In-depth investigation of the sub-micronic equiaxed grain microstructure of a NdFeB permanent magnet fabricated by Laser Powder Bed Fusion

Aymeric WOLZ, Olivier Tosoni, Camille Flament, Jean-Paul Garandet

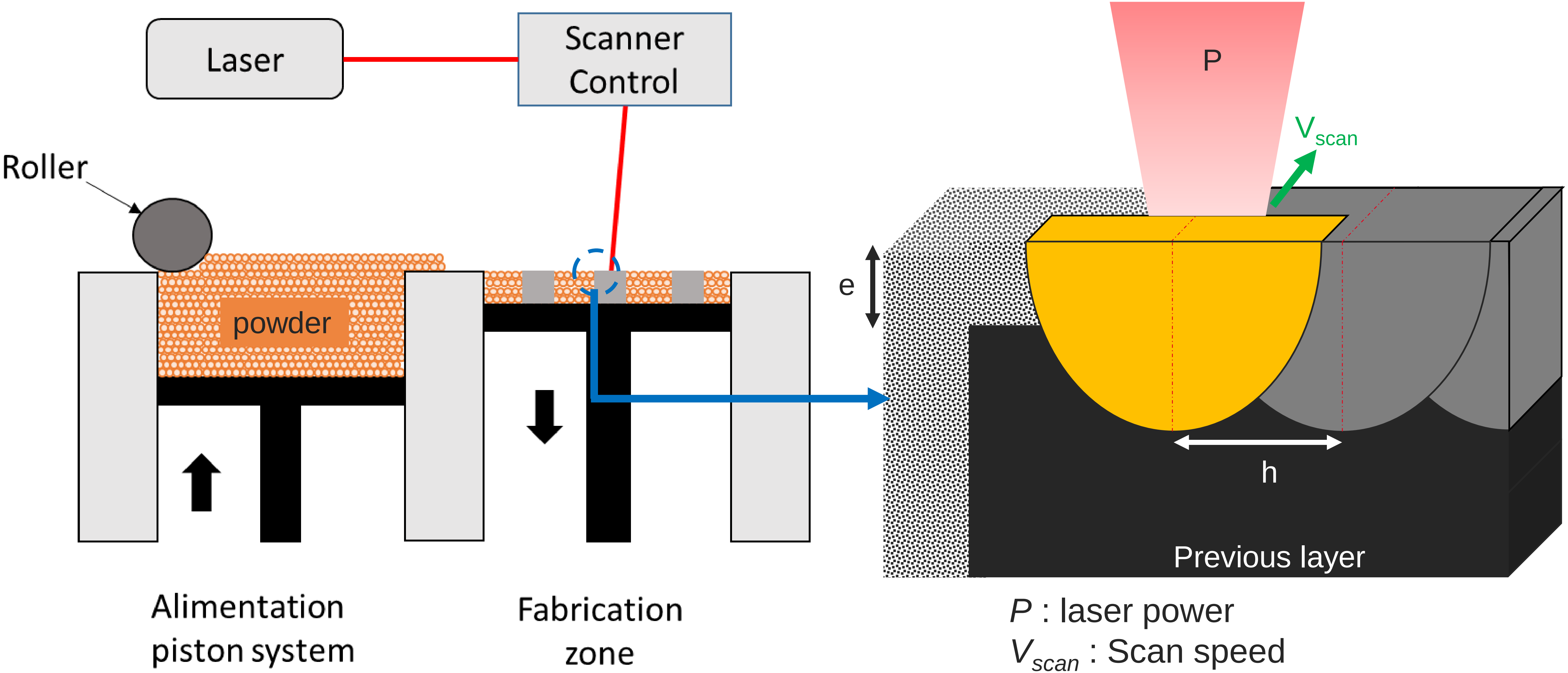
CEA LITEN – Laboratory of Materials and Magnetic Components (LMCM)

Univ. Grenoble Alpes, CEA, LITEN, Grenoble, 38000, France

REPM 2025 NIMS TSUKUBA

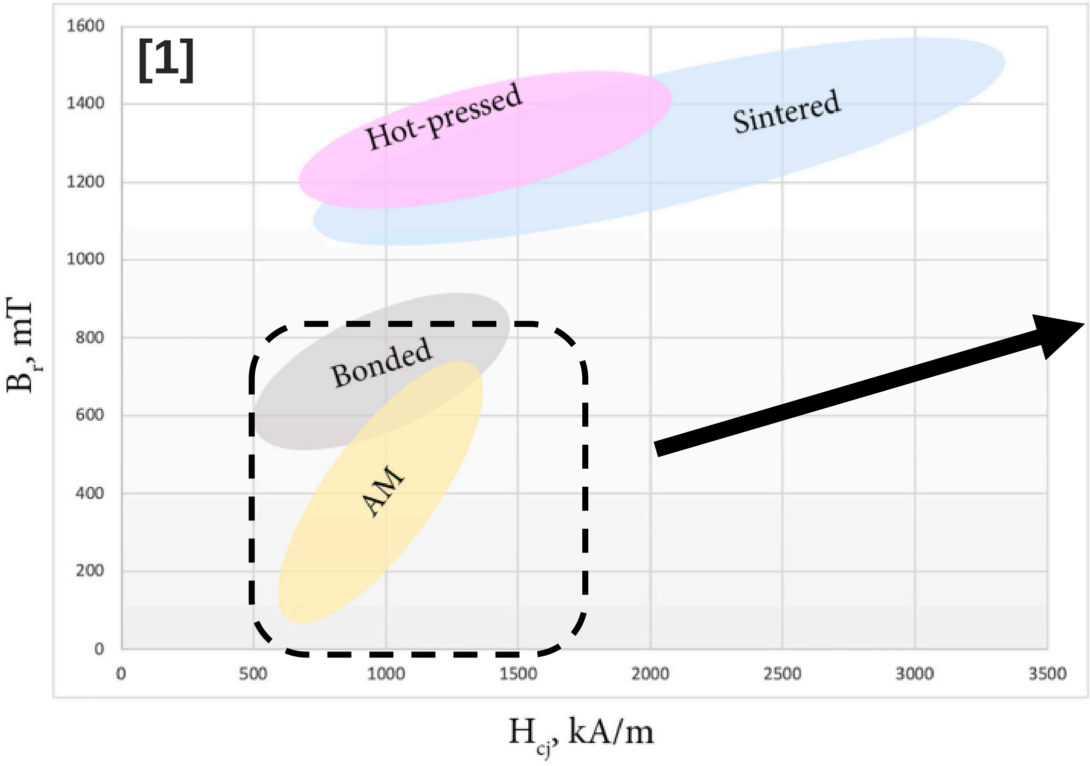
INSTITUT CARNOT Energies du Futur

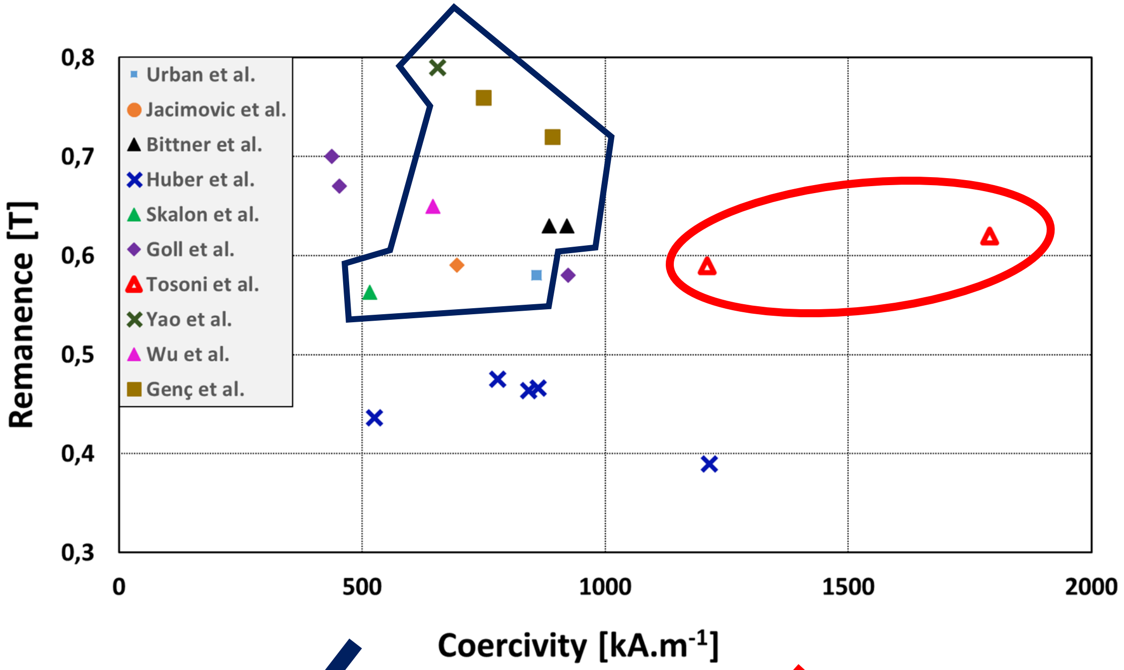
The Laser Powder Bed Fusion Technique



P : laser power
V_{scan} : Scan speed
e : powder bed thickness
h : hatch distance

State-of-the-art





Commercial powder:

