An Introduction to the Additive Manufacturing of Metallic Materials - Two Case Studies on the Processing of Stainless Steel 316L and of Ti Alloy Ti-6Al-4V

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- O. Lemaire – CRM, Liège

Outline

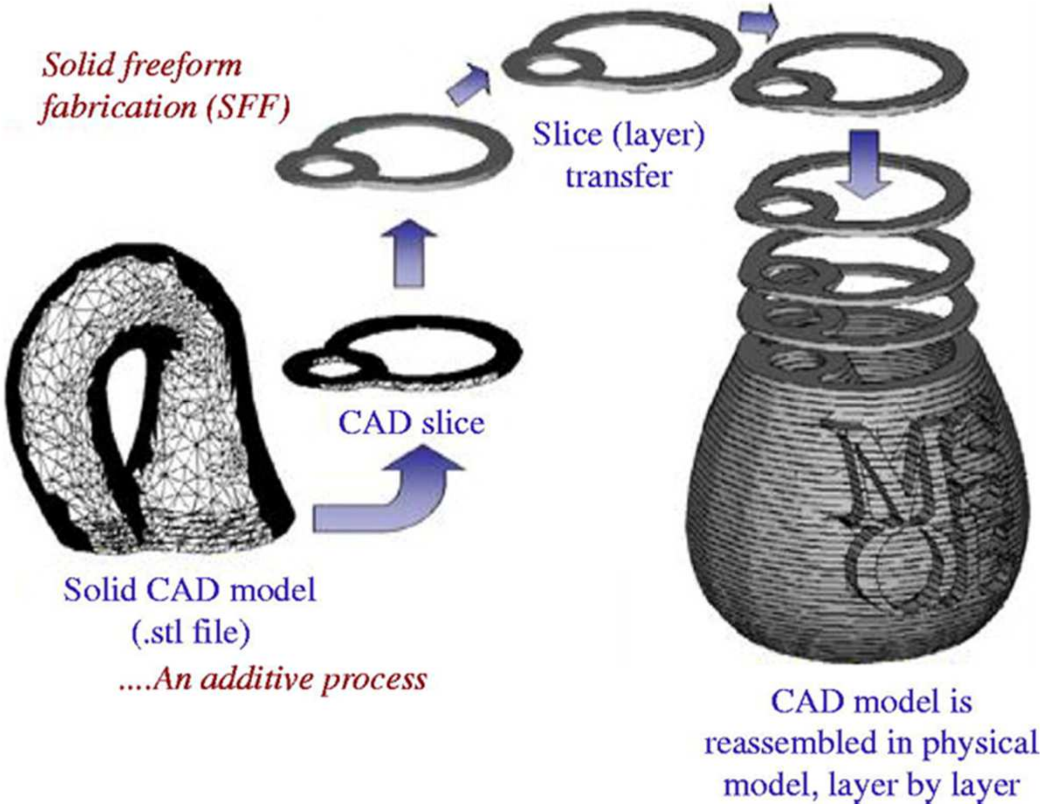
- **Introduction**
  - **Additive manufacturing**
    - **General introduction**
    - Laser Beam Melting - Operating principles
    - Specificities (1) ultra-fast thermal cycles
    - Specificities (2) directional process
  - Aims of the research
- Experimental procedure
- Results and discussion
  - Stainless Steel 316L
  - Ti-6Al-4V
- Summary

Introduction (1)

- "Instead of starting with a solid block of material and removing the unnecessary parts, additive manufacturing builds layer upon layer"

- Economic near-net shape process
- Complex shapes
- Small series, prototypes...
- Different materials:
  - Polymers
  - Ceramics
  - **Metals**

[3D printed Ceramic mug, Source: http://dharrounmodels.blogspot.be/2013_05_01_archive.html ; retrieved on 05/12/14]

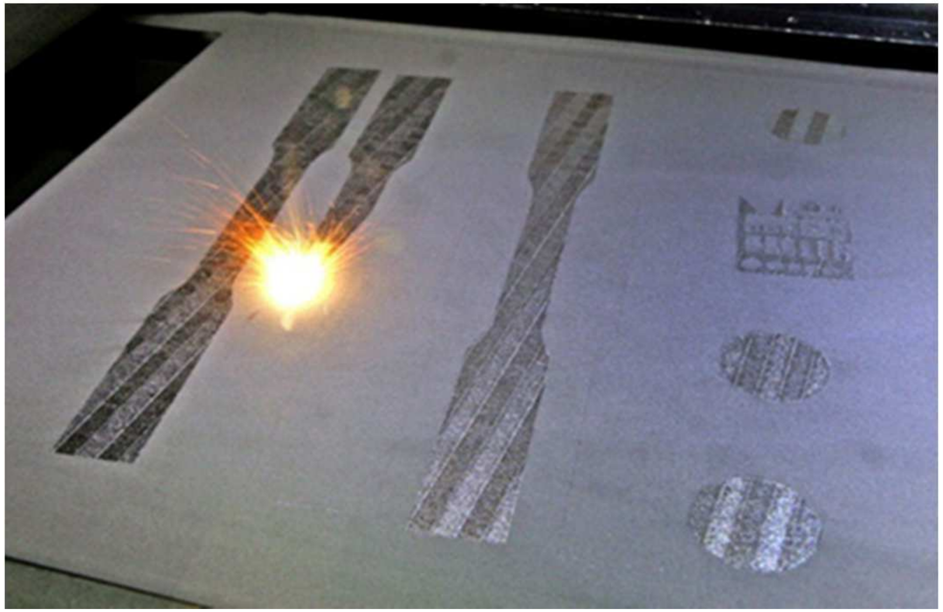


[source: http://blog.cafefoundation.org/additive-manufacturing-for-electric-motors/ ; retrieved on 05/12/2014]

Introduction (2)

Great diversity of additive techniques

Powder-bed



Laser Beam Melting
Electron Beam Melting

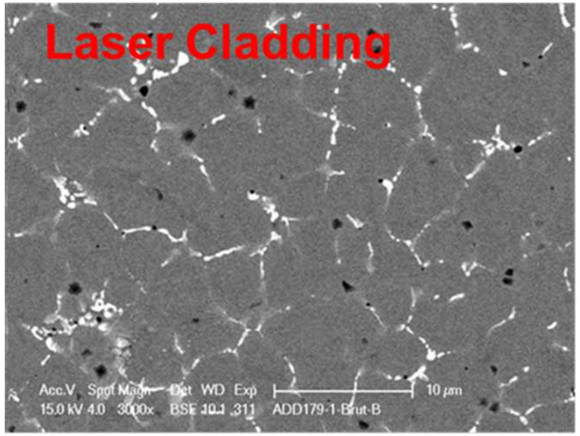
Powder-feed

Laser Cladding

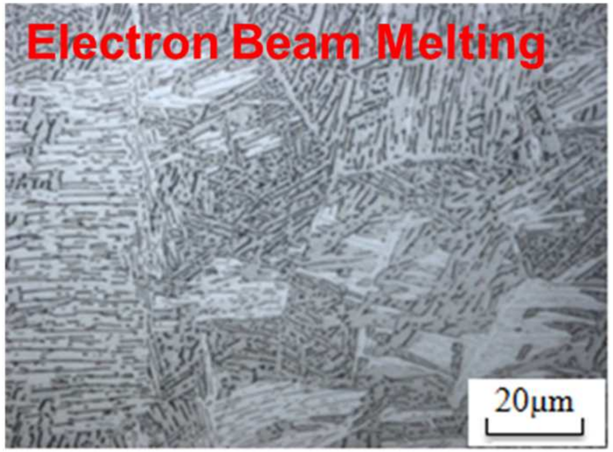
Introduction (3)

Diversity of microstructures and properties depending on...

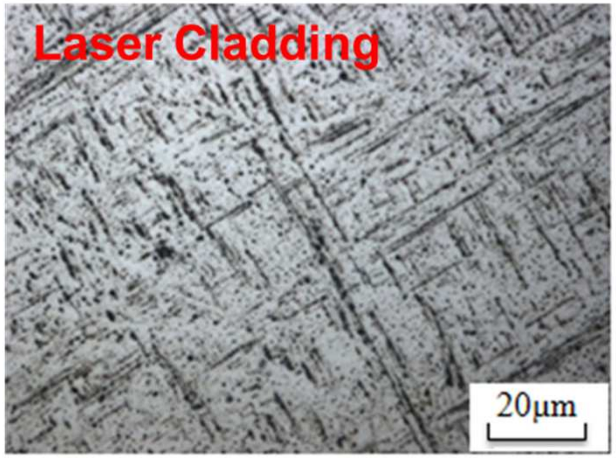
- Process
- Processing parameters (substrate/powder-bed preheat, scanning strategy, power…)
- Material
- This talk will focus on one technique **(LBM)** and two materials **(SS 316L and Ti-6Al-4V)** to discuss some specific issues of the additive manufacturing of metals



Tool steel AISI M4
[J.T.Tchuindjang]



Ti-6Al-4V



[Reginster et al., 2013]

