Current issues in the processing of Ti alloy Ti6Al4V by laser additive manufacturing techniques

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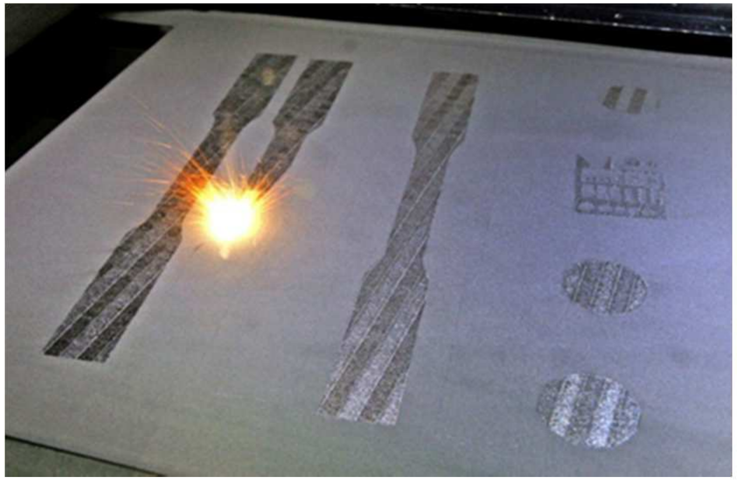
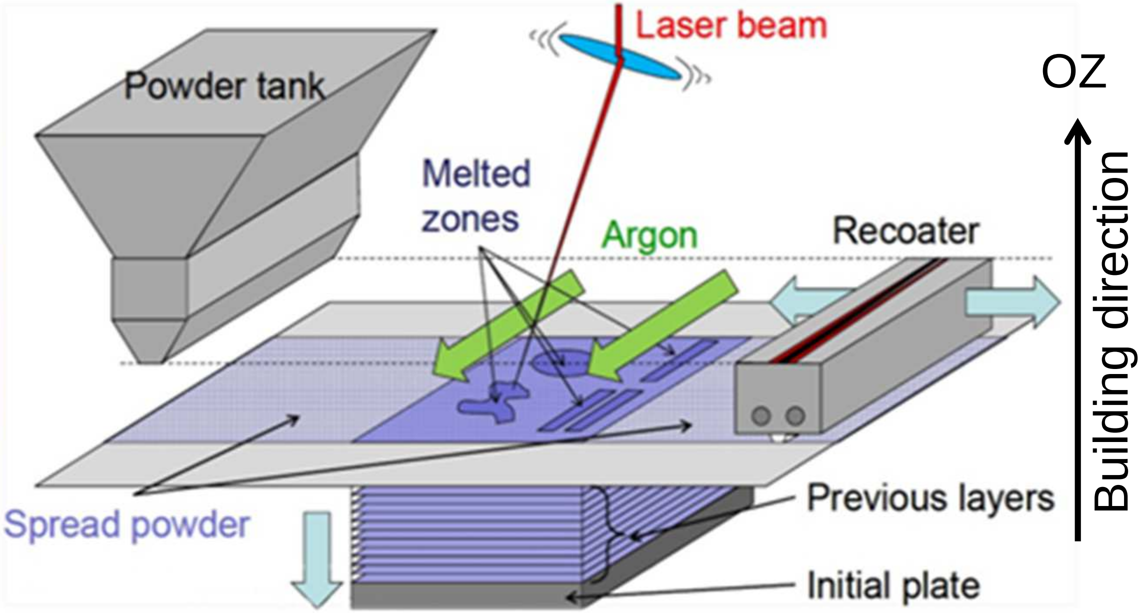
Outline

- **Introduction**
  - **Additive manufacturing**
    - Laser Beam Melting vs Laser Cladding
    - Specificities (1) ultra-fast thermal cycles
    - Specificities (2) directional process
  - Background on Ti-6Al-4V
- Importance of thermal history
  - Defects and porosities (LBM and LC)
  - Dimensional accuracy (LC)
- Influence of laser power in LC Ti6Al4V
- Anisotropy in LBM Ti6Al4V
- Summary

Introduction (1)

Laser Beam Melting



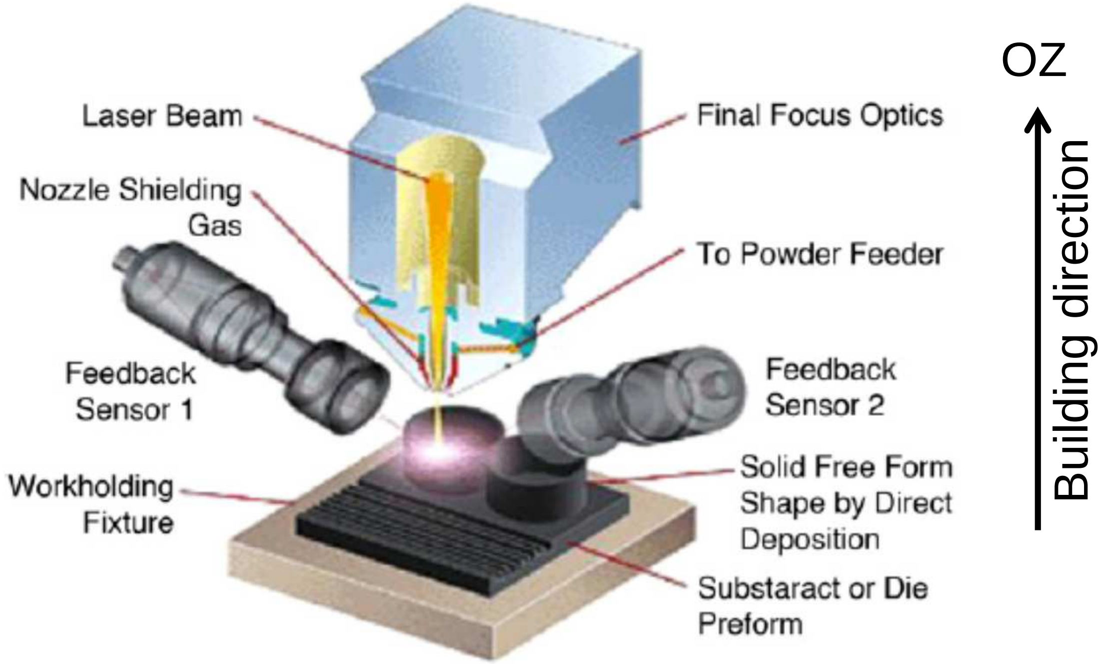


- Metallic powder is deposited layer by layer in a **powder-bed**…
- … then molten locally by a laser according to the desired shape

Introduction (2)

Laser Cladding

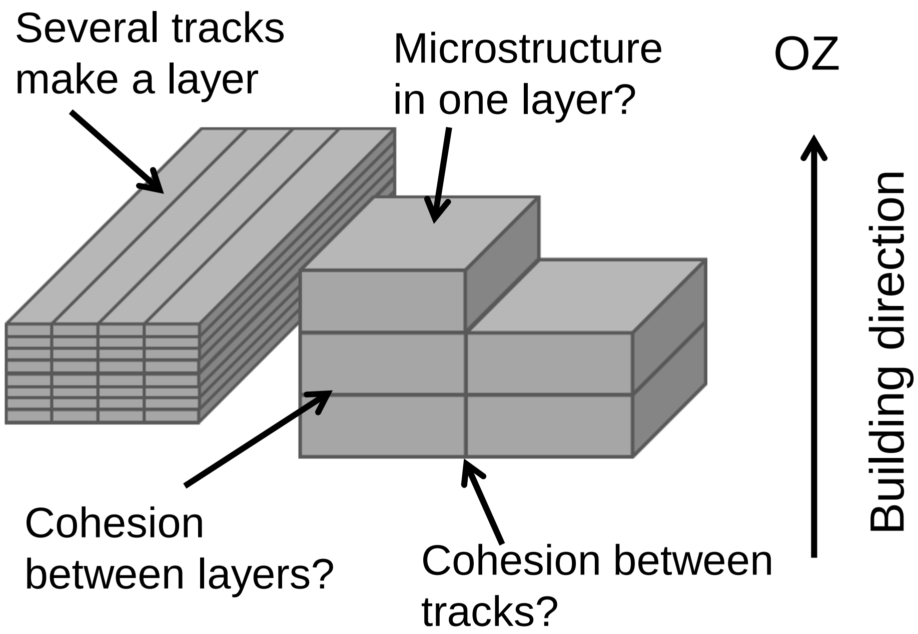
- Metallic powder is projected onto a substrate and simultaneously melted through a laser beam: **Powder-feed** process
- Suitable for **fabrication** and **repair**
- Not limited to planar surfaces



[Bhattacharya et al., MSEA (2011)]

Introduction (3)

