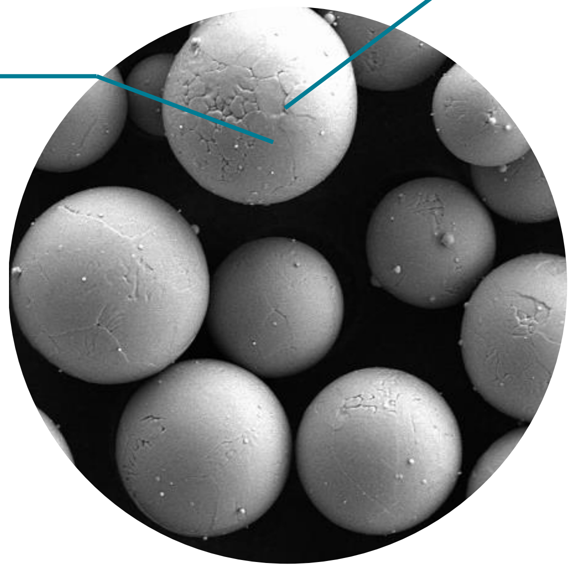
Particle size and distribution

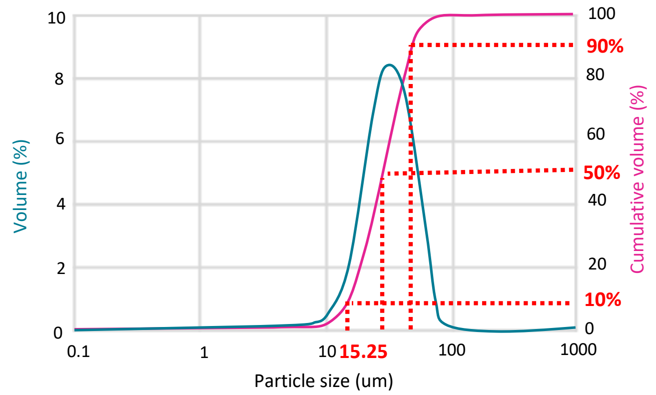
- Range





https://www.advancedpowders.com/powders/titanium/ti-6al-4v-23

- Distribution



Key distribution parameters:

- D10: is that size below which 10% of the material is contained.
- D50: is the size below which 50 % of the material is contained.
- D90 : is the point in the size distribution, which includes 90% of the total volume of material

Parameter	
D10	15.25um
D50	30.22um
D90	52.57um

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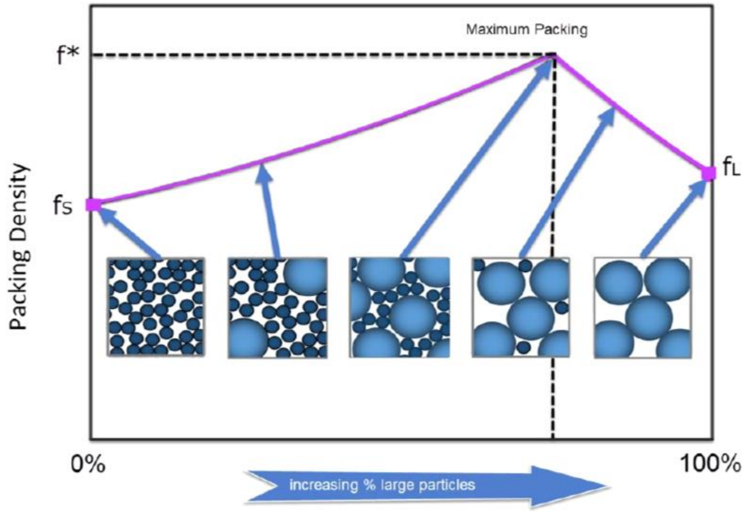
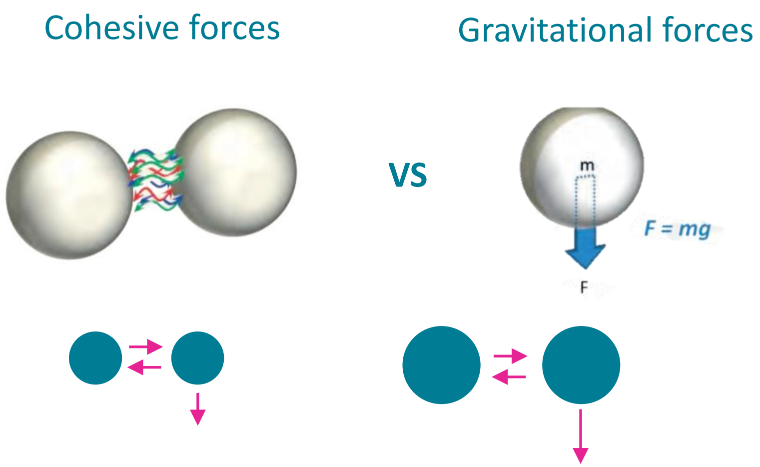
Particle size and distribution

- Influence of the particle size distribution
  - Powder performance
    - Packing density



Picture courtesy: Malvern Instruments Limited

- Flowability



https://www.alfatest.it/keyportal/uploads/l30_an-introduction-to-powders-booklet.pdf

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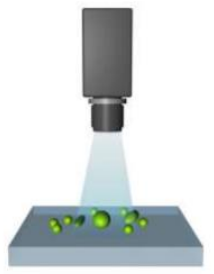
SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Co-funded by the Erasmus+ Programme of the European Union

Particle size and distribution

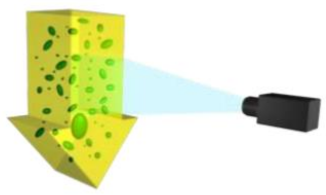
- Test methods

Digital image analysis



Static

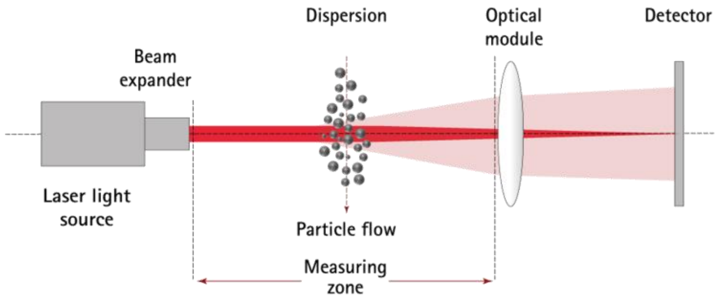
ISO 13322-1



Dynamic

ISO 13322-2

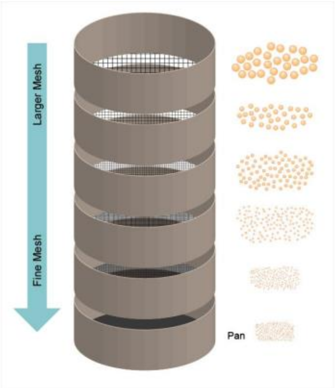
Laser diffraction analysis



https://www.sympatec.com/en/particle-measurement/sensors/laser-diffraction/

ISO 13320

Sieving analysis



ISO 4497:2020

Key parameter/variables affecting powder

Morphology

Particle size distribution

Flowability

Spreadability

Characteristic densities

Chemistry

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Powder flowability

https://www.engineering.com/AdvancedManufacturing/ArticleID/13836/5-Million-Grant-to-Improve-Metal-Powders-for-Additive-Manufacturing.aspx

- Flowability : ability of a powder to flow
- Function of factors
  - Powder size and size distribution
  - Powder morphology and surface (inter-particle friction affected by surface roughness)
  - Cohesive strength by adsorbed water on the particle's surfaces

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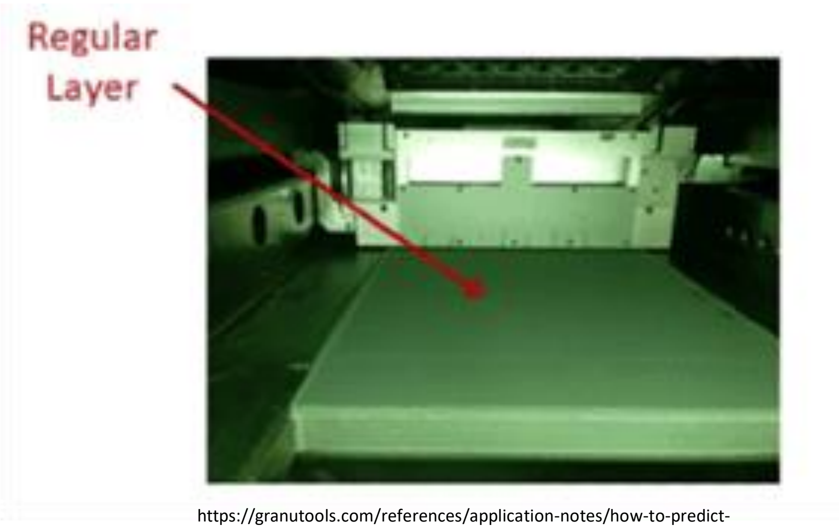
Powder flowability

- Influence of flowability on powder performance / build quality
  - Influences the **uniformity of the powder bed**
  - Influences the powder delivery in system piping



https://granutools.com/references/application-notes/how-to-predict-spreadability-in-powder-bed-based-am/

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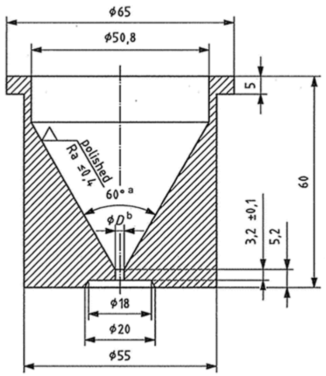
Powder flowability

- Common Flowability test methods for PB-PBF powders



http://www.labulk.com/iso-4490-metallic-powders-flow-ratehall-flowmeter/

https://granutools.com/references/application-notes/how-to-predict-spreadability-in-powder-bed-based-am/

Method: Hall flowmeter

Output: Flowability s/g

Standard: ISO 4490 or ASTM B213

https://www.semanticscholar.org/paper/Advances-in-SLS-Powder-Characterization-Amado-Schmid/eade2810c90ee0ba64531626af907d98fc0e0116

Method: Rotating drum

Output:
- Dynamic angle of repose (low value for good flowability)
- Dynamic cohesive index (0 for non cohesive powder)

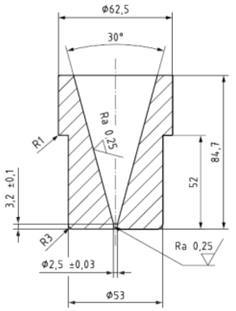
Standard: Not available

- Test methods for non free flowing powder

Method: Gustavsson funnel
Used for fine particles

Output: Flowability s/50 g

Standard: ISO 13517

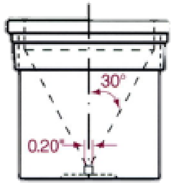


http://fishersubsievesizer.blogspot.com/2017/08/iso13517-metallic-powder-gustavsson.html

Method: Carney funnel

Output: Flowability s/150 g or s/200 g

Standard: ASTM B964



https://www.mcssl.com/store/ea8c48e7c1884434b664b991d8c792/carney-funnel

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Powder flowability

- Flowability tests are not representative of the physical phenomenon happening in the process, where powder is spread across build plate

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Key parameter/variables affecting powder

Morphology

Particle size distribution

Flowability

Spreadability

Characteristic densities

Chemistry

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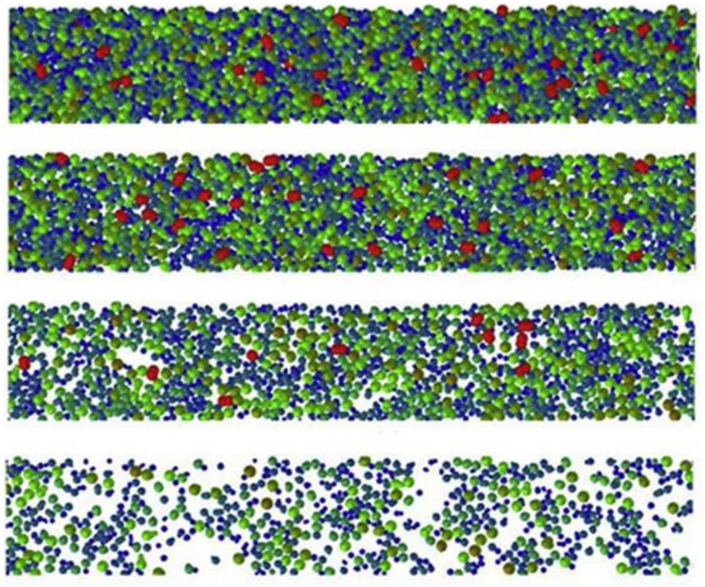
Powder spreadability

- Powder spreadability: ability of the powder to be spread uniformly during the process.

"measure of the ease with which a powder is spread uniformly without the formation of empty patches"
https://www.sciencedirect.com/science/article/pii/S0032591020303193

→ Representative of the physical phenomena occurring in process



https://www.sciencedirect.com/science/article/pii/S0032591020303193

- Development of a standardised test method in the pipeline of ISO TC 261 and ASTM F42. Source: I.S. EN ISO/ASTM 52907:2019

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Key parameter/variables affecting powder

Morphology | Particle size distribution | Flowability | Spreadability | **Characteristic densities** | Chemistry

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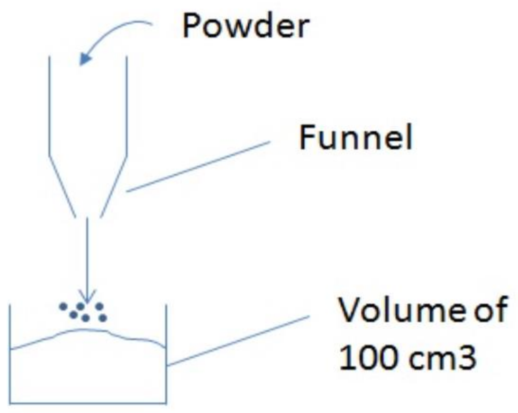
Characteristic densities

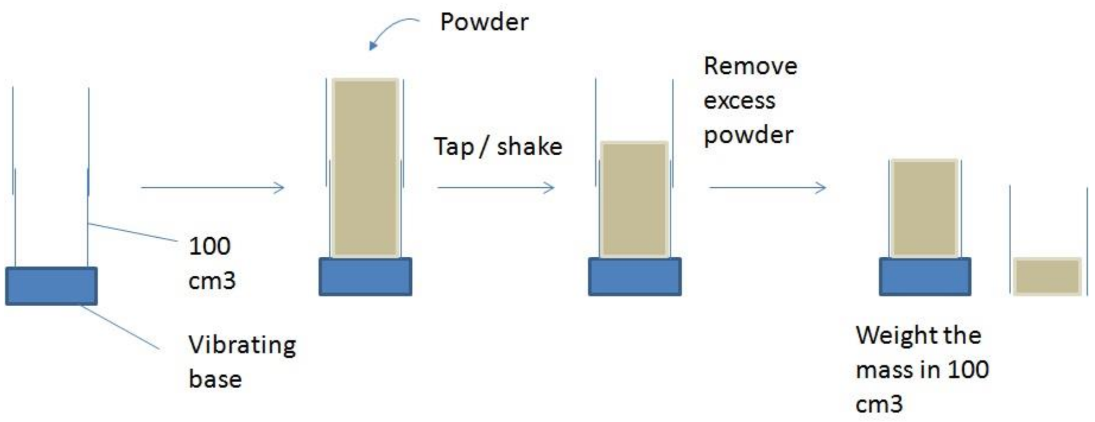
- Apparent density
  - Defines the “loose condition” of powder



https://powderprocess.net/bulk_density.html

- Test method:
  - measure mass for a given volume (ISO 3923-1)

- Tapped density
  - Compressive ability of the powder



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Characteristic densities

- Apparent density
- Tapped density

- Compressibility index

$$= \frac{(V_0 - V_F)}{V_0} \cdot 100$$

- Hausner ratio

$$= \frac{V_0}{V_F}$$

- Information on interparticulate interactions
- Give information on flowability

Compressibility index (per cent)	Flow character	Hausner ratio
1-10	Excellent	1.00-1.11
11-15	Good	1.12-1.18
16-20	Fair	1.19-1.25
21-25	Passable	1.26-1.34
26-31	Poor	1.35-1.45
32-37	Very poor	1.46-1.59
> 38	Very, very poor	> 1.60

https://particle.dk/methods-analytical-laboratory/bulk-and-tapped-density/

with V_0 unsettled apparent volume
V_F final tapped volume

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Key parameter/variables affecting powder

Morphology

Particle size distribution

Flowability

Spreadability

Characteristic densities

Chemistry

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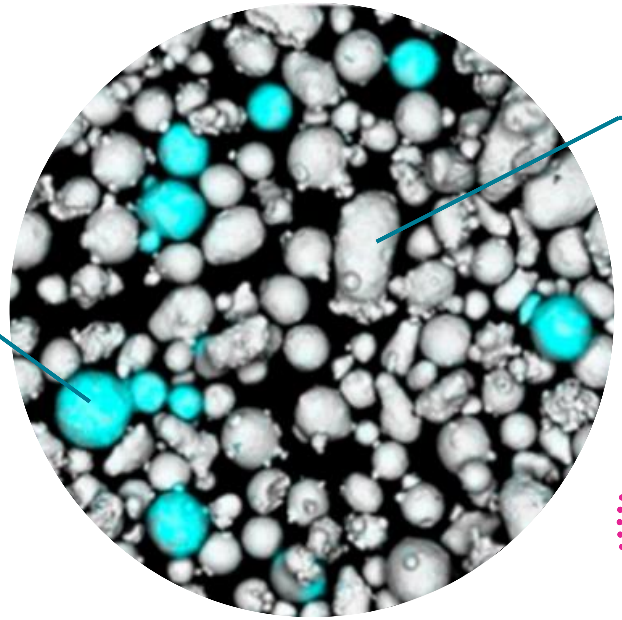
Powder chemistry



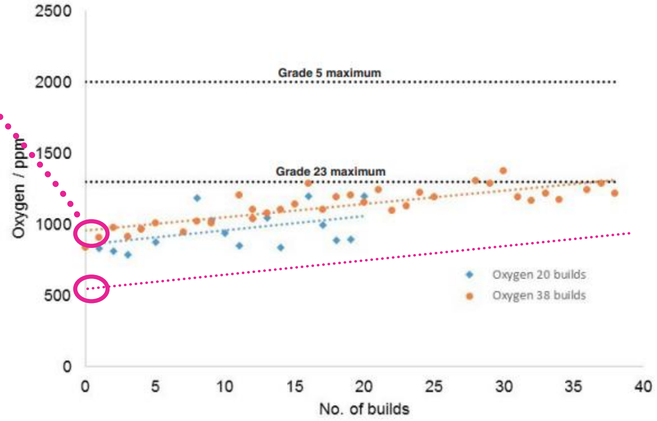
https://www.mdpi.com/1996-1944/12/15/2342/pdf

Contamination •

• Composition

Composition Ti6Al4V ELI [ASTM F3001 - 14]

Element	min	max
Aluminum	5.50	6.50
Vanadium	3.50	4.50
Iron	...	0.25
Oxygen	...	0.13
Carbon	...	0.08
Nitrogen	...	0.05
Hydrogen	...	0.012
Yttrium	...	0.005
Other elements, each	...	0.10
Other elements, total	...	0.40
Titanium	remainder	



https://resources.renishaw.com/download.aspx?data=83164&lang=en&showForm=true&&RPSAction=Login&RPSUserXfer=6bee1e8d-12ba-4d0d-88b8-40ce326b95e9

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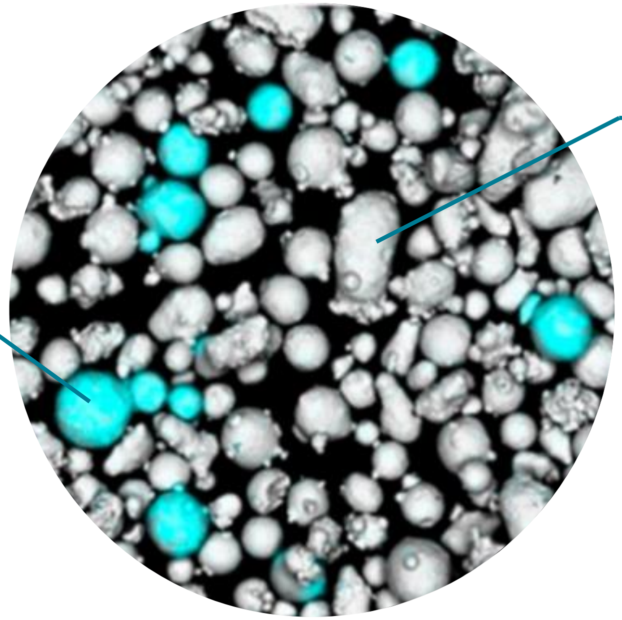
Powder chemistry



https://www.mdpi.com/1996-1944/12/15/2342/pdf

Contamination

Contamination with external powders

Contamination with oils, coolant, rubber gloves

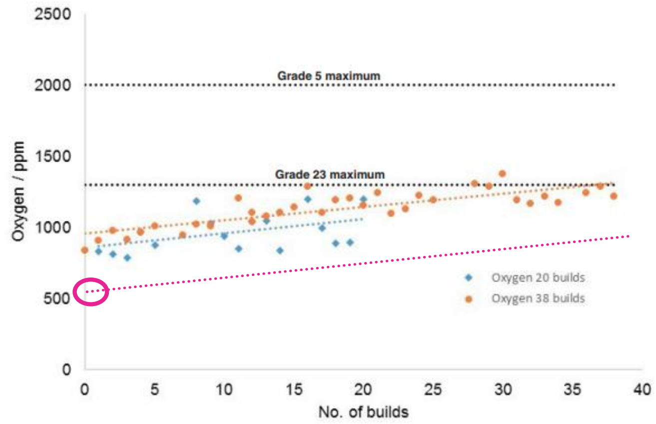
Occurring during material change

Occurring while handling powder

- **Composition**

Composition Ti6Al4V ELI [ASTM F3001 - 14]

Element	min	max
Aluminum	5.50	6.50
Vanadium	3.50	4.50
Iron	...	0.25
Oxygen	...	0.13
Carbon	...	0.08
Nitrogen	...	0.05
Hydrogen	...	0.012
Yttrium	...	0.005
Other elements, each	...	0.10
Other elements, total	...	0.40
Titanium	remainder	



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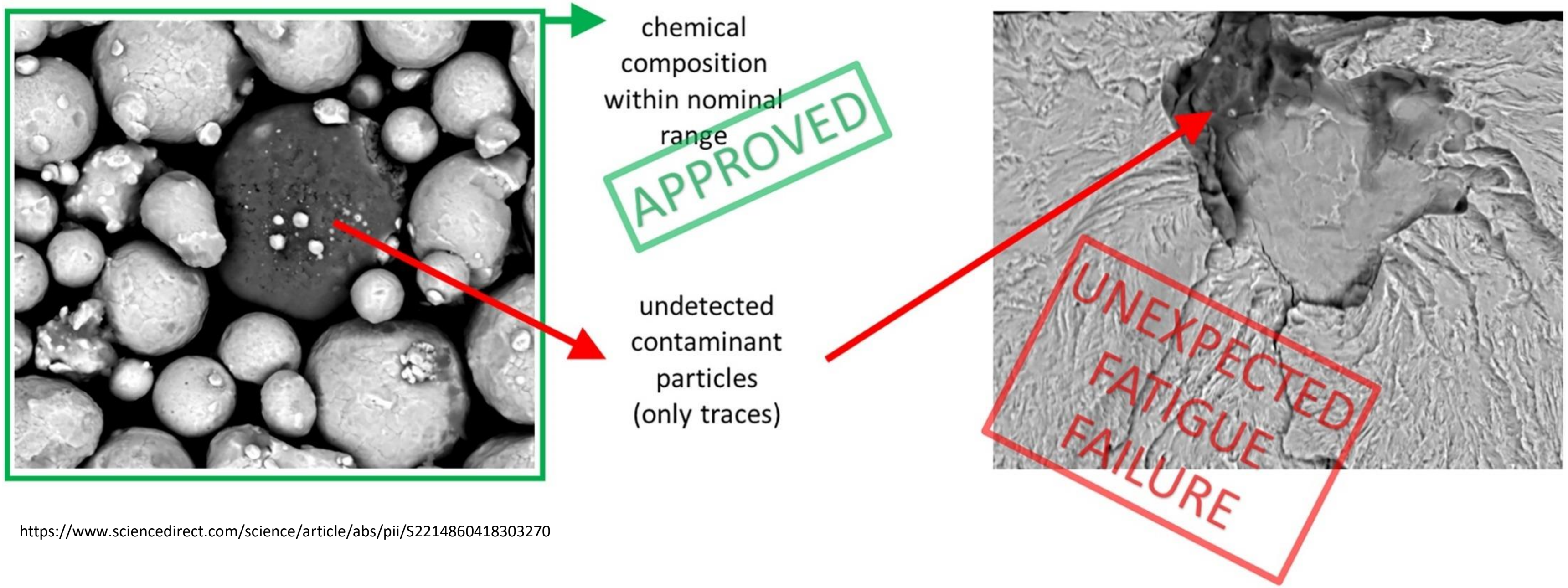
Powder chemistry

- Influence of chemistry on part quality



https://www.sciencedirect.com/science/article/abs/pii/S2214860418303270

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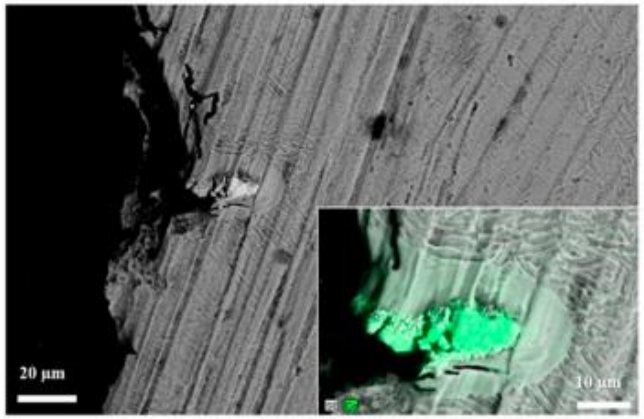
Powder chemistry

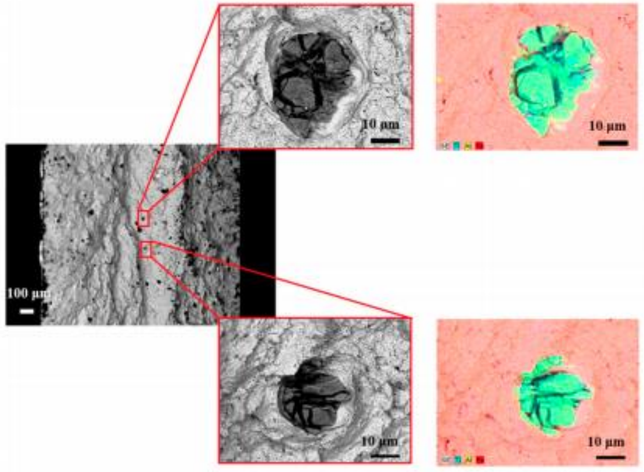
- Influence of chemistry on part quality

Micrograph of failure surface during flexural test
Co-Cr-Mo inclusion in Ti6Al4V sample



https://www.semanticscholar.org/paper/Cross-Contamination-Quantification-in-Powders-for-A-Santecchia-Mengucci/778b4a34005865391ffe0484c80ed5e302d89d71

Micrograph of failure surface during fatigue test
Ti6Al4V inclusion in maraging steel sample



https://www.semanticscholar.org/paper/Cross-Contamination-Quantification-in-Powders-for-A-Santecchia-Mengucci/778b4a34005865391ffe0484c80ed5e302d89d71

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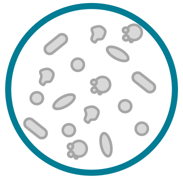
Key performance parameters

- What are the key parameters to control & met in order for the system to met its operational gaols?



Morphology

spherical without agglomerates and satellites

Particle size distribution

Particle range 10 - 45 um

D10, D50, D90 not specified

Flowability

Not specified

Spreadability

No current values/specifications

Characteristic densities

Not specified

Chemistry

Composition meeting specifications per relevant standard

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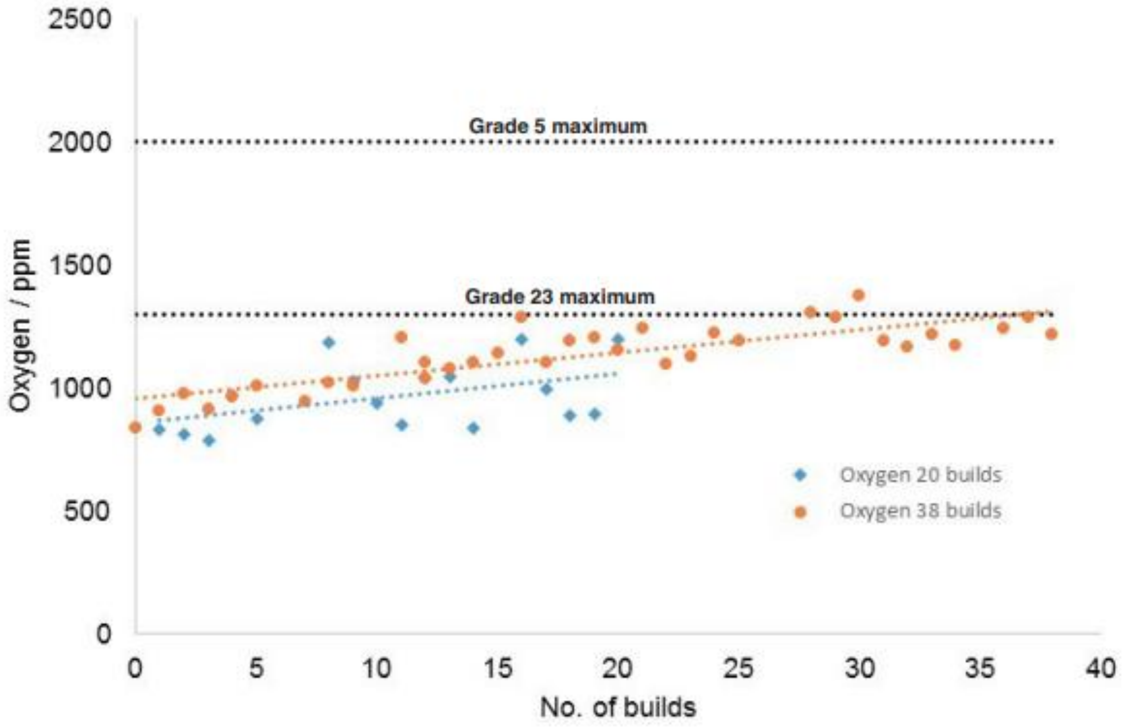
Effect of powder reuse

- Powder chemistry



https://resources.renishaw.com/download.aspx?data=83164&lang=en&showForm=true&&RPSAction=Login&RPSUserXfer=6bee1e8d-12ba-4d0d-88b8-40ce326b95e9

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Effect of powder reuse

- Chemistry → Oxygen pick up
  - During process spatters are picking up oxygen
  - Oxygen pick up in the heat affected zones

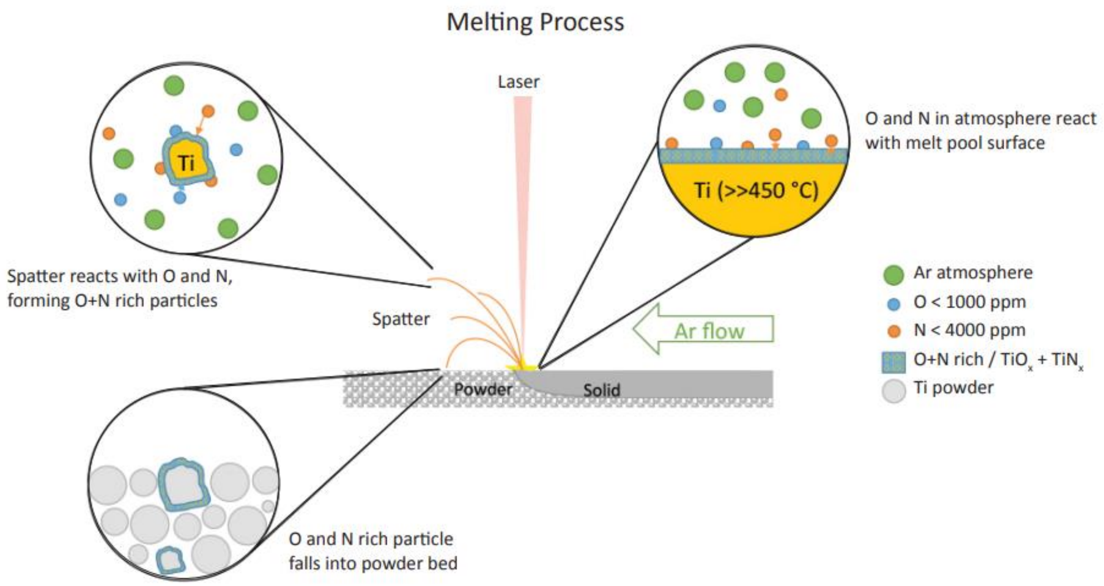

Image courtesy: LPW Carpenter Additive

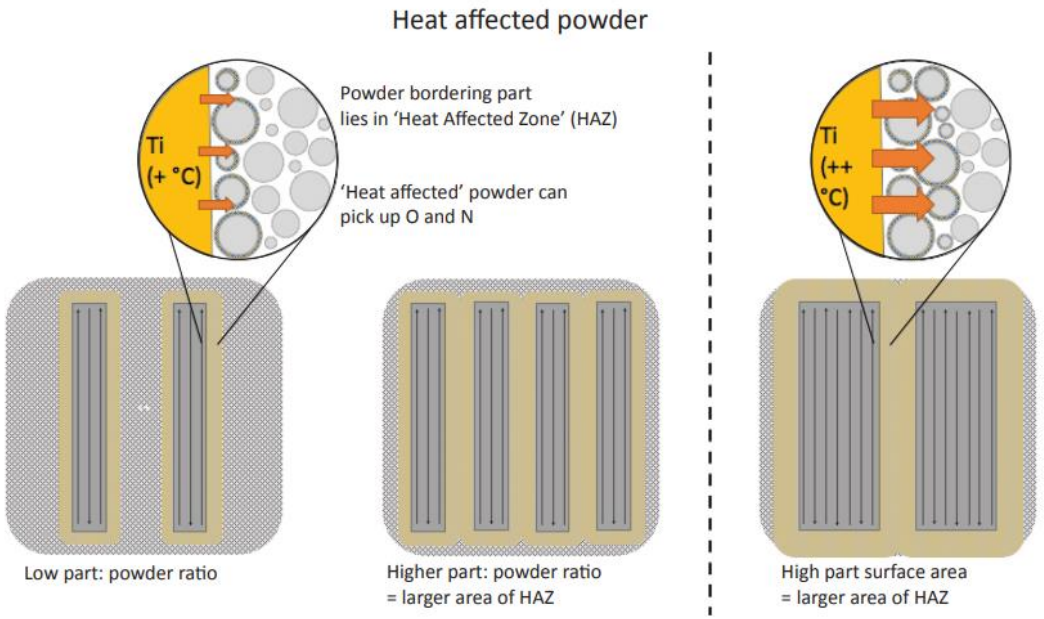

Image courtesy: LPW Carpenter Additive

http://maschinetech.com/wp-content/uploads/2018/06/Powder-Degradation-in-Serial-Production-Pt-I.pdf

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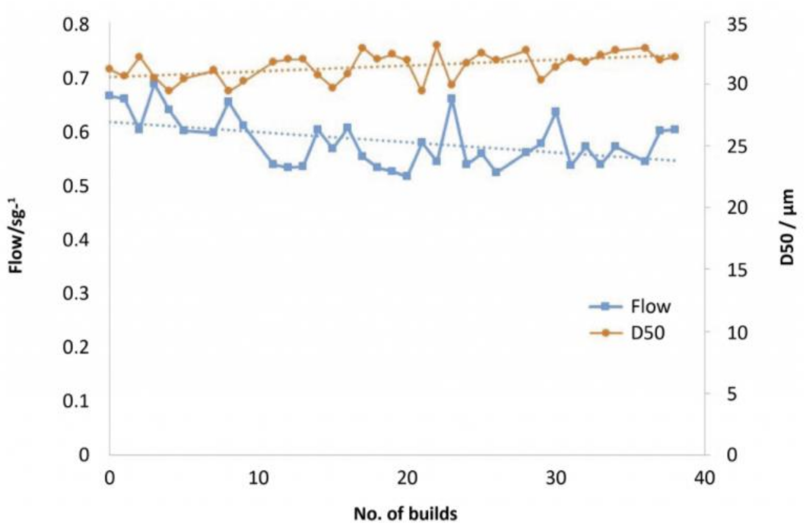
Effect of powder reuse

- Flowability



Source: https://www.metal-am.com/articles/understanding-the-impact-of-powder-reuse-in-metal-3d-printing/

- Particle size:
  - Can see some particle size variation due to segregation

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Standards

General metallic powders / General feedstock materials

- ISO/ASTM 52907:2019 Feedstock Materials – Methods to characterize metal powders
- WK74931 Feedstock Materials – Powder Life Cycle Management
- WK62190 Feedstock Materials – Technical specifications on metal powder

Material specific standards for LBPFB

Standard Specification for Additive Manufacturing

…………………. with Powder Bed Fusion

- ASTM F3184-16 Stainless Steel Alloy (UNS S31603)
- ASTM F2924-14 Titanium-6 Aluminum-4 Vanadium
- ASTM F3001-14 Titanium-6 Aluminum-4 Vanadium ELI
- ASTM F3055-14a Nickel Alloy (UNS N07718)
- ASTM F3056-14e1 Nickel Alloy (UNS N06625)

Material specific standards for LBPFB – Finished Parts properties

Specification for …………………. with Powder Bed Fusion

- ASTM F3302-18 Titanium Alloys
- ASTM F3318-18 AlSi10Mg
- ASTM F3213-17 Cobalt-28 Chromium-6 Molybdenum

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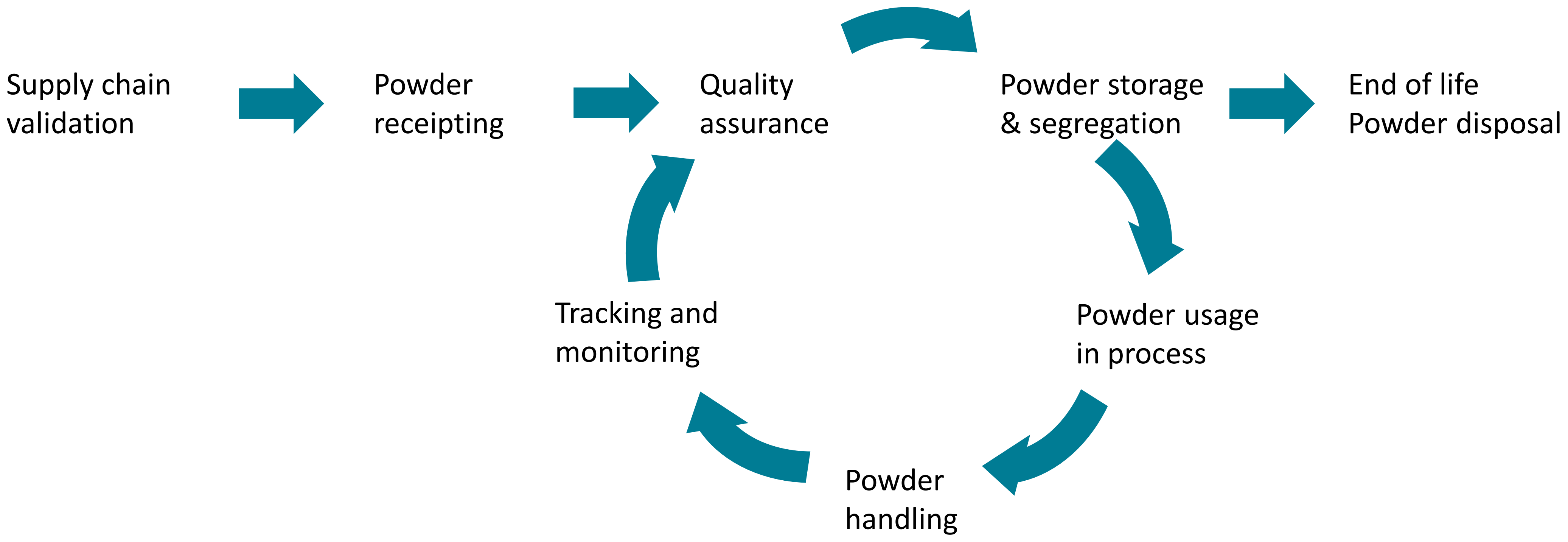
Feedstock management in LBPBF



https://www.youtube.com/watch?v=JMr-0XfI9J4

Feedstock traceability in a manufacturing environment

- Finished part should be related to feedstock, hence the importance of material traceability

- Material should present statement of conformity and inspection document to ensure traceability, with the following specifications:
  - a unique document reference,
  - the name and the address of the supplier,
  - the reference of powder lot,
  - the product description, including chemical composition, standard and/or trade/common name,
  - the nature of powder production process (including e.g. type of gas used, environment conditions),
  - the packaging description, including the packaging, the nature of the shielding gas and the desiccant bag, if relevant,
  - the date of analysis,
  - storage and preservation instructions,
  - all of the information to ensure the traceability (e.g. order number, applicable specification).

- Powder properties after reuse should be tracked as best practice. Traceability should be established a each step of the life cycle.

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Feedstock inspection

- At reception of feedstock, the performance parameters are certified by the powder manufacturer in a material certificate.

MATERIAL CERTIFICATE No:

Customer:
Purchase Order: — **Internal Order:**
Material Description: Ti-6Al-4V grade 23 powder — **Laboratory No:**
Size: 10-45 µm — **Lot #:**
Specification: ASTM F3001 — **Quantity:**

POWDER COMPOSITION (weight percent)				
Element	**ASTM F3001**	**Measured**	**Testing method**	**Status**
Aluminum, range	5.50 - 6.50	6.38	ASTM E2371	Conforming
Vanadium, range	3.50 - 4.50	3.95	ASTM E2371	Conforming
Iron, max.	0.25	0.22	ASTM E2371	Conforming
Oxygen, max.	0.13	0.10	ASTM E1409	Conforming
Carbon, max.	0.08	0.02	ASTM E1941	Conforming
Nitrogen, max.	0.05	0.02	ASTM E1409	Conforming
Hydrogen, max.	0.012	0.002	ASTM E1447	Conforming
Yttrium, max.	0.005	< 0.001	ASTM E2371	Conforming
Others each, max.	0.10	< 0.10	ASTM E2371	Conforming
Others total, max.	0.40	< 0.40	ASTM E2371	Conforming
Titanium	Balance	Balance	ASTM E2371	Conforming
Chemical analysis laboratory:				

POWDER CHARACTERIZATION			
Description	**Required**	**Measured**	**Status / Comments**
Particle size distribution per ASTM B214			
Particle Size (µm)	**% By Mass**	**% By Mass**	
> 45	Max. 5.0	0.4	Conforming
≤ 45	Min. 95.0	99.6	Conforming
Particle size distribution per ASTM B822 (Coulter® LS Particle Size Analyzer)			
D_{10}	Not specified	20 µm	NA
D_{50}	Not specified	32 µm	NA
D_{90}	Not specified	44 µm	NA
< 10 µm	Not specified	1 % by volume	NA
Flow Rate per ASTM B213			
Flow Rate (sec. for 50 g)	Not specified	31	NA
Apparent Density per ASTM B212			
Apparent Density (g/cm³)	Not specified	2.52	NA
Analyses were done by	**at their location and reported results are rounded following ASTM E29.**		

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Feedstock handling and storage

- Prevent cross contamination
- powder should be climatized (temperature & humidity) before introduced to the machine.
- If required by the customer, powder containers can be filled by inert gas (argon or nitrogen) to provide protective atmosphere.

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Risks

- ATEX risks with feedstock handling
- Powder Inhalation & Contact

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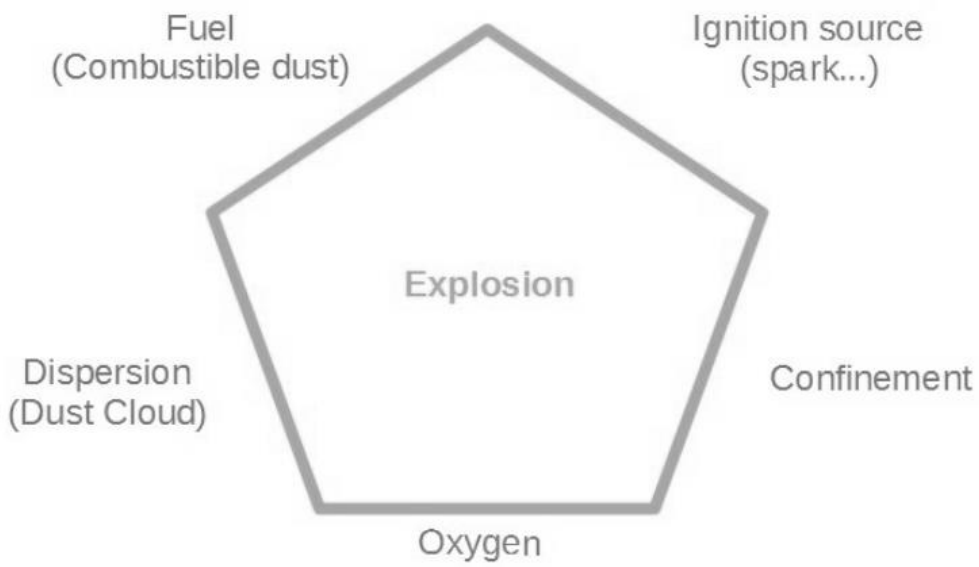
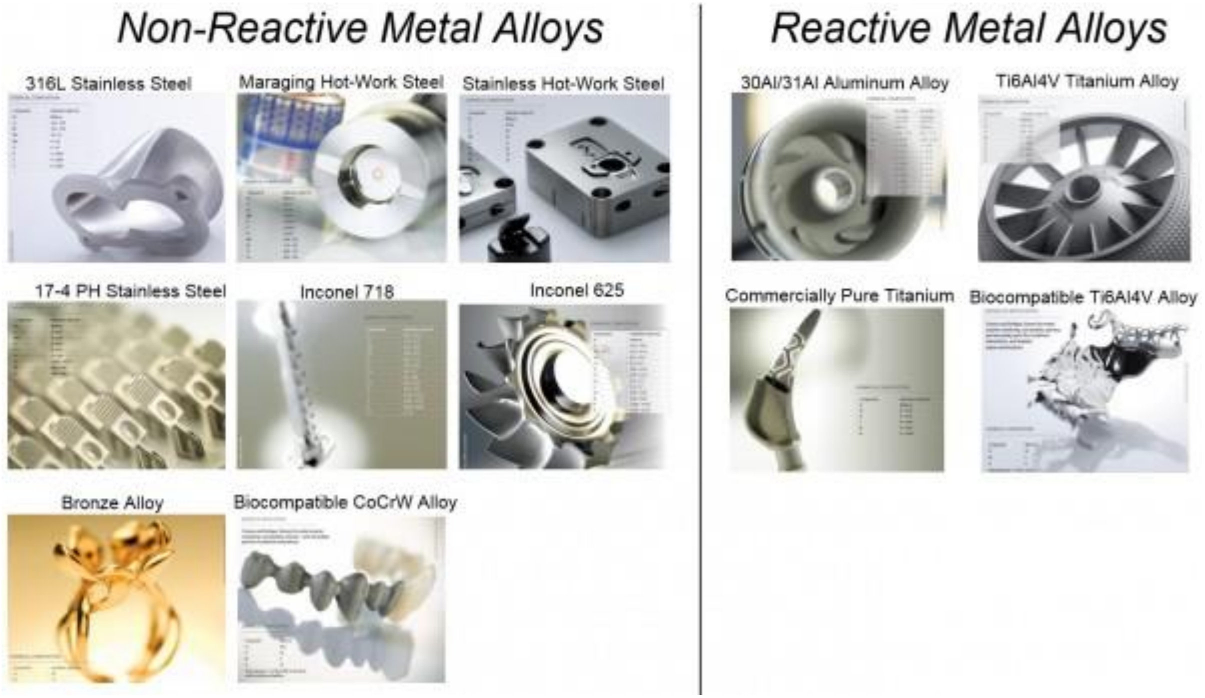
Risks

- ATEX risks with feedstock handling

Dust explosion pentagon





https://powderprocess.net/Safety_ATEX.html#:~:text=Powders%2C%20when%20they%20are%20put,been%20recorded%20accross%20process%20industries.

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Risks

- Prevention of dust explosion

Housekeeping

Image curtesy Shutterstock

Inert atmosphere

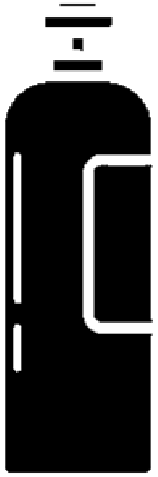

Image curtesy Vectorstock

Remove sources of inflammation

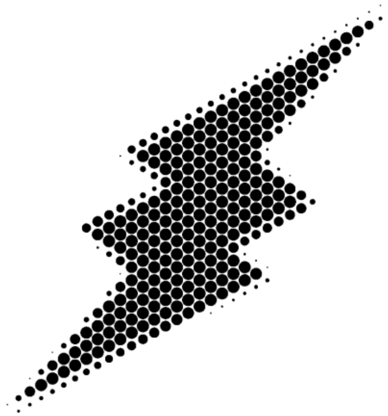

Image curtesy Vectorstock

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Risks

- Powder Inhalation & Contact:

Inhalation

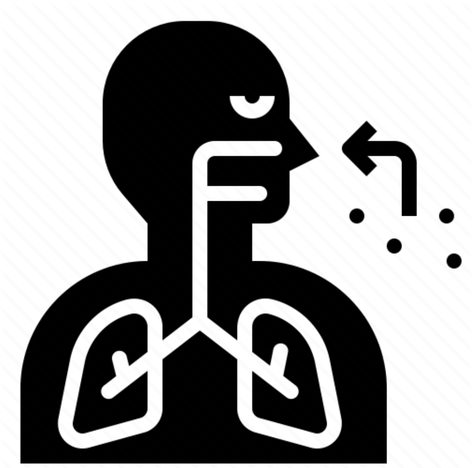

Image curtesy Iconfinder

Effects of long-term exposure on lungs and organs

Contact

Image curtesy Iconfinder

Skin irritation

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Risks

- Prevention of powder inhalation & contact:

Inhalation

Image curtesy Iconfinder

Respirator FFP2/FFP3

Contact

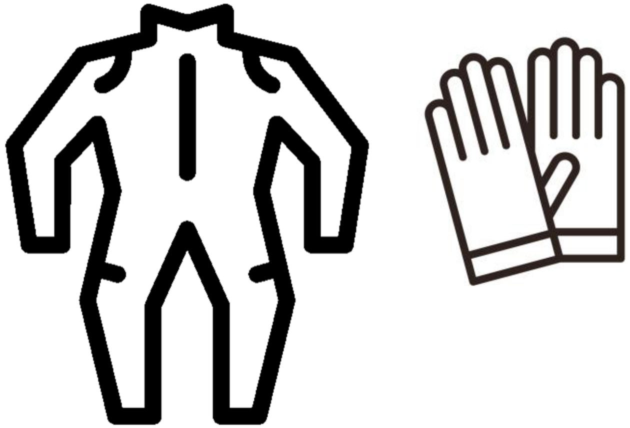

Image curtesy Iconfinder

Skin irritation

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SAM
SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

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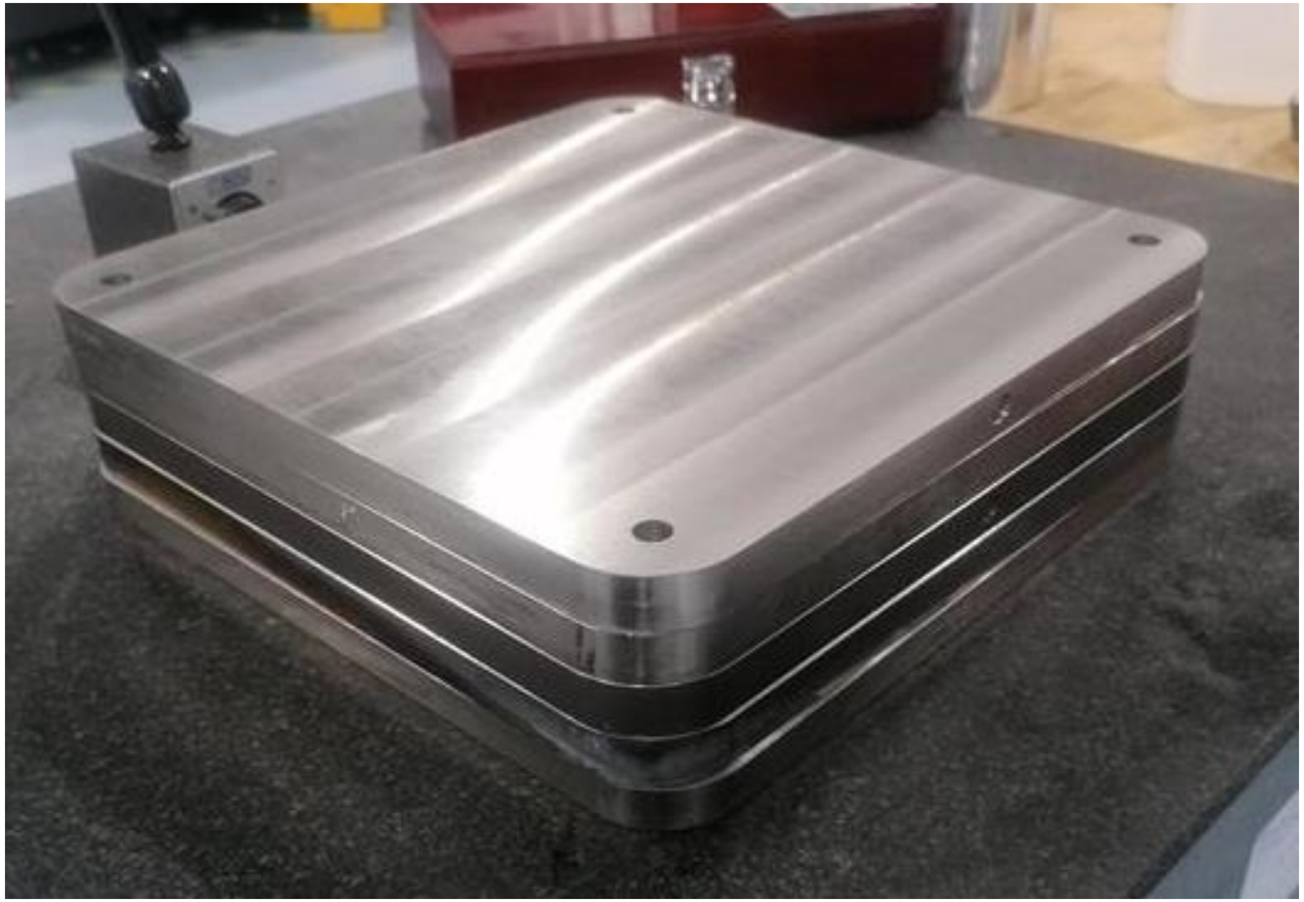
Intro – Consumables



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author, and the Commission cannot be held responsible fc

Buildplates – Fundamentals

Buildplate property	***Impact on part***
Provide a level surface for powder spread	*Supports a stable meltpool at the point where the part connects to the build plate.*
Provide a stiff substrate to constrain material during build	*Prevents general deformation of the part during build*
Provide a thermal sink to remove heat energy from a part	*Prevents localised warping and cracking of the part*

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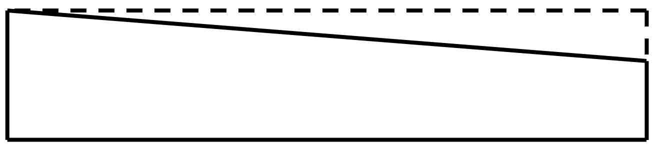
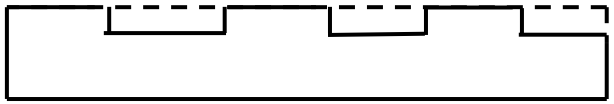
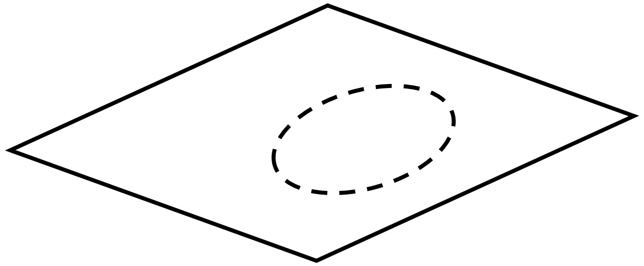
Buildplates: Tolerances



Out of parallel but flat



Not flat – waviness (milling)



Not flat - local dishing (hand finishing, local grinding, or warping)

- Max tolerances on the order of layer thickness (± 10-20%)
- Plates should be identified to allow flaws and thickness to be easily logged and addressed

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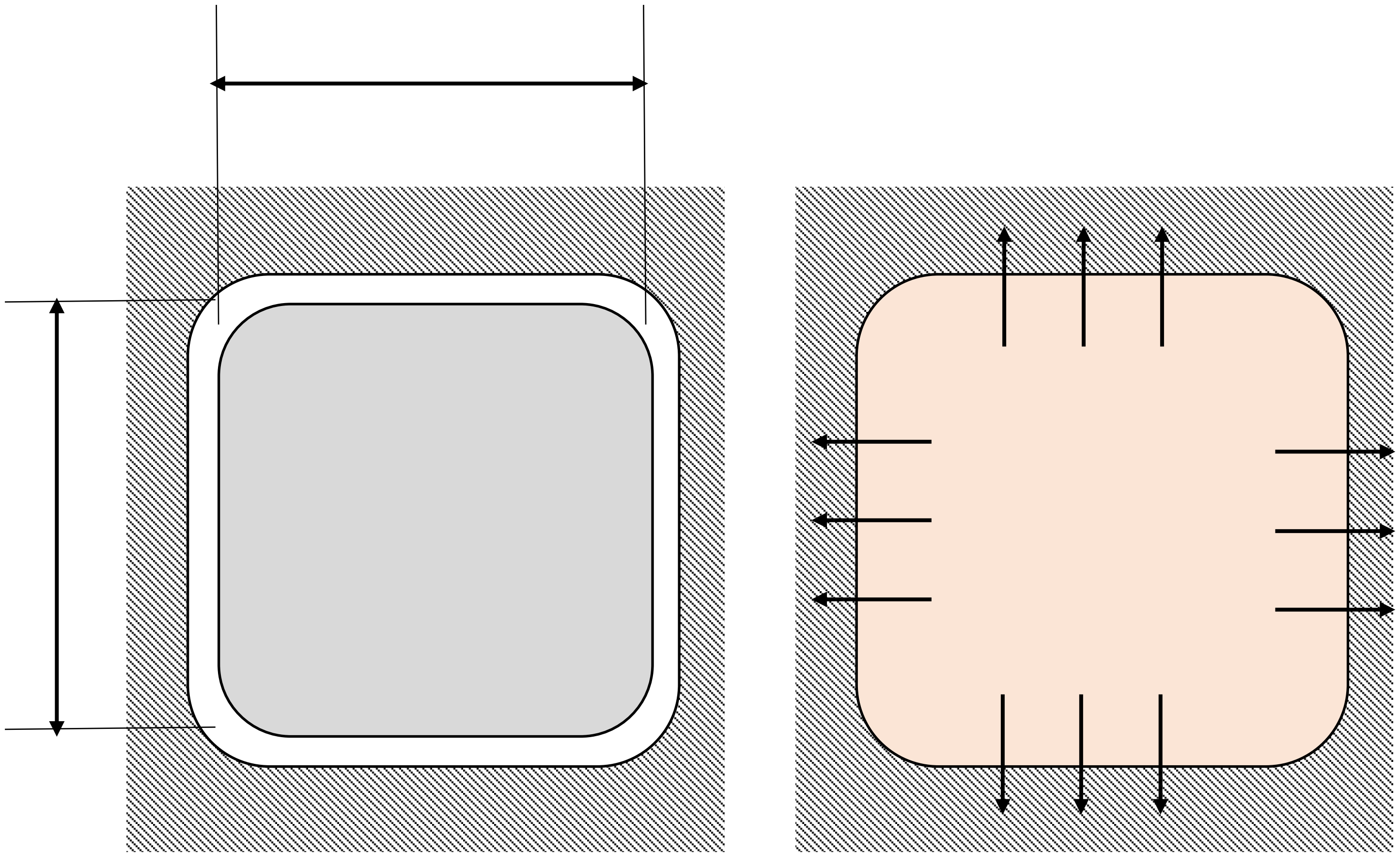
Buildplates: Tolerances



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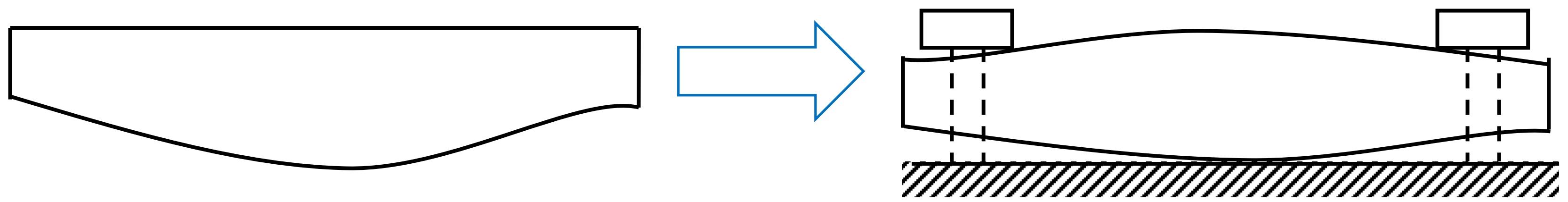
Buildplates: Tolerances



Flat surface becomes bowed under load

- Some distortion is only obvious under load – this becomes more obvious as plates become thinner.
- It is important to check plates in the machine prior to loading powder.