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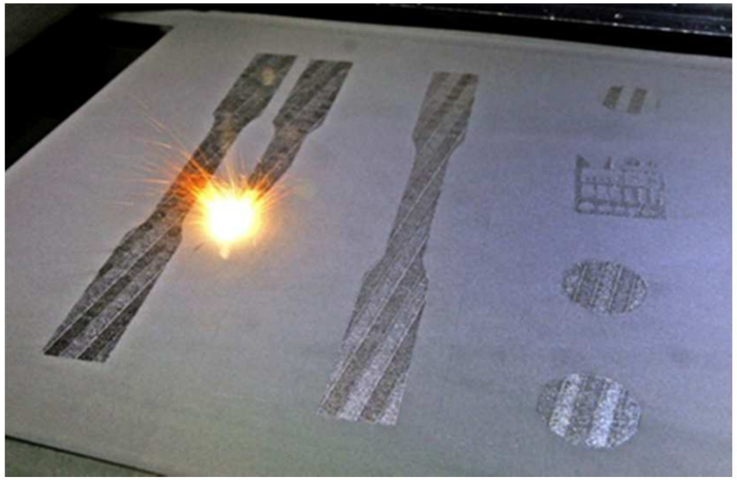
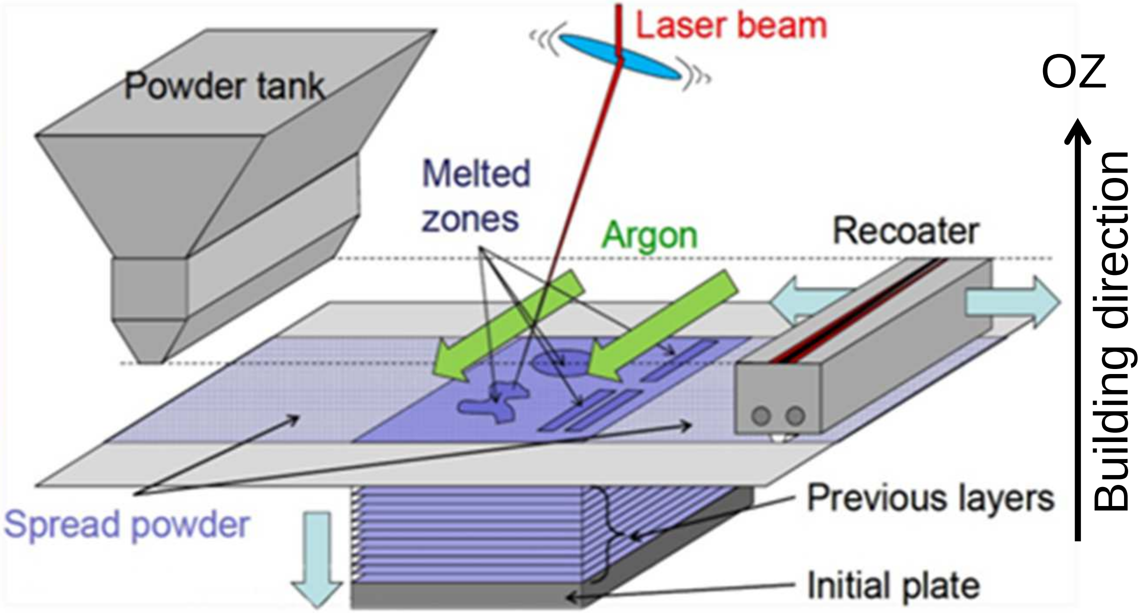
Introduction (4)

Laser Beam Melting – Operating principles

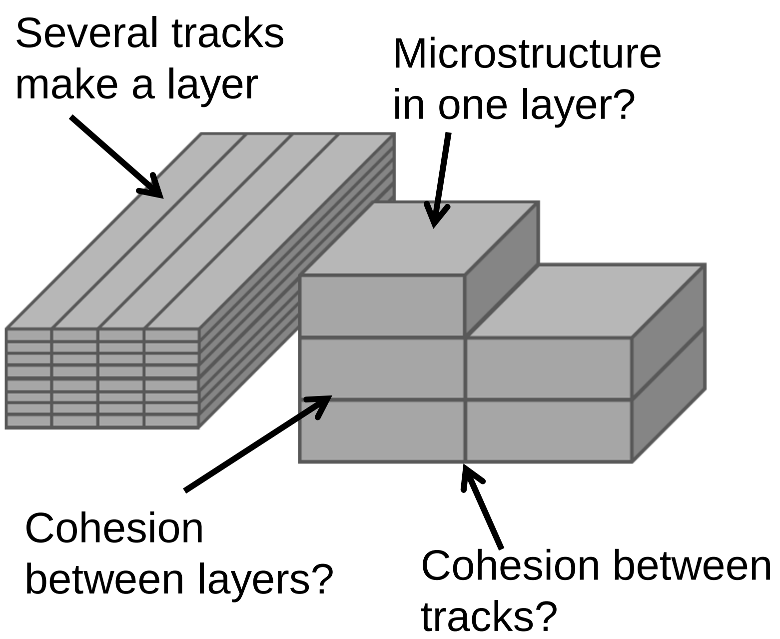


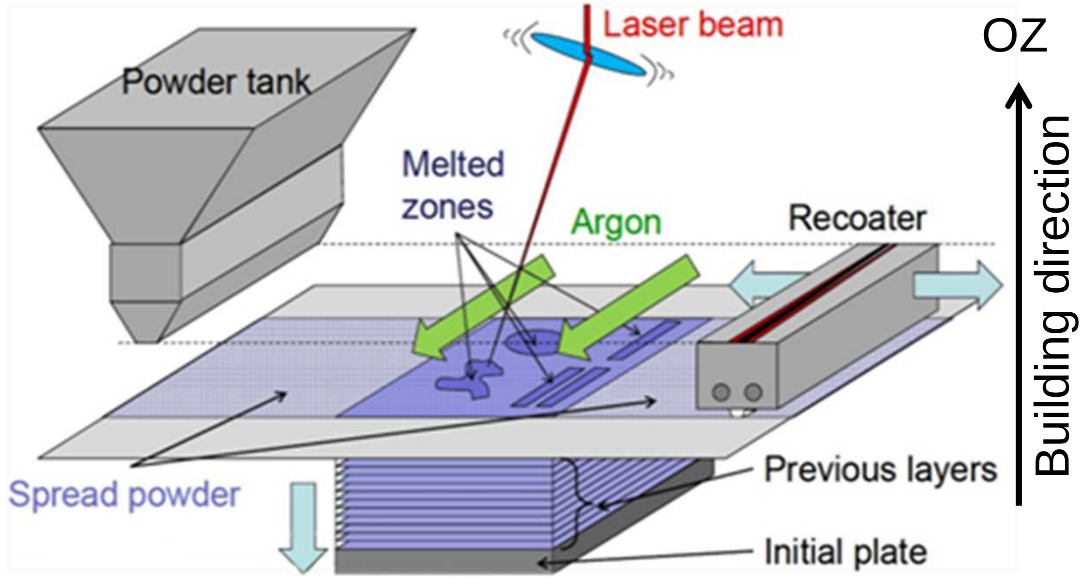


- Metallic powder is deposited layer by layer in a powder-bed…
- … then molten locally by a laser according to the desired shape

Introduction (5)

Laser Beam Melting – Operating principles





- Processing parameters: laser power, scanning speed, layer thickness, hatch space...
- Formation of defects: porosities, inclusions, oxides... ?
- Specificities of additive manufacturing for metallic materials...

