Simulation of magnetic coatings on textile fibers

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Abstract. While the properties of conductive fibres and coatings on textiles can easily be measured and calculated, magnetic coatings of fibres, yarns and fabrics still lack descriptions of their physical properties. Since magnetic textiles can be used for a variety of applications, from magnetic filters to invisible water-marks to magnetic coils and sensors, simulations would be supportive to understand and utilize their properties. The article gives an overview of different coatings on textile fibres, varying the magnetic materials as well as the fibre composition, giving rise to the interactions between neighbouring coated fibres. In this way, it is possible to understand the strong shape anisotropy which must be taken into account when the magnetic properties of textiles are to be tailored. Additionally, the differences between several possible magnetic coating materials become visible. This study can help adjusting the magnetic properties of textile fabrics to a desired application.

1. Introduction
In the area of smart textiles, conductive properties of fibres, yarns, and fabrics are being investigated intensively in simulation and experiment. Theoretical examinations of magnetic textiles, however, are scarce. Only few articles report on modelling magnetic cores of textile coils [1] or magnetic microfibers [2,3].

This is especially unsatisfactory since several applications can be imagined which are based on the magnetic properties of textiles, necessitating a deeper insight into the behaviour of intrinsically magnetic fibres or magnetic coatings on fibres and textile fabrics.

Magnetic coatings can, e.g., be used to change other properties of a finishing layer. Magnetic nanoparticles with hydrophobic properties can become superhydrophobic when coated in an external magnetic field. For this experiment, Fe₃O₄ (magnetite) nanoparticles were coated with a fluoroalkyl silica layer, resulting in significantly increased contact angles for field coating, which was attributed to the formation of nano- and microstructured surface features [4]. Alternatively, maghemite or magnetite particles were introduced into a polysiloxane matrix to produce similar switchable magnetic properties [5].

Applying a magnetic field after the coating process can change the hydrophobic properties, such as contact angle and roll-off angle, to enable cleaning of hydrophobic surfaces [6,7]. This effect was attributed to an increase in the surface roughness.

Magnetic fields can also be used to change other properties of textiles containing magnetic particles. Magneto-rheological fluids can, e.g., be integrated in spacer fabrics to produce composites which an external magnetic field can harden [8]. The optical properties of a textile can be modified by...
an external magnetic field if structural colours are formed by magnetic nano-structures, e.g. for utilization as pixels in a colour-changing pattern [9].

Measuring magnetic properties of textiles can be used, e.g., for magnetic ink in order to overcome the low efficiency of artificial eyes [10] or for brand protection [11].

Several other applications exist in the area of smart textiles, such as magnetic coils for sensors and actuators [12,13], shielding of static magnetic fields [14], magnetic stimulus in shape memory polymers [15,16], textile whiteboards [17], textile antennae with artificial magnetic conductor planes [18,19], making medical implants visible by included superparamagnetic nanoparticles, [20], etc.

Due to the lack of simulations in this area and the large number of possible applications, this article depicts the influences of the magnetic materials chosen for fibre coating as well as the interdependence between neighbouring fibres with magnetic coating.

2. Methods
Round geometries, such as fibre coatings, can be modelled better by Magpar which is based on the finite element method [21] than by OOMMF [22] or similar programs which use finite differences. Using finite tetrahedral elements with dimensions of maximum 3 nm, dynamical integration of the Landau-Lifshitz-Gilbert equation of motion was used to simulate hysteresis loops.

For the comparison of different magnetic coating materials, iron (Fe) and cobalt (Co) layers on fibres with lengths 10 µm and diameters 1 µm were modelled. Single fibres as well as fibre bundles (cf. Fig. 1) were simulated. For Fe and Co, the exchange constants were chosen as $A_{Fe} = 2.0 \times 10^{-11} \text{ J/m}$ and $A_{Co} = 1.3 \times 10^{-11} \text{ J/m}$, the magnetic polarization at saturation $J_{Fe} = 2.1 \text{ T}$ and $J_{Co} = 1.76 \text{ T}$, and the Gilbert damping constant $\alpha = 0.01$.

The simulation was performed sweeping from zero external field up to +900 kA/m (with the external field in the sample plane), and back, up to -900 kA/m and to +900 kA/m again to close the hysteresis loop, using a field sweeping speed of 10 kA/(m ns).

![Figure 1](image1.png)

**Figure 1.** Geometry of simulated fibre bundle modelled with Co coating. Demagnetizing fields are imaged by material colours (left panel) and as the vector fields (right panel).

3. Results
The results of Fe single fibre and fibre bundle coatings are depicted in Fig. 2. In both cases, the maximum magnetization which is reached during the hysteresis loop is significantly decreased for angles unequal 0° (i.e. parallel to the fibre / fibre bundle), showing the strong shape anisotropy which causes the magnetization to stay in the fibre plane. For 0° orientation, the hysteresis loops for a single fibre and a whole fibre bundle are very similar; for the other angles, however, coercive fields and loop shapes differ. In all cases, the coercivities are relatively small, showing values of maximum 25 mT.

It should be mentioned, however, that modelling magnetic coatings on fibres of the dimensions used here show relatively smooth hysteresis loops with irreversible parts (i.e. an open loop) even in case of 90°, which has been shown to be significantly different in smaller fibres with identical aspect ratio of 1:10 [3].
Figure 2. Hysteresis loops, simulated for a single Fe coated fibre (left panel) or an Fe coated fibre bundle (right panel) of fibre lengths 10 µm and diameters 1 µm.

Fig. 3 depicts the identical geometries, modelled for a Co coating on single fibres and fibre bundles. Obviously, the hysteresis loop is in all cases much broader than for an Fe coating. Additionally, the loop shape is more rectangular, indicating coherent rotation of all magnetic moments in the samples, as opposed to domain wall processes and other partial magnetization reversal processes.

In both the single Co coated fibre and the fibre bundle, the coercive field for a field orientation of 45° is strongly reduced. This effect, although not visible for the Fe coated fibres, is typical for orientations deviating from the easy axis. Especially in nano-systems, however, completely different angle dependencies may occur.

Figure 3. Hysteresis loops, simulated for a single Co fibre (left panel) or a Co fibre bundle (right panel) of fibre lengths 10 µm and diameters 1 µm.

It should be mentioned that the simulated geometries, while being relatively small from a textile point of view, are already quite large for micromagnetic simulations. Table 1 gives an overview of the simulation durations of the results depicted here, using a cluster with 16 cores. This shows one of the largest problems in modelling magnetic coatings on textile fabrics, yarns and fibres: While the thin coating layers necessitate micromagnetic simulations to gain reliable results, the relatively large coated areas cause large models with respectively long computation times.

Table 1. Simulation durations for the results shown in this article.

| Material | Single fibre | Fibre bundle |
|----------|--------------|--------------|
| Fe       | 4-8 days     | 24-28 days   |
| Co       | 3-9 days     | 15-31 days   |
4. Conclusion
In conclusion, we have shown the influence of material and orientation on the magnetic properties of fibre coatings, with coercivities being more than one order of magnitude larger for Co than for Fe and a strong shape anisotropy reducing out-of-plane magnetization. Especially for Co coatings, significant differences occur between single fibre and fibre bundle simulations which have to be taken into account in preparation of real magnetic textile samples.

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