Model for calculating $J(H)$ curves of Ni coated Nd-Fe-B magnets

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Abstract: An analytical model to describe the influence of the surface degradation and the Ni layer itself on the magnetic properties of Ni coated Nd-Fe-B magnets is presented. Starting from the bulk magnetic properties, the dimensions, the thickness of the Ni coating and the affected surface layer, the $J(H)$ demagnetization curve is calculated. Subsequently the expected values of $(BH)_{\text{max}}$ and the reversible permeability are deduced from the calculated $J(H)$ curves. For flat magnets the surface effects lead to a decrease of $B_r$ and an increase of the permeability which lowers $(BH)_{\text{max}}$. For strait magnets a step in the $J(H)$ curve appears at $H = 0$. The deteriorating effect of the Ni coating and the surface layer scale with the dimensions of the magnet and the thickness of these layers, which depend on the processing and the grain size of the magnet. These effects can not be neglected if one or more dimensions of a Ni coated magnet are less than about 5 mm. SmCo$_5$ magnets show similar effects but there the coercivity of the damaged surface layer is higher. Pinning type Sm$_2$Co$_{17}$ magnets show almost no deterioration of the surface due to machining. As a result, Sm-Co magnets are usually better suited for applications with dimensions smaller than about 2 mm.

Key words: Nd-Fe-B magnets, Sm-Co magnets, Ni coating, surface effects, demagnetization curves

1 Introduction

Sintered Nd-Fe-B and Sm-Co magnets show excellent hard magnetic properties. However, it is well known that the surface layer of Nd-Fe-B and SmCo$_5$ magnets have a much smaller coercivity compared to the bulk$^{[1,3]}$. The thickness of this layer is at least equal to the diameter of the grains which amounts to about 10 µm. This layer behaves almost like a soft magnetic material and therefore affects the overall magnetic properties of small magnets. In the case of Ni coated magnets this effect is even pronounced. On the one hand the Ni layer itself is softmagnetic and on the other hand several surface grain layers are damaged by hydrogen during the electrolytic coating process.

It is the aim of this paper to present an analytical model to describe the influence of the surface degradation and the Ni layer itself on the magnetic properties of small Ni coated Nd-Fe-B magnets.

2 Experimental

To verify the predictions of the analytical model, small rectangular magnets with dimensions between 0.4 and 6 mm were cut from commercial sintered Nd-Fe-B blocks with a grain size of about 5 and 8 µm, respectively. For comparison, some small magnets where cut from commercial SmCo$_5$ and Sm$_2$Co$_{17}$ magnet blocks, too.

One set of the Nd-Fe-B magnets got a surface passivation to avoid corrosion during handling. The other set was coated electrolytically with about 25 µm Ni. The thickness of the Ni coating was measured by X-ray in the center of the largest magnet face. The magnetic properties of the Ni coated magnets were measured by a vibrating sample magnetometer. The $J(H)$ curves were corrected with demagnetization factors which were calculated

<table>
<thead>
<tr>
<th>mean grain size</th>
<th>$B_r$</th>
<th>$(BH)_{\text{max}}$</th>
<th>$H_{cJ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>µm</td>
<td>T</td>
<td>kJ/m$^3$</td>
<td>kA/m</td>
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<tr>
<td>8</td>
<td>1.42</td>
<td>391</td>
<td>1270</td>
</tr>
<tr>
<td>5</td>
<td>1.39</td>
<td>365</td>
<td>1140</td>
</tr>
</tbody>
</table>
according to the formula given by Fufaev[4].

3 Model

A Ni coated Nd-Fe-B magnet consists of three material regions, s. also Fig. 1:

1. the bulk, for this region the specified properties can be expected only, e.g.:
   \[ B_r = J_{r,bulk} = 1.4 \, \text{T} \]
   \[ H_{c,bulk} = 1200 \, \text{kA/m} \]
   \[ \mu_{rev,bulk} = 1.02 \]
2. the surface region affected by machining and coating, typical thickness about 10 µm:
   \[ J_{s,surf} = J_{r,bulk} \]
   \[ H_{c,surf} < 100 \, \text{kA/m} \]
3. the Ni layer, typical thickness about 15 µm:
   \[ J_{s,\text{Ni}} = 0.61 \, \text{T} \]
   \[ H_{c,\text{Ni}} = \text{almost 0} \]

where \( \mu_{rev} \) is the reversible permeability and \( J_s \) is the saturation polarization. The used indices are defined in Table 2. To calculate the magnetic moment of such a magnet, it is necessary to evaluate the polarization of each region separately and sum up these contributions at the end.