8%at RE
2.5%at Ti
2.5%at Zr

Tailored powder:

14.4%at RE
2%at Cu

$RE_2Fe_{14}B$ stoichiometry : 11.7%at. RE

No possibility for grain alignment
→ $B_r < 0.8$ T

Commercial Powder (RE content **under** 2:14:1 stoichiometry)

Fe-rich grain boundary phases

Low coercivity

Tailored Powder (RE content **over** 2:14:1 stoichiometry)

Nd-rich grain boundary phases

Higher coercivity

[1] Pelevin I, Lyange M, Fedorenko L, Chernyshikhin S, Tereshina I. The Laser Powder Bed Fusion of Nd2Fe14B Permanent Magnets: The State of the Art. Condensed Matter. 2025; 10(2):22. https://doi.org/10.3390/condmat10020022

Objectives and Approach

OBJECTIVES

01

- Fabricate **samples by L-PBF** with a specific high RE content powder composition but free of HRE
- Describe **the microstructure** of a L-PBF sample and propose a formation mechanism

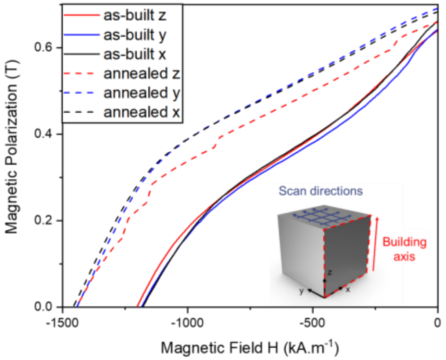
APPROACH

02

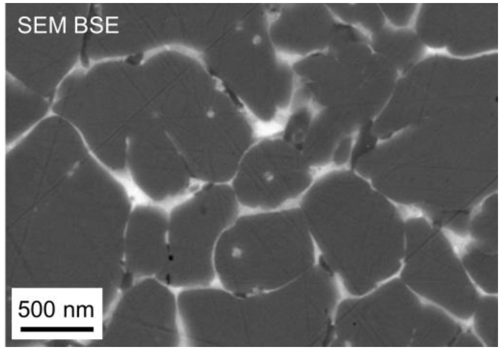
- Fabrication of a **tailored powder**
- Fabrication of **NdFeB samples by L-PBF**
- Magnetic characterization and selection of an optimal sample
- Microstructure investigation down to the nanoscale
- Elaboration of a solidification model to explain the formation of the microstructure

Powder

Samples



Properties



Microstructure

Sample elaboration

Powder

Raw Materials

↓

Strip Casting

↓

Annealing

↓

Hydrogen Decrepitation

↓

Jet Milling

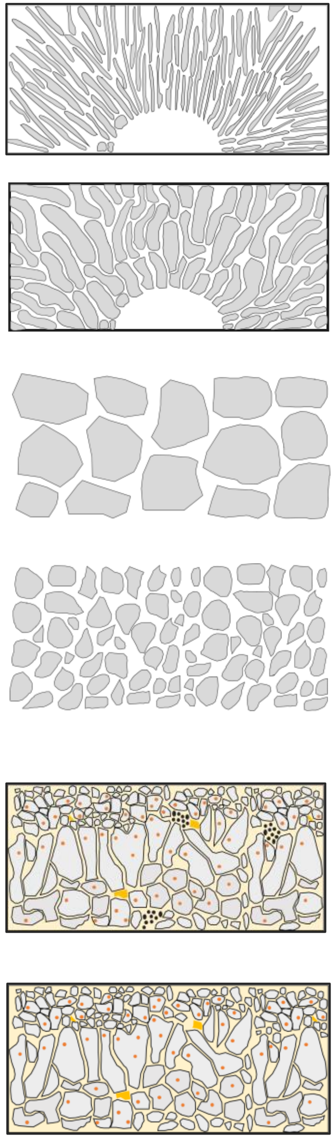
↓

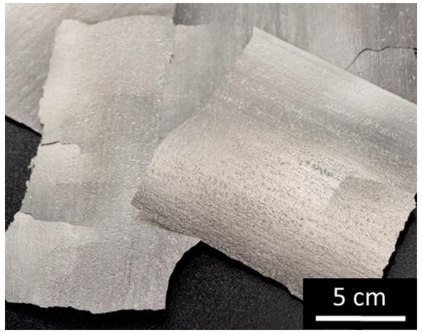
Samples

Laser Powder Bed Fusion

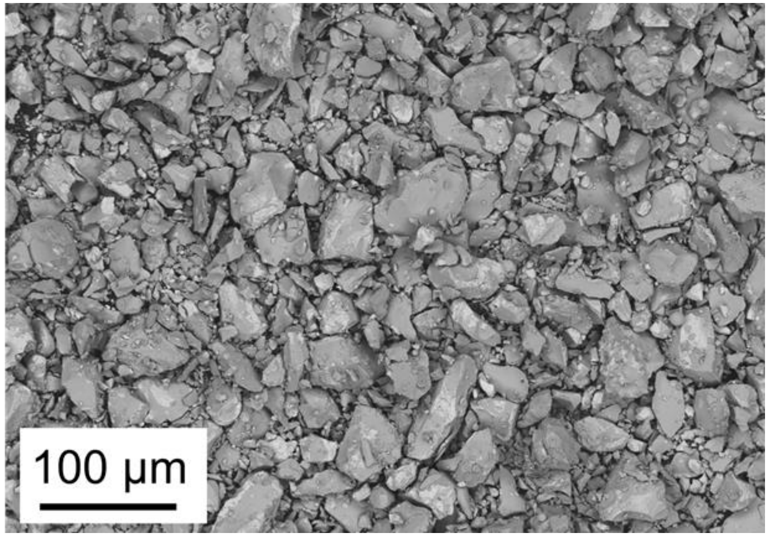
↓

Annealing





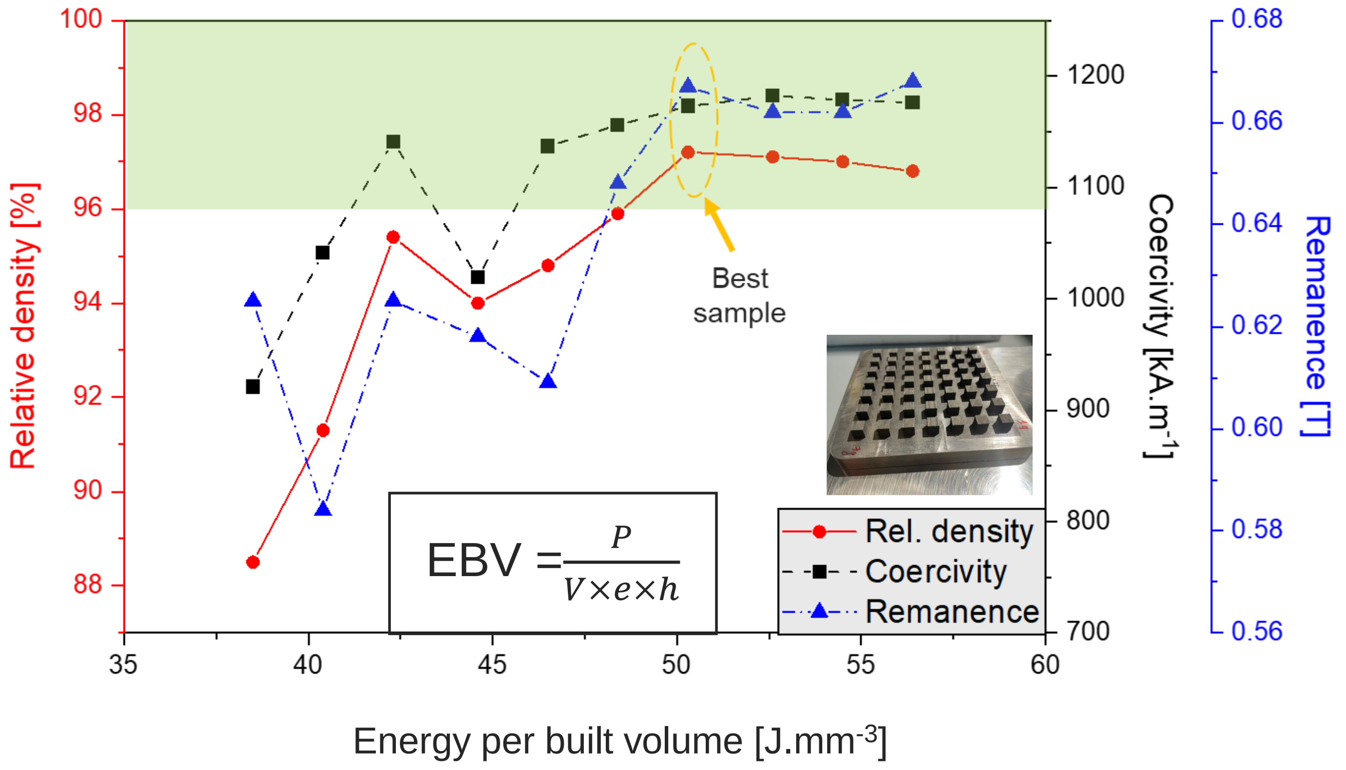
SEM BSE powder micrography
40 µm angular powder

