Additive manufacturing of magnetic materials

Webinar: The role of Additive Manufacturing (3D printing) in e-mobility and electrification

17.3.2021

Joni Reijonen
Research Scientist
VTT

My journey

- 1992 born in Outokumpu, FIN
- 2011 started Mechanical Engineering studies at LUT
  - Major in laser materials processing
  - Learned that you can 3D print metals – cool!
- 2015 Bachelor's thesis at LUT
  - “The effect of focal point parameters in fiber laser welding of structural steel”
- 2016 Master’s thesis at VTT
  - “Utilizing metallic waste streams as raw material for powder-based additive manufacturing”
- 2017 Graduated as M.Sc.(Tech)
- 2017→ working at VTT’s Advanced manufacturing technologies research group

VTT – beyond the obvious

VTT is one of the leading research, development and innovation organizations in Europe. We help our customers and society to grow and renew through applied research. The business sector and the entire society get the best benefit from VTT when we solve challenges that require world-class know-how together and translate them into business opportunities.

Our vision
A brighter future is created through science-based innovations.

Our mission
Customers and society grow and renew through applied research.

Strategy
Impact through scientific and technological excellence.

Established in
1942

268 M€
Net turnover and other operating income (VTT Group 2018)

2,049
Total of personnel (VTT Group 31.12.2018)

Owned by

Ministry of Economic Affairs and Employment

31%
Doctorates and Licentiates (VTT Group 2018)

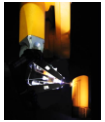
44%
From the net turnover abroad (VTT Group 2018)

