Additive Manufacturing of Metals and Alloys

3.2 Heat flow in the material and processing maps

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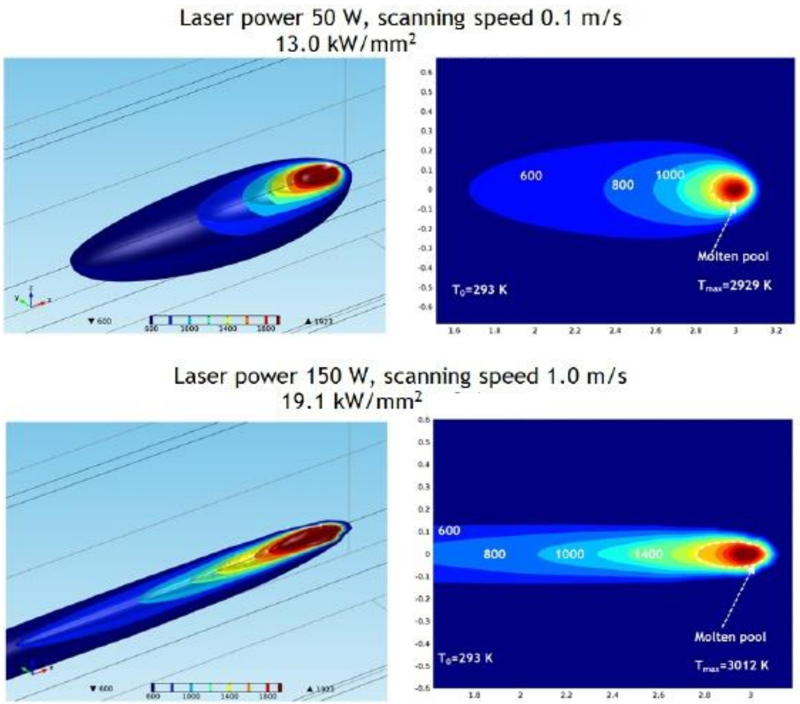
Outline

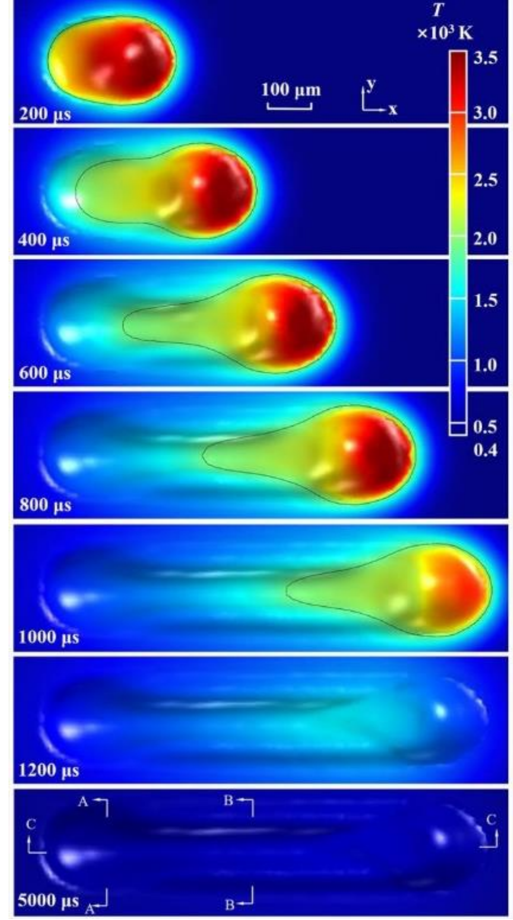
- Thermal history
- Heat flow at the melt pool scale
- Processing maps
- Heat flow : a multiscale problem
- Size effects

Thermal history

Melt pool morphology

The melt pool is elongated, with a high aspect ratio.





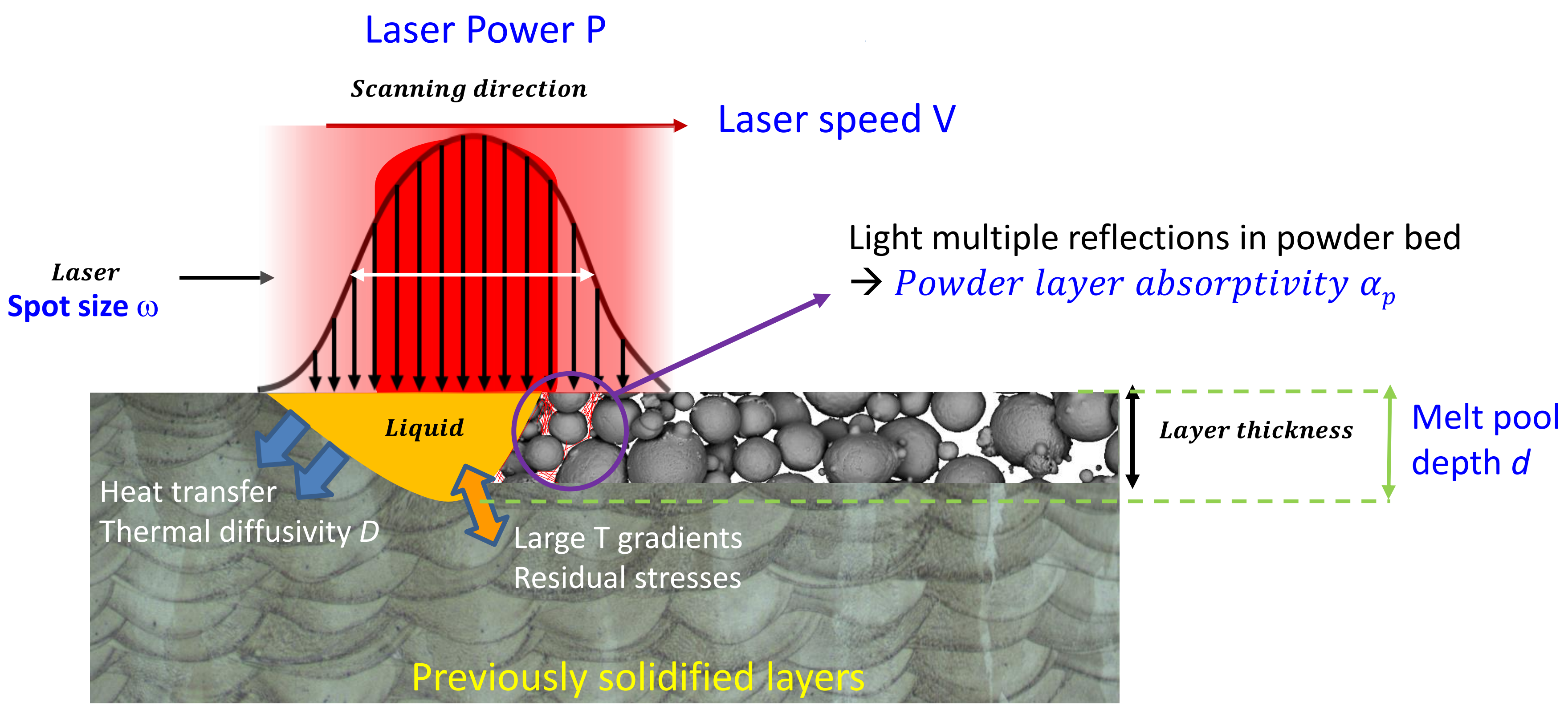
The melt-pool dimensions and morphology are related to:

- the process parameters (scanning speed, laser power…)
- the material and powder properties (thermal conductivity, packing density…)

Zhang et al., 2018

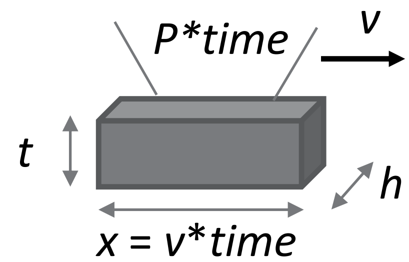
Heat flow in LPBF

Schematic view of the LPBF process
at the **melt pool scale**



Ghasemi-Tabasi et al., *Additive Manufacturing*, 2020

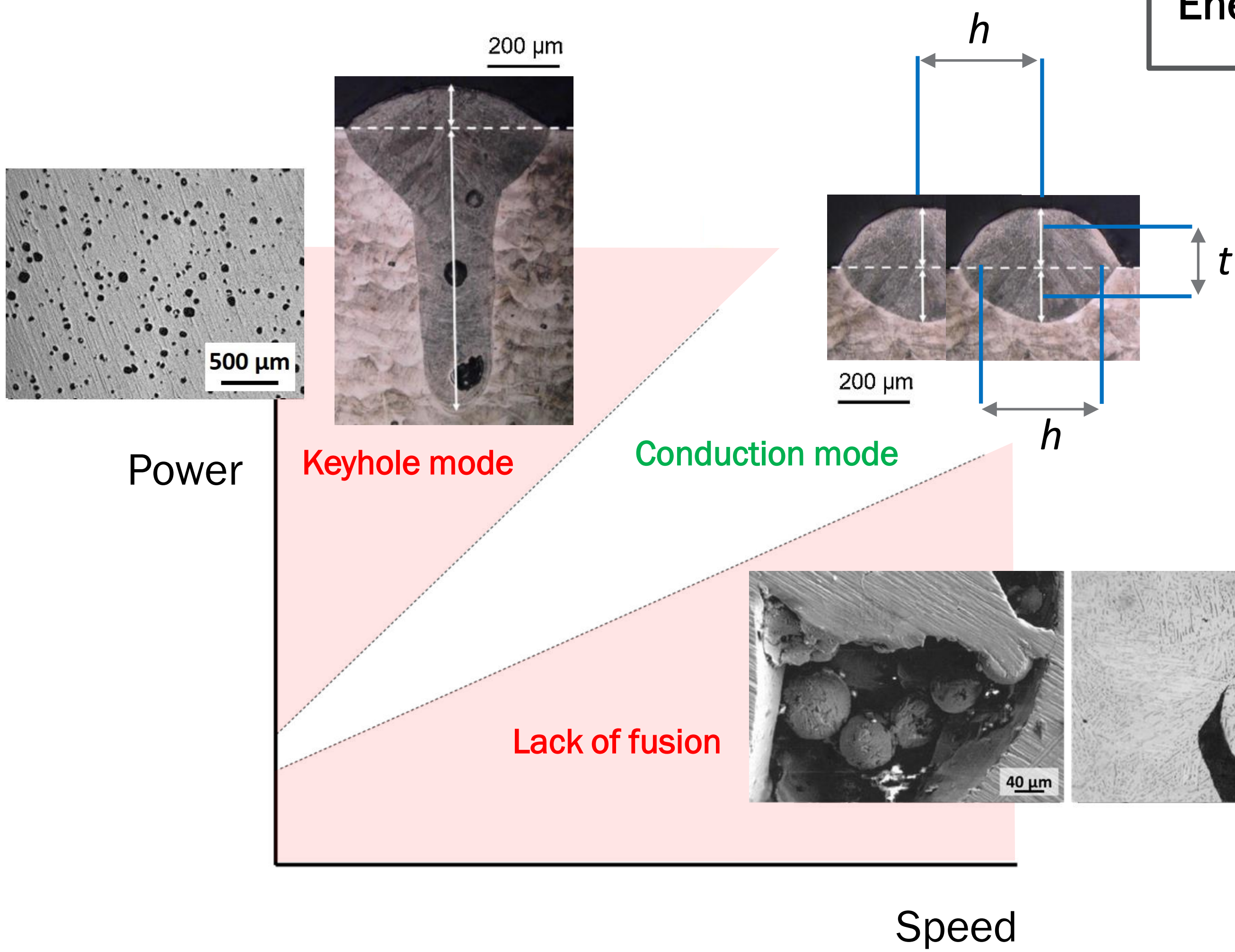
Porosity: processing map



Process window for high density

Energy density: $E = \dfrac{\alpha P}{v h t}$

P = laser power
v = scanning speed
h = hatching distance
t = layer thickness
α = absorptivity