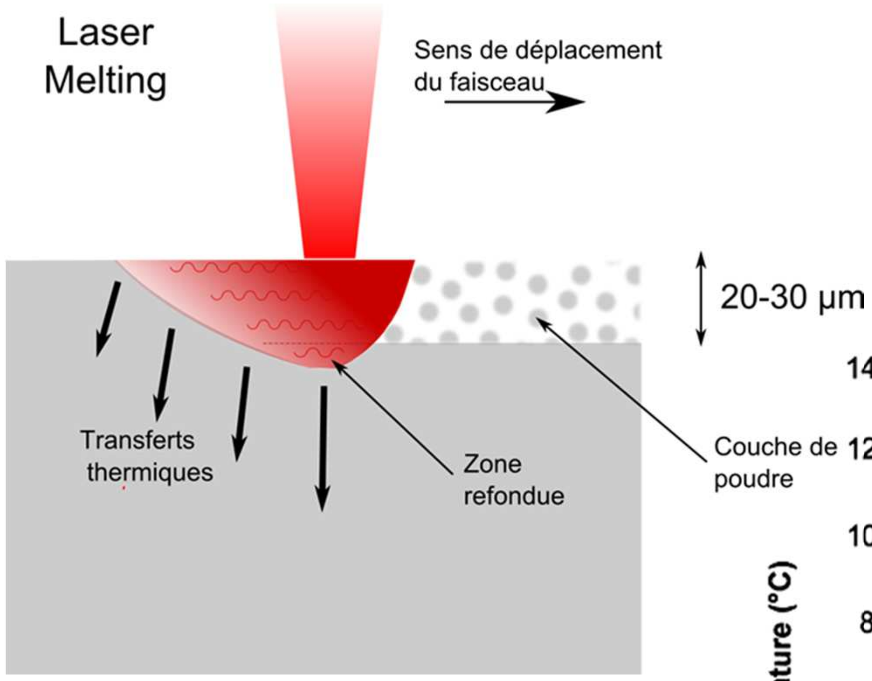
Laser Beam Melting (LBM) vs Laser Cladding (LC)



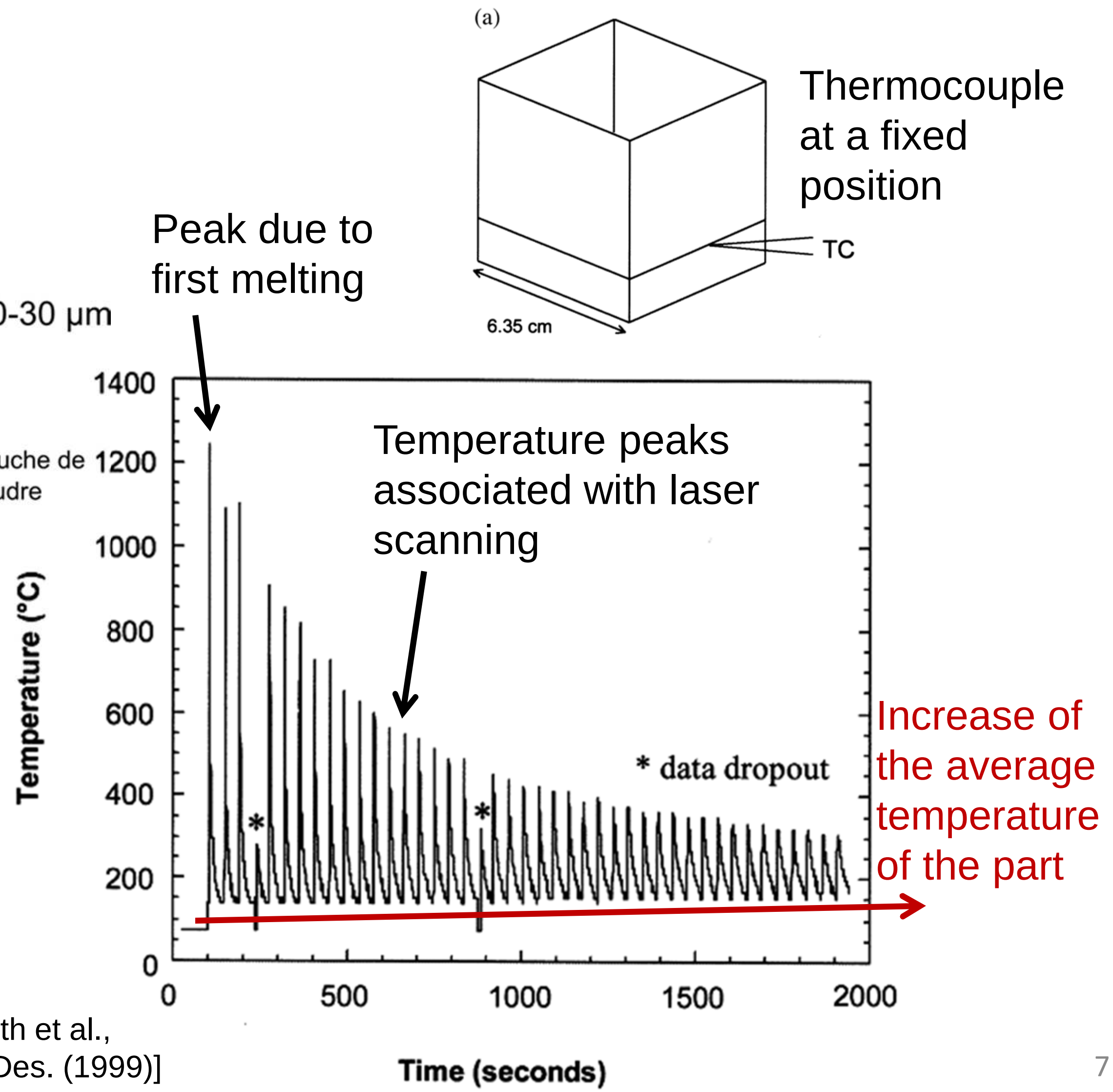
- Formation of defects: porosities, inclusions, oxides... ?
- Specificities of additive manufacturing for metallic materials
  $\Rightarrow$ microstructures and properties

	LBM	LC
Processing parameters	Laser power, Scanning speed, **Layer thickness**, Hatch space, Preheating T	Laser power, Scanning speed, Hatch space, Preheating T, **Powder feed rate** **Layer height is an outcome of the process !**

Introduction (4)
Ultra-fast thermal cycles



[Q.Contrepois, ULg]

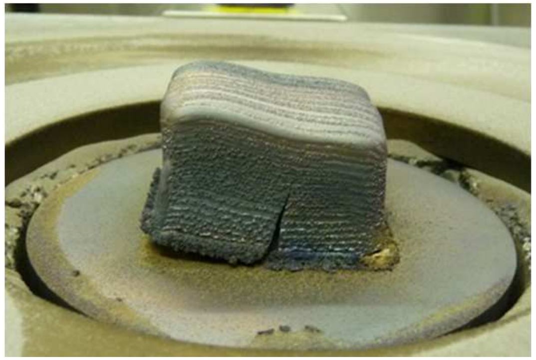


[M.L.Griffith et al.,
Mater. & Des. (1999)]

Introduction (5)
Ultra-fast thermal cycles

- Very high cooling rates
  - Build up of high internal stresses
    ⇒ Cracks, Deformations
    ⇒ Influence on mechanical properties

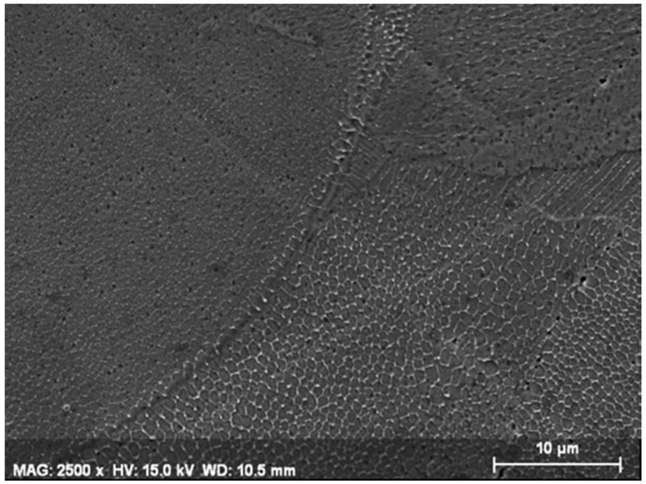
[J.T.Tchuindjang, ULg]



Tool steel, LC

  - Out-of-equilibrium microstructures
    e.g. chemical segregation at a very local scale

[Mertens et al., MSF (2014)]