Experimental facilities

From powder to product – agile pilots

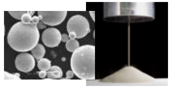
Material & component testing

Post processing



Direct Write Technology

Selective Laser Melting



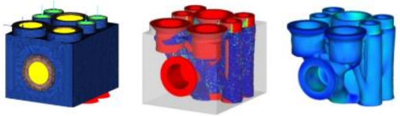
Powder characterization

Plasma spheroidization

Gas atomization

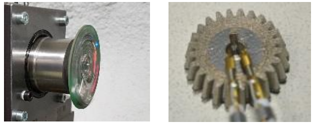
Application Services

Competitive products & new business models



Design for AM

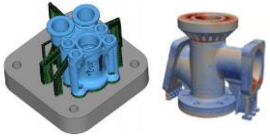
Digital spare parts



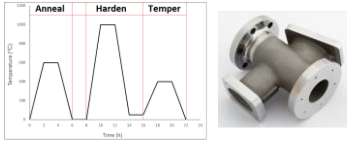
Added intelligence & functionality

Production Services

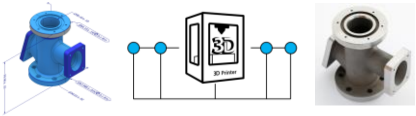
Increased productivity & quality



Thermal distortions mitigation



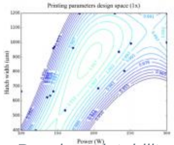
Post-processing



Integration of AM into production

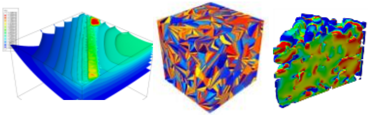
Material Services

Increased quality & material performance



Powder printability

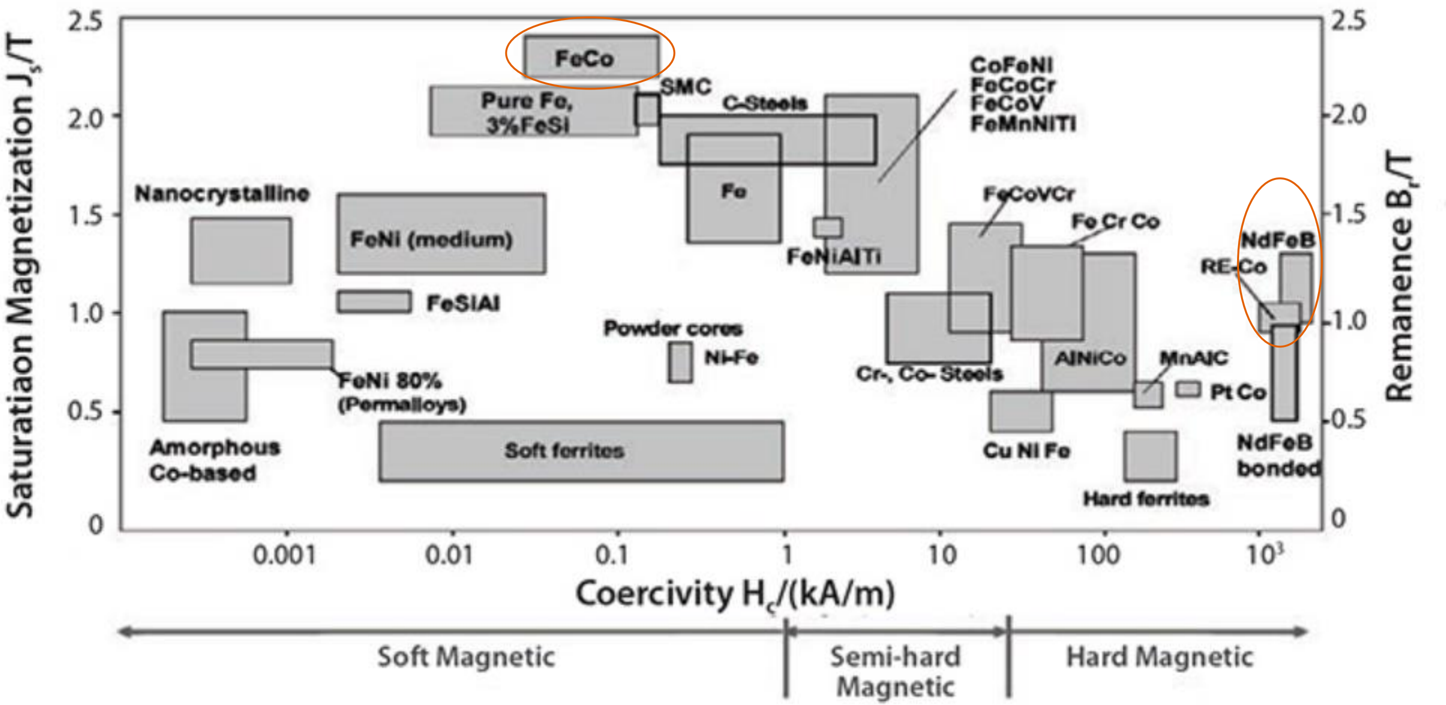
Application driven materials



Virtual material factory

Magnetic materials

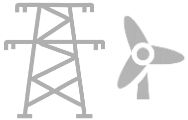
Magnetic materials



https://www.sigmaaldrich.com/technical-documents/articles/material-matters/additive-manufacturing-of-permanent-magnets.html

Applications

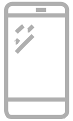
- Generators
- Motors
  - ~35 % of soft magnetic
  - ~70 % of hard magnetic
- Transformers
- Others
  - Magnetic recording
  - Voice coils



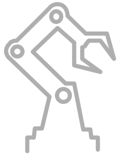
Power generation

E-mobility

Sensors



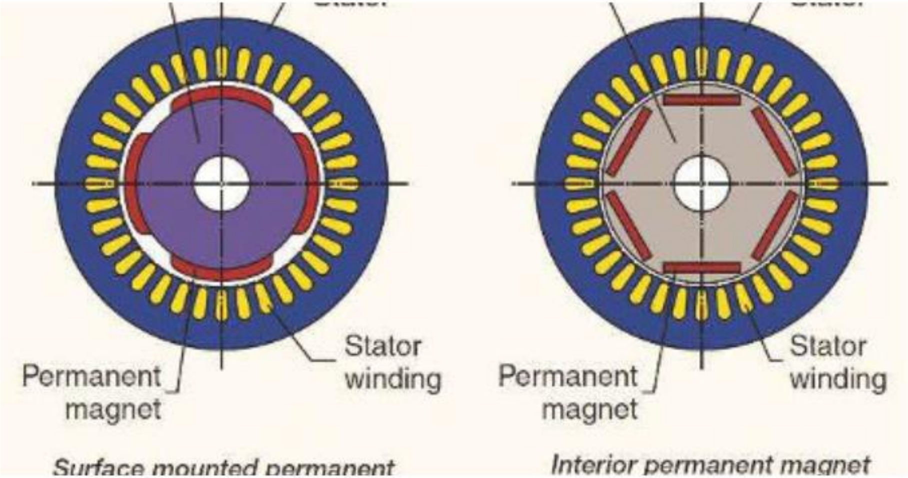
Electronics



Robotics

Magnetic materials in e-drives

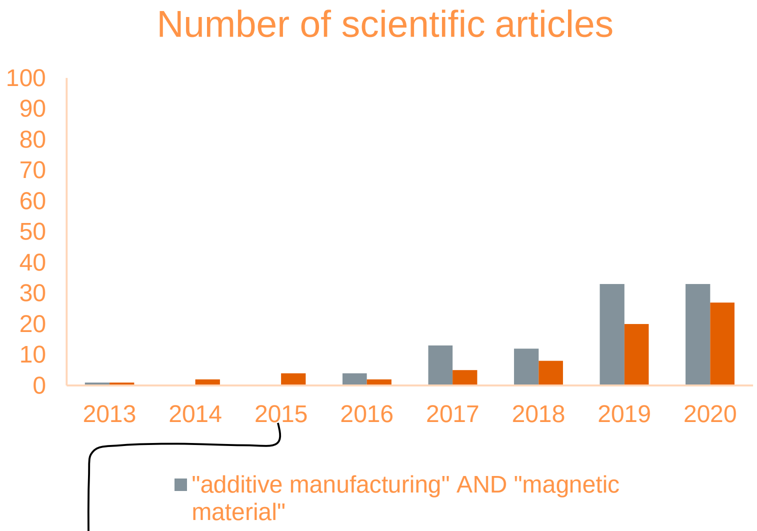
https://electronics.stackexchange.com/questions/479957/tesla-model-3-motor



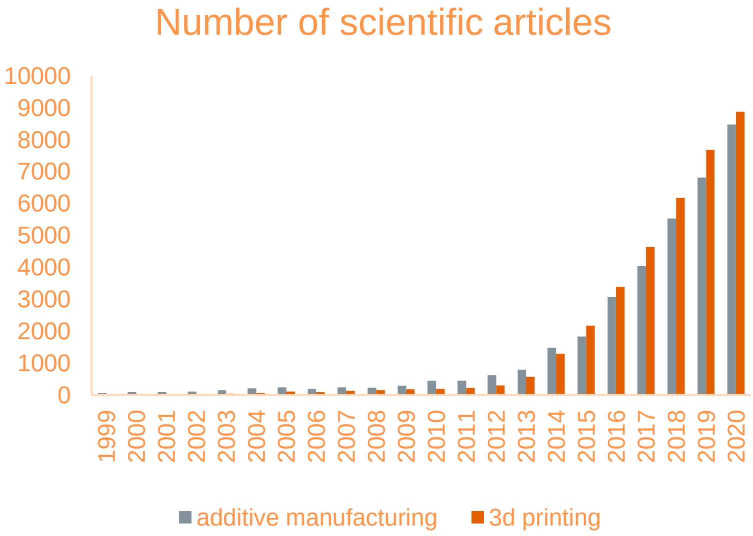
https://www.controleng.com/articles/understanding-permanent-magnet-motors/