Porosity: processing map

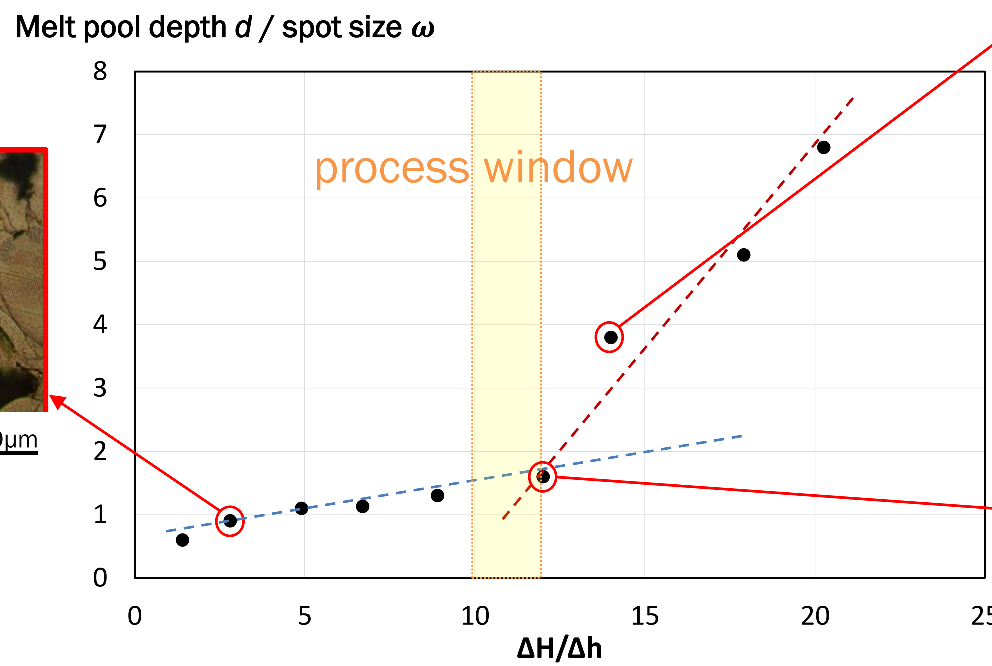
Normalized enthalpy vs normalized melt pool depth

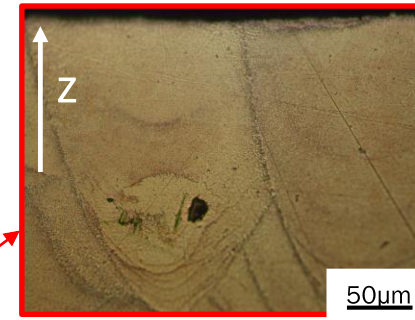
Increase in enthalpy (laser input) $$\Delta H = \frac{\alpha_p \boldsymbol{P}}{\sqrt{\pi \omega^3 \boldsymbol{V} D}}$$

Melting enthalphy $$\Delta h = \rho(C_p \Delta T + L_m)$$

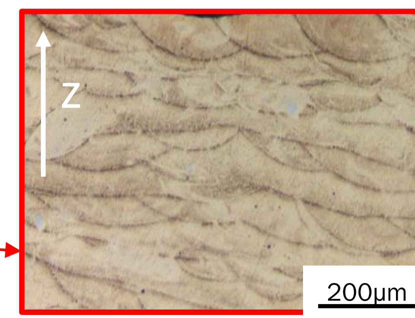
$$\boxed{\overline{\Delta H} = \frac{\Delta H}{\Delta h}}$$

Lack of fusion (LoF)





Deep melt pool and keyhole pores



No keyhole, no LoF
Conduction mode

⇨ The process window is often narrow

Ghasemi-Tabasi et al., *Additive Manufacturing*, 2020

Porosity: processing map

Is the processing map <u>universal</u>?

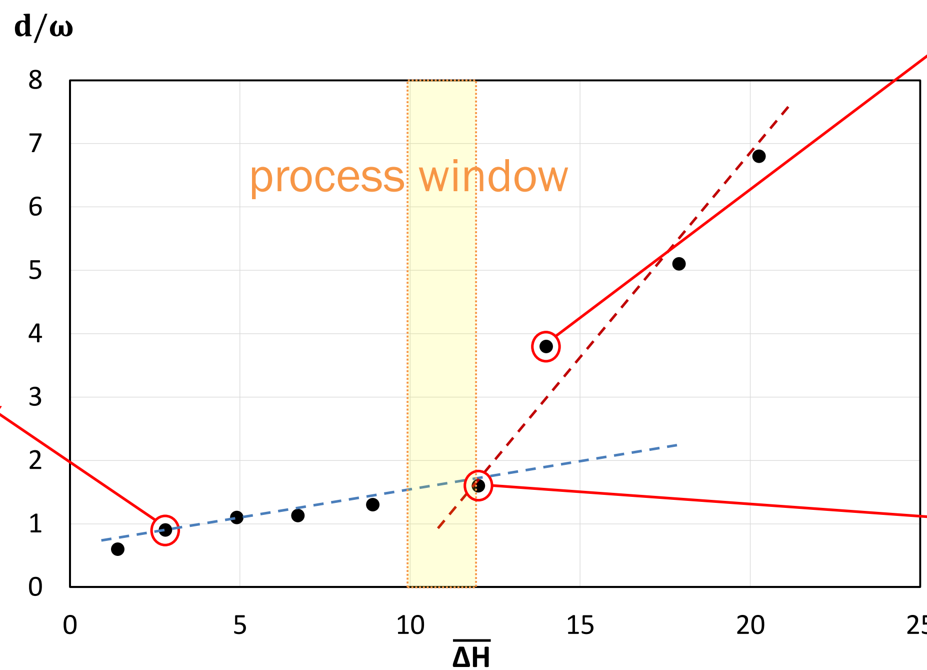
$$\overline{\Delta H} = \alpha_p M \frac{P}{\sqrt{\omega^3 V}} \qquad M = \frac{1}{\rho(C_p \Delta T + L_m)\sqrt{\pi D}}$$