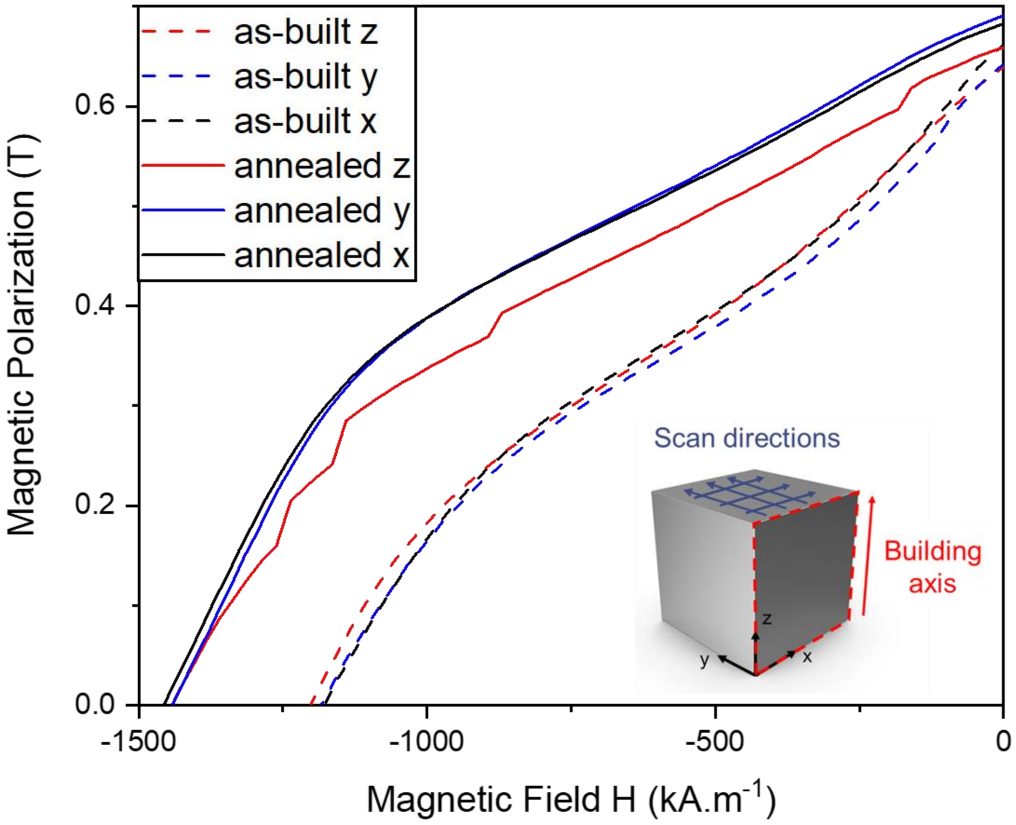


Powder composition (%mass.)

$RE_{32.8}Co_1B_1Al_{0.15}Cu_{0.1}Ga_{0.25}Fe_{Bal.}$

Magnetic properties





Best parameter set

P=120 W

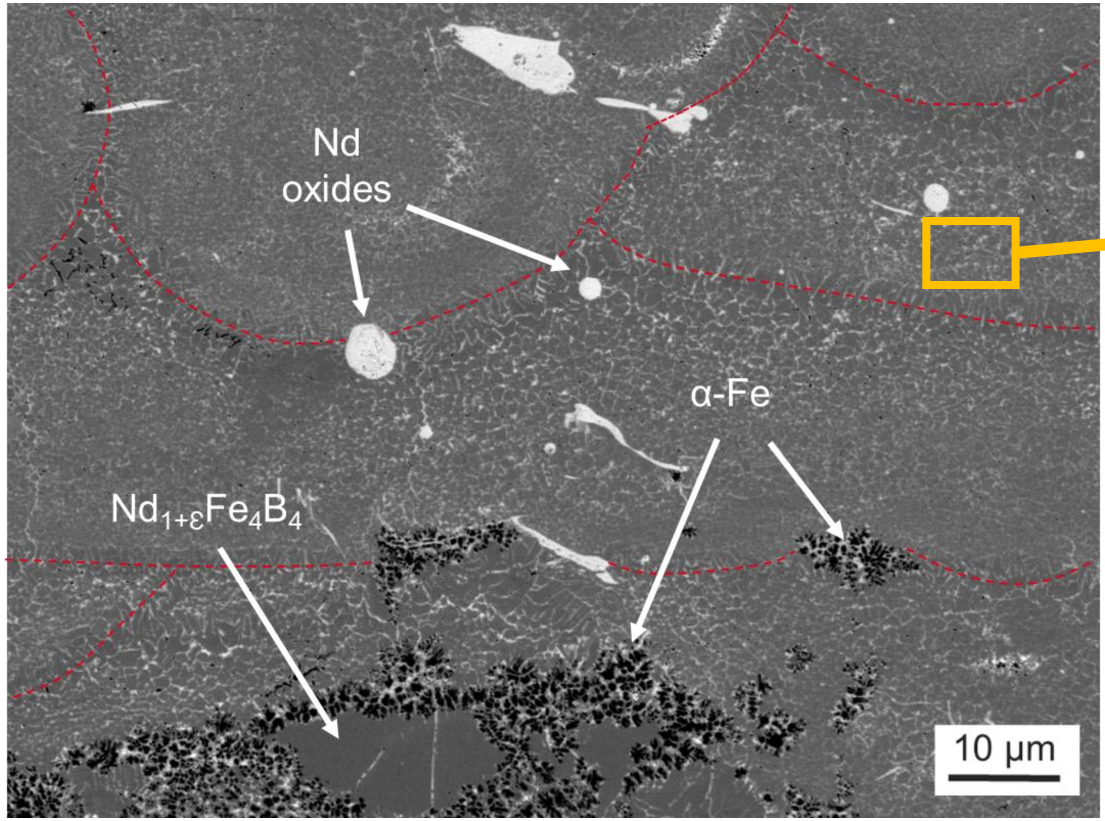
V=1250 mm.s^{-1}

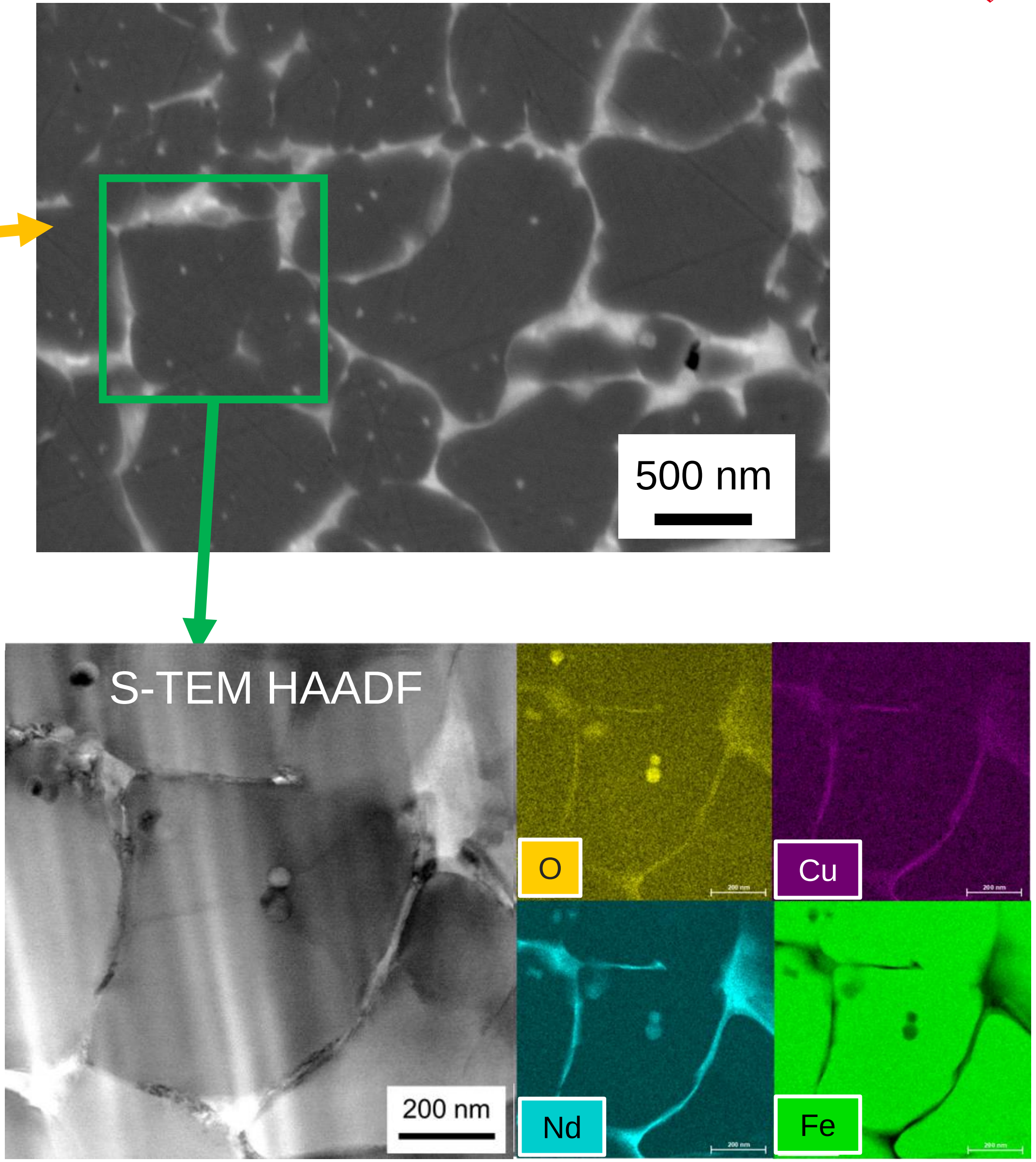
h=70 µm

e=30 µm

- Annealing realized at 600°C for 10 min. + 470°C for 1h
- Maximum as-built properties : B_r = 0.67 T and H_{cJ} = 1170 kA.m^{-1}
- Maximum annealed properties : **B_r = 0.69 T and H_{cJ} = 1440 kA.m^{-1} (1.8 T)**