Additive manufacturing of magnetic materials = young & growing research field

VTT



Print'EM and MIMES projects started at VTT



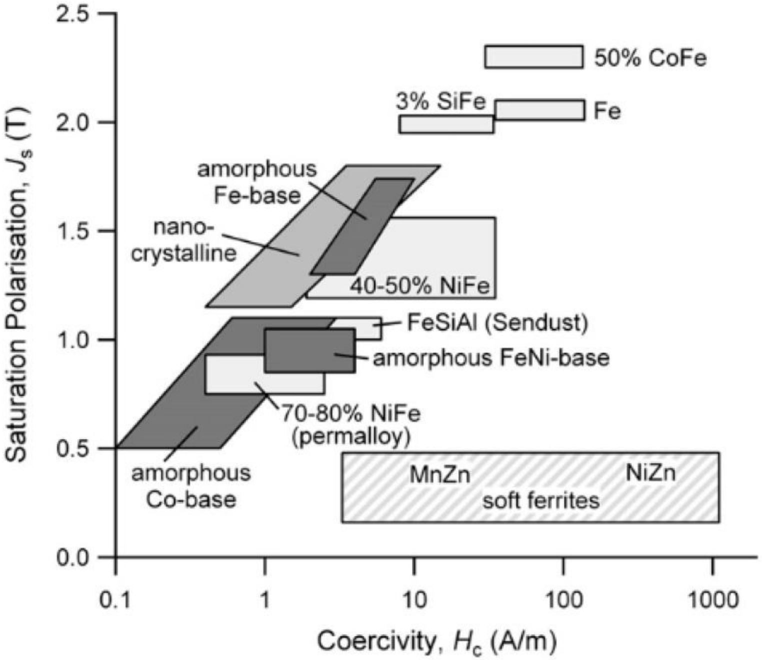
Source: Scopus

SOMA – Lightweight Solutions for E-Mobility by AM of Soft Magnetic Alloys

https://www.soma-eit.eu

Background

- Fe-Co based materials have the highest saturation magnetization
- Conventional manufacturing from laminated sheets or by press & sintering → limited shapes, manufacturing waste



Herzer, G. Modern soft magnets: Amorphous and nanocrystalline materials. *Acta Mater.* **2013**, *61*, 718–734.

Challenge

- We have shown in earlier studies that quasi-static magnetic, electrical and mechanical properties of L-PBF Fe-Co-V are comparable to standardized alloy

	H_c A/m	B_{max} T	μ_{max} -	ρ µohm·m	R_m MPa	$R_{0.2}$ Mpa	A(%)	E GPa
AM Fe-Co-V	47	2.23	13000	49	266	306	3	210
Ref. Fe-Co-V*	40	2.23	12000	46	250	350	3	215

*ASTM A801-09

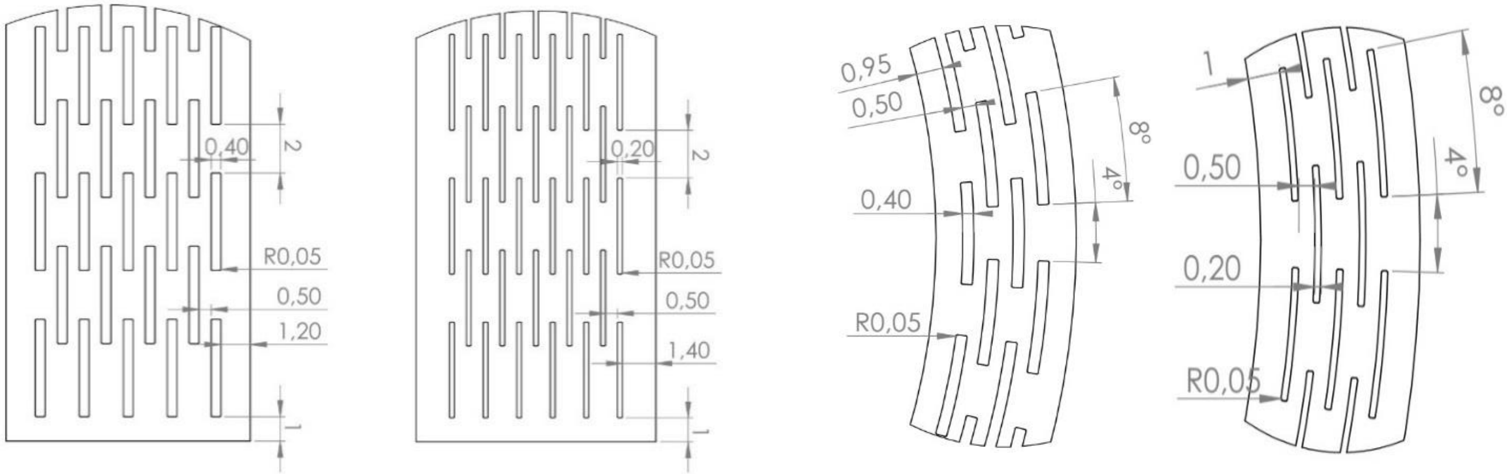
- Challenge, AC magnetic properties ➔ Mitigation of eddy current losses

➔ *L-PBF process is restricted to a single material per component*

➔ *Ways to tackle: materials with higher electrical resistivity, **optimized structures** and/or multi-material processes*