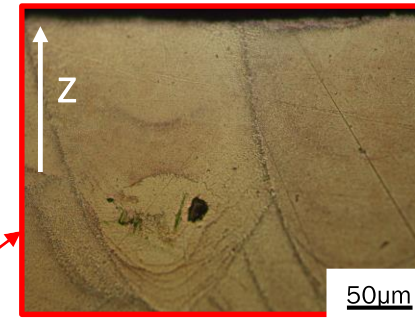
Powder layer absorptivity

Process parameter

Material parameter

Lack of fusion (LoF)





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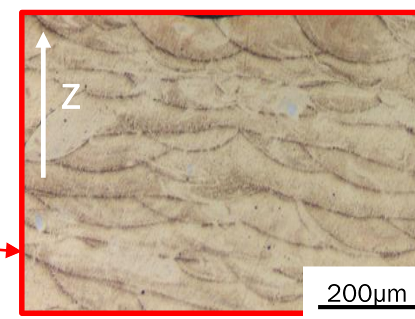
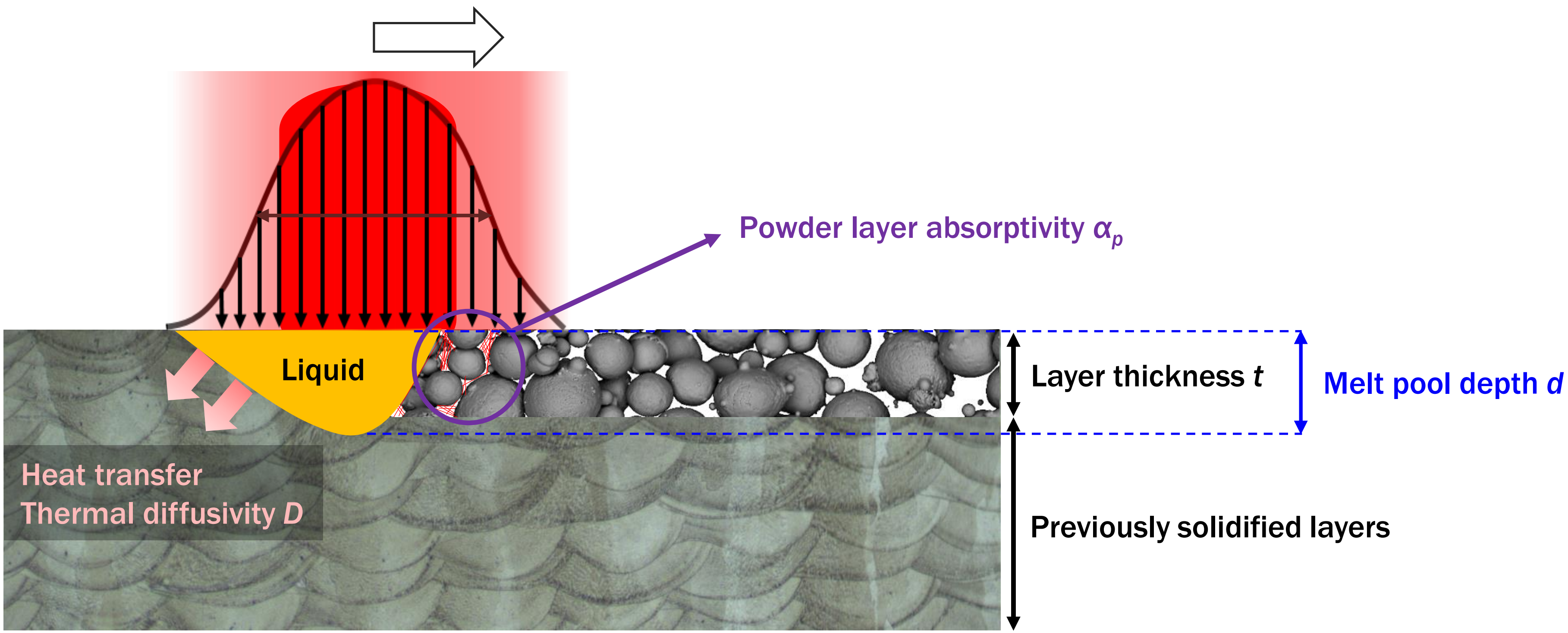


No keyhole, no LoF Conduction mode

Ghasemi-Tabasi et al., *Additive Manufacturing,* 2020

Porosity: processing map

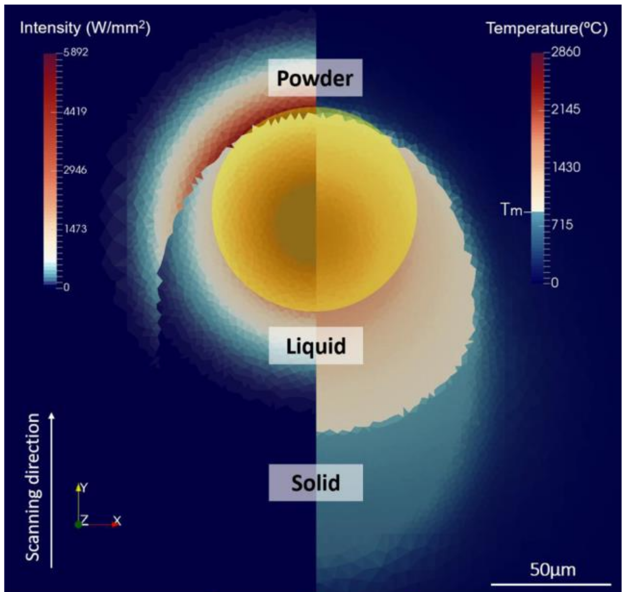
Powder vs liquid absorptivity?