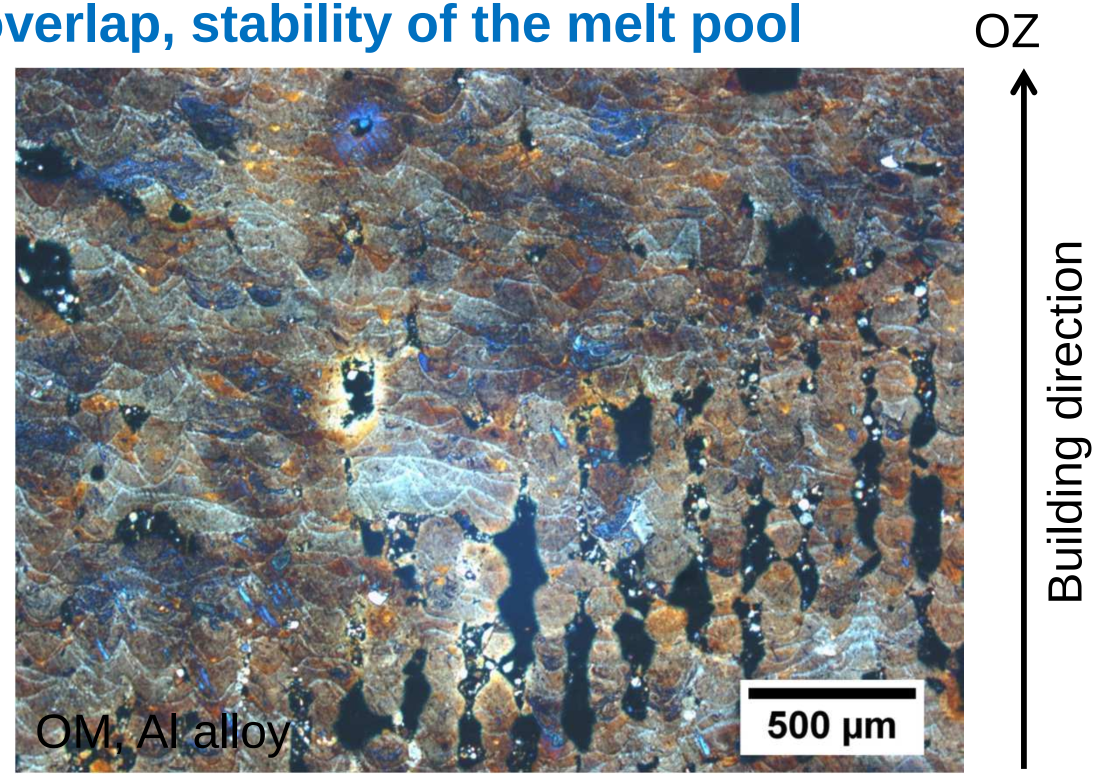


Microsegregation of Cr in stainless steel, LBM

Introduction (6)

LBM and LC are **directional** processes

- Formation of defects with particular orientations
- Cohesion between successive layers: a good wetting is important
  ⇒ **Partial remelting of the previously solidified layer**
- Cohesion between neighbouring tracks
  ⇒ **Tracks overlap, stability of the melt pool**

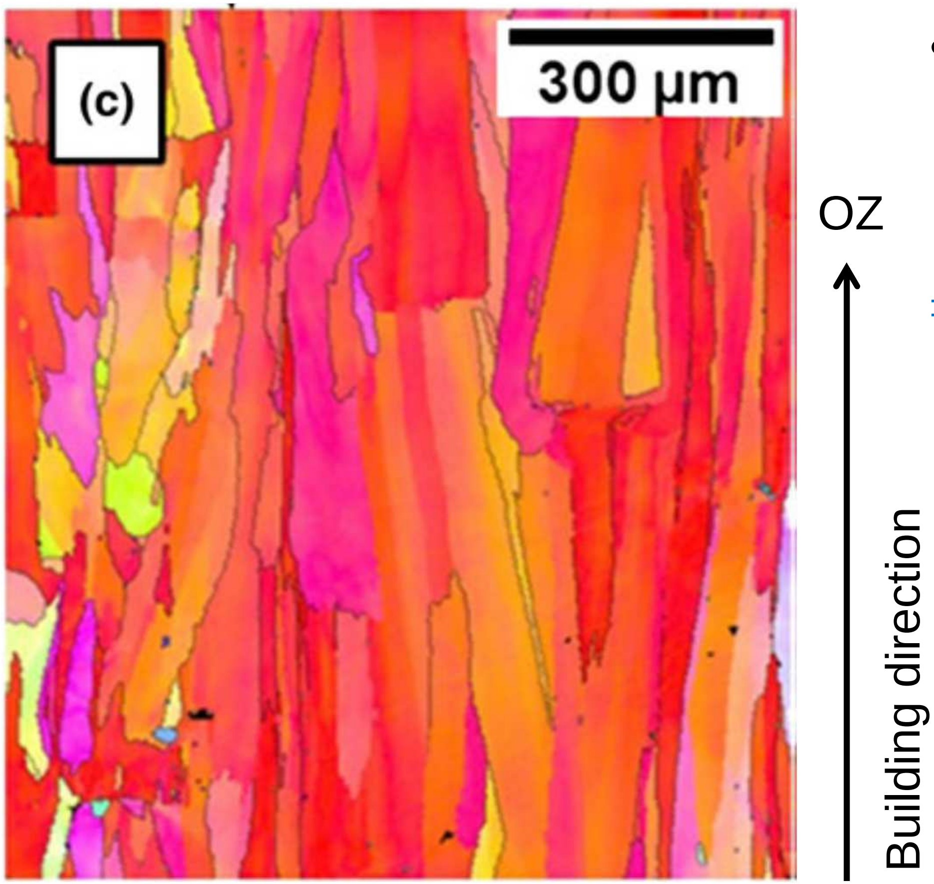


[Q.Contrepois, ULg]

Introduction (7)

LBM and LC are **directional** processes

[Niendorf et al., MMTB (2013)]



EBSD, Stainless steel

- Particular solidification processes may occur **for some materials and processing conditions**:

⇒ **Epitaxial growth** // to the direction of maximum heat conduction i.e.
the newly solidified layer crystallizes in the continuity of the previously solidified layer thus forming **elongated columnar grains.**

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Introduction (8)

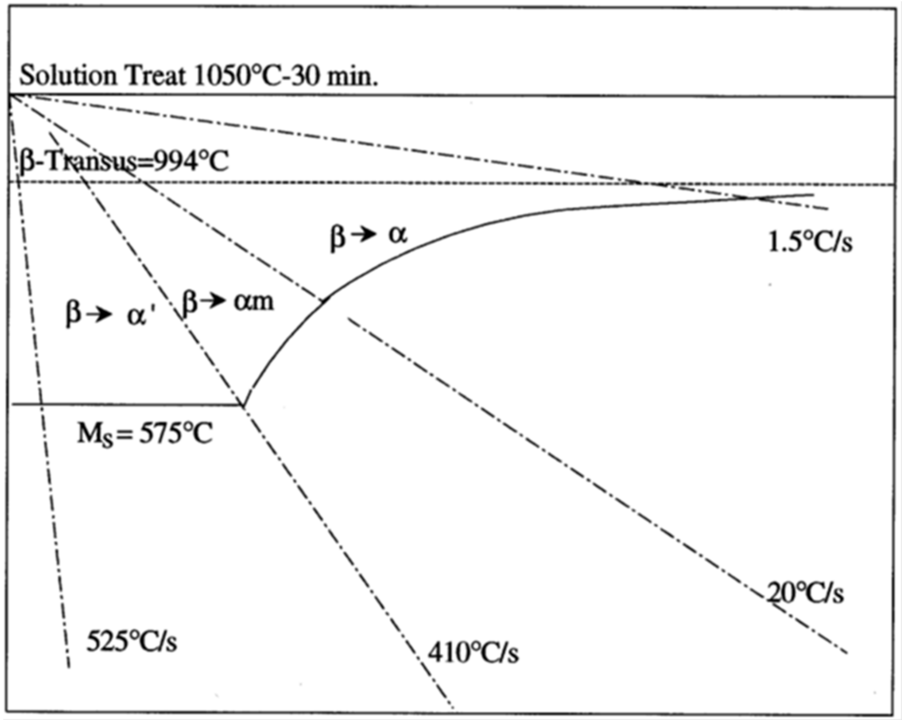
Ti-6Al-4V

- Ti – 6Al – 4V first solidifies in the β (BCC) structure ⇒ Elongated columnar primary β grains
- Upon cooling, β transforms into α (hcp): Exact nature, morphology and size of the transformation products are function of cooling rate