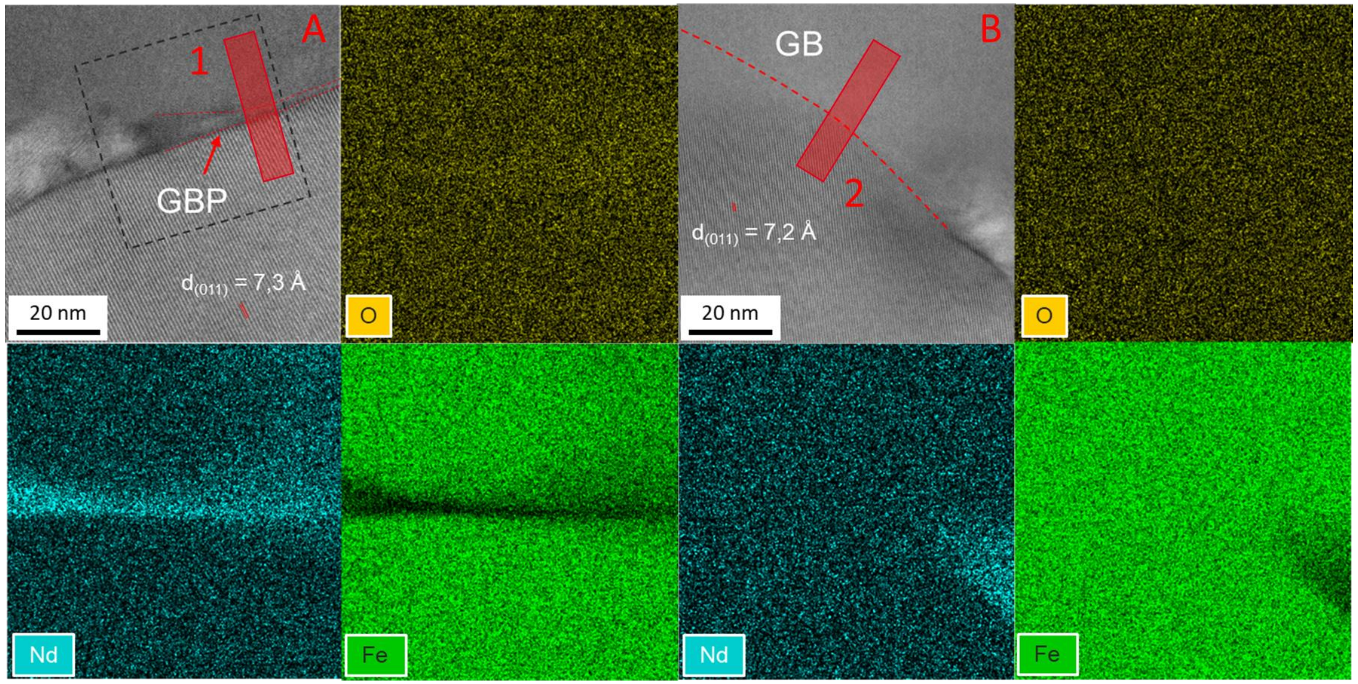
Microstructure investigation

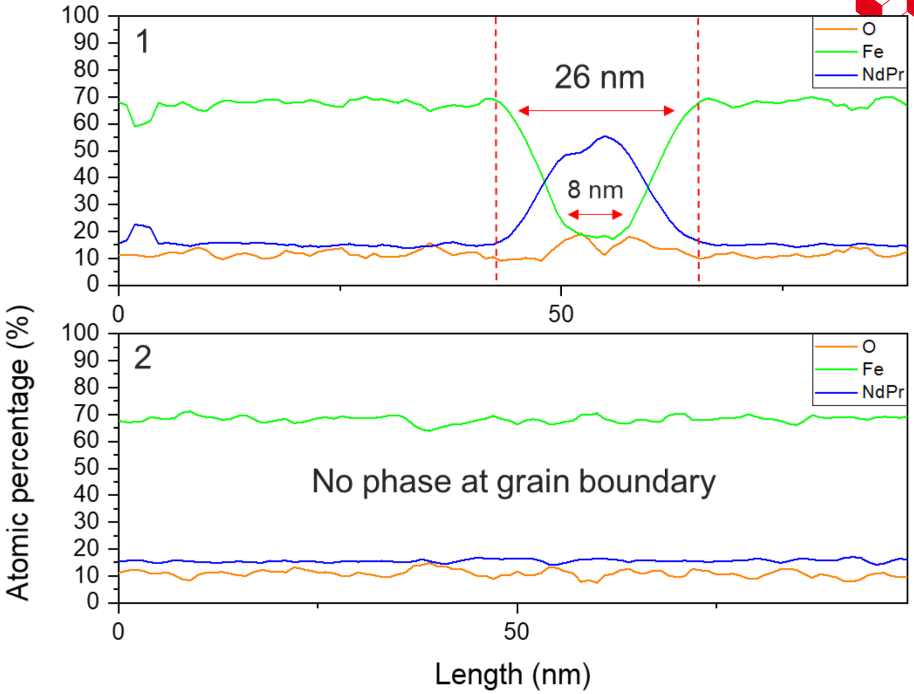


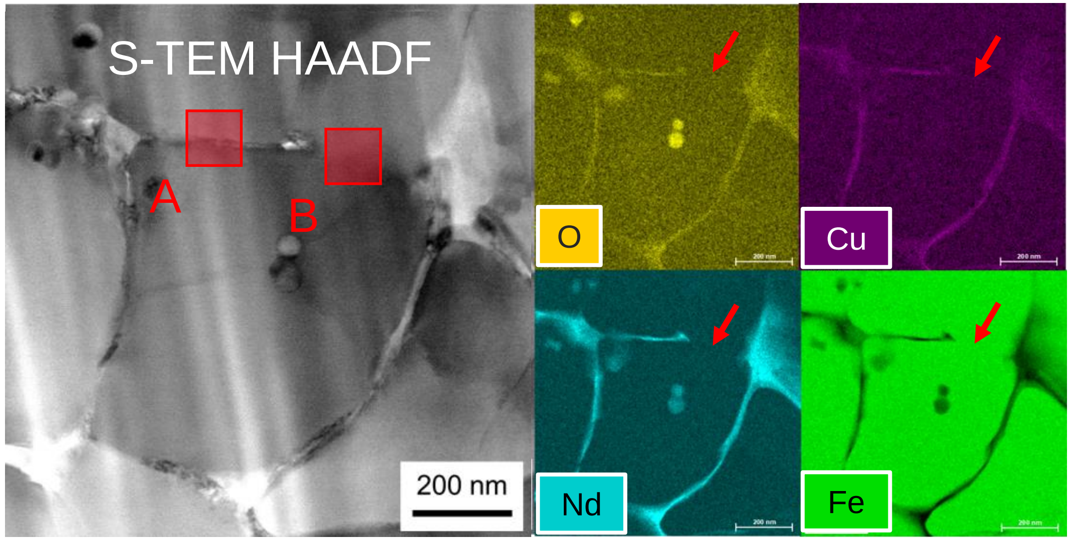


- Most of the microstructure is composed of small magnetic grains
- Non continuous grain boundary phase (GBP)
- Annealing does reorganise the GBP plus recombine α-Fe clusters with Nd-rich to obtain additional $Nd_2Fe_{14}B$ grains