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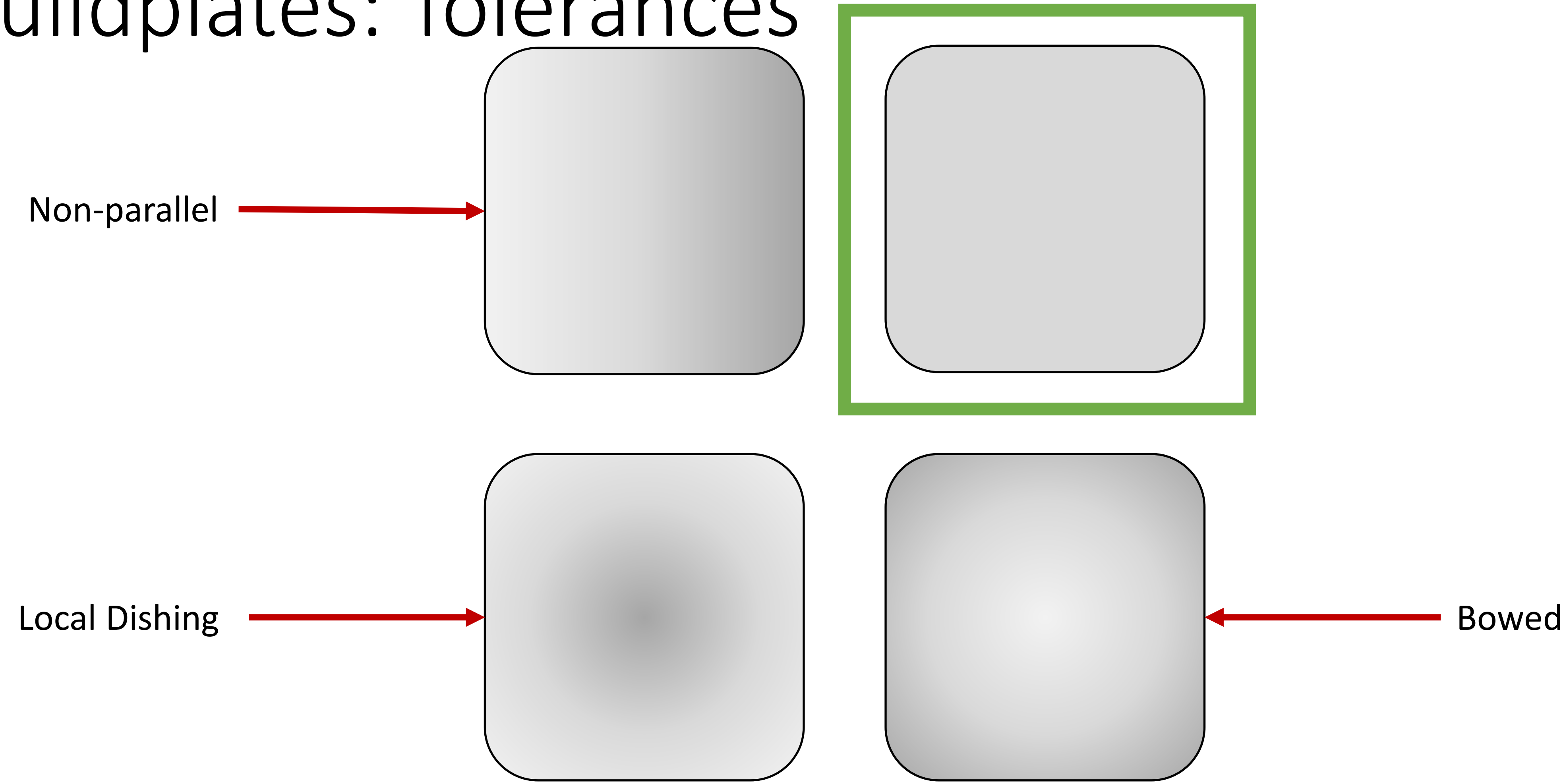
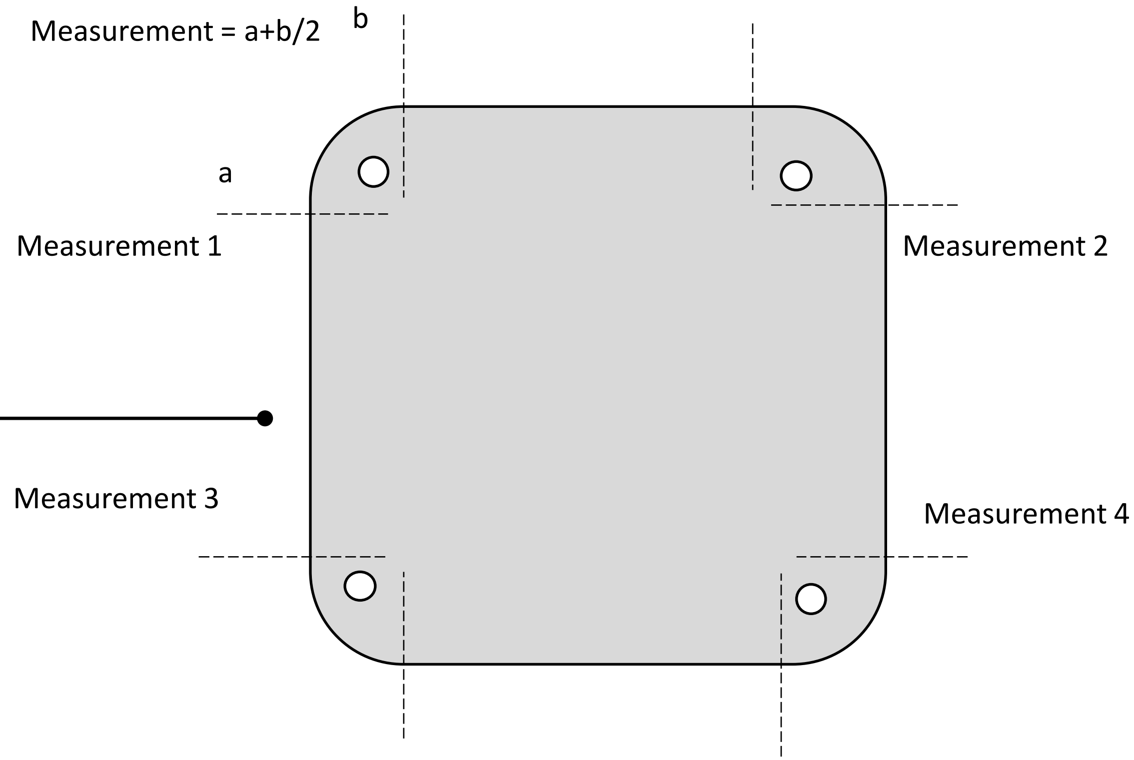
Buildplates: Tolerances



Watching Initial Powder Layers Is Critical

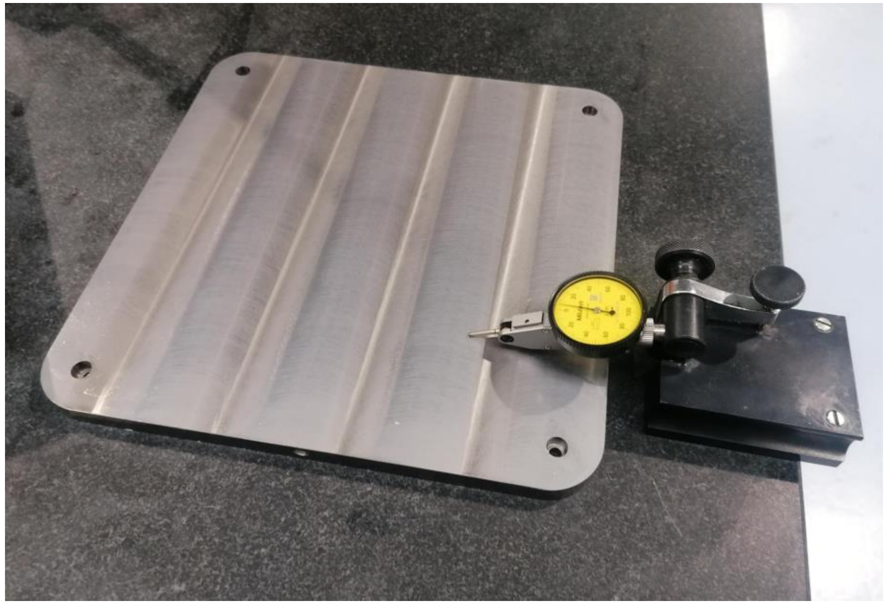
Co-funded by the Erasmus+ Programme of the European Union

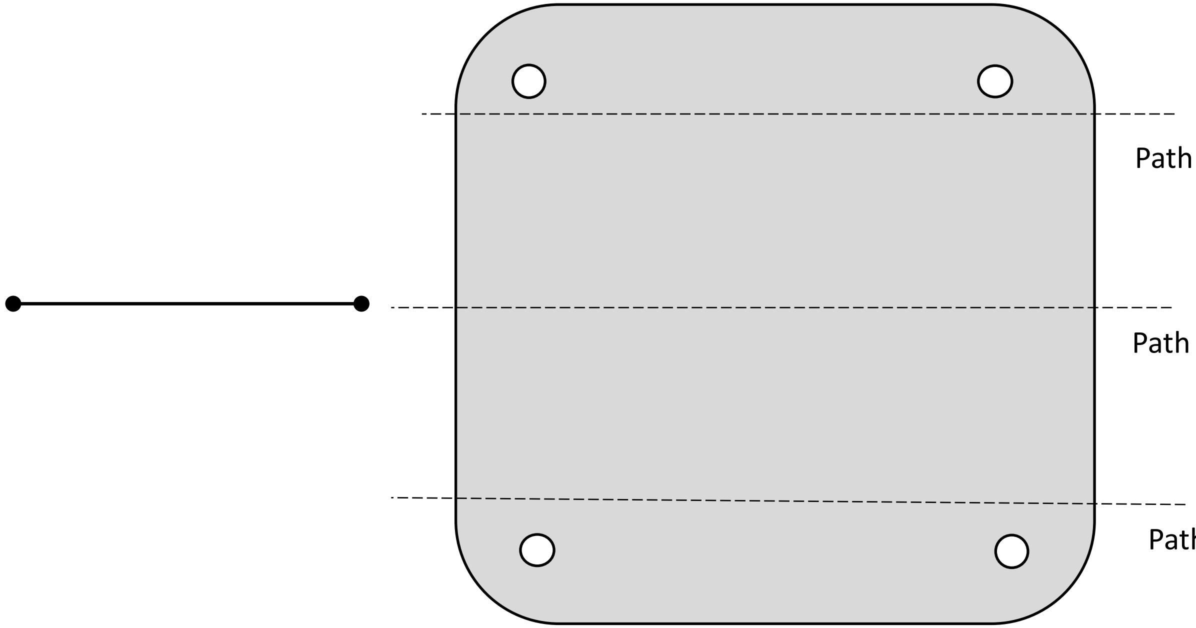
Build plate: Measurement



Measures Thickness Only

Build plate: Measurement





Measures Deflection & Thickness

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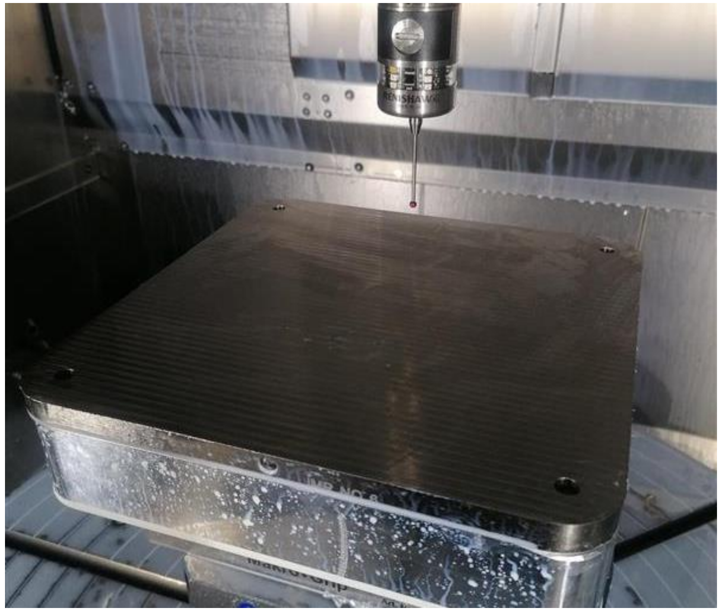
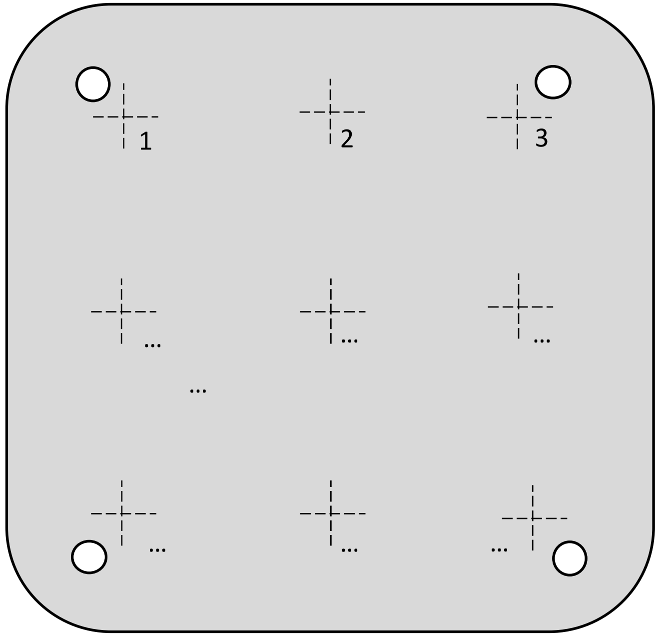
Build plate: Measurement





Measures Deflection & Thickness in Loaded State

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Build plates: Refinishing




	Hand Finishing	Cnc	Plane Grinding	Edm
Cost	Free	(E) 10k+	(E)50k-€80	(E) 50k-100k+
Tolerance		<100 Um	>20 Um	>5um
Material Removed	0um	50um-100um	<50um	~200um – 1mm
Comments	Feasible for smaller build plates but not in large volume	Can combine part removal and refinishing without re-fixturing	Less workhardening than milling	No additional work hardening. Challenged by loose powder in voids.

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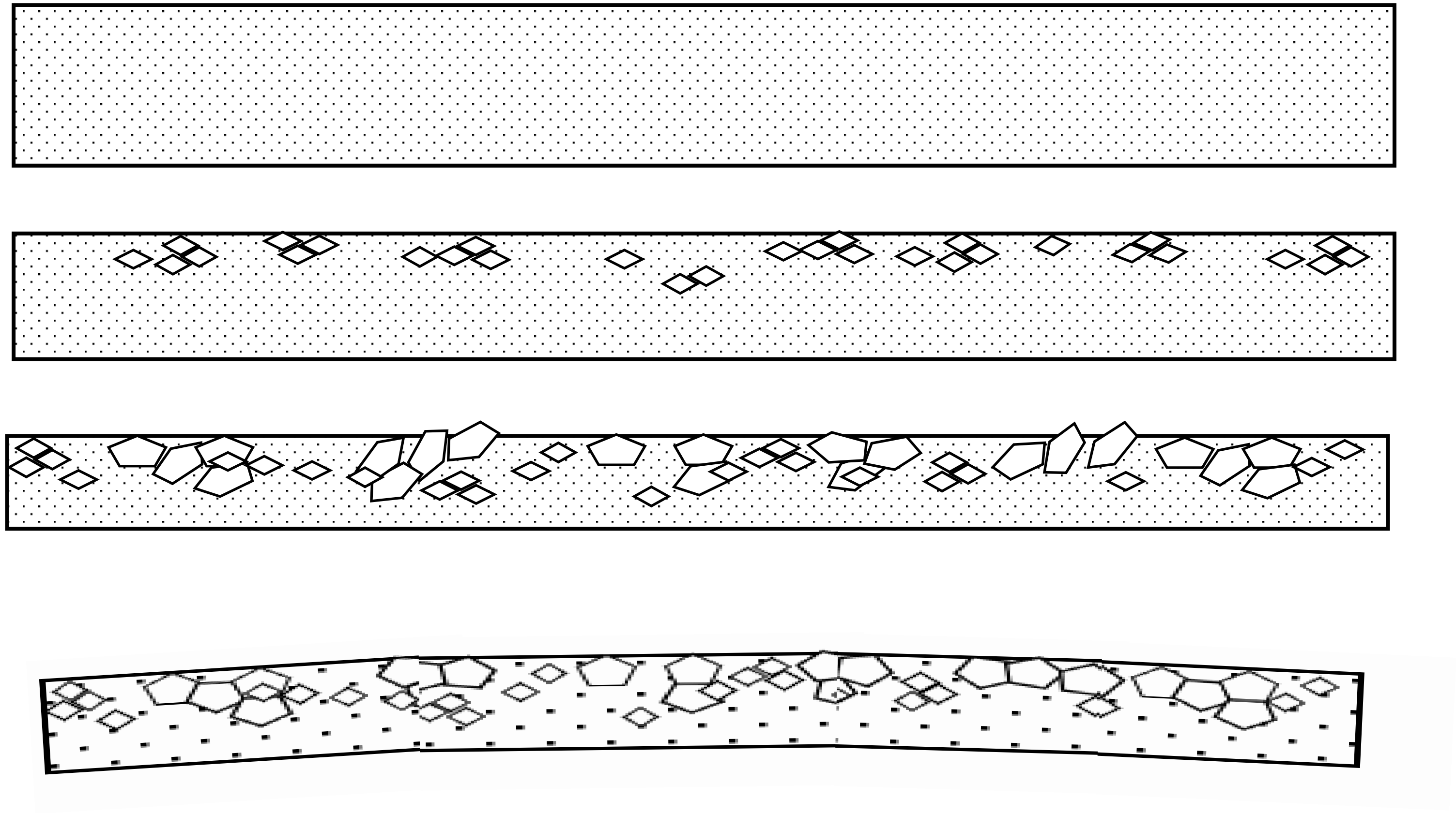
Buildplates: Causes of Deformation



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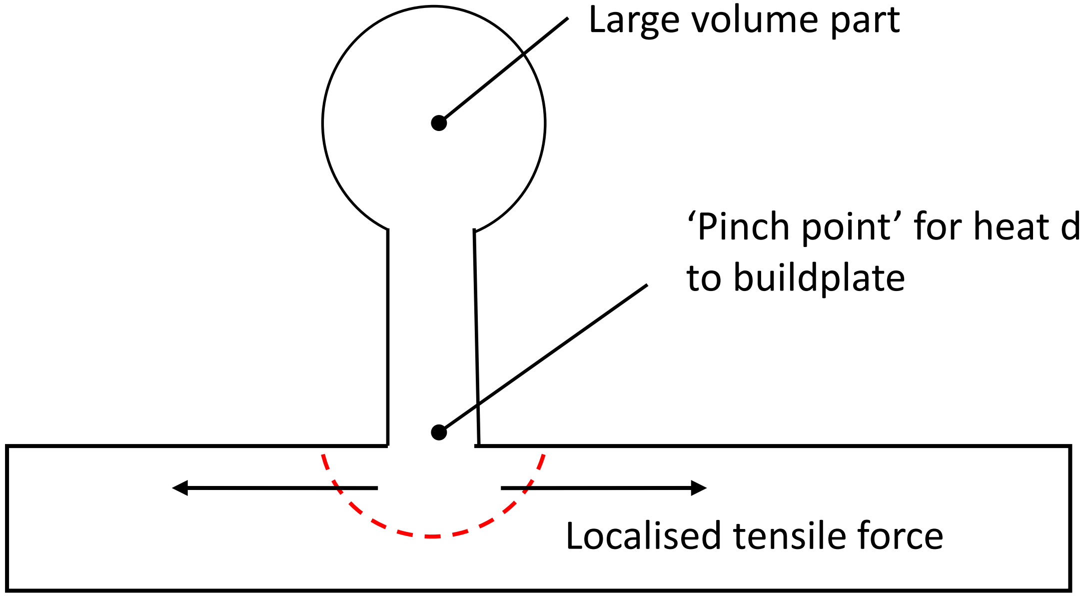
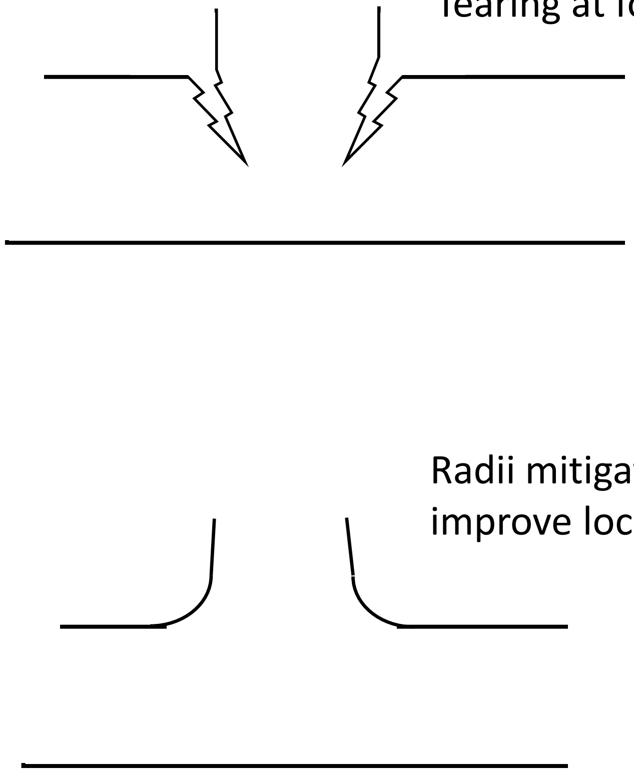
Buildplates: Causes of Deformation





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Process Gas - Intro

Process gas property	***Impact on part***
Shields meltpool from absorbing impurities in build chamber atmosphere	*Improves the chemical composition of the part*
Improves laser exposure and carries away the plume	*Reduces porosity*
Cools meltpool and the meltpool track	*Affects crystal structure*
Prevents ignition	

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Gas-Material Selection

Titanium Alloys (r)	Ar/He
Aluminium Alloys (r)	Ar/He
Cobalt Chrome	Ar/He
Copper Alloys	Ar/He, N
Nickel alloys	Ar/He, N
Inconel	Ar/He, N
Stainless steel	Ar/He, N
Maraging steel	Ar/He, N

	Ar	**N_2**	**He**	
Density, ρ	1.75	1.2	0.176	$\frac{kg}{m^3}$
Specific heat c_p,	0.52	1	5.19	$\frac{kJ}{kg \cdot K}$
Conductivity, λ	$17.9E^{-3}$	$26\ E^{-3}$	$156.7E^{-3}$	$\frac{W}{m \cdot K}$
Viscosity μ	$3.11E^{-5}$	$2.86E^{-5}$	$3.12E^{-5}$	$Pa \cdot s$
Cost	++	+	+++	€

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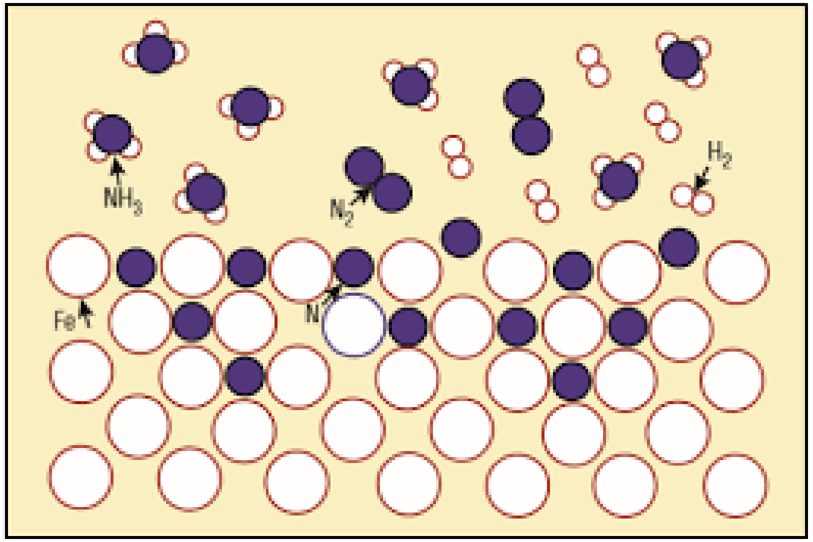
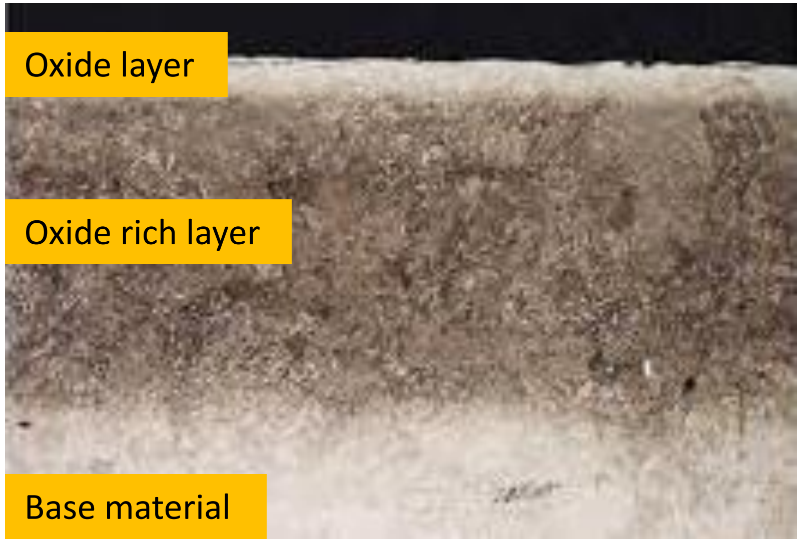
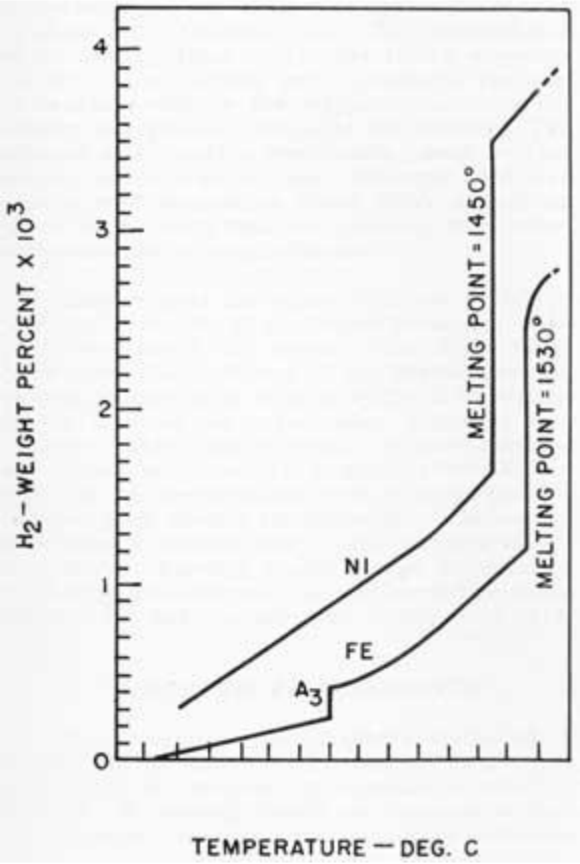
Process Gas – Absorption and Impurities







https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.industrialheating.com%2Farticles%2F95516-an-overview-of-nitriding-technology-and-tribological-benefits&psig=AOvVaw010S1IsgrZKolyiJdKUkbh&ust=1607640615920000&source=images&cd=vfe&ved=0CA0QjhxqFwoTCJCmr5L-we0CFQAAAAAdAAAAABAJ

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Process Gas – Absorption and Impurities

Material0.05	O (%)	N (%)	H (%)	Std
Ti-6Al-4V ELI	0.13	0.05	0.012	ASTM F3302
Ti-6Al-4V	0.2	0.05	0.015	ASTM F3302
CP Ti	0.35	0.05	0.015	ASTM F3302
CoCrMo	Not spec.	0.25	Not spec.	ASTM F75

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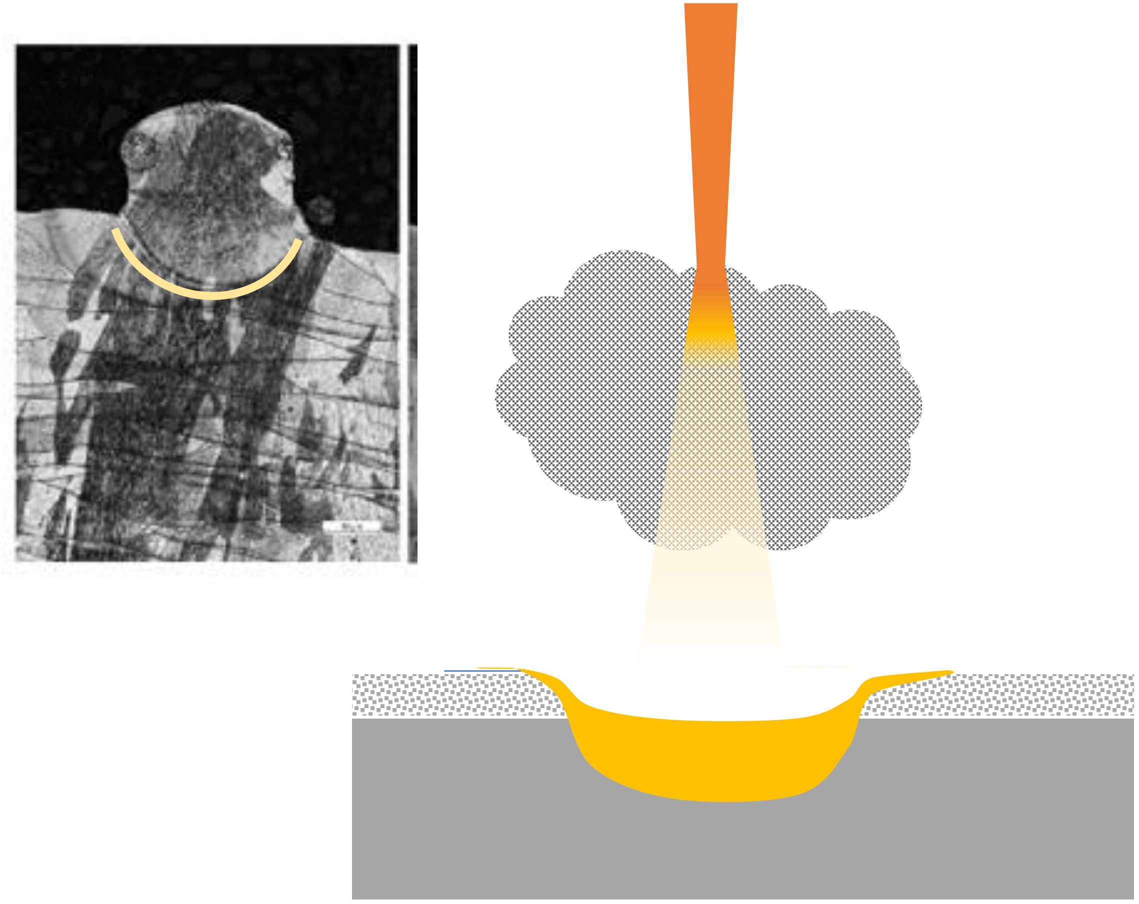
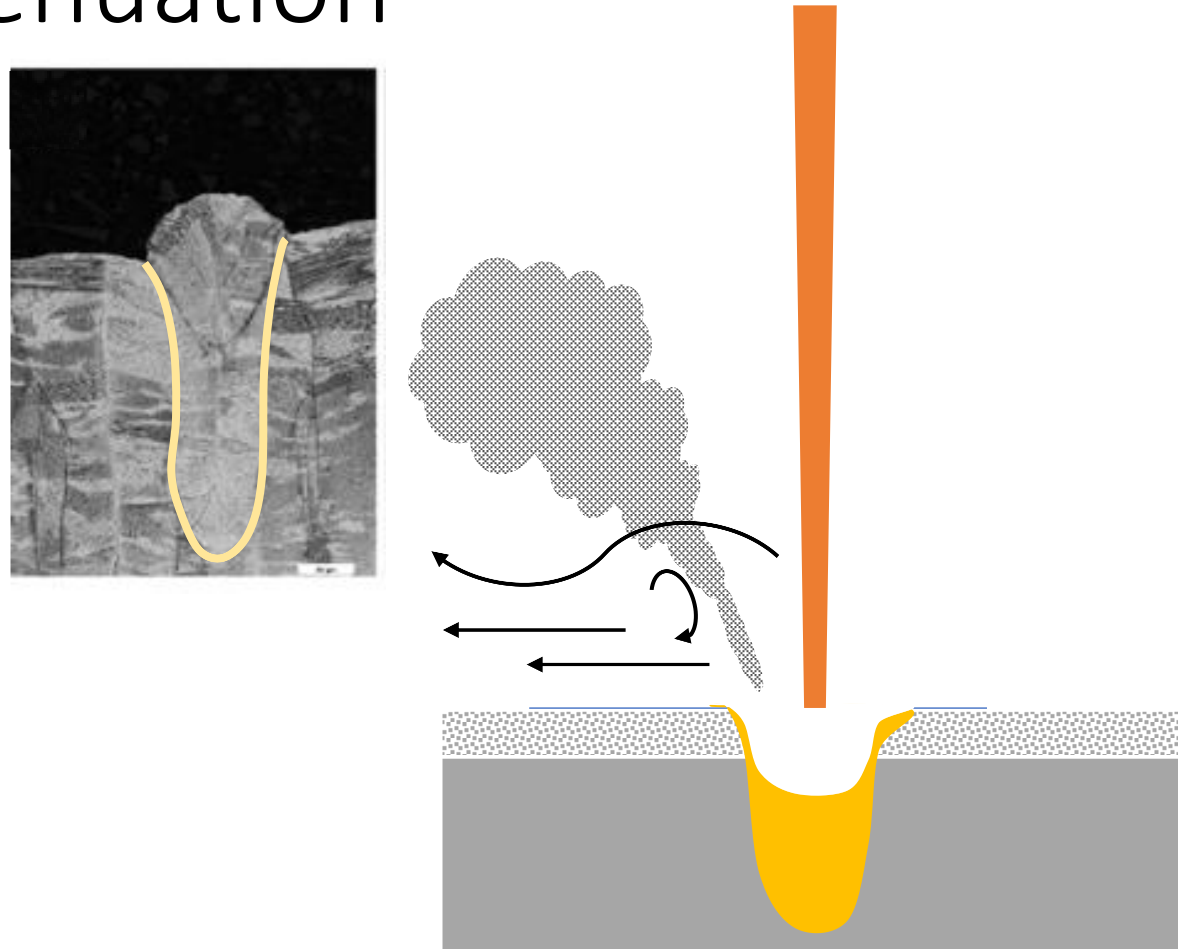
Process Gas: Plume Attenuation





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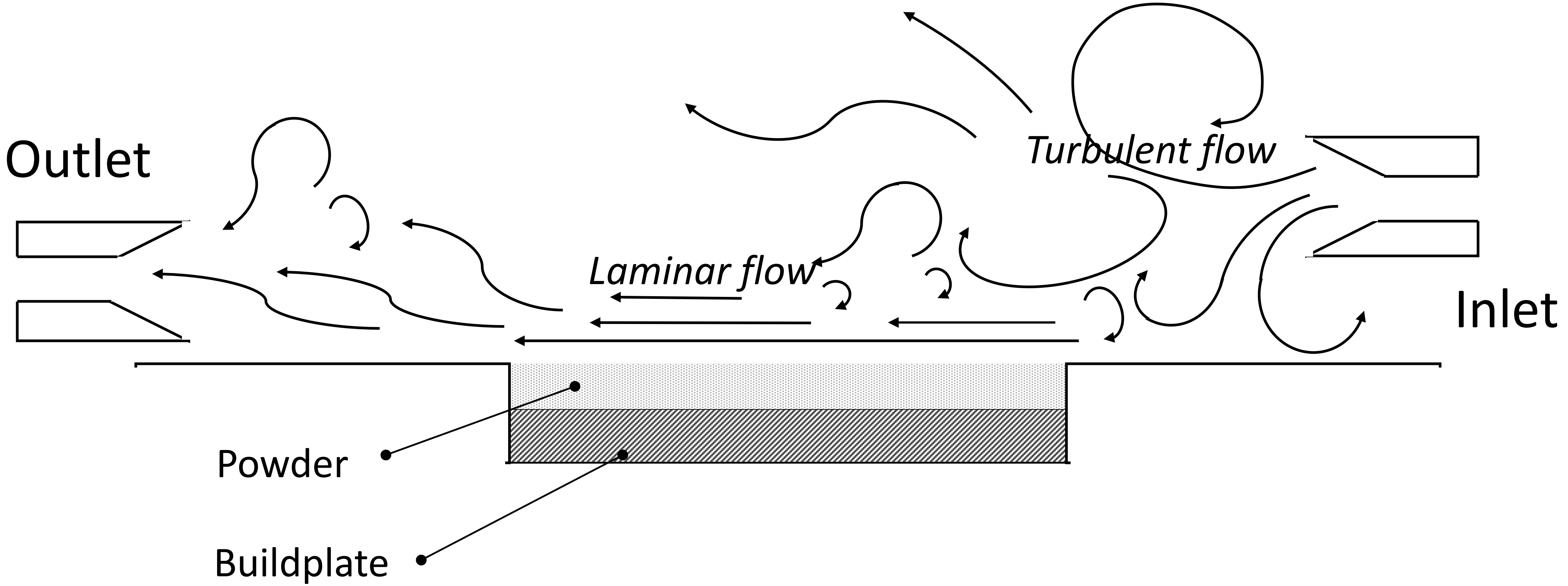
Process Gas – Flow Regimes



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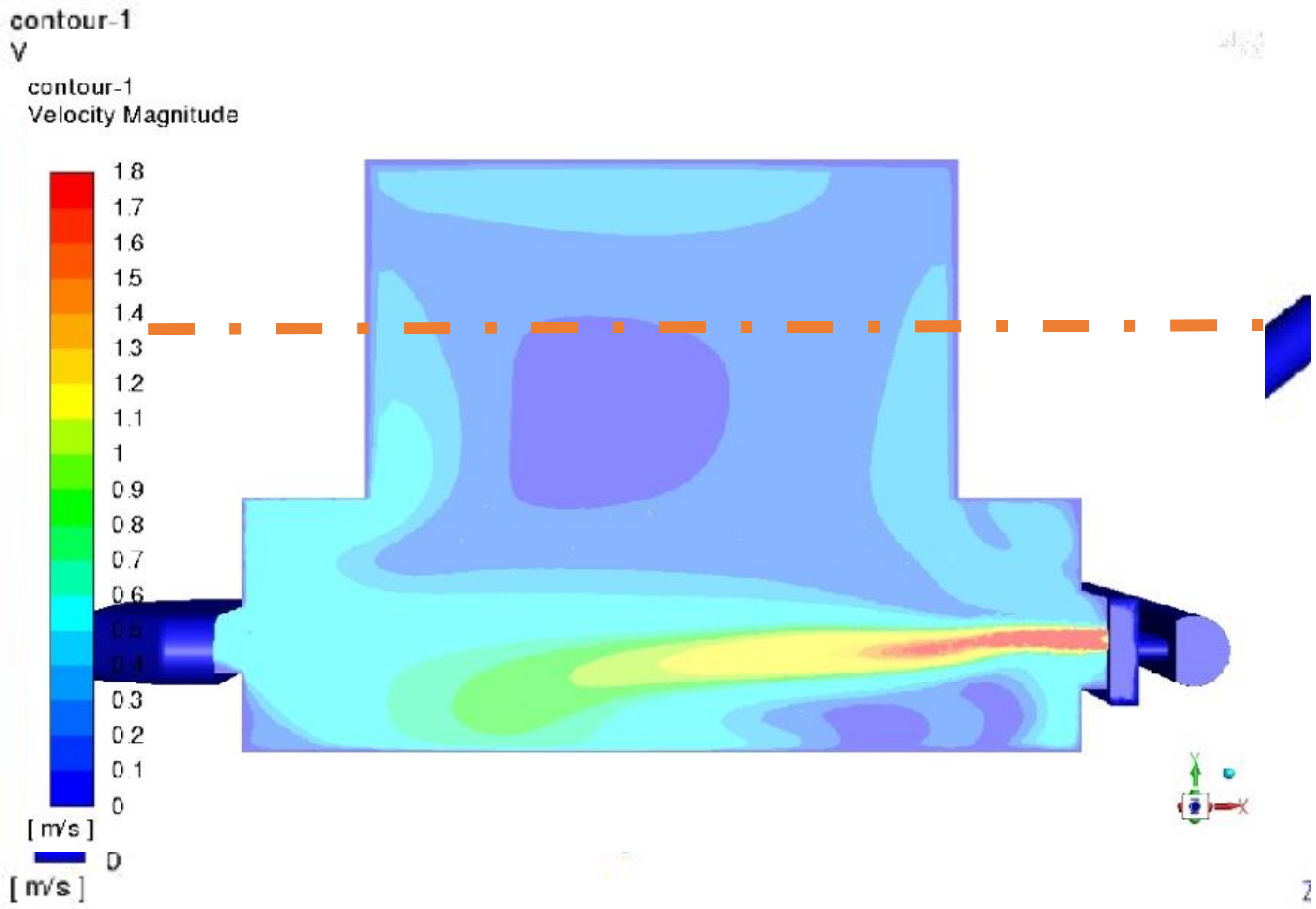
Process Gas – Flow Regimes



Chen, Y., Vastola, G., & Zhang, Y. (2018). OPTIMIZATION OF INERT GAS FLOW INSIDE LASER POWDER BED FUSION CHAMBER WITH COMPUTATIONAL FLUID DYNAMICS.

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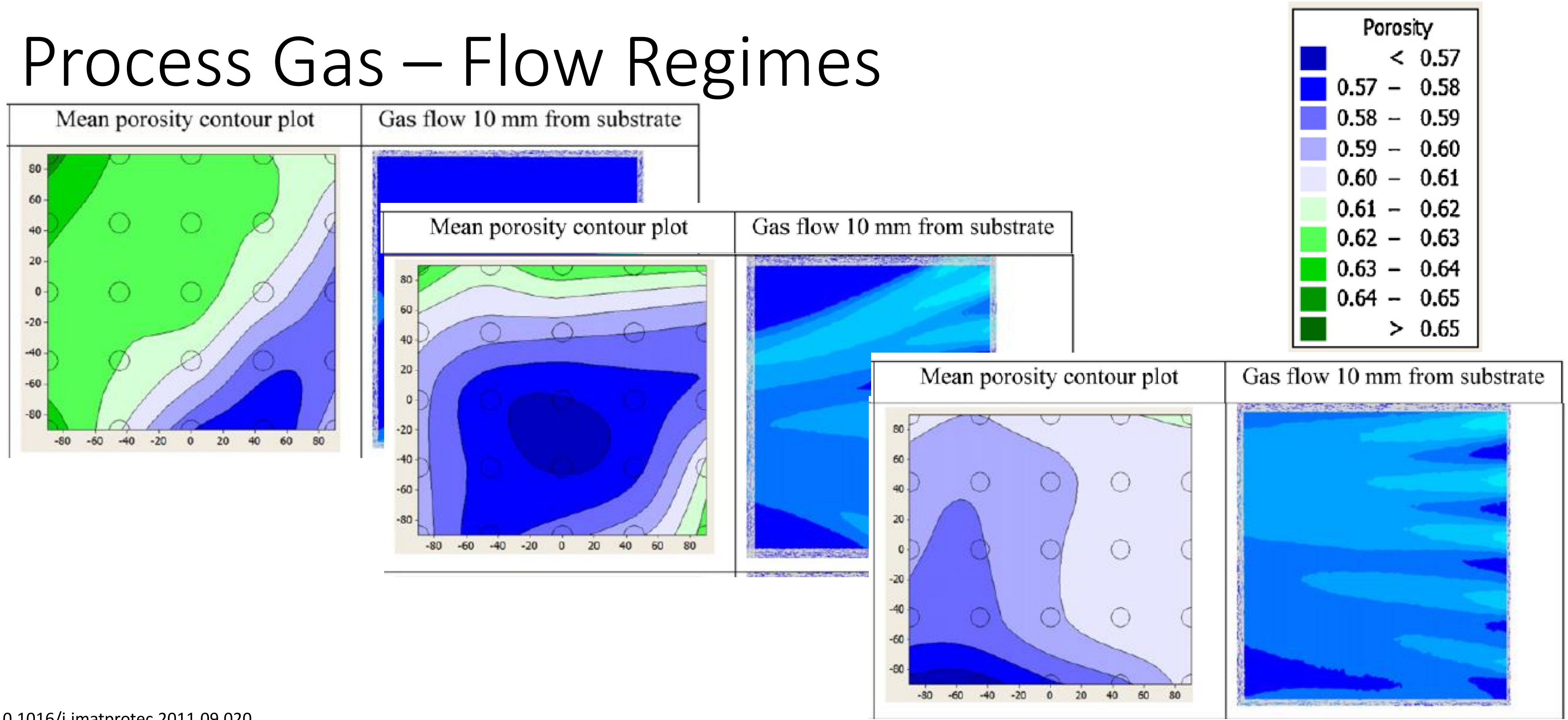
Process Gas – Flow Regimes



doi:10.1016/j.jmatprotec.2011.09.020

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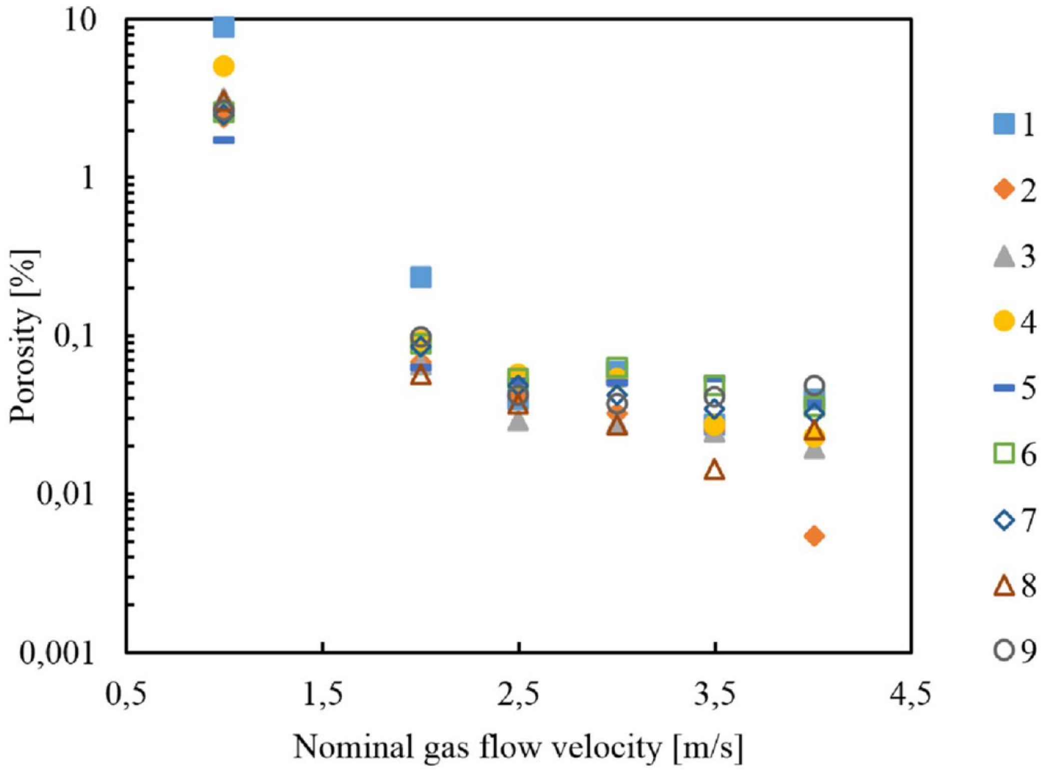
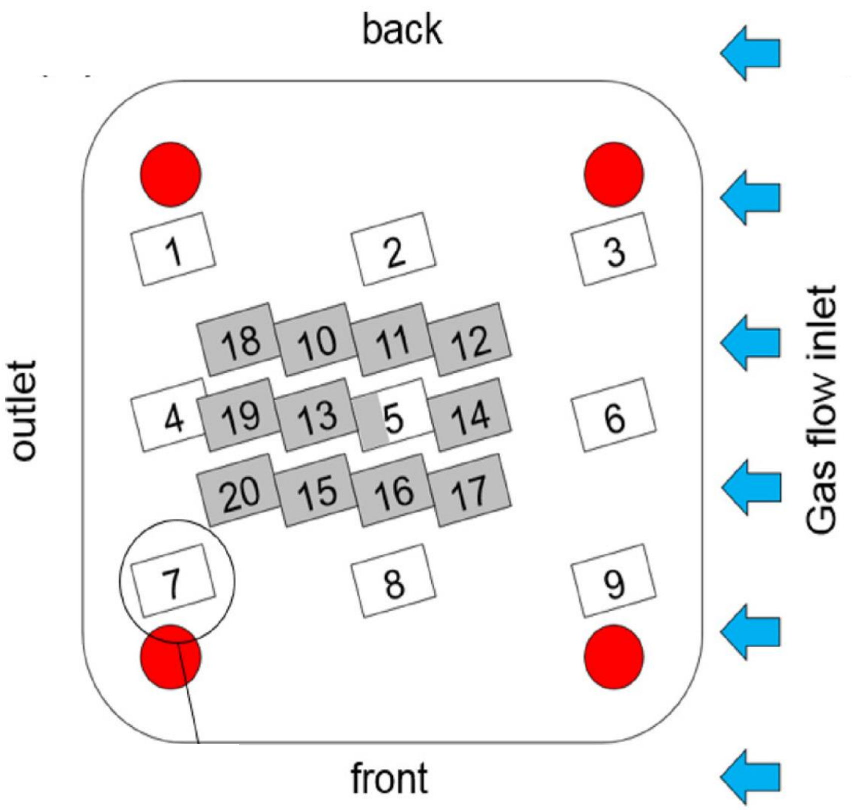
Process Gas – Flow Regimes



https://doi.org/10.1016/j.addma.2019.101030
Reijonen et al 2020



https://doi.org/10.1016/j.addma.2019.101030

Reijonen et al 2020

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Recap of Key Points

Buildplates

- Thickness and flatness tolerances are on the order 20-80um
- Good finishing and measurement methods are critical
- As buildplates get thinner from refinishing they will warp due to internal stresses

Process Gas

- Different gases will have a varying effect on part properties
- Only noble gases can be used with reactive metals.
- Slight changes in flow pressures can have a strong effect on part quality
- A good understanding of the impact of flow on part properties cross the build plate is critical.

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Thank you

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

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Post Processing

CU15-7: Post Processing

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Content

- Powder removal
- Stress relief operations
- Part removal
- Heat treatment
- Surface finishing

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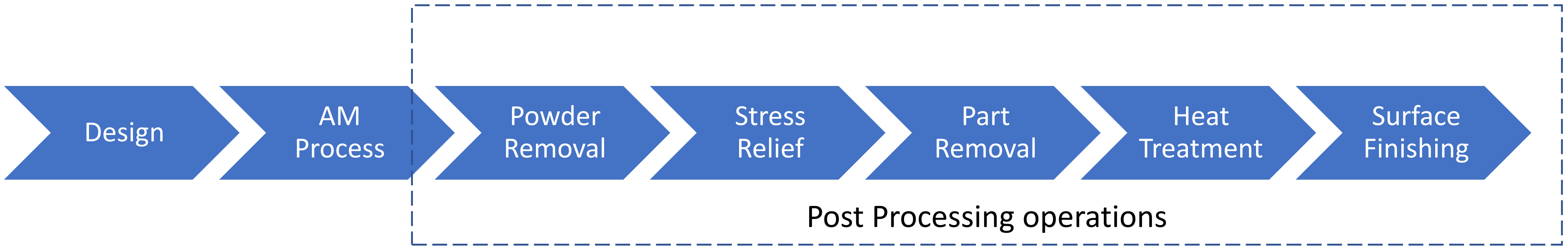
Introduction

- Post processing accounts for a significant part of the cost of an AM component
- It is required to achieve the right properties for determined application:
  - Surface roughness, geometrical accuracy and mechanical properties obtained in as-built components can be improved through post processing
- Post process operations range from heat treatment, separation of components from the build plate, removal of residual powder and surface finishing



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Powder Removal

- The **removal of powder** from the components is an important step that follows the completion of the AM process. Some residual powder particles can be trapped within the component or attached to the outer surface.

- **Why do residual powder have to be removed**?
  - Powder particles can clog small holes or channels and any other openings in the component.
  - The semi-sintered particles in the surface can detach from the surface and be released.
  - The efficiency of subsequent surface finishing methods depends on the preparation of the components surface.
  - For applications such as aerospace or medical components standardized protocols regarding the cleanliness might apply as part of the certification process.
  - Health and safety considerations: it is important to ensure minimum operator contact with the fine powder particles.

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Powder Removal

Challenges in powder removal in AM:

- Efficiency
- Repeatability and cost associated
- Powder waste
- H&S and Explosion risk

Source: https://www.metal-am.com/cerns-engineering-department-am-workshop-deploys-solukon-depowdering-unit/

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Powder Removal

Ultrasonic method

- Principles:
  - Transducers in the tank transmit high and low-pressure waves into the liquid.
  - Its compound structure tears apart and create microscopic vacuum bubbles near the surface of the component being cleaned.
  - When these implode, a pressure jet is directed towards the components surface - cavitation.
  - The particles are removed from the immersed components surface, even from small features and holes.
- The residual powder is submerged in water – avoiding creation of dust.

Source: https://www.turbex.co.uk/product/pro-line-manual-systems/

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Powder Removal

Ultrasonic method

- This method typically utilizes a combination of temperature, detergent and frequency
- Various tanks can be used in combination in more complex cleaning cycles, with different parameters to optimize the procedure.
- Advantages: operator safety, efficient removal of powder with optimized and tailored cycles, repeatability due to automated solutions
- Disadvantages: powder recovery

Source: https://www.turbex.co.uk/product/pro-line-manual-systems/

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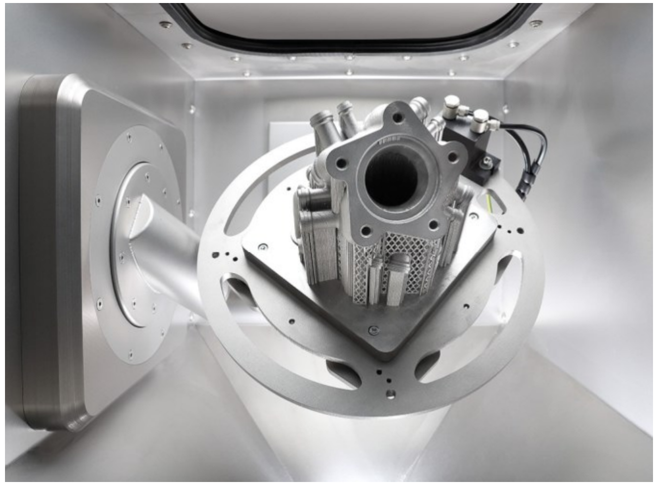
Powder Removal

Rotary & vibratory methods

- Combine vibration and rotation of the components in the build plate and rely on gravity to release the powder.
- The build plate with components is fixed to the machine which will rotate the plate around 2 axis, while vibrating
- Advantages: recovery of powder, contained environment
- Disadvantages: in very complex geometries it may be extremely challenging to remove powder through the effect of gravity



Source: https://www.solukon.de/en/metall/sfm-at200/

Solukon SFM-AT 1000-S. Source: https://www.solukon.de/en/metall/reinigungskabine-sfm-at1000-s/

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Powder Removal

Rotary & vibratory methods

- Solukon system SFM-AT800
  - Can accommodate a build plate containing parts to a volume of 800x400x550mm.
  - Automated and programable full 2-axis rotation device supports build plates weighting up to 300kg.
  - It is possible to input inert gas for processing of reactive metals.
- Inert – PowderShield system
  - 533mm diameter tilt table within an Argon atmosphere.
  - Through gas flow, tilting and vibration removes powder that can be collected for reuse.
  - It can integrate sieves, powder hoppers and other to create a closed loop workflow.

Source: https://www.youtube.com/watch?v=3Dx3eWTvmiA&t=100s

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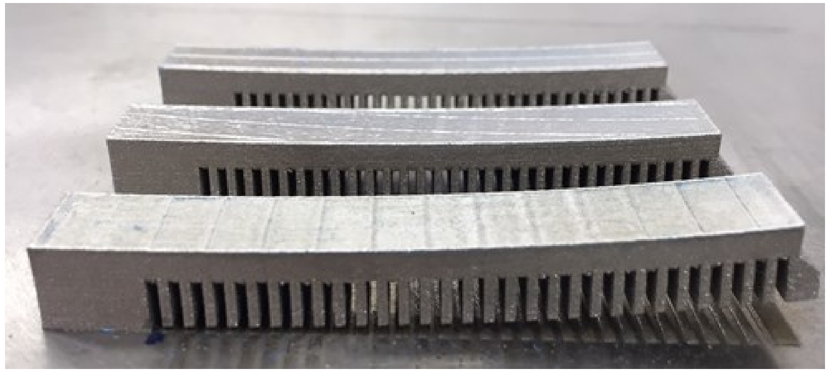
Stress relief options



Source: https://www.linkedin.com/pulse/want-build-accurate-am-parts-stress-marc-saunders/

- Goal:
  - Decrease residual stresses resulting from the fast cooling occurring during the process.
- Residual stresses:
  - Occur on large area sintered surfaces
- When to proceed to stress relief HT?
  - When parts are ON the build plate

  &
  - With characteristics such as:
    - Large parts
    - Parts printed flat on the build plate and present high thermal stresses.

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Part Removal

- Two main methods used are **EDM** and **bandsaw**
- AM components present new challenges for both methods
- Manual part removal can be performed in small batches
  - Pliers and other tools can be used

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Part Removal - **EDM**

Principles

- Metal-removal process by means of electric spark erosion
- Performed by applying a pulsating electrical charge through the electrode to the workpiece
- In wire EDM a small diameter wire is used to erode or cut through the workpiece

Challenges with AM components:

- Hollow spaces within components
- Loose powder residues

=> Wire breaks may occur

- Difficult flushing of swarf as more turbulence is originated when a hollow space within the component is found
- Additional conductive particles spark with each pulse, wearing the wire

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Part Removal - **EDM**

GF Machining Solutions - CUT AM 500 developed for AM applications. Source: https://www.gfms.com/com/en/machines/additive-manufacturing/cut-am-500.html

Novick - Novicut-M AM-3D developed for AM applications. Source: https://www.novick.eu/pt/novicut-3d-am-corte-aditivo/novicut-m-am3d-maquina-de-remocao-de-suporte-para-fabricacao-de-aditivos

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Part Removal - Bandsaw

Principles

- Workpieces are fed into the cutting edge
- The machine cuts the material by drawing a continuous metal band through the workpiece
- A constant flow of lubricant is needed to keep the blade cool, which prolongs tool life
- Different blades and speeds are used depending on the material being processed

Challenges with AM components:

- Clamping of build plates
- Support structures and trapped powder
- Damage to fine structures such as lattices or thin walls

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Part Removal - Bandsaw

Klaeger 3D Cut - VBS800-3D Cut bandsaw.
Source: https://www.3dcut.eu/en/

Solutions for AM components:

- Clamping devices developed to support build plate
- Enclosed systems
- Suction units for minimum dust generation
- Programable to suit components and build plate geometries

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Part Removal - Bandsaw

KASTOwin amc bandsaw. Source: https://www.youtube.com/watch?v=58QKOUfjCe8&t=1s

Heat Treatment

- Used to alter the physical, and sometimes chemical, properties of a material.
- Several types of HT:
  - Annealing
  - Normalizing
  - Aging
  - Quenching
  - Tempering
  - Etc

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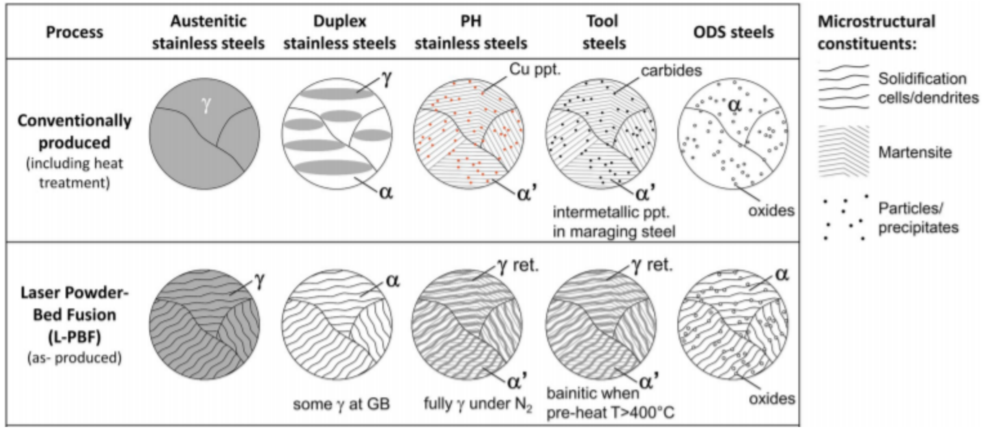
Heat treatments

- LB-PBF produces microstructure similar to quench



Source: http://www.dierk-raabe.com/app/download/5814916685/MSE+2019+Steels+in+additive+manufacturing.pdf

- Because starting with a completely different microstructure, usual heat treatment cycle used for wrought or cast parts will unlikely be best for LB-PBF parts

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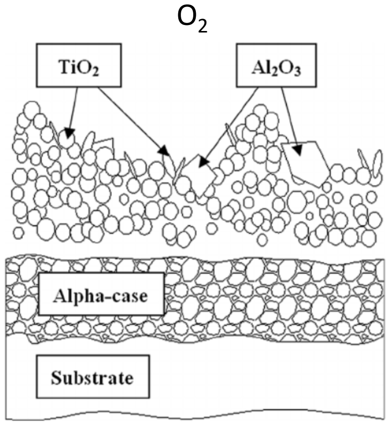
Heat treatments

- Oxidation at the surface can create hard and brittle layer initiating crack and affecting mechanical properties.