OZ

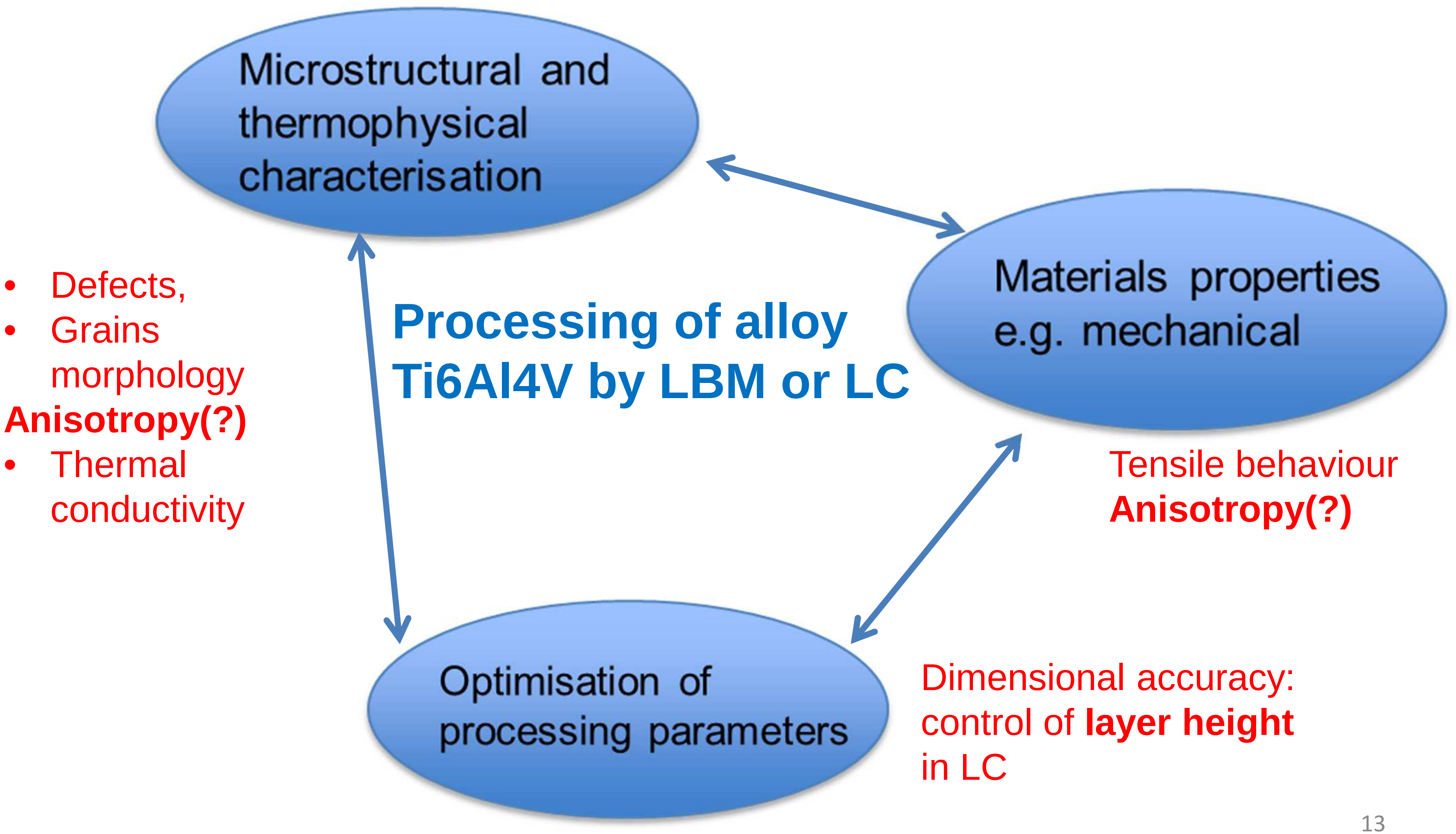
Building direction

[Reginster et al., MSF (2013)]



[Ahmed & Rack, MSEA, 1998]

Introduction (9)



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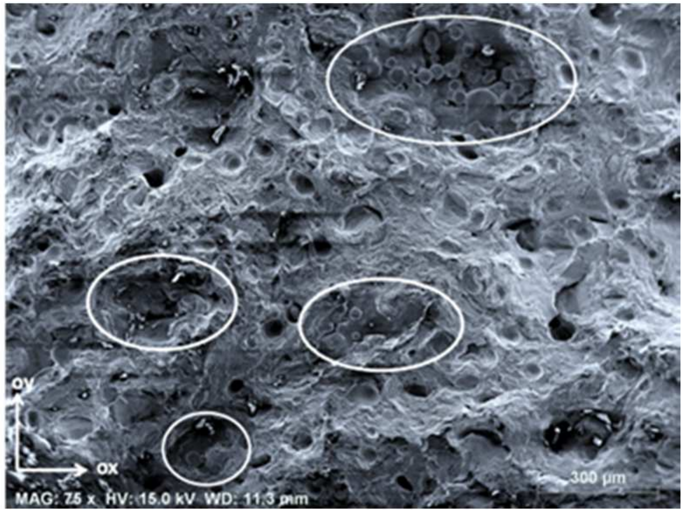
Thermal history (1) - Defects and porosities

Lack of fusion

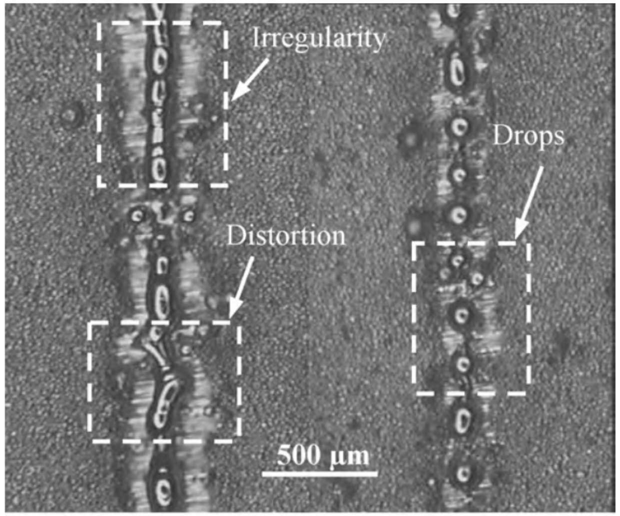
[Mertens et al., MSF (2014),]



- Very detrimental for mechanical properties
- Processing conditions are **too cold!**

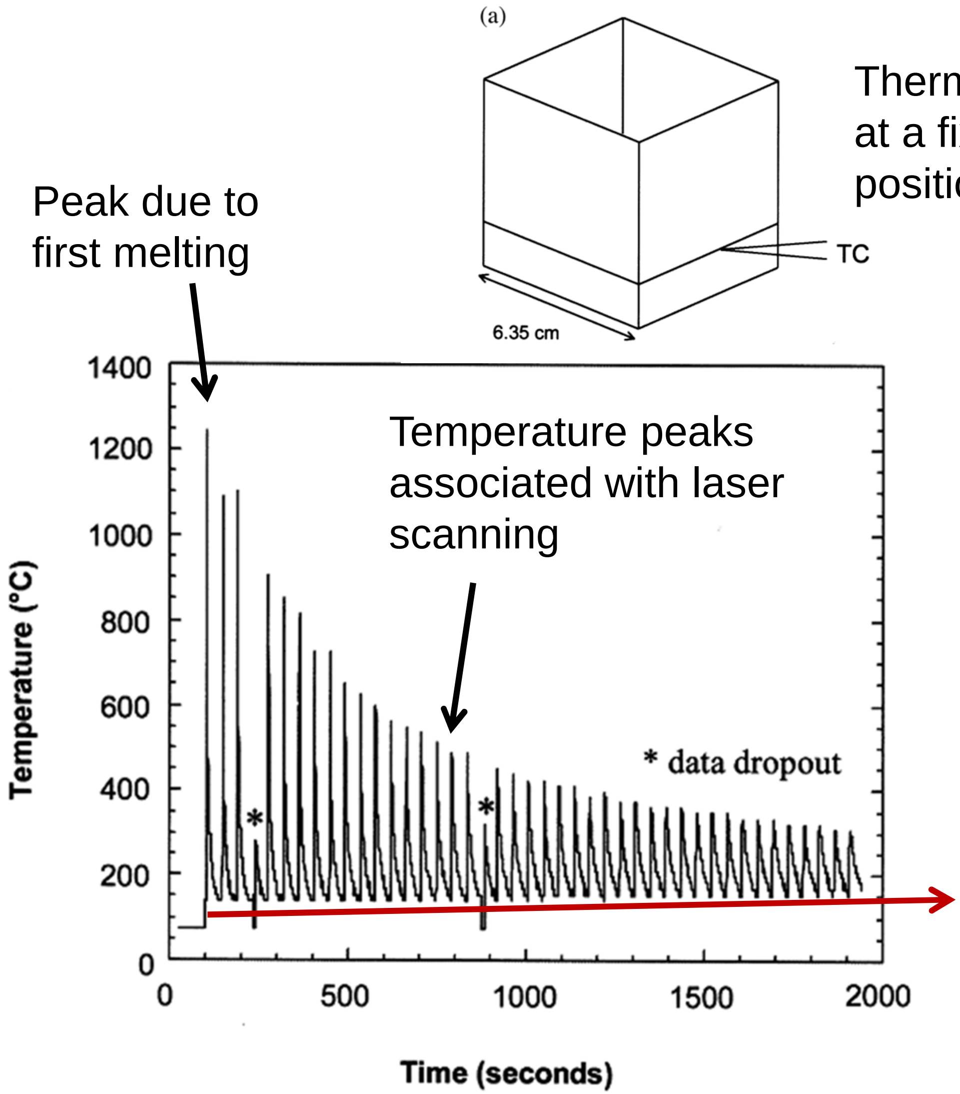
"Balling"