Microstructure investigation

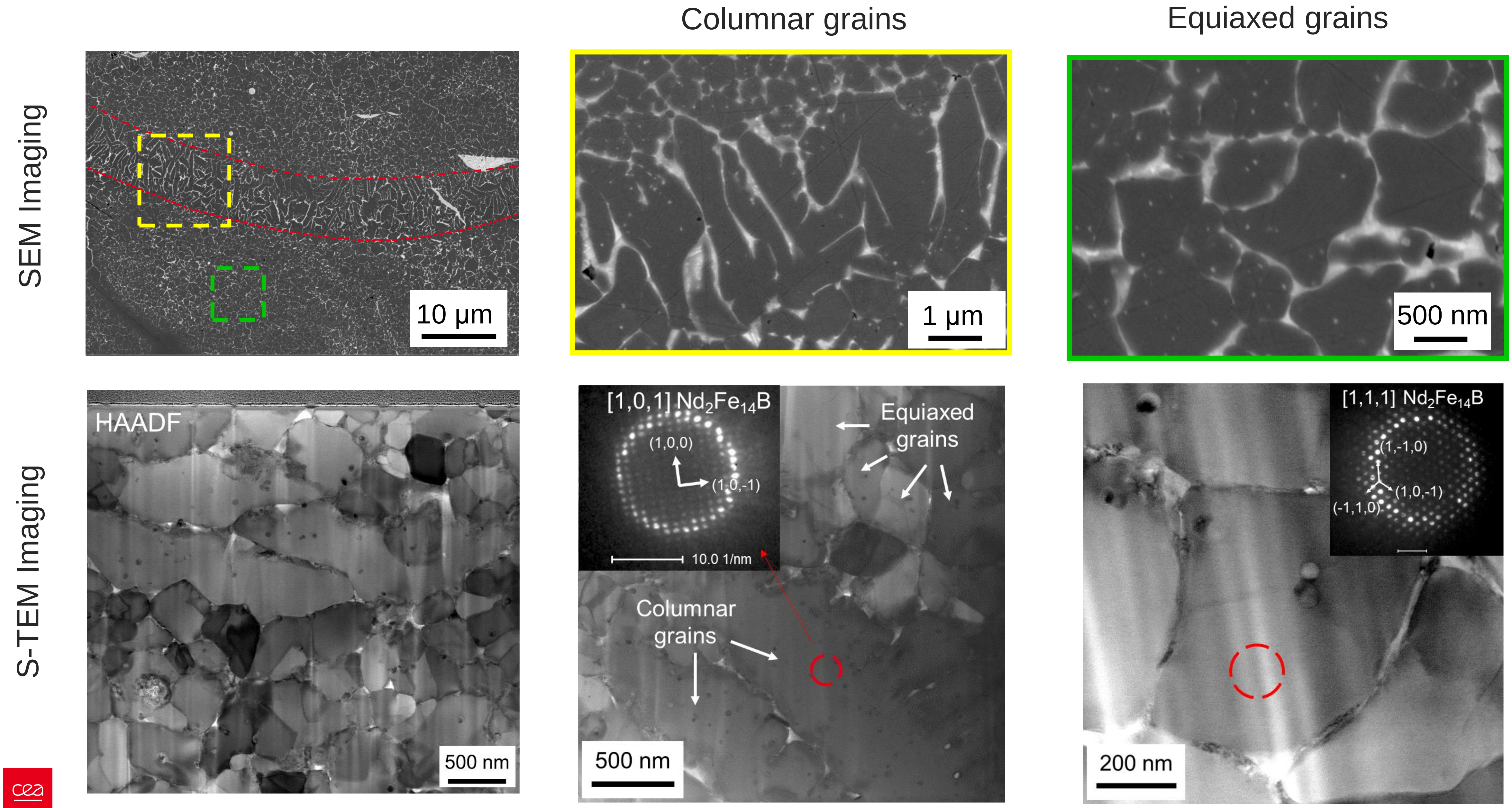






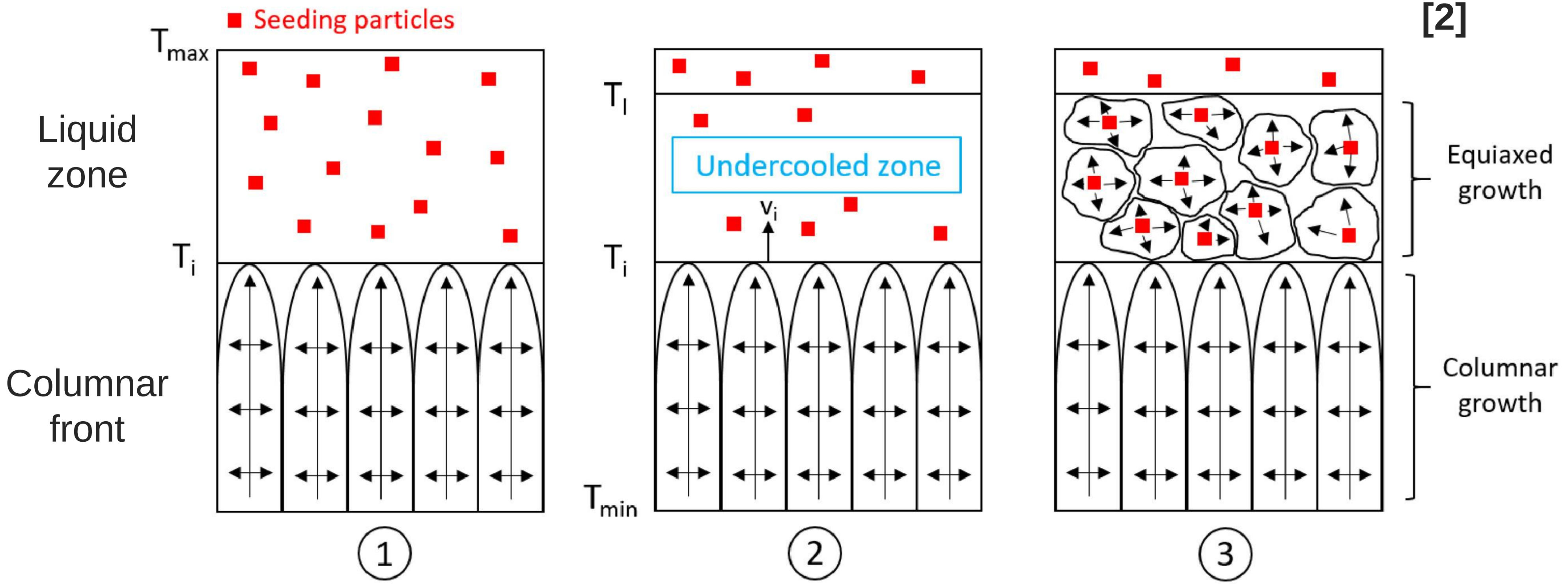
- Most of the microstructure is composed of small magnetic grains
- Non continuous grain boundary phase (GBP)
- Annealing does reorganise the GBP plus recombine α-Fe clusters with Nd-rich to obtain additional $Nd_2Fe_{14}B$ grains

Morphology of magnetic grains



Nucleation and growth process of the $Nd_2Fe_{14}B$ phase

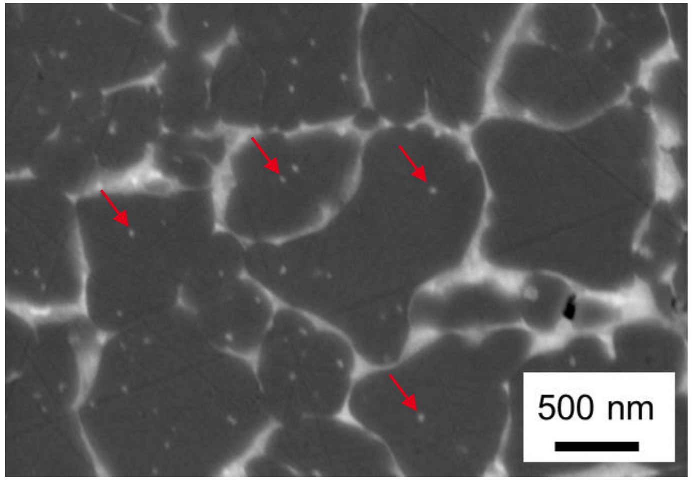
[2]

