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Hard magnetic material measurements in a pulsed field magnetometer considering coating and eddy current effects

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Abstract: Rare-earth permanent magnets are coated in order to avoid corrosion. When considering the rated geometrical properties of a sample, the coating thickness has to be known precisely as it wrongly enlarges the magnetically active volume which in turn affects the accuracy of the measured magnetic properties. In this work, the sensitivity of hard magnetic material property measurements regarding the consideration of different coating thicknesses is evaluated. Moreover, the impact of eddy current effects on the magnetic properties is studied when measuring in an open circuit. Additionally, an outlook for a measurement-based determination of the electric conductivity of permanent magnet samples is given.

Key words: eddy current effects, hard magnetic materials, magnetic property measurement

1. Introduction

Sintered rare-earth Neodymium-Iron-Boron (NdFeB) permanent magnets, as they are used in rotating electrical machines for high power densities, are highly corrosive. Therefore, these permanent magnets are coated by electrochemical plating using for instance zinc or nickel or with a polymeric epoxy resin layer [1, 2]. The coating material may also deteriorate the magnetic properties compared to an uncoated sample [3]. The thickness of the coating depends on the applied method [4, 5]. The rated geometrical properties of the permanent magnet (PM) sample then include the magnetically active and the coating volume. The coating should not have a contribution to the hysteresis measurement of the sample.

The properties of hard magnetic materials can either be measured in a closed or in an open circuit. The advantage of an open circuit is that the measurement range is not limited by magnetic saturation of iron yokes as in a closed circuit, however, eddy current effects have to be considered [6, 7]. In any case, the geometrical properties of the PM sample have to be known accurately for a precise determination of the magnetic properties of the sample.

This work presents a sensitivity study of hard magnetic material property measurements regarding the impact of the coating thickness and the evaluation of eddy current effects.

2. Measurement of magnetic properties

The hard magnetic material measurements are conducted in an open circuit using a pulsed field magnetometer (PFM). In a PFM, the completely magnetized PM sample is placed inside a field coil. This field coil provides via a capacitive discharge a time varying magnetic field that reverses the magnetization direction of the sample completely. During this reversal the magnetic properties are measured. The relation between the applied magnetic field and the field inside the sample is given by its intrinsic geometrical demagnetization factor N [7]. For repetitive measurements, the sample has to be turned manually such that its magnetization direction counteracts the direction of the magnetic field in the field coil.

According to [8], the polarization$J$ as a function of the magnetic field strength H is measured in a PFM by considering the volumetric change rate of the magnetic moment m

$$J = \mu_0 \cdot \frac{m}{V} . \tag{1}$$

Therefore, the resulting measured magnetic properties have an inversely proportional relation regarding the assumed volume of the sample. When the geometrical volume V of the sample is reduced by volume ΔV, the measured polarization changes approximately with

$$\Delta J \propto \frac{1}{V - \Delta V} \approx \frac{\Delta V}{V^2} \tag{2}$$

for small deviations ΔV.

From (1)–(2) it follows, on the one hand, that a reduction of the assumed magnetically active sample volume increases the measured magnetic properties, on the other hand that the change rate is approximately proportional to the reduction of the sample's volume. Moreover, (1)–(2) imply that the impact of general inaccuracies regarding the sample's geometrical properties on the measured hysteretic behaviour decreases for increasing sample volumes.

3. Sensitivity analysis of measured magnetic properties

An industrially manufactured brick shaped NdFeB sintered permanent magnet sample S1 with the rated geometrical properties enlisted in Table 1 is considered. The PM is coated with an epoxy resin layer and it is assumed that the coating itself does not deteriorate the magnetic properties of the sample.

Table 1. Magnetic properties for varying coating thicknesses

Length l	**Width w**	**Height h**	**Volume V**	**Coefficient of Demagnetization N**
15 mm	13.4 mm	4 mm	804 mm^3	0.625

3.1. Sensitivity analysis of coating thickness

For the sensitivity study, the coating thickness of S1 is theoretically varied, whereby it is assumed that the coating layer is homogenous along the surface of the sample. Thus, the magnetically active volume of the PM sample changes accordingly. Table 2 shows the resulting magnetic parameters for different coating thicknesses or resulting magnetically active sample volumes.

Table 2. Magnetic properties for varying coating thicknesses

Coating thickness/PM volume	**Remanence B_r**	**Coercivity H_{cB}/H_{cJ}**	**Maximum Energy Product $(BH)_{max}$**
0 µm/804 mm^3	1.198 T	930.1 kA/m/2143.7 kA/m	278.8 kJ/m^3
10 µm/798 mm^3	1.203 T	938.1 kA/m/2146.7 kA/m	282.6 kJ/m^3
20 µm/791 mm^3	1.209 T	943.2 kA/m/2140.7 kA/m	285.1 kJ/m^3
30 µm/785 mm^3	1.225 T	948.9 kA/m/2129.6 kA/m	290.9 kJ/m^3
40 µm/779 mm^3	1.229 T	959.5 kA/m/2135.9 kA/m	295.1 kJ/m^3
50 µm/773 mm^3	1.241 T	967.2 kA/m/2132.4 kA/m	300.6 kJ/m^3

Figures 1 and 2 illustrate the demagnetization curves $B(H)$ and $J(H)$ in the second quadrant of the full hysteresis. The solid line represents the case measuring the sample with the rated geometrical properties. The dashed curves show in comparison the demagnetization behavior for assumed coating thicknesses of d = 30 µm and d = 50 µm.