[Yadroitsev et al., JMPT, (2010)]



- Instability of the melt pool, due to an unfavourable combination of surface tension and viscosity
- This may happen because processing conditions are **too hot!**

Thermal history (2) - Defects and porosities



[Griffith et al., Mater. & Des. (1999)]

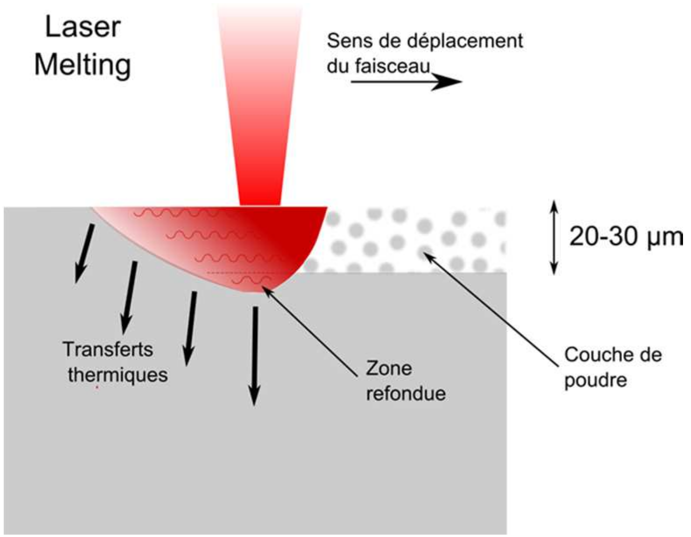
- Heat accumulation may cause "balling"
- One can try and adapt the processing parameters to limit heat accumulation...
- ... but not too much!

⇒ **Need for better optimized (path-dependent) processing parameters...**

Thermal history (3) - Defects and porosities

⇒ ...Need for better optimized (path-dependent) processing parameters

- Knowing the temperature evolution during processing
  - Not that simple: absolute measurements possible only locally
  - Models for thermal transfer ⇒ **Thermal conductivity**



- Thermal conductivity values at room temperature are often used in FE models
- ... but the actual range of temperature during the process is much bigger: RT- T_{melt}

Thermal history (4) - Defects and porosities

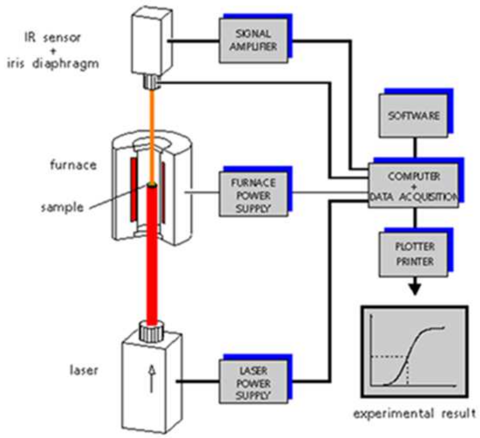
- Determination of **thermal conductivity**

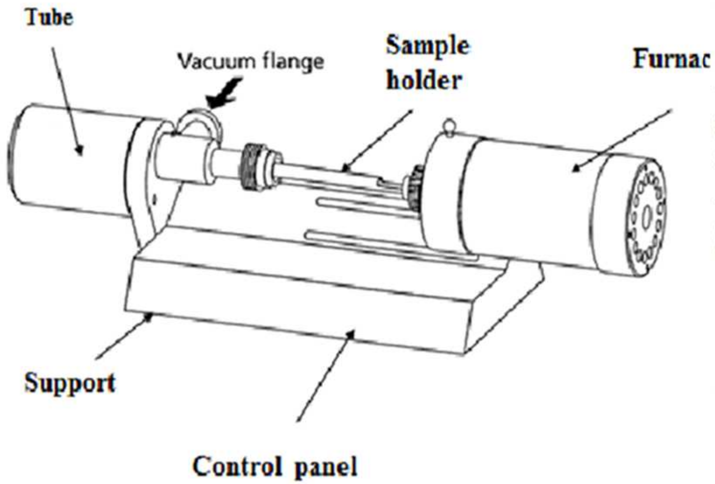
  Laplace's Equation : $\chi(T)=\alpha(T)*\rho(T)*C_p(T)$

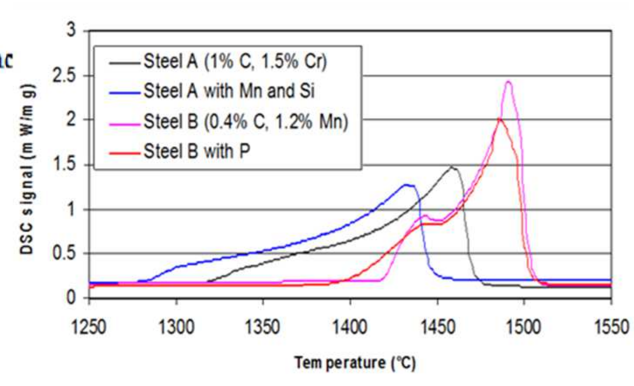
$\alpha(T)$= thermal diffusivity, (Laser Flash)

$\rho(T)$= Density, (dilatometry also gives **CTE**)

$C_p(T)$= Specific heat, (DSC)



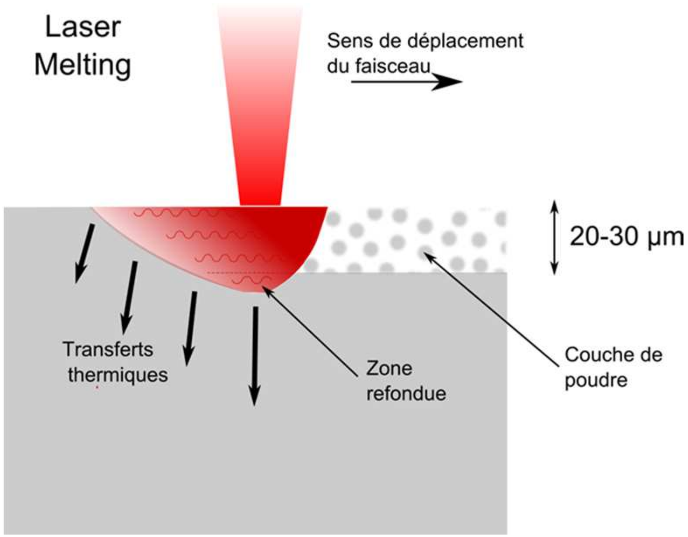


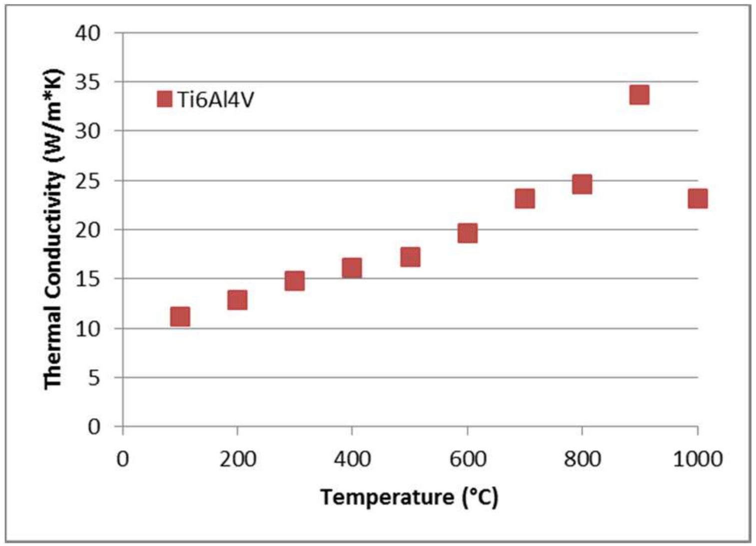


Thermal history (5) - Defects and porosities

⇒ ...Need for better optimized (path-dependent) processing parameters

- Knowing the temperature evolution during processing
  - Not that simple: absolute measurements possible only locally
  - Models for thermal transfer ⇒ **Thermal conductivity**