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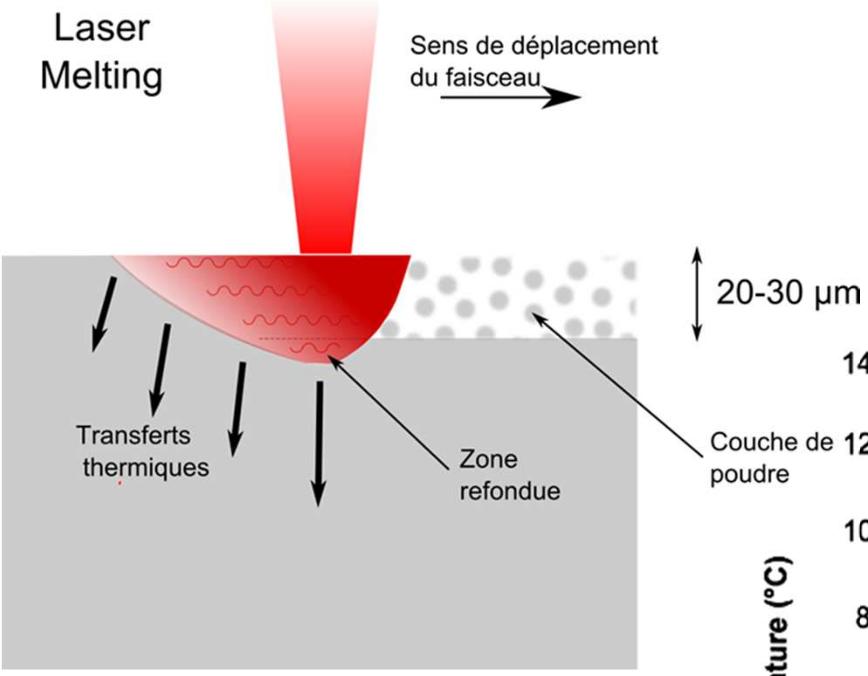
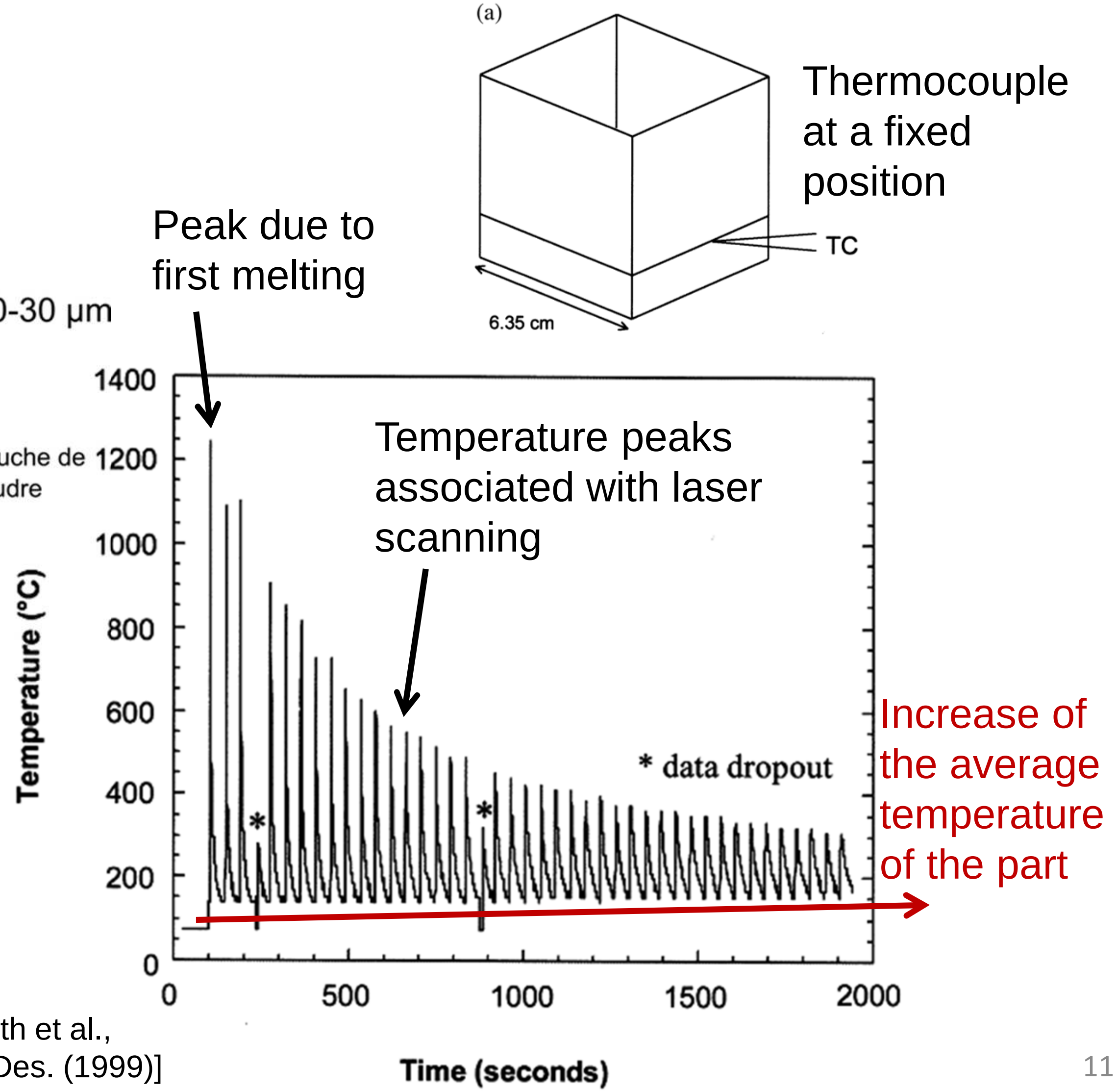
Introduction (6)
Laser Beam Melting – **Ultra-fast thermal cycles**



[Q.Contrepois, ULg]



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

Introduction (7)

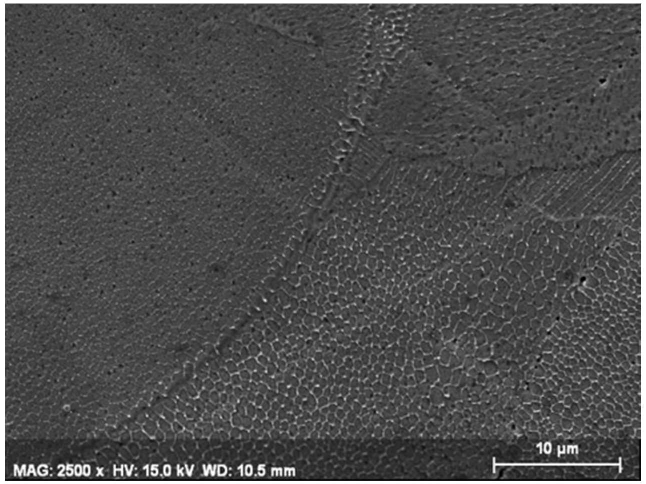
Laser Beam Melting – **Ultra-fast thermal cycles**

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

[J.T.Tchuindjang, ULg]

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

[S.Reginster and A.Mertens, ULg]



Microsegregation of Cr in stainless steel

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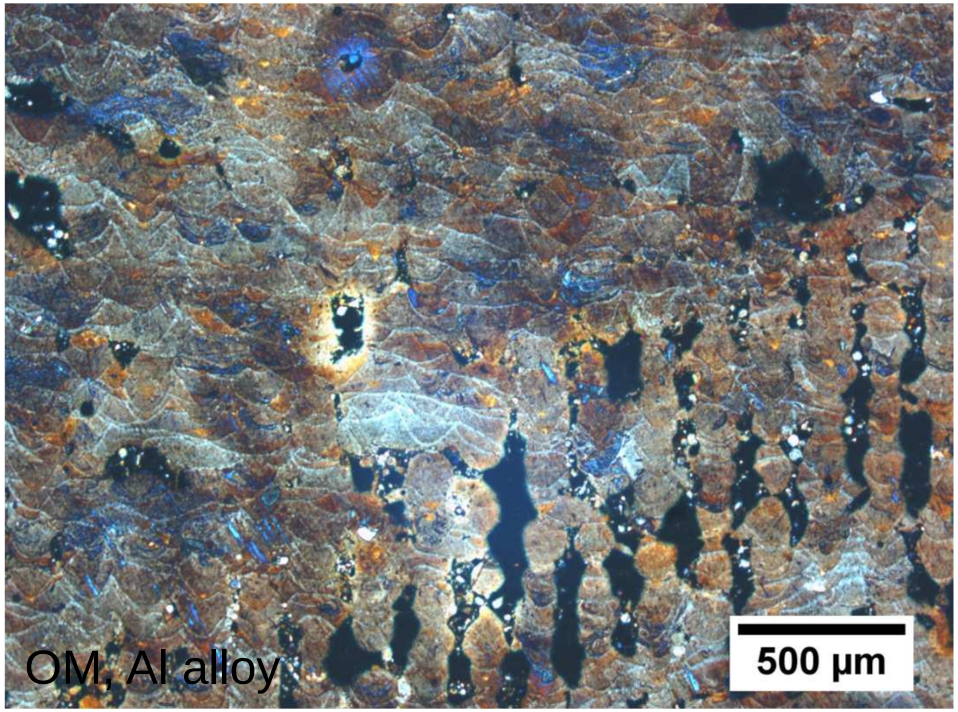
Introduction (8)

Laser Beam Melting is a **directional** process

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



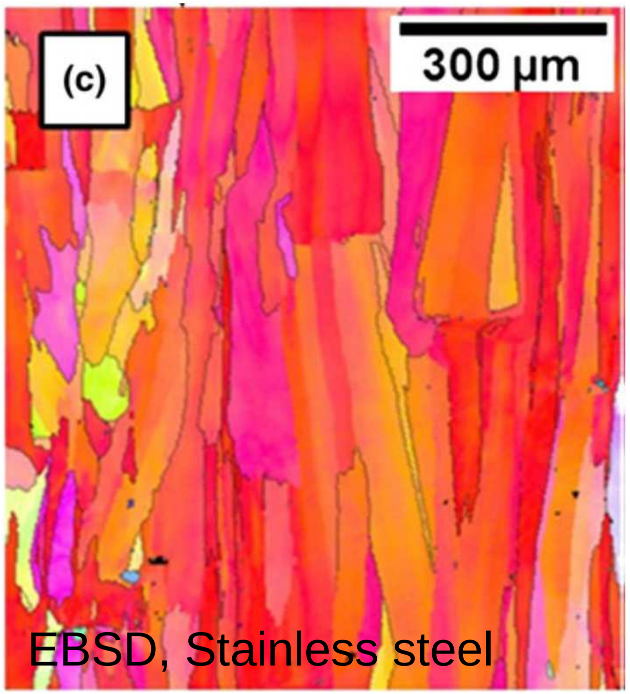
[Q.Contrepois, ULg]

Introduction (9)

Laser Beam Melting is a **directional** process

- 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** (β crystals).