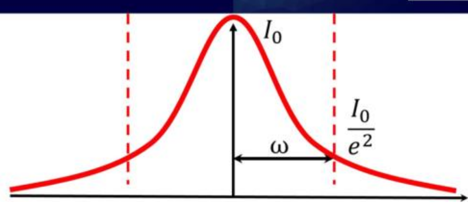


Ghasemi-Tabasi et al., *Additive Manufacturing,* 2020

Porosity: processing map

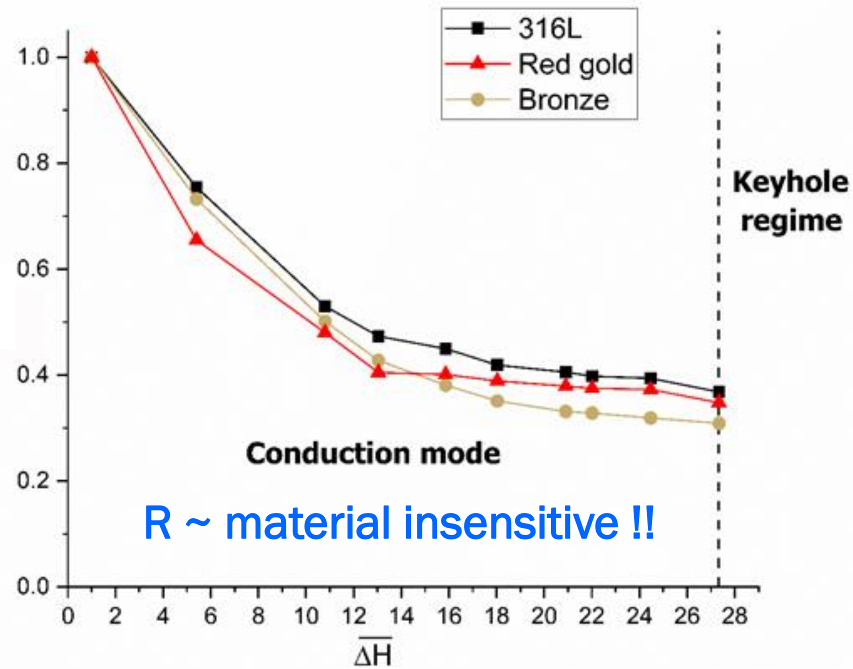
Finite element calculations and translation rule





The optimal normalized enthalpy is a unique reference value for most materials

$$R = \frac{\text{Average absorptivity}}{\text{Powder layer absorptivity}}$$

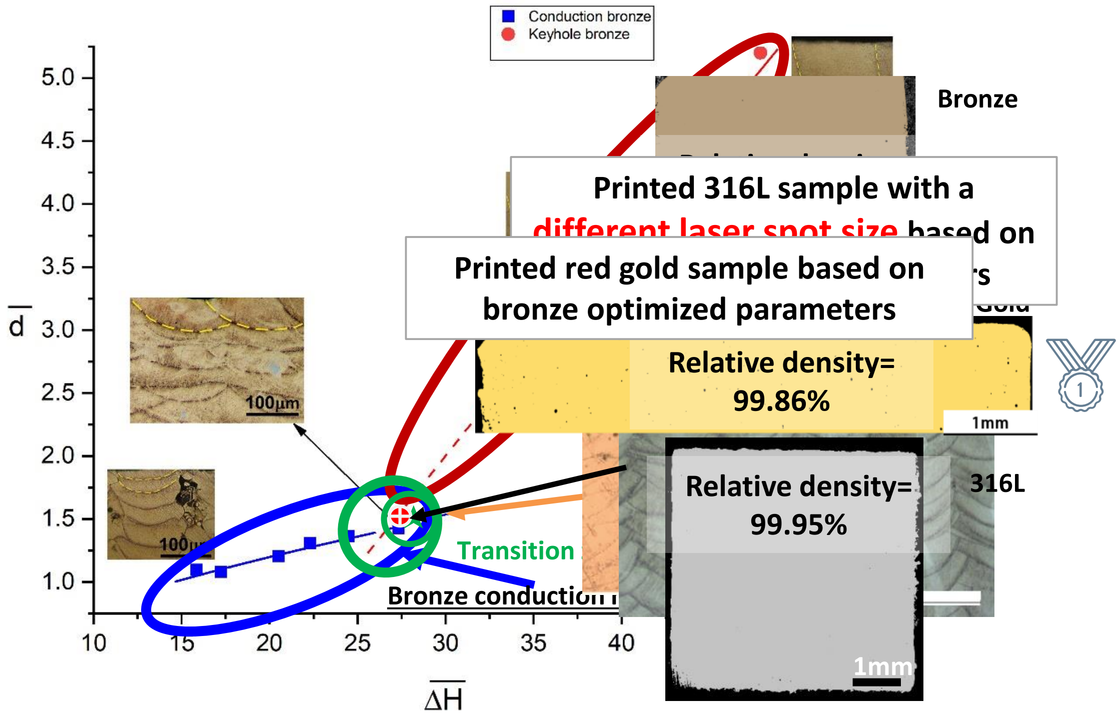


Translation rule : material B → material A

$$\left(\frac{P}{\sqrt{\omega^3 V}}\right)_A^{opt} = \left(\frac{\alpha_p^B}{\alpha_p^A}\right) \cdot \left(\frac{P}{\sqrt{\omega^3 V}}\right)_B^{opt} \frac{M^B}{M^A}$$

Porosity: processing map

Predicting optimal LPBF conditions for red gold and stainless steel, based on bronze data



Ghasemi-Tabasi et al., *Additive Manufacturing*, 2020

Porosity: processing map

Normalized enthalpy vs normalized melt pool depth

Increase in enthalpy (laser input)