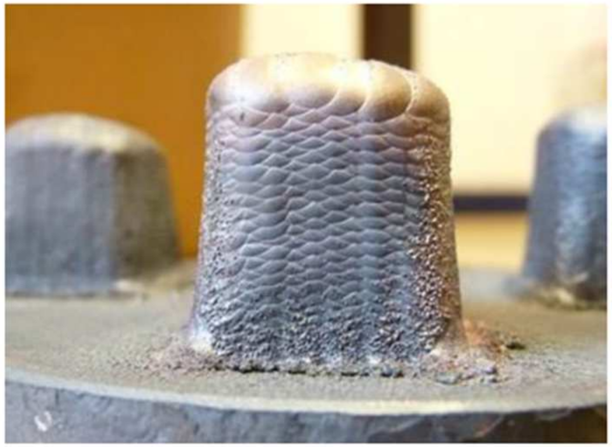


[Mertens et al., Powder Metall. (2014)]

⇒ **Thermal conductivity is strongly dependent on temperature!**

Thermal history (6) - Dimensional accuracy in LC

[N.Hashemi, ULg]



High Speed Steel, LC

Heat accumulates during processing

⇒ More powder is "captured" in the melt pool

⇒ Layer height varies as a function of local thermal history in each point

⇒ **Need for optimized (path-dependent) processing parameters to produce a deposit with a constant layer height**

e.g. HSS deposit with a target total height of 23 mm, and a target layer height of 0,7 mm

Laser power (W)	Measured total height (mm)	Measured layer height (mm)
940	26,1	**0,79**
1020	29,8	**0,903**

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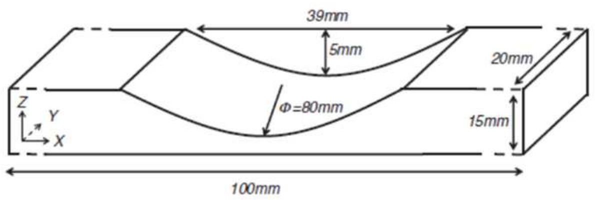
Influence of laser power in LC Ti6Al4V (1)

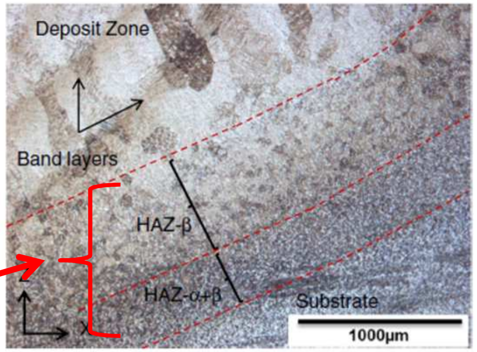
- High laser power are often preferred for high productivity

Laser power (W)	Scan speed (mm/min)	Incident energy (W*min/mm)	Building time (min)
1100	400	2,75	**5,4**
210	600	0,33	**40**

- But a high laser power also leads to coarser and more heterogeneous microstructure



Laser power: 1100 W
Heat Affected Zone : ~1 mm !

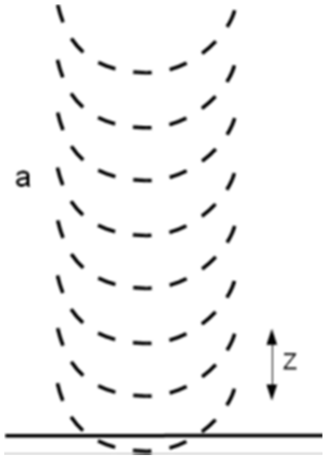


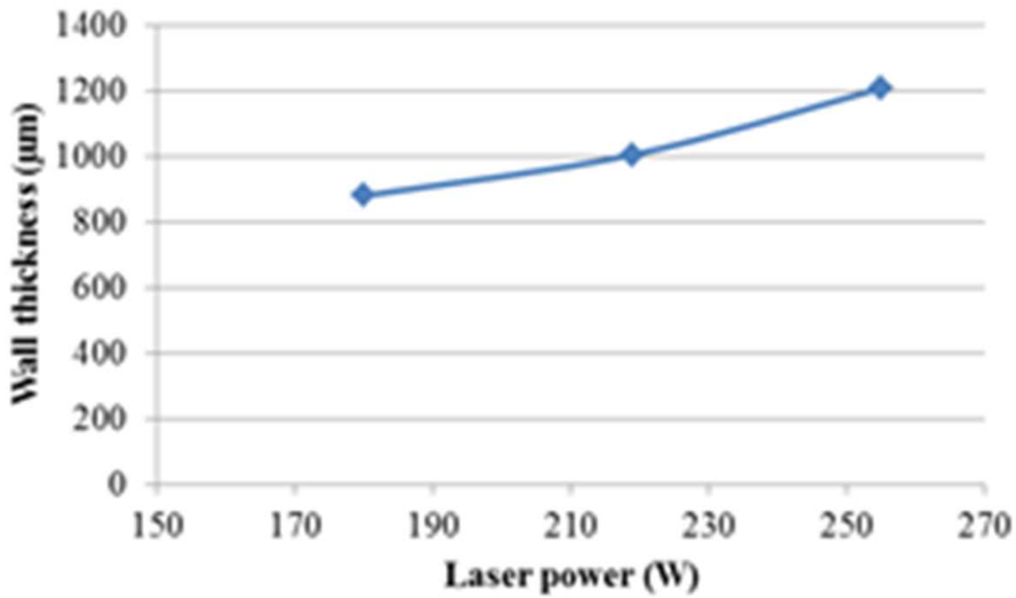
[Paydas et al., Mater. & Des., (2015)]

- Investigating the potential of using a low power laser source
  - New 300 W source, installed beside the original 2kW source
  - Effect on microstructures and on process flexibility?

Influence of laser power in LC Ti6Al4V (2)

- Fabrication of thin walls by superposing single tracks
- Decreasing the laser power decreases the wall thickness

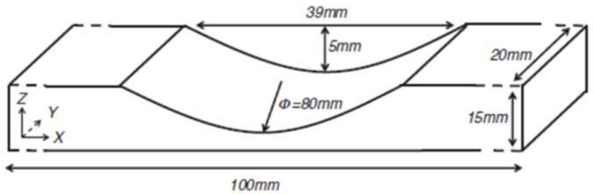




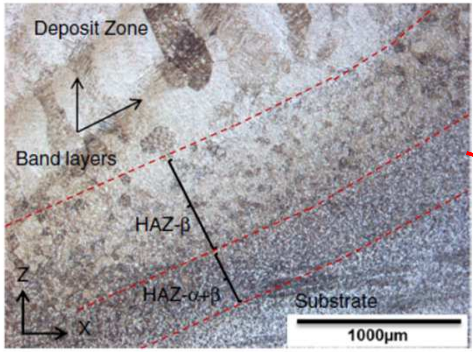
[Mertens et al., Proc. Conf. Ti 2015]

Influence of laser power in LC Ti6Al4V (3)

"Refilling" a cup = Repair

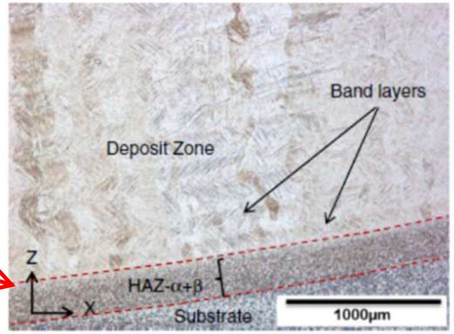


1100 W

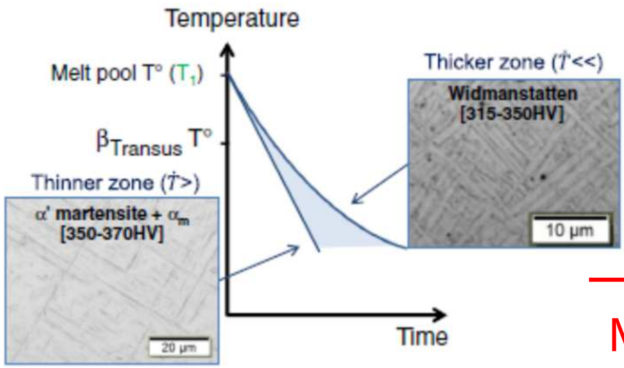


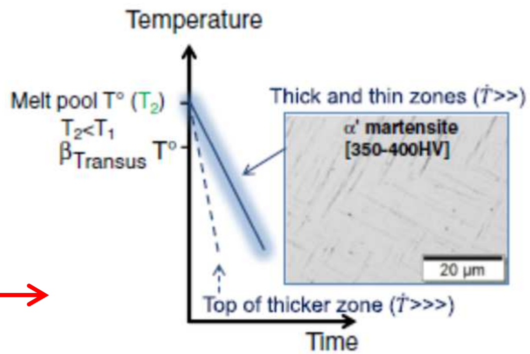
Smaller HAZ

210 W

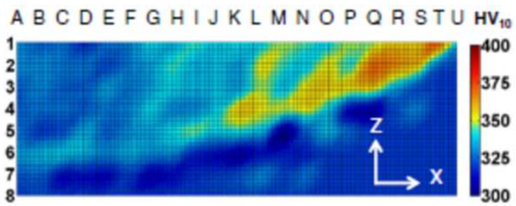


[Paydas et al., Mater. & Des., (2015)]