Source: https://link.springer.com/article/10.1007/s11085-017-9770-0

- To prevent any interaction with oxygen some solution exists:
  - Inert gas heat treatment
  - Vacuum heat treatment

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Inert atmosphere heat treatment

- Principles of operation
  - HT carried out under inert gas

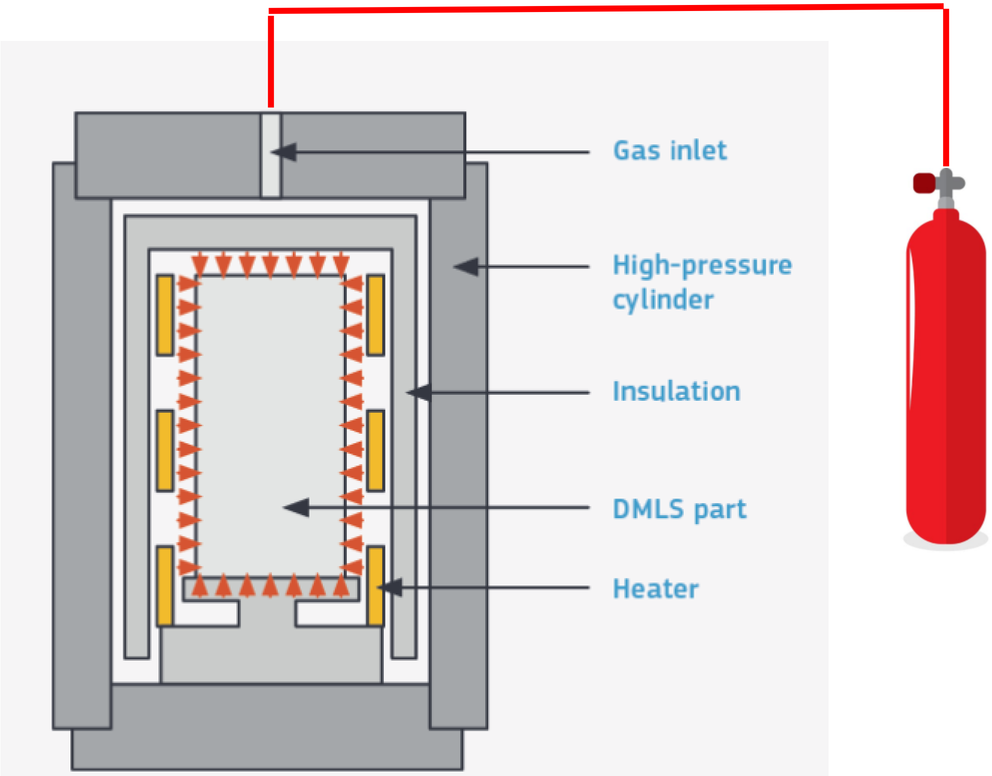

Image courtesy: Protolab

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Vacuum Heat treatment

- Principles of operation:
  - HT carried out under vacuum and cooled using inert gas

Image courtesy: ecm-furnaces

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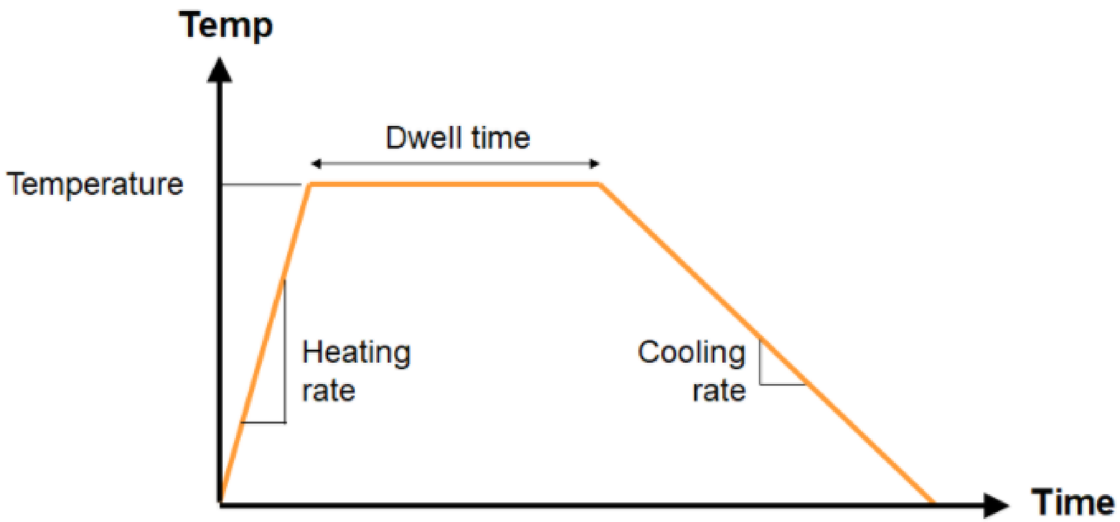
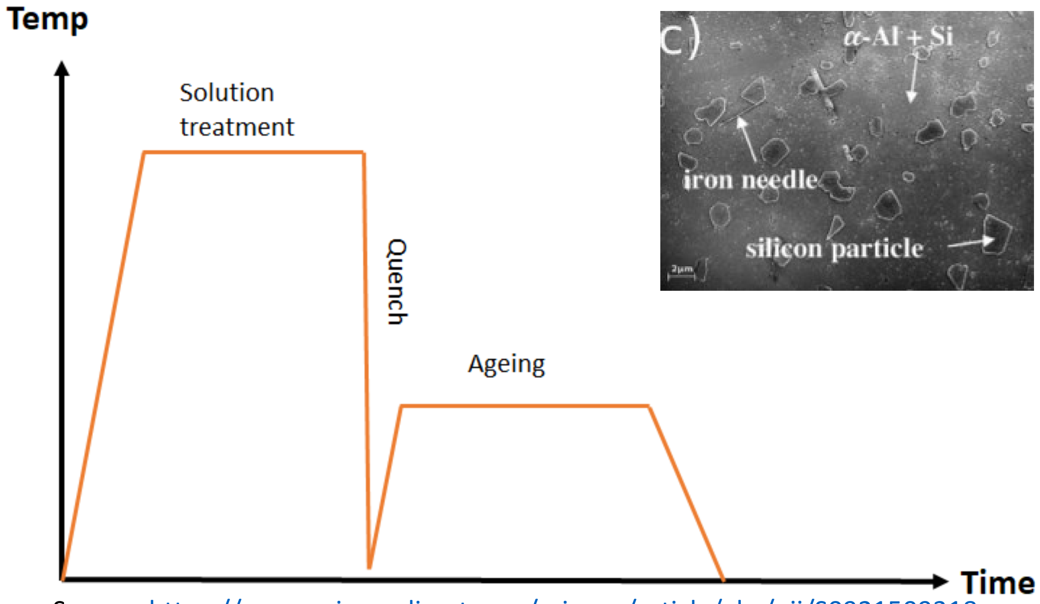
Annealing and Ageing

- Annealing
  - Increase ductility and reduce hardness



Source: https://www.linkedin.com/pulse/heat-surpass-wrought-performance-marc-saunders/

- Ageing
  - Increase yield strength



Source: https://www.sciencedirect.com/science/article/abs/pii/S0921509318316964

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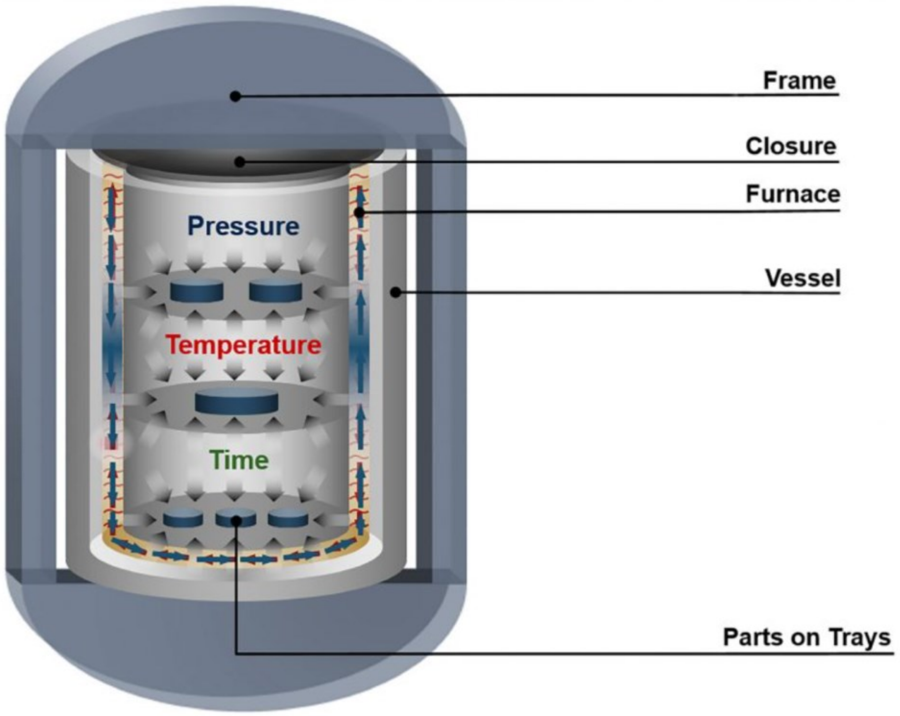
Hot Isostatic Pressing

- **High temperature** and **high isostatic pressure** act on the components leading to densification
- Argon is mostly used as the pressure medium
- **Mechanisms for densification** are plastic deformation, creep and diffusion:
  - Plastic deformation is the dominant mechanism initially – the voids in the material collapse due to the high pressure (superior to the yield strength)
  - Creep and diffusion contribute subsequently, collapsing and closing the pores to create a defect-free material
- Requirements: gas tight surface
  - Usually not a problem in AM components – the PBF-LB process usually produces high density parts



Source: https://www.metal-am.com/articles/hot-isostatic-pressing-improving-quality-and-performance-in-3d-printing/

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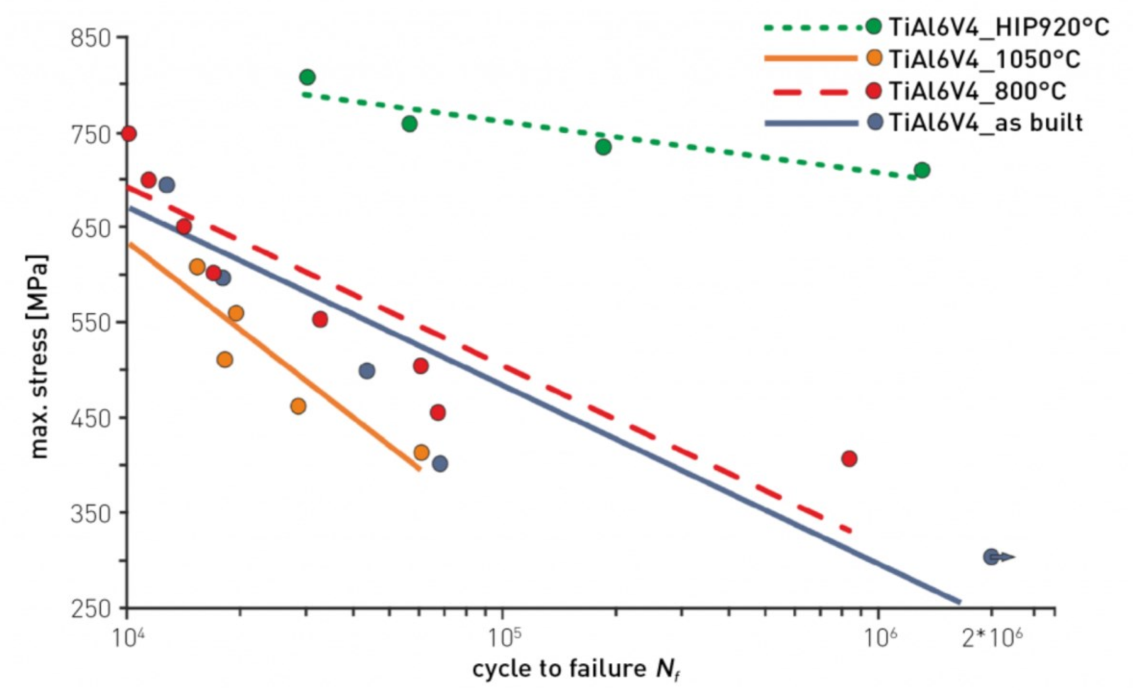
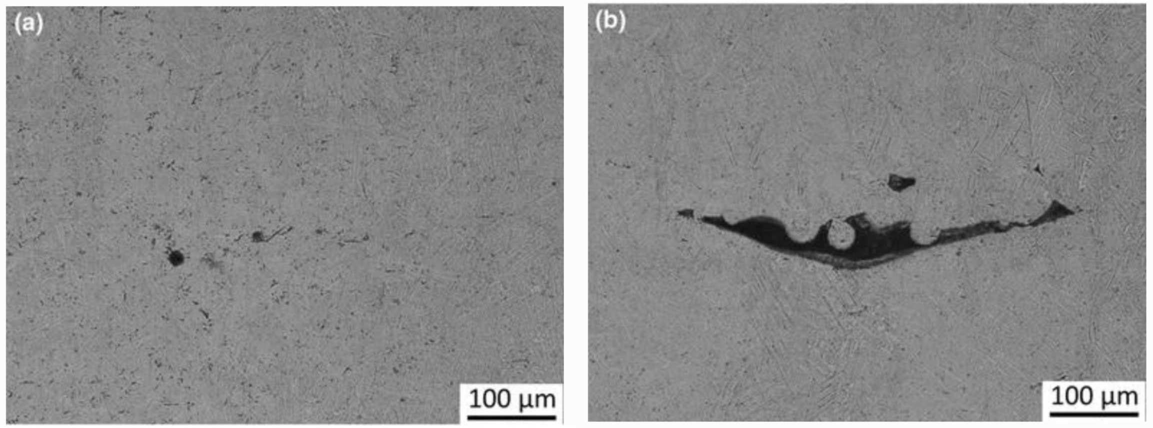
Hot Isostatic Pressing



- In AM, defects in the material such as **pores** and **internal cracks** are common
  - These defects influence the mechanical properties such as fatigue life and ductility

- Particularly important for components for aerospace and medical industries:
  - Applications where **fatigue behaviour is critical**



Allison M. Beese, Beth E. Carroll, (2015), "Review of Mechanical Properties of Ti-6Al-4V Made by Laser Based Additive Manufacturing Using Powder Feedstock", *The Minerals, Metals & Materials Society,* Published Online

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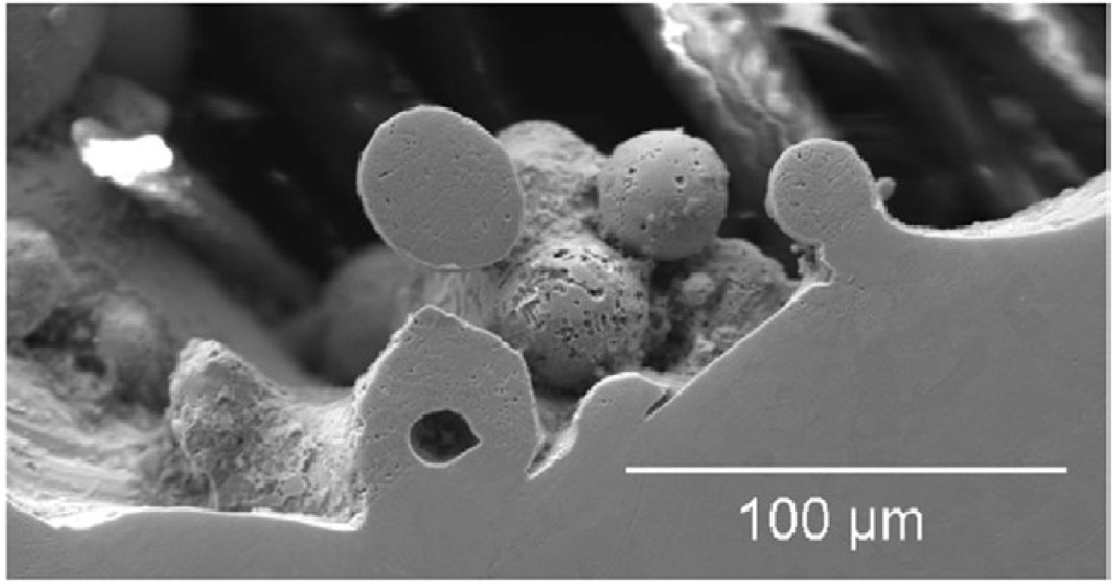
Surface Finishing

- As a result of the PBF-LB process, the components surface is characterized with a directional and chaotic texture:
  - The directional texture is caused by the "stair step" effect due to the layer deposition.
  - The chaotic texture derives from the partially melted powder particles in the components surface.

  Although the first case can be minimized by reducing the layer thickness, the threshold for the layer thickness is limited by the powder size and technical barriers.
- As-built PBF-LB components present R_a between 10 – 20 µm



R. E. Winter *et al*. (2014), "Plate-impact loading of cellular structures formed by selective laser melting", *Modelling and Simulation in Materials Science and Engineering, 22.*

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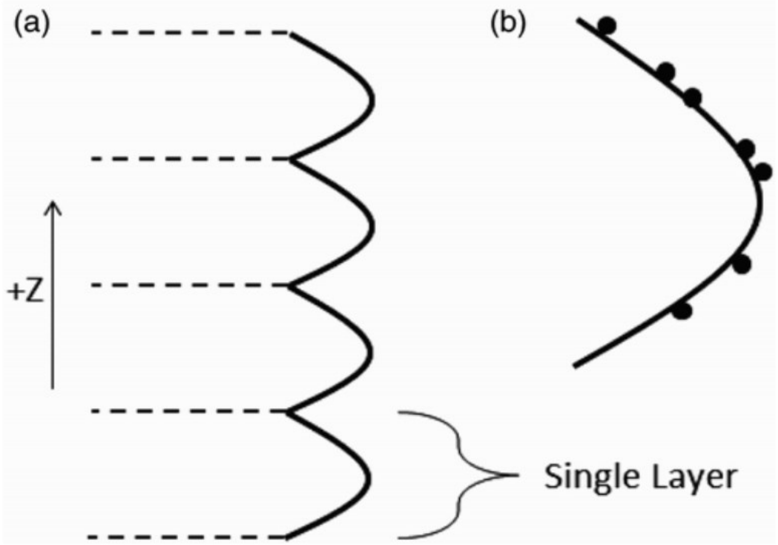
Surface Finishing

- There are several factors contributing for the surface roughness in AM parts:
  - **Layering process** - creates the "Stair Casing" effect. On a macro level the addition of layers originates a directional texture in the surface of the component.
  - **Semi-sintered powder particles**. This creates a chaotic texture.
  - Differences in **up-skin** and **down-skin** surfaces.
  - Tessellation of the 3D model



W. J. Sames *et al*. (2016), "The metallurgy and processing science of metal additive manufacturing", *International Materials Reviews*, 315-360.

- The high surface roughness mainly contributes to:
  - Difficulty in **meeting tolerances**
  - **Poor mechanical properties**, especially fatigue life, since the valleys in the profile may act as stress concentrators for crack initiation, leading to fracture

Surface Finishing

- Common surface finishing methods:
  - Manual finishing
  - Abrasive Blasting
  - Shot peening
  - Mass finishing
    - Barrel finishing
    - Centrifugal Barrel Finishing
    - Vibratory finishing
  - Abrasive Flow machining
  - Electrochemical
  - Machining

- As the AM industry scales, the post processing methods must scale
  - Automated processed that deliver repeatable results to meet the requirements

- Traditional surface finishing methods are time consuming
  - These are typically manual operations - providing inconsistent results as a product of manual labor and are costly

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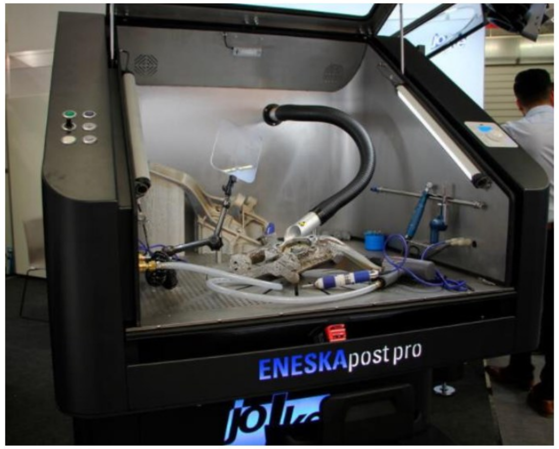
Manual finishing

- Suitable for low volume production and non-tolerance dependent components
- Components can be polished using abrasives or mops in a multistage process.
  - Initially coarse grit abrasives are applied to remove rough surface defects as pits, lines and scratches.
  - Subsequently, fine grit abrasives are used to remove the residues and smooth the surface.
  - Finally, cotton mops give a mirror-like finish.
- Much of this work is performed manually - inconsistent results, dependent on operator
- Developed for AM components - ENESKApostpro by *joke Technology:*
  - Enclosed workstation allows manual support removal and surface finish to be performed in a controlled environment
  - Equipped with electrical and pneumatic tools
  - suitable for reactive and non-reactive materials.
  - Several tools can be added for different purposes such as support removal and/or surface finish

Source: https://www.joke-technology.com/3d-shop/en/eneskapostpro



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Abrasive blasting

- Projection of abrasive media towards the component surface
  - Silica or glass beads are common abrasives
- Compressed air or water are the transport media for the abrasive
- Blasting with grit and ceramic media provides a matte finish.
  - This finish is relatively uniform but is subject to variability as it is usually performed manually.
  - Difficult to access geometries in more complex components may not achieve a finish as good as external surfaces

Source: https://www.guyson.co.uk/news/guyson-finishing-for-additive-manufacturing

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Shot Peening

- Cold working process that produces a compressive residual stress layer - modifying the mechanical properties of the component.
- Round metallic or ceramic particles impact the surface with sufficient force to create small indentations.
- Similar to abrasive blasting, but it operates by the mechanism of plasticity rather than abrasion.
- Can significantly improve the fatigue life of components, depending on the characteristics of the component and the parameters of the finishing process

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Mass Finishing

- Abrasive processes that allow to process large batches of components in bulk.
- Involves cyclical action to create contact between surfaces, removing material and decreasing the roughness.
- A free abrasive material (media) is utilized, and the components are processed within a chamber/container.
- Dry or wet setup.
- Media types
  - Natural or synthetic, abrasive or nonabrasive, random or preformed in shape
- Most processes do not require jigs and fixtures.

Challenges:

- Critical dimensional tolerance requirements in certain locations of components
- Internal channels or holes

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Barrel Finishing

- Principles
  - Barrel rotation creates movement of media and parts
  - Media and parts reach the turnover point
  - Gravity overcomes cohesive action of the mass, which slides to the lower area of the barrel
  - The abrading work is mostly performed in this slide zone
- Various barrel configurations and orientations
  - Most common is an octagonal chamber horizontally oriented

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Centrifugal Barrel Finishing

- Similar to barrel finishing in principles
  - Barrel container filled with media
  - Motion creates a sliding action of media and parts
- Main differences:
  - Higher pressures between media and parts – induced by rotational and centrifugal forces
  - Shorter processing times due to higher energy
- Allows reaching finer finishes and processing more complex components
  - Smaller media particles can be utilized
- Various barrel configurations and orientations
  - Most common is an octagonal chamber horizontally oriented

BelAir centrifugal finishing equipment. Source: https://www.youtube.com/watch?v=Dj0C-T1yYSw

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Vibratory finishing

- Vibratory finishing combines the action from abrasive media and water to process parts
- The vibratory motion of media and forward motion within the chamber may be adjusted
- Water levels are critical to the process
  - Insufficient water input may reduce media cutting efficiency
- Fast vibration promotes collision between the component and abrasive tumbling media.

BelAir vibratory finishing equipment. Source: https://www.youtube.com/watch?v=Dj0C-T1yYSw

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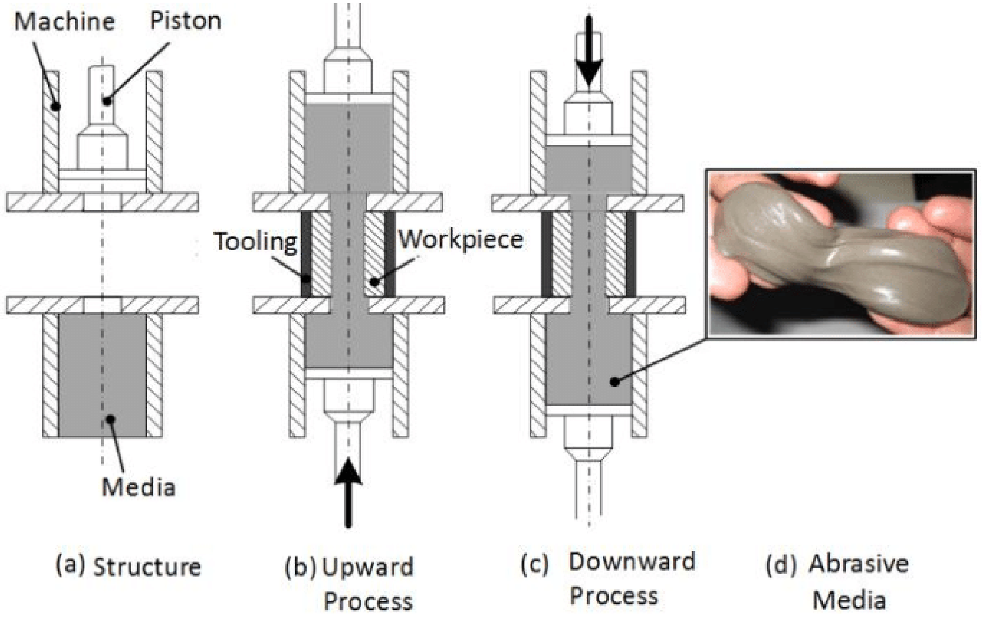
Abrasive Flow Machining

- This method permits smoothing and polishing of internal surfaces, producing controlled radii.
- An abrasive media flows through the component performing erosion. The abrasive particles contact with the peaks of the surface roughness, removing them.
- One-way or two-way flow of an abrasive media is extruded through a workpiece, finishing rough surfaces.
  - In one-way systems, the media flows through the component and then exits the part.
  - In two-way systems, two opposed cylinders flow the abrasive back and forth.



Can Peng *et al.*, (2018), "Study on Improvement of Surface Roughness and Induced Residual Stress for Additively Manufactured Metal Parts by Abrasive Flow Machining", 4th CIRP Conference on Surface Integrity, China 2018, Elsevier Ltd.

- This process is adequate for components with difficult to reach internal passages, bends and cavities.
- It can be utilized in internal passages as small as 50µm, in a variety of materials from aluminium to Inconel.

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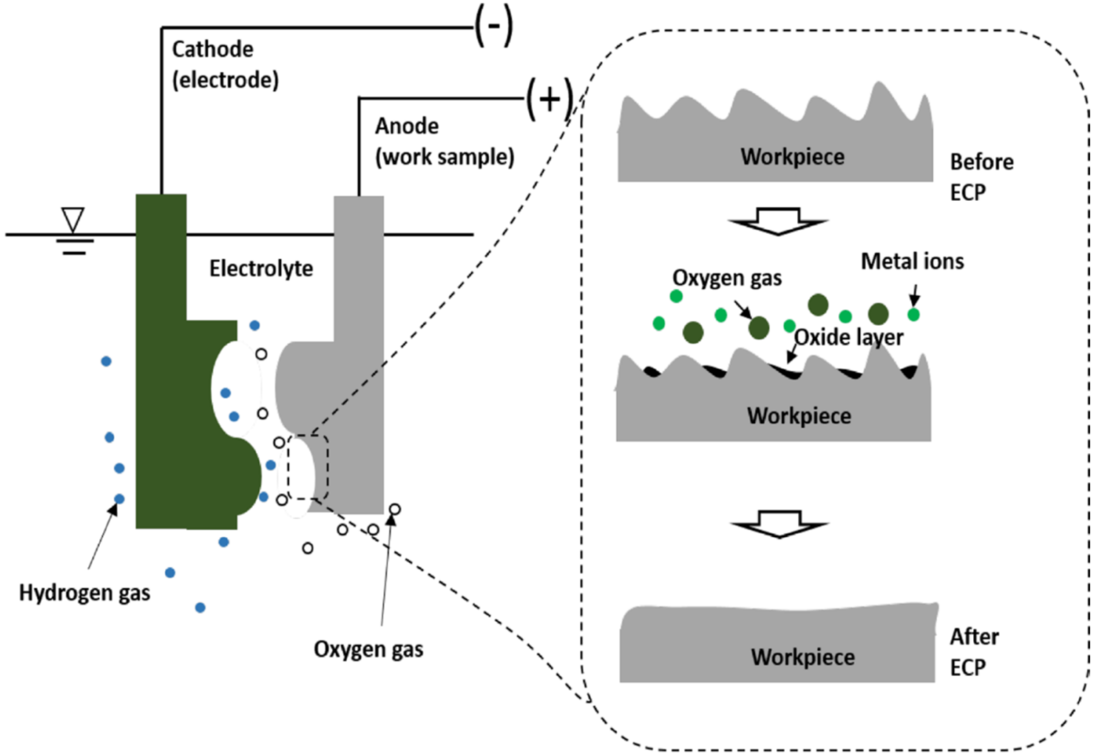
Electrochemical

- Electrochemical methods remove metal from the surface of the workpiece in a selective manner
- This is accomplished in an electrolytic cell by applying a positive potential to the workpiece (anode) that is placed in an electrolyte. The negative terminal attaches to the cathode
- Converts the metal into ions by means of an applied electric field – levelling peaks and valleys on the surface as the peaks dissolve faster.



Uk Su Kim, Jeong Woo Park. (2017), "High-Quality Surface Finishing of Industrial Three-Dimensional Metal Additive Manufacturing Using Electrochemical Polishing", *International Journal of Precision Engineering and Manufacturing-Green Technology.*

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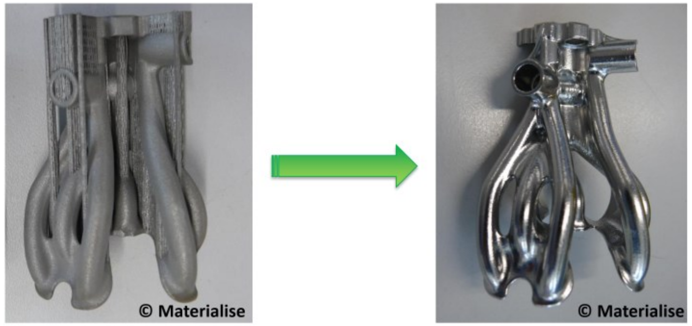
Electrochemical
Hirtisation

- The Hirtisation® process created by *hirtenberger* allows for support structure removal and surface enhancement simultaneously.
- The process combines **electrochemical pulse methods**, **hydrodynamic flow** and **particle assisted chemical removal** to perform the surface finish of AM parts.
- Developed specifically for metal AM parts, this technology consists of three steps:
  - Firstly, the support structures and the semi-sintered powder are removed and the surface roughness is reduced significantly.
  - The second step reduces the part's surface roughness to a level that suits most applications.
  - In the third step, which is optional, a high polishing is applied, resulting in a decorative, smooth finish



Source: https://www.rena.com/en/products/additive-manufacturing/finshing-modules/

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Machining

- Traditional machining applies to AM components
- Performed to smooth surfaces, add critical features and hit tolerances
- Challenges on AM components:
  - Part distortion from stresses
  - Ingress of coolant into porous structures
  - Work holding on organic structures
  - Having workable datums
- Part surface considerations:
  - Number of contours to ensure no porosity exists close to the surface/depth of ‘skin’
  - Excess material must be added from design phase

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

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Introduction

- Optical system
  - Laser
  - Lens
  - Scanning system
- Powder system
  - Mechanics of powder spreading
  - Blade levelling
  - Powder dosing system
- Atmosphere system
  - Vacuum system for chamber
  - Build chamber process gas concentrations
  - Filters (Powder delivery and recovery)
- Process monitoring
  - On axis and off axis systems
  - Data processing and storage
  - Vision systems
  - Spectrum monitoring
  - Optical Tomography

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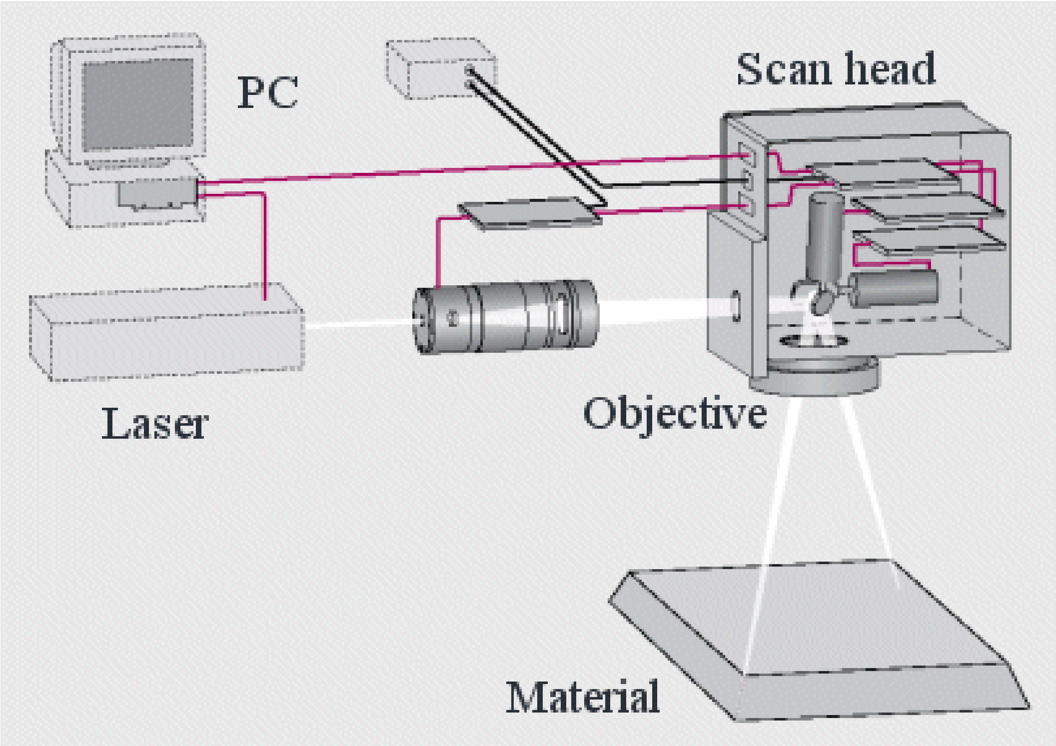

Scanlab https://www.scanlab.de/en/file/2005-09alacnewdevelopementsscanheadtechnologypdf

Type	Build-Volume	Power, Spot-Size
Concept M1	250 x 250 x 250 mm	200 or 400 W, 50 µm
Concept M2 Multilaser	250 x 250 x 280 mm	2 x 400, 50-500 µm
Concept X Line 2000R	800 x 400 x 500 mm	2 x 1kW, 100-500 µm
EOS M 080	Ø 80 x 95 mm	100 W, 30 µm
EOS M 100	Ø 100 x 95 mm	200 W, 40µm
EOS M 290	250 x 250 x 325 mm	400 W, 100 µm
EOS M 400	400 x 400 x 400 mm	1000 W, 90 µm
EOS M 400-4	400 x 400 x 400 mm	4 x 400 W, 100 µm
SLM 280	280 x 280 x 365 mm	2 x 700 W, 80-115 µm
SLM 500	500 x 280 x 365 mm	4 x 700 W, 80-115 µm
Trumpf TruPrint 1000	Ø 100 x 100 mm	200 W
Trumpf TruPrint 3000	Ø 80 x 95 mm	500 W, 100-500 µm
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Hinke 2017 DOI: 10.1109/HPD.2017.8261077

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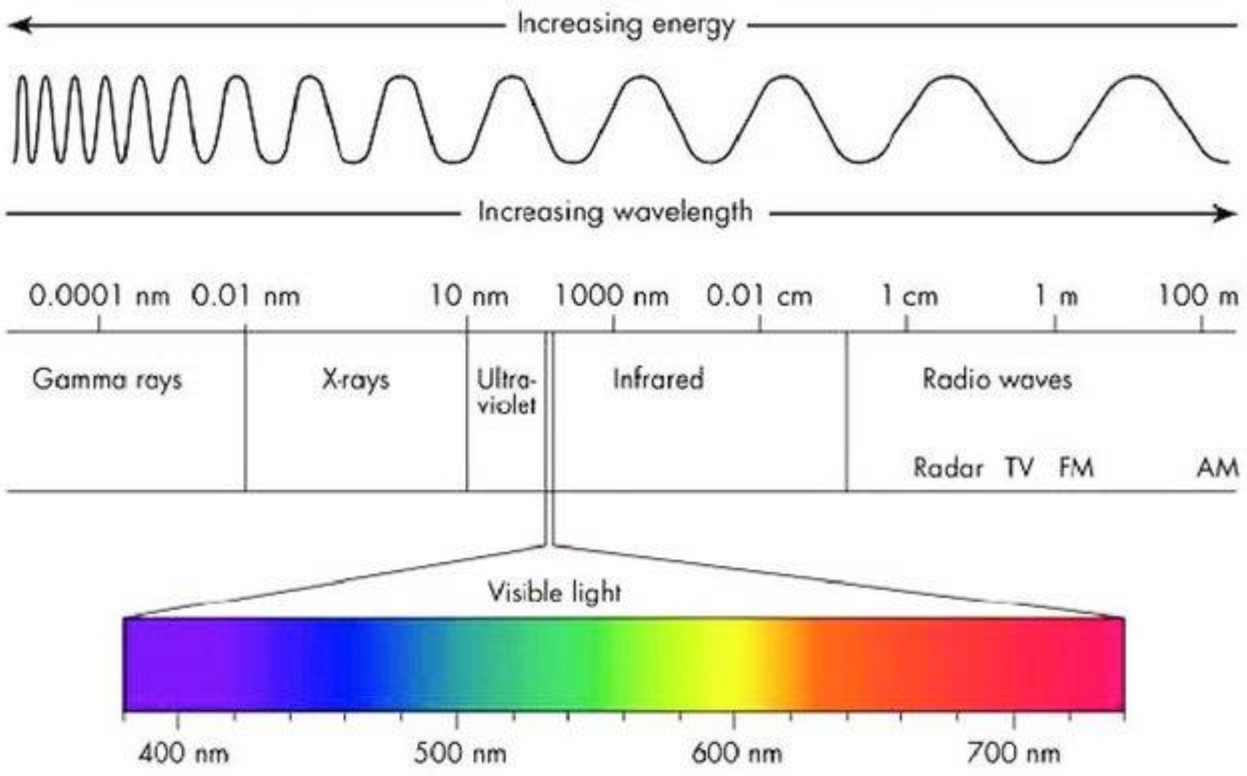
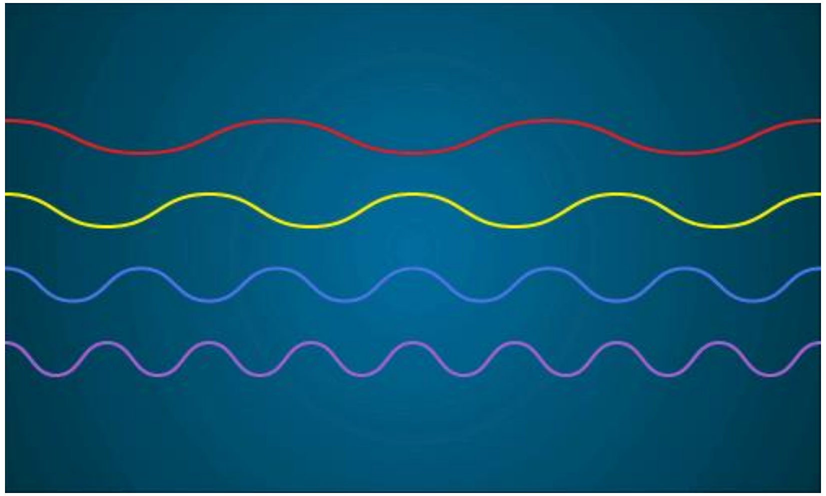
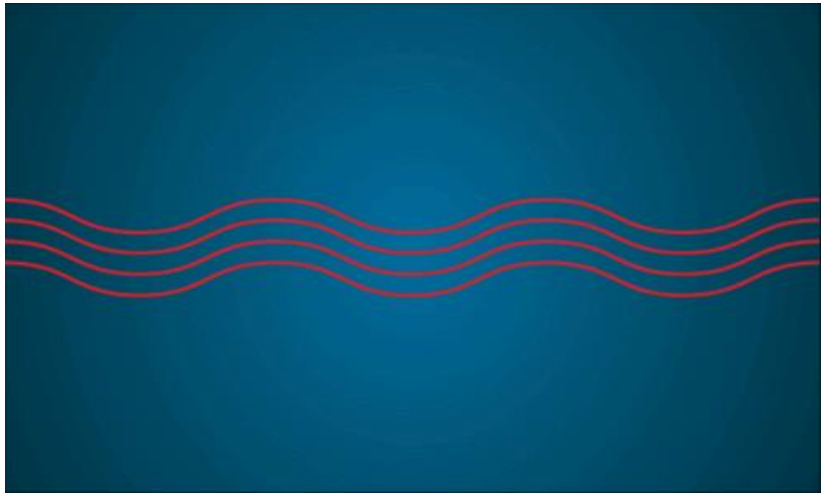
Light as a medium for energy







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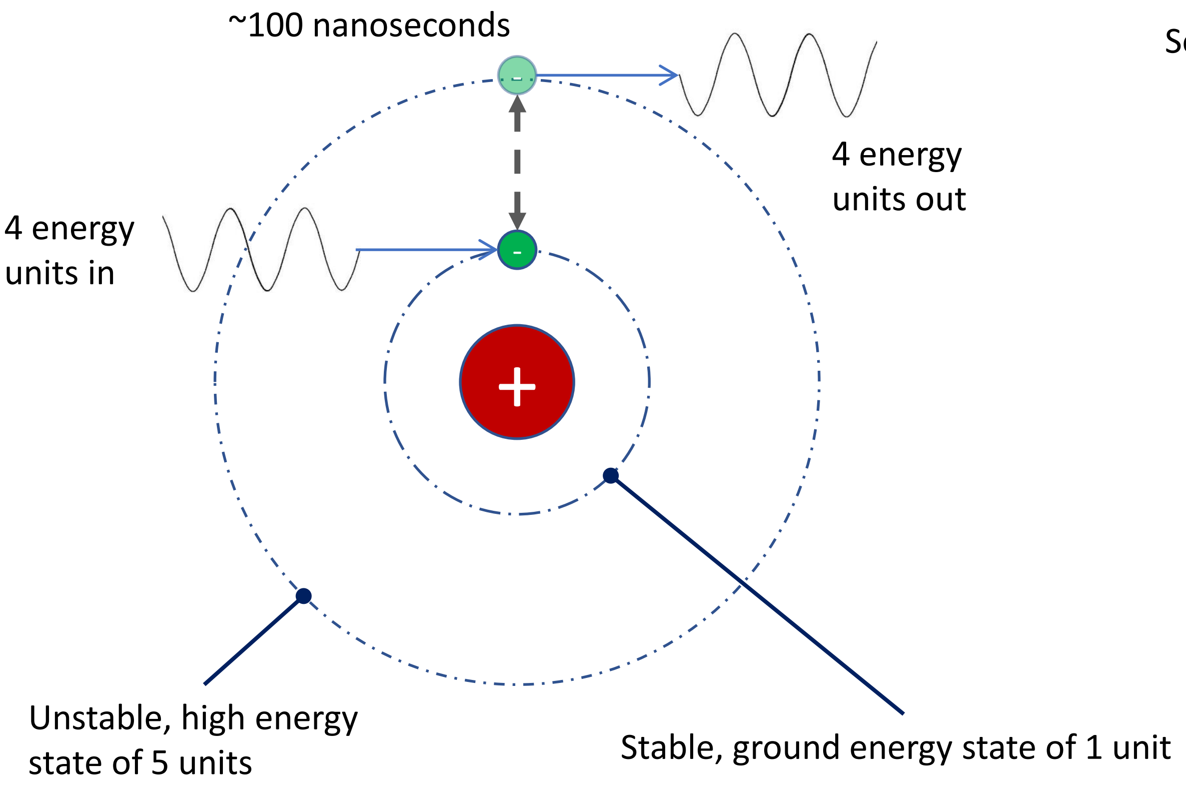
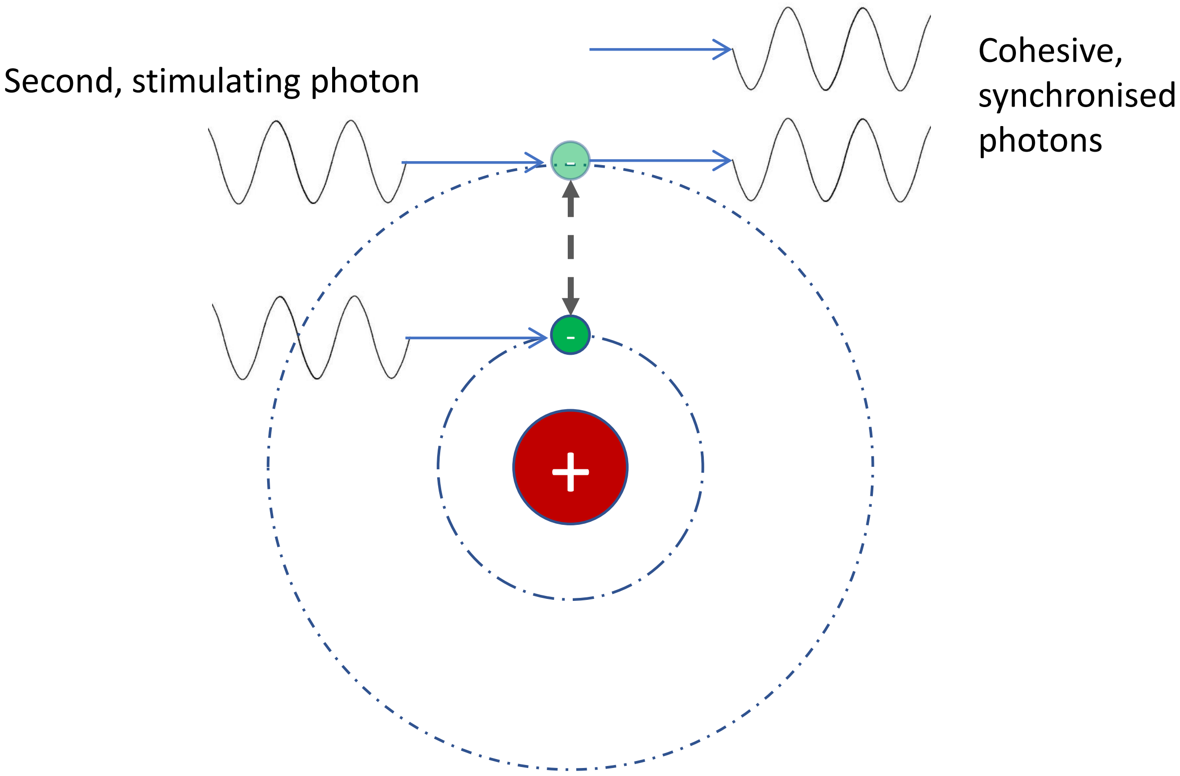
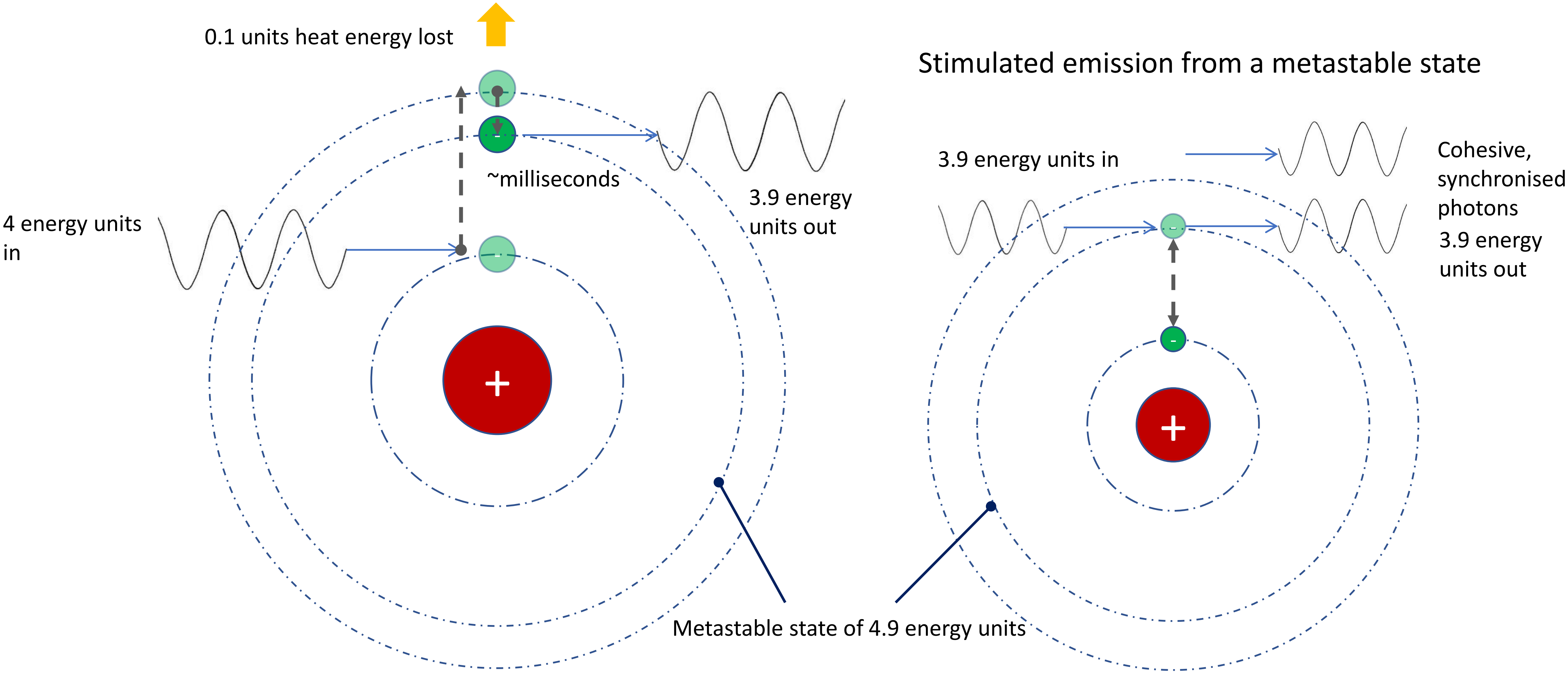


Stimulated Absorption and Spontaneous Emission



Stimulated Emission



Decomposition to and spontaneous emission from a metastable state

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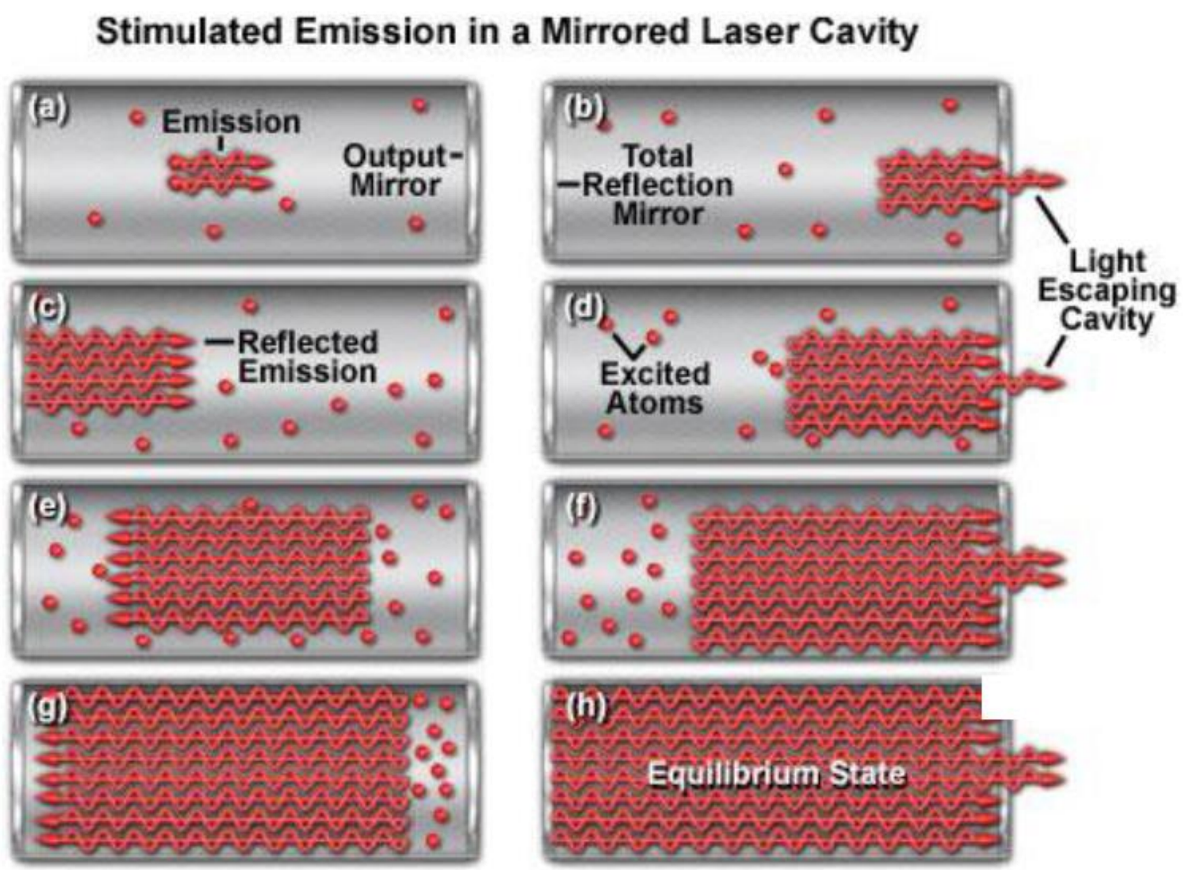
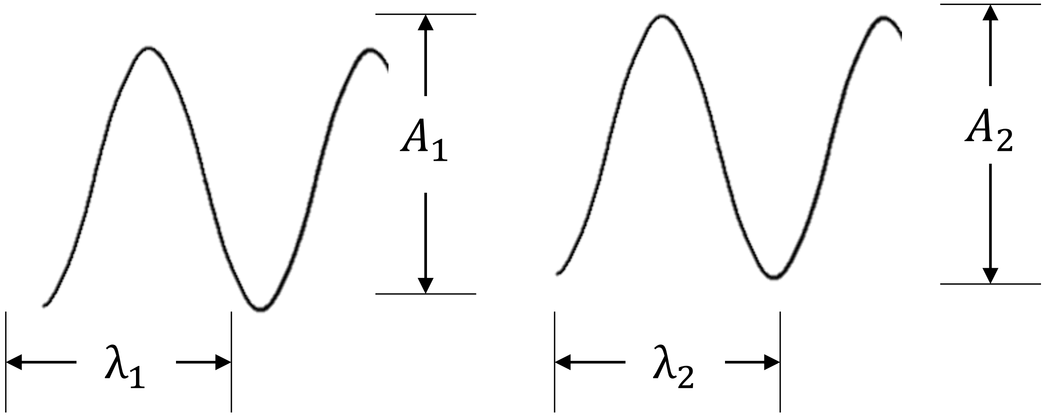
clideo.com

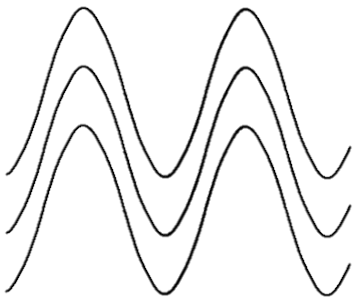


http://micro.magnet.fsu.edu/primer/java/lasers/heliumneonlaser/index.html



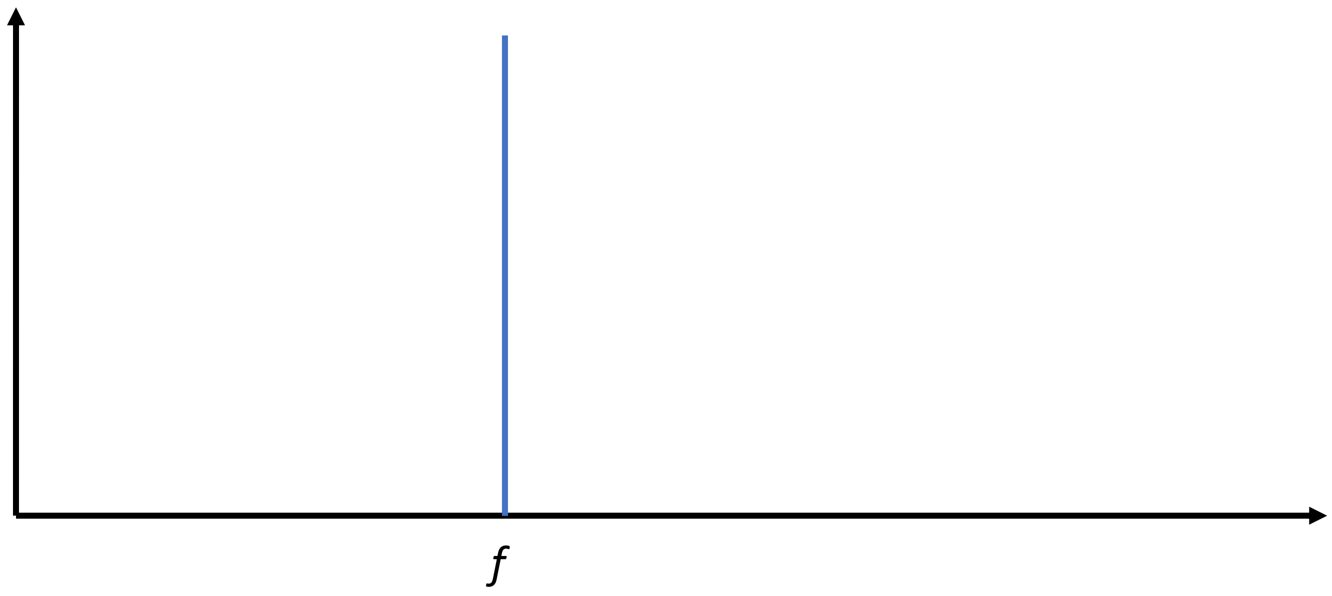
$A_1 = A_2$ waves have same **intensity**

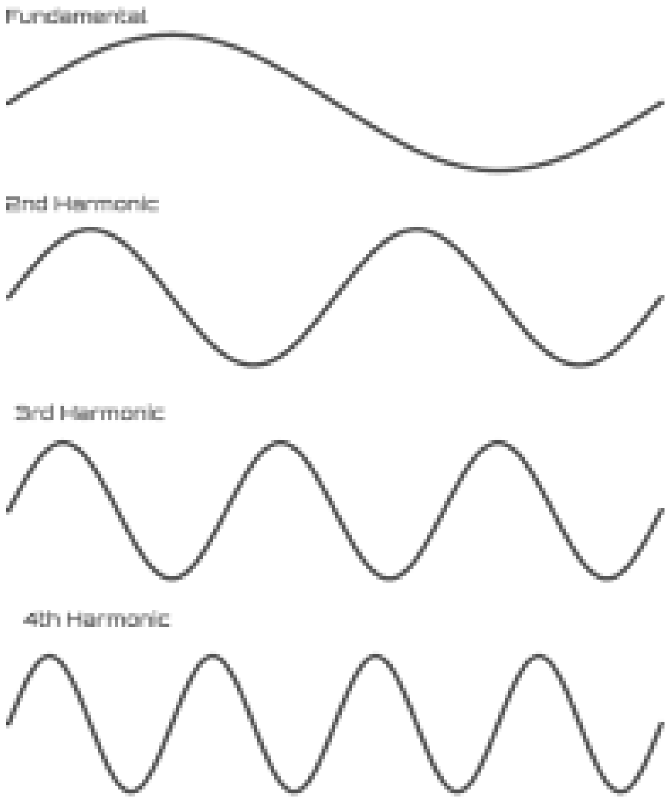
$\lambda_1 = \lambda_2$ waves have same wavelength and therefore the same frequency - the light is monochromatic



Peaks and troughs coincide – the light is coherent

Resonance, allowable frequencies, distribution, and gain material – small line width