The polarization of the bulk is given by

\[ J_{\text{bulk}} = J_{r,\text{bulk}} + (\mu_{rev} - 1)\mu_0H_{\text{bulk}} \]  \hspace{1cm} (3)

where \( H_{\text{bulk}} \) is the internal magnetic field strength:

\[ \mu_0H_{\text{bulk}} = \mu_0H_{\text{ext}} - NJ_{r,\text{bulk}} \]  \hspace{1cm} (4)

The last equation in (6) holds, because the induction must be continuous. Combining

\[ B_{\text{bulk}} = J_{r,\text{bulk}} + \mu_0H_{\text{bulk}} \]  \hspace{1cm} (7)

with equations (2) and (3) leads to the result

\[ J_{\text{Ni,pole}} = J_{r,\text{bulk}} + \frac{\mu_{rev}(\mu_0H_{\text{ext}} - NJ_{r,\text{bulk}})}{1 + (\mu_{rev} - 1)N} \]  \hspace{1cm} (8)

for \(-0.61 \, \text{T} < B_{\text{bulk}} < +0.61 \, \text{T} \) and

\[ J_{\text{surf,pole}} = J_{r,\text{bulk}} + \frac{\mu_{rev}(\mu_0H_{\text{ext}} - NJ_{r,\text{bulk}})}{1 + (\mu_{rev} - 1)N} \]  \hspace{1cm} (9)

Table 2  Nomenclature

<table>
<thead>
<tr>
<th>Index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>...-bulk</td>
<td>respective property of the bulk</td>
</tr>
<tr>
<td>...-surf</td>
<td>respective property of the affected surface layer</td>
</tr>
<tr>
<td>...-Ni</td>
<td>respective property of the Ni layer</td>
</tr>
<tr>
<td>...-pole</td>
<td>respective property of a pole face layer</td>
</tr>
<tr>
<td>...-side</td>
<td>respective property of a side face layer</td>
</tr>
</tbody>
</table>

Fig. 1  Schematic cross section of a magnetized Ni coated Nd-Fe-B magnet

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1 + (µ_{rev} – 1)N

for \(-J_{r,\text{bulk}} < B_{\text{bulk}} < +J_{r,\text{bulk}}\).

With the help of equations (3 – 5) and (8 – 9), the polarizations of the various regions can be calculated for a given magnet as a function of the external applied magnetic field. The independent parameters are the remanence of the bulk, \(J_{r,\text{bulk}}\), the reversible permeability of the bulk, \(µ_{\text{rev}}\), the external magnetic field strength, \(H_{\text{ext}}\), and the demagnetization factor of the bulk, \(N\). The total magnetic moment can finally be calculated by summing up all the contributions from the different regions:

\[ M_{\text{tot}} = \sum J_i V_i \]

(10)

The various volumes, \(V_i\), can easily be calculated from the geometry of the magnet taking into account the thickness of the surface layer and of the Ni coating. A mean polarization can be defined by dividing \(M_{\text{tot}}\) by the total volume, \(V_{\text{tot}}\), of the magnet:

\[ J_{\text{tot}} = \frac{M_{\text{tot}}}{V_{\text{tot}}} \]

(11)

4 Nd-Fe-B magnets

With the formulas derived in section 3 the expected \(J(H)\) demagnetization curves of small Ni-coated Nd-Fe-B magnets can be calculated. Fig. 2 shows the measured and calculated demagnetization curves of uncoated and Ni-coated Nd-Fe-B magnets with a mean grain size of about 8 µm.

For the uncoated large magnets, where all dimensions are larger than 2 mm, the demagnetization curves are almost identical to the curves of the bulk samples. But the demagnetization curve of the strait samples with a width of 0.4 mm show a pronounced step for demagnetizing fields less than 200 kA/m. These steps are caused by the almost soft magnetic side areas\(^{[1,2]}\). For the uncoated magnet, the height of the step can be fitted under the assumption of a thickness for the damaged surface layer of 12 µm, s. Table 3.

For the Ni-coated magnet the step is much larger compared to the uncoated one. This is because the Ni layer itself is soft magnetic and the thickness of the affected surface layer is increased by hydrogen during the initial state of the electrolytic coating process. The dashed line in the left part of Fig. 2 was calculated under the assumption of a thickness of the Ni layer of 35 µm and the damaged surface layer of 31 µm, s. Table 3. With these assumptions, the saturation magnetization, the height of the step and the permeability of the recoil curve can be well reproduced. The fitted thicknesses of the Ni layers are always somewhat larger than the values measured in the center of the large side surfaces, compare Table 3 with insets in Fig. 2 and 3. This is consistent with the fact that the thickness of electrolytic Ni coatings increases considerably at the edges of thin magnets\(^{[5]}\).