[Niendorf et al., MMTB (2013)]



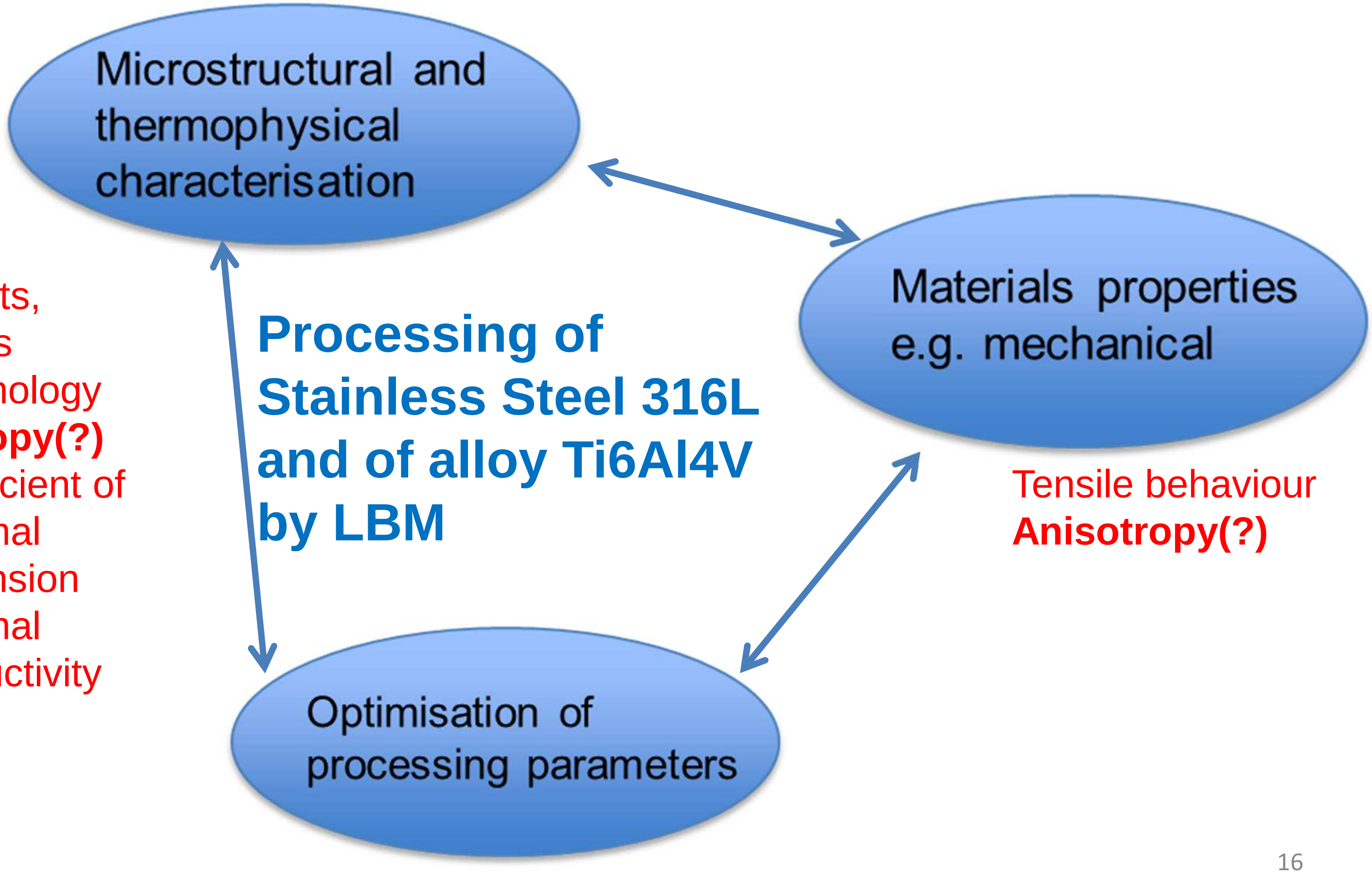
OZ

Building direction

[A.Mertens, ULg]

Upon cooling, β→α (laths)

Introduction (10)



- Defects,
- Grains morphology

Anisotropy(?)

- Coefficient of Thermal Expansion
- Thermal conductivity

Tensile behaviour
Anisotropy(?)

Introduction (11)

Aims of the research

- Microstructures and mechanical properties of
  - Stainless steel 316L
  - Ti6Al4V
- Correlation with the processing parameters
- **How does the difference of behaviour between the two materials correlate with their thermophysical properties (CTE, Thermal conductivity…)?**

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Experimental procedure (1)

- Materials:

(wt %)	Fe	C	Cr	Ni	Ti	Al	V
SS 316L	Bal.	0,019	17,30	10,90	_	_	_
Ti6Al4V	_	_	_	_	Bal.	5,91	4,20

Particle size in the range 10 - 45 µm for SS 316L and 25 - 50 µm for Ti6Al4V

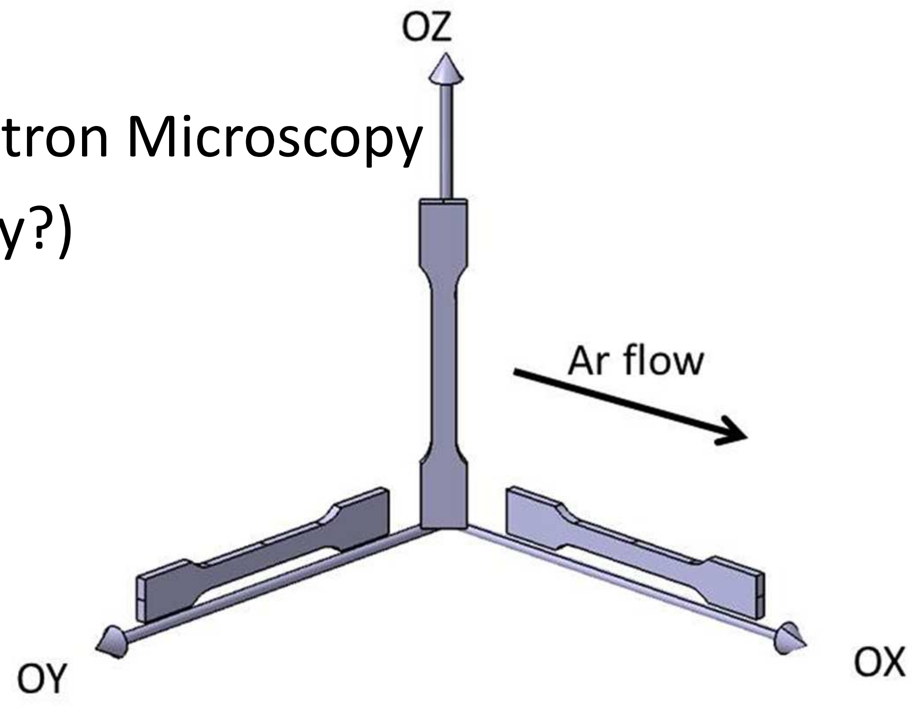
- Laser Beam Melting:
  - MTT SLM 250 laser melting deposition system
  - Fairly similar constant processing conditions for both materials

Material	Layer thickness/µm	Focus offset/mm	Laser power/W	Scanning speed/mm s^{-1}	Hatch spacing/µm
SS 316L	60	1	175	700	120
Ti6Al4V	30	2	175	710	120

Mertens et al., ESA SP-691, July 2012; Reginster et al, MSF **765** (2013), 413-417; Mertens et al., MSF **783-786** (2014), 898-903 ; Mertens et al., Powder Met. **57** (2014), 184-189; Publications available at http://orbi.ulg.ac.be/

Experimental procedure (2)

- Laser Beam Melting:
  - 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?)