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Melting enthalphy

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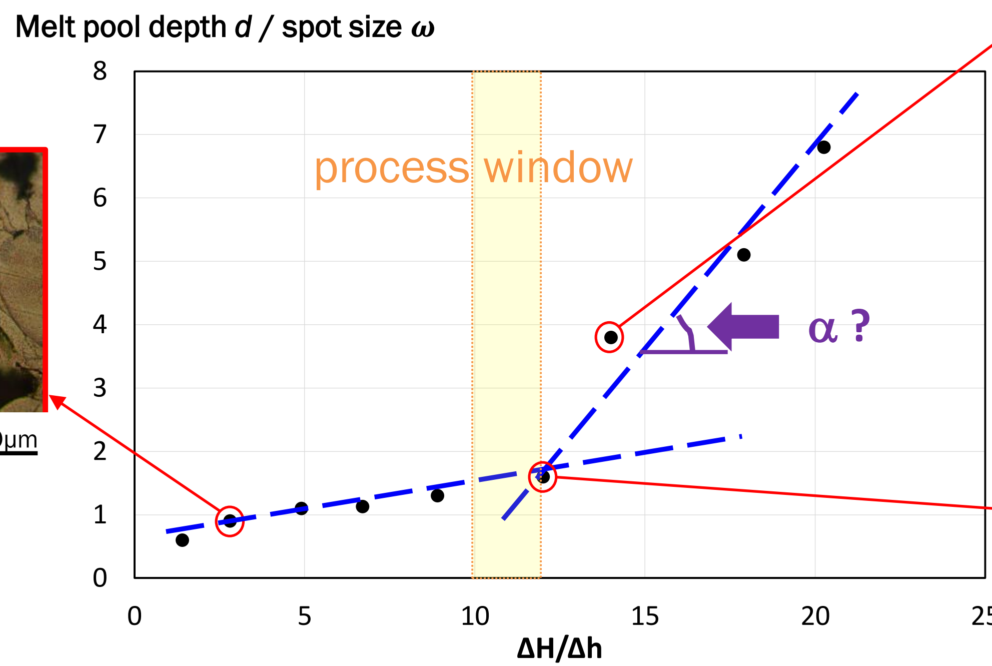
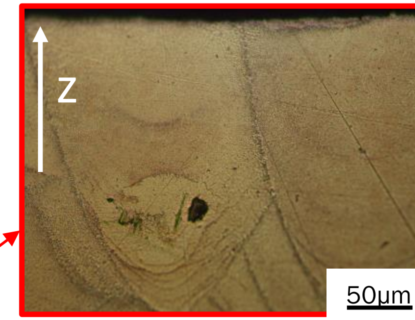
Lack of fusion (LoF)





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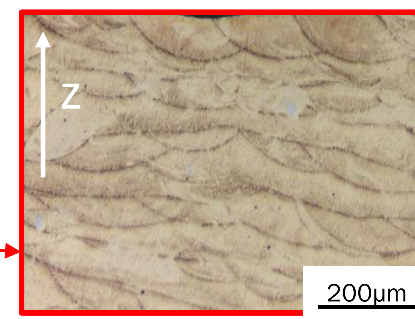

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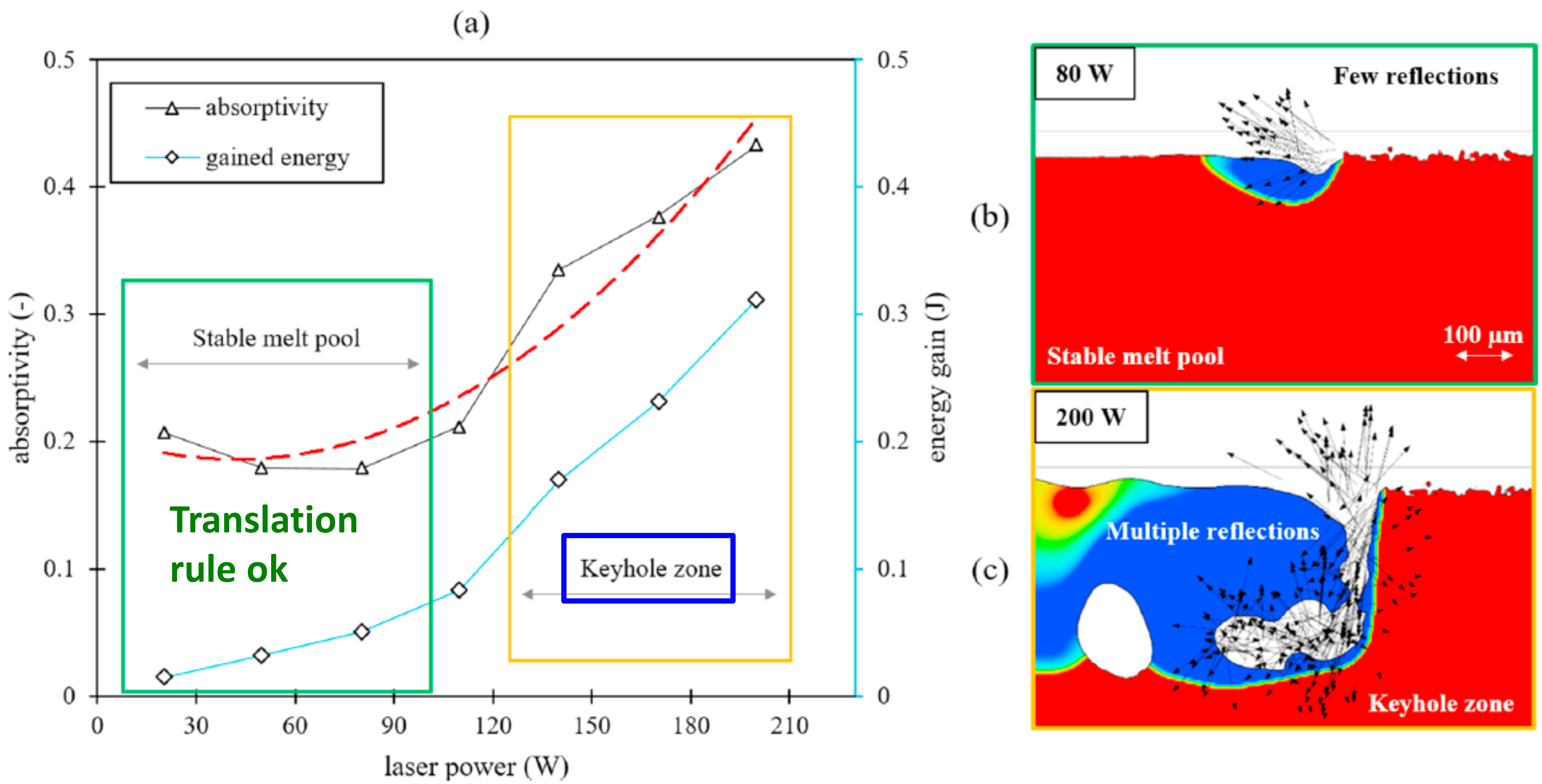
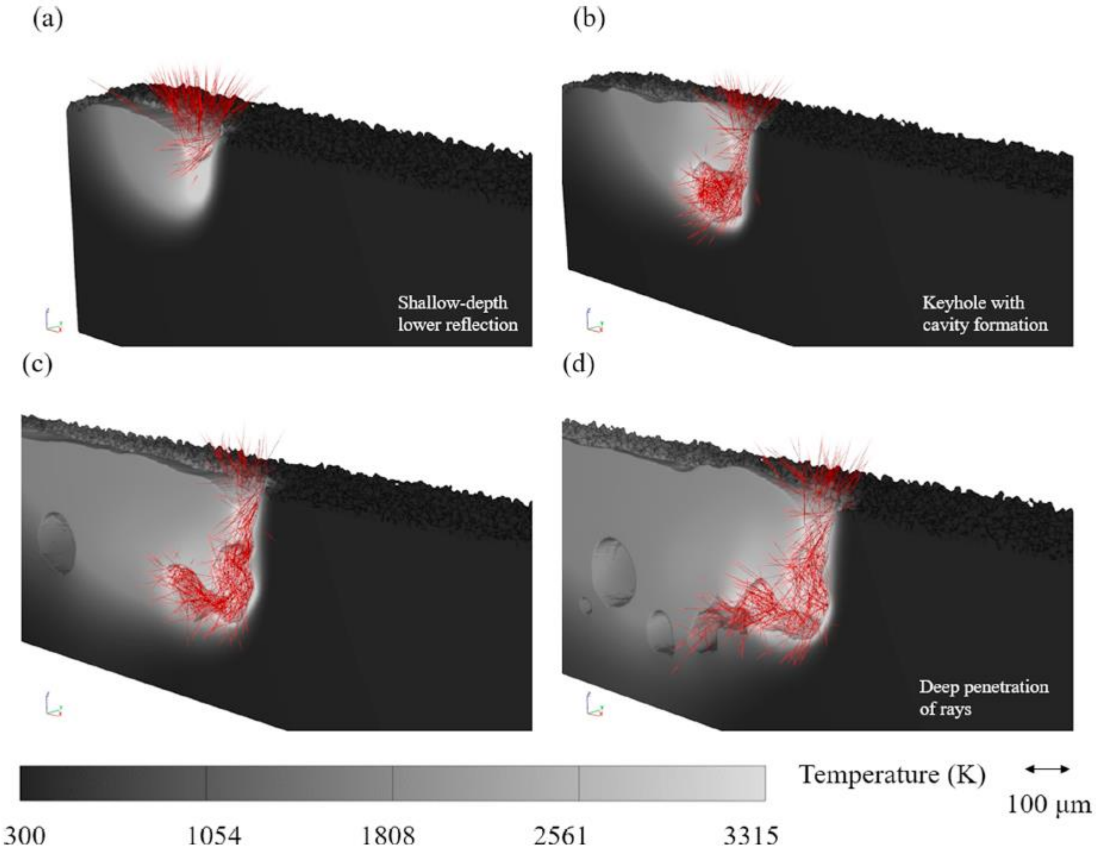
Ghasemi-Tabasi et al., *Additive Manufacturing*, 2020