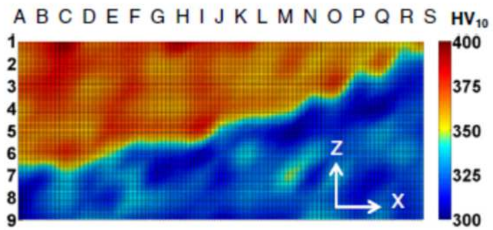




Microstructure is more homogeneous



Local hardness



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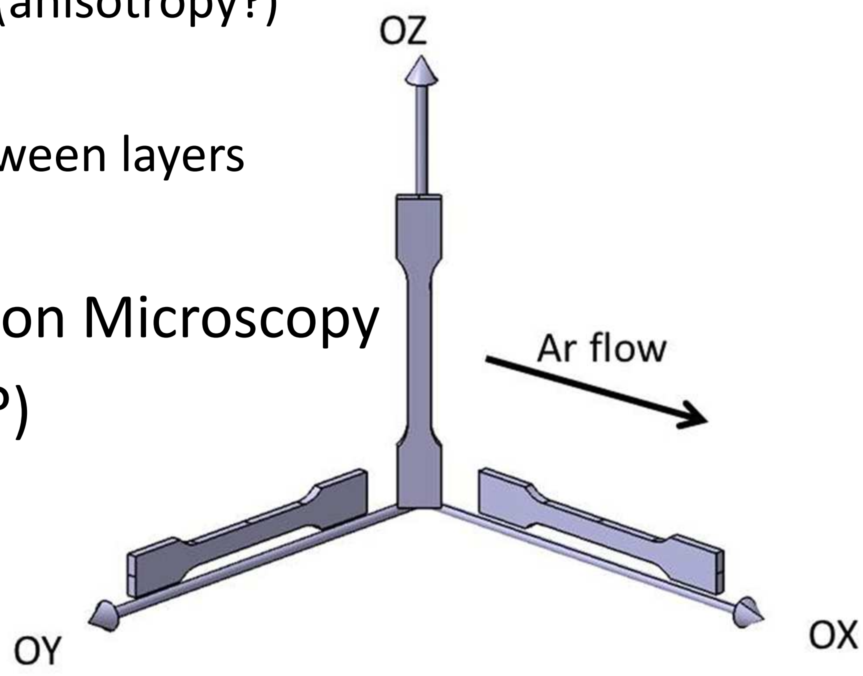
Anisotropy in LBM Ti6Al4V (1)

- Laser Beam Melting:

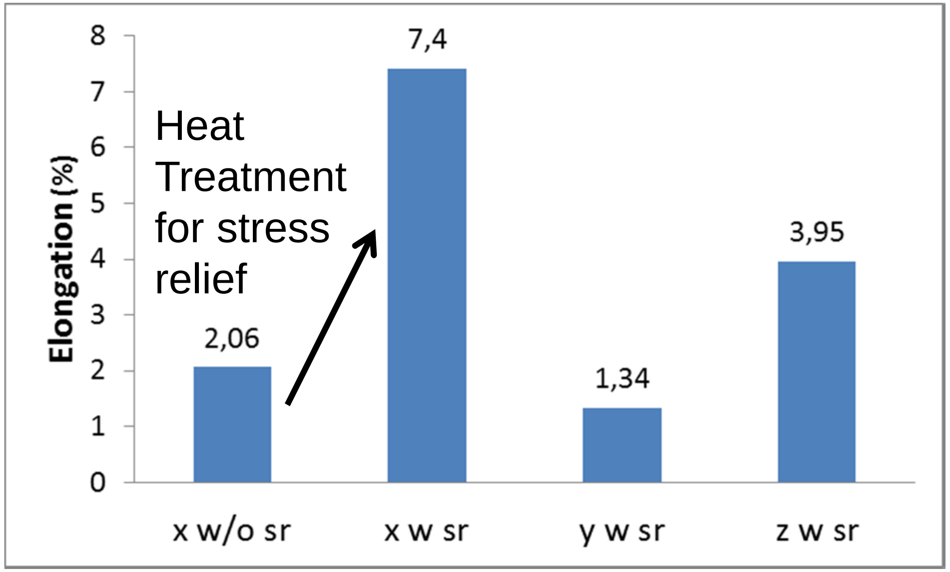
Layer thickness/µm	Focus offset/mm	Laser power/W	Scanning speed/mm s^{-1}	Hatch spacing/µm
30	2	175	710	120

  - Samples produced in three directions (anisotropy?)
  - Ar flowing in the ox direction
  - Rotation of the scanning direction between layers
- Microstructural characterisation :
  Optical microscopy, Scanning Electron Microscopy
- Uniaxial tensile testing (anisotropy?)

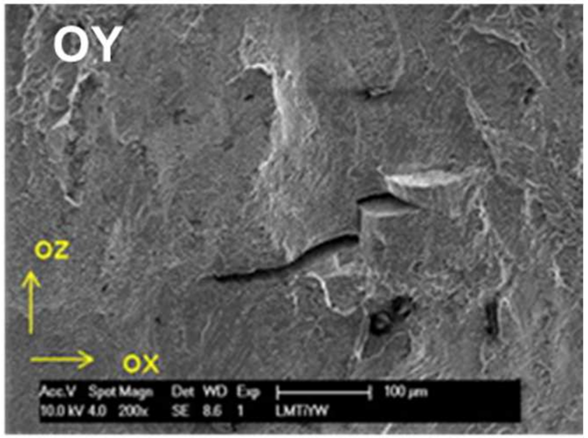


[Mertens et al., Proc. ECSSMET (2012)]

Anisotropy in LBM Ti6Al4V (2)

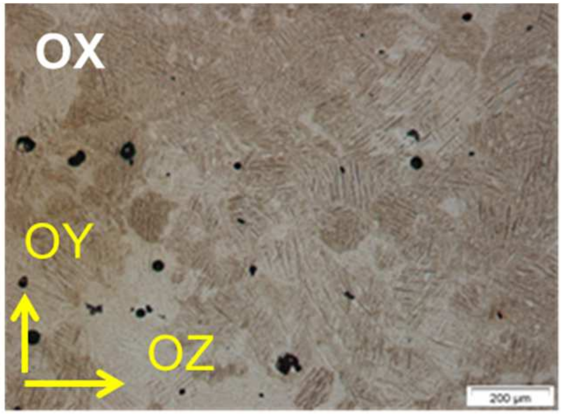


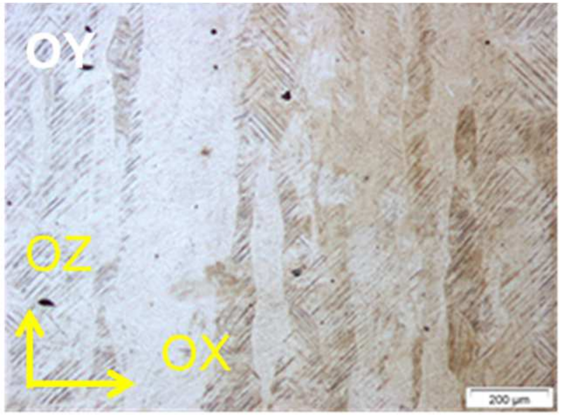
- LBM is a directional process
  - Epitaxial growth
- Strong anisotropy in building direction and **inside the deposition plane**
  - Cracks with specific orientation in the OY and OZ samples
  - Correlation with the microstructure ?