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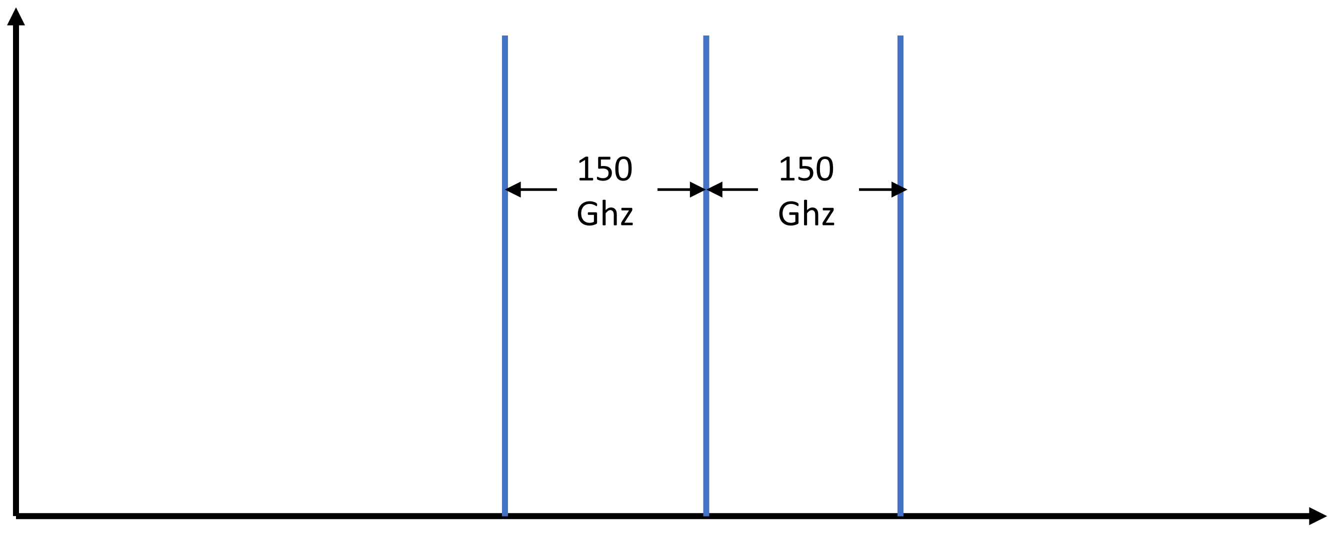
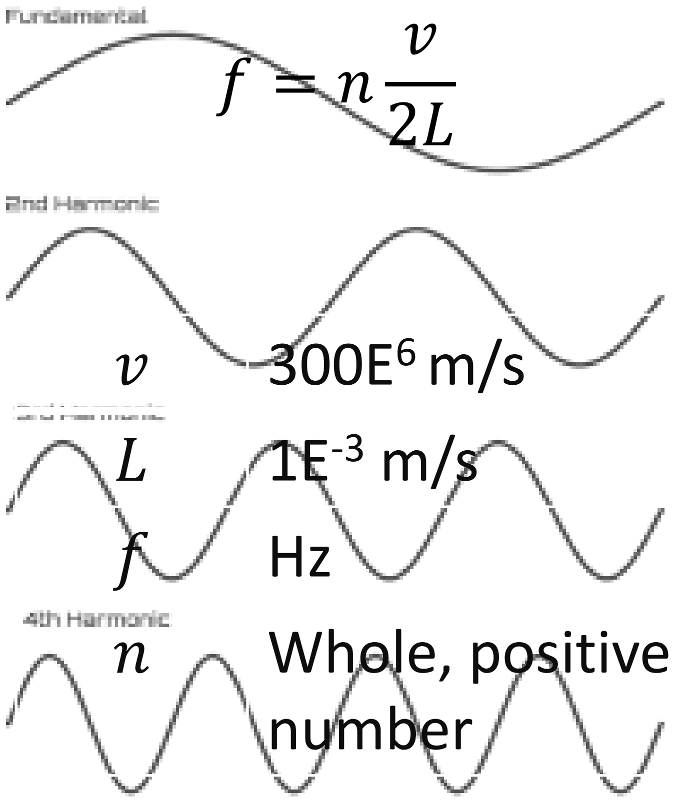


f_1 f_2 f_3

$$f = n \times \frac{300\ million\ ms^{-1}}{2 \times 1\ mm} = n \times 150\ GHz$$



$$f = n\frac{v}{2L}$$

v	300E^6 m/s
L	1E^{-3} m/s
f	Hz
n	Whole, positive number

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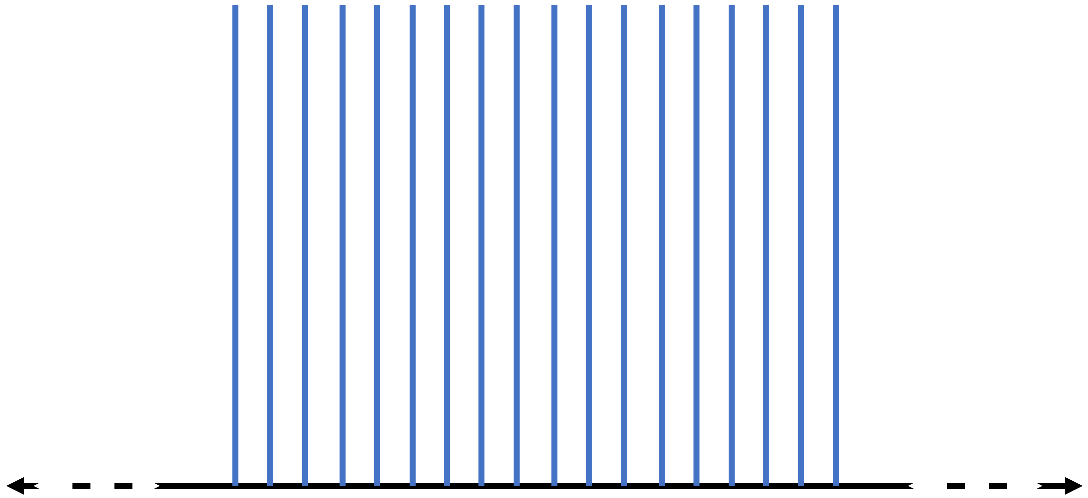
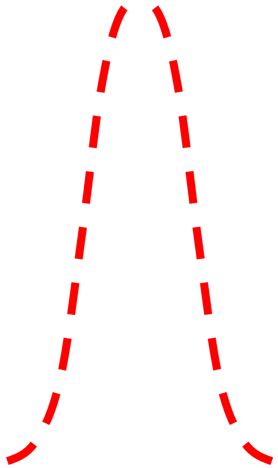
Resonance, allowable frequencies, distribution, and gain material – small line width



Allowable frequencies for laser cavity geometry

+



Energy distribution curve for gain material

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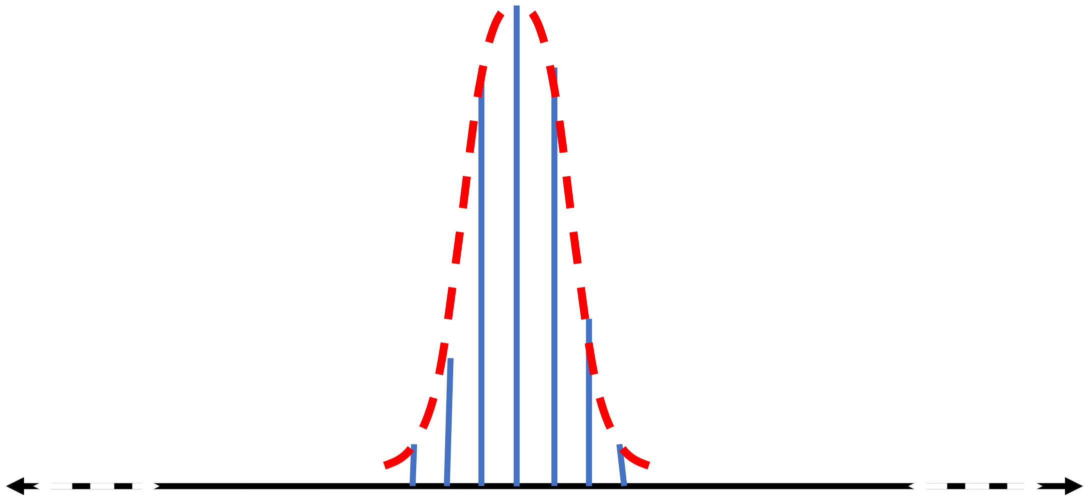
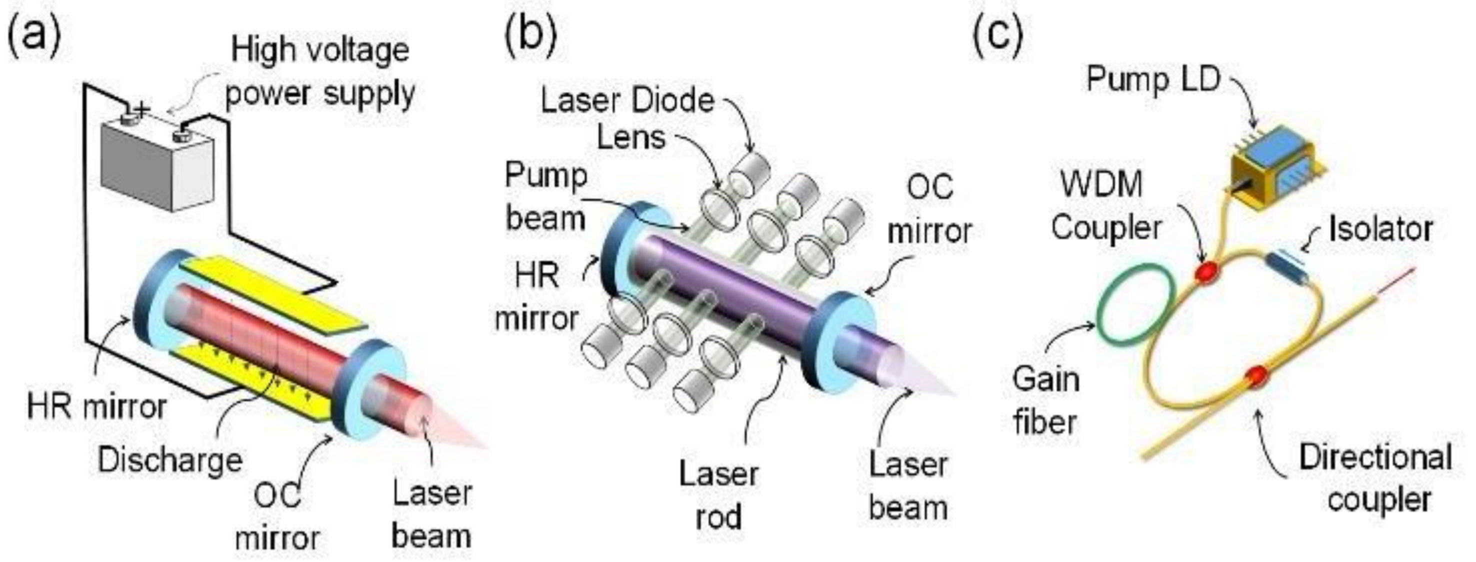
Resonance, allowable frequencies, distribution, and gain material – small line width



The gain curve of the laser

LB-PBF: Laser Types

- CO_2 lasers used initially, higher efficiency with Polymer materials, now found in polymer LB-PBF and Metal DED machines.
- Nd:YAG laser were initially favoured over CO_2 due to the beam wavelength along with the ability to deliver it through a fibre.
- The vast majority of Metal LB-PBF machines are currently now using Yb-Fibre lasers due to the increase in efficiency and reduction in maintenance over Nd:YAG laser.



Laser schematics with different gain materials: (a) Gas laser(CO_2), (b) Solid-state laser, (Nd:YAG) (c) Rare-earth-doped fibre laser(Yb-Fibre)

Lasers in additive manufacturing: A review, July 2017, International Journal of Precision Engineering and Manufacturing-Green Technology 4(3):307-322

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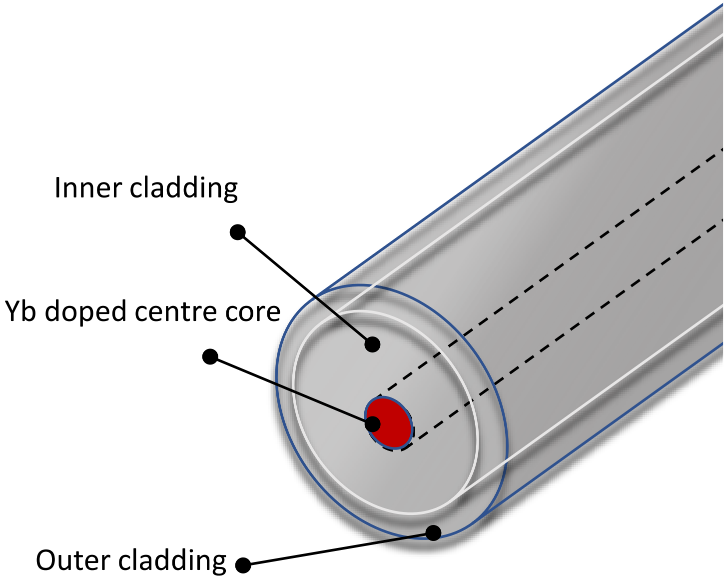
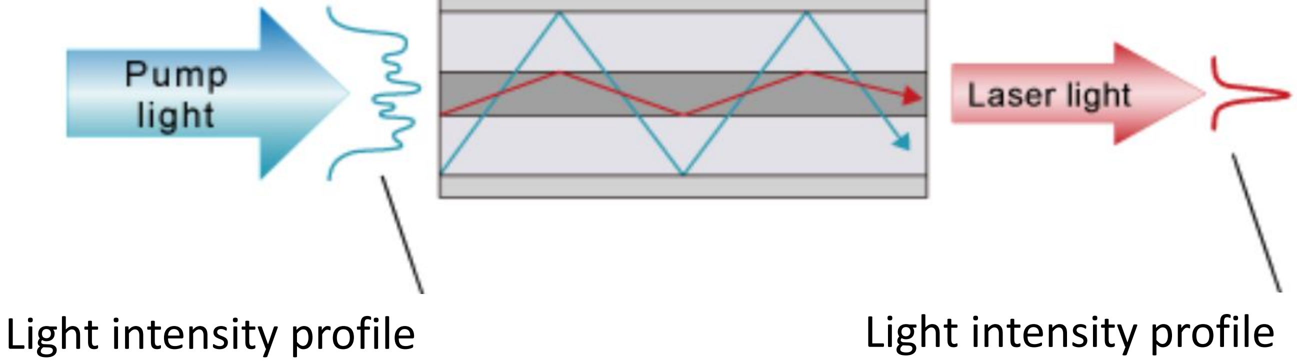
How does a YG fibre laser work?



Cross section of a fibre



Propagation along a fibre

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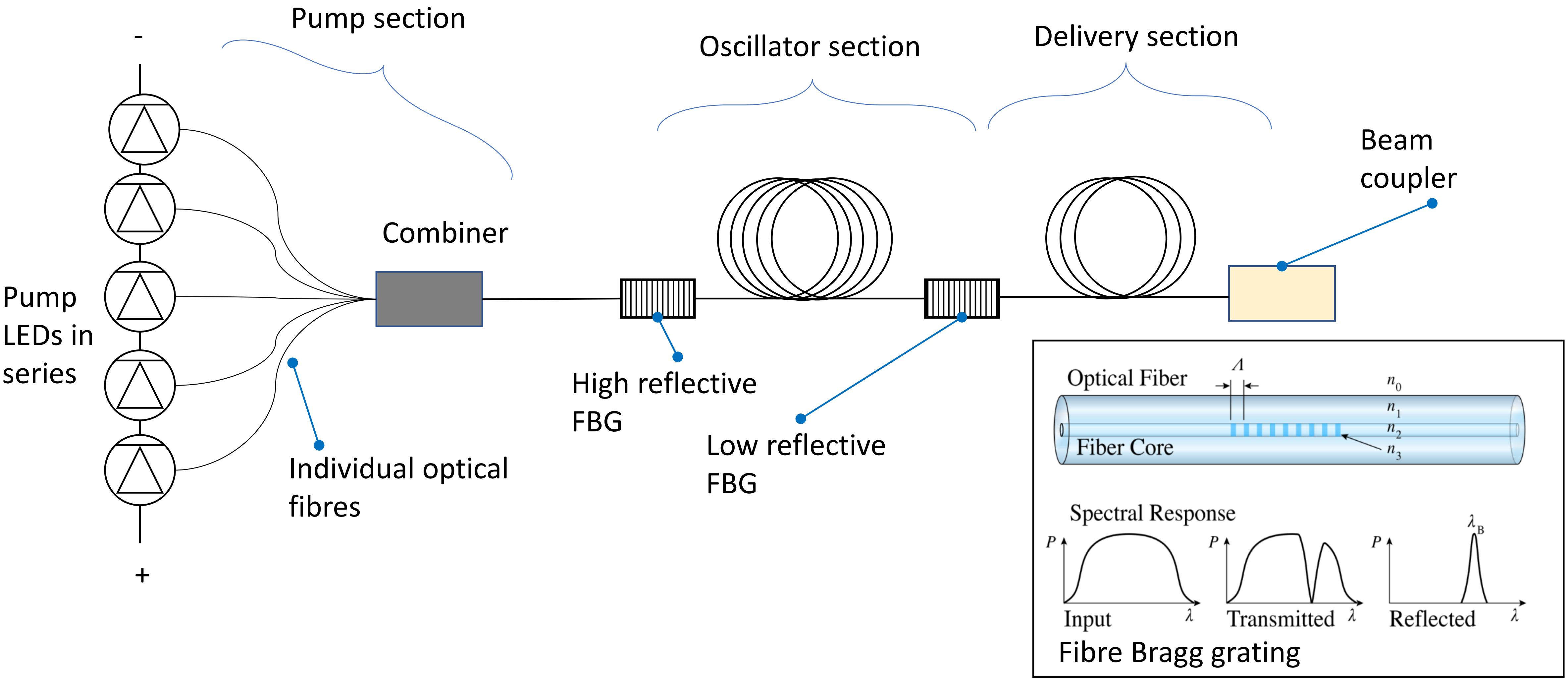

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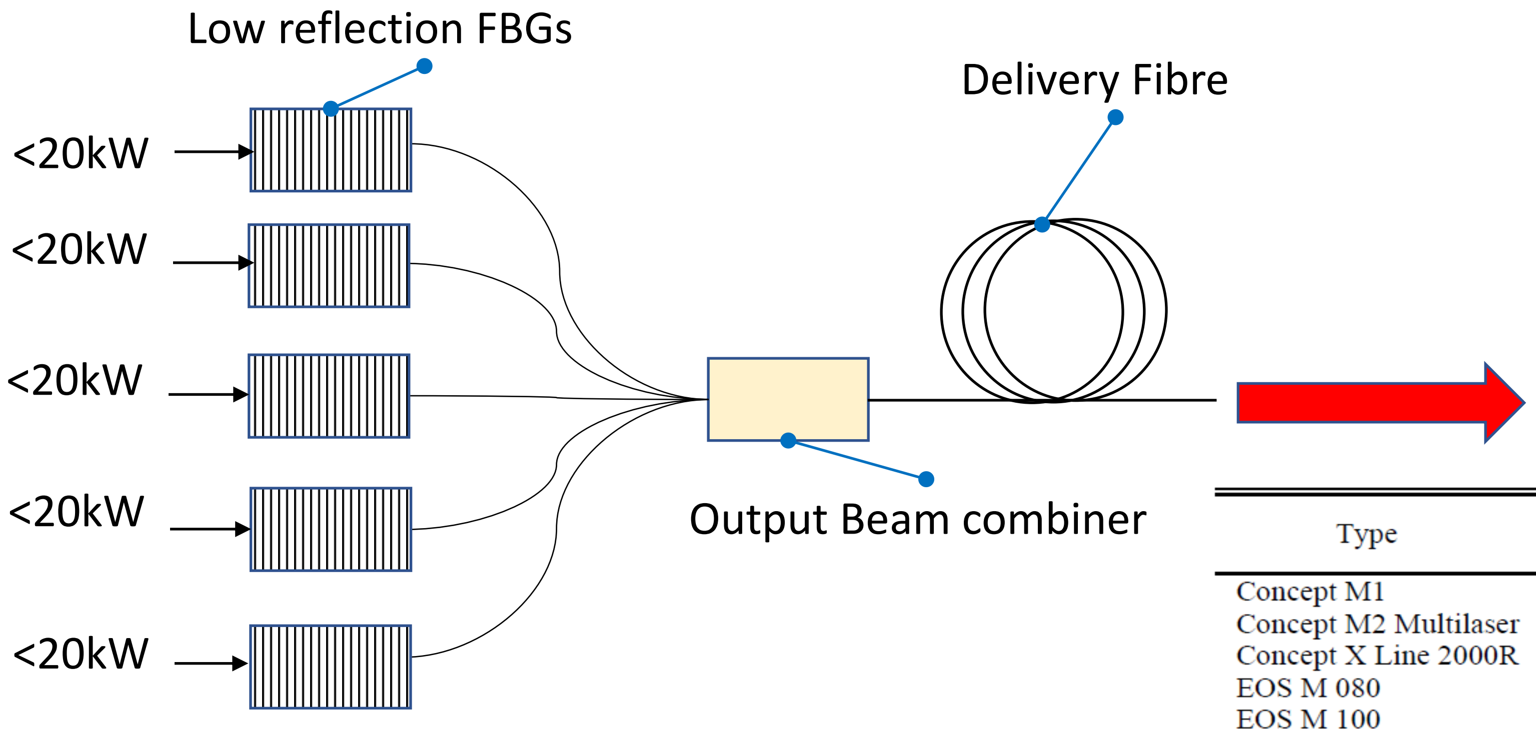
Separate doped Yb oscillator fibres



http://www.fiberlaser.fujikura.jp/eng/products/about-fiber-laser.html

Type	Build-Volume	Power, Spot-Size
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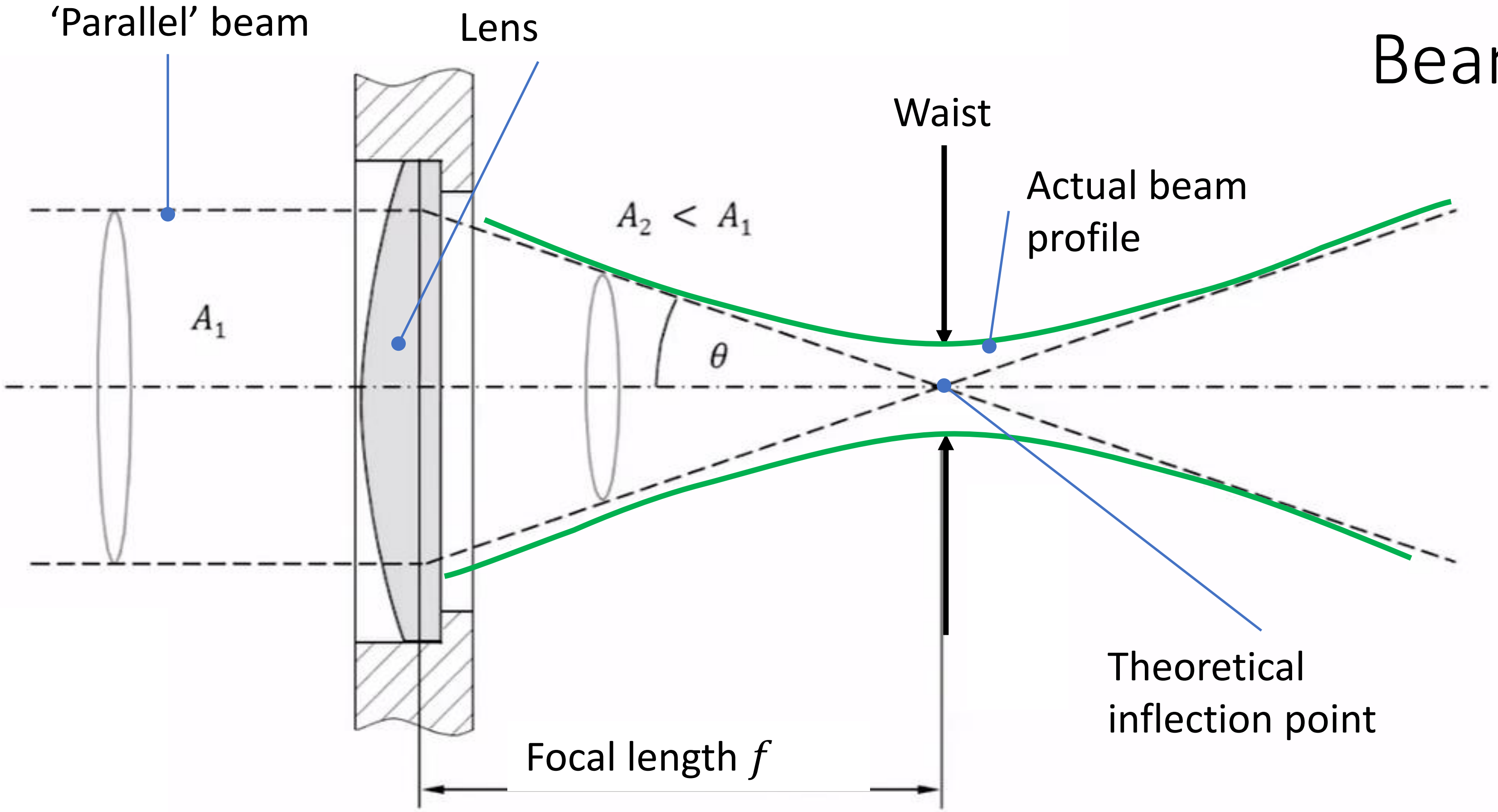
Beam focusing - physics



$$I = \frac{P}{A}$$

$$P = laser\ power\ (eg\ 200W)$$

$$I_1 = \frac{P}{A_1}; I_2 = \frac{P}{A_2}$$

$$I_3 = \frac{P}{?} \ldots\ldots I_3 \neq \infty$$

The Feynmann lectures on Physics; Volume I

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Transversal intensity distribution

$$I(z,r) = \frac{2P}{\pi w(z)^2} \exp\left(-2\frac{r^2}{w(z)^2}\right)$$

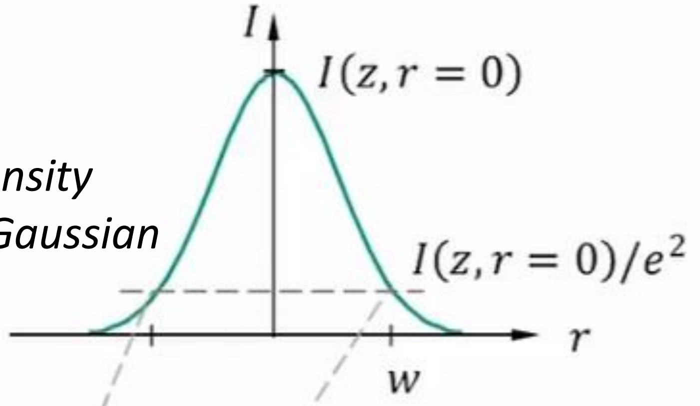
Beam radius in dependence upon the position (caustic)

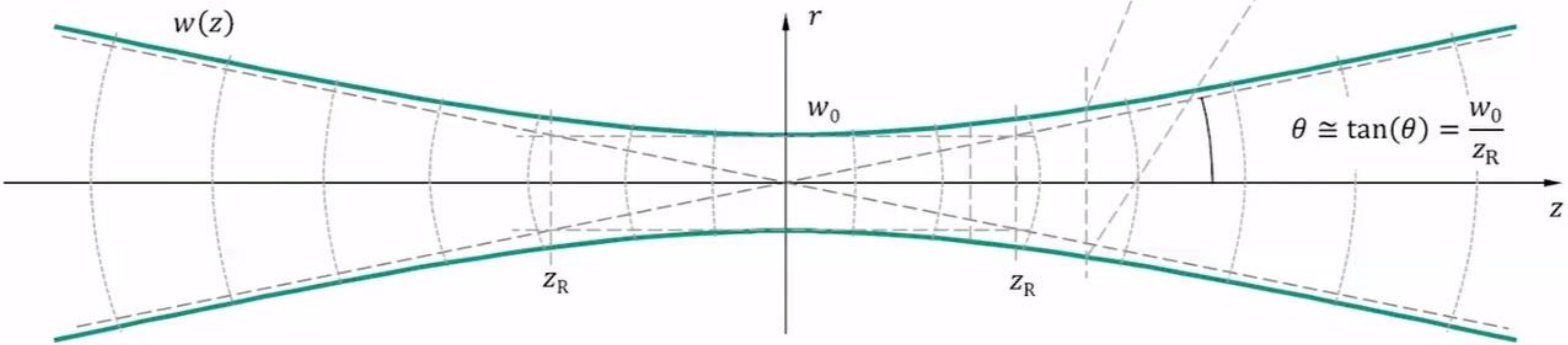
$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2}$$

Rayleigh length

$$z_R = \frac{\pi w_0^2}{\lambda}$$

Transverse intensity distribution is Gaussian





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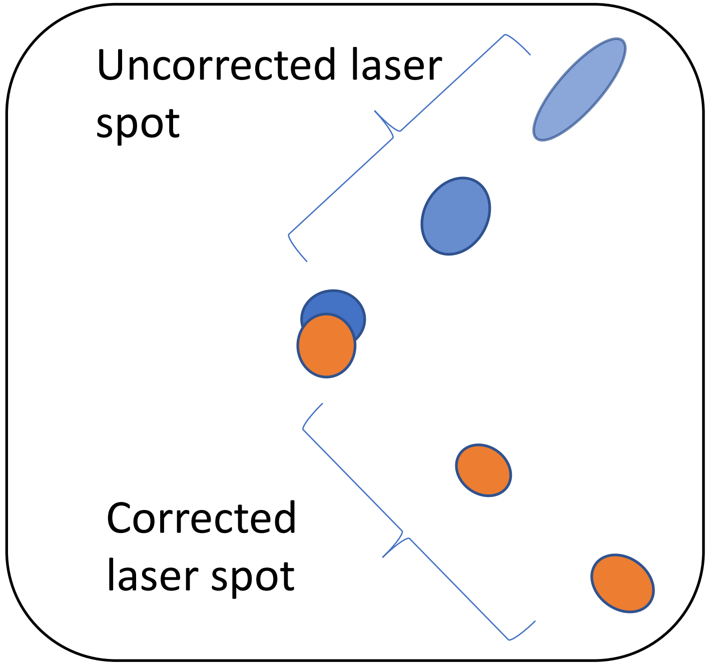
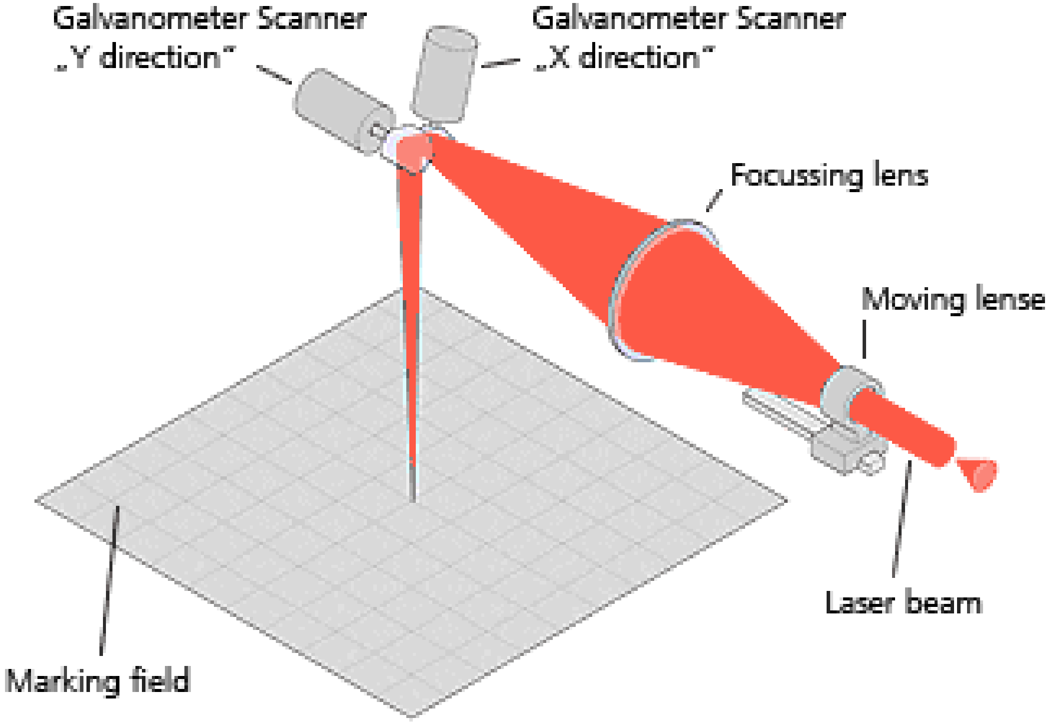
Scanner – Overview, F theta lens





https://www.raylase.de/en/products/

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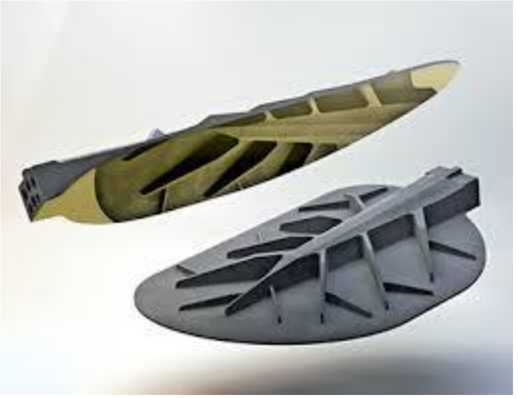
Scanner – key components



MIrror	Beryllium
Servo	50 rad/s,
Encoder	<11urad

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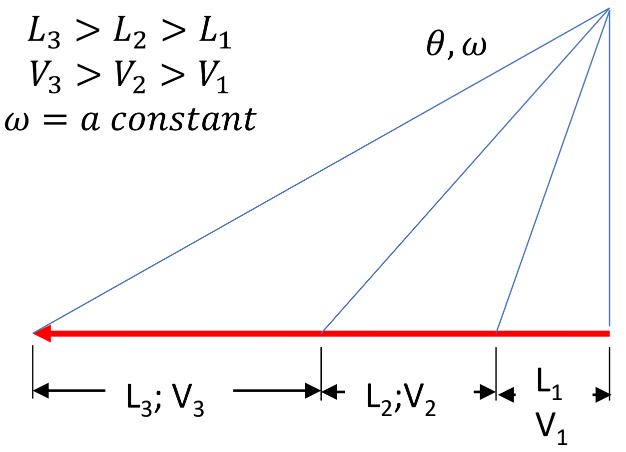
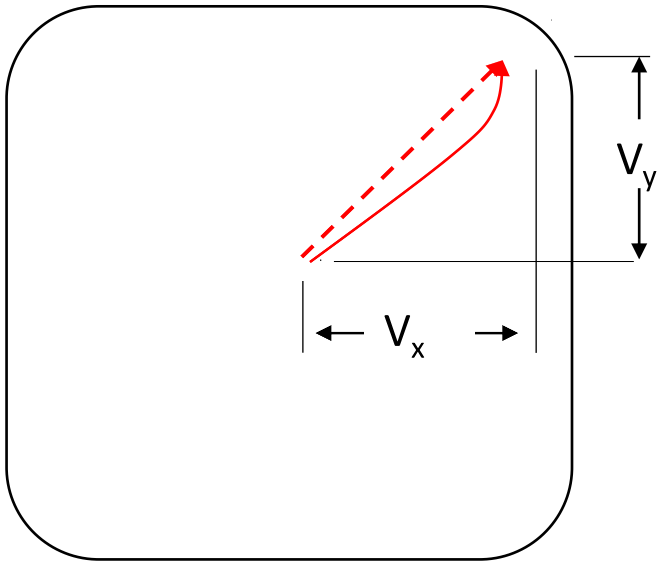
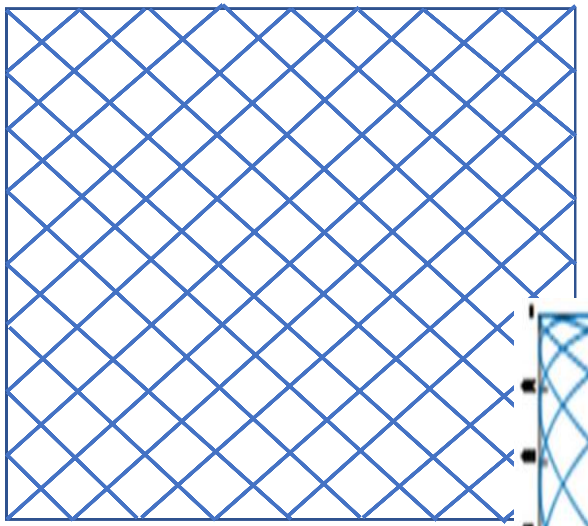
$L_3 > L_2 > L_1$
$V_3 > V_2 > V_1$
$\omega = a\ constant$

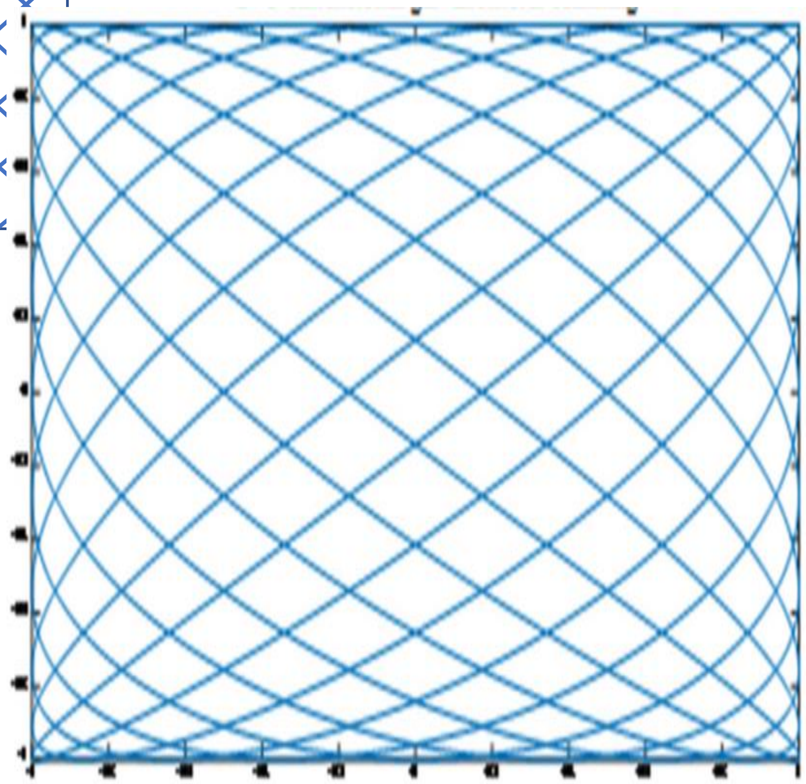






Ideal scan strategy

Actual scan strategy



Meng et al 2019 10.1088/1742-6596/1345/2/022068

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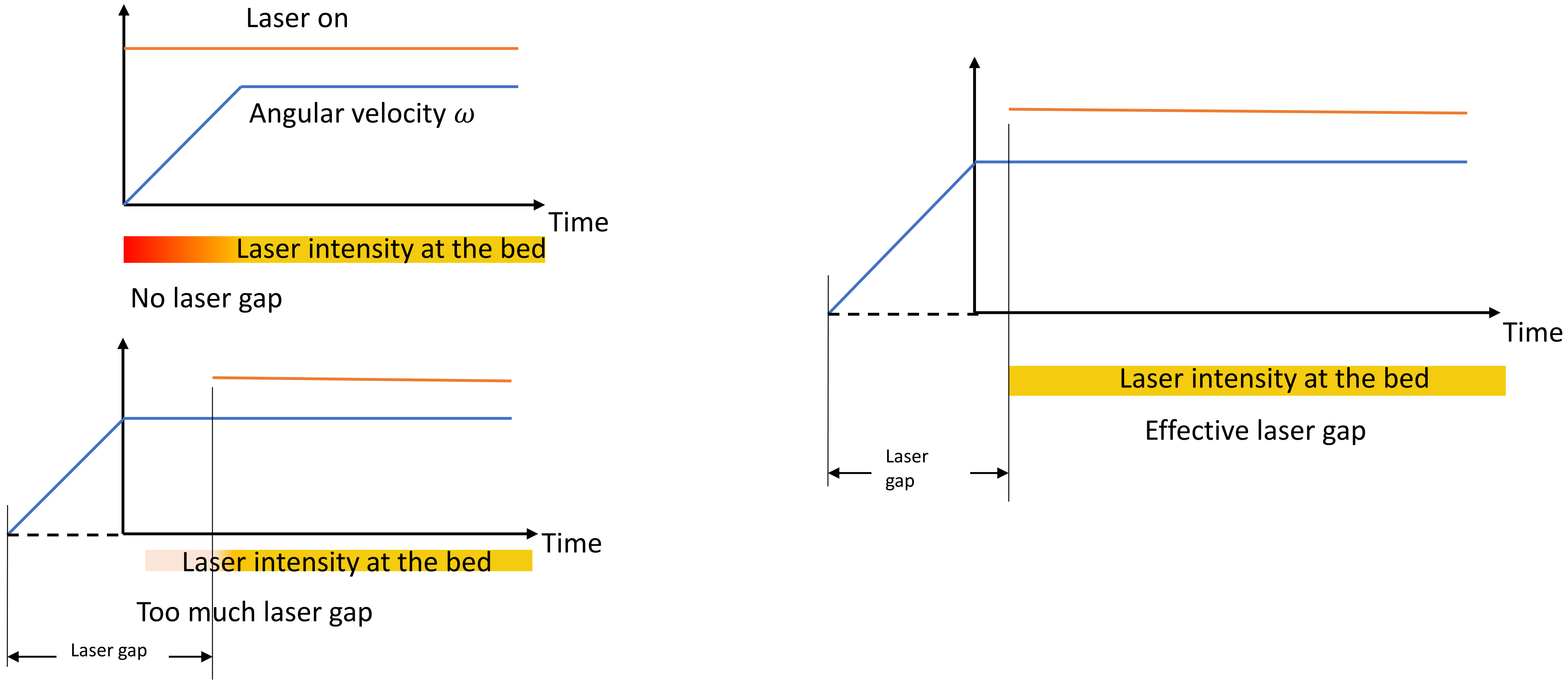
Scanning- run in and run out



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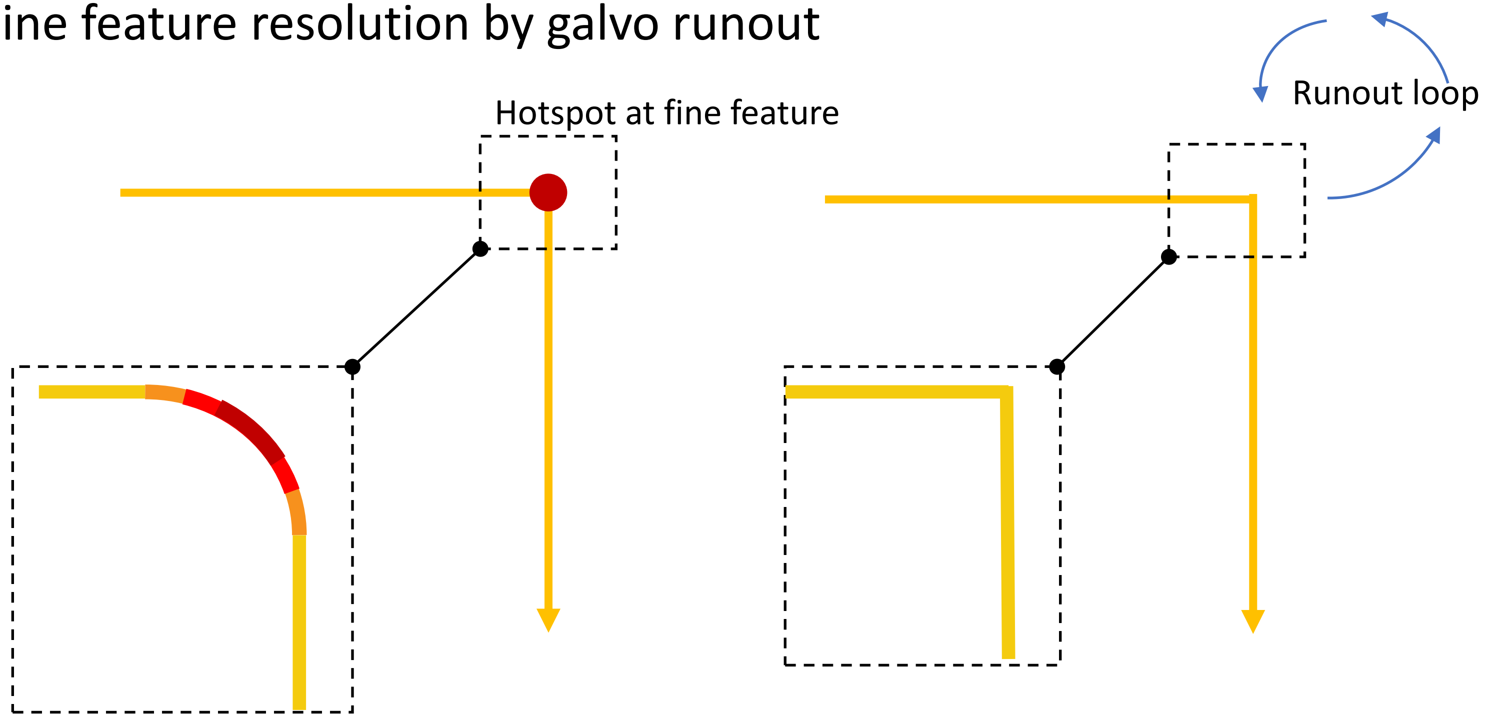
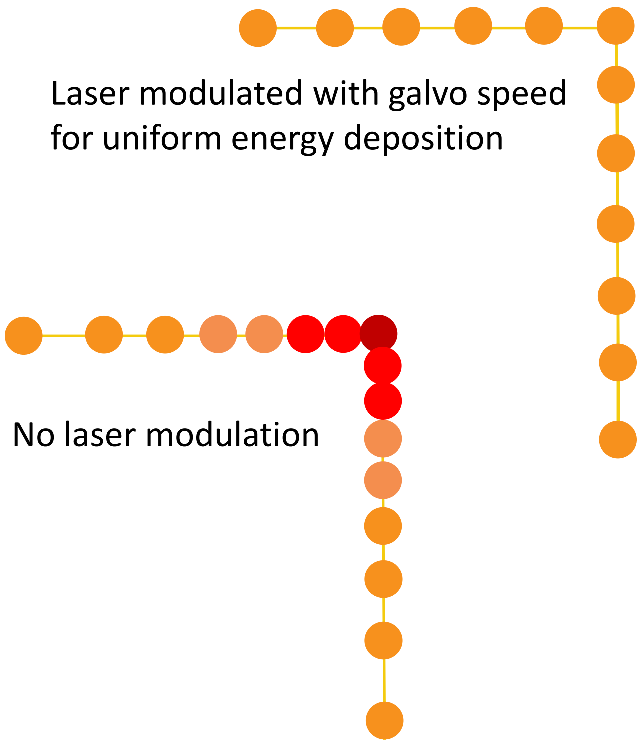
Fine feature resolution by galvo runout



Galvanometers are forced to describe a radius as a comprmise between laser path and energy deposition rate

Galvanometers describe a loop, running out and into a corner at constant speed during a laser gap

Fine feature resolution by laser modulation



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Optical system recap

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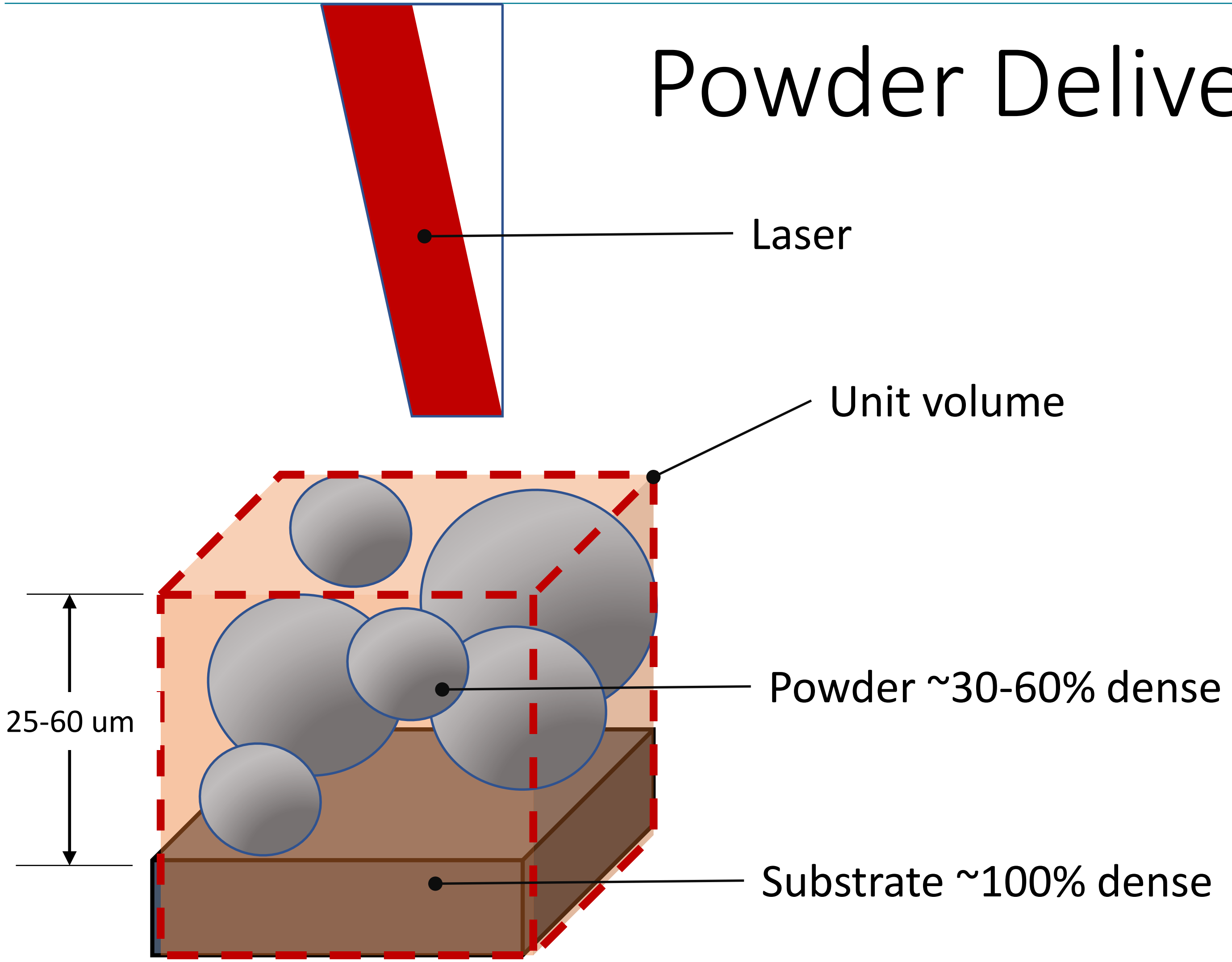
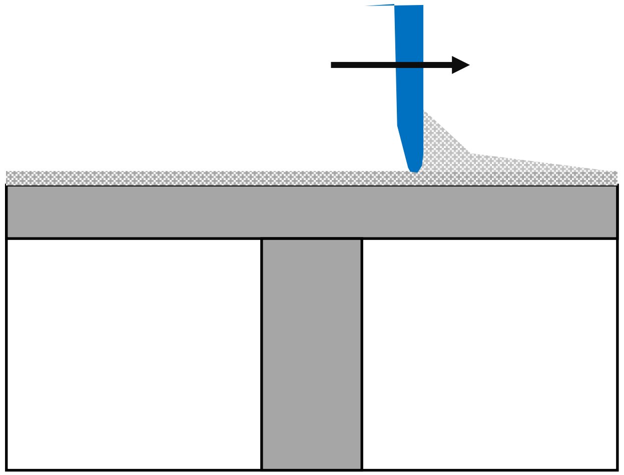
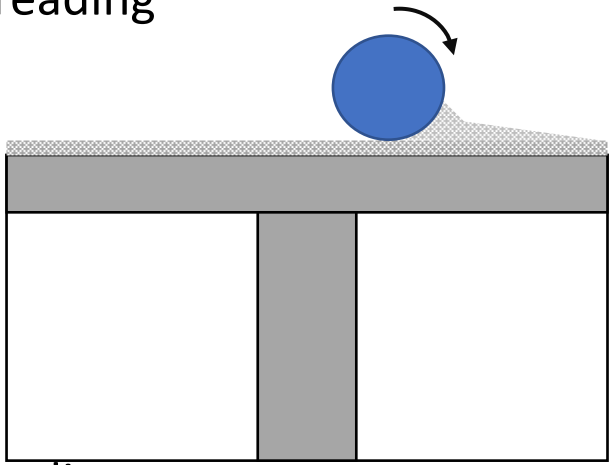
Powder Delivery





Blade spreading



Roller spreading

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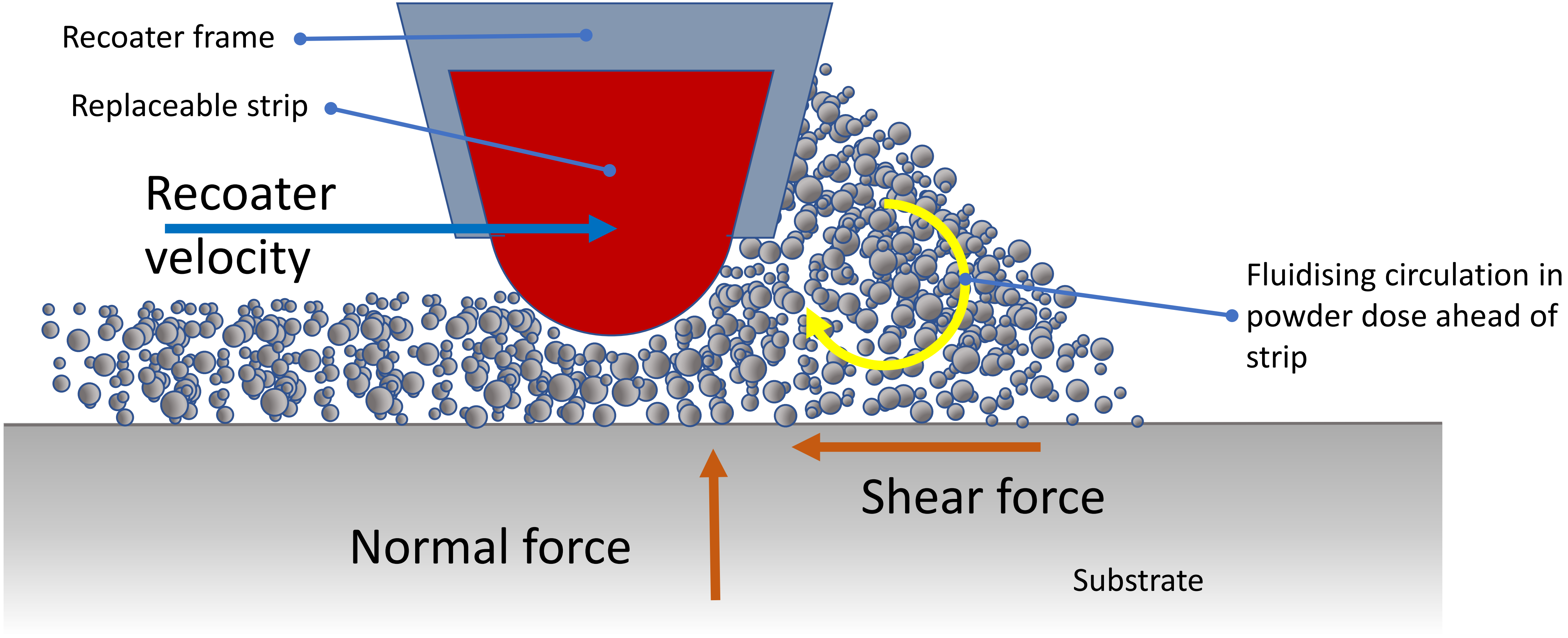
Powder Spreading with a blade



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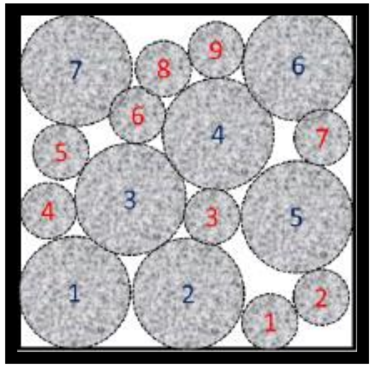
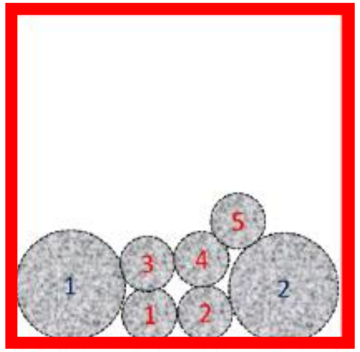
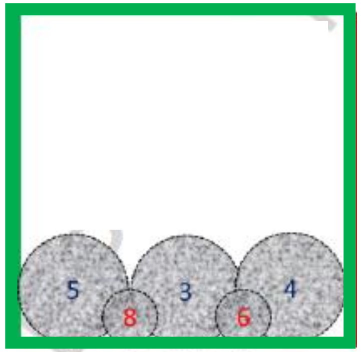
Powder Spreading



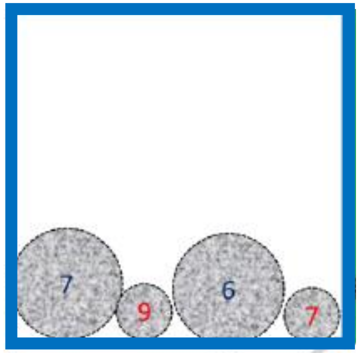
At powder elevator



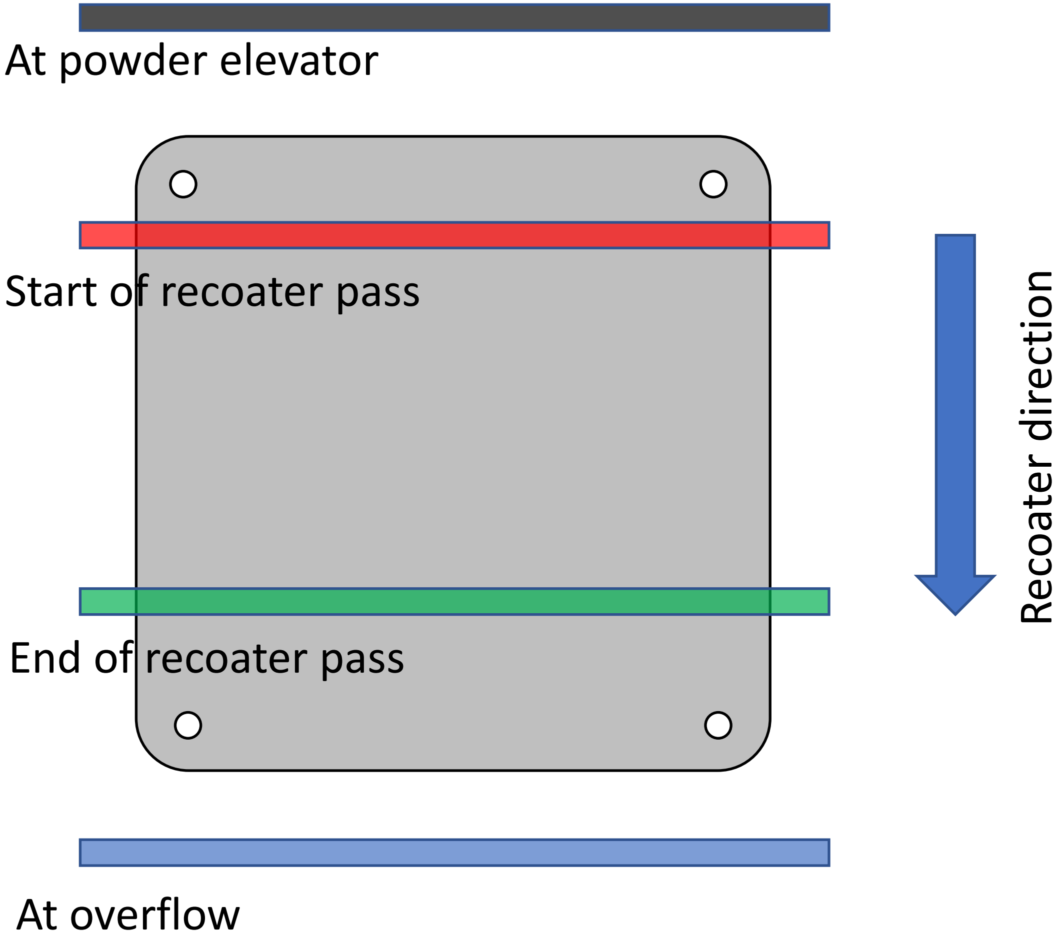
Start of recoater pass



End of recoater pass



At overflow



Ali et al; *Materials and* Design **2018**
doi:10.1016/j.matdes.2018.06.030

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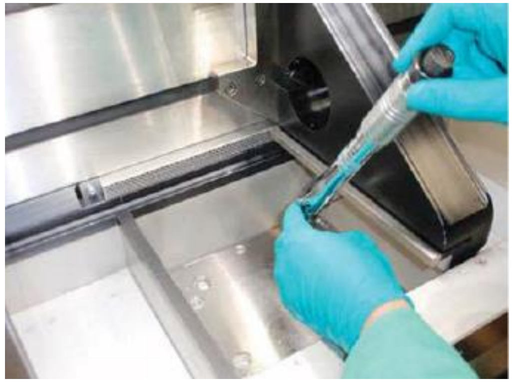
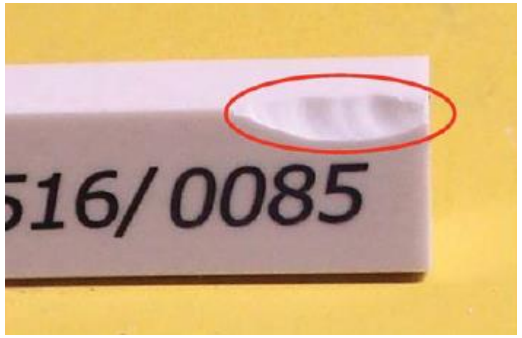
Blade levelling