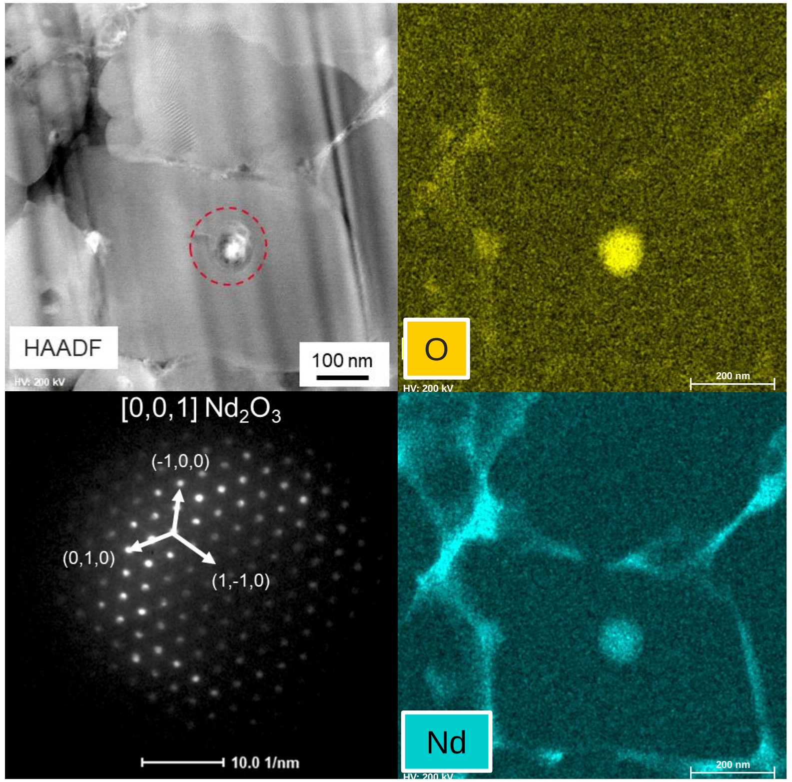


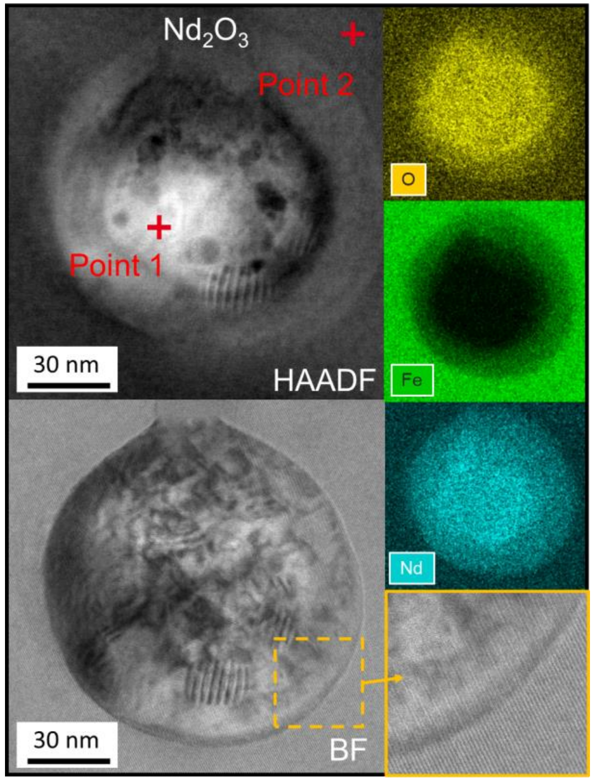
- For the formation of **equiaxed grains** by a **heterogeneous nucleation** process, 3 components are needed :
  - ❑ **Seeding/Nucleating particles** already in solid state in the melt
  - ❑ Sufficient **undercooling** to initiate the nucleation
  - ❑ Enough time to allow the equiaxed grains to grow and to block the columnar front

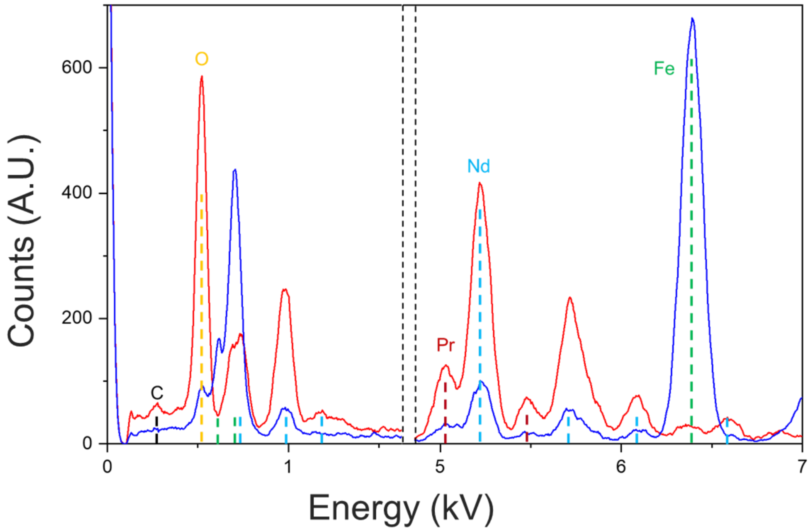
[2] M. Opprecht, J.-P. Garandet, G. Roux, C. Flament, An understanding of duplex microstructures encountered during high strength aluminium alloy laser beam melting processing, Acta Materialia, Volume 215, 2021, 117024, ISSN 1359-6454, https://doi.org/10.1016/j.actamat.2021.117024.

Intragrain Nd oxide inclusions





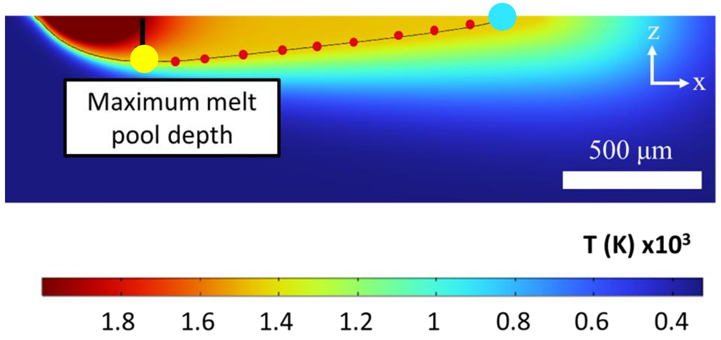


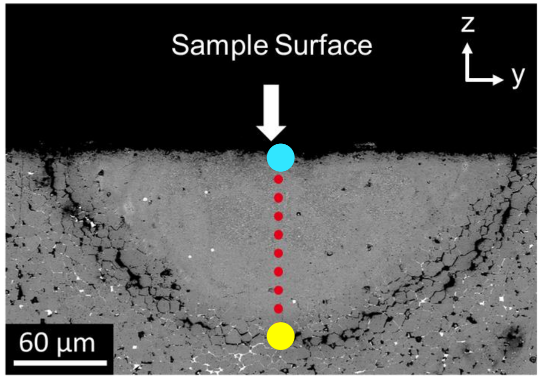


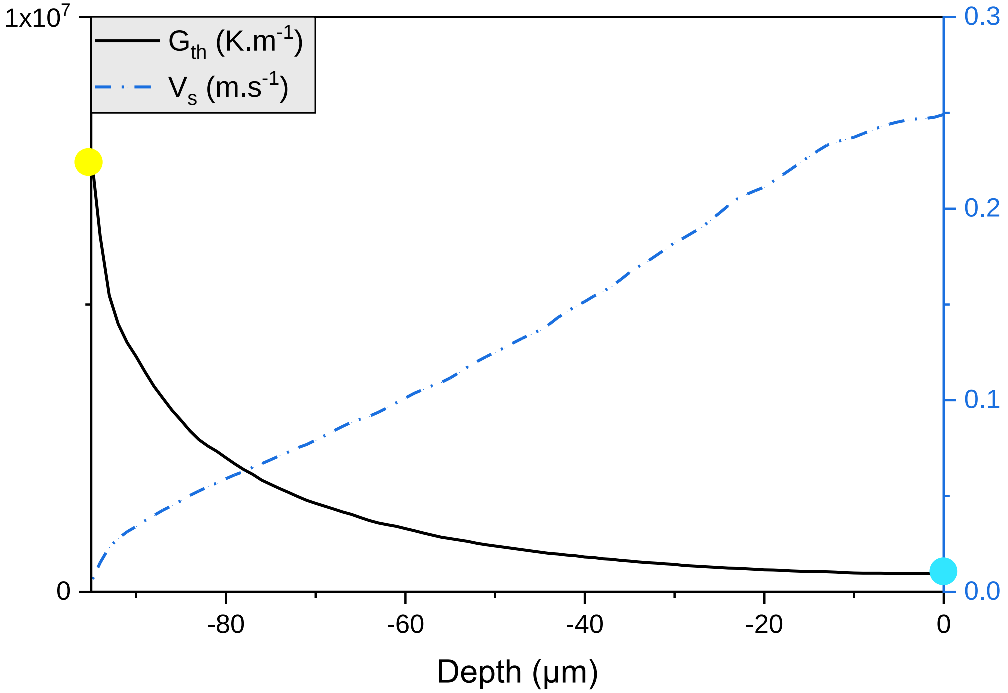
% at	O	Fe	RE	Co,Cu,Ga,Al
Point 1	57,6	1,6	40,9	1,4
Point 2	19,2	53,3	24,5	3

- Nd oxide inclusions as the only intragranular phase
- Size of ≃ 90 nm for this case (Typically 30 to 100 nm)
- Nd_2O_3 hexagonal structure

Kinetic aspect of the growth process







Determination of cooling conditions by Finite Elements simulation

- The growth of the equiaxed grains depends on the local cooling conditions. The following relationship can be established in LPBF [2]:

$$R_{max} = f(V_s, G_{th}) = \frac{V_s}{2 \times G_{th} \times K}$$

With K a kinetic constant ($cm.K^{-1}.s^{-1}$), V_s, G_{th}

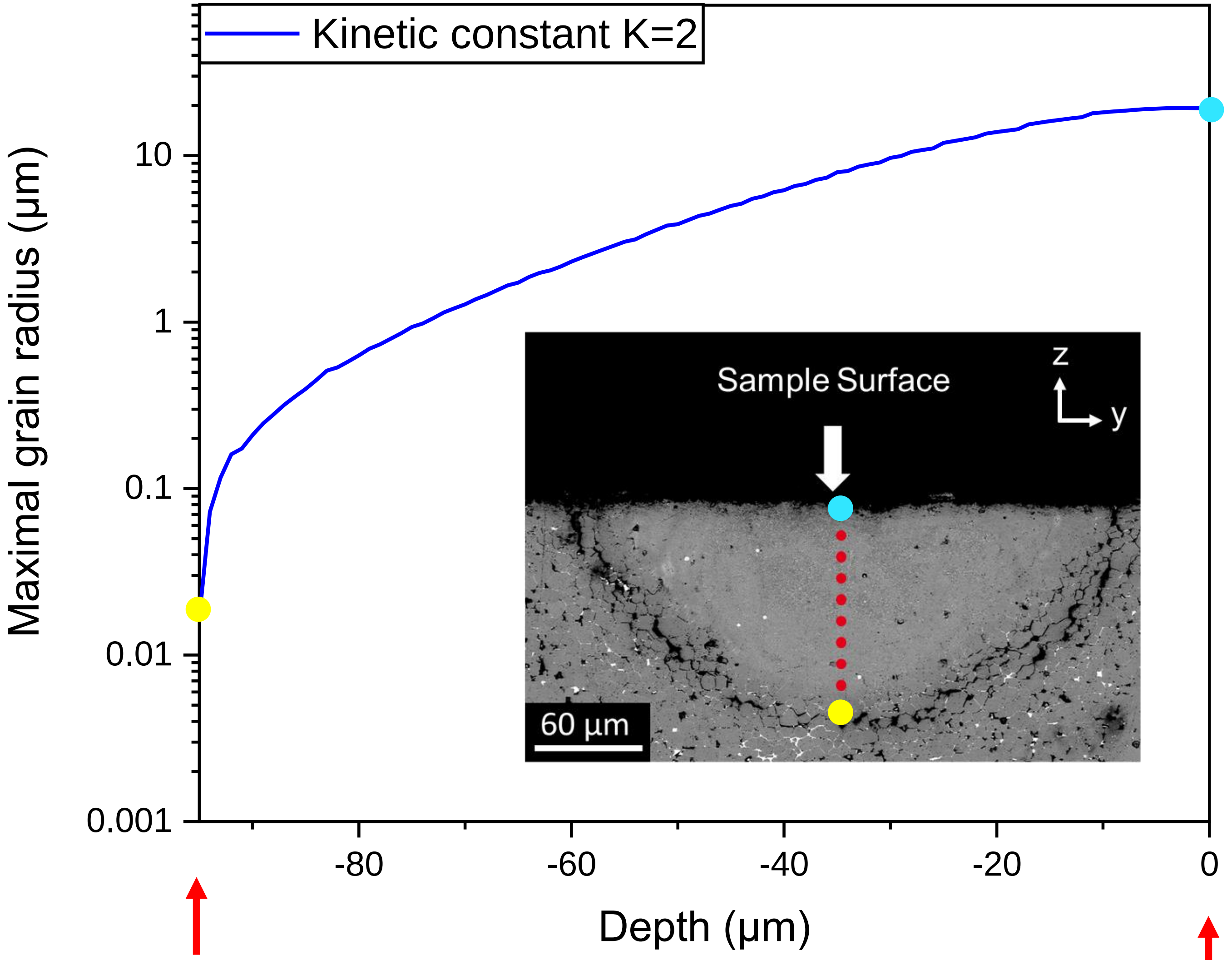
- V_s (solidification velocity) and G_{th} (thermal gradient) can be estimated thanks to Finite Elements thermal model developed using Comsol Multiphysics software [3].

- Thermal cooling conditions have been extracted vertically at the center of a melt pool

[3] **A. Wolz**, R. Caniou, O. Tosoni, C. Rado, et J.-P. Garandet, « On the Effect of Cooling Parameters on Solidification Structure in NdFeB Alloys », *Advanced Engineering Materials*, vol. n/a, nº n/a, p. 2400978, doi: 10.1002/adem.202400978.

[2] M. Opprecht, J.-P. Garandet, G. Roux, C. Flament, An understanding of duplex microstructures encountered during high strength aluminium alloy laser beam melting processing, Acta Materialia, Volume 215, 2021, 117024, ISSN 1359-6454, https://doi.org/10.1016/j.actamat.2021.117024.

Evaluation of the grain growth

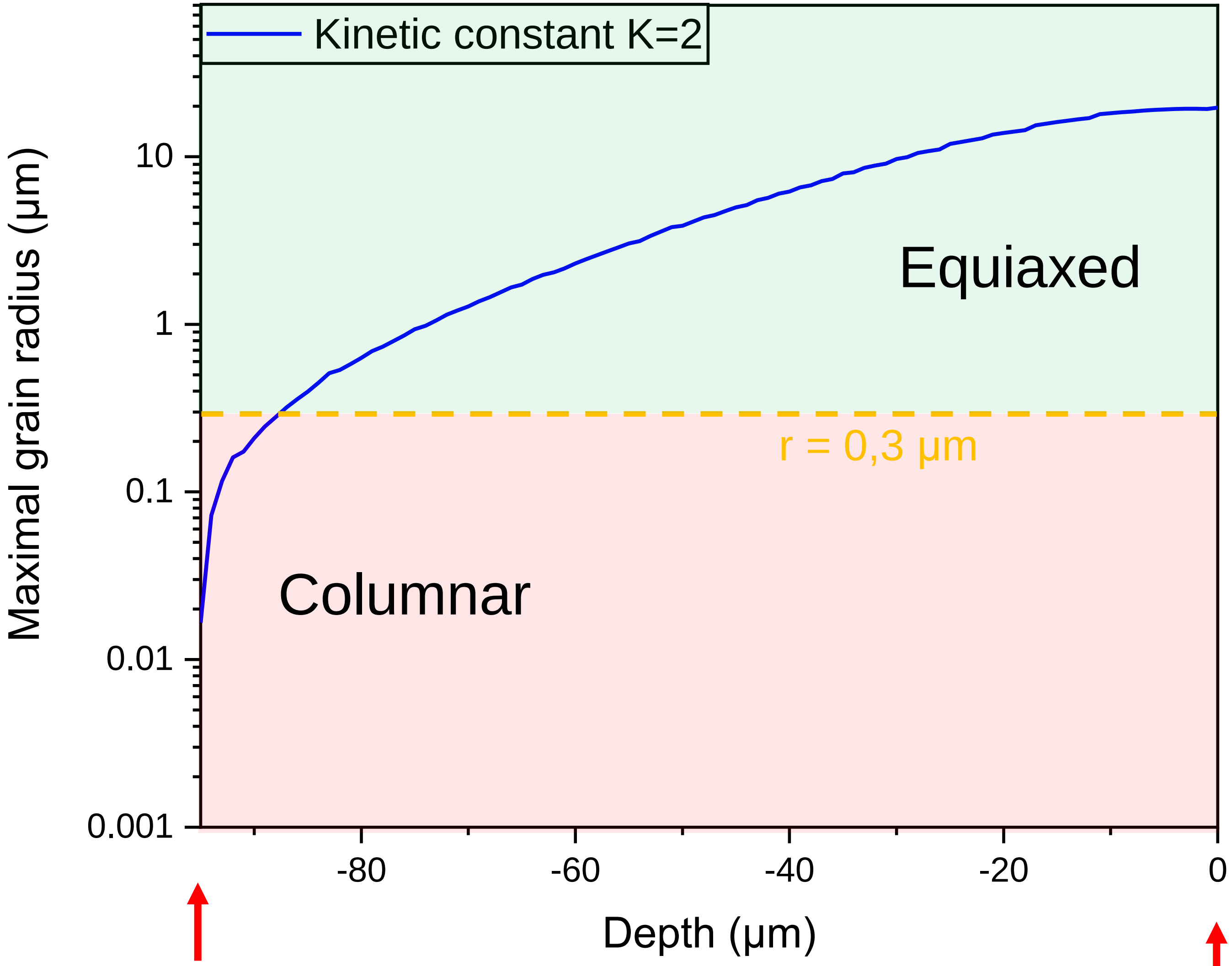


Bottom of the melt pool

Upper part of the melt pool

- We've been able to represent the maximum equiaxed grain size possible depending on the vertical location inside of the melt pool