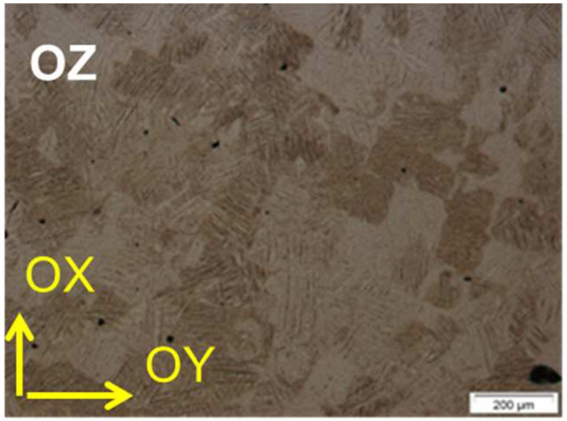


[Mertens et al., Proc. ECSSMET (2012)]

Ti-6Al-4V (4) – microstructures







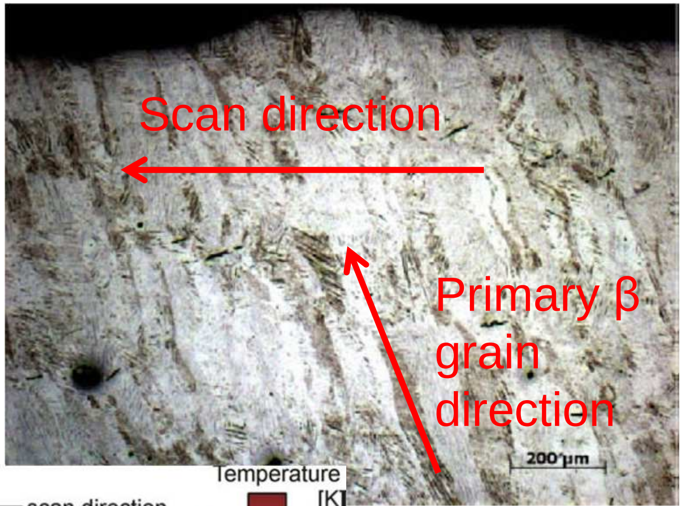
- Spherical porosities due to entrapped gas < 0,5 %
- Elongated primary β grains (// OZ) in the OY sample…
- …but not in the OX sample, suggesting that the grains are actually **tilted** with respect to the building direction
- Primary β grain boundaries or α/β interphase boundaries might play a role in fracture
  $\Rightarrow$ Anisotropy in fracture behaviour could be related to the tilt in grains longest direction (?)

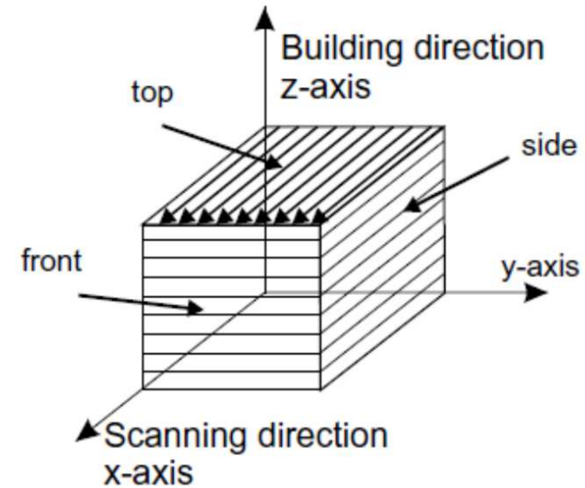
[Mertens et al., Proc. ECSSMET (2012)]

Ti-6Al-4V (5)

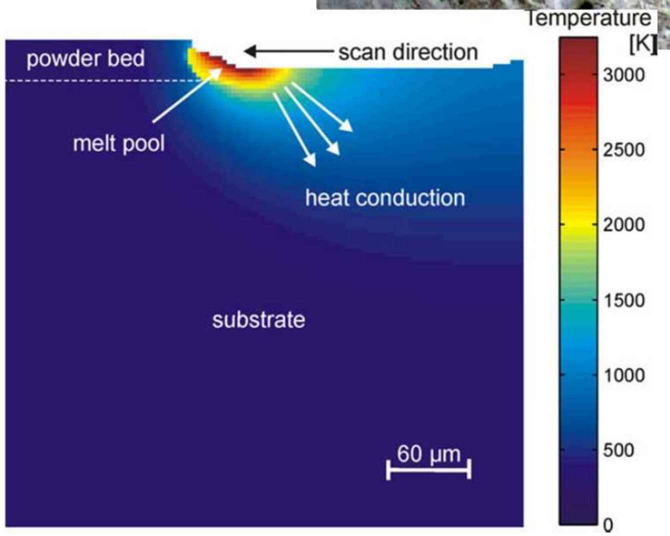
Anisotropy between ox and oy – Heat conduction

- Primary β grains grow following the direction of maximum heat conduction
- This direction for maximum heat conduction may become tilted with respect to the building direction
  - Scanning strategy





[Mertens et al., Proc. ECSSMET (2012)]

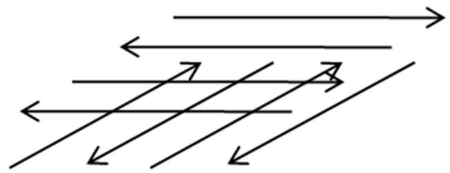


[Thijs et al., Acta Mater., 2010]

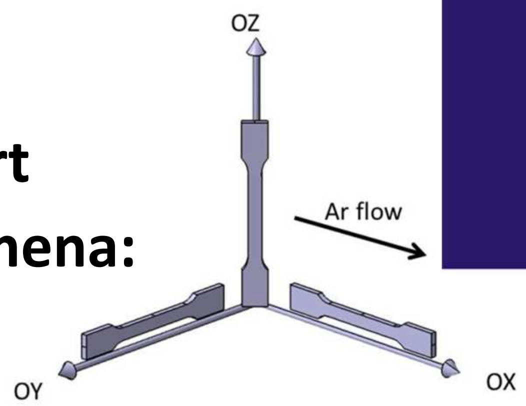
Ti-6Al-4V (6)

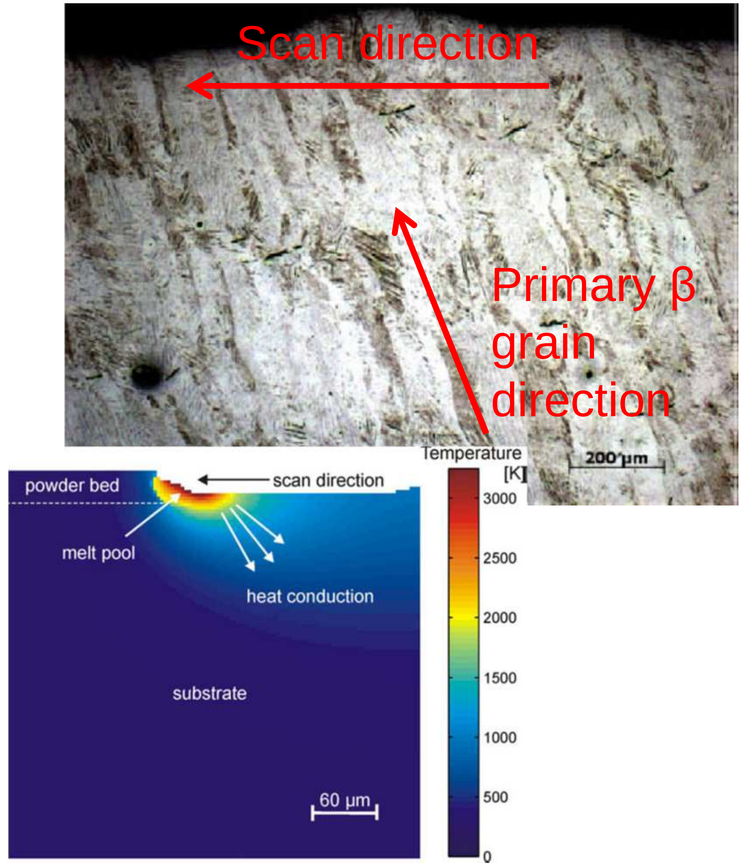
Anisotropy between ox and oy – Heat conduction

- Primary β grains grow following the direction of maximum heat conduction
- This direction for maximum heat conduction may become tilted with respect to the building direction
  - Scanning strategy: no, rotation!



  - Scanning velocity
  - **Geometry of the part**
  - **Evaporation phenomena: Effect of Ar flow**





[Thijs et al., Acta Mater., 2010]

Summary

- Laser Additive Manufacturing technologies are strongly directional processes, characterised by ultra-fast thermal cycles. As a consequence, one might observe:
  - Internal stresses
  - Anisotropy of the microstructure and mechanical properties
- Local thermal history is of paramount importance to control
  - local microstructure
  - formation of defects
  - dimensional accuracy of the parts (particularly in LC by controlling the layer height)

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