Design - Loss mitigating structures

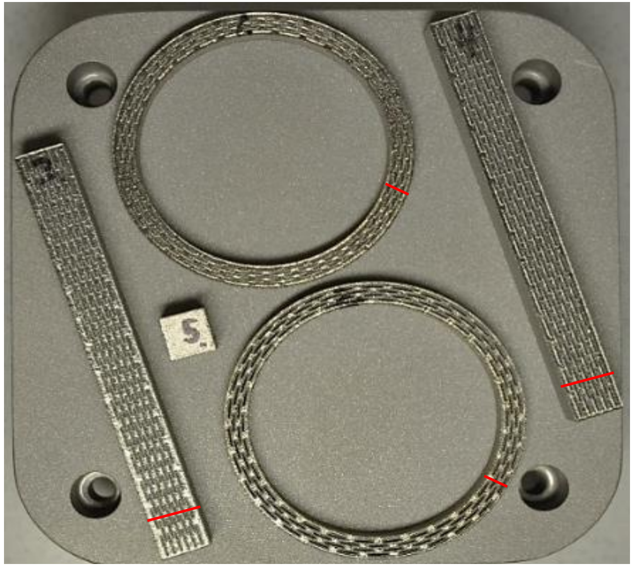
- Alternative designs based on the bar and ring geometries
- Mimicking laminated structures by adding gaps with different dimensions in attempt to reduce the eddy currents losses



Detailed views of perforated bar and ring sample designs with 0.2 mm and 0.4 mm gap width.

L-PBF loss mitigating samples

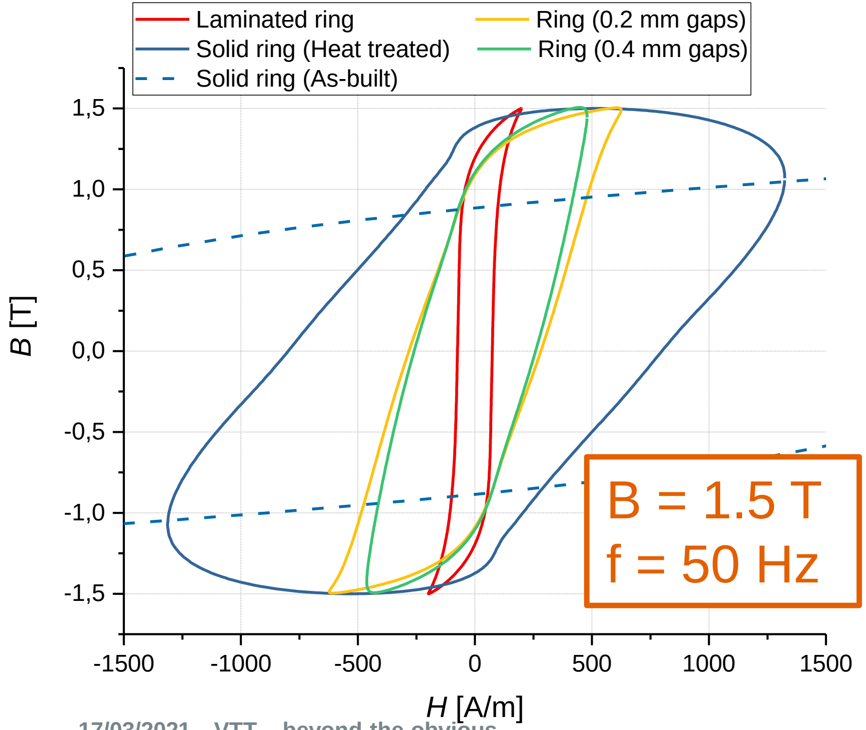
Two sample sets, **solid and perforated**, from same raw material and exactly same process parameters and post treatments.