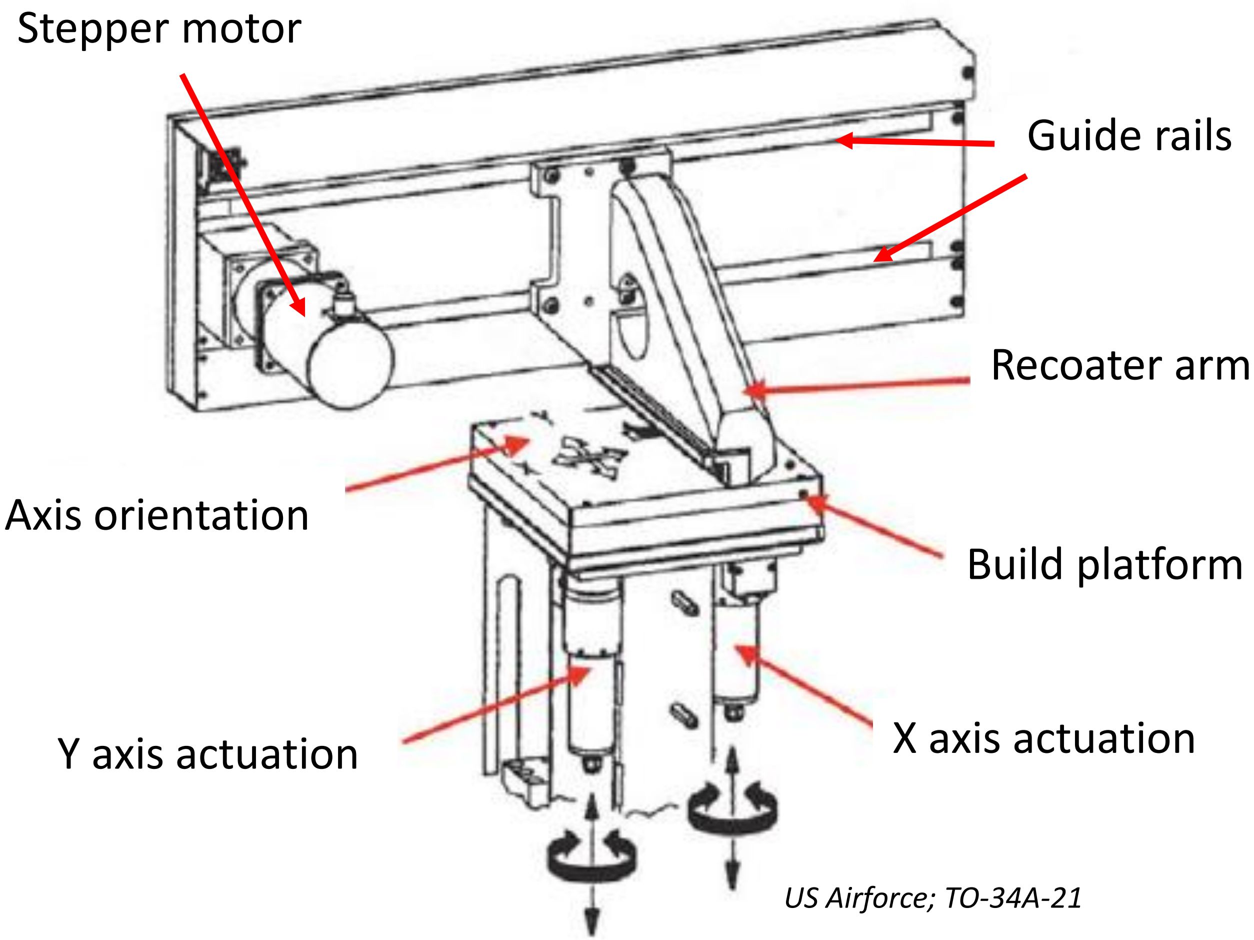
Installing ceramic blade on rigid arm

US Airforce; TO-34A-21



Chipped recoater blade

US Airforce; TO-34A-21



US Airforce; TO-34A-21

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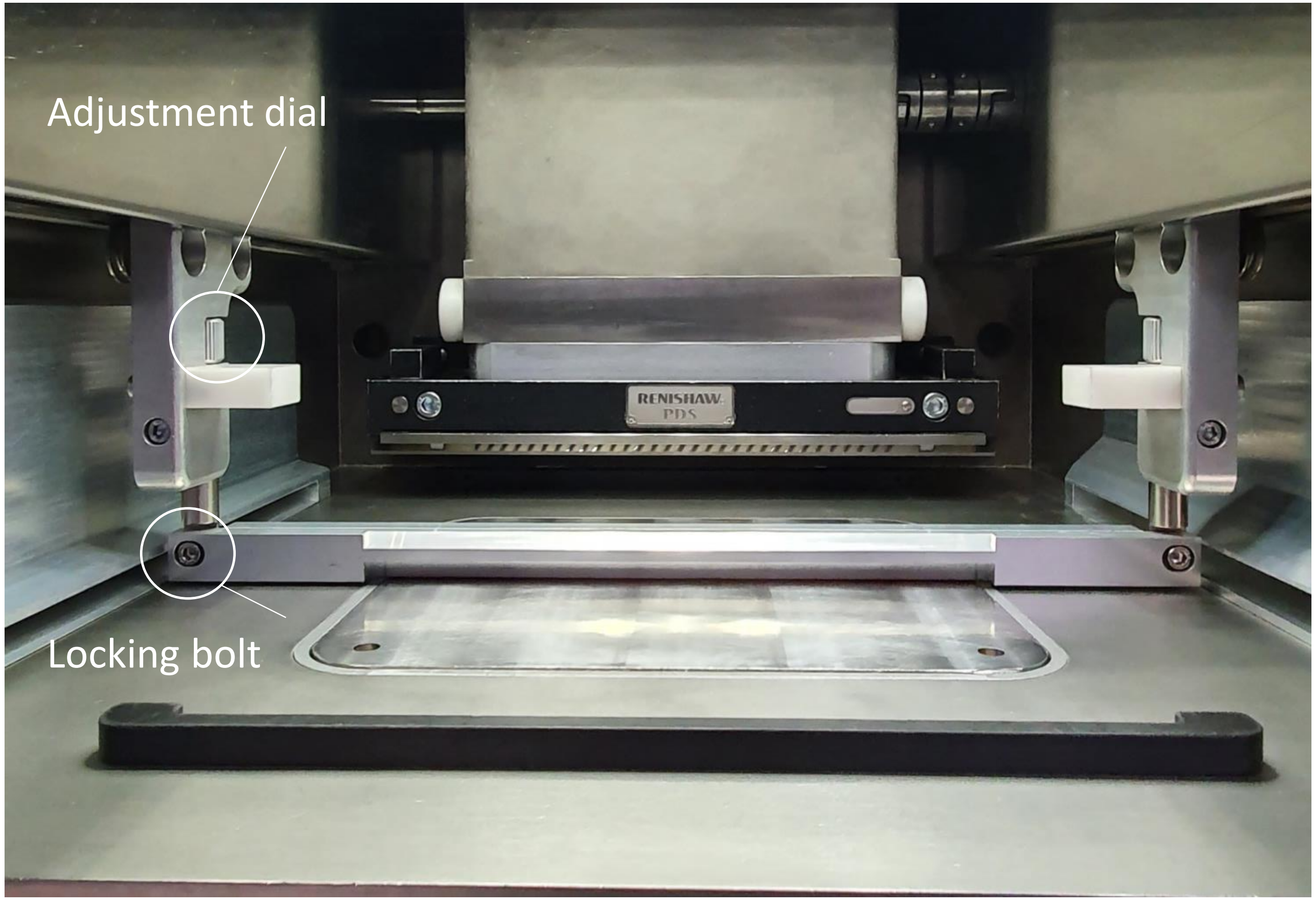
Blade levelling

Disposable rubber blade

Feeler gauge checking height



RenAM 500M OEM User Guide

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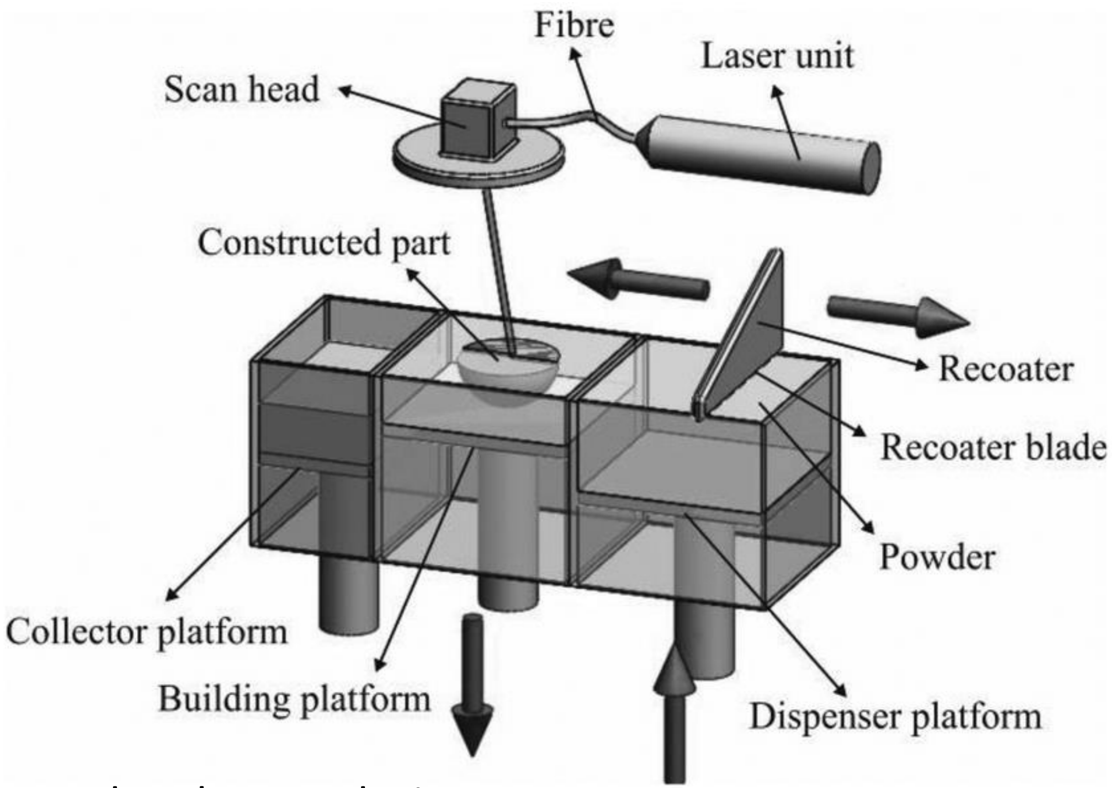
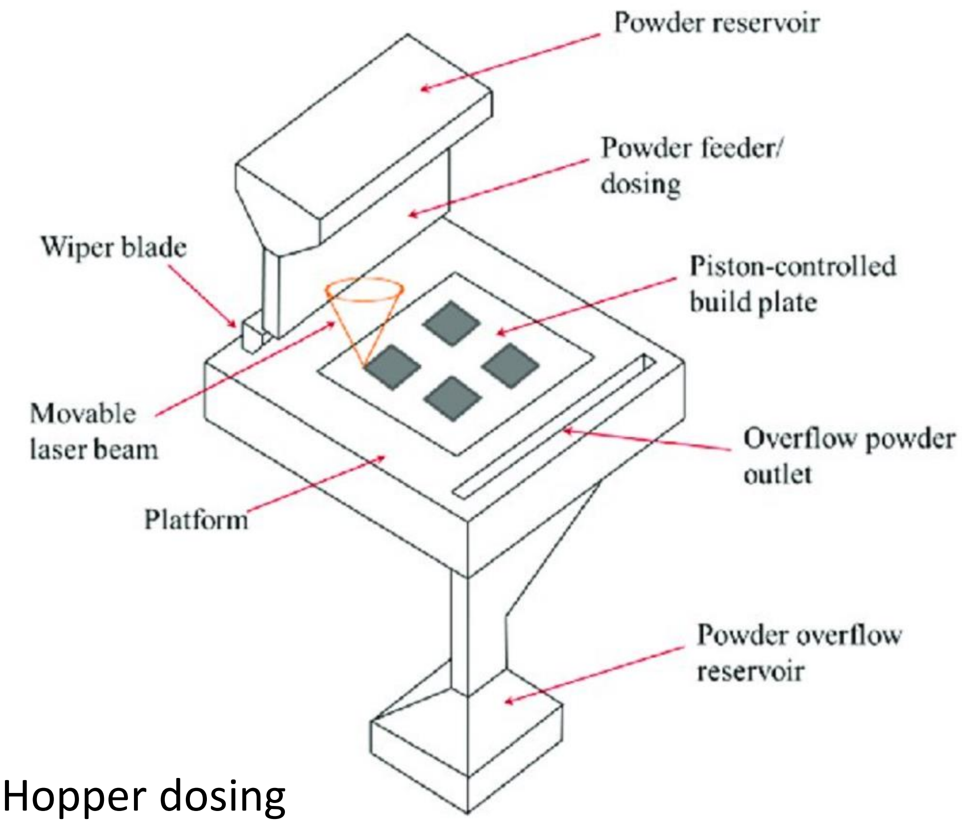
Powder spreading – Dosing systems



Powder elevator dosing

Longhitano et al *Materials Research* B2015

DOI: 10.1590/1516-1439.014415



Hopper dosing

Aboulkhair et al *Progress in Materials Science* **2019**

DOI: 10.1016/j.pmatsci.2019.100578

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Power handling recap

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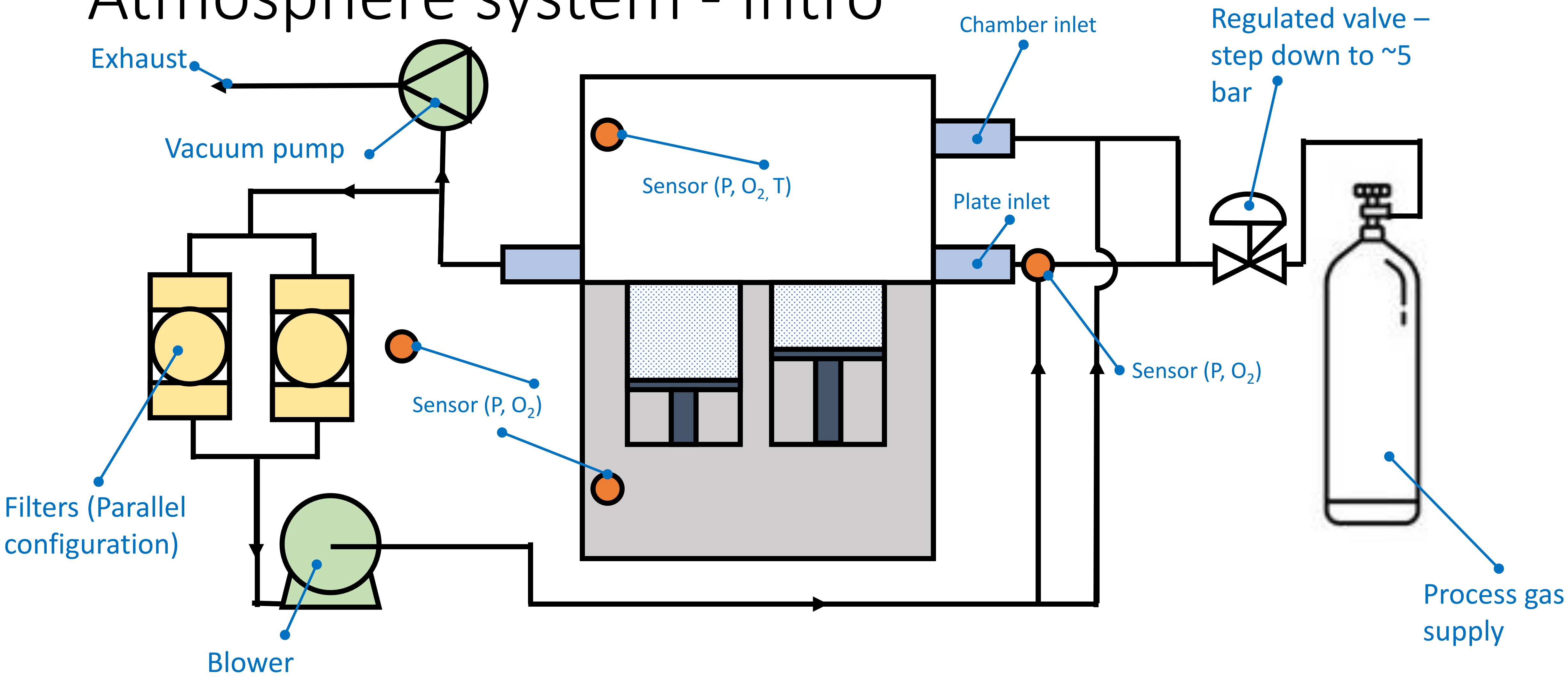
Atmosphere system - Intro



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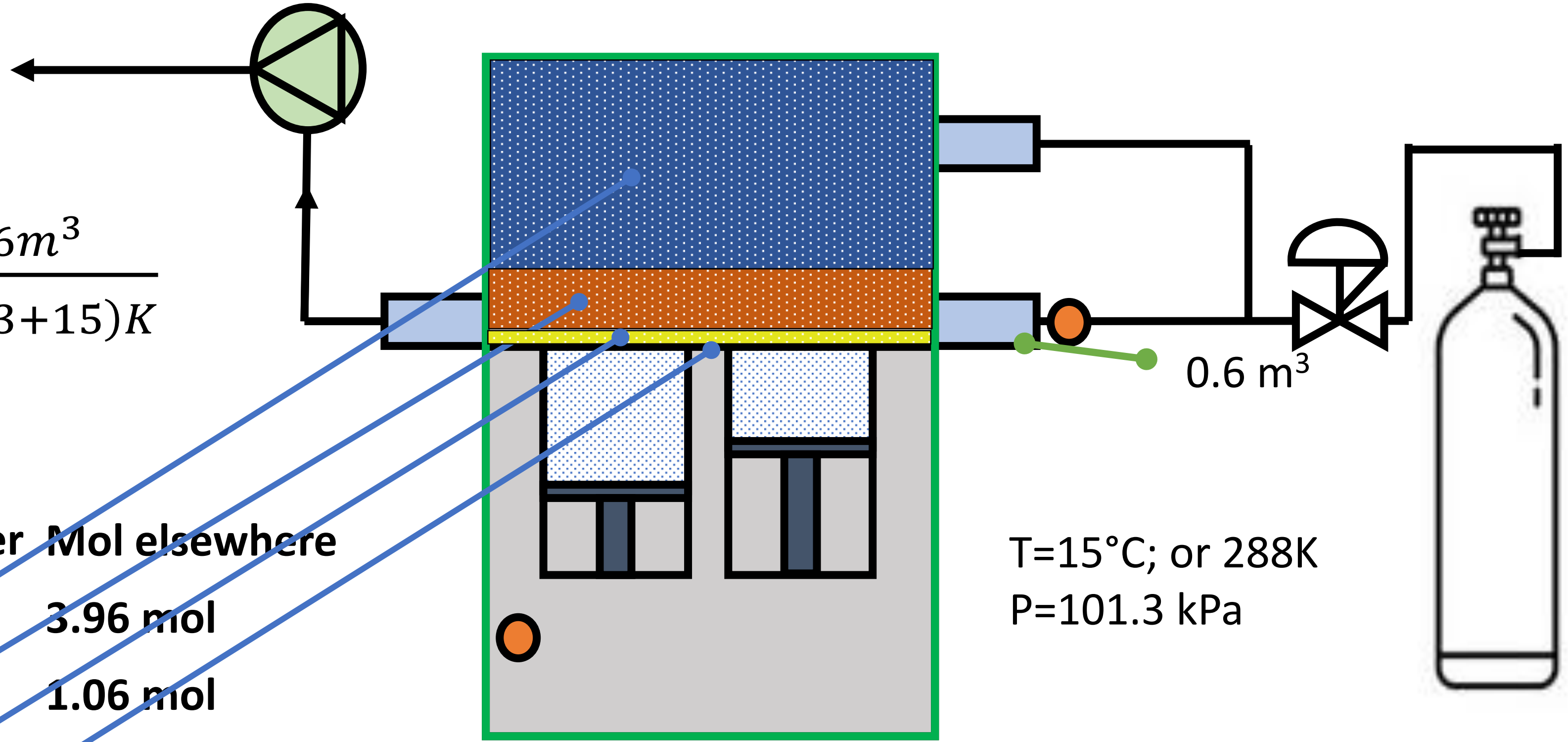
Vacuum system

$$pV = nR_U T$$

$$n = \frac{pV}{R_U T} = \frac{101.3E^3 Pa \cdot 0.6m^3}{8.3145\frac{J}{mol \cdot K} \cdot (273+15)K}$$

$$n = 25.38\ mol$$



T=15°C; or 288K
P=101.3 kPa

Gas	Mol/ratio	Mol in chamber	Mol elsewhere
N_2	78.08%	19.82 mol	3.96 mol
O_2	20.95%	5.32 mol	1.06 mol
Ar	0.93%	0.24 mol	0.05 mol
Other	0.04%	0.01mol	0.002 mol

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Useful ideal gas realtionships

$$PV = nR_UT$$

Ideal gas relationship

$$P_{total} = P_{gas1} + P_{gas2} \ldots P_{gasn}$$

Dalton's Law of partial pressures

$$P_{total} = \frac{(n_1 + n_2 .. n_n)R_UT}{V}$$

$$\frac{P_1}{P_{total}} = \frac{n_1}{n_{total}} = X_1$$

$$n_{total} = X_1n_1 + X_2n_2 \ldots X_n + n_n$$

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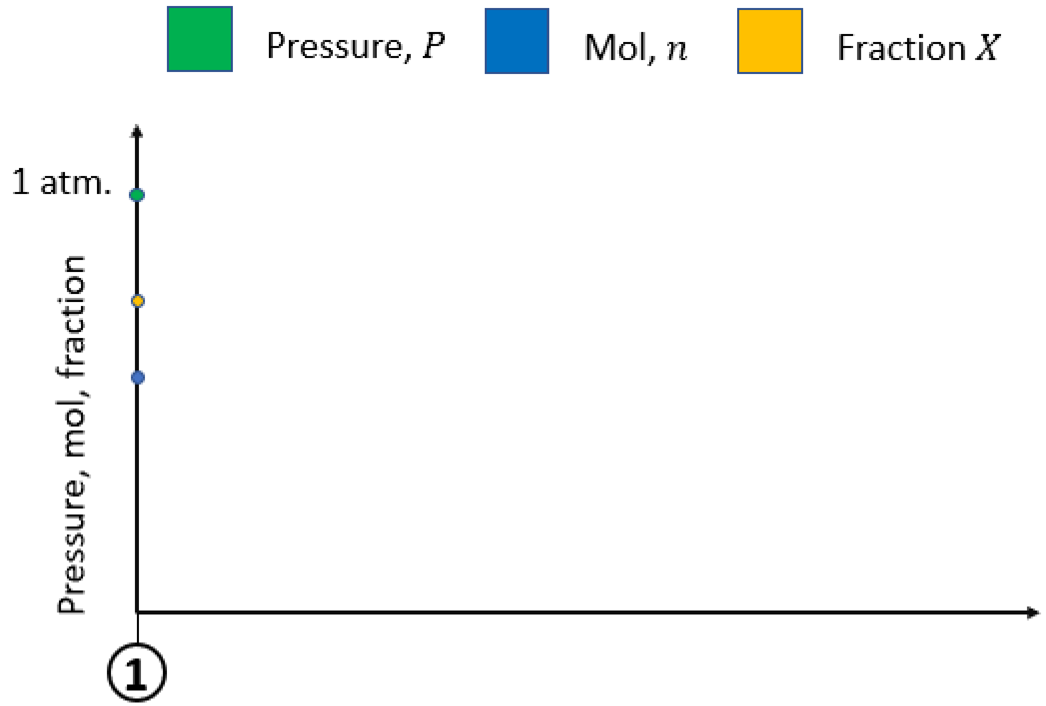
Partial pressures during evacuation

	P	XO_2	$Sens.O_2$	$Mol\ O_2$	action
1	1 bar	0.2	200 000	5.32	Lock off inlets to build chamber, run vacuum pump



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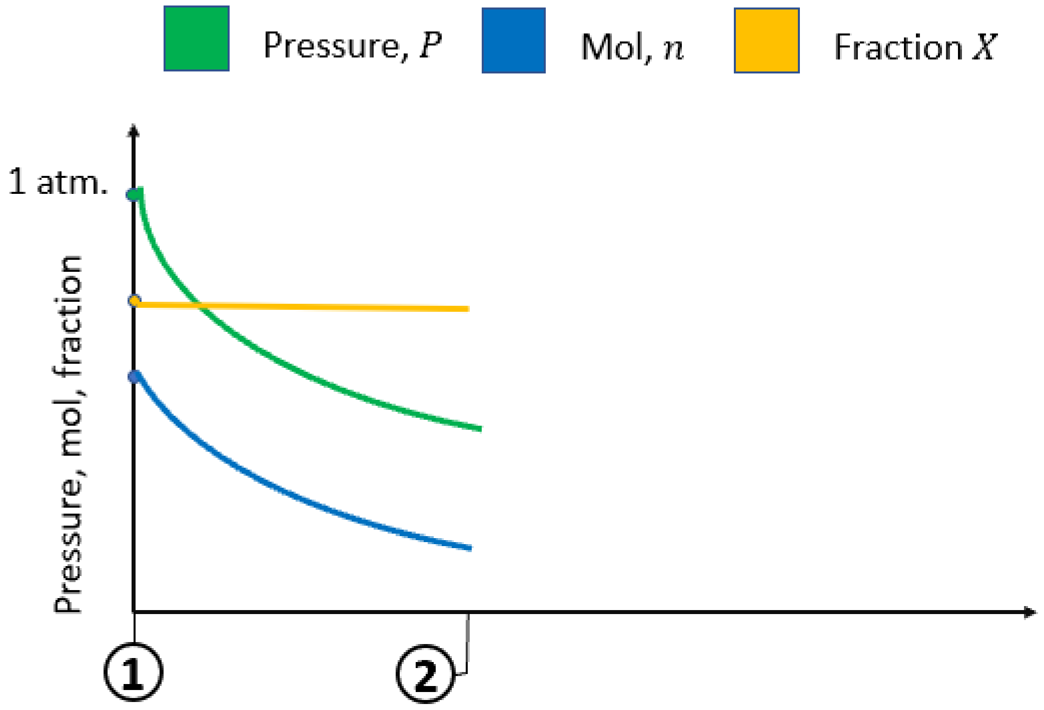
Partial pressures 1-2

$$P_2 = 0.1P_1 \approx 0.1\,atm.$$

$$n_2 = 0.1n_1 \approx 0.532$$

$$X = \frac{n_{2o_2}}{n_2 total} = \frac{n_{1O_2}}{n_{1total}} \approx 20\%$$

	P	XO_2	$Sens.O_2$	Mol O_2	action
1	1 bar	0.2	200 000	5.32	Lock off inlets to build chamber, run vacuum pump
2	0.1 bar	0.2	20 000	0.532	Lock off outlet to bc, run Ar



Partial pressures 2-3

$P_3 = 0.8P_1 \approx 0.8\ atm.$

$n_{3O_2} = n_{2O_2} \approx 0.532\ mol\ etc\ for\ other\ gases$

$P_{ArInlet} = P_{3total} - P_{3O_2} + P_{3N_2} + P_{3ArAtmos}$

$$= 800E^3Pa - \frac{(0.532mol + 1.982mol + 0.024mol)\left(\frac{8.314J}{molK}\right)(388K)}{(0.6m^3)}$$

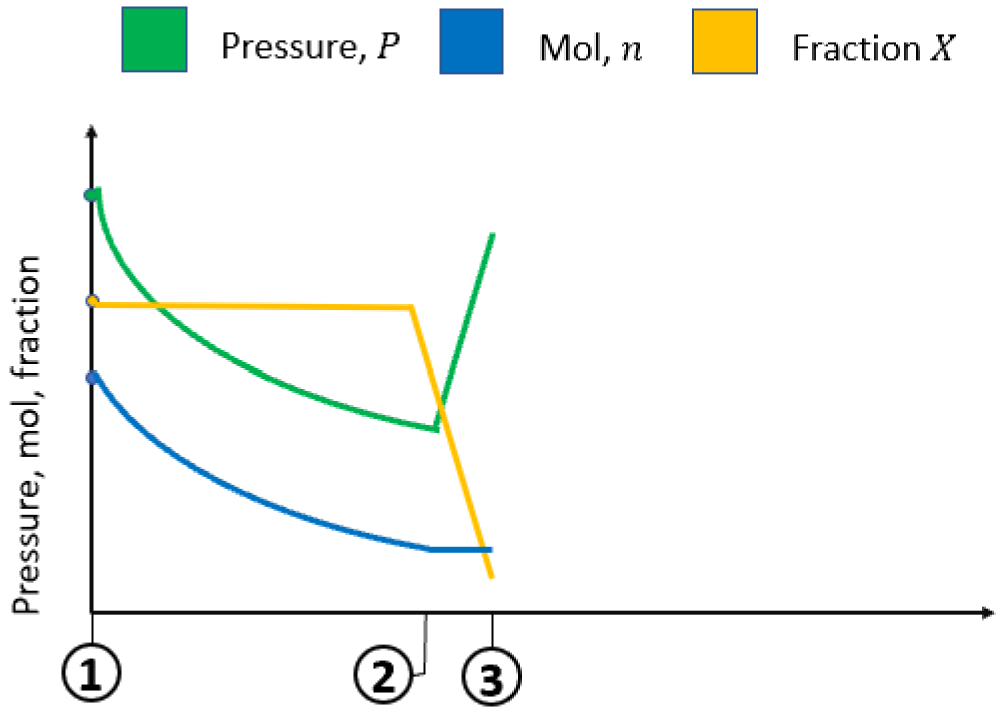
$-800E^3 - 13{,}65E^3 = 78.63kPa$

$$n_{ArInlet} = \frac{P_{ArInlet}V_{chamber}}{R_U T} = \frac{(78.63kPa)(0.6m^3)}{\left(\frac{8.314J}{molK}\right)(288K)} = 19.7mol$$

$n_{3total} = n_{2O_2} + n_{2N_2} + n_{ArAtmos} + n_{other_{nArInlet}}$

$$X_{O_2} = \frac{n_{3O_2}}{n_{3total}} = \frac{0.532}{20.78} = 0.026$$

	P	XO_2	Sens.O_2	Mol O_2	action
1	1 bar	0.2		5.32	Lock off inlets to build chamber, run vacuum pump
2	0.1 bar	0.2	20 000	0.532	Lock off outlet to bc, run Ar
3	0.8 bar	0.026	20 000	0.532	Open other inlets, run Ar



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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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Partial pressures 3-4

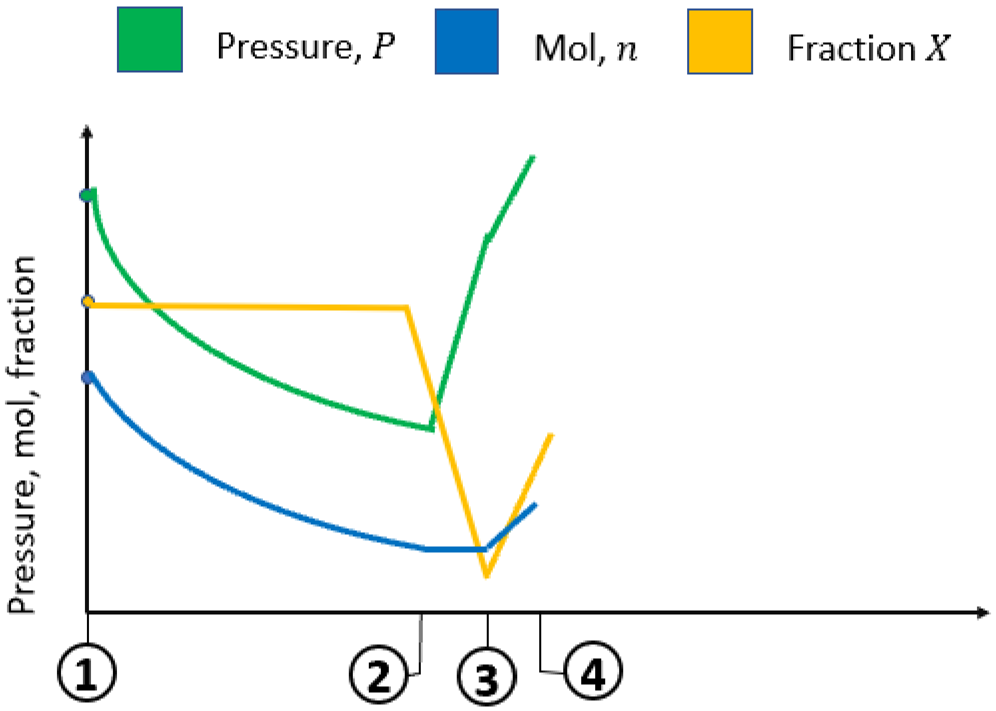
$$n_{4O_2} = n_{O_2 other} + n_{4O_2} = 1.06mol + 0.532mol = 1.92mol$$

$$P_{O_2 other} = \frac{(1.92mol)\left(8.3145\frac{J}{molK}\right)(288K)}{0.6\text{m}^3 + 0.12\text{m}^3} = 6.38\text{kPa}$$

$$P_{4ArInlet} = P_{4total} - \left(P_{O_2} + P_{ArAtmos} + P_{N_2}\right) - P_{3Ar}$$
$$= 110kPa - 26.26kPa - 78.63\text{kPa}$$
$$= 5.11kPa$$

$$X_{O_2} = \frac{P_{O2}}{P_{total}} = 0.058$$

	P	XO_2	Sens.O_2	Mol O_2	action
1	1 bar	0.2	200 000	5.32	Lock off inlets to build chamber, run vacuum pump
2	0.1 bar	0.2	20 000	0.532	Lock off outlet to bc, run Ar
3	0.8 bar	0.026	20 000	0.532	Open other inlets, run Ar
4	1.1 bar	0.058	72 180	1.92mol	Cycle ends, return to one.



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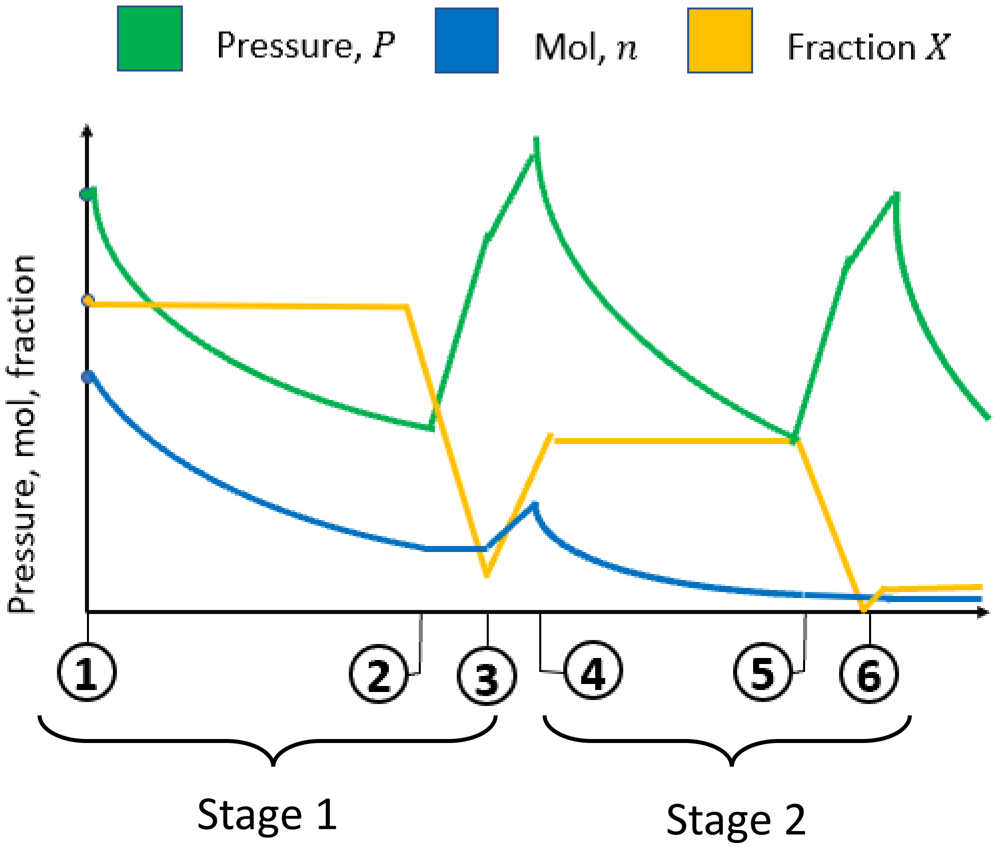
Partial pressures during evacuation 4-6

	P	XO_2	Sens.O_2	Mol O_2	action
1	1 bar	0.2	200 000	5.32	Lock off inlets to build chamber, run vacuum pump
2	0.1 bar	0.2	20 000	0.532	Lock off outlet to bc, run Ar
3	0.8 bar	0.026	20 000	0.532	Open other inlets, run Ar
4	1.1 bar	0.058	72 180	1.92mol	Cycle ends, return to one.
5	0.1 bar	0.0058	7 218	0.192 mol	Per 2
6	0.8 bar	0.65E-3	7 218	0.192 mol	Per 3



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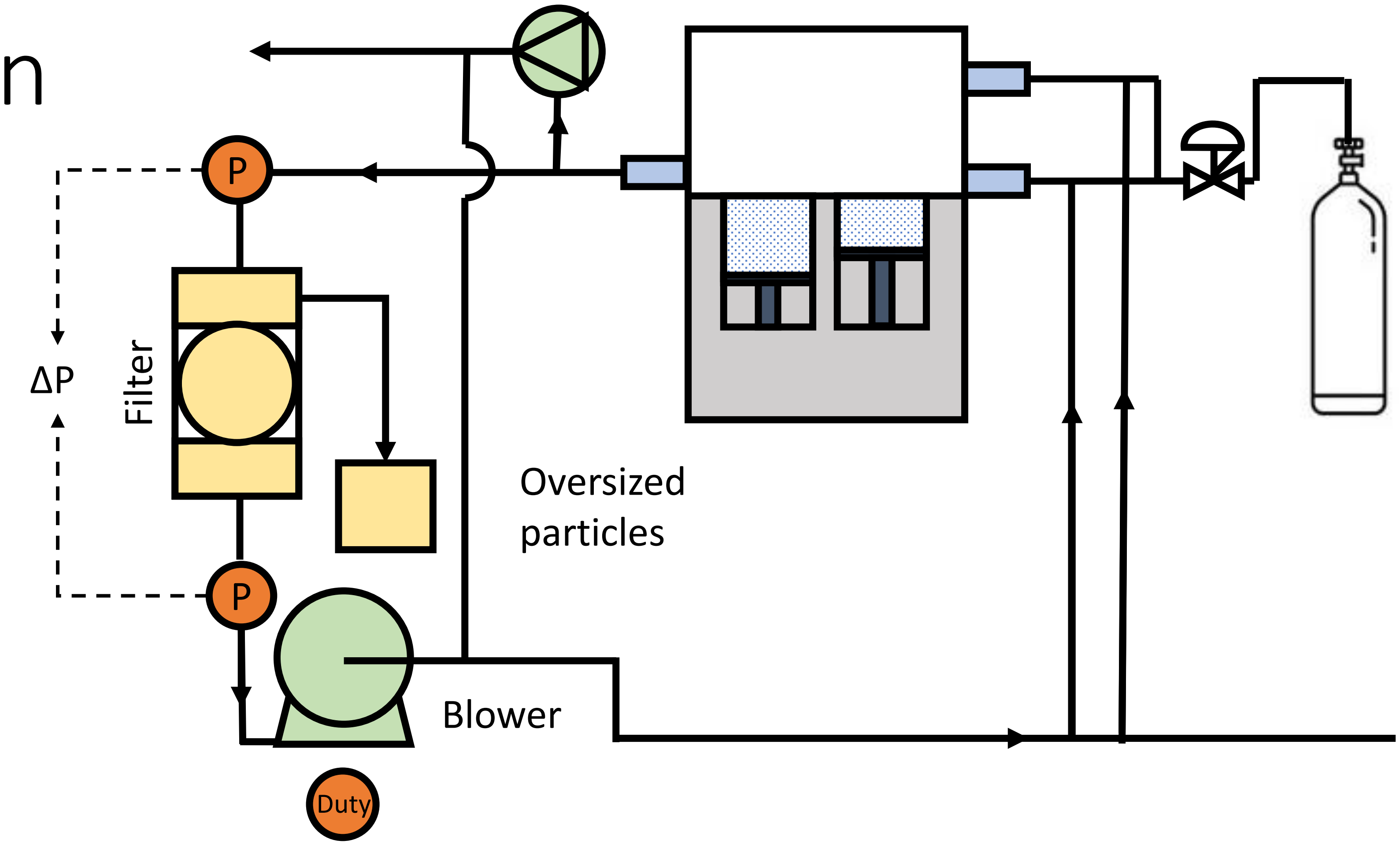
Filters - Function

Housing (removable)

Internal filter (disposable)



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Filters – safe change

Buddy system for changing large filters which cannot be isolated pre-removal

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Process monitoring: overview

Build monitoring

- Buildplate temperature
- Elevator temperature
- Chamber concentration
- Gas pressure
- Recoater position

a 'simple' parameter, usually logged against time

In-process monitoring

- Powder density across bed
- Powder surface
- Powder bed compaction
- Plume and spatter behaviour
- Particle gas emissions
- Thermal monitoring

logged against time and position

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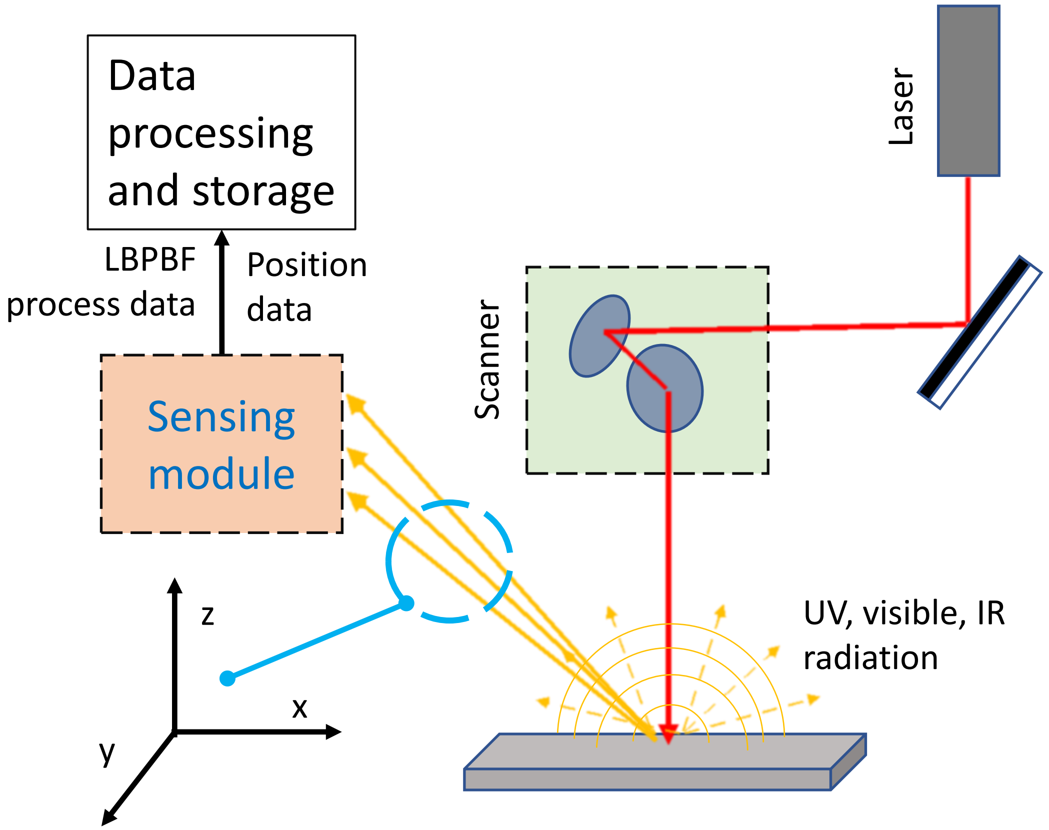
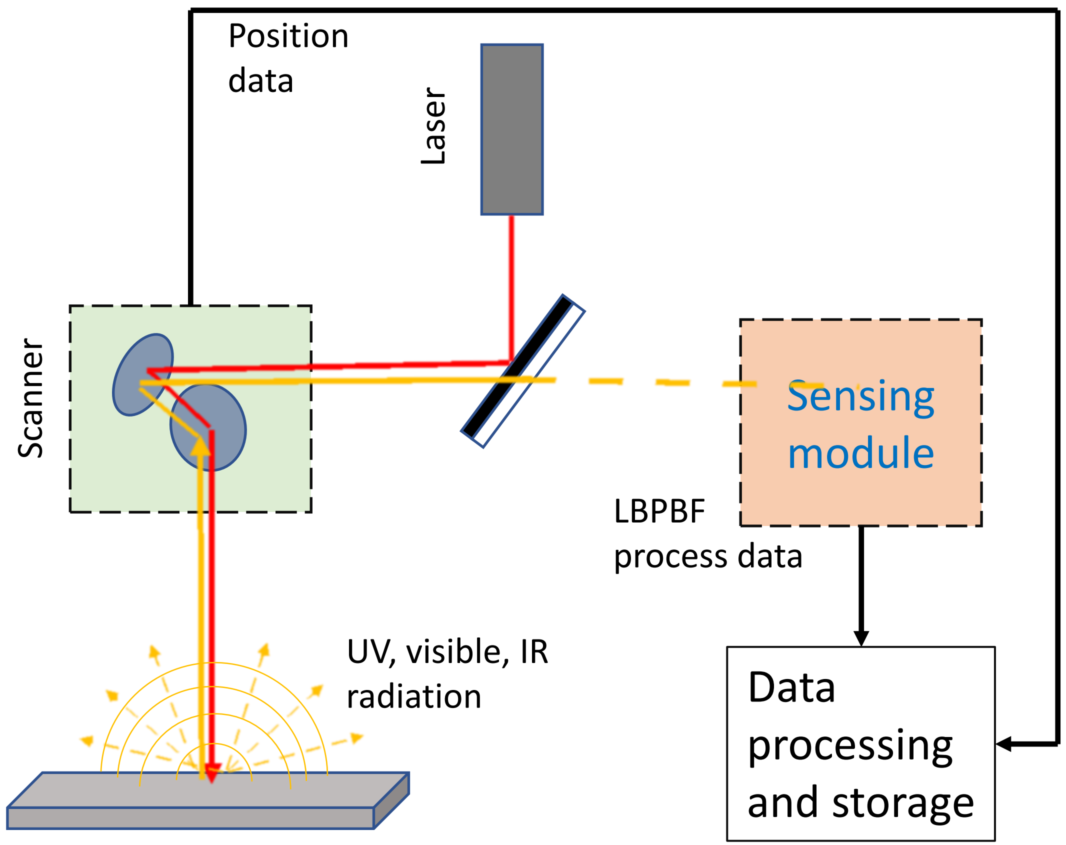
In-process monitoring



Off axis sensing



On axis sensing

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In-process monitoring

Parameter	Method	On/off	Sensor	Example
Powder coverage	Interferometry	On	low resolution interferometer	experimeal only doi: 10.1016/j.phpro.2014.08.100
	Vision system	Off axis	Optical camera	ConceptLaser QMCoating/ 3D Systems DMP Vision Trumpf TrumpfMonitoring SLM LayerCOntrolSolutions
Part distortion	Fringe projection	off axis	CMOS camera	experimental only
	OT	on axis	CMOS camera	experimental only doi:10.3390/met10010103
Meltpool quality	thermal imaging	on axis	High speed CMOS camera/diode	ConceptLaser QMmeltpool3D
	thermal imaging	in axis	infra red diodes	Renishaw InfiniSpectral
	thermal imaging	off axis	Photodiode	DMP meltpool
	Thermal imaging	combined	Diodes	EOState Meltpool
	Optical tomography	Off axis	High speed CMOS camera	EOState Exposure OT

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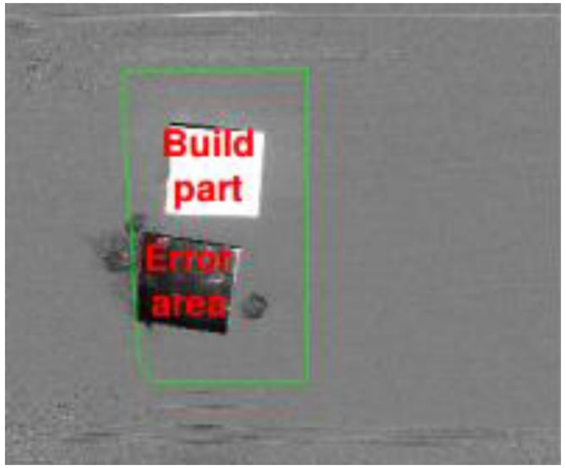
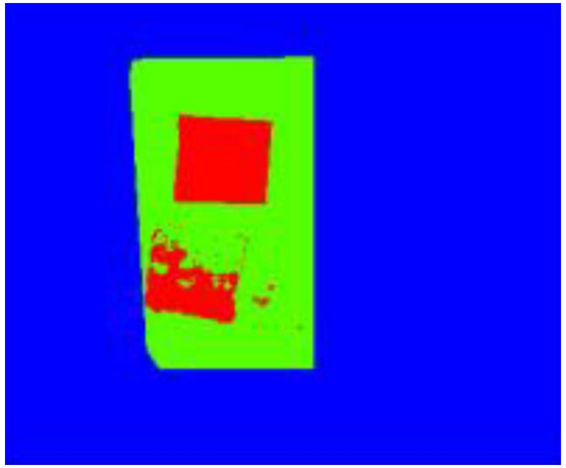
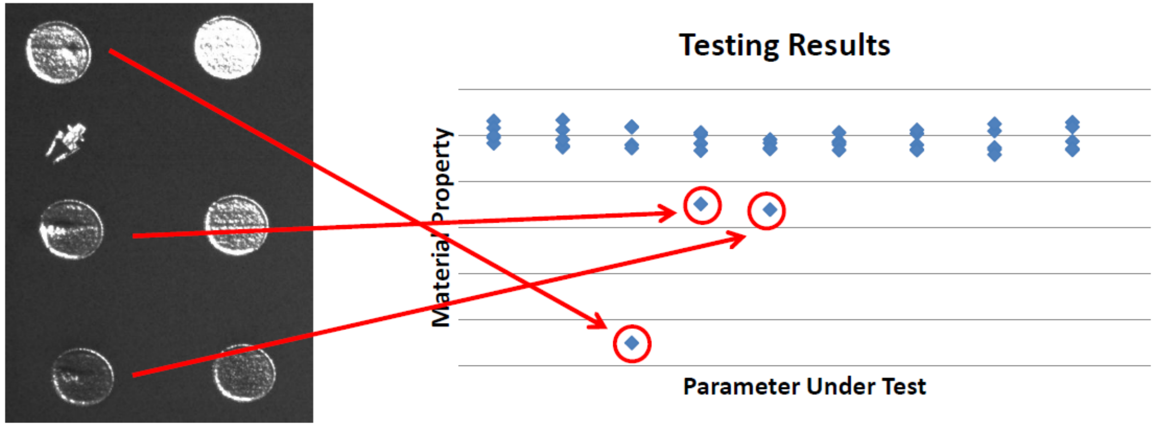
Periodic Off axis vision system

- High resolution camera captures optical images before and after each recoating.
- Gray scale values of before and after images are compared to determine if dosing is sufficient, or if recoating is required.







Bagg, Jones, 2019 https://ntrs.nasa.gov/search.jsp?R=20140016891 2019-08-31T16:37:53+00:00Z

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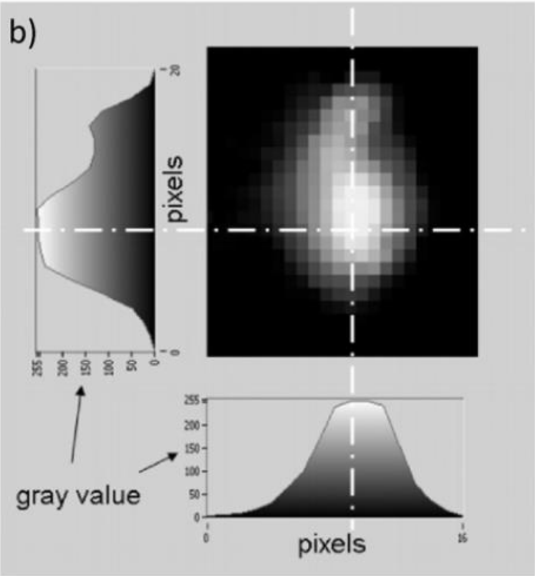
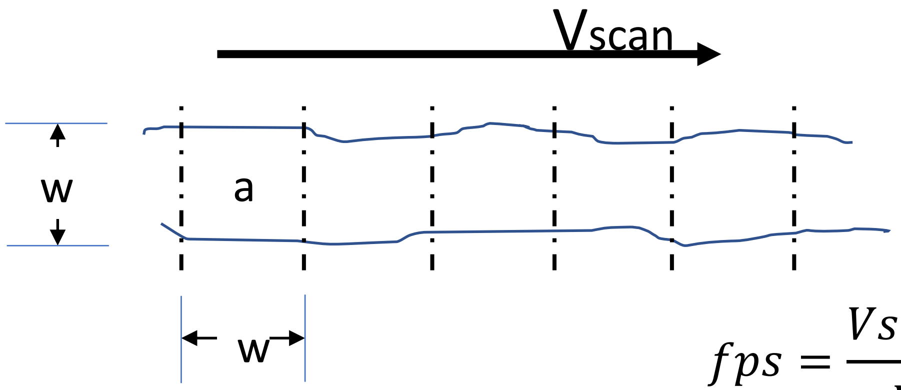
Continuous On Axis optical monitoring –

System description

1. A high speed IR camera captures the meltpool
2. A photodiode measures the brightness intensity of the meltpool

The spatial information from the camera is calibrated by the intensity information from the diode





$$fps = \frac{Vscan}{w}$$

$$n_{data} = (res_x \cdot res_y \cdot bits)(fps)(laser\ time)$$

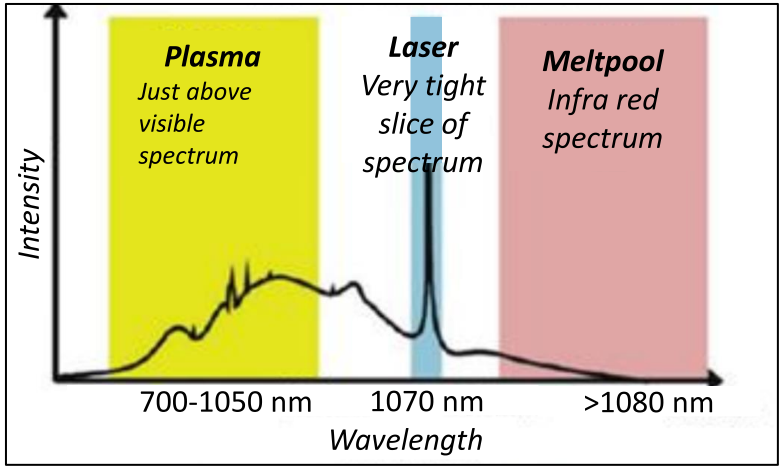
Resx, resy	bits	ndata
40	8	552 Gb
200	12	20.1 Tb

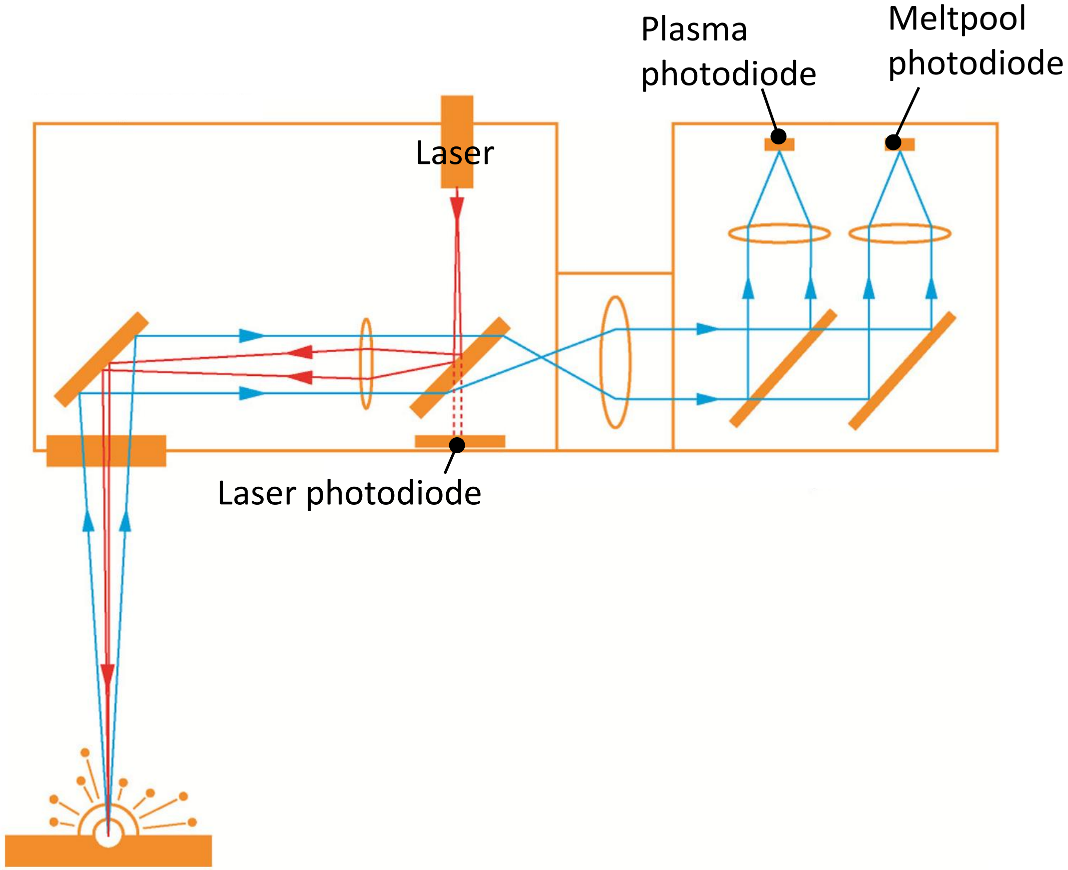
http://dx.doi.org/10.1016/j.matdes.2016.01.099

Continuous On axis spectrum monitoring

System description

1. Diode tightly tuned to 1070 monitors reflected laser
2. IR diodes monitor emitted radiation from meltpool and plasma emmissions





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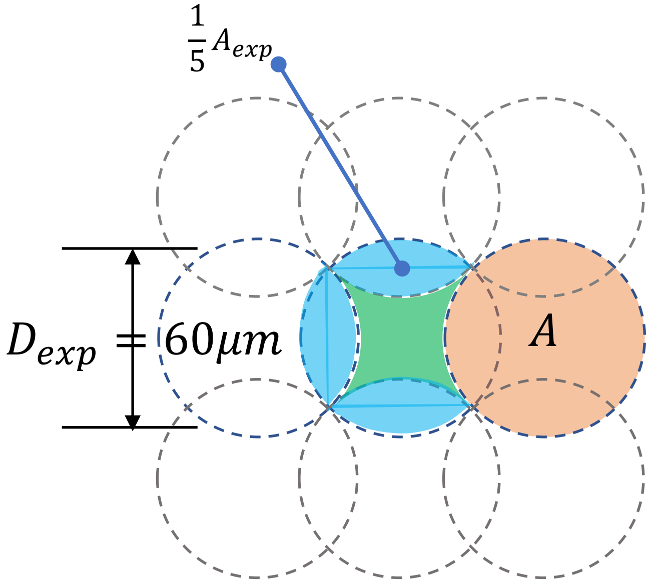
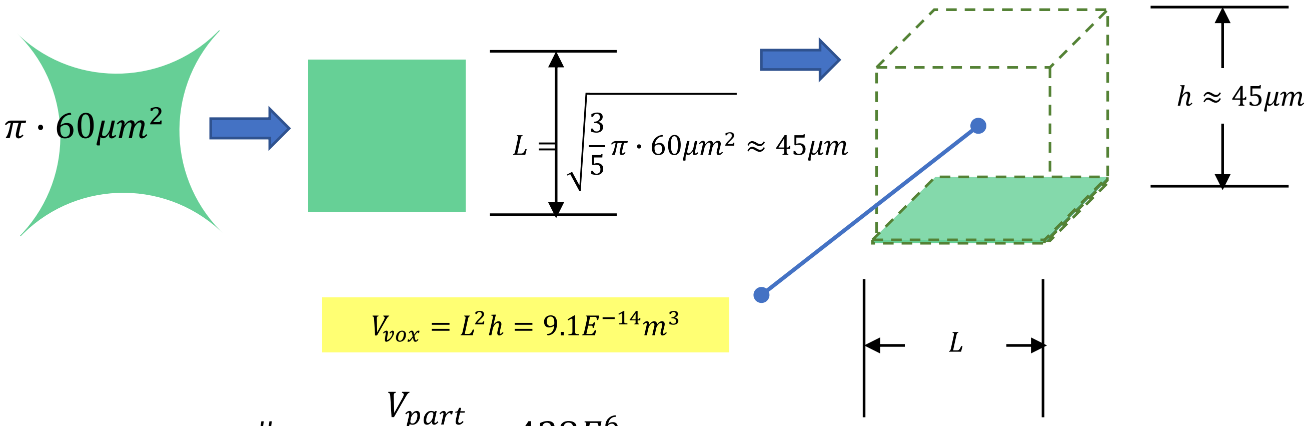
Estimating Volumetric resolution

$$data_{raw} = fps \cdot data/sample \cdot time$$
$$= \frac{10E^3 samples}{second} \cdot 68 \frac{bits}{sample} \cdot 10.8E^3\ seconds$$
$$data_{raw} = 69GB\ file$$