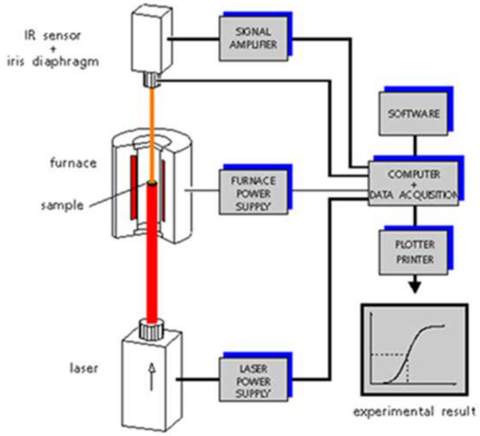


Experimental procedure (3)

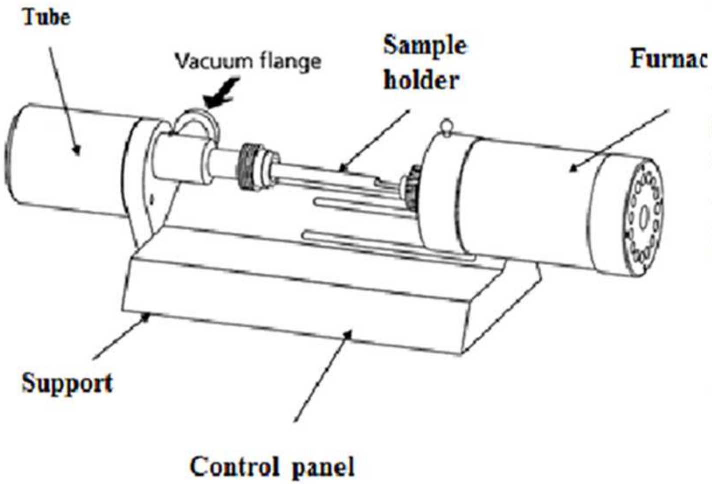
- Determination of **thermal conductivity**

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

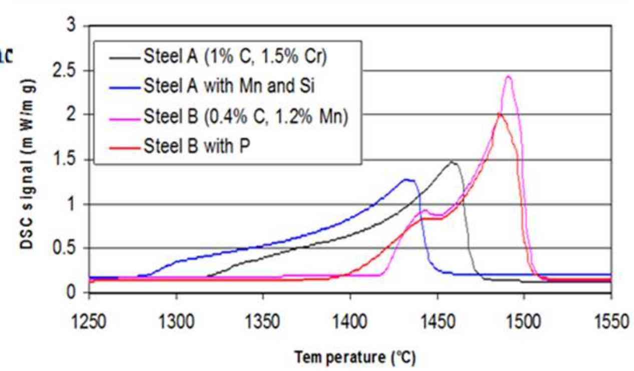
$\alpha(T)$= thermal diffusivity, (Laser Flash)



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



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



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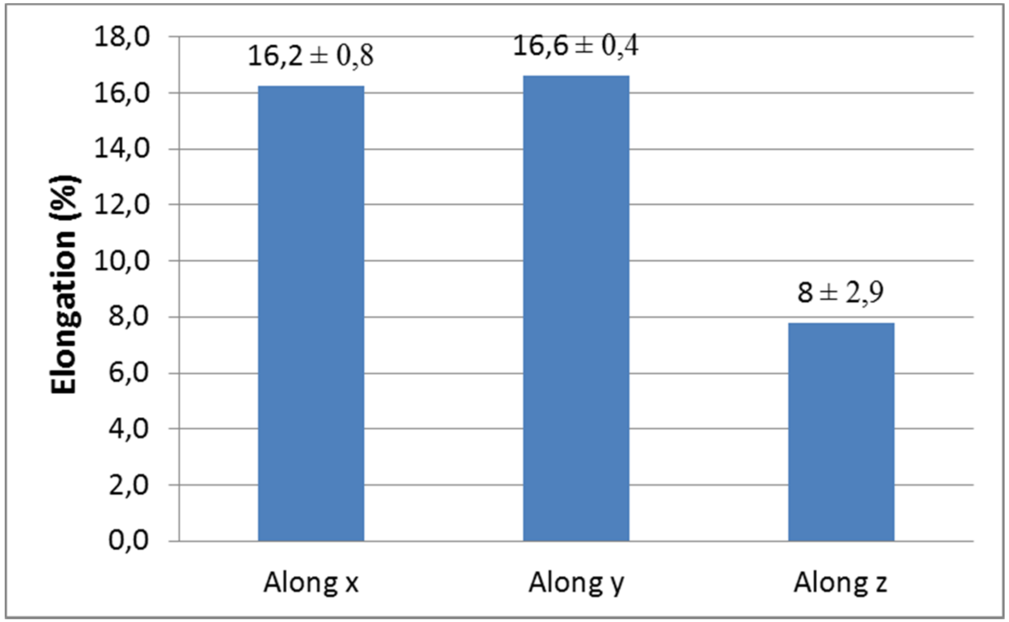
Stainless steel 316L (1) – Tensile properties

Anisotropy between oz and (ox, oy)

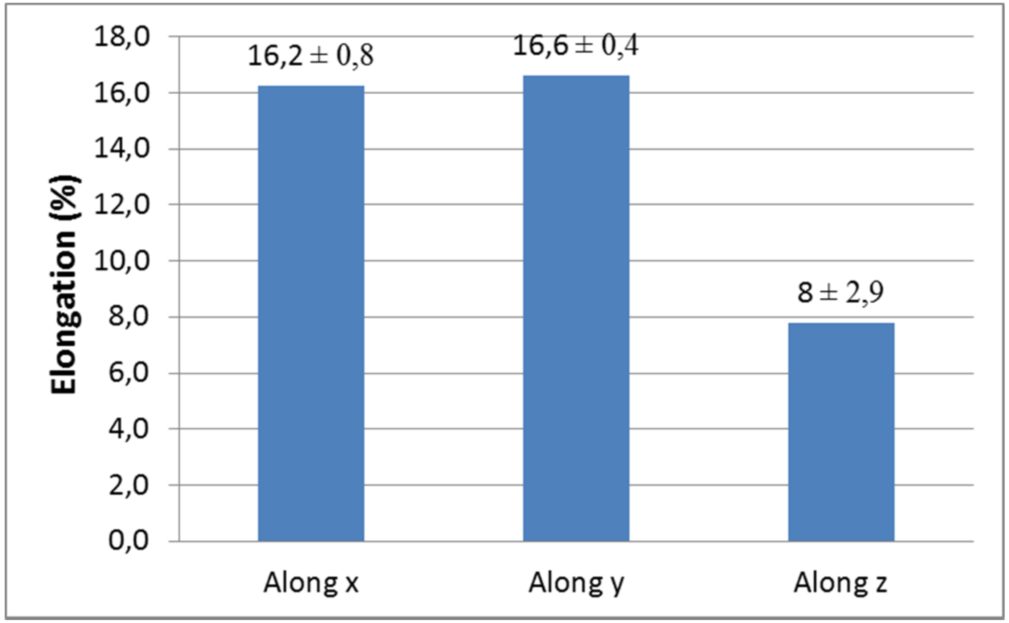


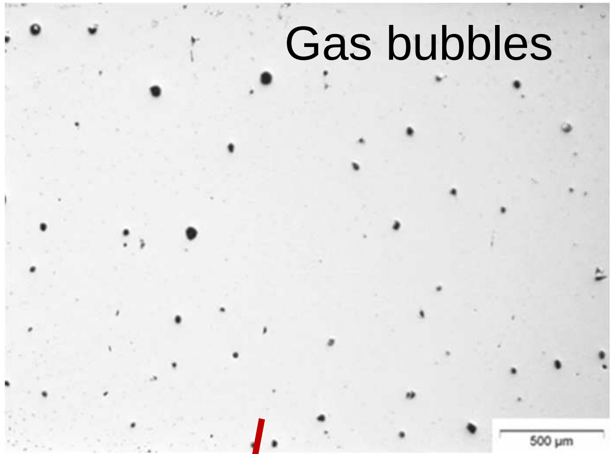
Lower ductility for specimens elongated in the oz direction

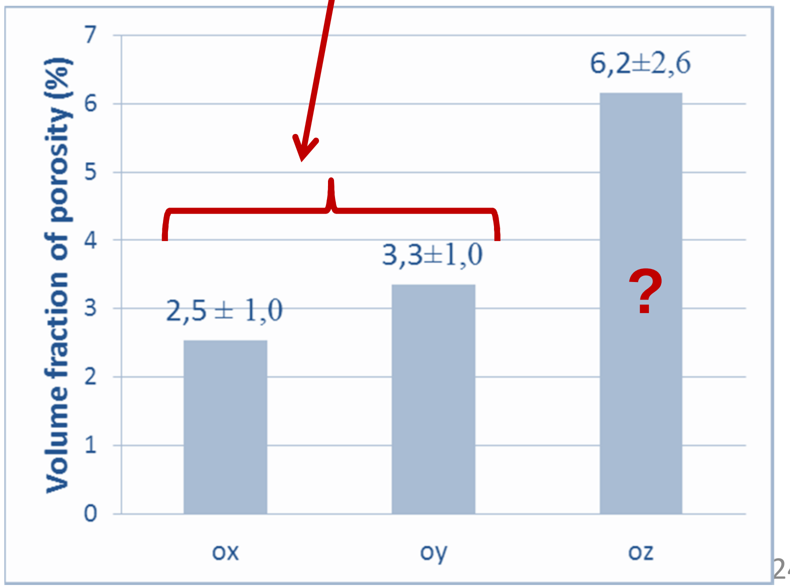
⇒ **Why?**

Stainless steel 316L (2) – Tensile properties

Anisotropy between oz and (ox, oy)