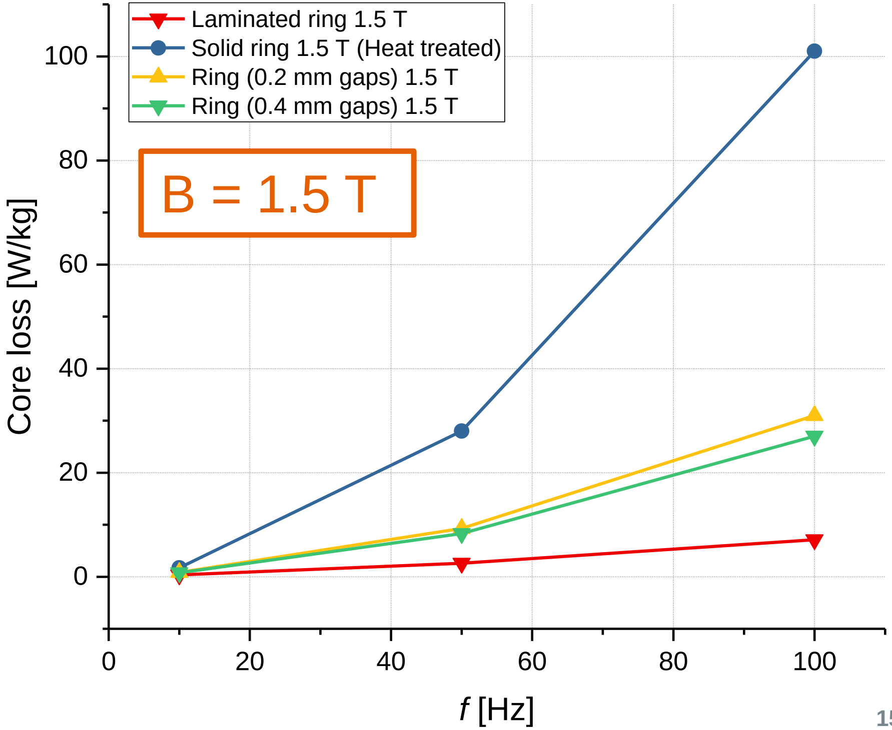
AC magnetic measurements

VTT

Hysteresis ➔ solid vs. perforated



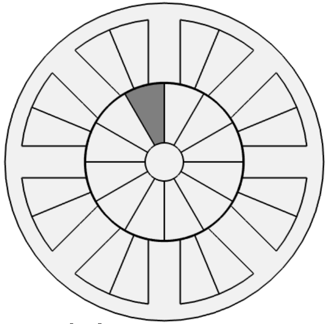
Magnetic losses ➔ solid vs. perforated

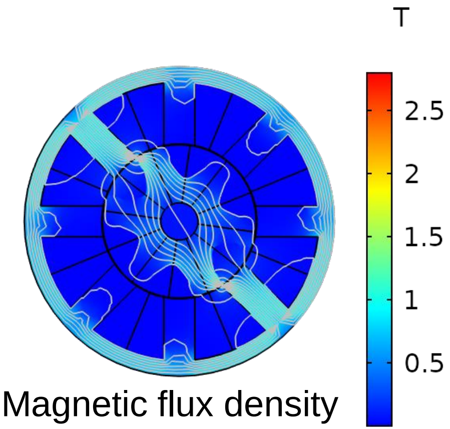


Topology optimization (TO) of electrical machines: Switched reluctance motor

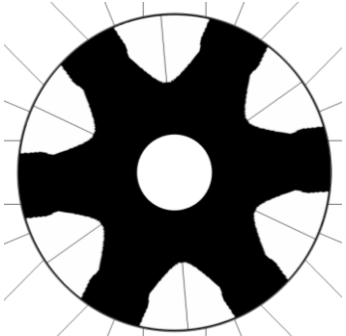
- Goal: Maximization of torque while minimizing rotor mass of an 8/6 switched reluctance motor
- Rotor is symmetric -> TO design space is half of one rotor pole
- During each TO iteration, magnetic flux density, motor torque, and rotor mass are computed
- Torque varies depending on the rotor angle -> multistatic sweep with 15 angles during a 15° rotor turn was performed to obtain the average motor torque
  - 15° is sufficient due to symmetry
- TO algorithm allows free material distribution inside the TO space
- Globally Convergent Method of Moving Asymptotes (GCMMA) + penalization (SIMP)

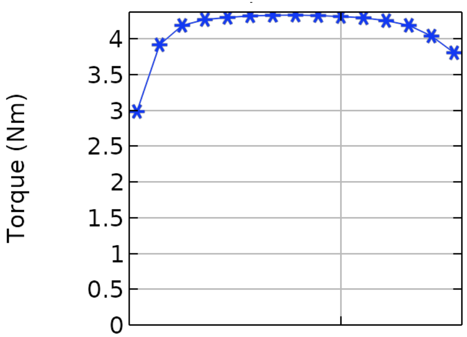
$$\underset{\rho}{\text{minimize}} \quad f = \sum_{j=1}^{n} \left(\frac{V(\boldsymbol{\rho})}{V_\Omega} - \frac{T_j(\boldsymbol{\rho})}{T_t} \right) \qquad (6)$$
$$\text{subject to } 0 < \rho_k < 1, \; k = 1, \ldots, ND.$$


Model geometry



Magnetic flux density


Optimized rotor

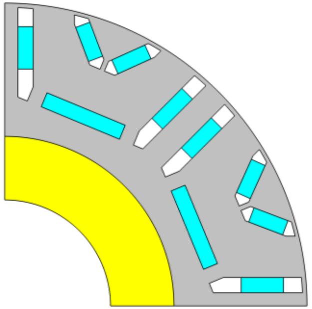


Motor torque

Topology optimization (TO) of electrical machines: Rotor mass minimization

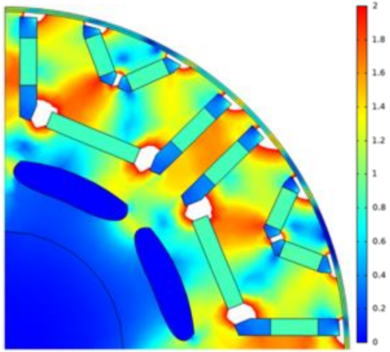
- Goal: to minimize the rotor mass of a high-speed permanent magnet synchronous machine, while maintaining mechanical strength of the rotor
- Solution: TO with structural mechanics model
  - Electromagnetic design was done before the TO
  - TO space was near the shaft, where the magnetic flux density is low (< 0.6T)
  - TO objective was to minimize rotor mass, with total elastic strain energy as a constraint
- Results: Mass reduction by 8.8%, while the von Mises stress did not exceed the yield strength of the material ($4.4 \cdot 10^8$ N/m^2), and the magnetic flux density did not decrease
- TO is solved using GCMMA method in COMSOL Multiphysics

$$\text{minimize } \frac{1}{A_\Omega}\int_\Omega \rho(\boldsymbol{x})\, d\Omega, \qquad (7)$$
$$\text{s.t. } W_{s,tot} \leq W_{s,max}$$
$$0 \leq \rho \leq 1,$$

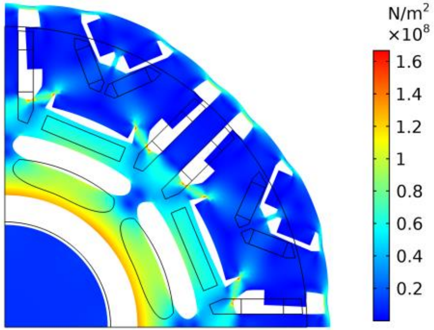


Model geometry, TO space in yellow

TO result



Magnetic flux density (T)



Von Mises stress (N/m^2)

SOMA – Lightweight Solutions for E-Mobility by AM of Soft Magnetic Alloys

Challenge:

- E-mobility needs more optimized electromechanical devices with enhanced performance, lower material consumption and life cycle cost. This demand is pushing the manufacturers and research community to explore nonconventional designs and manufacturing methods. Additive manufacturing (AM) technologies are opening up new possibilities for realizing novel magnetic circuit designs.