The demagnetization curves of flat magnets are less affected by surface degradation and Ni coatings, s. Fig. 2, right part. These magnets do not show a distinct step in the demagnetization curve but with increasing relative thickness of the surface layer the reversible permeability increases. The model predicts

\[ \text{Fig. 2} \quad \text{Demagnetization and recoil curves of strait (left) and flat (right) Nd-Fe-B magnets with a mean grain size of about 8 µm for various dimensions and surface treatments. The dashed curves were calculated by the model described in the text.} \]

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this behaviour satisfactorily. According to equations 8 and 9, the polarization of the pole surface layers is a function of the applied magnetic field, as long as these layers are not saturated. Because these layers have almost no coercivity, this contribution is reversible and adds to the reversible permeability of the magnet.

The magnets cut out of blocks with a mean grain size of about 5 µm show a very similar behaviour like the more coarse magnets, s. Fig. 3. However, the thicknesses of the affected surface layers are smaller and therefore the steps for the strait magnets and the reversible permeabilities for the flat magnets are smaller, s. Table 3.

For uncoated magnets, the thickness of the affected surface layer is always equivalent to about 1.5 grain layers. For strait Ni coated magnets, 3 – 4 grain layers are affected during coating, for flat Ni coated magnets even about 6 grain layers are damaged during the coating process. This anisotropy may be explained by the higher hydrogen reactivity of the pole faces of sintered Nd-Fe-B magnets compared to the side faces

The Ni-coated magnets show a clearly smaller coercivity compared to the bulk, s. Fig. 2 and 3. This decrease is much more pronounced for the flat magnets. The decrease and its anisotropy might be explained by the coercivity model from Blank who proposed that the demagnetization of sintered Nd-Fe-B magnets starts from the damaged surface layers at the pole faces.

5 Sm-Co magnets

In Fig. 4 the demagnetization curves of small commercial SmCo₅ and Sm₂Co₁₇ magnets are shown. SmCo₅ develops a similar step in the demagnetization curve like Nd-Fe-B, but the coercivity of the damaged layer is considerably higher compared to Nd-Fe-B[1-3]. As a result, tiny SmCo₅ magnets can be used in applications with demagnetizing fields up to 300 kA/m without almost any losses, irrespective of

<table>
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<th>mean grain size µm</th>
<th>dimension</th>
<th>surface layer</th>
<th>Ni layer</th>
<th>µrev</th>
<th>(BH)max</th>
<th>kJ/m³</th>
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<td>32</td>
<td>34</td>
<td>1.31</td>
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Fig. 3  Demagnetization and recoil curves of strait (left) and flat (right) Nd-Fe-B magnets with a mean grain size of about 5 µm for various dimensions and surface treatments. The dashed curves were calculated by the model described in the text.

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The best choice for micro magnets from a magnetic point of view are pinning type Sm$_2$Co$_{17}$ magnets. In these magnets, the thickness of the magnetically affected surface layers are in the order of about 100 nm and for mm-sized magnets no deterioration of the demagnetization curve can be observed at all, s. Fig. 4.

6 Conclusions

An analytical model to describe the influence of the surface degradation and the Ni layer itself on the magnetic properties of Ni coated Nd-Fe-B magnets is presented. Starting from the bulk magnetic properties, the dimensions, the thickness of the Ni coating and the affected surface layer, the $J(H)$ demagnetization curve is calculated. For flat magnets the surface effects lead to a decrease of $B_r$ and an increase of the permeability which lowers $(BH)_{max}$. For strait magnets a step in the $J(H)$ curve appears at $H = 0$. The deteriorating effect of the Ni coating and the surface layer scale with the dimensions of the magnet and the thickness of these layers, which depend on the processing and the grain size of the magnet. For the production of very small Nd-Fe-B magnets it is beneficial to start with a grain size as small as possible$^{[3]}$. These effects can not be neglected if one or more dimensions of a Ni coated magnet are less than about 5 mm. SmCo$_5$ magnets show similar effects but there the coercivity of the damaged surface layer is higher. Pinning type Sm$_2$Co$_{17}$ magnets show almost no deterioration of the surface due to machining. As a result, Sm-Co magnets are usually better suited for applications with dimensions smaller than about 2 mm.

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References: