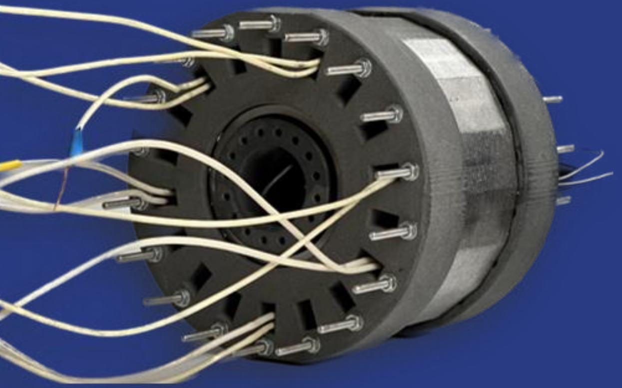
Topological optimization of electric motors



Jan Kaska 2025

FACULTY OF ELECTRICAL ENGINEERING
UNIVERSITY OF WEST BOHEMIA

Additive manufacturing is not just prototyping

Additive manufacturing is not just prototyping

Companies using printers for the production of final parts*

2017: 27 %

2021: 62 %

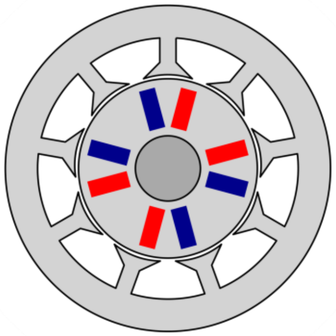
ISO / ASTM standardization

* Jabil, d. r. *3D PRINTING TECHNOLOGY TRENDS, A Survey of Additive Manufacturing Decision-Makers*, MARCH 2021

1

Ways to use AM in electric machines

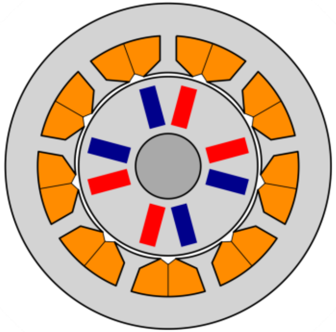
Ways to use AM in electric machines



➔ **Magnetic cores**

→ Soft magnetic materials (guiding the magnetic flux)

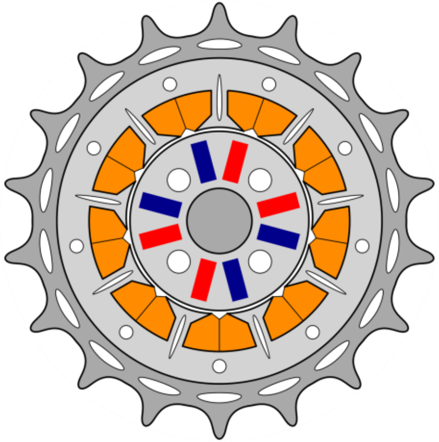
→ Hard magnetic materials (permanent magnets)



Ways to use AM in electric machines

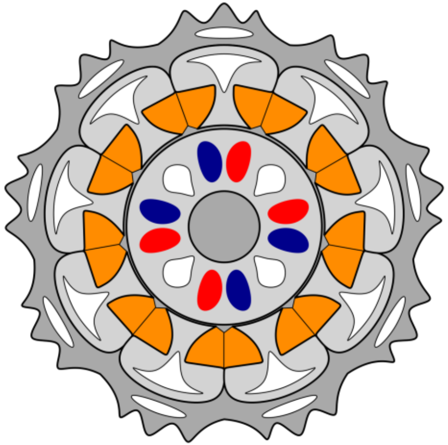
- ➔ **Magnetic cores**
  - → Soft magnetic materials (guiding the magnetic flux)
  - → Hard magnetic materials (permanent magnets)
- ➔ **Windings**
  - → Electrically conductive materials
  - → Electrically insulating materials

Ways to use AM in electric machines



- ➔ **Magnetic cores**
  - → Soft magnetic materials (guiding the magnetic flux)
  - → Hard magnetic materials (permanent magnets)
- ➔ **Windings**
  - → Electrically conductive materials
  - → Electrically insulating materials
- ➔ **Machine frames and cooling**
  - → Structural materials
  - → Thermally conductive materials

Ways to use AM in electric machines



- ➔ **What AM brings?**
  - → New machines topologies
  - → Complex magnetic flux routes
  - → Geometries with inner channels
  - → Merging multiple parts into one
  - → Functional anisotropy

Metal AM technologies

2

Metal AM technologies

➔ **Powder Bed Fusion**
→ Most common technology (54 % of AM market 2019)*
→ Powder + Laser / Electron beam

* Cherdo, L. Metal 3D printers in 2021: a comprehensive guide. https://www.aniwaa.com/buyers-guide/3d-printers/best-metal-3d-printer/.

Metal AM technologies

➔ **Powder Bed Fusion**
→ Most common technology (54 % of AM market 2019)*
→ Powder + Laser / Electron beam

➔ **Binder Jetting**
→ Powder + Binder + Sintering

* Cherdo, L. Metal 3D printers in 2021: a comprehensive guide. https://www.aniwaa.com/buyers-guide/3d-printers/best-metal-3d-printer/.

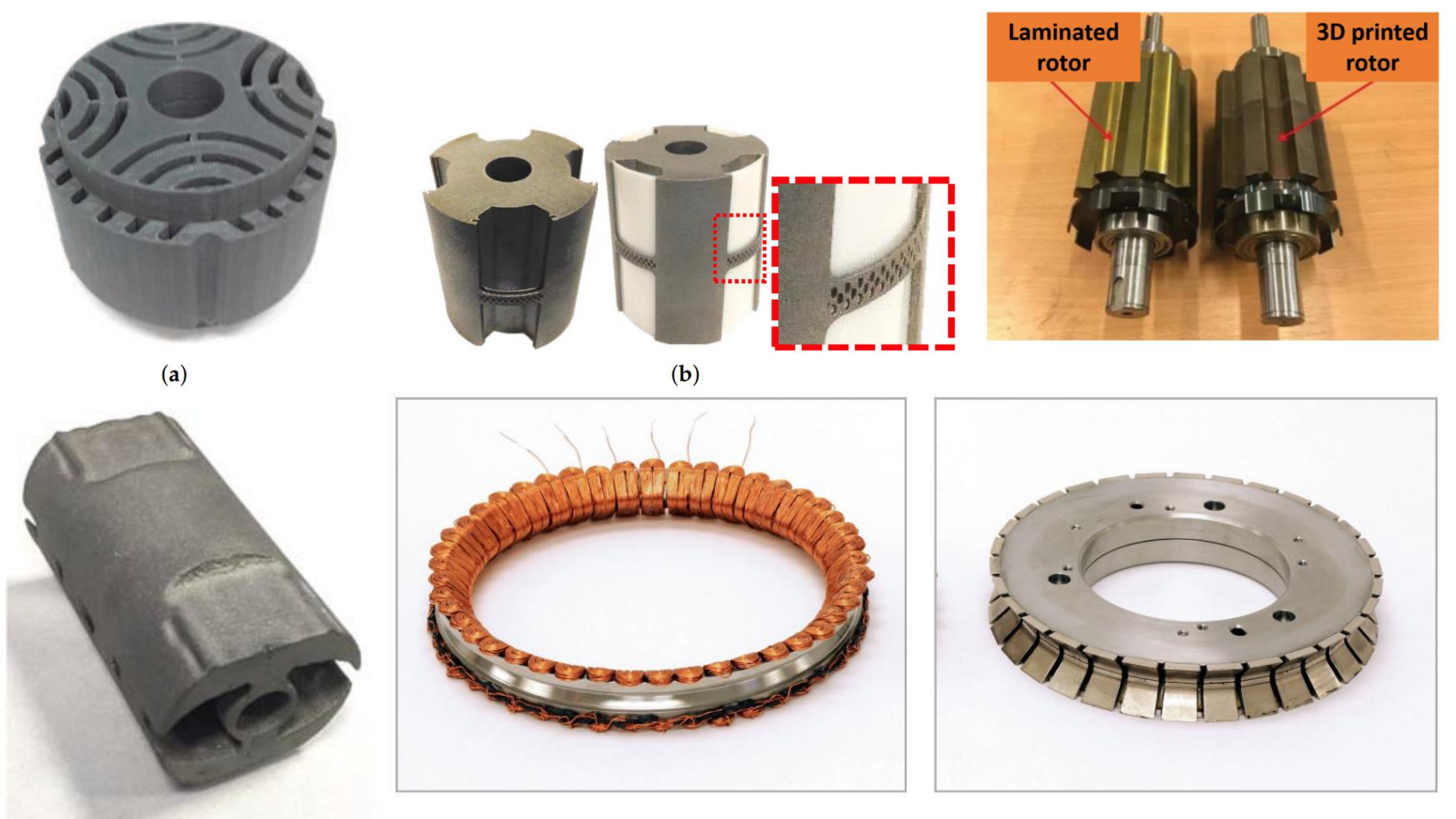
Metal AM technologies

- ➔ **Powder Bed Fusion**
  → Most common technology (54 % of AM market 2019)*
  → Powder + Laser / Electron beam
- ➔ **Binder Jetting**
  → Powder + Binder + Sintering
- ➔ **Directed Energy Deposition**
  → Lower accuracy, part of CNC systems

* Cherdo, L. Metal 3D printers in 2021: a comprehensive guide. https://www.aniwaa.com/buyers-guide/3d-printers/best-metal-3d-printer/.

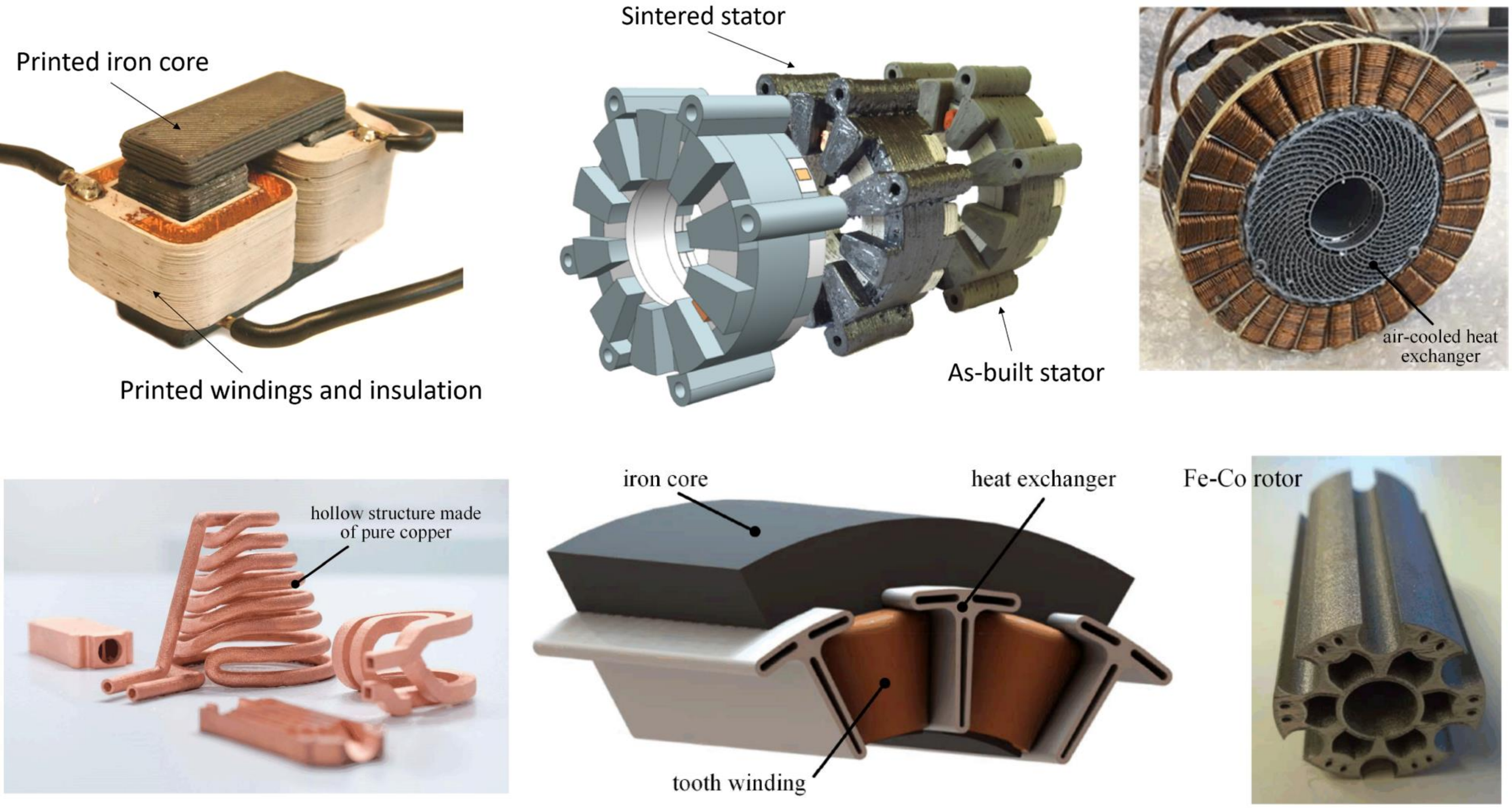
3

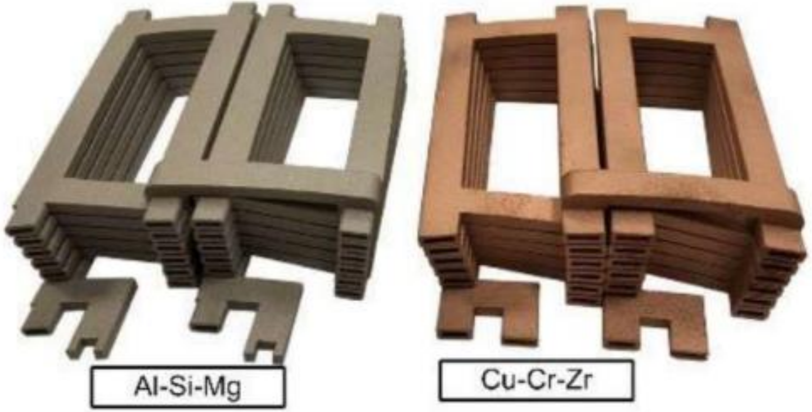
State of the art



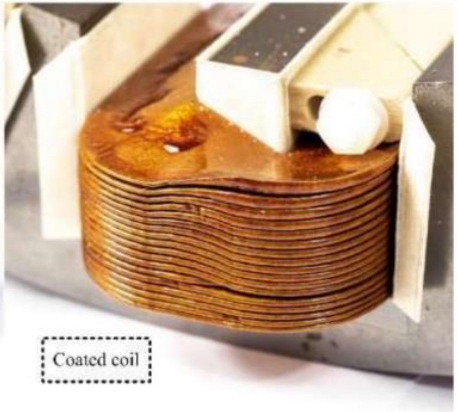
(a)

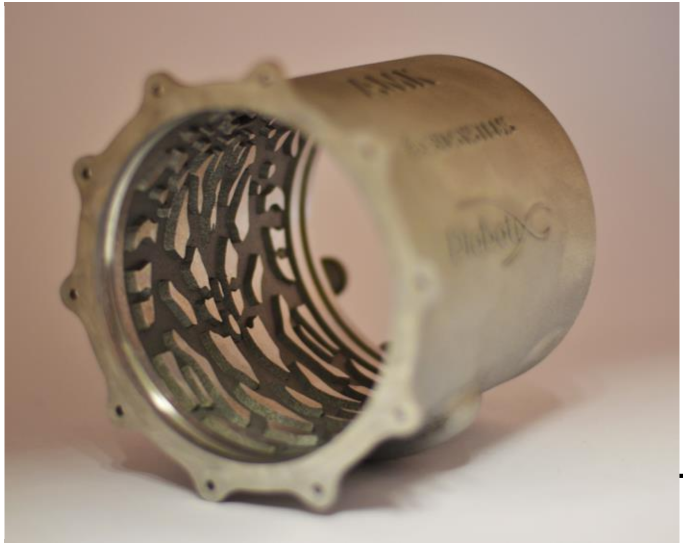
(b)


Printed iron core
Printed windings and insulation
Sintered stator
As-built stator
air-cooled heat exchanger
hollow structure made of pure copper
iron core
heat exchanger
tooth winding
Fe-Co rotor


Al-Si-Mg
Cu-Cr-Zr


Cu-Cr-Zr


Coated coil



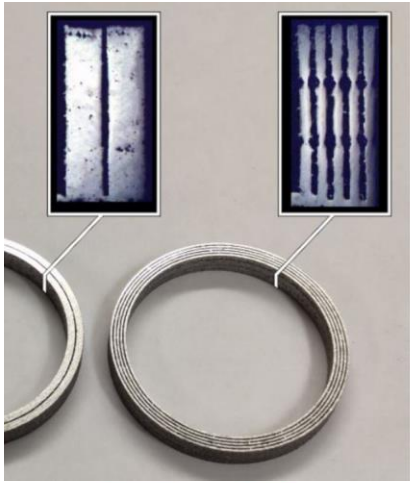
State of the art

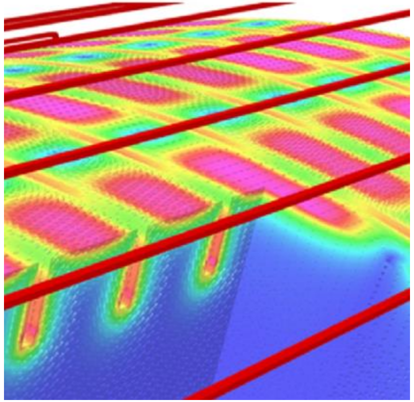
➔ **Powder Bed Fusion**
→ Most widespread technology

State of the art

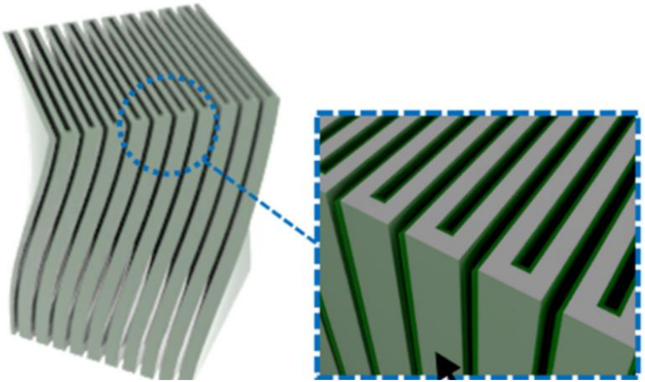
- ➔ **Powder Bed Fusion**
  → Most widespread technology
- ➔ **Magnetic cores**
  → The materials have the required properties
  → ***Little use of optimization techniques***
  → ***Insufficient iron loss reduction***

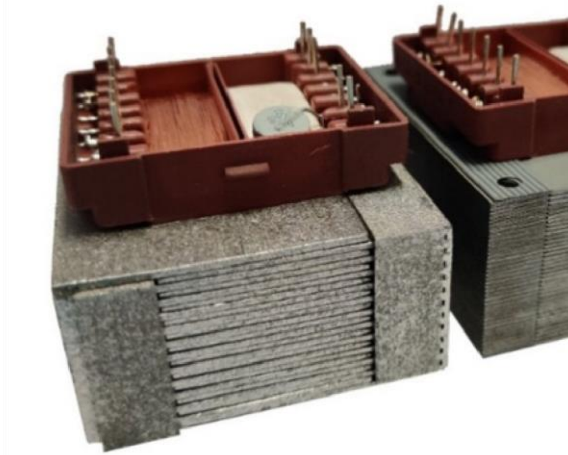
State of the art / Iron loss reduction





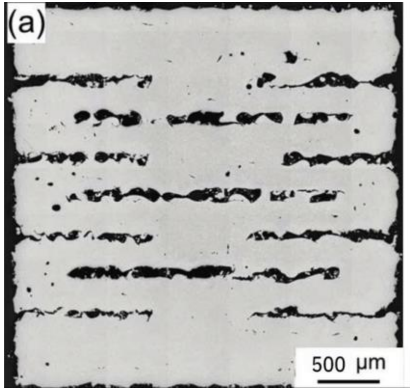
- → **Grooves / Slots**
  → Problem of minimum gap width and wall thickness



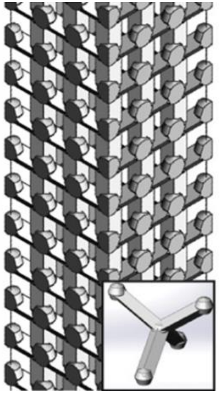


* Tiismus, H. et al. AC magnetic loss reduction of SLM processed Fe-Si for additive manufacturing (...). Energies. 2021, 14, 5, s. 1241.
** Urbanek, S. – Ponick, B. Surface eddy current loss reduction (...). In 2018 XIII ICEM, s. 1317–1322. IEEE, 2018.

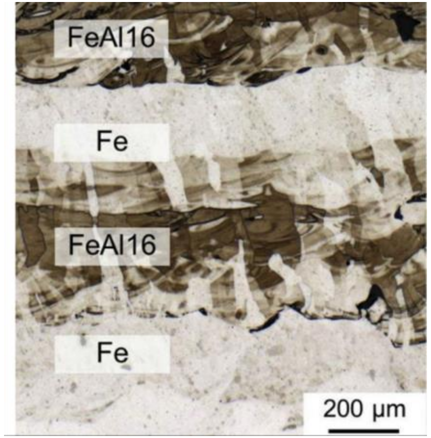
State of the art / Iron loss reduction



- ➔ **Grooves / Slots**
  → Problem of minimum gap width and wall thickness
- ➔ **Inner structures**
  → Hard to pour out the remaining powder

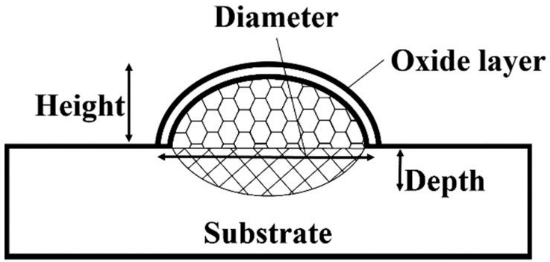


* Plotkowski, A. et al. Influence of scan pattern and geometry on the microstructure (...). Additive Manufacturing. 2019, 29, s. 100781
** Goll, D. et al. Additive manufacturing of soft magnetic materials and components. Additive Manufacturing. 2019, 27, s. 428–439



State of the art / Iron loss reduction

- ➔ **Grooves / Slots**
  → Problem of minimum gap width and wall thickness
- ➔ **Inner structures**
  → Hard to pour out the remaining powder
- ➔ **Multimaterial printing**
  → Low technology availability
  → Combinable metals have similar properties

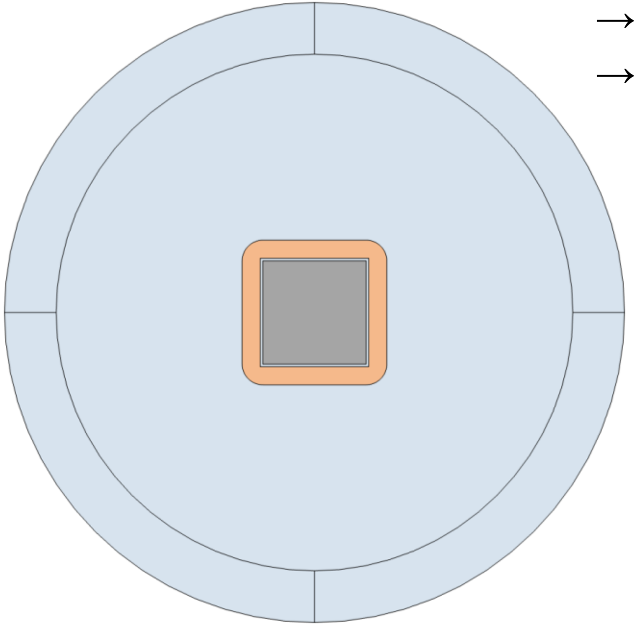


* Goll, D. et al. Additive manufacturing of soft magnetic materials and components. Additive Manufacturing. 2019, 27, s. 428–439.
** Jhong, K.-J. et al. Characteristic of high frequency Fe-Si-Cr material for motor application by selective laser melting. AIP Advances. 2019, 9, 3.