Objective:

- By tailoring material compositions together with optimized processing parameters and particularly, with post-treatments, high performance soft magnetic components can be manufactured by laser powder bed fusion (L-PBF). Further, it has been shown that through topology optimization, the weight of an electrical machine can be decreased significantly without compromising the other key characteristics.
- Electrical machine (EM) and drive industry, with a value of 6.3 B€ in Europe, is among potential end-users.

Solution: Designing materials solutions

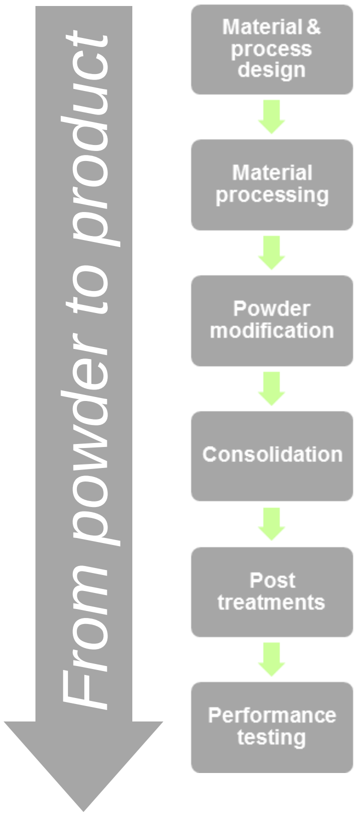
- Upscale soft magnetic alloys tailored for additive manufacturing with minimized amount of critical raw materials.
- Demonstrate a manufacturing route where the restrictions of conventional manufacturing methods do not apply enabling groundbreaking changes in designs and consequently leading to lightweight and material efficient solutions for, e.g., future e-mobility.

Duration: 1.1.2021-31.12.2024

Funding: EIT Raw Materials

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

SOMA approach



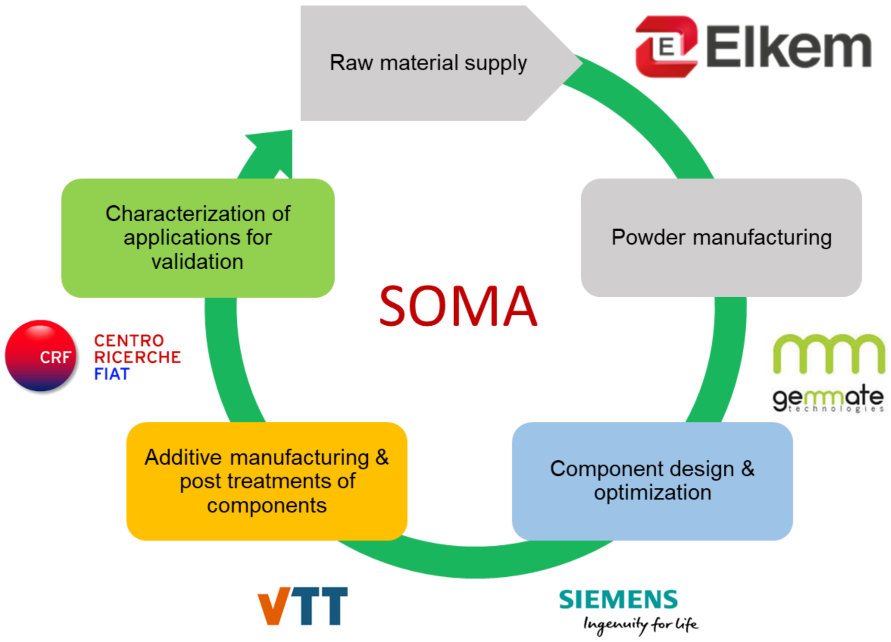


Figure 8. Value chain of the SOMA project.

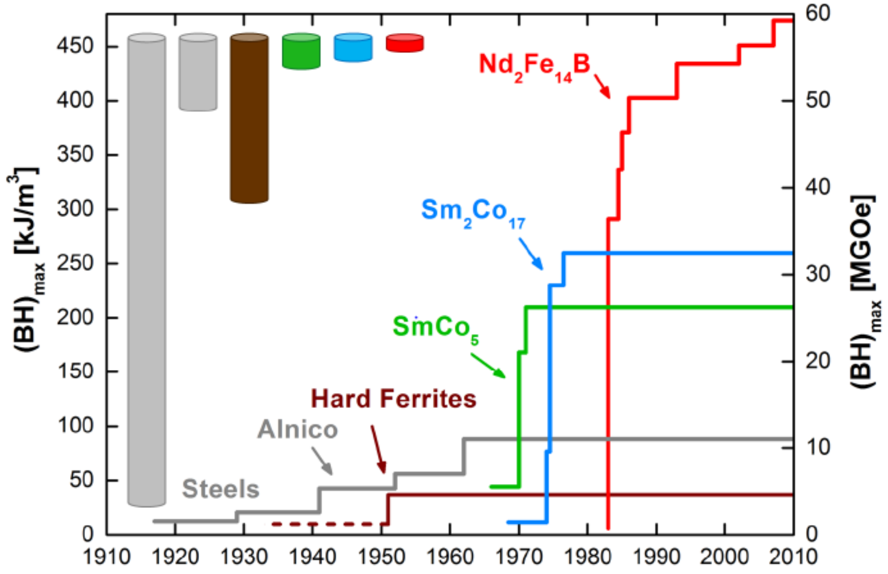
3DREMAG – 3D printing of rare-earth permanent magnets

https://3dremag.eu

Background

- Nd-Fe-B based permanent magnets have highest energy product at room temp.