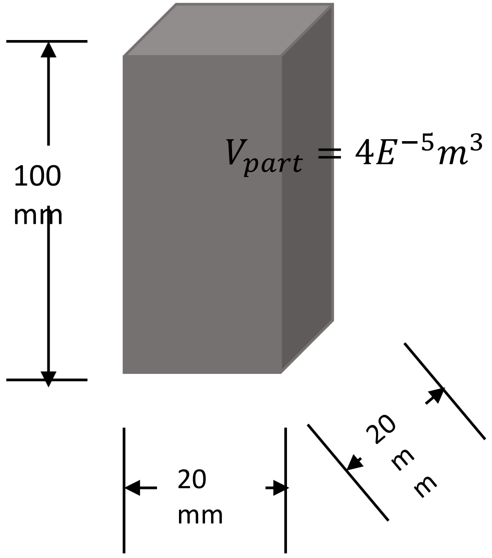


Overlapping pulsed exposures

$$\frac{3}{5}A_{exp} = \frac{3}{5}\pi \cdot 60\mu m^2$$

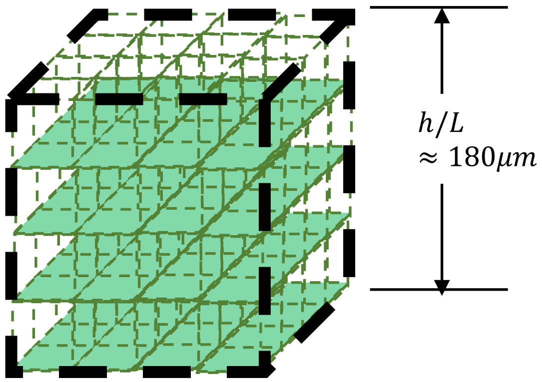


$$V_{vox} = L^2 h = 9.1E^{-14}m^3$$



$$\#vox = \frac{V_{part}}{V_{vox}} = 438E^6$$

$$438E^6 vox \cdot \frac{128bit}{vox} = 56GB$$



$$\#vox = \frac{V_{part}}{V_{vox}} = 6.8E^6$$

$$438E^6 vox \cdot \frac{128bit}{vox} = 878MB$$

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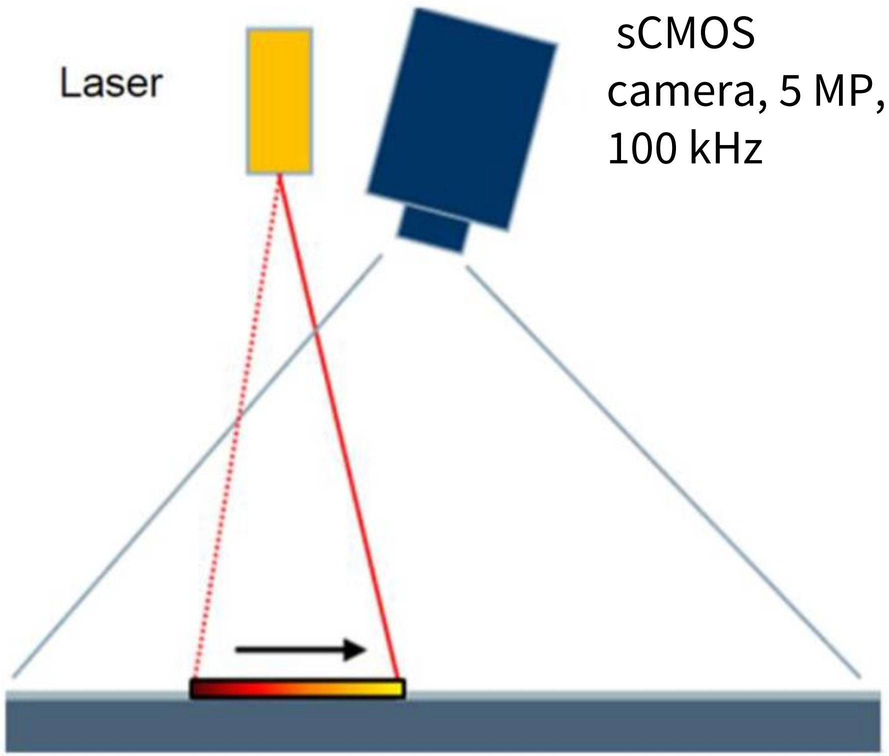
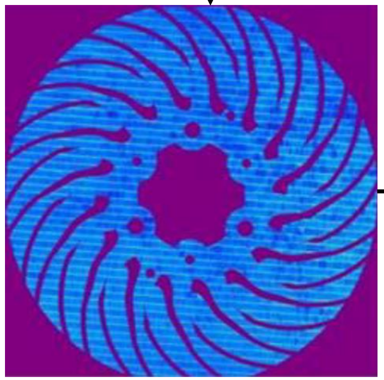
Continuous, Off Axis Optical Tomography



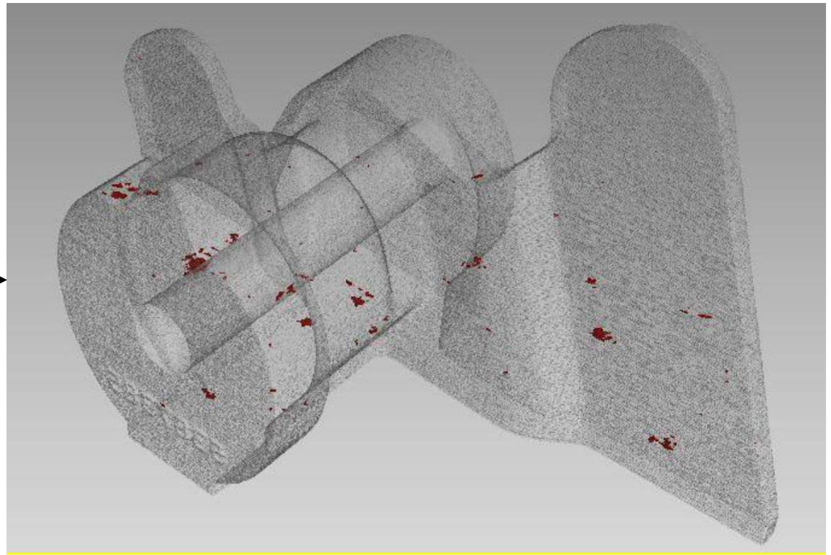
sCMOS camera, 5 MP, 100 kHz

Proprietary data filtering



Single slice

Slices compiled by CT software



Bamburg et al 2014 DOI: 10.1063/1.4914606

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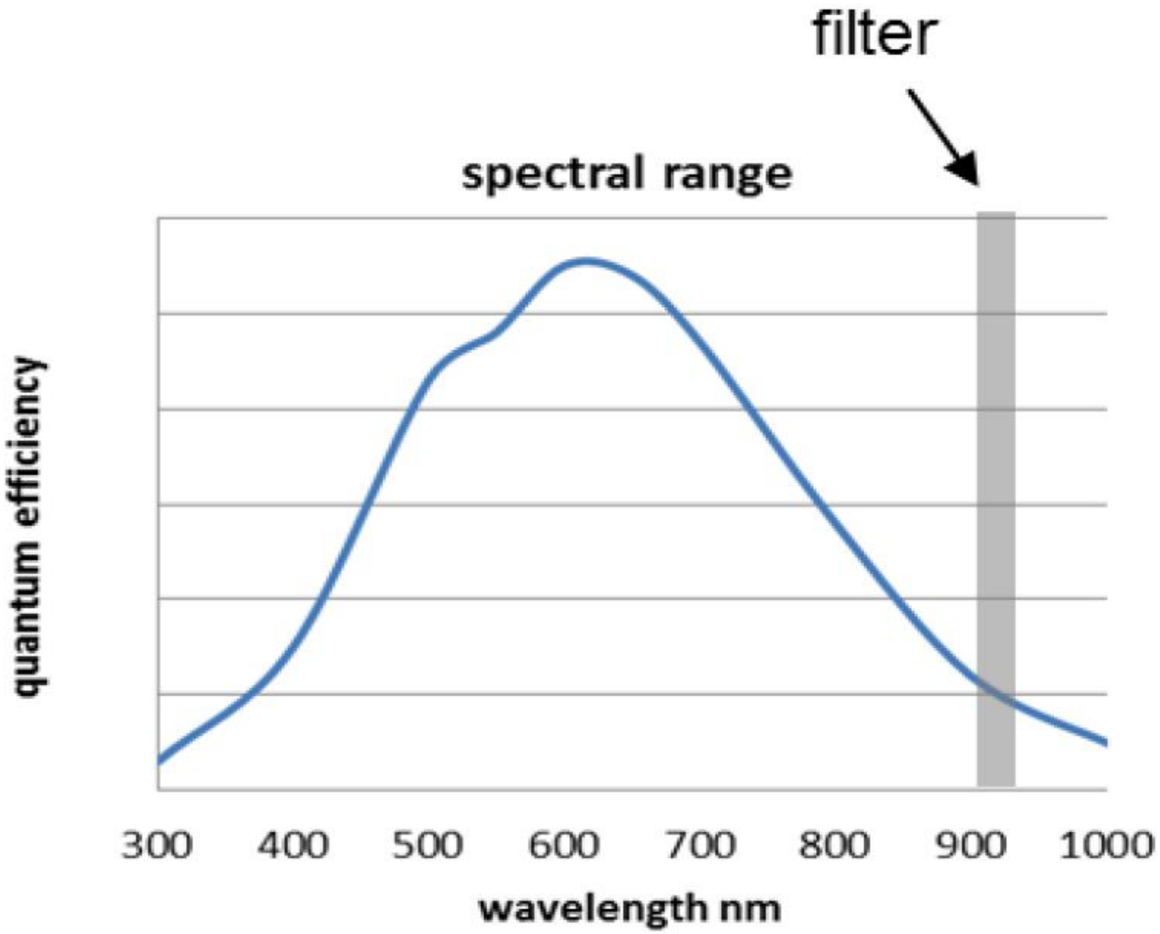
Off Axis Optical Tomography –spectral resolution



Process Monitoring Recap

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SAM
SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

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Support Structures

CU15-9-1: Manufacturing Strategy

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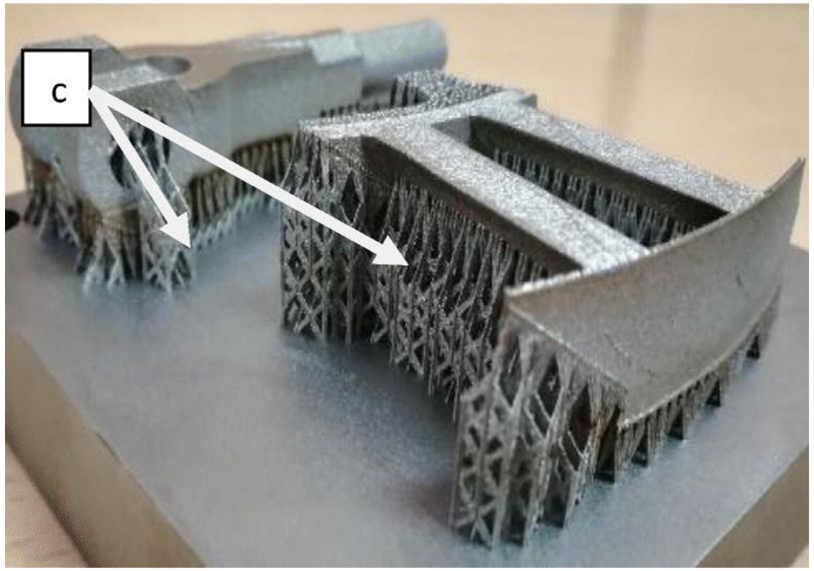
What Are They

Sacraficial structures included within the PBF-LB process which connect specific geometries to the build plate or back to the component



Why Do We Need Them

The use of support structures in PBF-LB is fulfills 3 primary functions:

The primary function of support structures within PBF-LB are to:

- Restrict distortion due to **residual stresses** formed within the part
- Facilitate improved **heat transfer** from the part
- Resist the forces imparted onto the part by the **recoater action**

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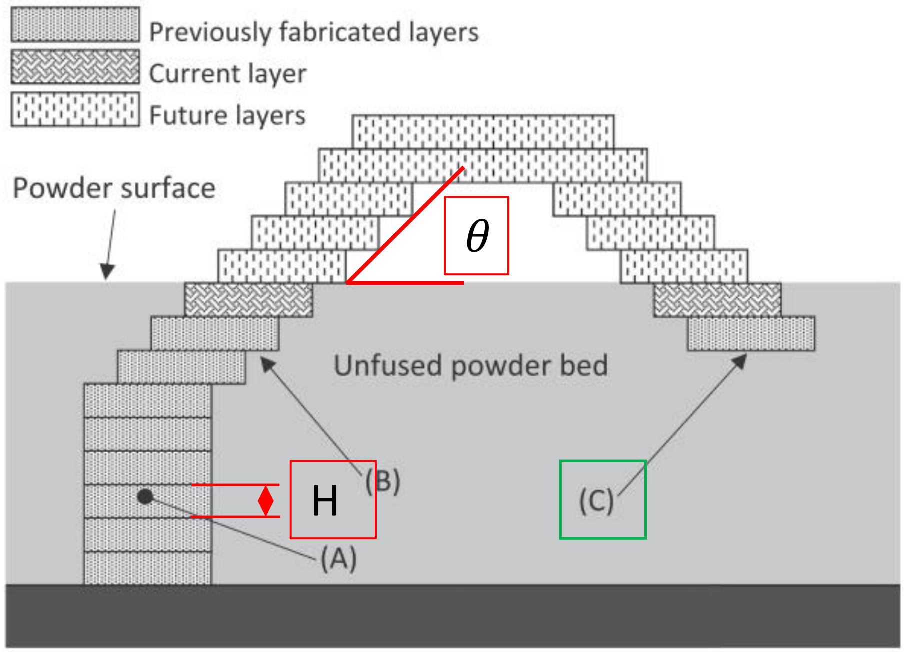
When are they needed

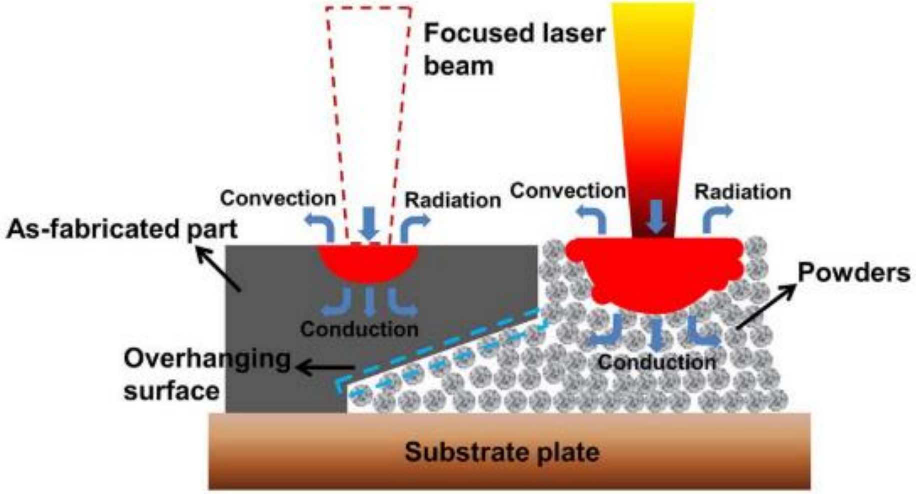
- Component is **overhanging** the powerbed at a steep angle
  - Critical angle varies between materials and machine
  - Common critical angle 45° - 35°
- Feature will be **free floating** within the build chamber
  - Part built above build plate
  - Geometry creates an island
- Parts have large cross sectional area and insufficient **heat transfer**
- Parts have **high aspect ratio** features



$$\emptyset_{meltpool} = H \cdot ctg\theta$$

Heat Transfer

- Thermal conductivity in solid is ~100 x that of conduction through powder
- Supports are needed to aid in heat transfer
- Poor thermal conductivity results in differential cooling within layer
  - Leads in increased residual stress / warp / curl



$$K = \frac{Qd}{A\Delta T}$$

K = thermal conductivity

Q = amount of heat transferred

d = distance between the two isothermal planes

A = area of the surface

ΔT = difference in temperature

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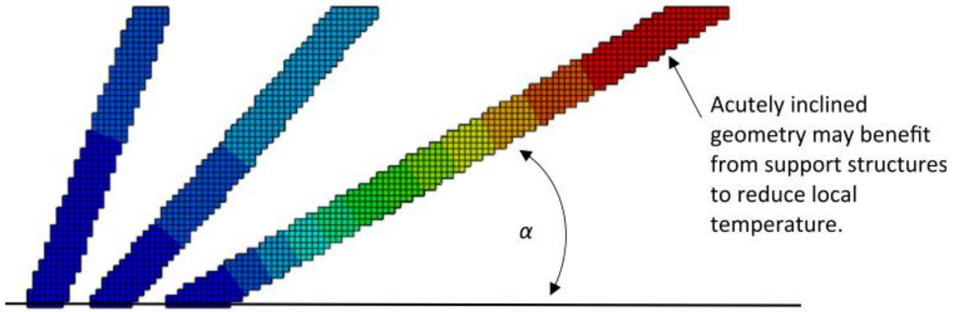
Overheating



- Insufficient thermal conductivity leads to overheating of layer
  - Effects alloying of material
  - Can lead to undesirable microstructure formation
  - Can lead to increased levels of shrinkage

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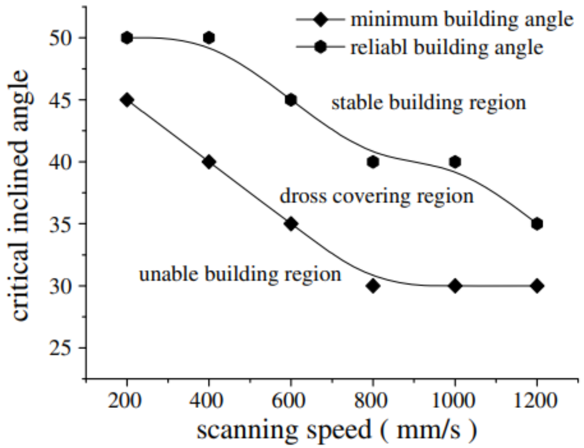
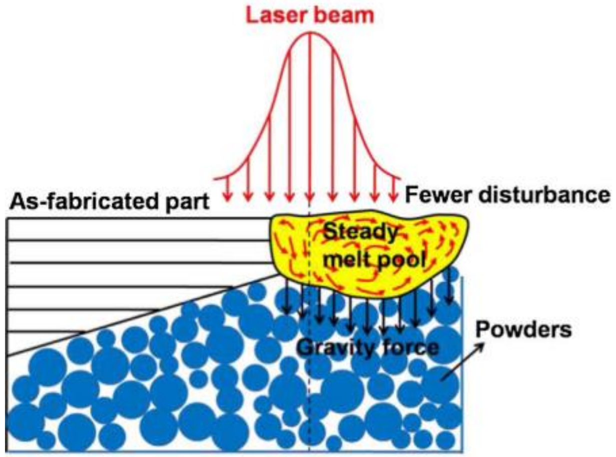
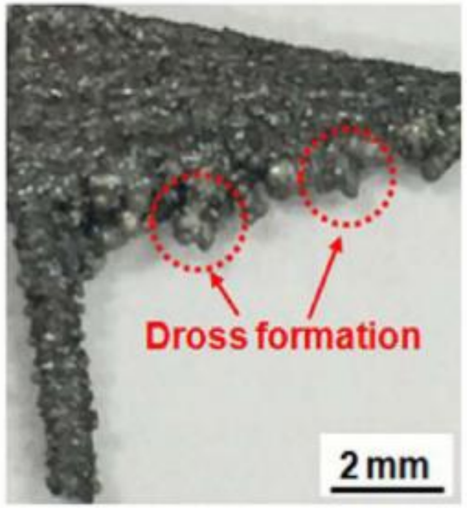
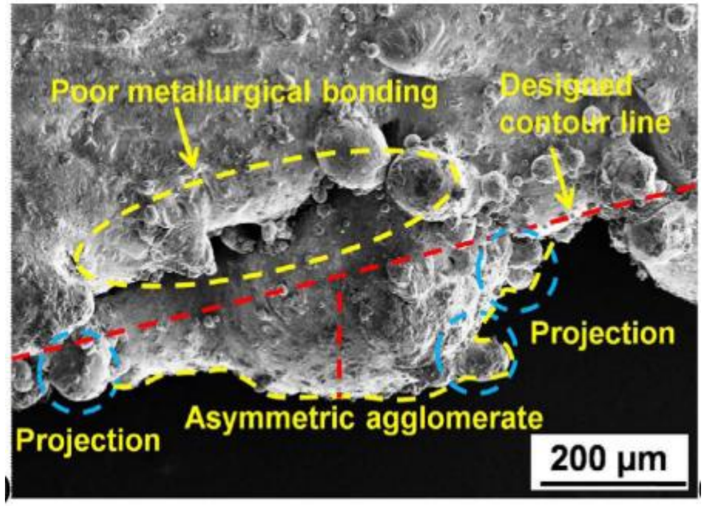
Dross Formation

- Spread of melt pool leads in increase dross on downskin
  - Lower thermal conductivity in the powder bed causes an increase in melt temperature
  - This in turn spreads the melt pool
  - Melt sinks into powder due to gravity









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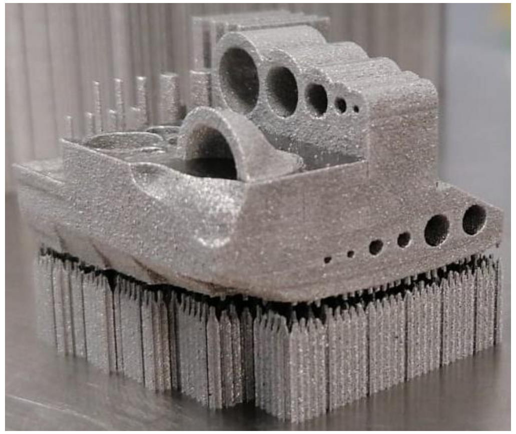
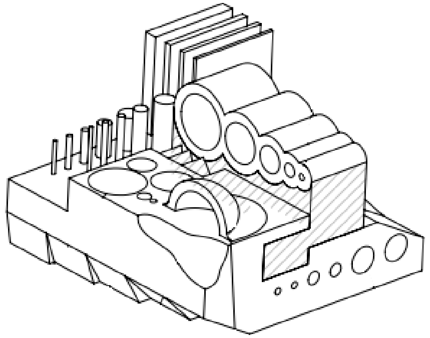
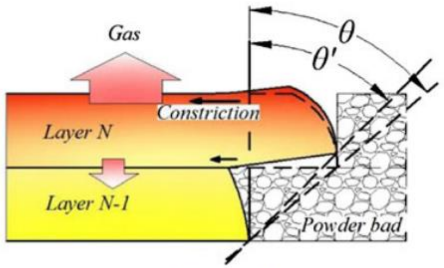
Warping

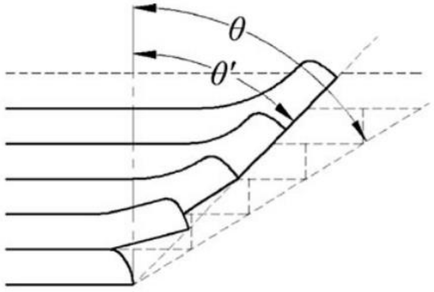




- Rapid cooling and extreme temperature gradiants leads to the formation of stress within the component
- Overhanging geometery is very susceptable to this
  - Curling
- Warping can occur in various modes
  - Strength of supports must be > internal stress due to cooling
- Severe warping = recoater crashes!



(a) warping principle



(b) warping accumulation

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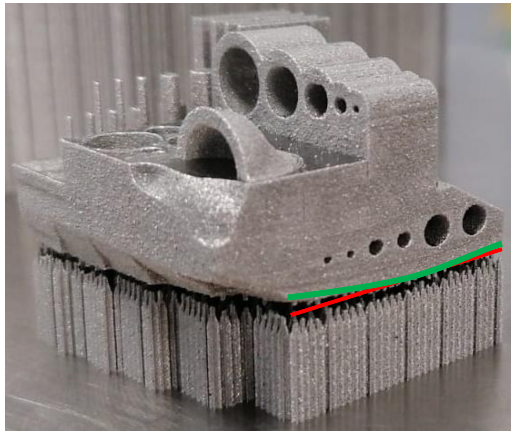
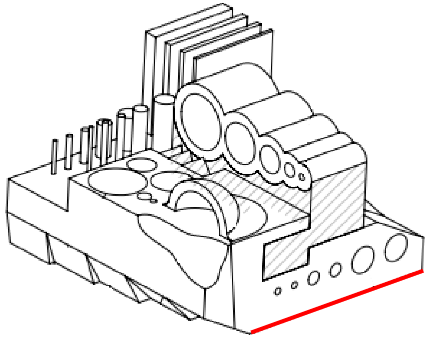
Warping





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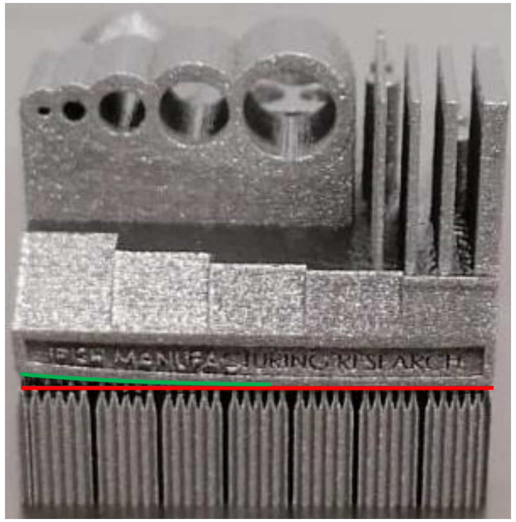

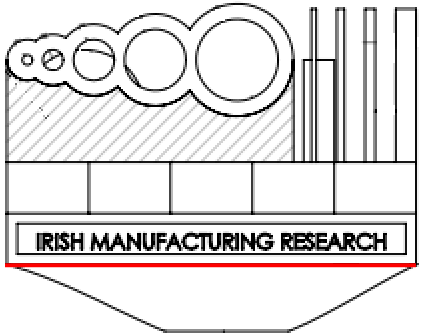

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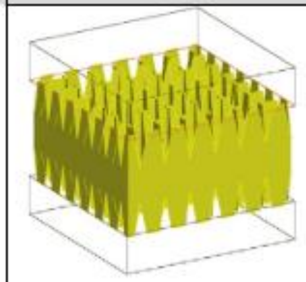
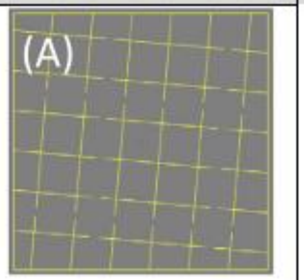
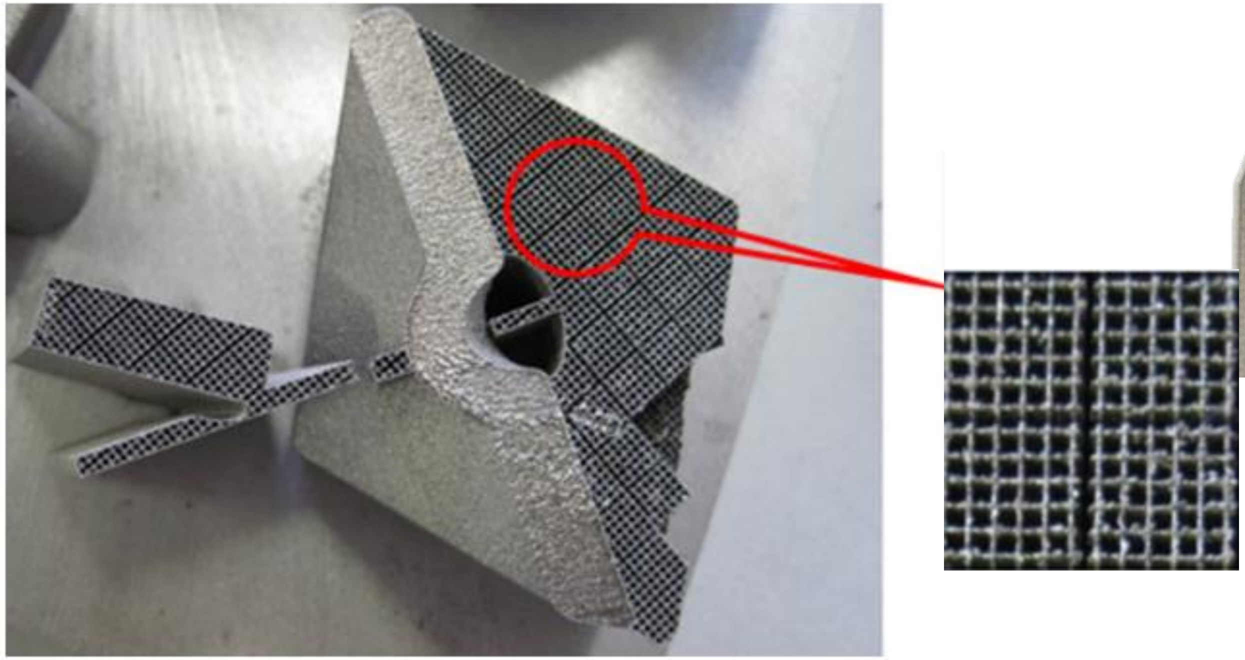
Support Types

- **Block**

Type	3D view	Plan view
Block		



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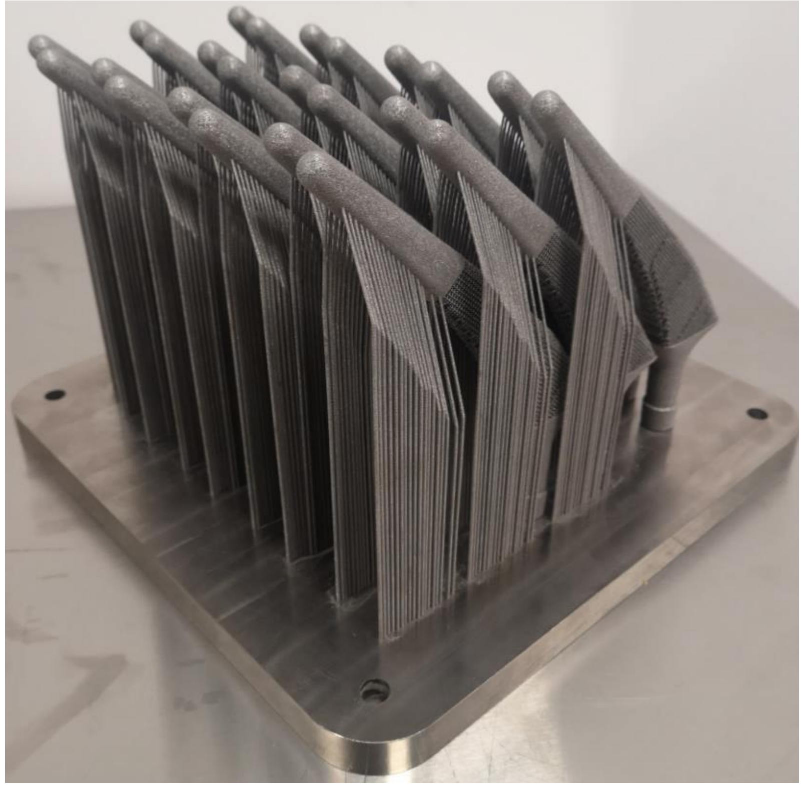
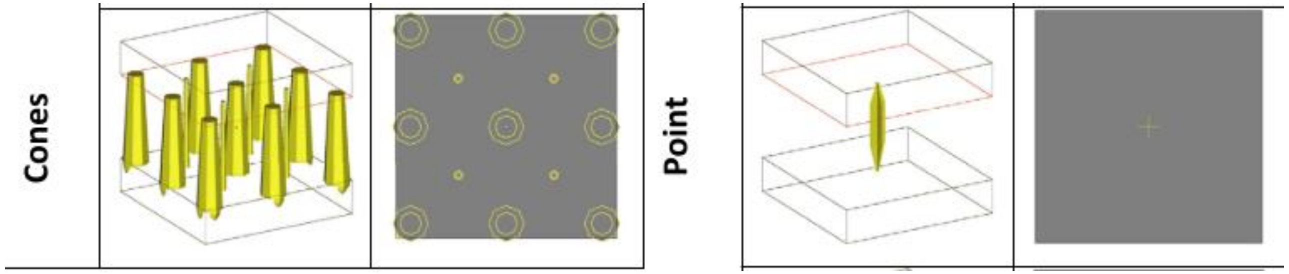
Support Types

- Block
- **Bar**

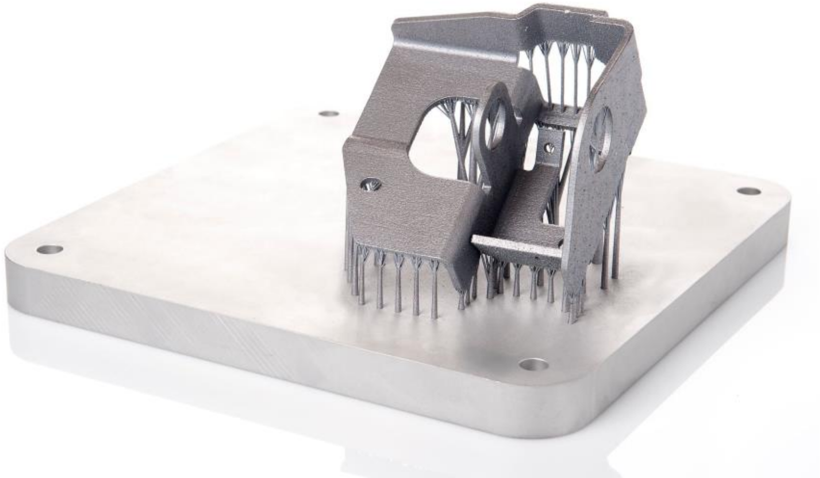


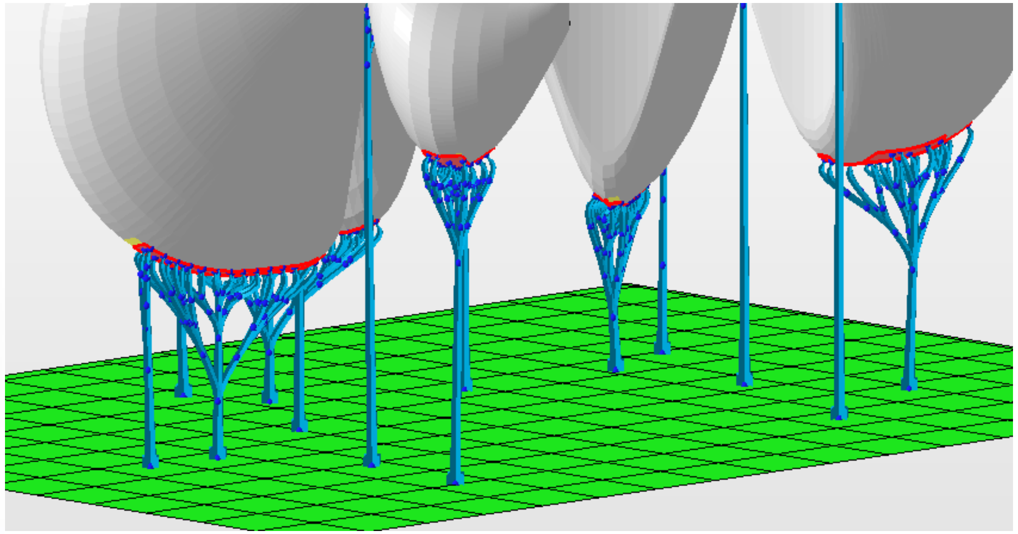


Support Types

Design

- Block
- Bar
- **Tree**





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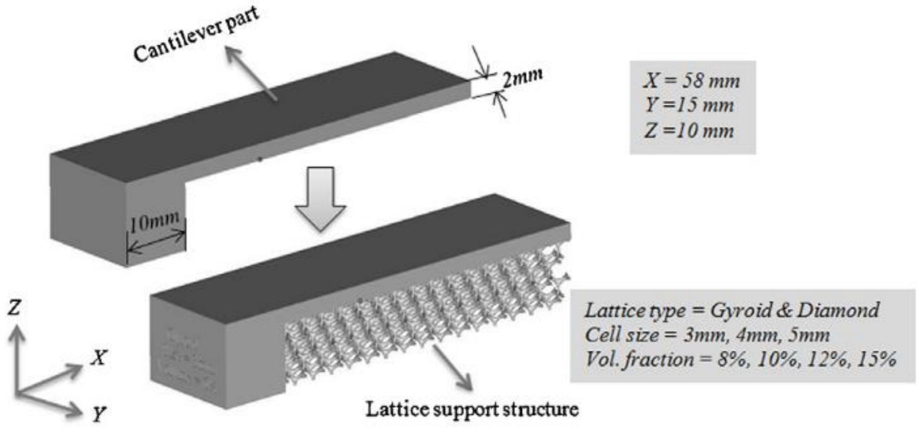
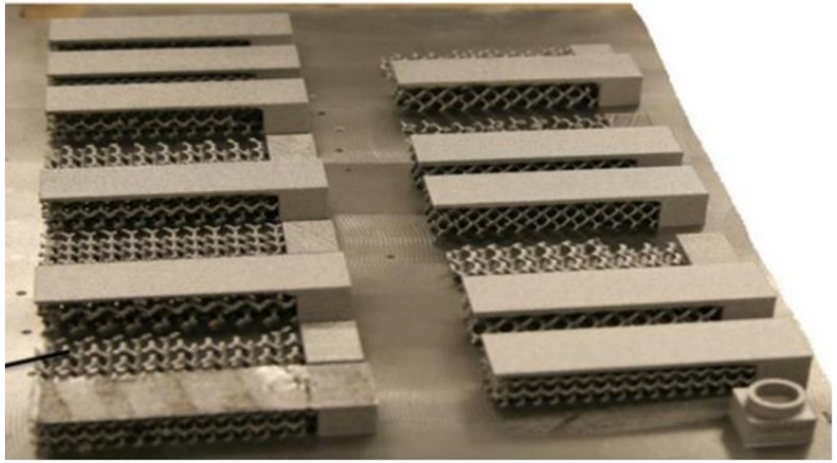
Support Types

- Block
- Bar
- Tree
- **Lattice**





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Investigation of support structures for direct metal laser sintering (DMLS) of IN625 parts - Ö. Poyraz et. al,

Optimisation of support structures for the laser additive manufacturing of Ti64 – Lindecke, Peter Nils Johannes et. al – Procedia CIRP - 2018

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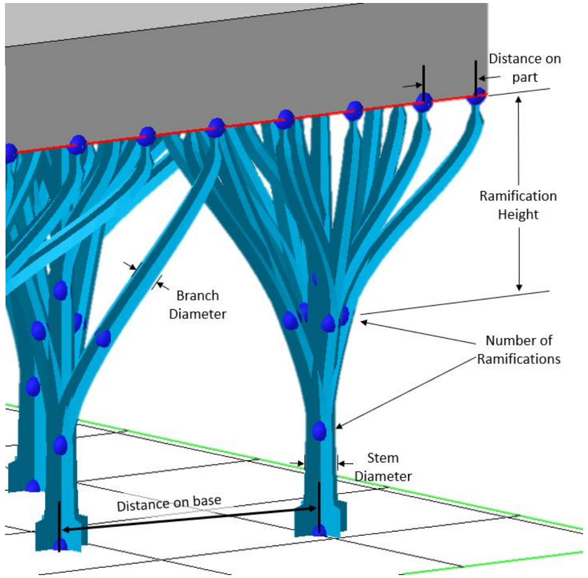
Design Considerations

Key Design Considerations

- Minimize the overall material usage, while maximizing the ease of powder removal from the support structures
- Provide an appropriate surface finish for the affected surfaces of the component
- Consider the specific strength of the connecting structure.

design parameter	support strength	part strength	surface roughness	support removal time	printability	material consumption	printing time
diameter stem	↑	→	→	↑	↗	↑	↑
diameter branch	↑	→	→	↑	↗	↑	↑
number of branches	↑	→	↘	↗	↗	↑	↑
number of ramifications	→	→	→	↗	↗	↑	↑
ramification height	↗	→	→	→	↗	↘	↘
distance of points on part	→	→	↑	↘	↓	→	→
distance of points on base	→	→	↗	↘	↘	→	→



Follow On Sections

- Component Orientation
- Scanning Strategies
- PBF Defects
- AM Standards Landscape

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Scanning Strategies

CU15-9-3: Manufacturing Strategy

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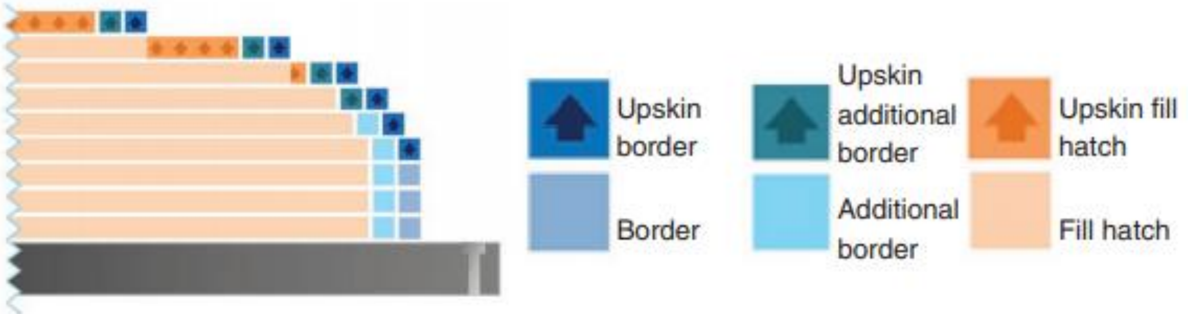
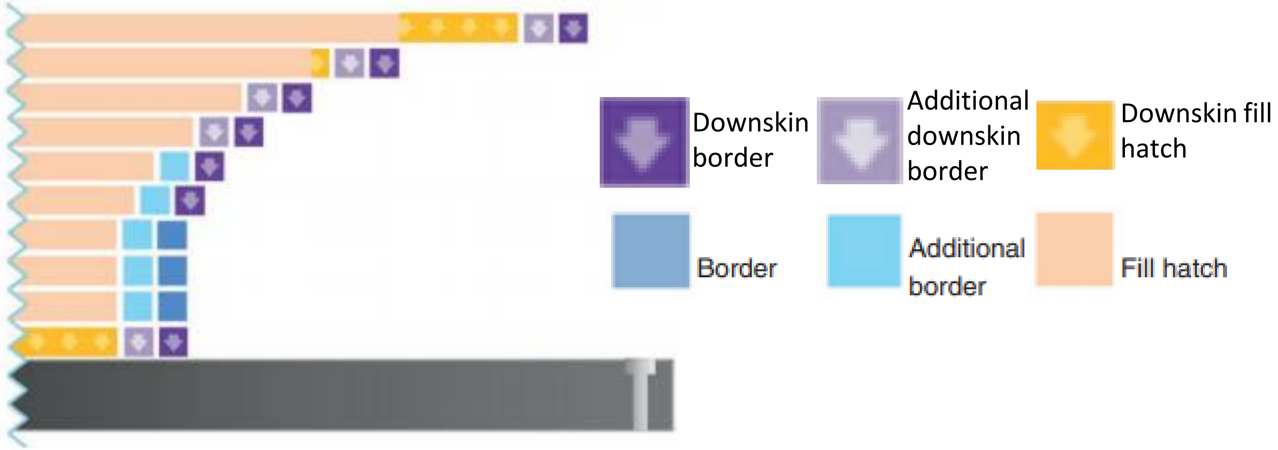
Introduction

- Method of laser tracing is changed depending on required task
- Different laser parameter sets are used depending on required task
- Common tasks include
  - Border creation
  - Bulk infill
  - Additional border hatching
  - Area remelt





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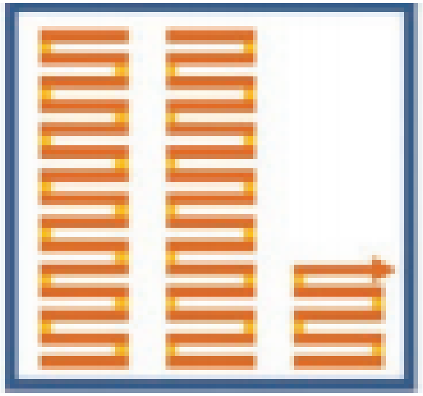
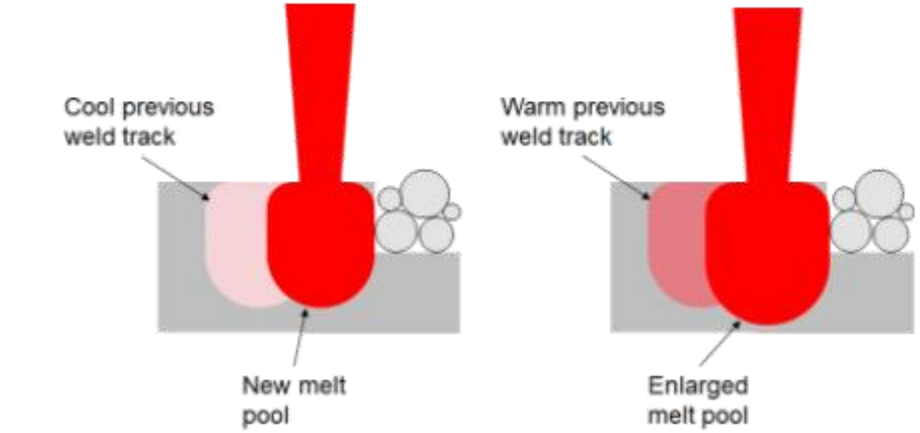
Infill Styles

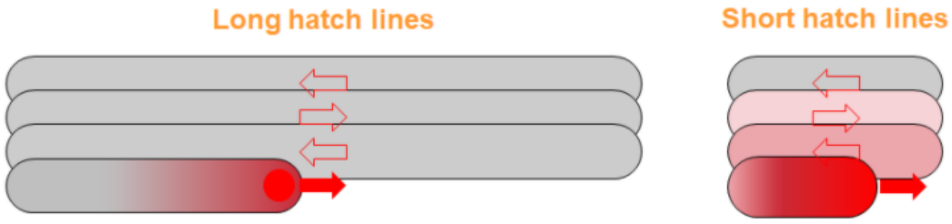
- Stripe
    - Simple Pattern
    - Fast and efficeient
    - Well suited to small cross sections
- Meander
    - Even heat distribution
    - Slower than stripe
    - Suited to large cross section
- Chessboard
    - Even heat distribution
    - Slowest style
    - Suited for difficult materials and very large cross sections

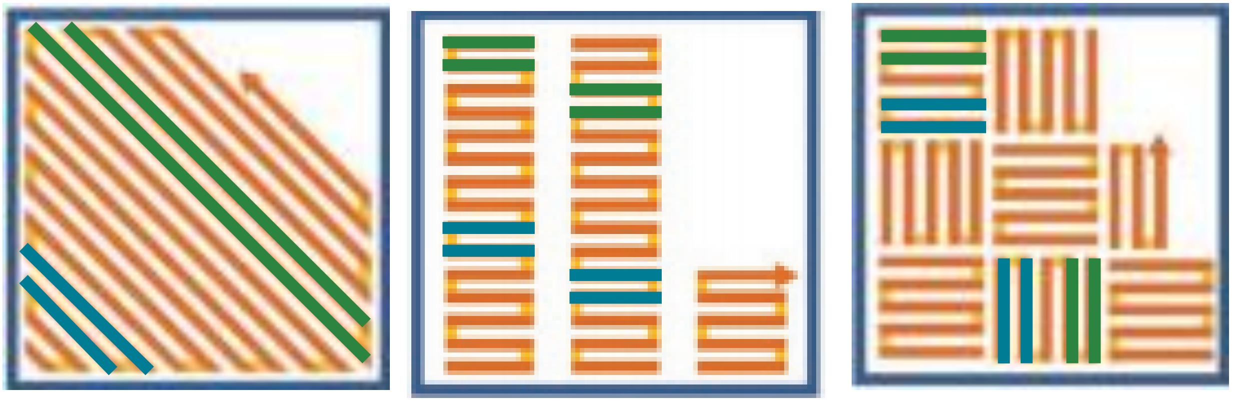


Melt Track Geometery

- We want to maintain a consistent melt pool / track
- Heat of adjedcent melt pool will effect follow on melt pools
- Changes to the size and shape of the melt pool can create porosity







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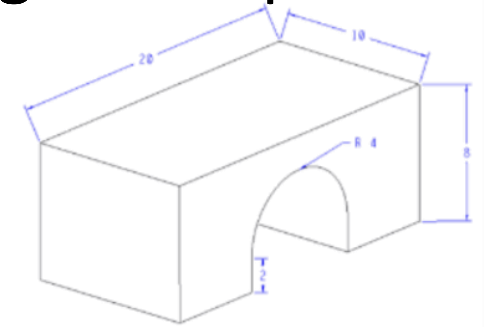
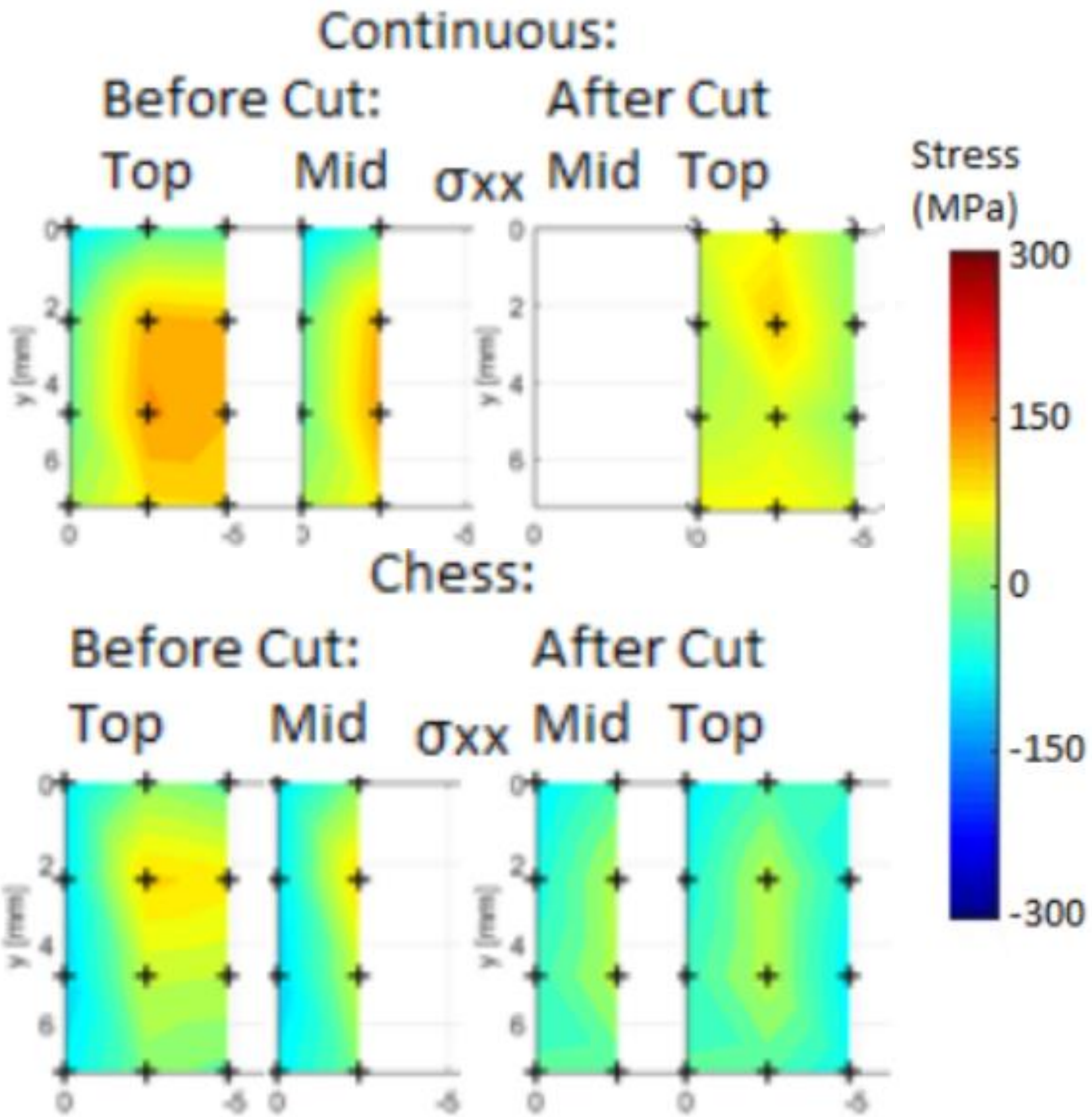
Residual Stress

- We want to minimise residual stress / defect formation
- Long scan paths result in greatest thermal gradient
- Residual stress greatest parallel to scan vector





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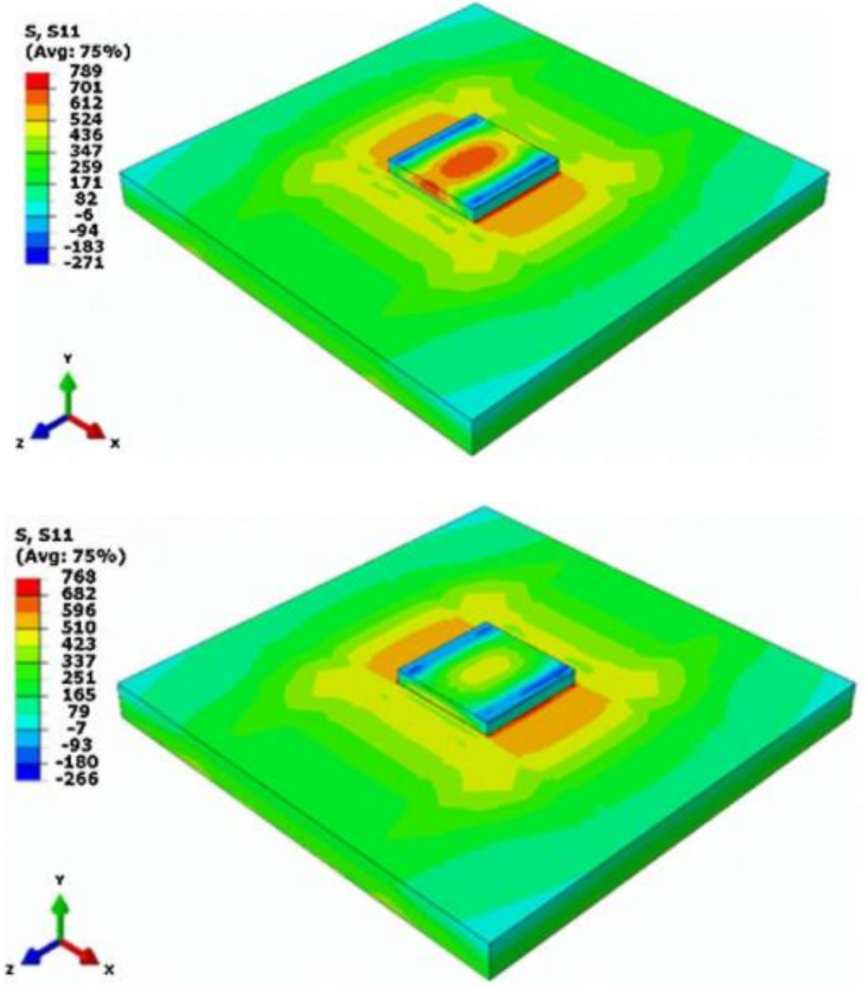
Scan Rotation

- Modern scanning patterns will rotate after each layer
- Residual stress is related to the direction of scan vectors
- Consistent scan patterns allow defects to propagate



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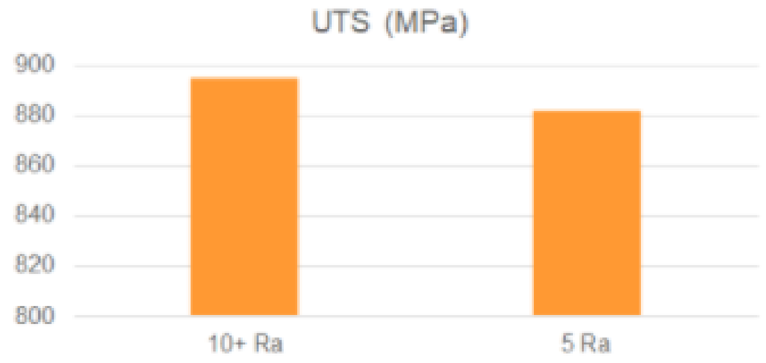
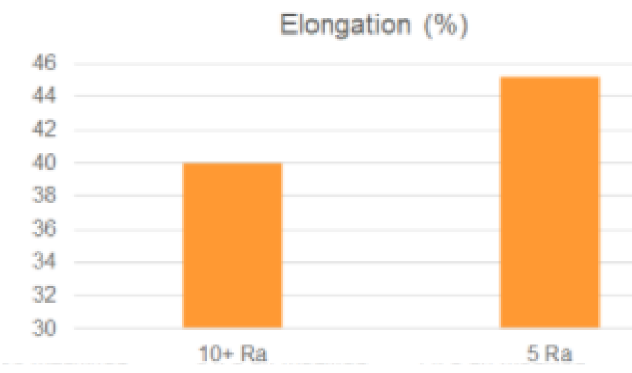
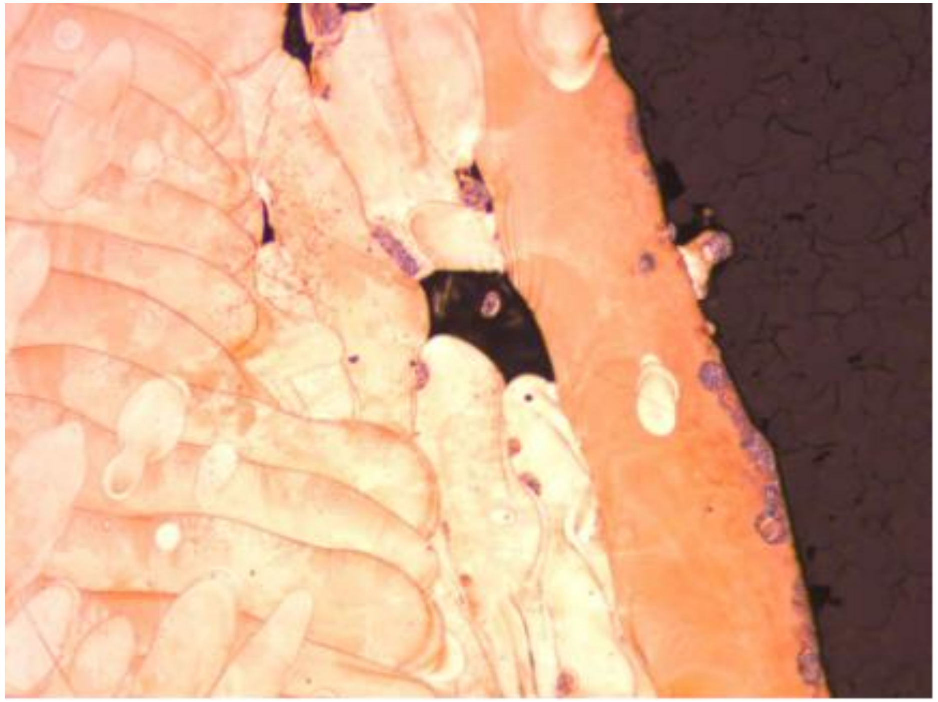
Border Scans





- Trace and define the outer contour of the component
- Optimised to
  - Reduce surface linked porosity
  - Reduce surface roughness
  - Maximise resolution
- Create a fully dense connection to internal hatch



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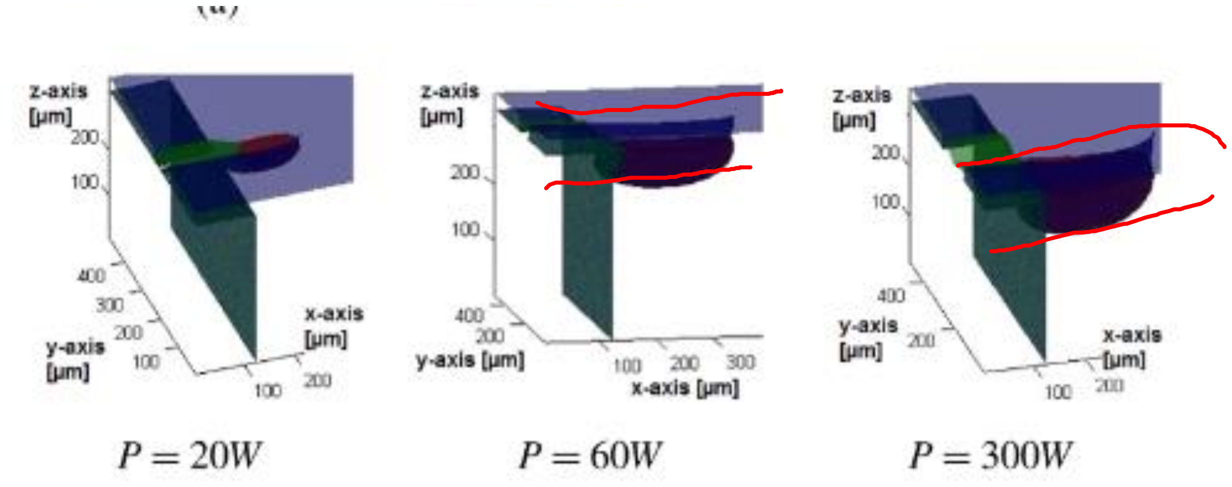
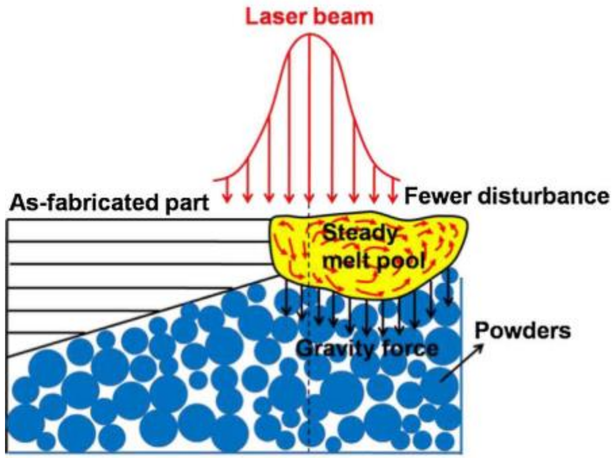
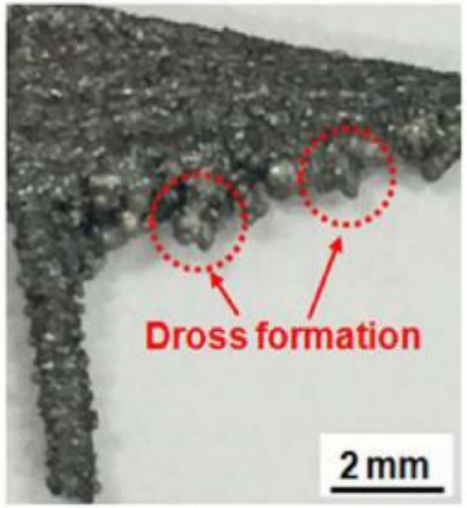
Scanning Strategies

- Special parameter set used for downward facing surfaces
- Thermal conductivity of solid is 10 times that of powder
- Downskin aims to reduce penetration of melt pool into powder bed
- Improves maximum achievable overhang
- Improves surface finish







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Follow on content

- Support structures
- Part positioning
- AM Standards Landscape
- Layer Height
- Defects

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SAM
SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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Layer Thickness

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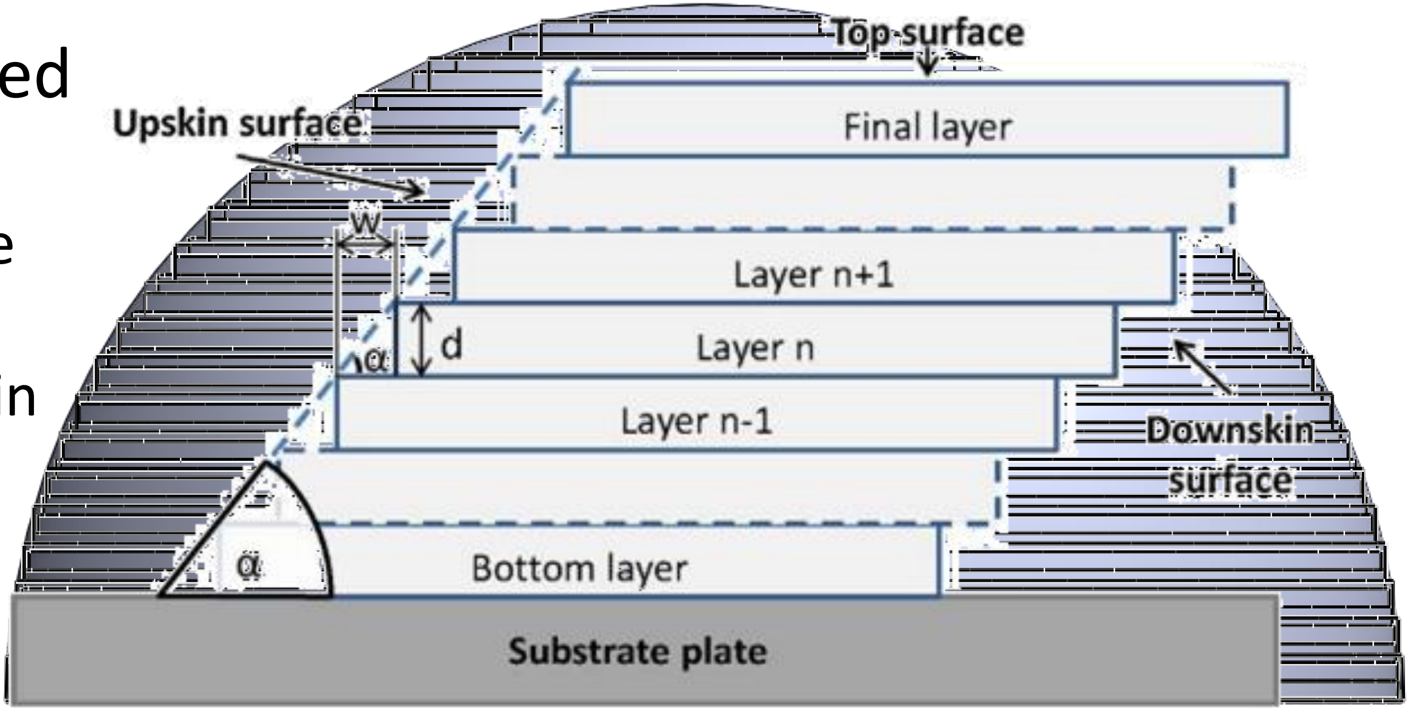
Basic Effects of layer thickness

- Geometeries are “sliced” based on layer thickness
  - This is an approximation of the geometery
  - Increased layer height results in increased loss of resolution



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Layer Thickness

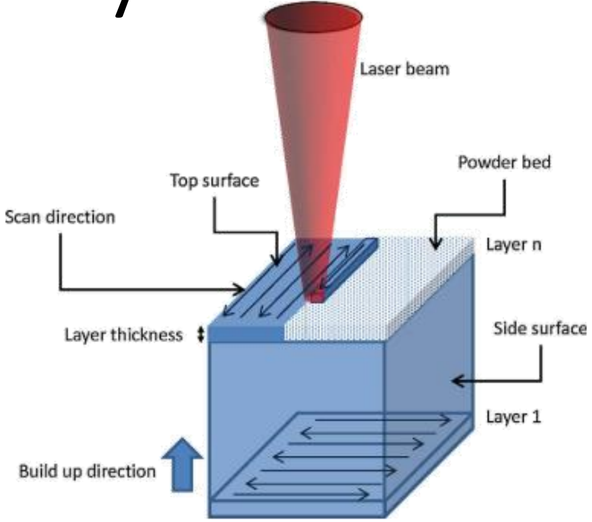


Fig. 3. Schematics of the SLM principle.

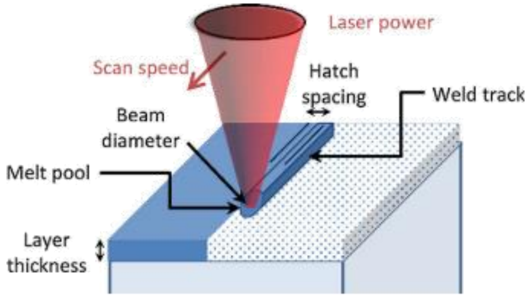
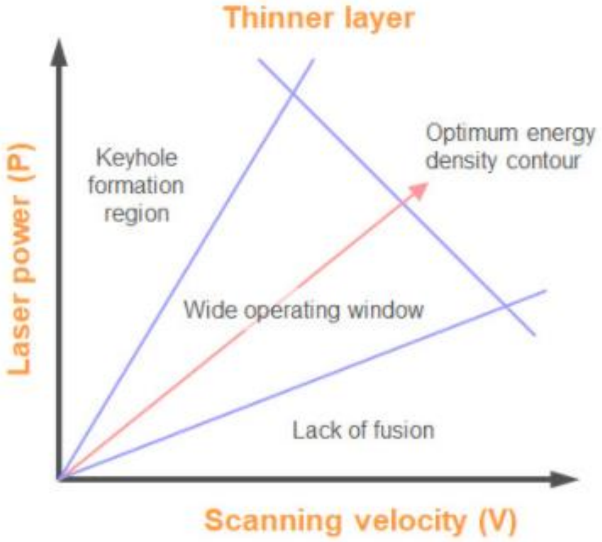
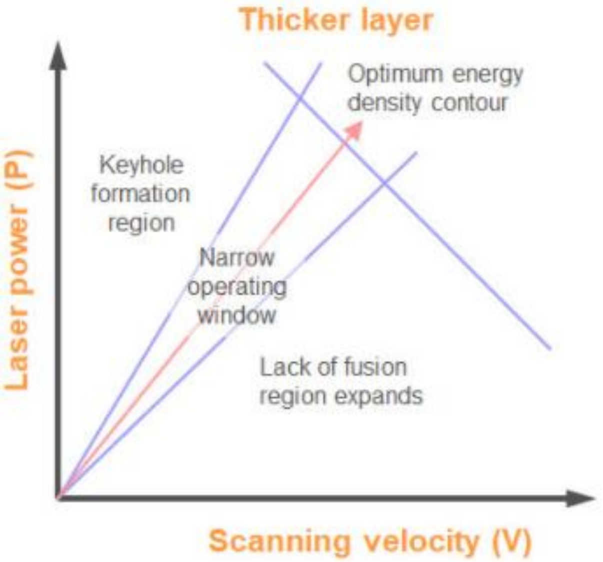


Fig. 4. Main SLM parameters.

$$E = \frac{P}{v\,h\,t}$$

$E = Energy\ Density$
$P = Power$
$v = Scan\ Speed$
$h = hatch\ spacing$
$t = layer\ thickness$





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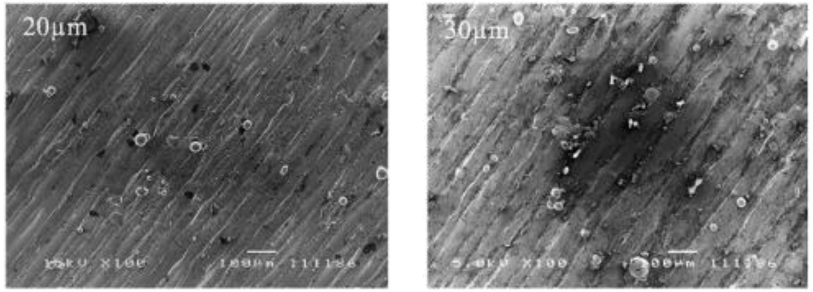
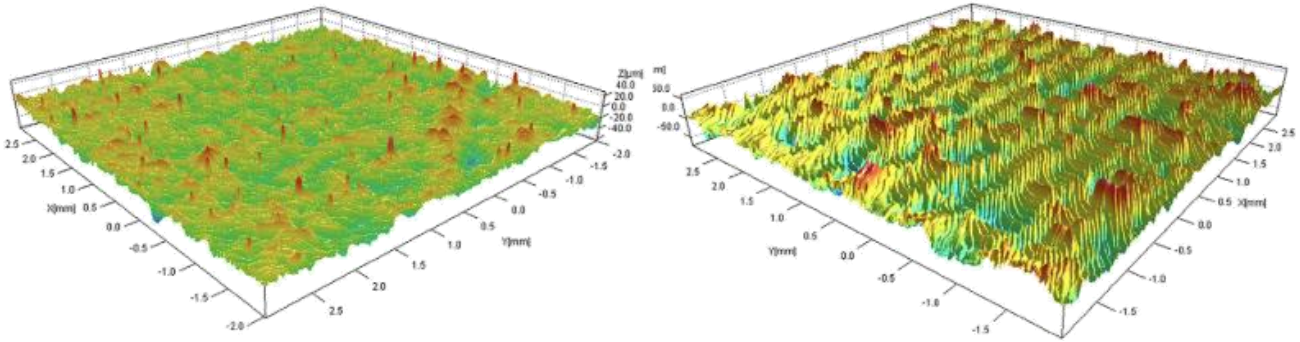
Surface Finish

- What causes surface roughness
    - Increased power / laser intensity results in greater instabilities of melt pool
        - Increased balling
        - Increased rippling of melt pool
    - Increased heat realised in increased layer height results in greater heating of surrounding particles resulting in higher levels of satellite particle adhesion.





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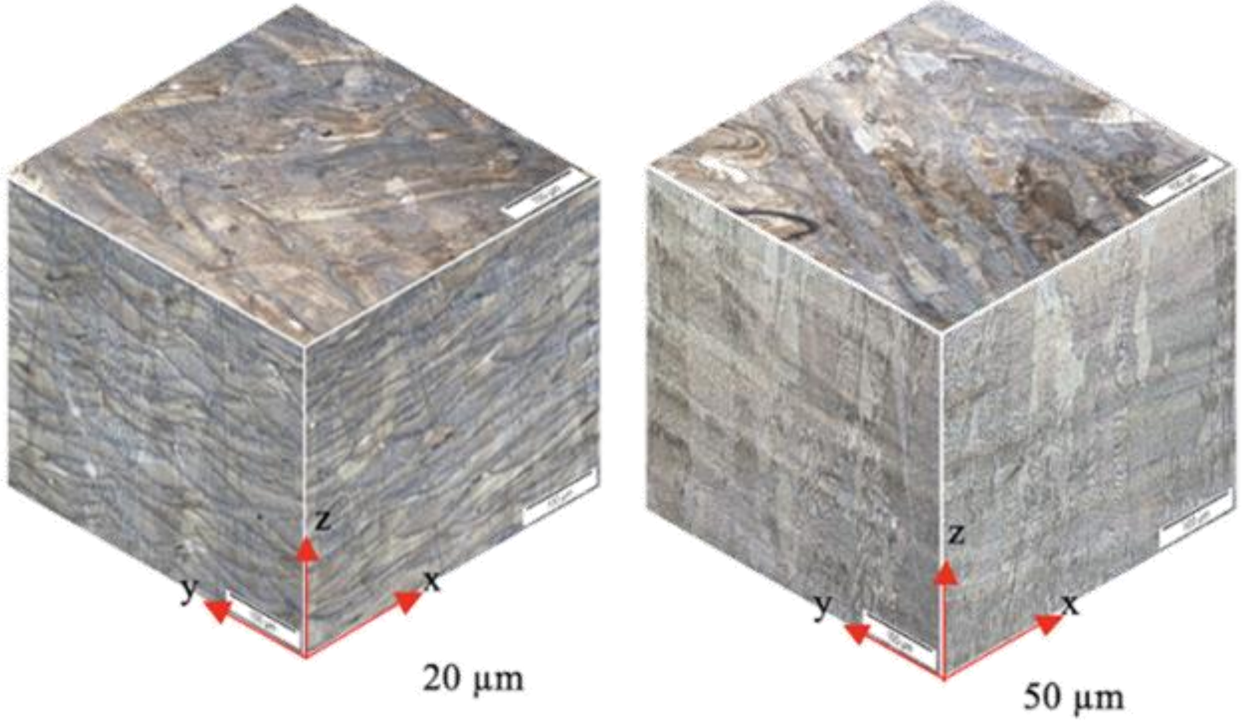
Microstructure

- Increased layer height leads to a lower cooling rate due to larger heating effect – leads to increased grain size
- In extreme cases a change in microstructure can be seen with a move from martensitic structures to lamellar structures



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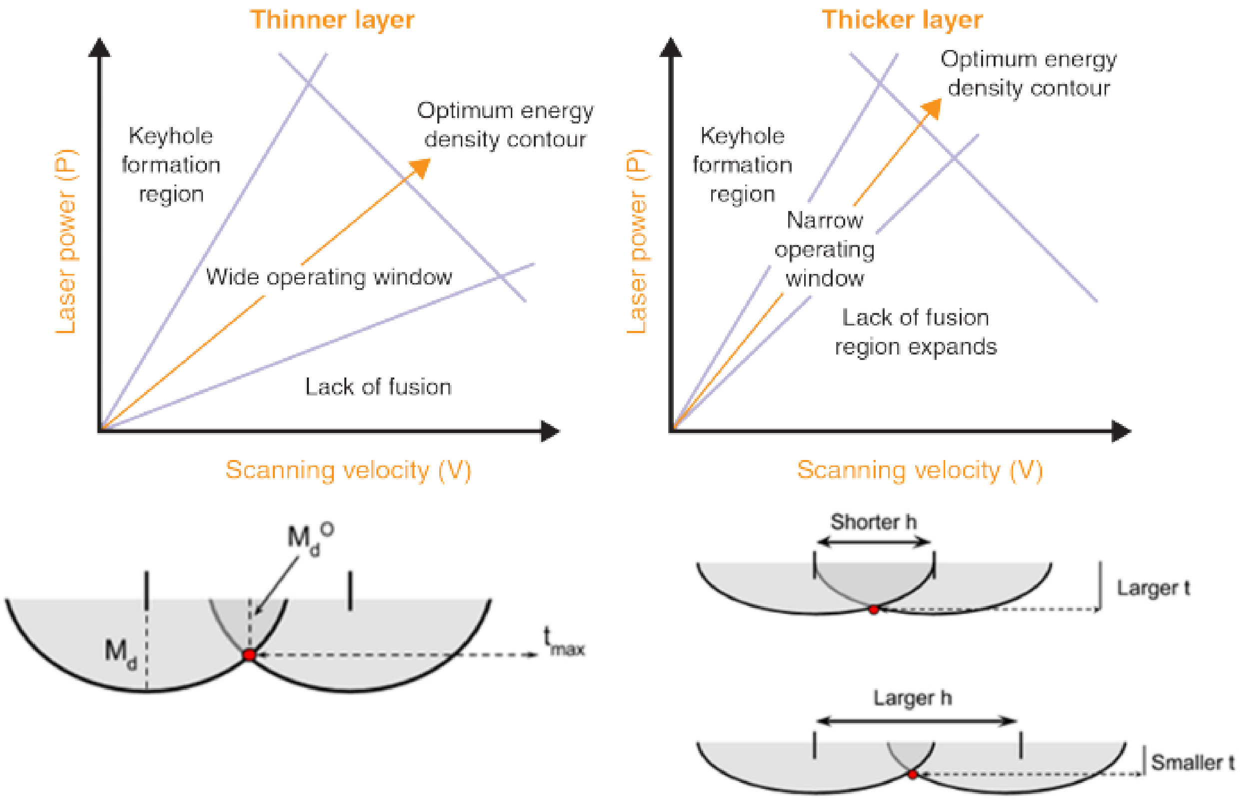
Defect Formation



- Increased layer heights can result in increased defects
- Keyholing porosity is not directly effected by the layer thickness – however if in an attempt to achieve adequate energy density the laser power is increased or scan speed decreased below certain thresholds then keyholing may occur.
- There is an increased likelihood of gas entrapment at increased layer heights
- The relationship between hatch spacing and the melt track size will determine the maximum layer thickness which can be achieved without lack of fusion defects occuring

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Follow on content

- Support Structures
- Part Positioning
- Standards
- Scanning Strategies
- Defects

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Positioning

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Introduction

- Key considerations
  - Inert gas flow
  - Recoater movement
  - Part position and rotation
- Additional factors to consider for multiple laser systems

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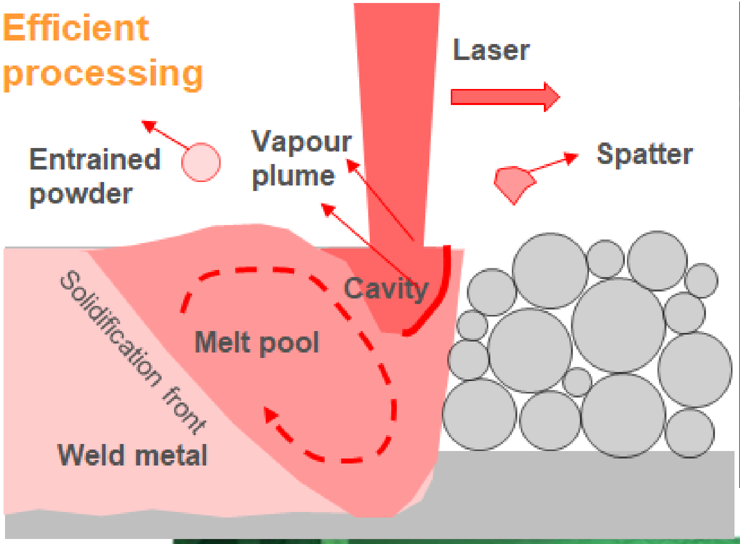
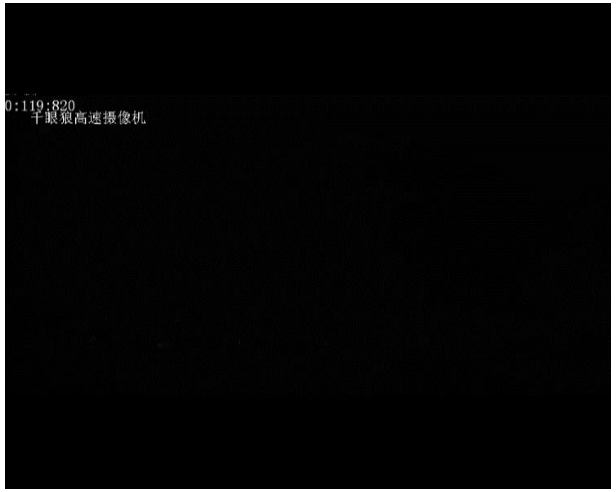
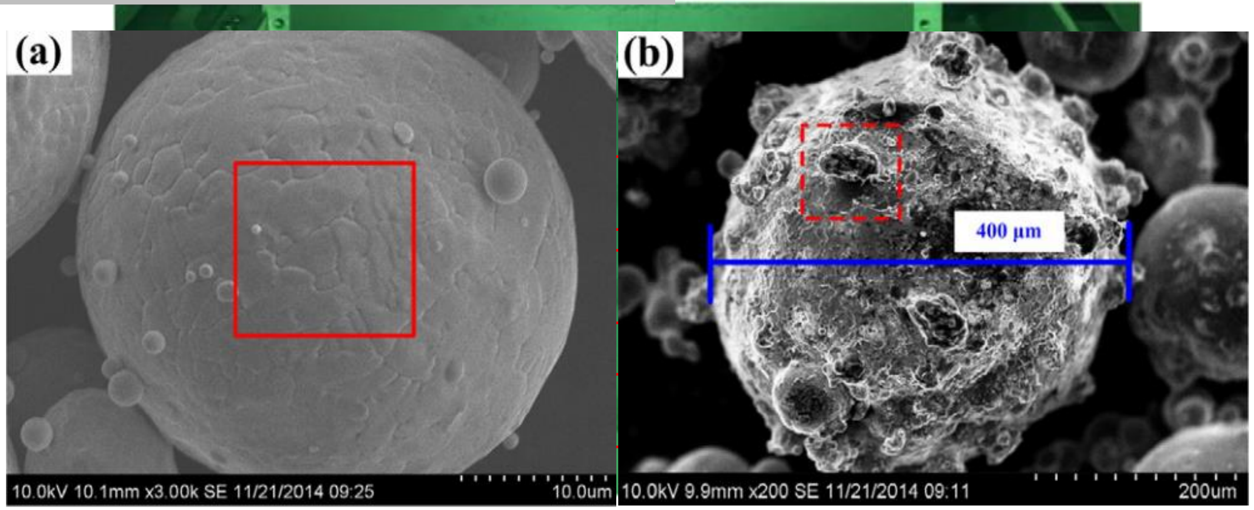
Melt pool ejection

- Spatter
  - Ejected particles from the melt pool
  - Significantly larger than virgin powder
  - Different chemical composition to virgin powder
  - Greater surface roughness







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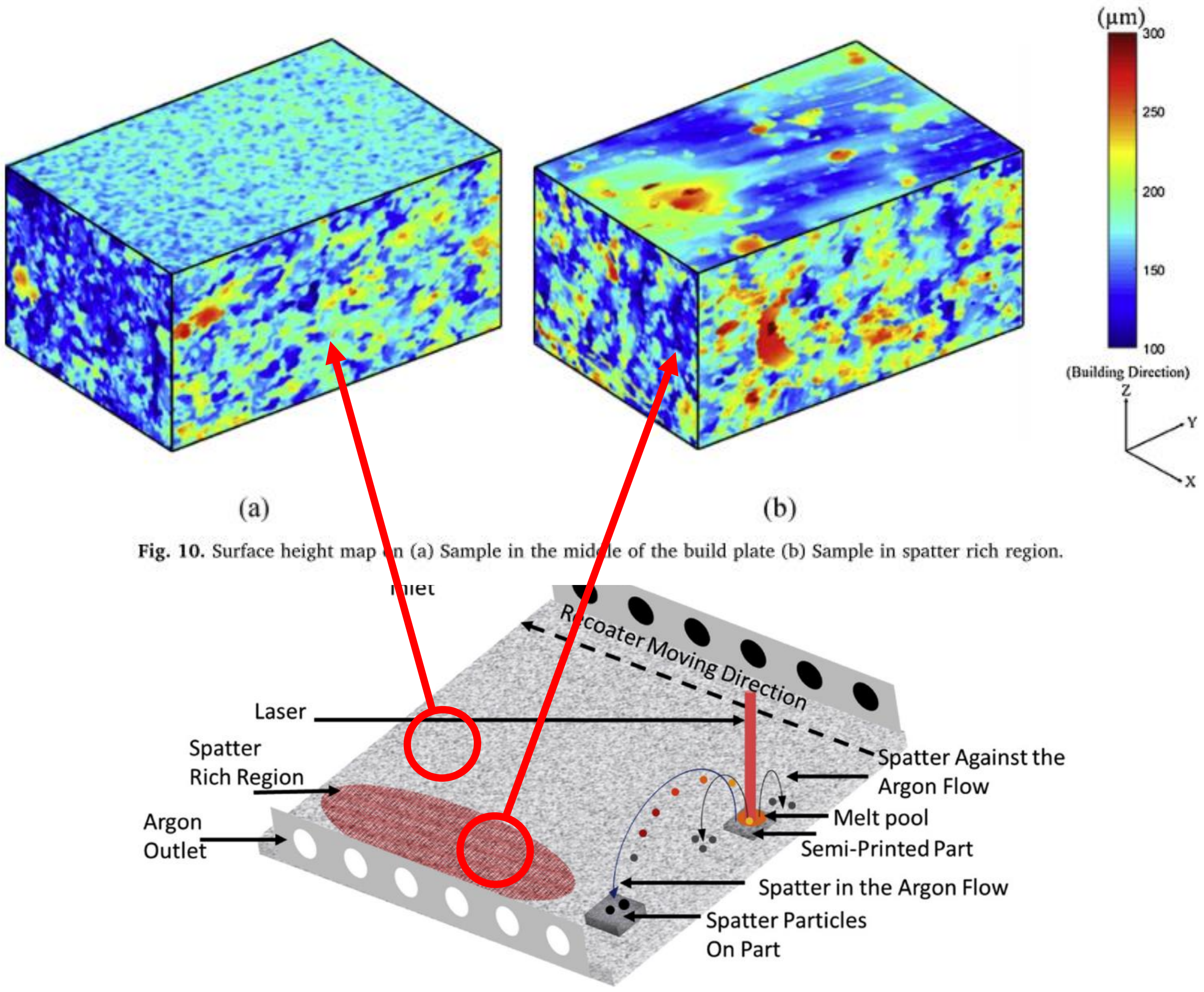
Melt pool ejection

- Increased Surface Roughness
  - Spatter can adhere to external surfaces of components leading to increased surface roughness
  - Spatter can be larger than layer height and lead to distruption of recoater mechanism



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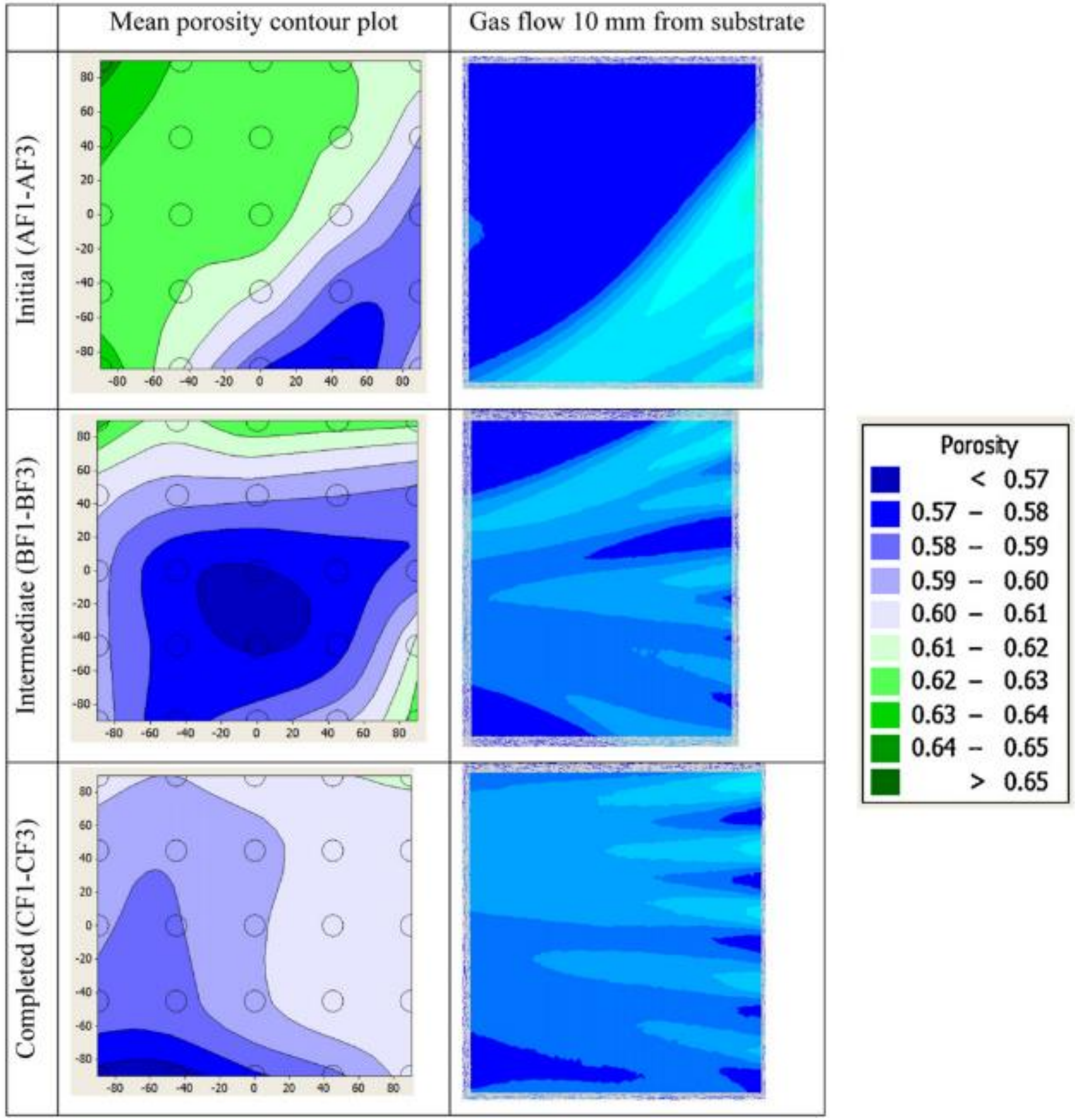
Melt pool ejection

Increased Porosity

- Spatter particles have different absorbtivity properties compared to the rest of the powder bed
- Larger particle sizes can effect melt behaviour
- Ejected particles can contain internal porosity



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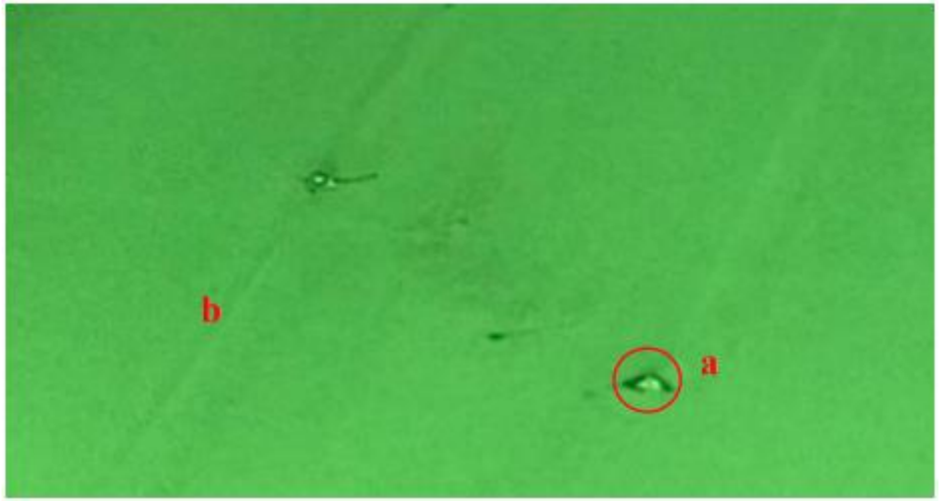
Recoater impact



- Excessive warpage can lead to solid material protruding from powderbed
- Can lead to impact with recoater mechanism
- Can cause part distortion / damage
- Can cause recoater jam / crash

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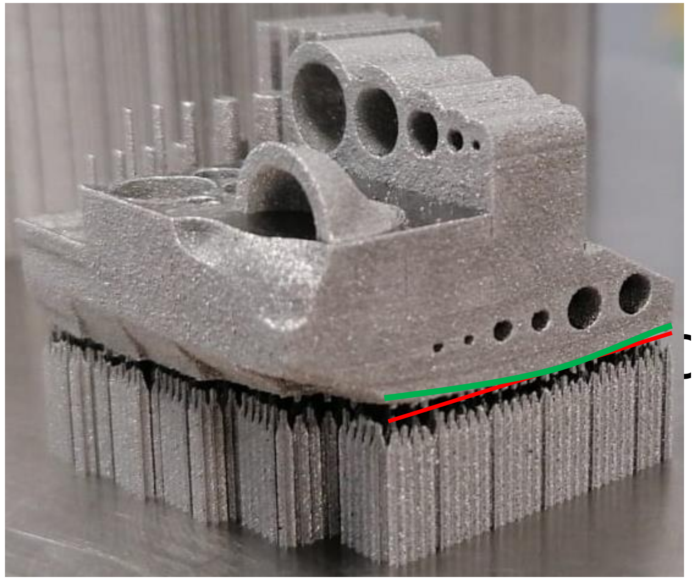
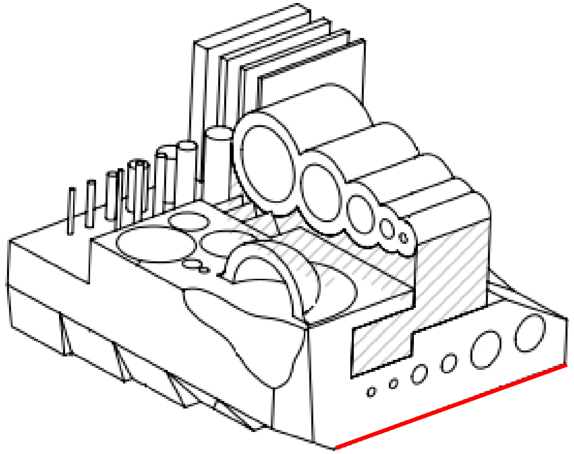
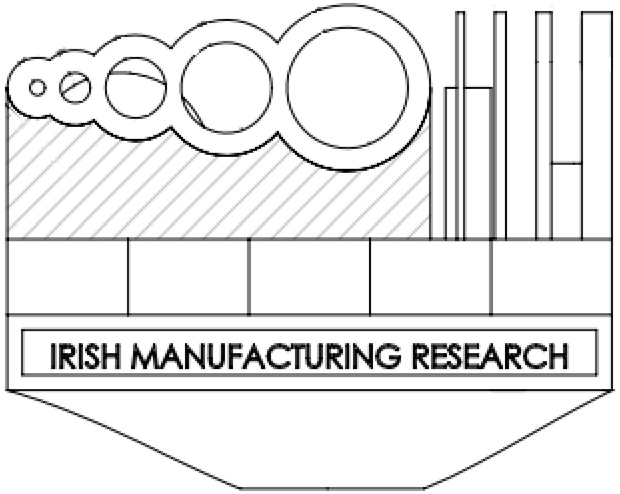
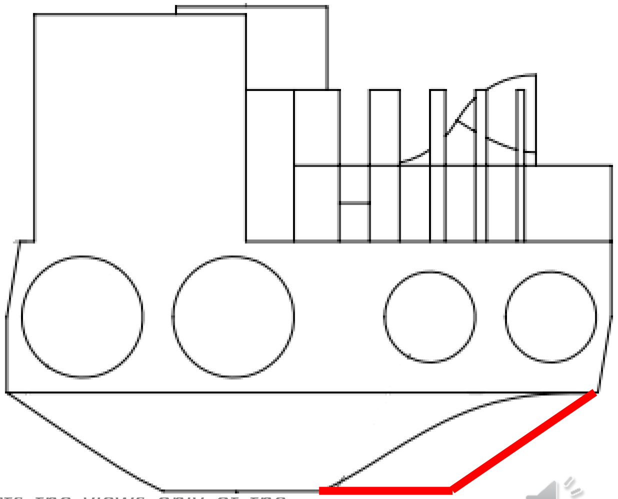
Avoiding a crash

- Minimise opportunities for excessive warpage
  - Adaquate support geometery
  - Improved design for AM
- Orient parts to minimise recoater forces
- Position parts to minimise recoater forces
- Determine best recoater type









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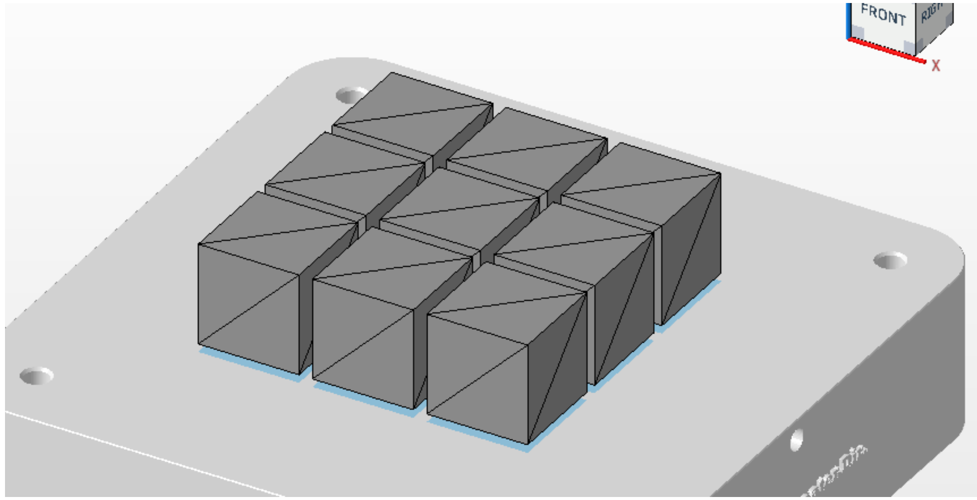

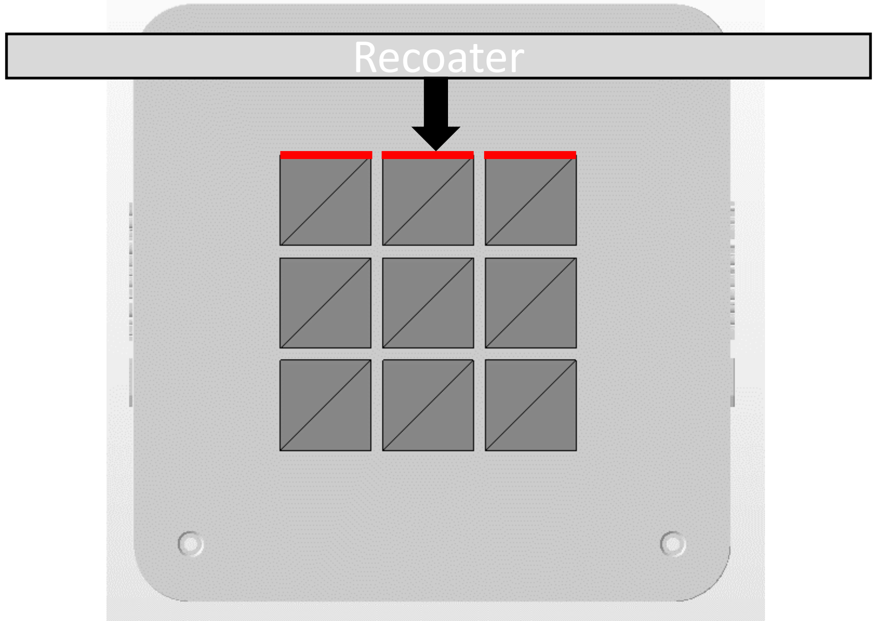

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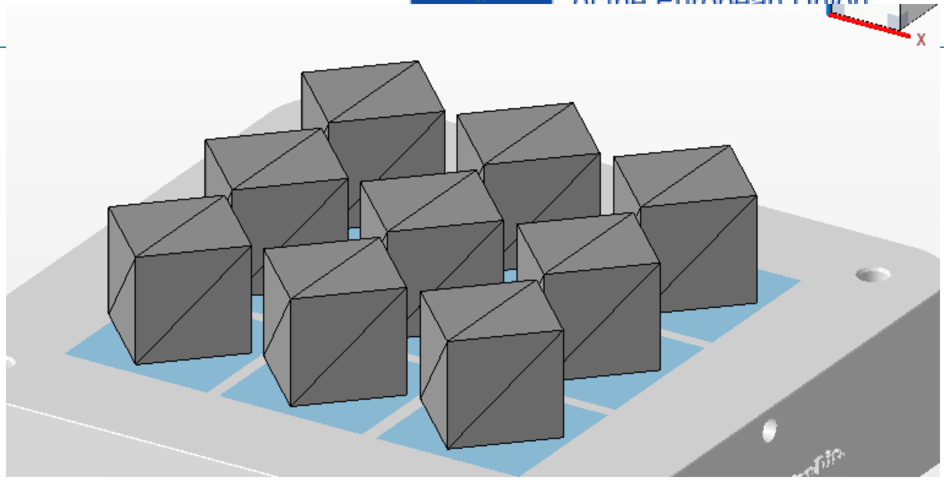

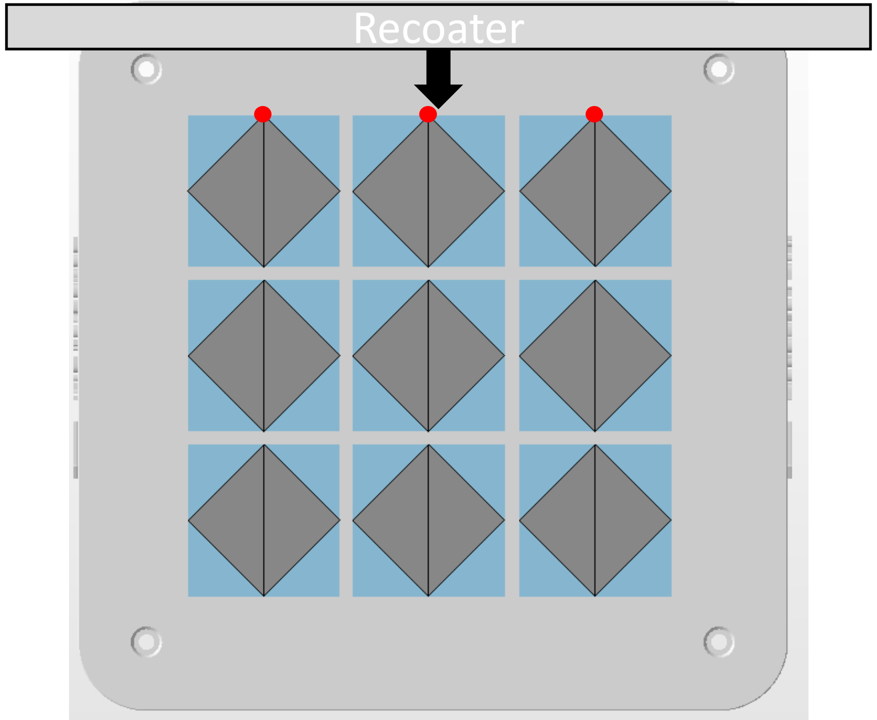

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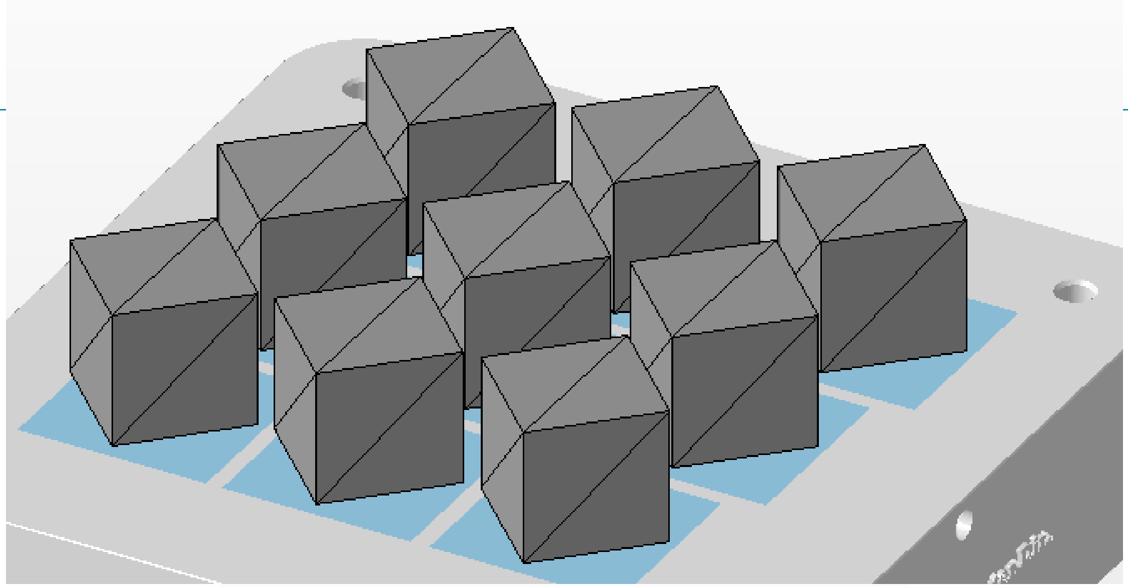

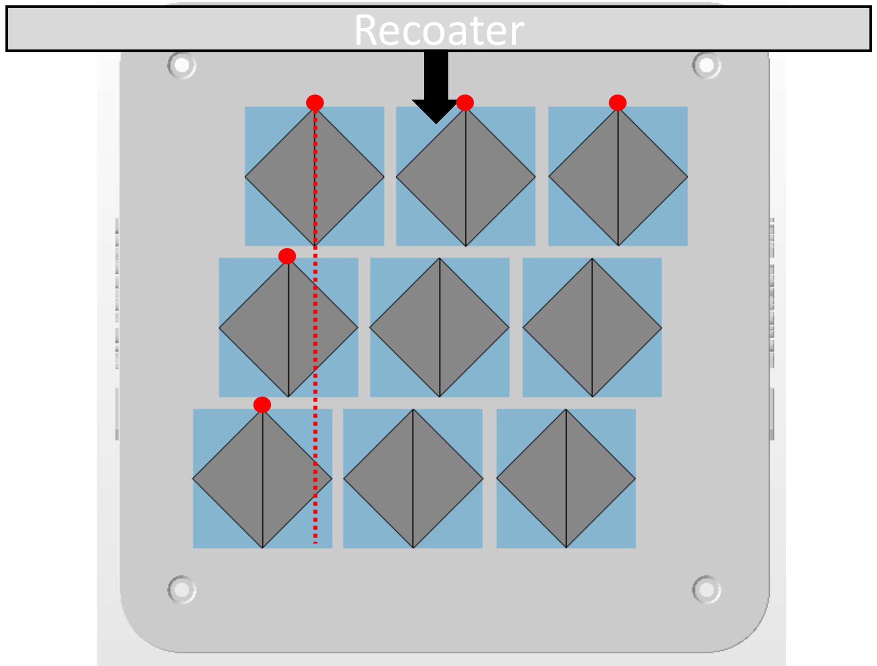

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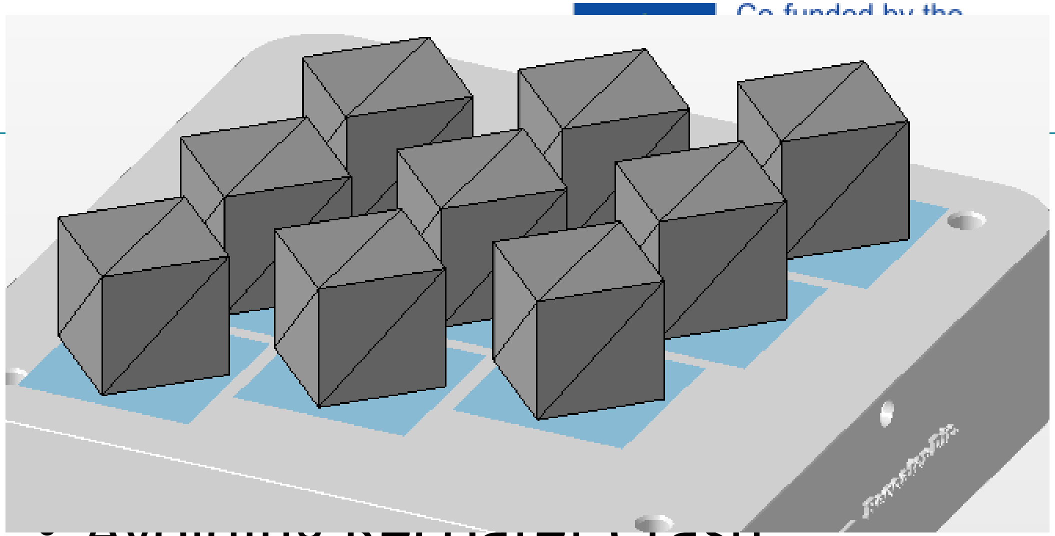

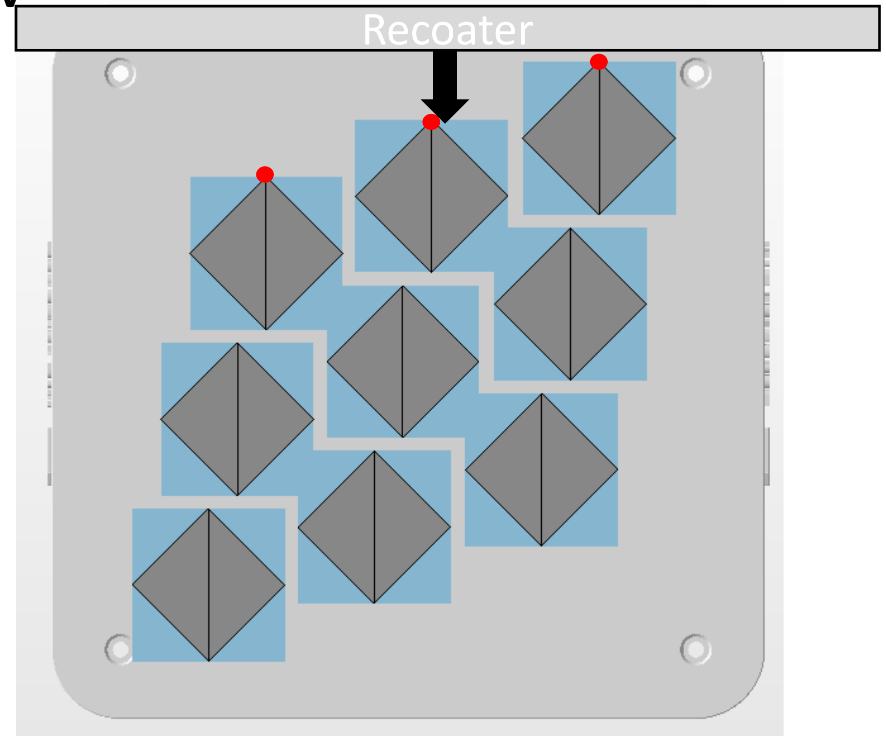

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White paper: Multi-laser processing strategies for high-integrity component manufacture - https://resources.renishaw.com/en/details/White%20paper%3a%20%20Multi-laser%20processing%20strategies%20for%20high-integrity%20component%20manufacture(112228)

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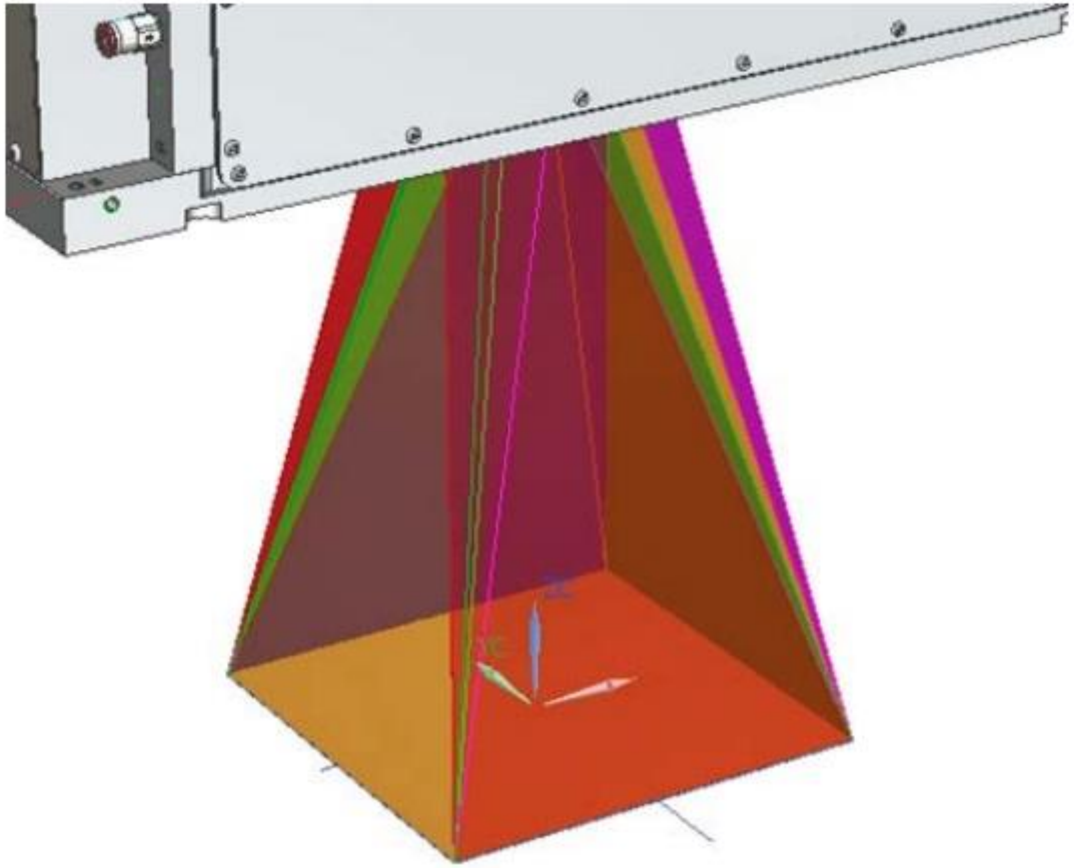
Multilaser Systems

- 2, 3, 4 + Independent laser systems
- Zoned system with overlap region
- Full volume overlap region



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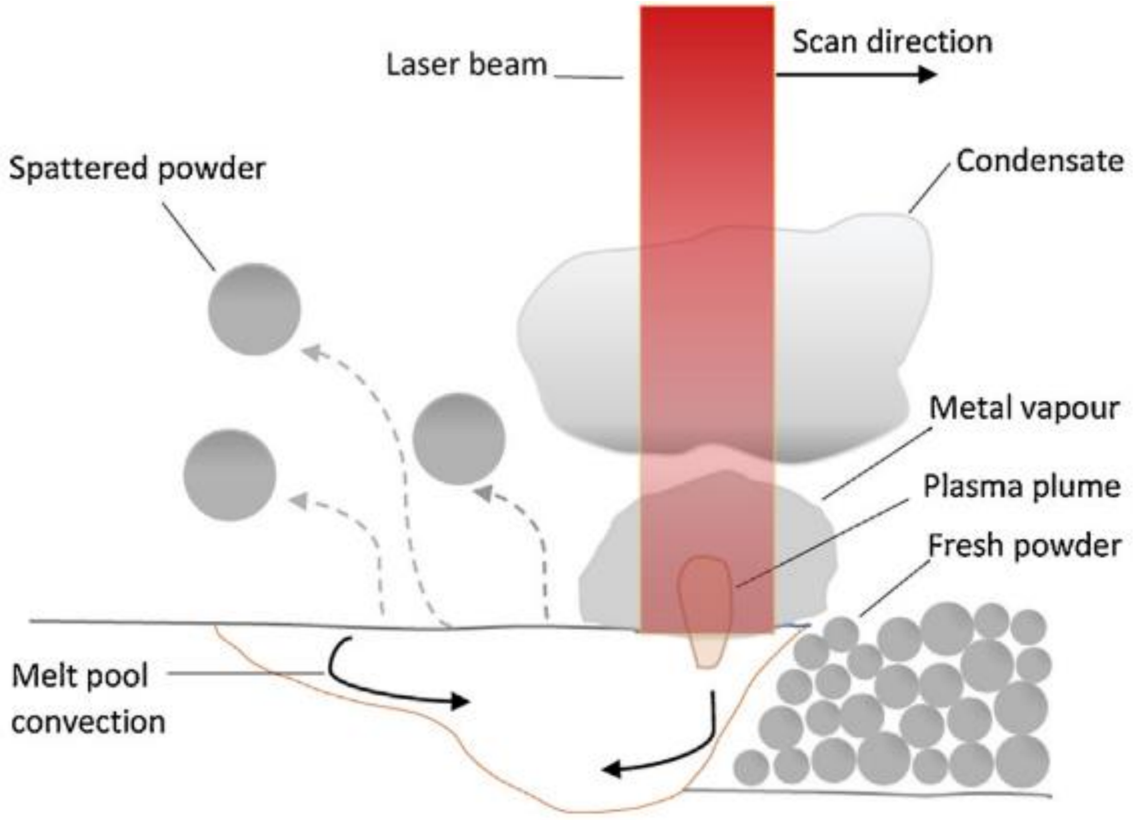
Multilaser Systems

- Increased opportunities for undesirable laser interactions
- Critical relationship is established between laser and inert gas flow
- Condensate vapour ejection



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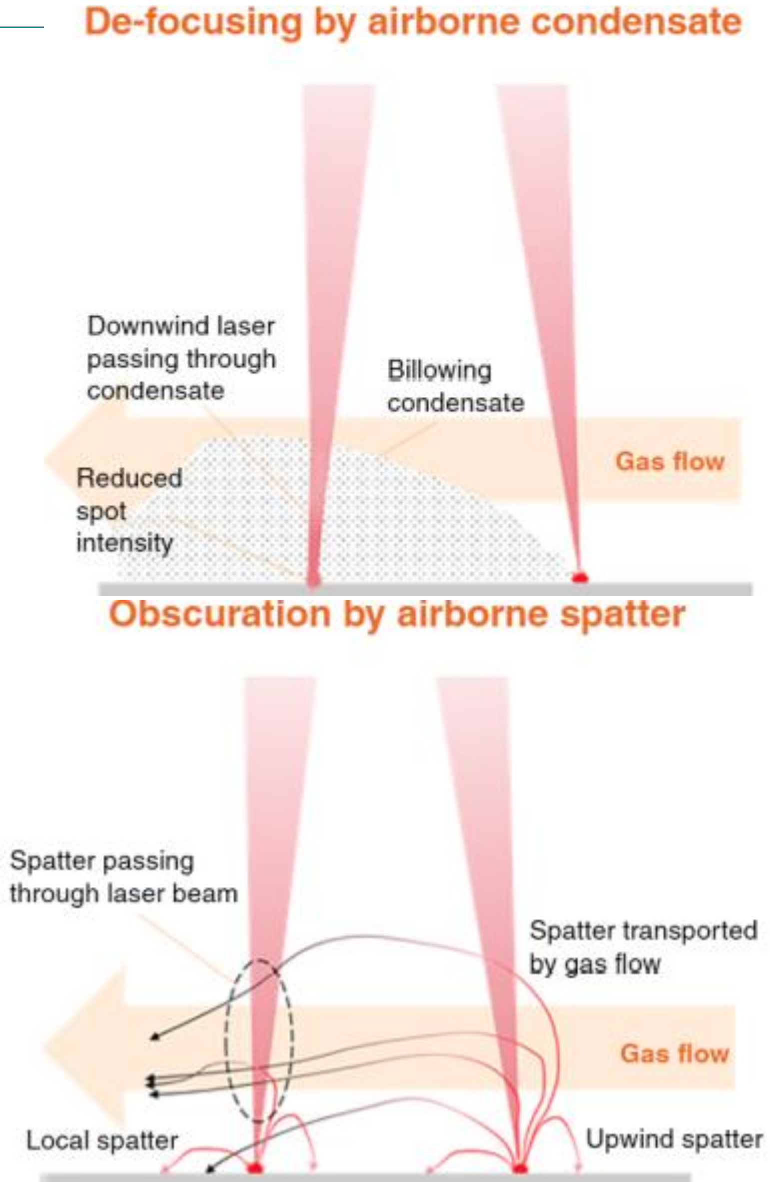
Multilaser Systems

- Condensate / smoke reduces effectiveness of laser beam
  - Absorption
  - De-focusing
- Additional flow of inert gas to clear condensate / smoke
- New methods of intert gas flow delivery methods requied



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Follow on content

- Support structures
- Layer Height
- Scanning Strategies
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- AM Standards Landscape

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Defects

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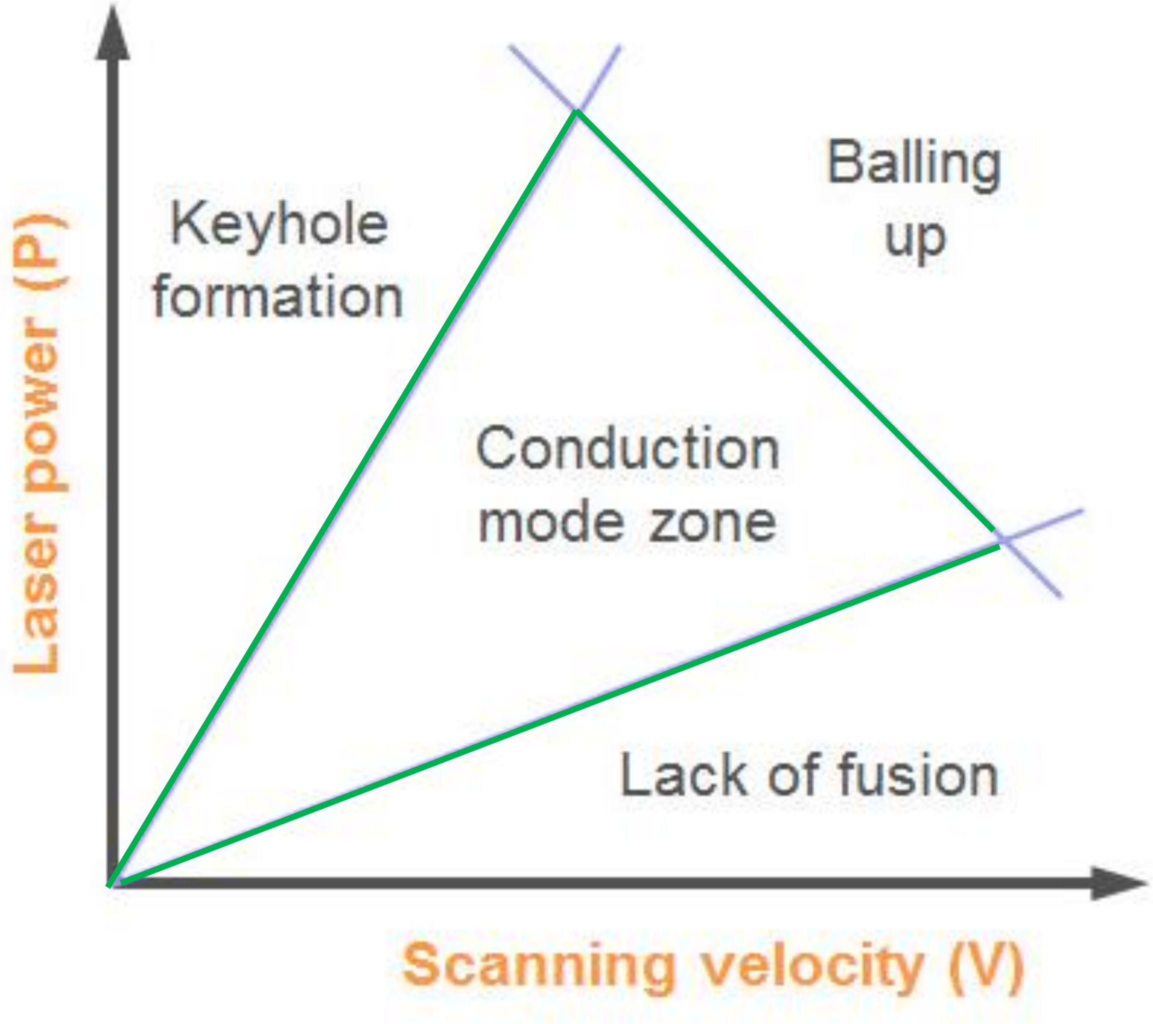
PBF-LB Defects

- PBF-LB has moved beyond its early origins of Metal Sintering and now achieves full melting
- Achieving fully dense components still poses a challenge



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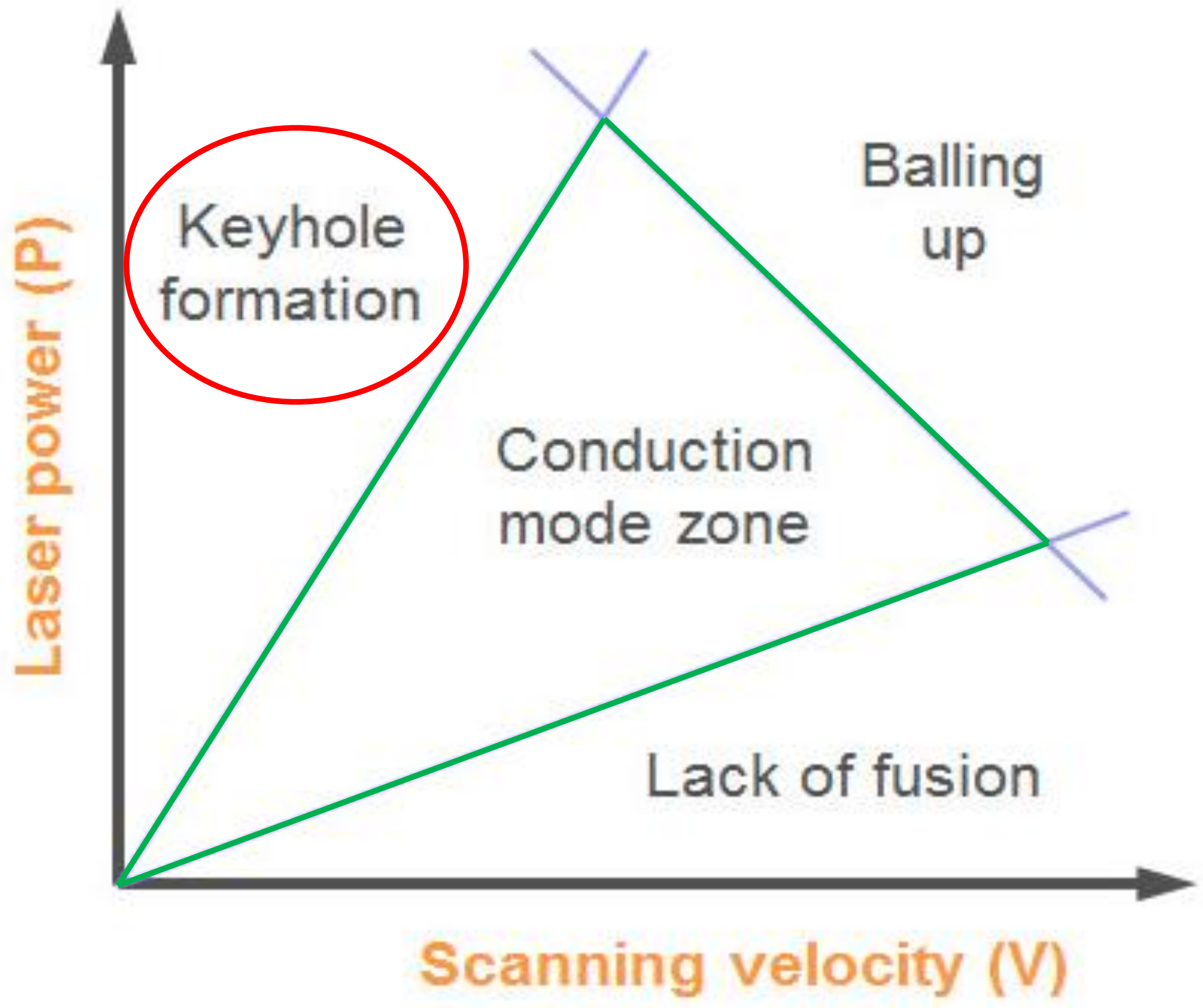
Keyhole Porosity

- Spherical Pore shape
- Formed deep below melt pool
- When laser intensity exceeds threshold value, melting mode changes from conduction to keyholing
- Meltpool is extremely unstable along its depth – pores are created as the melt pool collapses



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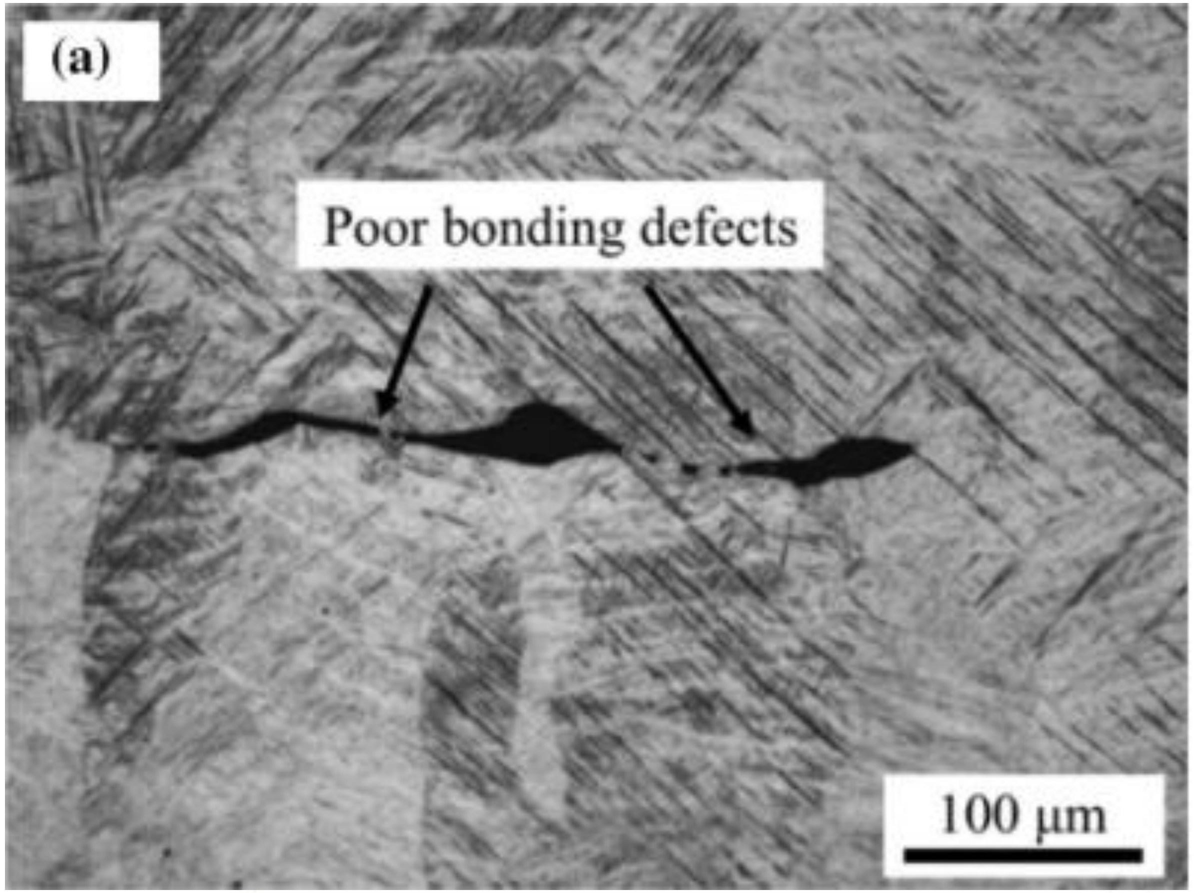
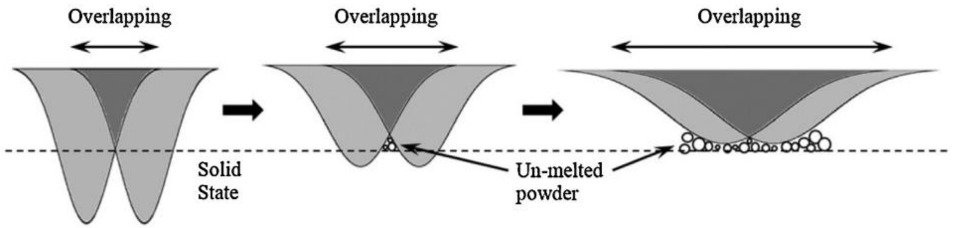
Lack of Fusion

- Melt pool overlap is insufficient to create consistant melt pattern
- Gaps are created
    - Between layers
    - Within layer
- Long sharp pores
- Highly detrimental to mechanical properties





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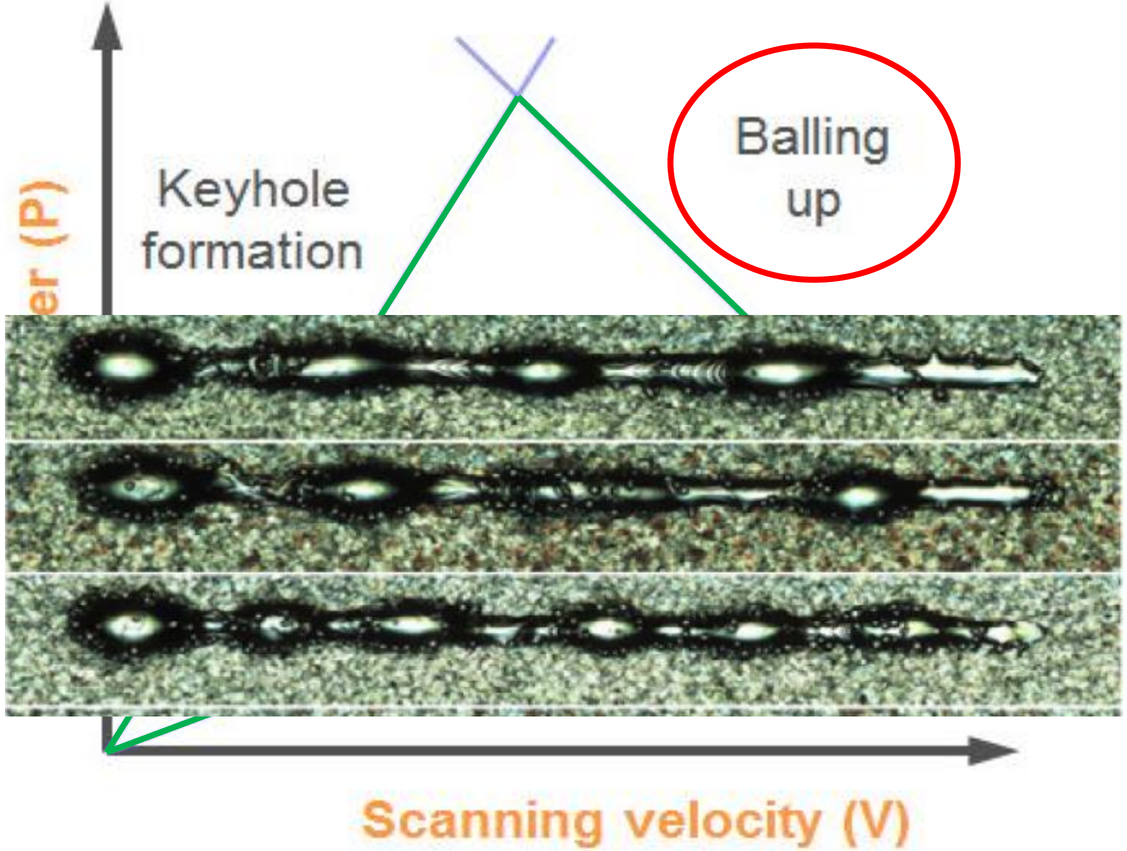
Balling

- Driven by highly unstable melt pool
- Melt track becomes discontinuous and breaks into balls
- Results in poor interlayer fusion
- Leads to increased surface roughness



'X marks the spot – find ideal process parameters for your metal AM parts', Marc Saunders 2017

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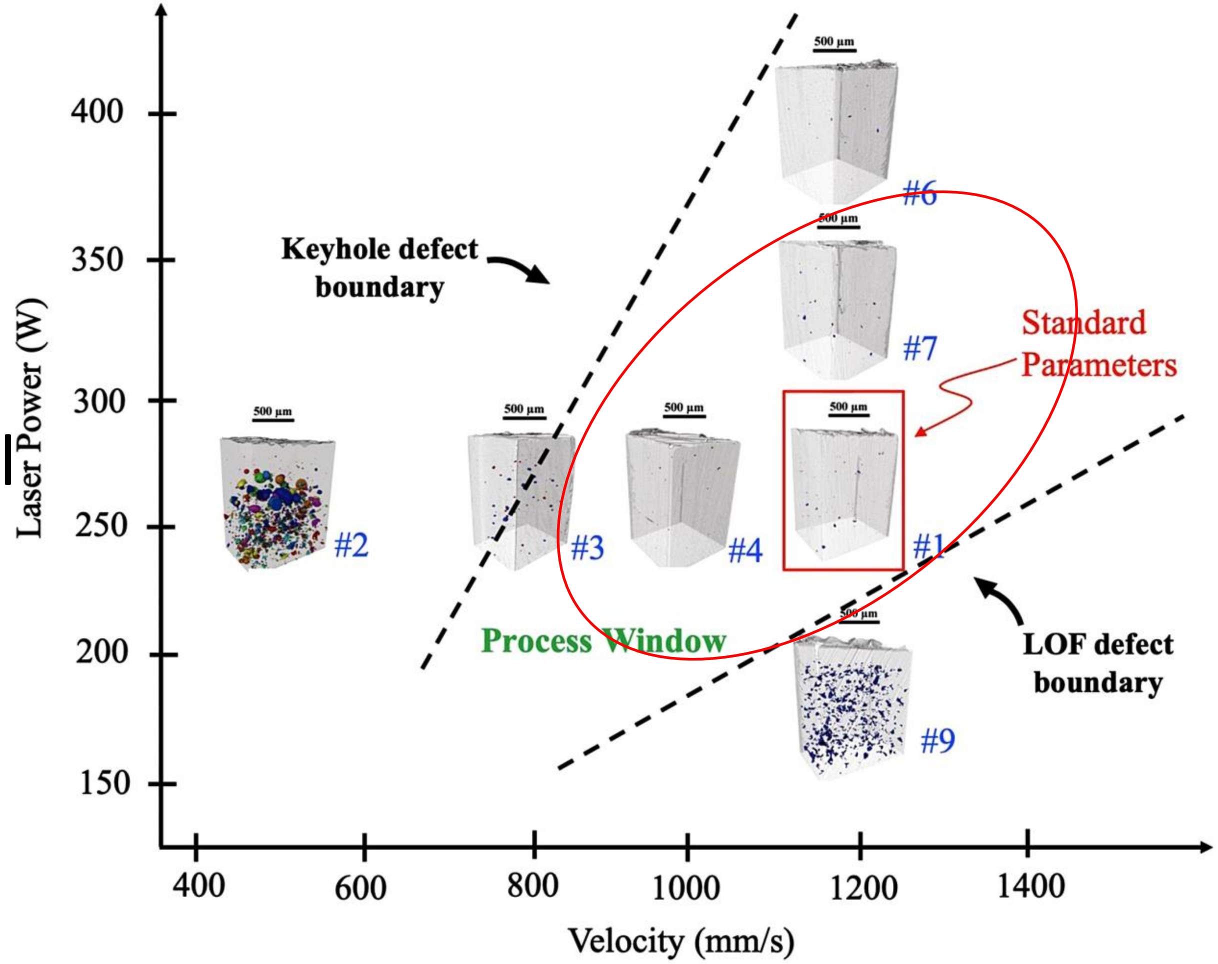
Gas Porosity

- More difficult to quantify
- Porosity mas exist within original feedstock
- Evaportation of elemental components can cause porosity
- Typically much lower quantity than other porosity forms



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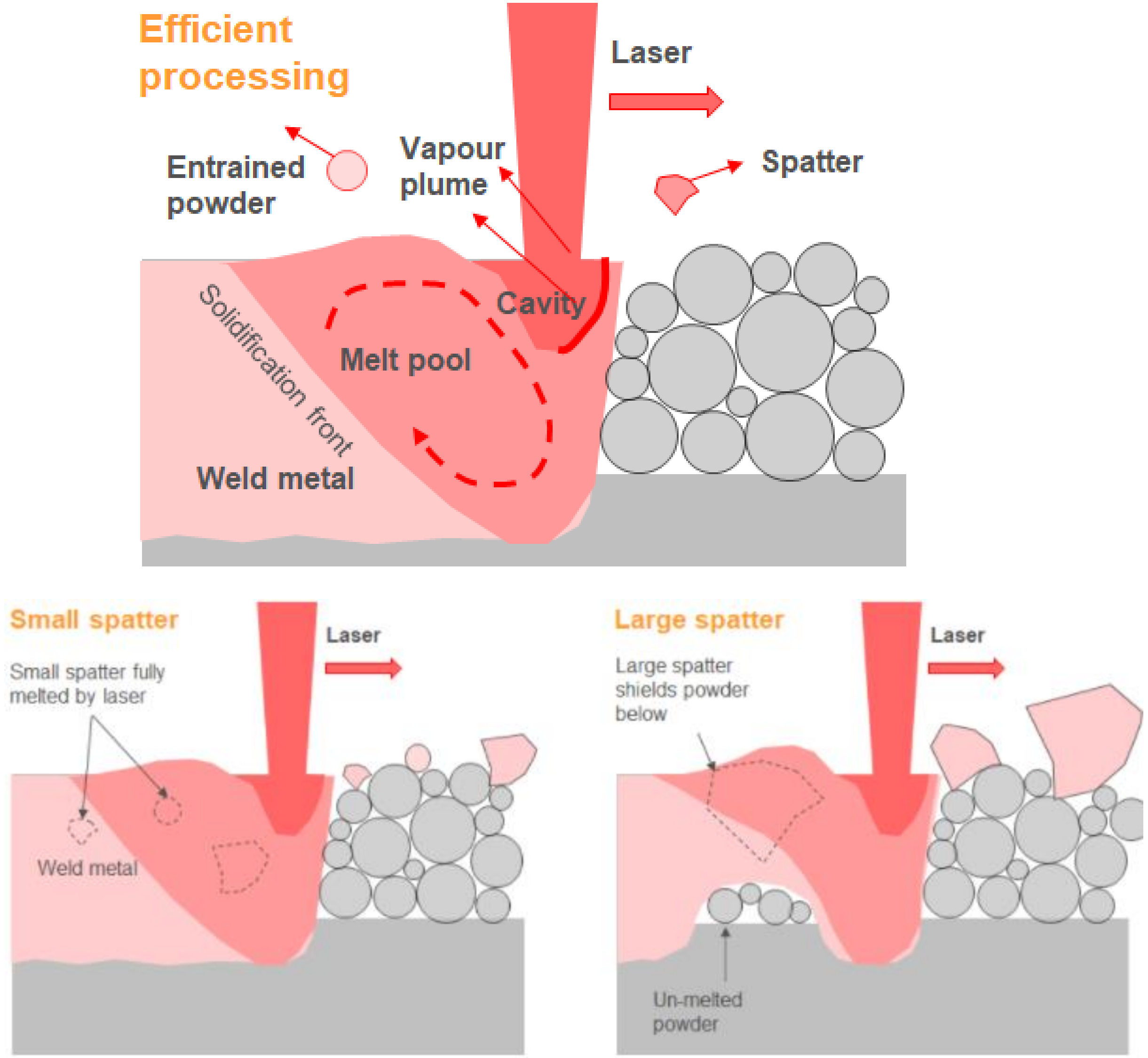
Spatter

- Ejected matter from melt pool
- Significantly larger than virgin powder
- Different absorbtivity values to virgin powder
- Reduce effectiveness of laser on melt pool and trigger lack of fusion defects
- Can be dragged across powder bed and disrupt powder deposition



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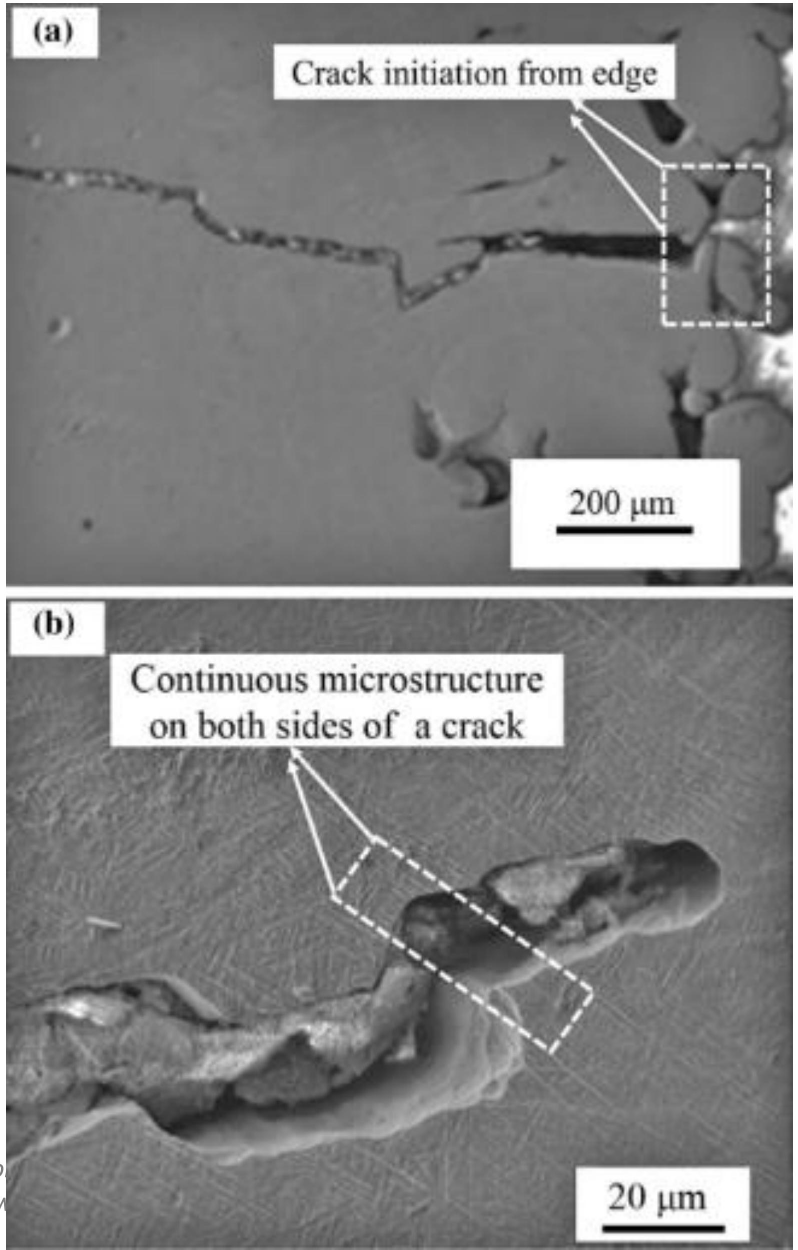
Cracking

- Large thermal gradients formed within the PBF-LB process lead to the formation of high residual stress
- Coupled with rough outer surface to provide initiation sites cracking can occur
- Materials with low conductivity and high thermal expansion are particularly vunerable
    - Stainless Steels
    - Nickel-based superalloys
- Heated chambers and build plates can reduce the formation of cracks by reducing residual stress formation



Follow on content

- Support structures
- Part positioning
- AM Standards landscape
- Layer height
- Scanning Strategy

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SAM

SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

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Standards

CU15-9-3: Manufacturing Strategy

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Sta

Stand

• Rev

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Standards

What is ISO / ASTM TC261

- Joint group for developing global standards across all areas of AM
- 19 Published Standards
- 28 Standards in Development

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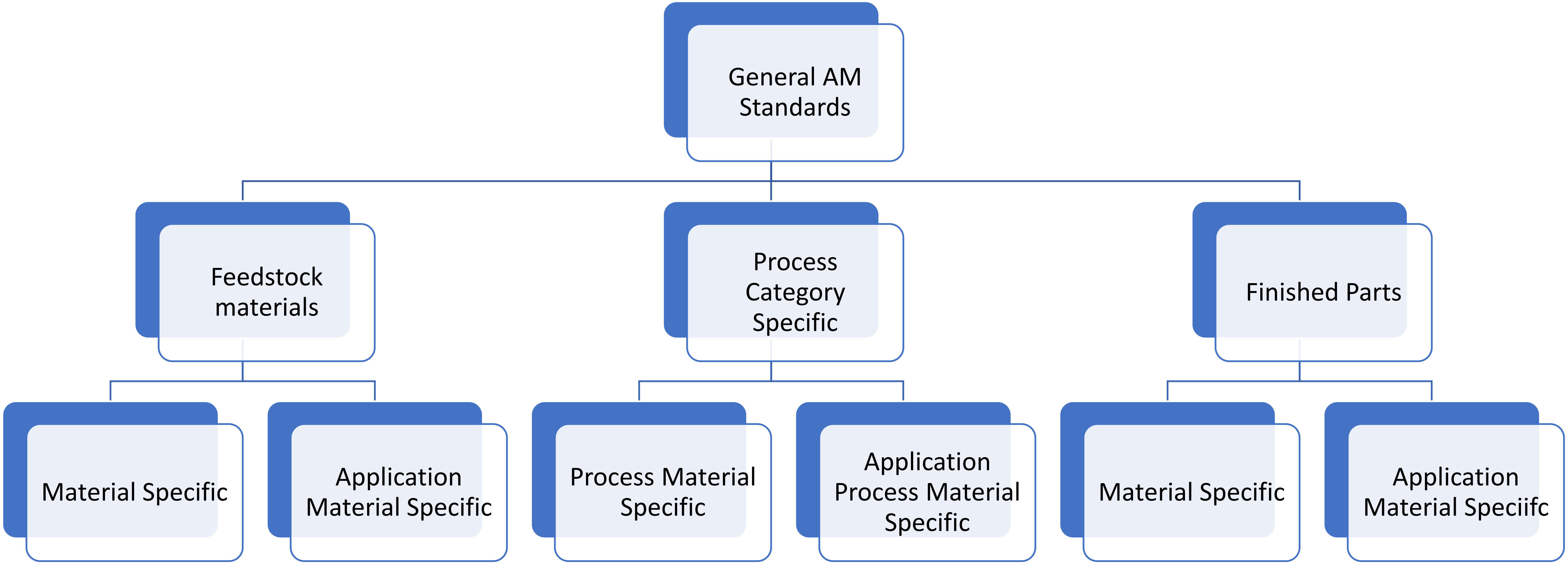

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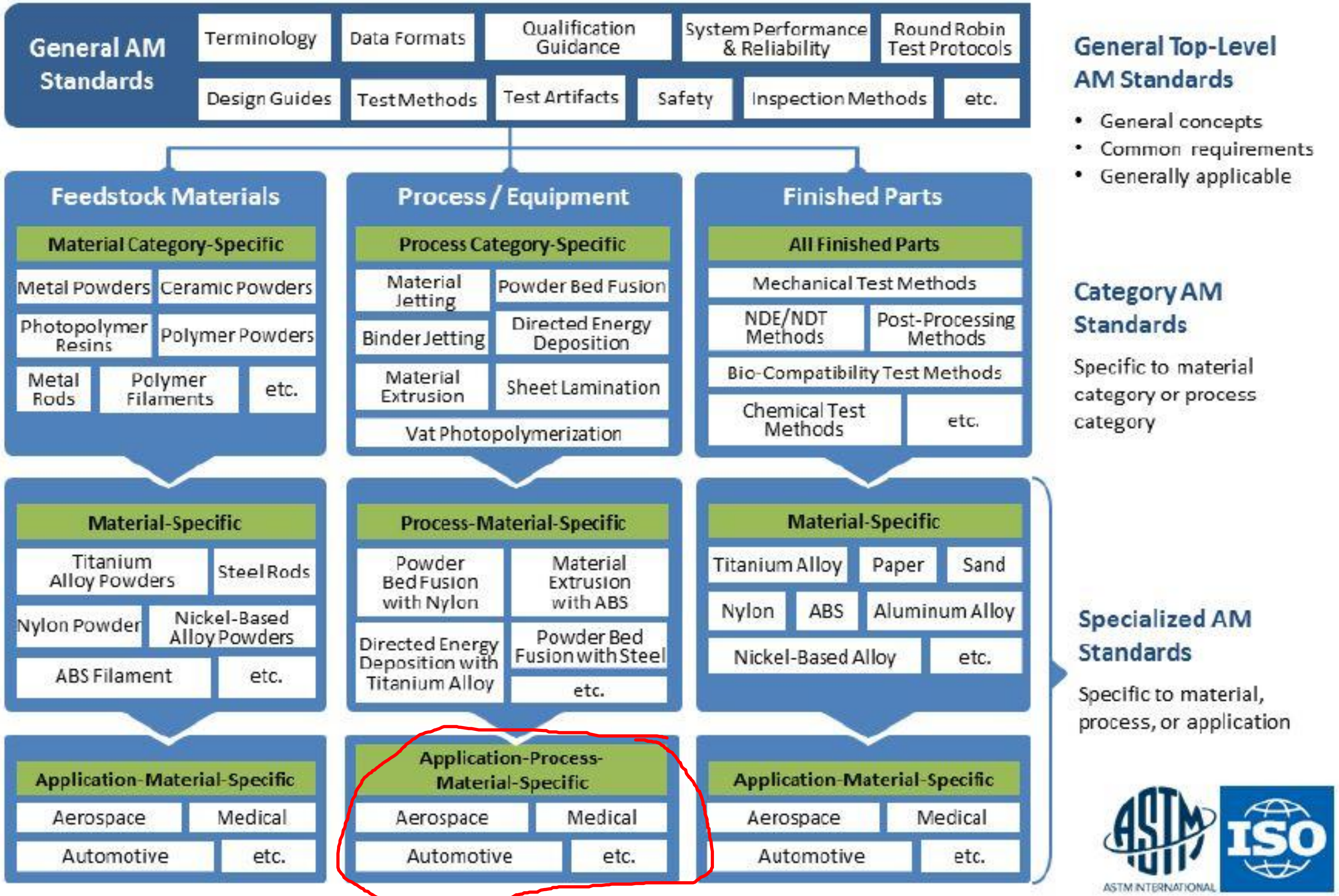

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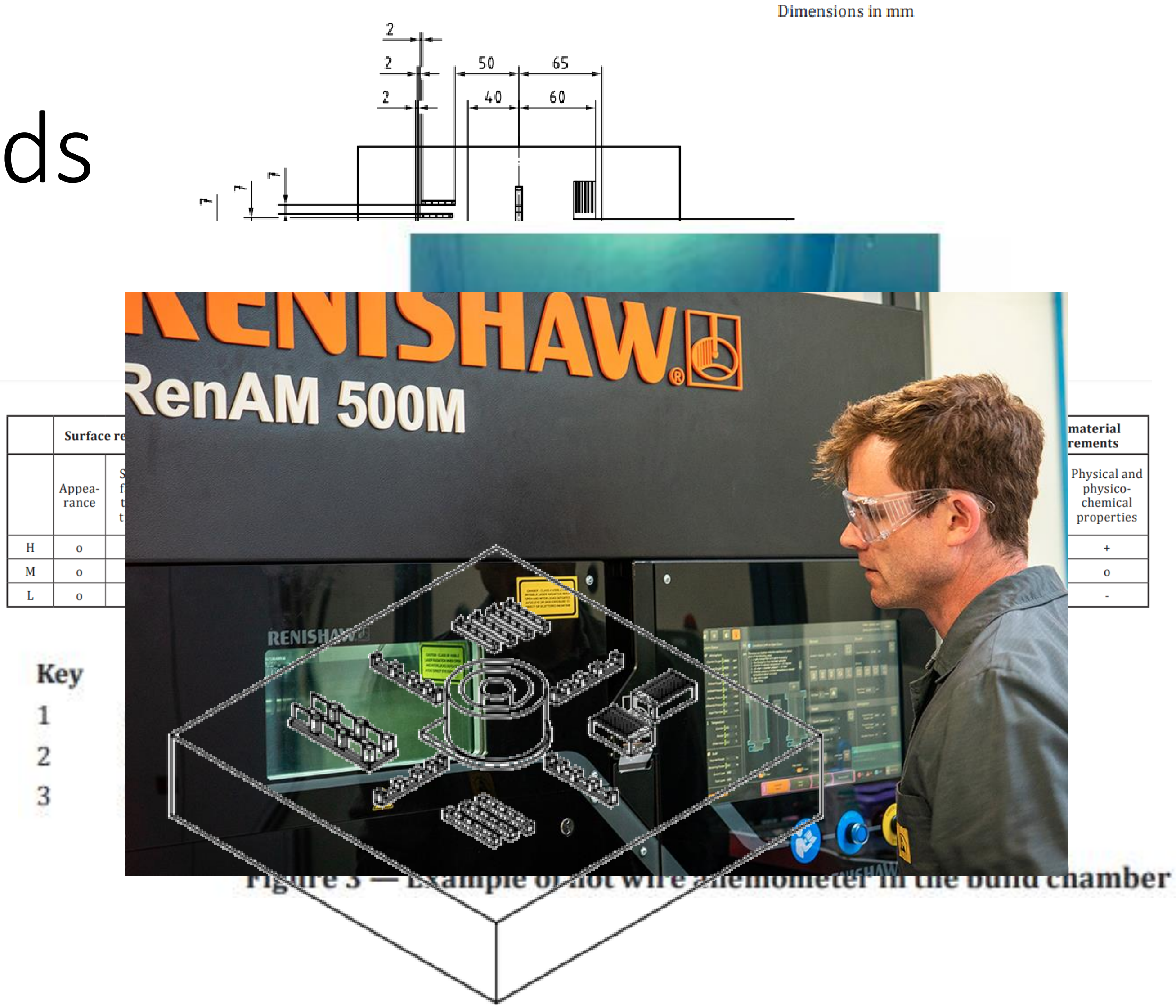
Some Current Standards

- ISO 52902 - Geometric capability assessment of additive manufacturing systems
- ISO 17296-3 - Main characteristics and corresponding test methods
- ISO 52941 - Acceptance tests for laser metal powder-bed fusion machines for metallic materials for aerospace application
- ISO 52942 - Qualifying machine operators of laser metal powder bed fusion machines and equipment used in aerospace applications



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Future Developments

NDT → Location / Orientation → EH&S → Operator Qualification

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Follow on content

- Support structures
- Positioning
- Layer height
- Scanning strategies
- Defects

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Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

Manufacturing Strategies Part 3

- Importance of process optimisation
  - Mechanics of parts
  - Build time optimisation
  - Support optimisation

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Process Optimisation

Part optimization

Cost optimization

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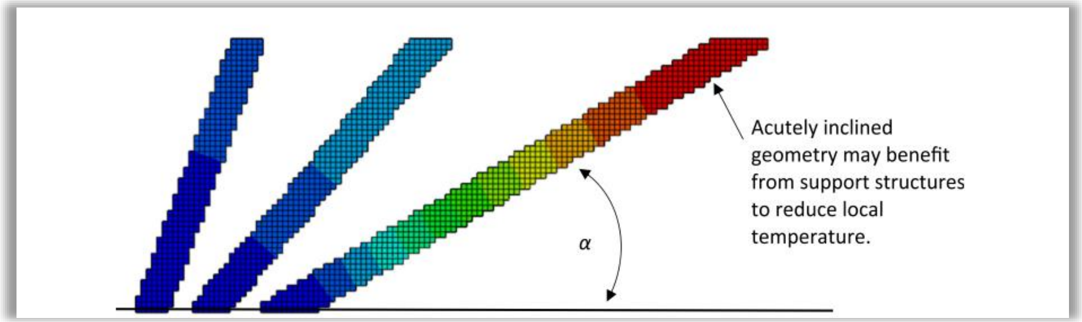
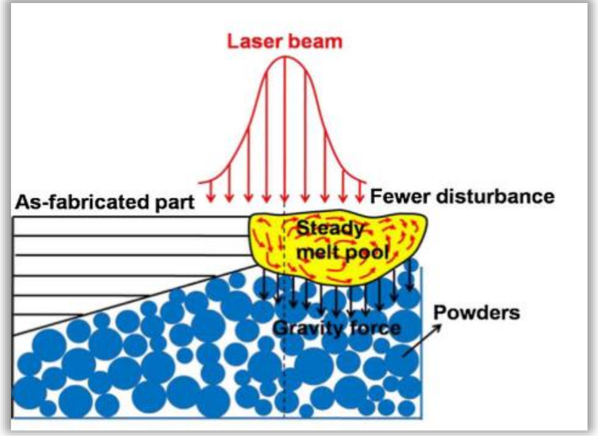
Support optimisation

$$K = \frac{Qd}{A\Delta T}$$

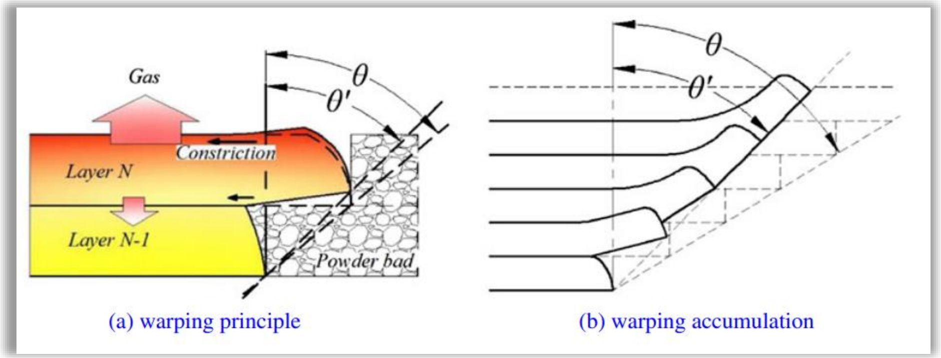
- K = thermal conductivity
- Q = amount of heat transferred
- d = distance between the two isothermal planes
- A = area of the surface
- ΔT = difference in temperature



Overheating



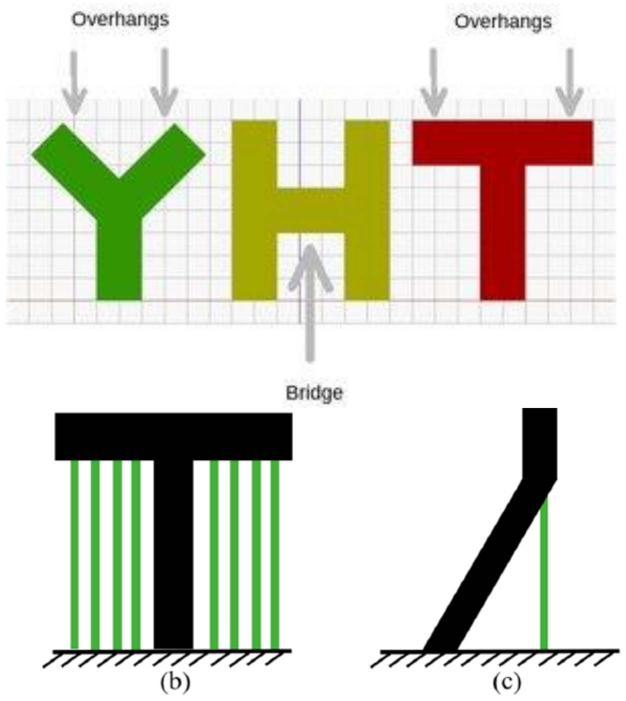
Dross on downskins



Warping

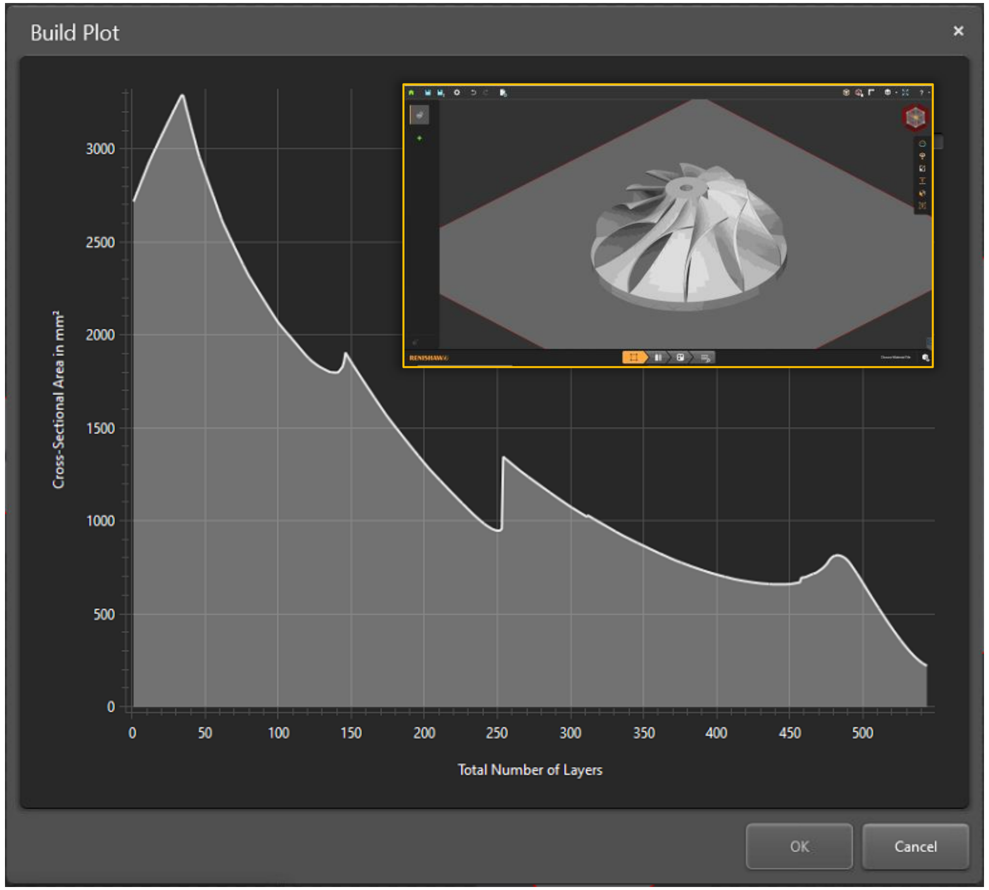
Support optimisation

Re-orientation

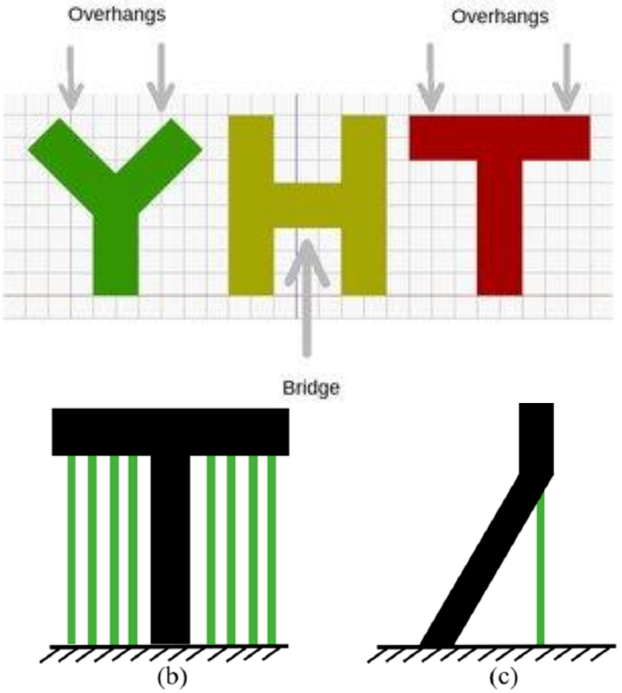


Jiang et al. Support Structures for Additive Manufacturing

Support optimisation



Re-orientation



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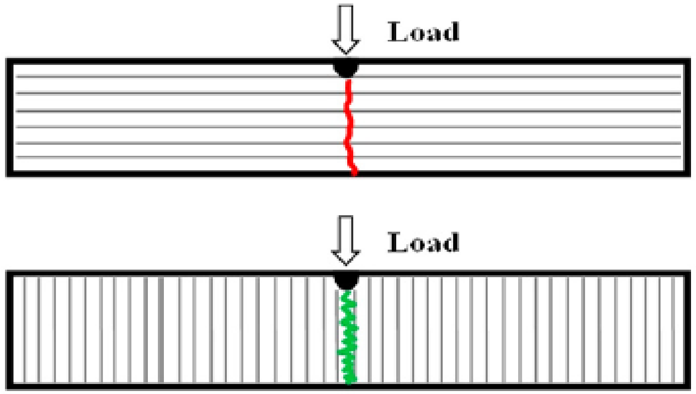
Process Optimisation

- Mechanical properties and anisotropy
  - Impact resistance will also change. Impacts parallel to built direction need to propagate through layers, where as impacts perpendicular can propagate between more fragile layer boundaries.
  - Tensile strength (yield and UTS) can vary as much as 20-30% based on tensile bars built horizontally and vertically. Failure will also change from brittle fracture to ductile mode.



A.A.Deev at el (2016) 'Anisotropy of Mechanical Properties and its Correlation with the Structure of the Stainless Steel 316L Produced by the SLM Method', 9th international conference on Photonics Technologies

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Presentation 3

- Mechanical properties and anisotropy
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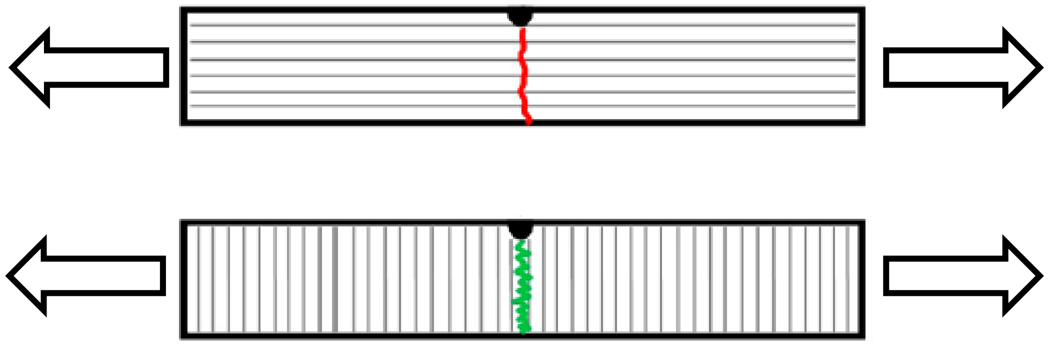

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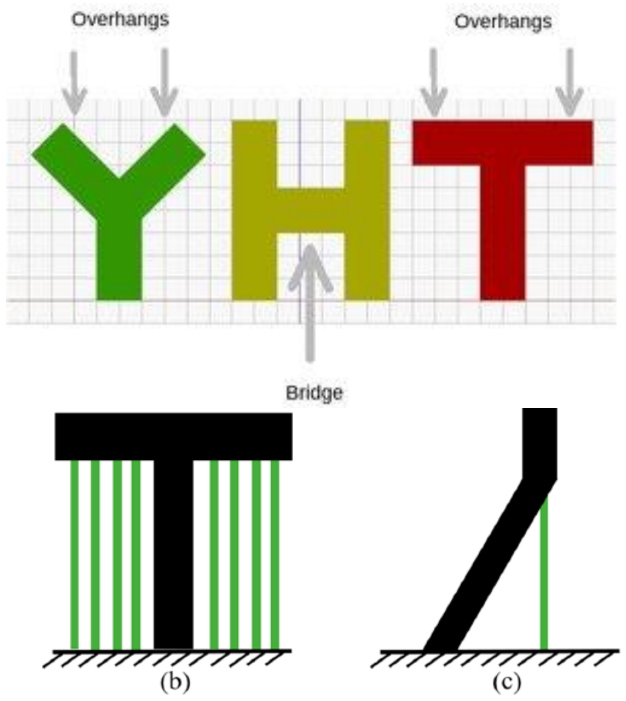
Support optimisation

Re-orientation



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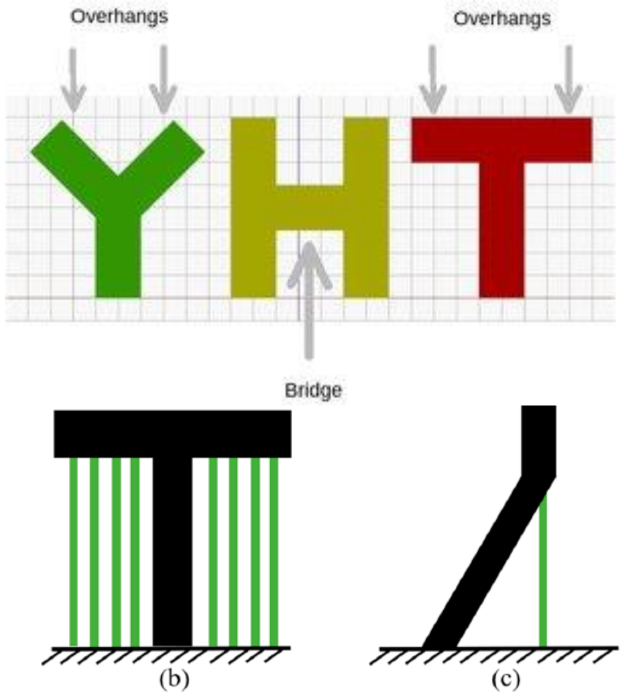
Support optimisation

Re-orientation?



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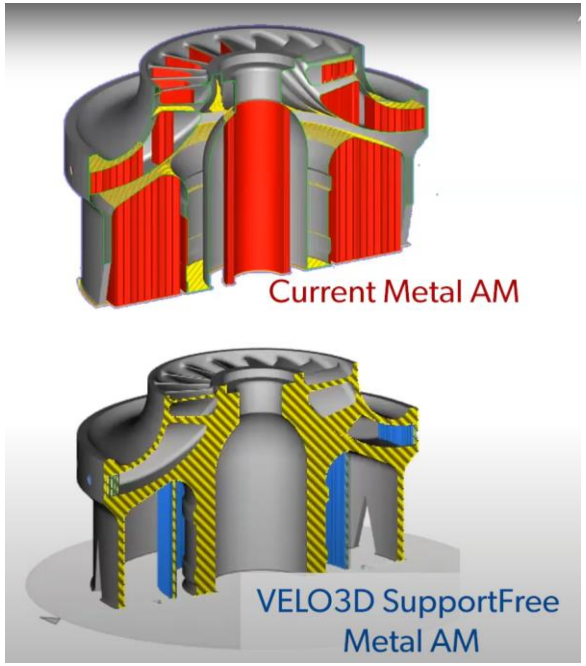
Support optimisation

Parameter setup



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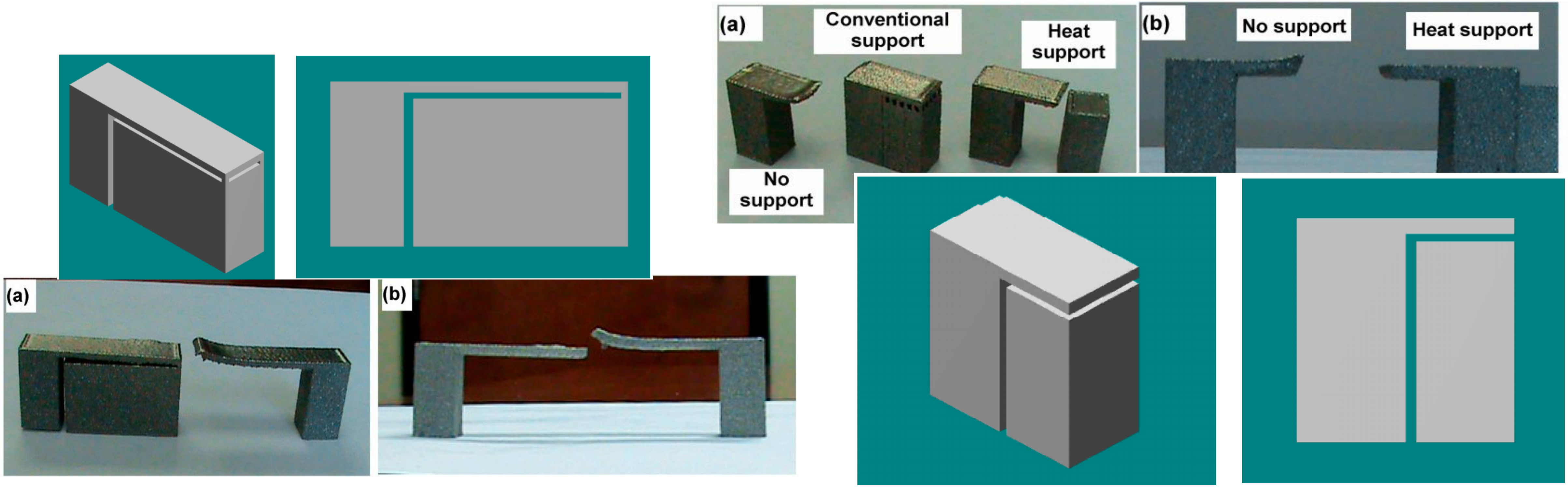
Support optimisation

Minimum and non-contact support structures



Cooper, Kenneth et al. 2017 'Contact-free Support Structures for Part Overhangs in Powder-Bed Metal Additive Manufacturing'

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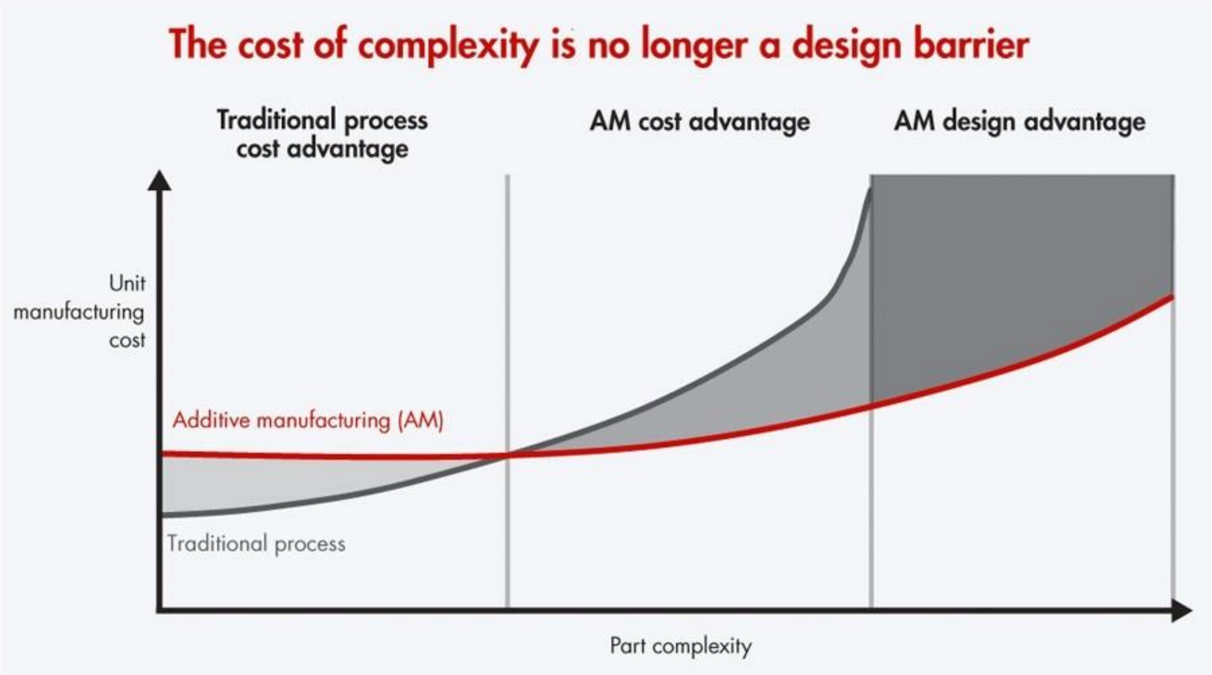
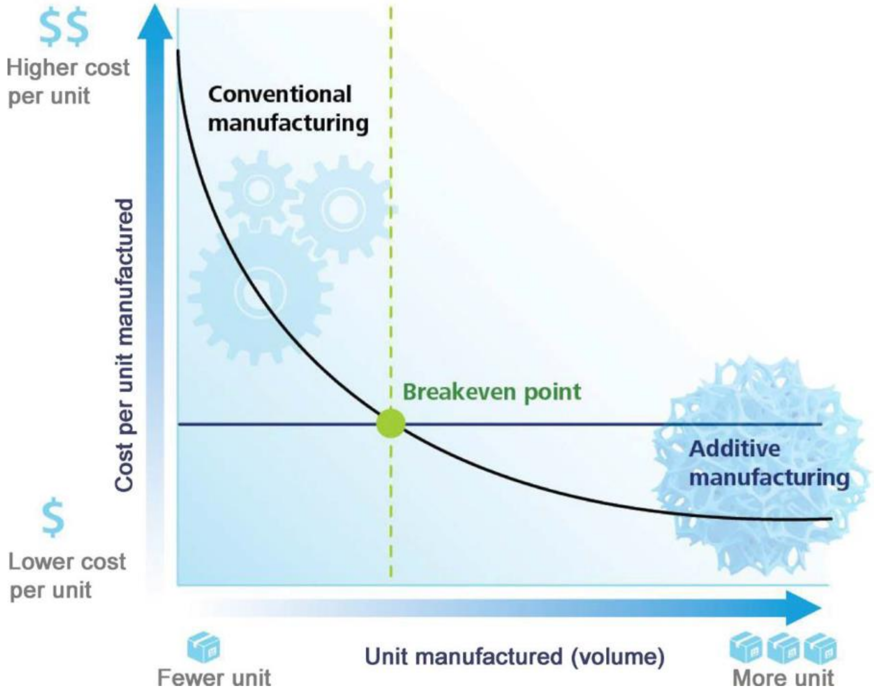
Process Optimisation



https://www.linkedin.com/pulse/cost-modelling-additive-manufacturing-3d-printing-shubham-saxena/



Attaran, Mohsen. 2017 ‘Additive Manufacturing: The most promising technology to alter the supply chain and logistics’ Journal of Service Science Management

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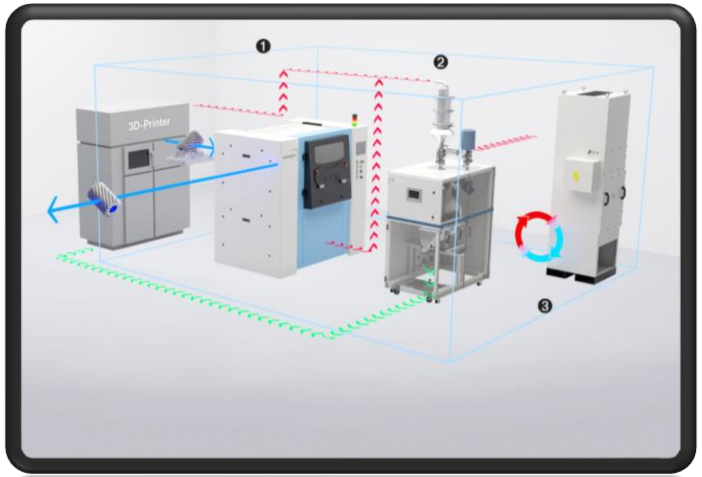
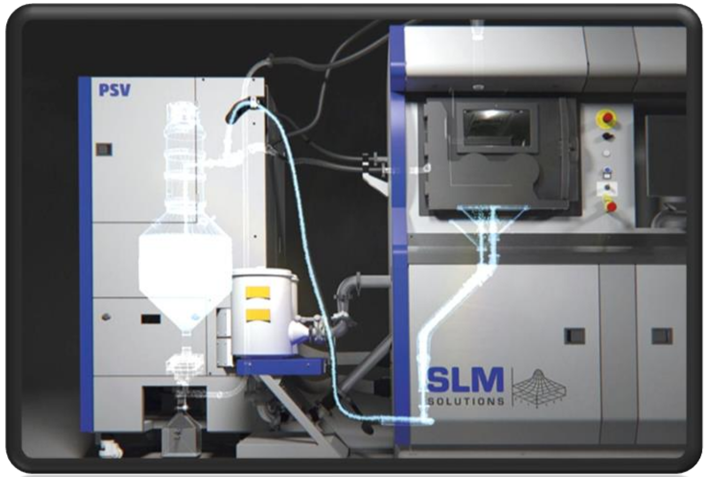
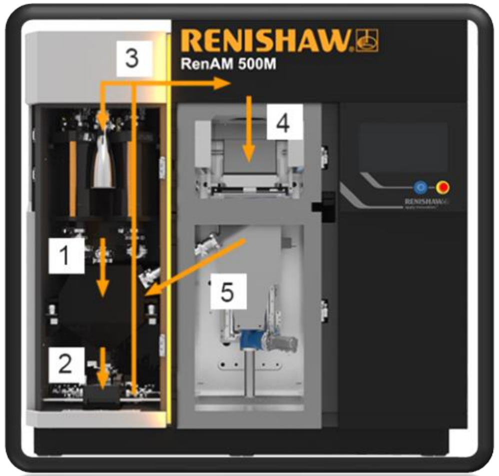
Machine utilization and automatic powder handling







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