Evaluation of the grain growth



Bottom of the melt pool

Upper part of the melt pool

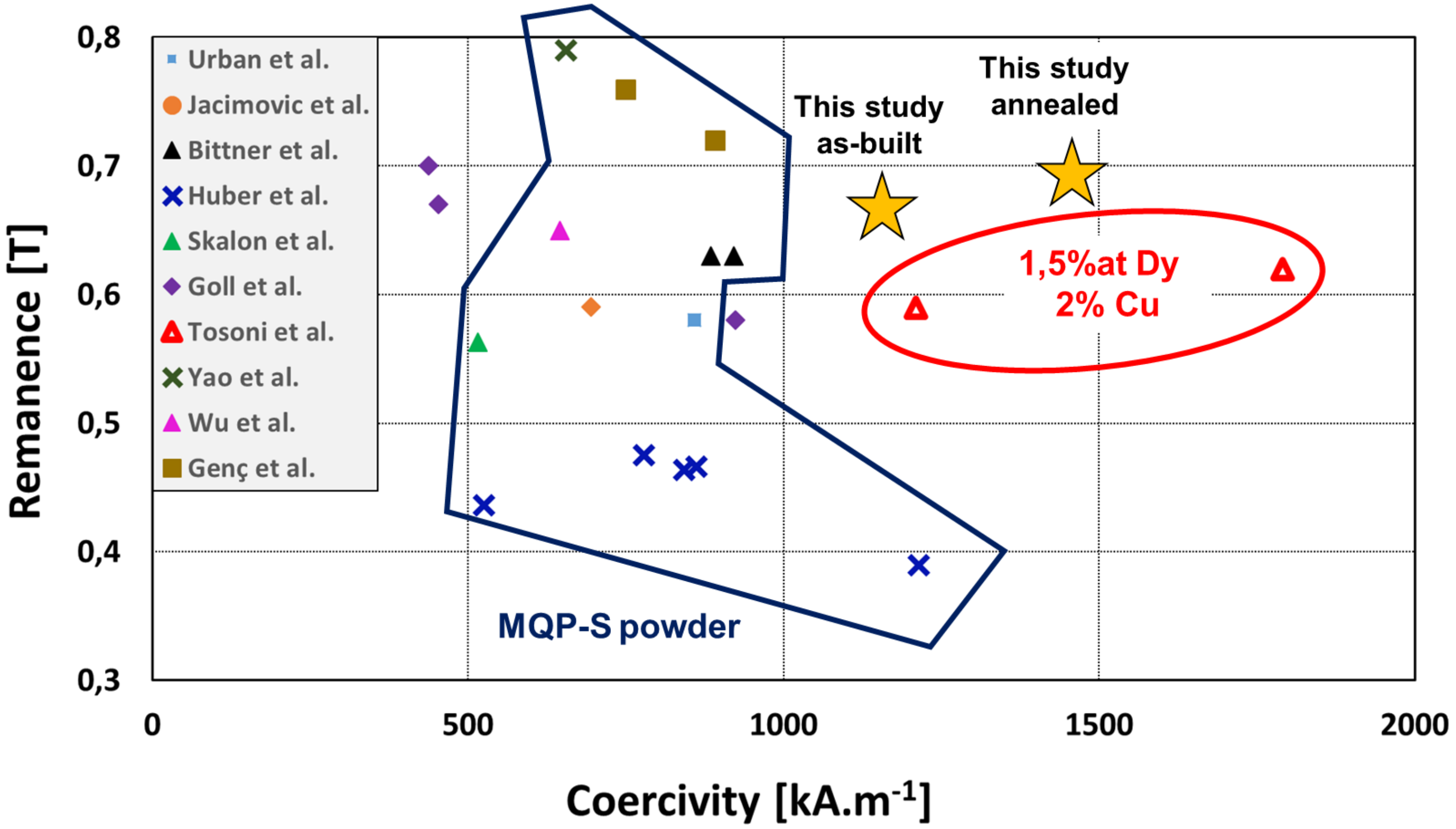
- We've been able to represent the maximum equiaxed grain size possible depending on the vertical location inside of the melt pool
- We placed the critical value to reach to block the columnar front (r=300 nm) which is the size of the effective equiaxed grains observed in the samples
- This confirm that in the edges of the melt pool the microstructure is columnar, and a transition to an equiaxed structure occurs after a few microns.

Conclusion

01

MAGNETIC PROPERTIES

- **High coercivity** samples compared to the L-PBF state of the art, up to **1440 kA.m^{-1}**.
- Nearly isotropic samples and remanence still limited (<0,7 T)
- Annealing heat treatments at 600°C+470°C strongly improve the coercivity



Conclusion

01

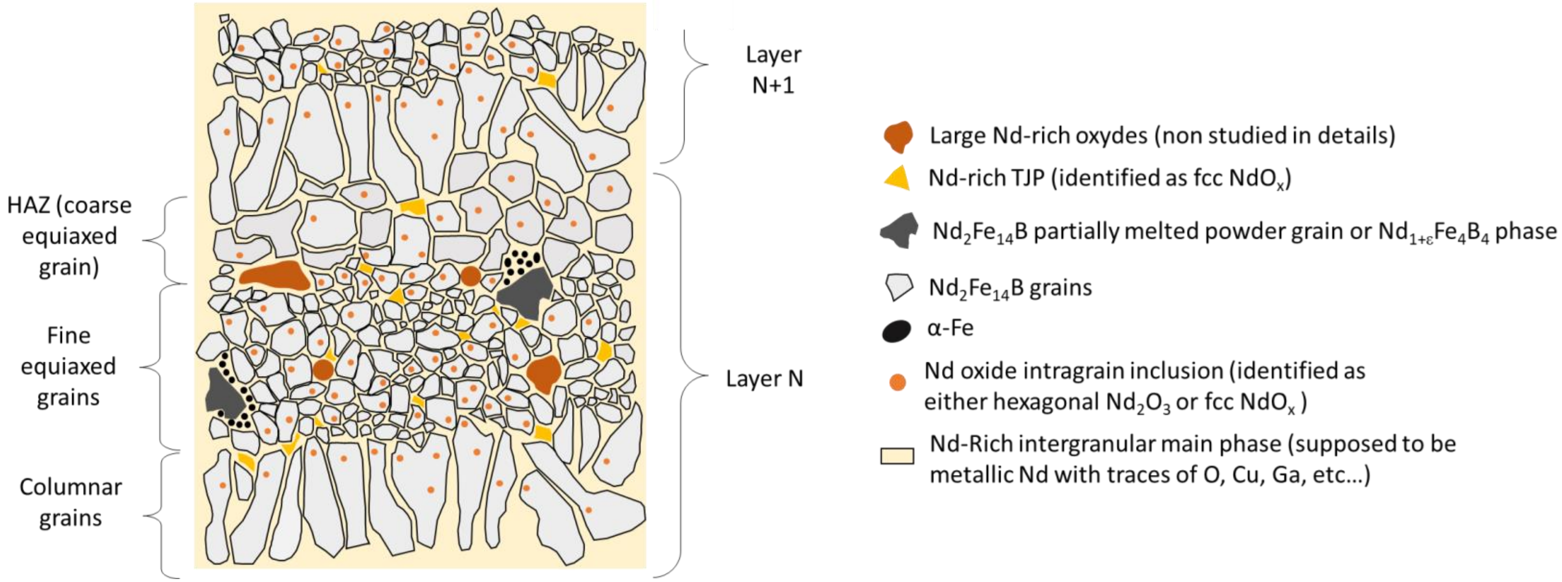
MAGNETIC PROPERTIES

- **High coercivity** samples compared to the L-PBF state of the art, up to **1440 kA.m^{-1}**.
- Nearly isotropic samples and remanence still limited (<0,7 T)
- Annealing heat treatments at 600°C+470°C strongly improve the coercivity

02

MICROSTRUCTURAL ANALYSIS [4]

- A mainly **sub-micronic equiaxed $Nd_2Fe_{14}B$ grains** microstructure was obtained.
- The grain boundaries are mainly composed of Nd-rich phase
- Isolated punctual phases like Nd oxides, α-Fe, $Nd_{1+\varepsilon}Fe_4B_4$



*[4] **A. Wolz**, O. Tosoni, C. Flament, J.-P. Garandet, High–coercivity HRE–free NdFeB magnets by laser powder bed fusion, Journal of Magnetism and Magnetic Materials, Volume 630, 2025, 173363, ISSN 0304-8853, https://doi.org/10.1016/j.jmmm.2025.173363.*

Conclusion

01

MAGNETIC PROPERTIES

- **High coercivity** samples compared to the L-PBF state of the art, up to **1440 kA.m^{-1}**.
- Nearly isotropic samples and remanence still limited (<0,7 T)
- Annealing heat treatments at 600°C+470°C strongly improve the coercivity

02

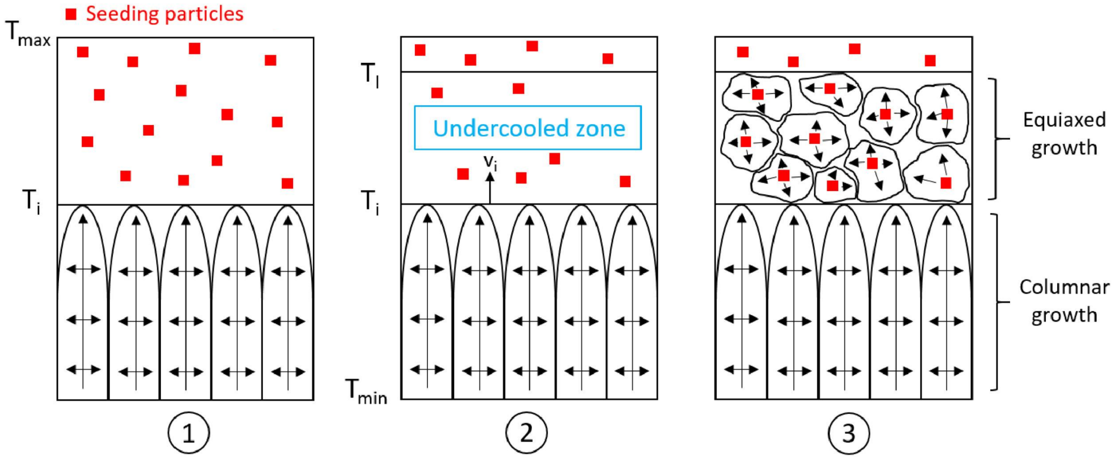
MICROSTRUCTURAL ANALYSIS

- A mainly **sub-micronic equiaxed $Nd_2Fe_{14}B$ grains** microstructure was obtained.
- The grain boundaries are mainly composed of Nd-rich phase
- Isolated punctual phases like Nd oxides, α-Fe, $Nd_{1+\varepsilon}Fe_4B_4$

03

FORMATION OF THE MICROSTRUCTURE

- Systematic **Nd-oxide** inclusions (30 to 100 nm) appear as **likely candidates** to play the role of **nucleating agent**.
- A **simple kinetic model** can explain the presence of both equiaxed and columnar grain inside of the samples.



Many thanks for your attention

Feel free to ask questions !

Aymeric WOLZ
CEA Grenoble, Liten
aymeric.wolz@cea.fr