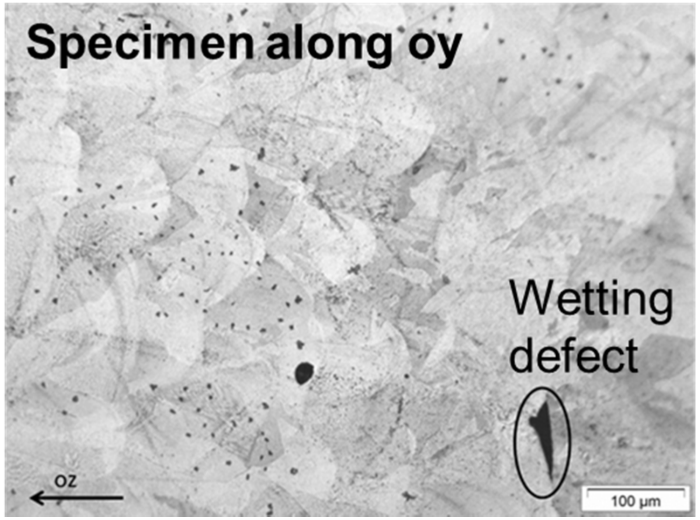


Lower ductility for specimens elongated in the oz direction

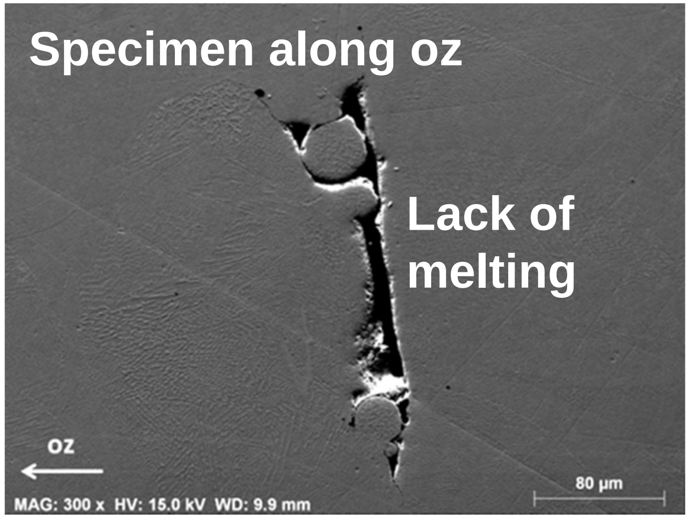
Higher f_v of porosities

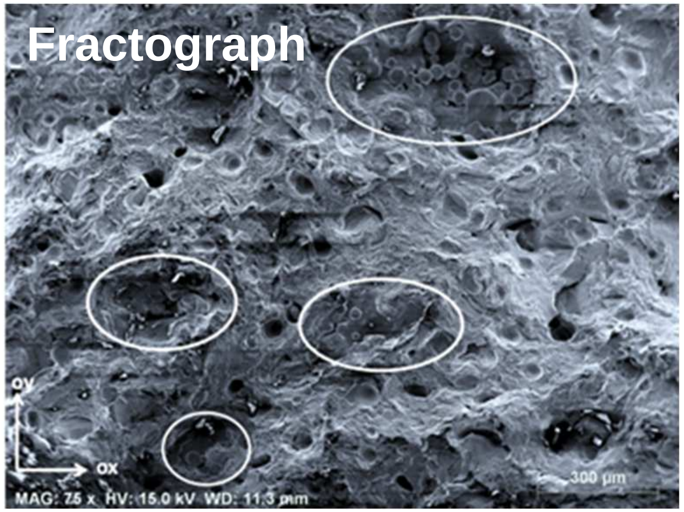
Stainless steel 316L (3) - microstructures

What about the oz specimens? ⇒ Wetting defects



Deterioration of the mechanical properties for the oz specimens due to their **higher volume fraction of defects** and to their very **detrimental orientation** (i.e. perpendicular) with respect to the loading direction

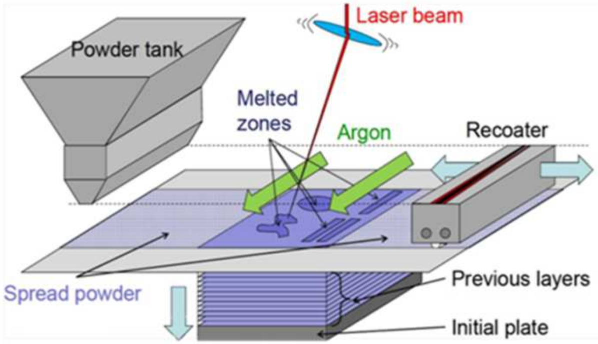




Stainless steel 316L (4)

Thermal history of the (ox, oy) and oz specimens?

- All specimens were produced during one single job
- First building steps involve the production of ox, oy and oz specimens
  - Laser scanning a big overall surface for each layer
  - High overall heat input



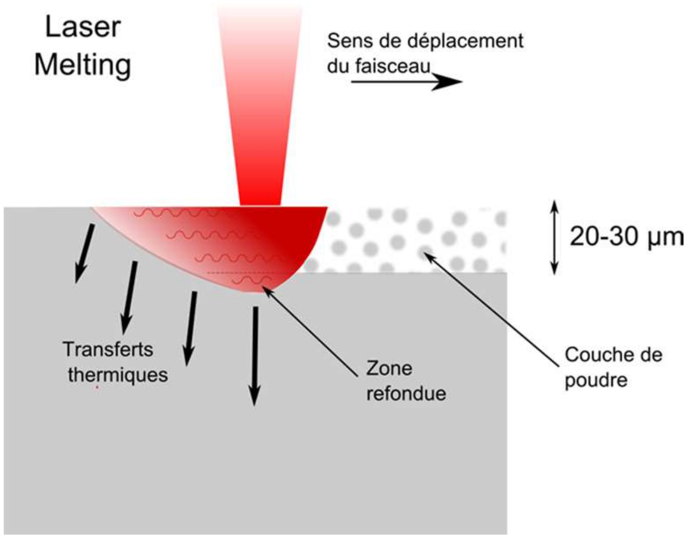
- Later stages involve only the processing of oz specimens
  - Laser scanning a smaller surface for each layer
  - Lower overall heat input ⇒ **Colder processing conditions**

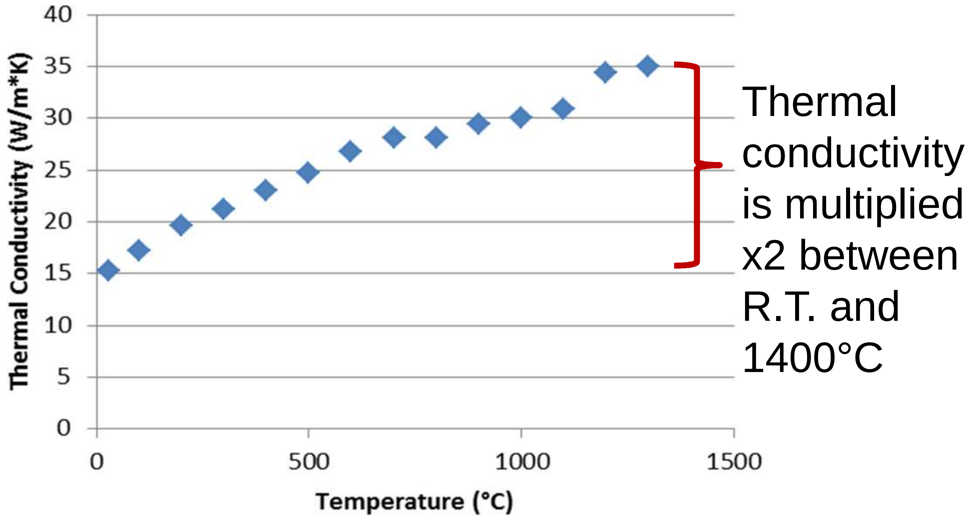
⇒ **Need for better optimized (path-dependent) processing parameters...**

Stainless steel 316L (5)

⇒ ...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 is strongly dependent on temperature!**