- Conventional manufacturing
  - Fully dense sintered blocks, machined to dimensions → limited geometries, waste
  - Polymer-bonded injection moulded magnets → poor properties, expensive mold

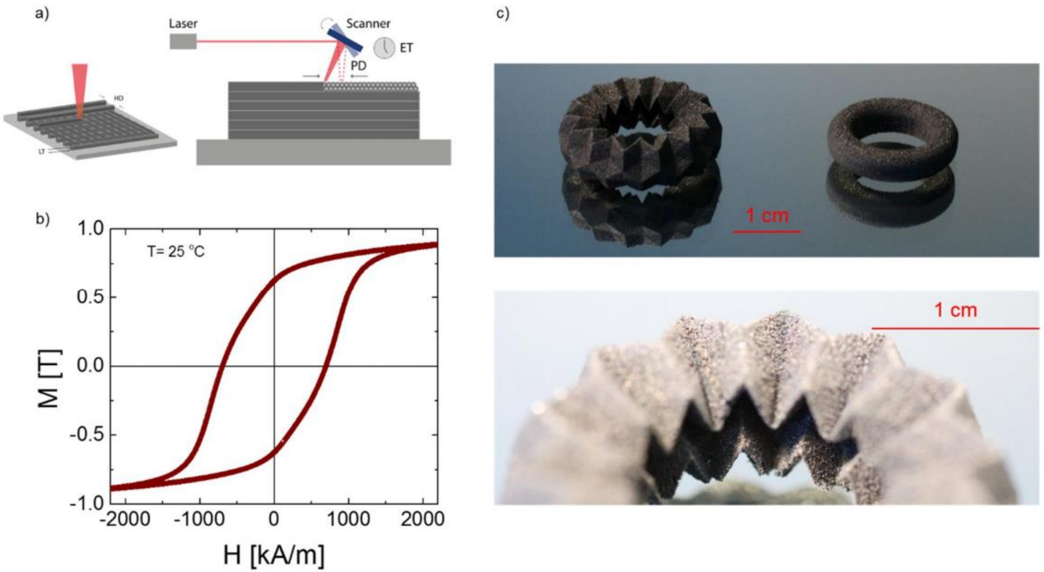


O. Gutfleisch, M.A. Willard, E. Brück, C.H. Chen, S.G. Sankar, J.P. Liu, Magnetic Materials and Devices for the 21st Century: Stronger, Lighter, and More Energy Efficient, Advanced Materials 23, 2011, 821-842

Background

- AM of Nd-Fe-B has the potential to make fully dense, net-shape magnets [1]

- Performance is limited by an absence of suitable high-grade Nd-Fe-B based powder material for AM [2]
  - L-PBF ~800 kA/m, 0.65 T
  - Sintered high Br grade ~ 1000 kA/m, 1.4 T [3]
  - Sintered high Hc grade ~ 3000 kA/m, 1.0 T [3]



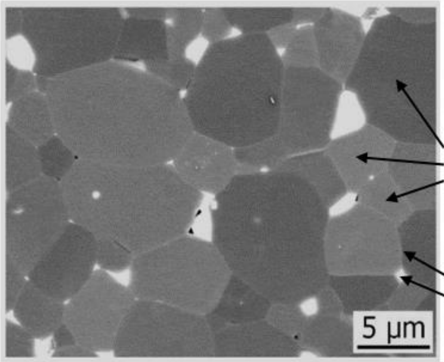
[2] Skalon, M.; Görtler, M.; Meier, B.; Arneitz, S.; Urban, N.; Mitsche, S.; Huber, C.; Franke, J.; Sommitsch, C. Influence of Melt-Pool Stability in 3D Printing of NdFeB Magnets on Density and Magnetic Properties. Materials 2020, 13, 139. https://doi.org/10.3390/ma13010139

[3] https://neorem.fi/permanent-magnets/

[1] J. Jaćimović, F. Binda, L.G. Herrmann, F. Greuter, J. Genta, M. Calvo, T. Tomše, R.A. Simon Net shape 3D printed NdFeB permanent magnet. Adv. Eng. Mater., 19 (2017), pp. 1-7, 10.1002/adem.201700098

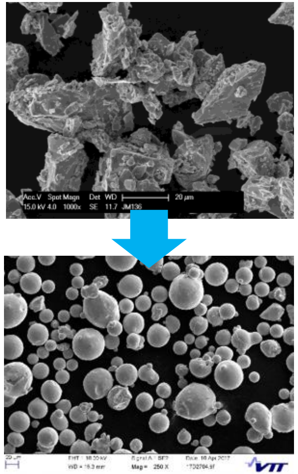
Challenge

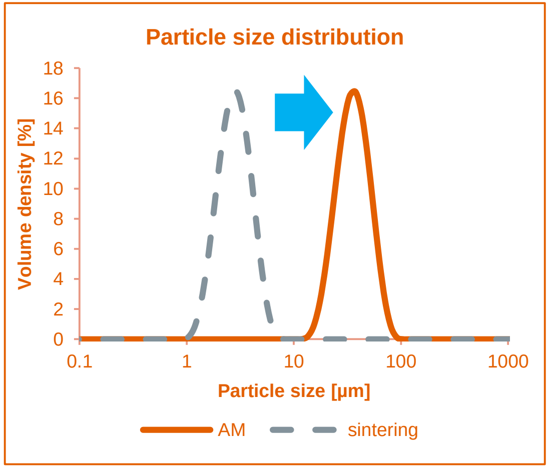
- Specific microstructure (magnet)
- Specific particle shape & size (powder)



1) K. Löwe, D. Benke, C. Kübel, T. Lienig, K. Skokov und O. Gutfleisch, Acta Materialia, Bd. 124, p. 421, 2017.

- Low oxygen content
- High density
- No cracking (brittle material)
- Magnetic alignment





3DREMAG – 3D printing of rare-earth permanent magnets

Need

- Rare-earth (RE) permanent magnets (such as NdFeB) are key for high power density e-drives needed in future mobility
- NdFeB magnets contain ~30 wt-% of Nd and Dy, both classified as critical raw materials (CRMs) by the EU. Heavy reliance on CRMs is a cost, availability and sustainability issue
- The available NdFeB powders used in polymer-bonded or sintered magnets are not designed for use in 3D printing

Approach

- 3DREMAG aims to up-scale and introduce to the market a 3D printable NdFeB powder

Benefit

- 3D printing allows near-net-shape manufacturing of magnets in complex shapes
- avoiding waste during magnet manufacturing
- enabling optimized magnet configurations for e-drives needed in future mobility applications
- reduced use of CRMs

Duration: 1.1.2020-31.12.2021

Funding: EIT Raw Materials

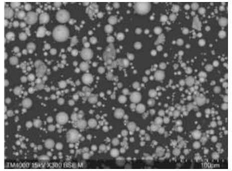
This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

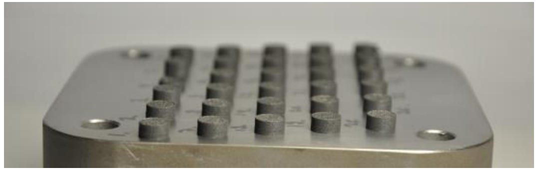
3DREMAG approach

NdFeB 3D-printed magnet process chain

- Strip casting
- Hydrogenation and Milling
- Plasma spheroidization
- Laser Powder Bed Fusion
- Post Processing
- Part Characterization

Life Cycle Assessment





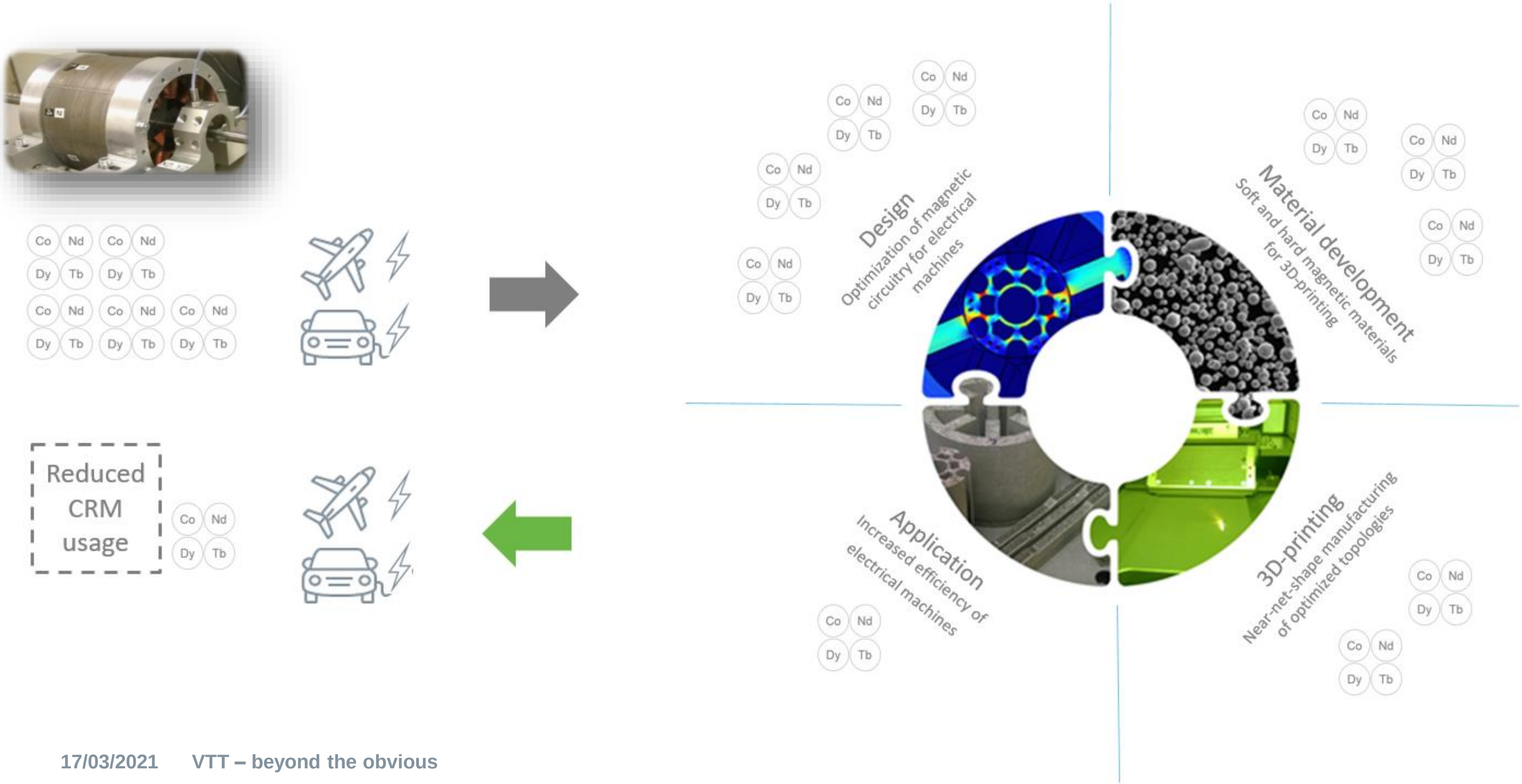
2021

Powder optimization	L-PBF optimization	Alloy & HT optimization
(PSD, morphology)	(density, mech. prop)	(magnetic properties)

Summary

Vision: 3D-printed electrical machines

VTT



Conclusions

- Solid foundation established and great opportunities identified in additive manufacturing of magnetic materials for electrical machines
- Further research needed (on-going in 3DREMAG & SOMA) to meet and exceed properties of conventional soft & hard magnetic materials & components
- Material development + design optimization + net-shape additive manufacturing = significant potential to reduce use of critical raw materials (Nd,Dy,Co,Cu) in electrical machines

References

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beyond
the obvious

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www.vtt.fi
www.vttresearch.com/3d-printing/

17/03/2021