Manufacturing of topology optimized soft magnetic core through 3D printing

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Motivation

• Electrical machines are becoming more and more engineered and their application areas wider, e.g. in vehicle propulsion.

• Traditional manufacturing methods are well established and cost-effective but, on the other hand, partly limit the design choices and may hinder further development.
Hypothesis

• Through powerful design tools and additive manufacturing, the shapes, volumes, mass and materials of the machines could be comprehensively optimized, the potential impacts of which are 1) improved performance and 2) decreased material consumption and costs.
Objectives

- Our main objectives are to explore
  1) How suitable materials of soft magnetic cores are for selective laser melting.
  2) How well the characteristics of the printed parts meet the requirements of modern electrical machines.
  3) The potential of 3D printing in manufacturing of complex shaped electrical machine parts.

How about we print the soft magnetic cores?
Our test samples were prepared by selective laser melting (SLM). In SLM powder bed process, the objects are formulated by melting powder particles together layer by layer.

Almost any material that can be welded is suitable for this process.

Supply of suitable commercial powder materials is currently limited but growing all the time.

**SLM®125HL**

- Powder bed fusion technology
- Maximum build size: 125 mm x 125 mm x 125 mm
- Optimal for material development and testing
- Materials: e.g. stainless steels, tool steels, Inconel, cobalt-chromium, aluminium, titanium
- Laser: 400 W IPG fibre laser
- Manufacturing parameters adjustable
Gas atomization of powder

- Fe-Co materials exhibit the highest known saturation magnetic flux density.
- Gas atomized Fe-Co powder was prepared at VTT.
- In order to ensure good flowability of powder, the particle size distribution should be between certain values. The maximum particle size of powder is commensurate to layer thickness. In our case, the maximum size of the particles was 63 µm.
Design

• Lee et al. studied the minimisation of the torque ripple and mass of the rotor of a switched reluctance machine through topology optimization (Lee et al. 2010).

• The final design is rather different from that of a typical switched reluctance machine.

• The design of the soft magnetic cores that were studied in this work was adapted from (Lee et al. 2010).

Results

• Suitable printer parameters for processing Fe-Co powder were first searched based on the literature and practical test.  
  – The aim here was to maximise the density of the parts.

• Besides the topology optimized rotors of a switched reluctance machine, various test specimens for the magnetic, electrical, mechanical and structural characterisation were prepared.

Test specimens for, e.g., tensile stress experiments.

3D printed rotor for a switched reluctance machine. Outer dimensions of the rotor are approximately 3 cm x 4.5 cm.
Results: Volumetric mass density

- Based on the analysis of the microstructure, the relative volumetric mass density of the printed samples is at most >99.9% which is a very good result.
- The printer parameters have a significant impact on the volumetric mass density the range of which was found to be 90.0->99.9%.

Image-based definition of the density of the samples.
Results: Mechanical properties

• Results from tensile tests

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Offset Yield Strength (0.2%) (MPa)</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Elongation at break, A (%)</th>
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<tr>
<td>3</td>
<td>523</td>
<td>643</td>
<td>31</td>
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<tr>
<td>4*</td>
<td>525</td>
<td>593</td>
<td>4.3</td>
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<tr>
<td>5</td>
<td>519</td>
<td>632</td>
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</tbody>
</table>

*small elongation value is probably a result of internal defects

Stress-strain curve of tensile test sample No. 5
Results: Electromagnetic properties

- Magnetic characteristics are promising, saturation flux density ~2.3 T
  - Further analysis in works
- Resistivity ~52 µohm/cm
  - Optimally, the resistivity should be higher to mitigate the losses.
Summary

• The results that we have obtained are promising, i.e. the key characteristics mainly fulfil the requirements of commercial electrical machines.

• Further work includes:
  1) Comparison between different powder compounds
  2) Topology optimization
  3) Building and testing a machine with 3D printed cores
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Thank you for your attention
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