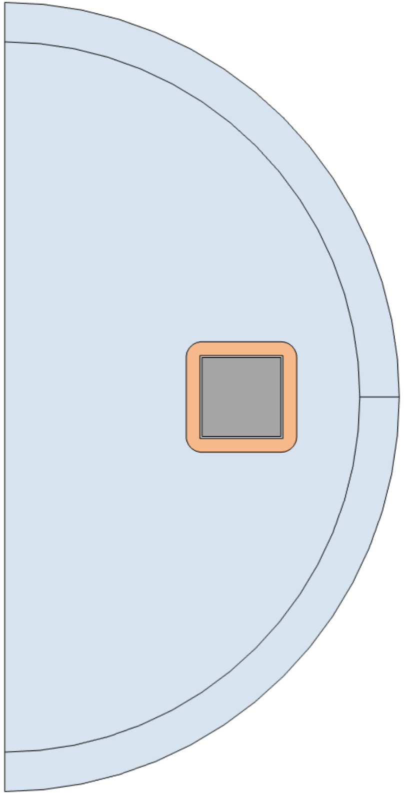
4

Topologically optimized inner structures

Topologically optimized inner structures



- **Two optimized geometries**
  → Toroidal core
  → Symmetrical rectangle

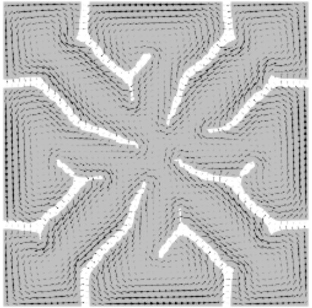


Topologically optimized inner structures

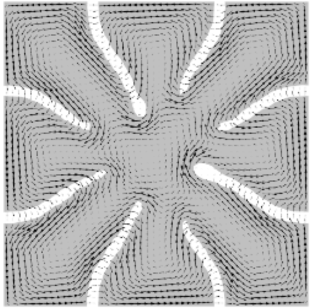
Setup	Linearity	Frequency	Objective	Initial cond.	Constraint	Exponents
1	Linear	25, 50, 100, 250	P	1	> 0.9	Manual
2	Linear	25, 50, 100, 250	P	1	> 0.9	Automatic
3	Linear	25	P	1	> 0.9	Manual
4	Linear	50	P	1	> 0.9	Manual
5	Linear	250	P	1	> 0.9	Manual
6	Linear	25, 50, 100, 250	P	1	> 0.8	Manual
7	Linear	25, 50, 100, 250	P	1	> 0.95	Manual
8	Linear	25, 50, 100, 250	P, ϕ	1	-	Manual
9	Linear	25, 50, 100, 250	P, 2ϕ	1	-	Manual
10	Linear	25, 50, 100, 250	P, 4ϕ	1	-	Manual
11	Linear	25, 50, 100, 250	P/f	1	> 0.9	Manual
12	Linear	25, 50, 100, 250	P	Stripes	> 0.5	Manual†
13	Nonlinear 1*	25, 50, 100, 250	P	1	> 0.9	Manual
14	Nonlinear 2**	25, 50, 100, 250	P	1	> 0.9	Manual

* MS1 BH curve, ** FeSi BH curve, † Previous step was used

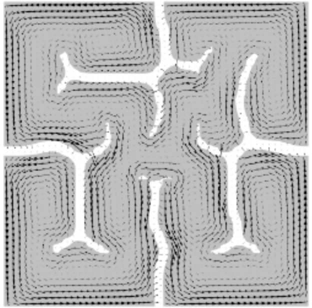
Topologically optimized inner structures



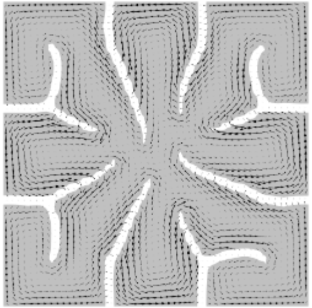
1



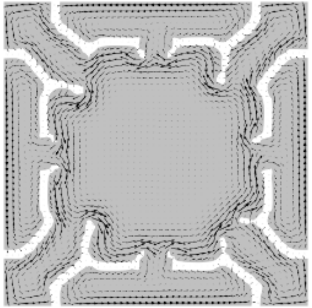
2



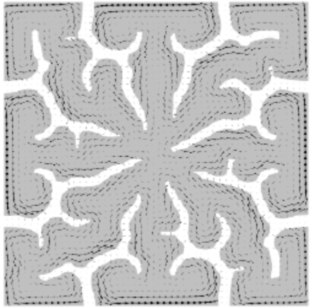
3



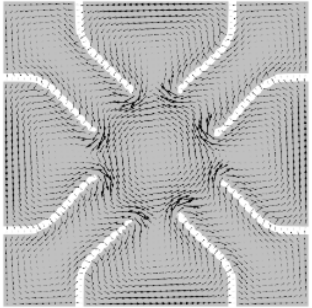
4



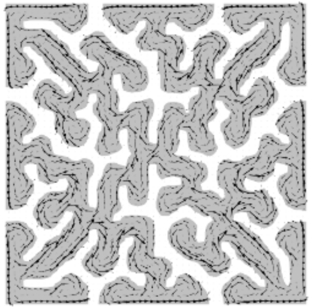
5



6

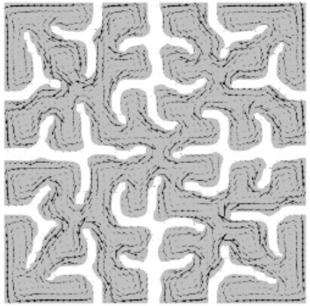


7

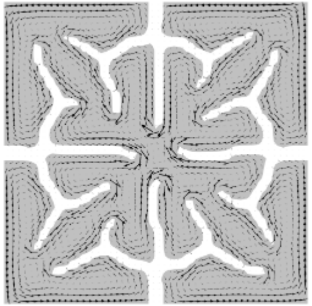


8

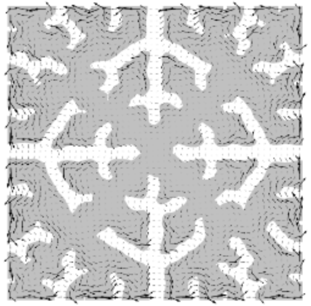
Topologically optimized inner structures



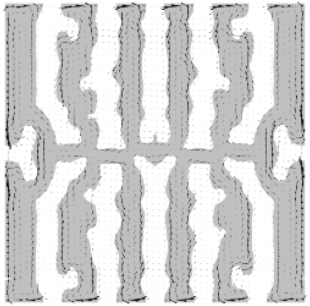
9



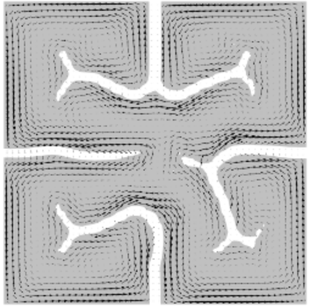
10



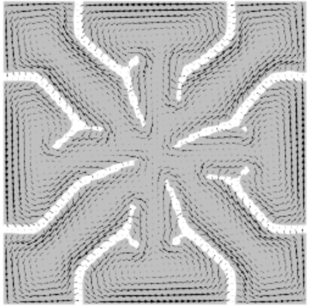
11



12



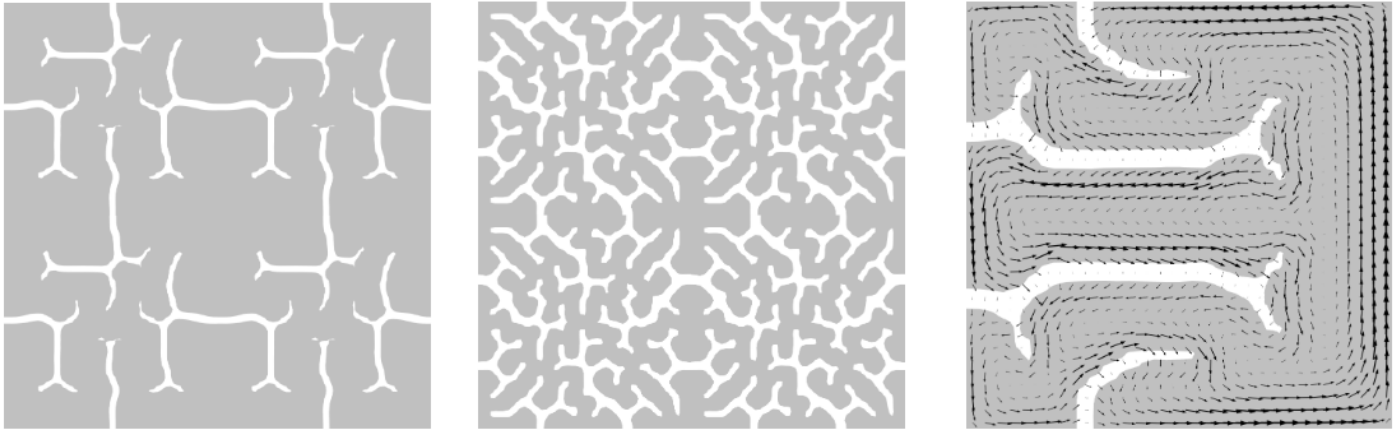
13



14

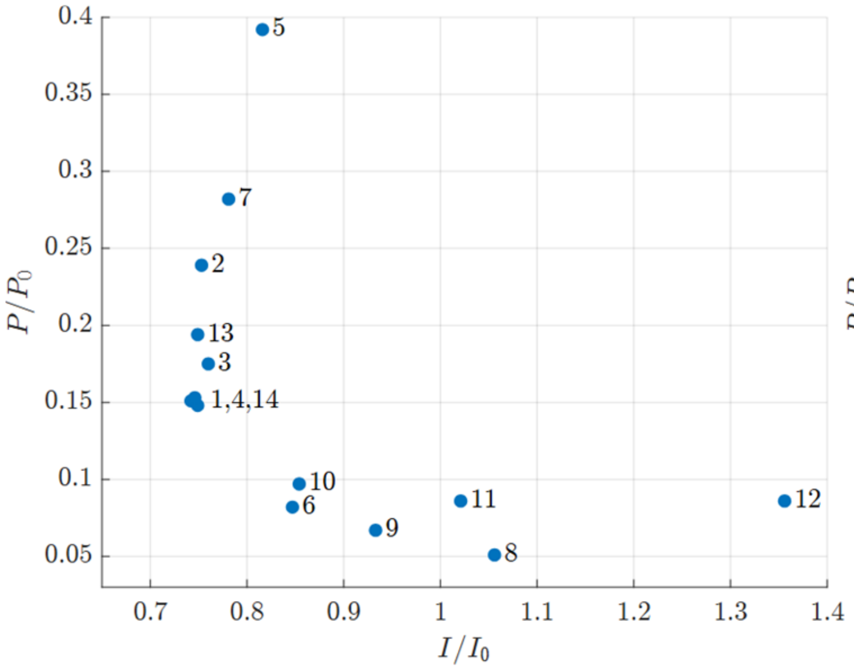
Topologically optimized inner structures

➔ **Resulting structures can be tiled**

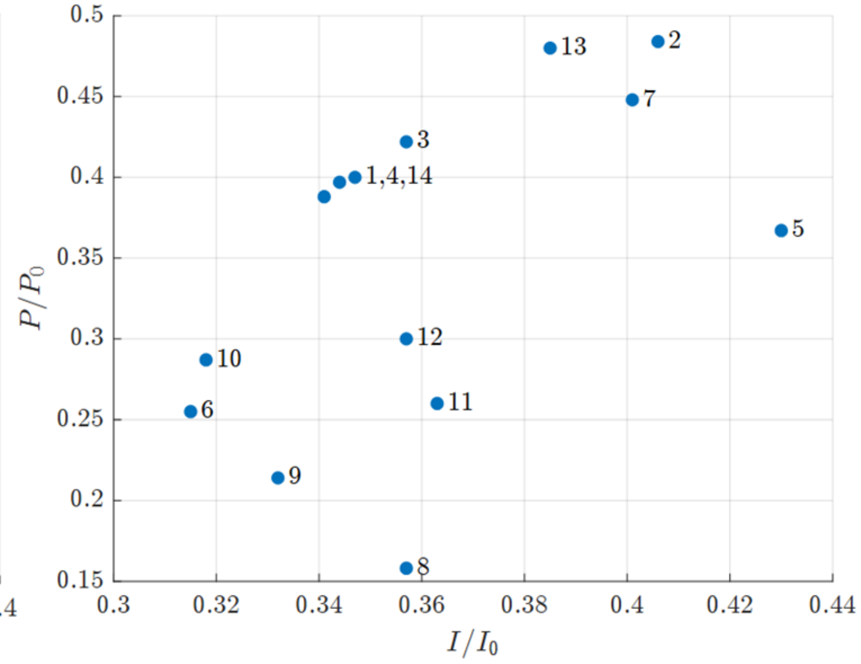


(a) Tiled setup 3 (b) Tiled setup 8 (c) Asymmetrical result

Topologically optimized inner structures



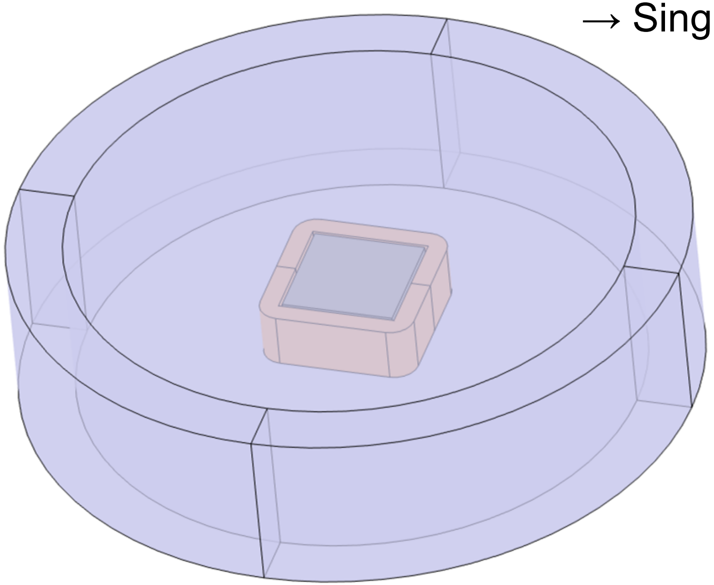
$f = 50$ Hz

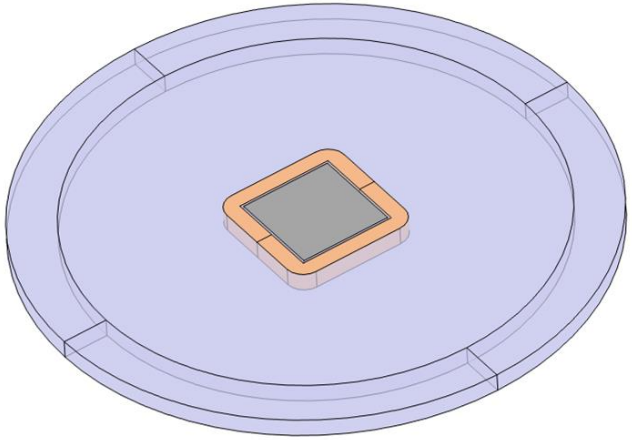


$f = 500$ Hz

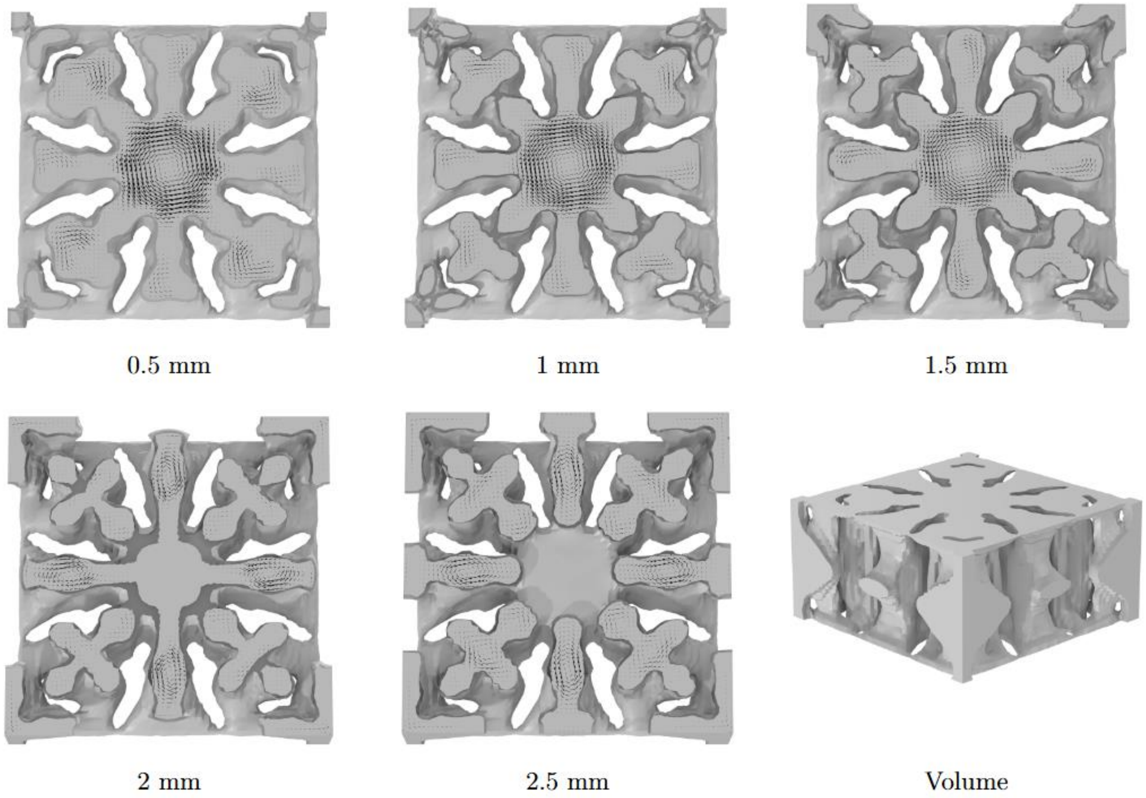
Topologically optimized inner structures

➔ **3D geometry**
→ Boundary conditions can’t be periodic
→ Single frequency, linear material





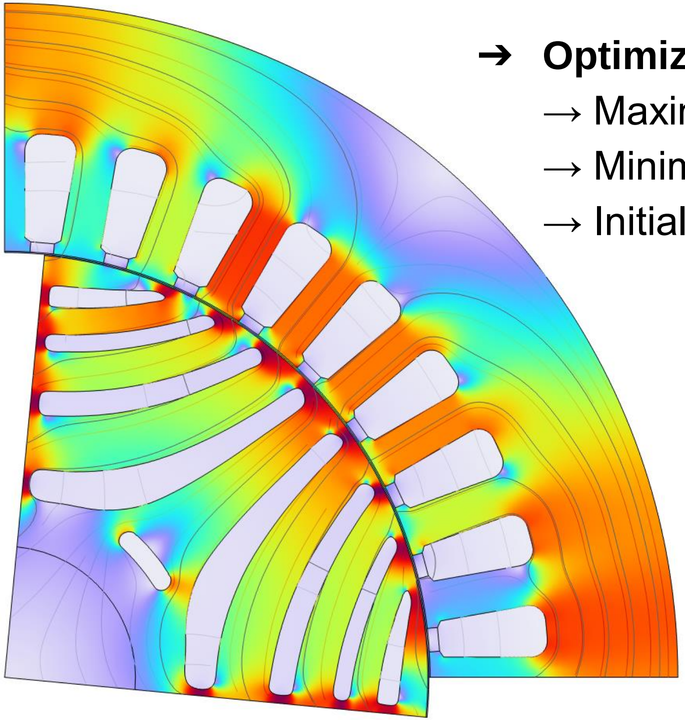
Topologically optimized inner structures



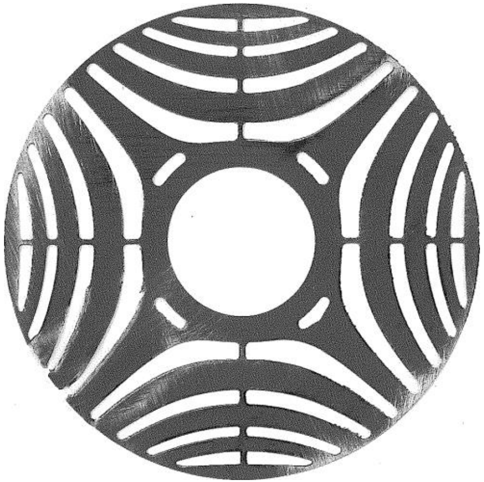
5

Topologically optimized reluctance rotor

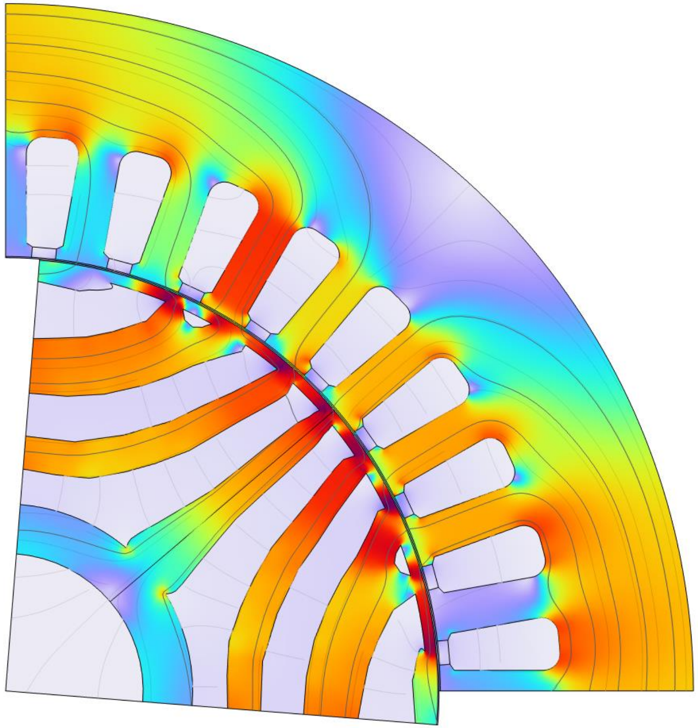
Topologically optimized reluctance rotor

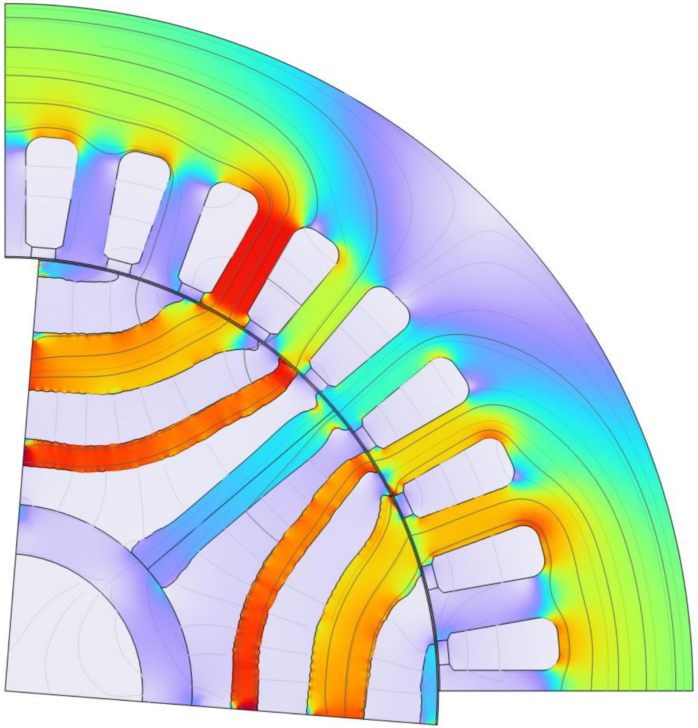


- ➔ **Optimization of AM rotor**
  → Maximization of torque
  → Minimization of torque ripple
  → Initial condition: Original geometry

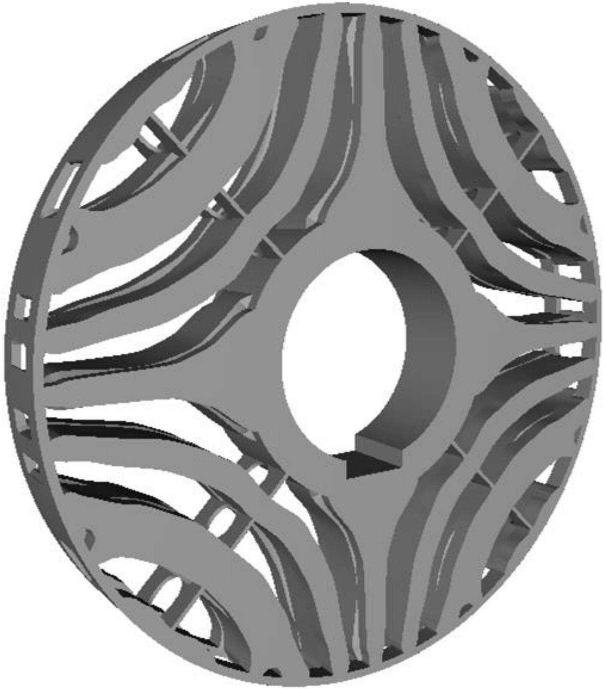


Topologically optimized reluctance rotor





Topologically optimized reluctance rotor



Thank you. Questions?