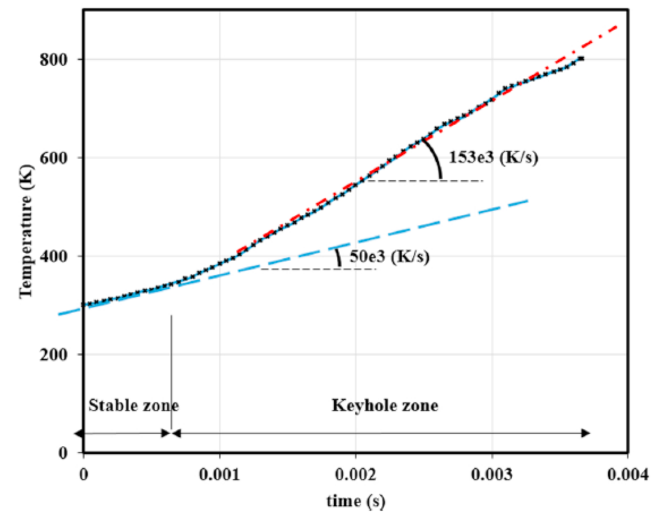
Absorptivity as a function of processing regime



M. Bayat, A. Thanki, S. Mohanty, A. Witvrouw, S. Yang, J. Thorborg, N. Skat Tiedje, J. Henri Hattel, Keyhole-induced porosities in Laser-based Powder Bed Fusion (L-PBF) of Ti6Al4V: High-fidelity modelling and experimental validation, Additive Manufacturing 30 (2019), 100835, https://doi.org/10.1016/j.addma.2019.100835

Absorptivity and energy absorption





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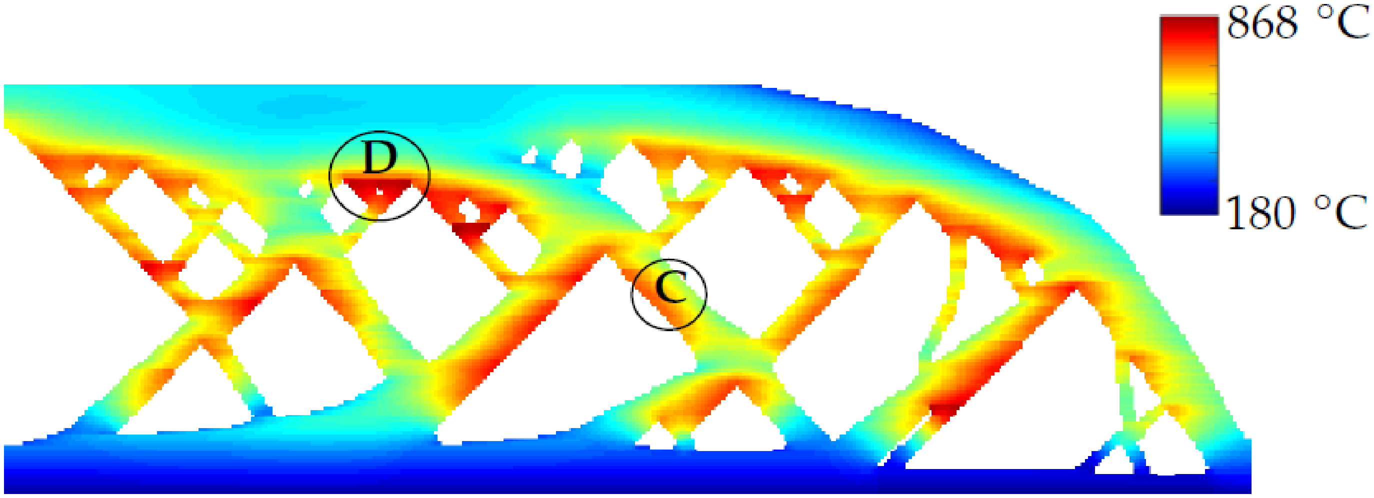
Heat flow in LPBF : a multiscale problem

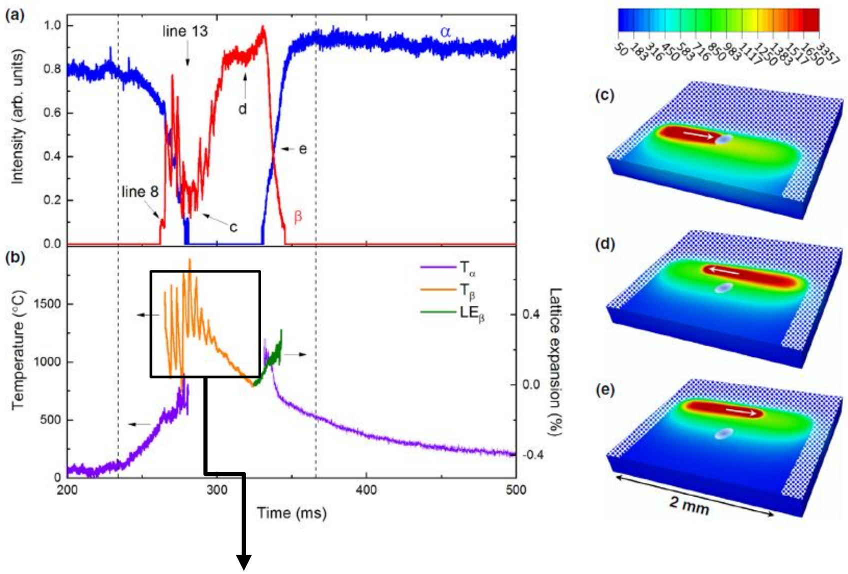
Schematic view of maximum T reached at the **part scale**

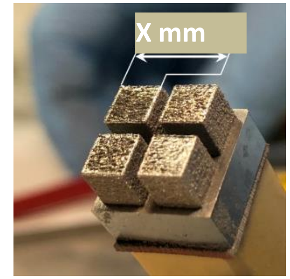


Contour plot of maximum temperature attained during the entire build simulation. Region D shows higher maximum temperatures than Region C.

Ranjan, R.; Ayas, C.; Langelaar, M.; van Keulen, F. Fast Detection of Heat Accumulation in Powder Bed Fusion Using Computationally Efficient Thermal Models. *Materials* **2020**, *13*, 4576. https://doi.org/10.3390/ma13204576

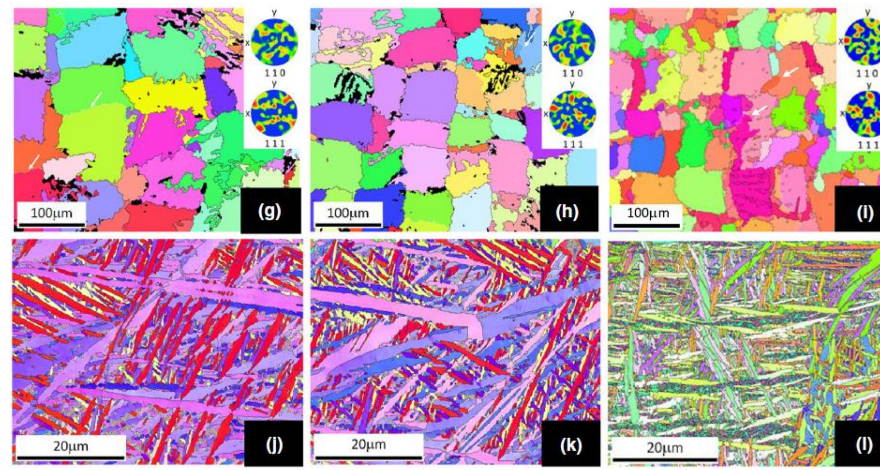
Size effects





Ti-6Al-4V

X = 2 mm　　X = 4 mm　　X = 6 mm



Depending on the value of X (sample dimension), the temperatures reached in samples change:

- β phase lasts **7 ms** for x= **6 mm** scanning vector
- β phase lasts **84 ms** for x= **2 mm** scanning vector

(β = high temperature phase in Ti-6Al-4V)

S. Hocine, H. Van Swygenhoven, S. Van Petegem, C. Sin Ting Chang, T. Maimaitiyili, G. Tinti, D. Ferreira Sanchez, D. Grolimund, N. Casati, Operando X-ray diffraction during laser 3D printing, Materials Today 34 (2020), 30-40, https://doi.org/10.1016/j.mattod.2019.10.001

(See chapter on microstructure control through processing)

References

- H. Ghasemi-Tabasi, J. Jhabvala, E. Boillat, T. Ivas, R. Drissi-Daoudi, R. E. Logé (2020), An effective rule for translating optimal selective laser melting processing parameters from one material to another, *Additive Manufacturing* 36, 101496. https://doi.org/10.1016/j.addma.2020.101496

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- Additive Manufacturing: Materials, Processes, Quantifications and Applications, edited by Jing Zhang and Yeon-Gil Jung, Butterworth-Heinemann, 2018.