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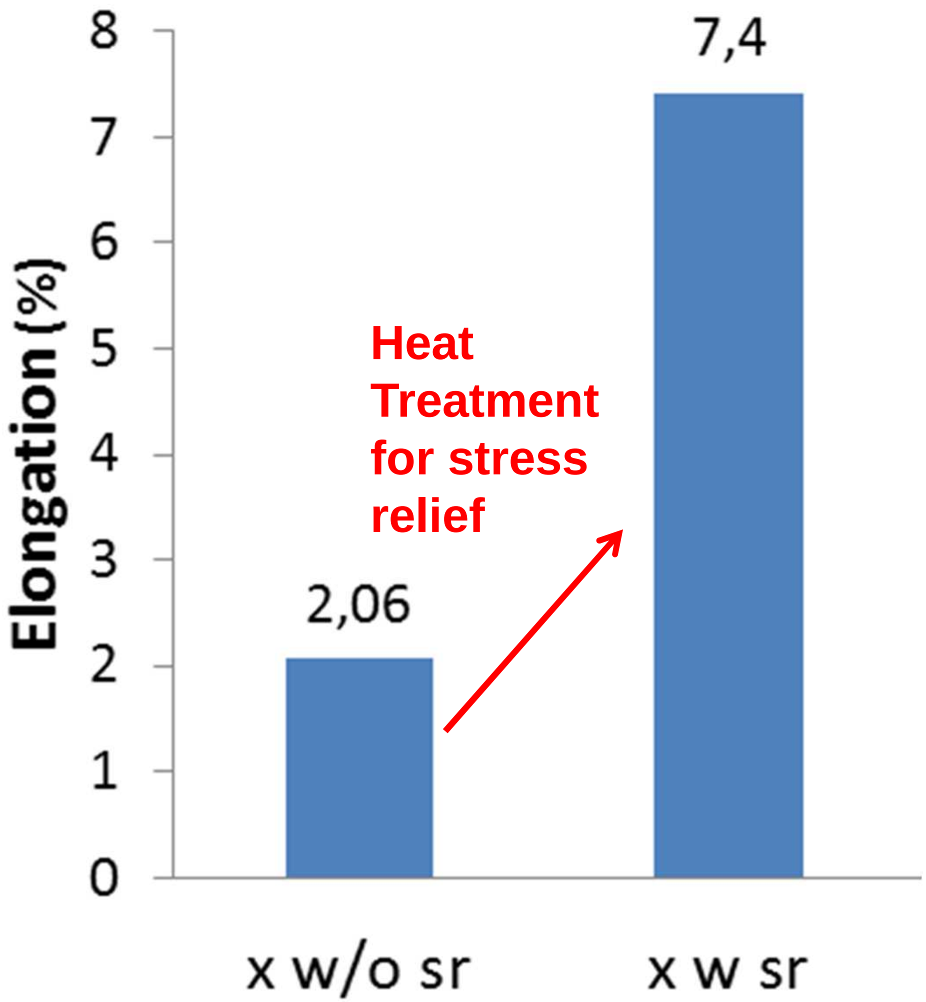
Ti-6Al-4V (1) – Tensile properties

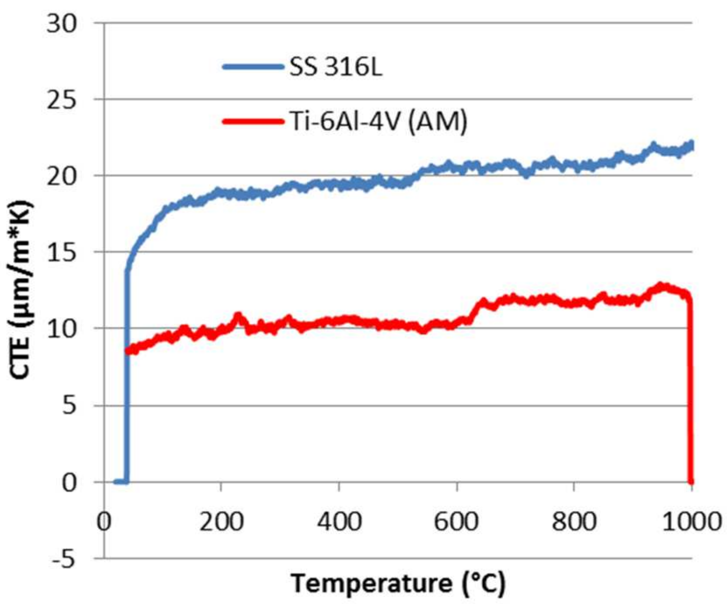


- Mismatches in thermal dilatation/contraction (CTE)
- Thermal gradients

High internal stresses ⇒ Heat treatment at 640°C for 4 hours to improve the ductility

Ti6Al4V (2) - Thermophysical properties

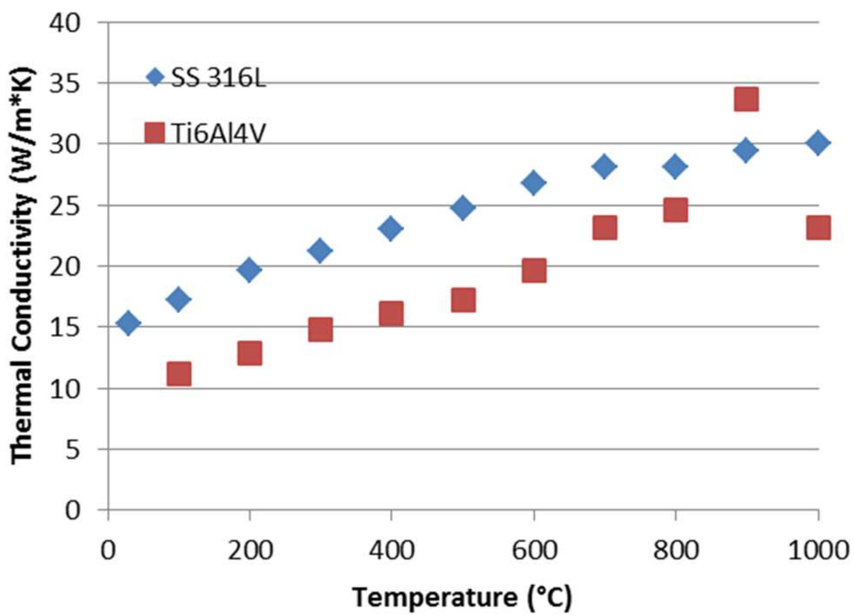
Thermal expansion



SS 316L has a higher CTE than Ti-6Al-4V

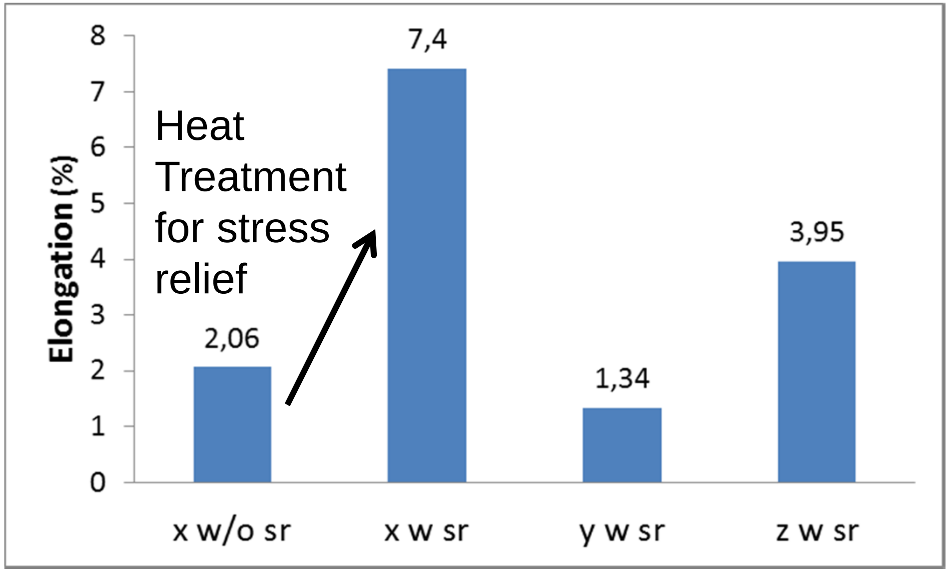
Mertens et al., Powder Metallurgy (2014), **57**, 184-189
Available at http://orbi.ulg.ac.be/

Thermal conductivity

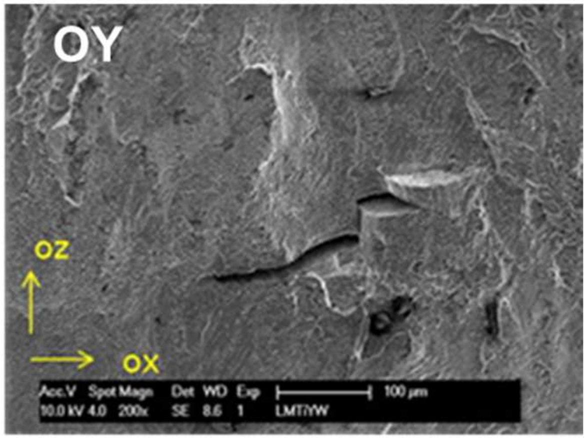


SS 316L has a much higher thermal conductivity than Ti-6Al-4V
⇒ Importance of thermal gradients in the build up of internal stresses

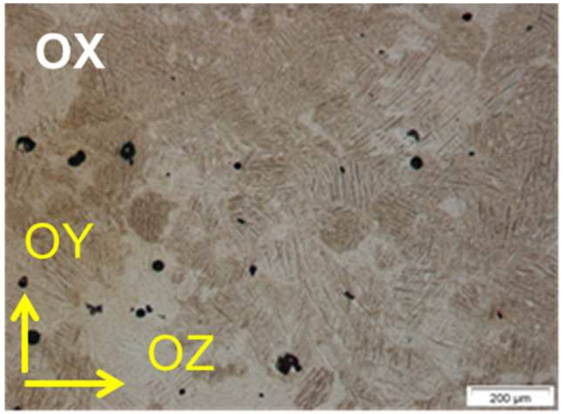
Ti-6Al-4V (3) – Tensile properties

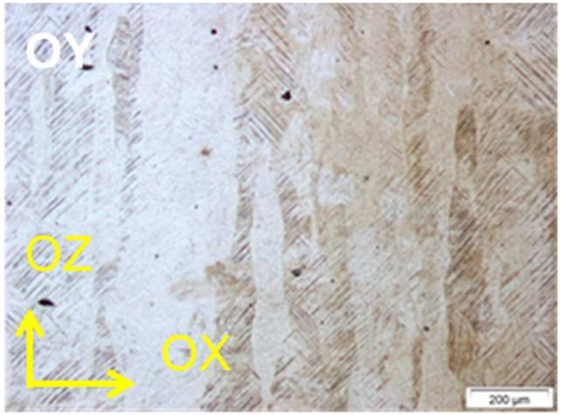


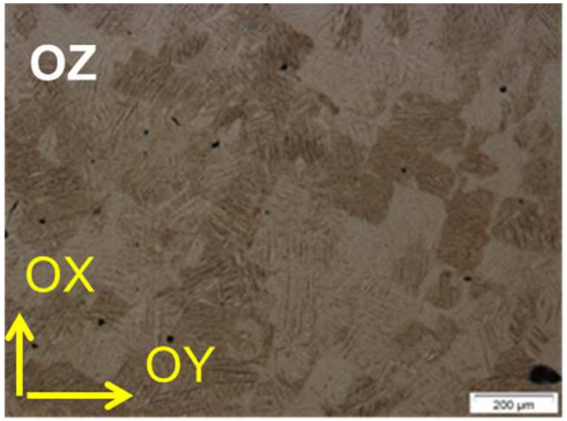
- LBM is a directional process
  - Epitaxial growth
- Strong anisotropy in building direction and **inside the deposition plane**
  - Cracks with specific orientation in the OY and OZ samples
  - Correlation with the microstructure ?



Ti-6Al-4V (4) – microstructures





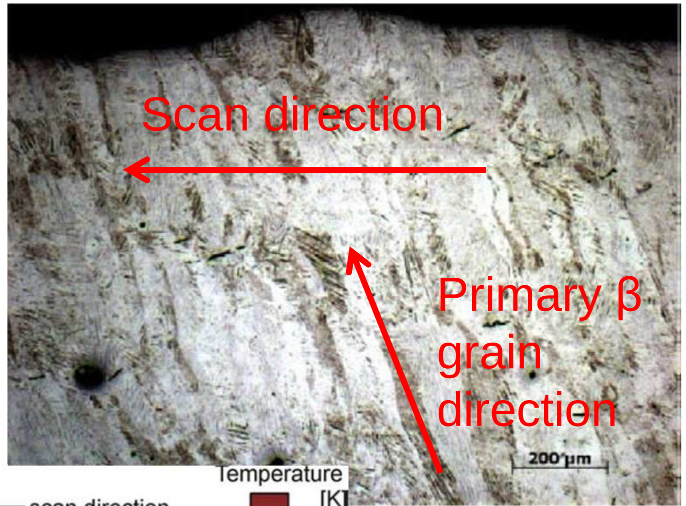


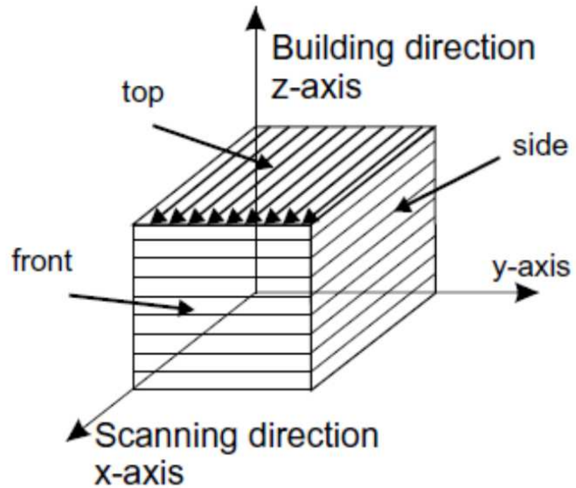
- Spherical porosities due to entrapped gas < 0,5 %
- Elongated primary β grains (// OZ) in the OY sample…
- …but not in the OX sample, suggesting that the grains are actually **tilted** with respect to the building direction
- Primary β grain boundaries or α/β interphase boundaries might play a role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

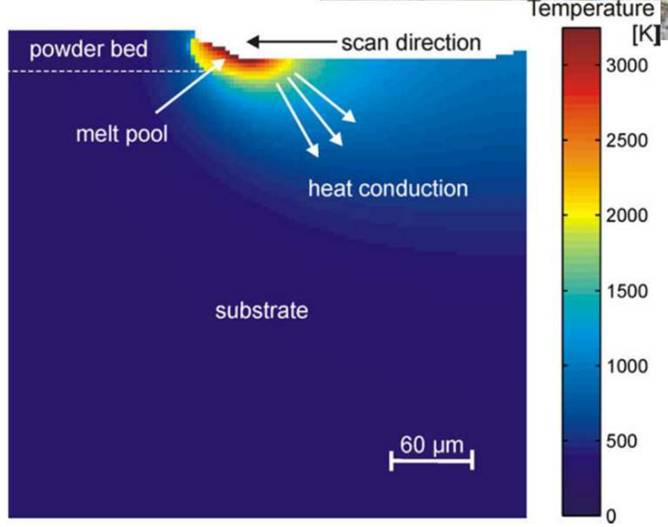
Ti-6Al-4V (5)

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





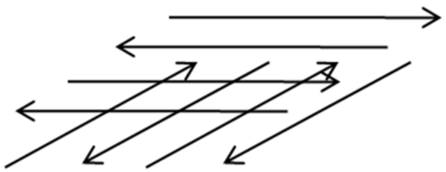


[Thijs et al., Acta Mater., 2010]

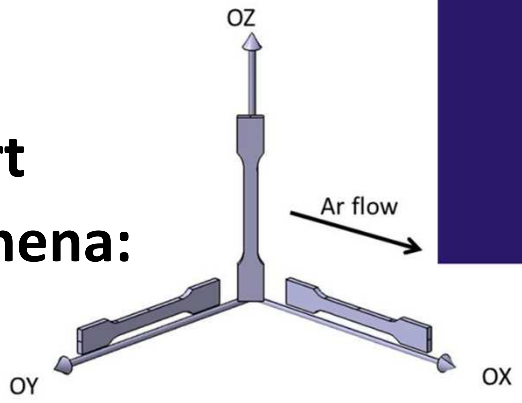
Ti-6Al-4V (6)

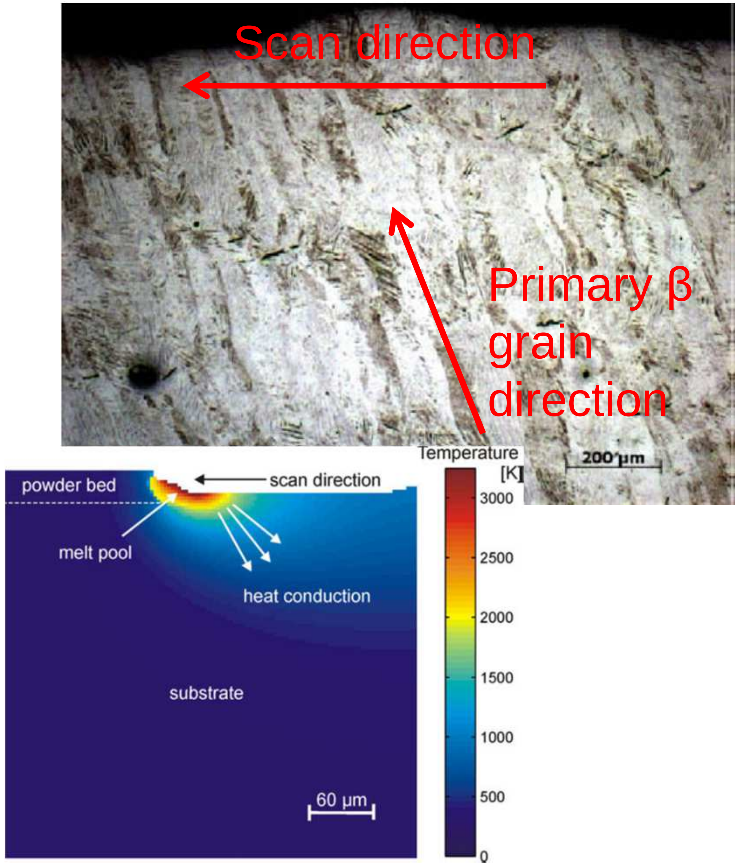
Anisotropy between ox and oy – Heat conduction

- 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

Stainless steel 316L

- Anisotropy between the (ox, oy) and oz direction
- "Lack of melting" defects
- No need for post-processing heat treatment
- Thermal homogeneity ↑

Thermal transfer ↑

Internal stresses ↓

Higher thermal conductivity

Ti-6Al-4V

- Anisotropy also between the ox and oy direction
- Tilt of the elongated primary β grains
- Post-processing treatment necessary to relieve internal stresses
- Thermal homogeneity ↓

Thermal transfer ↓

Internal stresses ↑

Lower thermal conductivity

References

- M.L.Griffith et al., Mater. & Des. (1999), **20**, 107-113
- A.Mertens et al., Proc. ECSSMET (2012), ESA SP-691
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