The remanence B_r and the coercivity H_{cB} change almost proportionally with a decreasing magnetically active sample volume in accordance with (1). Likewise, the maximal energy product has the double change rate.

Another result is that the intrinsic coercivity H_{cJ} remains nearly unchanged, whereas for reduced magnet volumes the polarization increases up to the threshold demagnetization field strength H_{cJ} in accordance with increasing remanence values.

Generally, a change of the magnetically active sample volume ΔV causes an inaccuracy regarding the measured magnetic properties of the PM sample. For the principle quantification of the measurement inaccuracy, a homogenously coated cylinder and cube are studied as they are the commonly used as sample geometries. The purely geometrical volume is denoted by V_{Geo}, the reduced magnetically active sample volume due to coating with the thickness d by V_{Coating}.

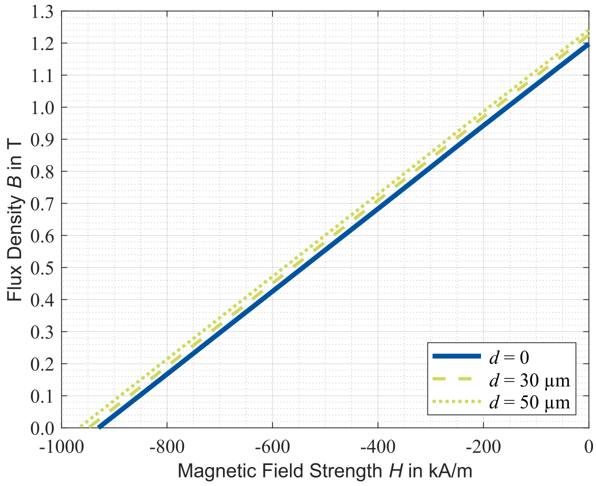

Fig. 1. Demagnetization curves $B(H)$ for varying coating thicknesses

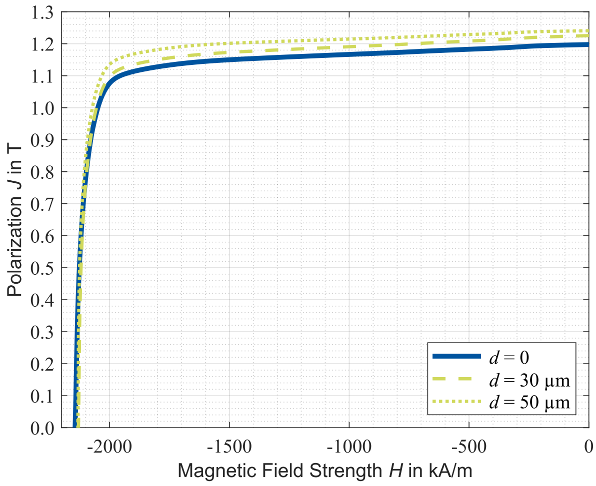

Fig. 2. Demagnetization curves $J(H)$ for varying coating thicknesses

The effective change in the sample's volume is then given by

$$\Delta V = V_{\text{Geo}} - V_{\text{Coating}} \,. \tag{3}$$

For a cylinder with the height h and radius r, the effective change is

$$\Delta V_{\text{Cylinder}} = \pi \cdot h \cdot r^2 - \pi \cdot (h - 2d) \cdot (r - d)^2. \tag{4}$$

For a cubic sample geometry with the edge length a, the effective change is given by

$$\Delta V_{\text{Cube}} = a^3 - (a - 2d)^3. \tag{5}$$

As the coating thickness is significantly smaller than the geometrical dimensions of the cylinder and the cube only the first order approximations are evaluated based on

$$\Delta V_{\text{Cylinder}} \approx d \cdot 2\pi r \cdot (r + h) = d \cdot S_{\text{Cylinder}} \tag{6}$$

and

$$\Delta V_{\text{Cube}} \approx d \cdot 6a^2 = d \cdot S_{\text{Cube}}\,, \tag{7}$$

where S_{Cylinder} denotes the surface area of the cylinder and S_{Cube} the surface area of the cube respectively. From (6) and (7) it follows that the resulting inaccuracy of hard magnetic material measurements decreases with a decreasing surface area of the PM sample.

In case that the cylindrical sample has a height of $h = 4/\pi \cdot a$ and a radius of $r = a/2$ it has an equal volume compared to the cube. For the surface areas follow

$$S_{\text{Cylinder}} = \left(\frac{\pi}{2} + 4\right) \cdot a^2 < 6 \cdot a^2 = S_{\text{Cube}}\,. \tag{8}$$

Therefore, a thin cylindrical sample is preferable to a cubic one when assuming equal volumes.

3.2. Analysis of eddy current effects

In a first measurement (pre-measurement) in a PFM, the sample's magnetization direction is reversed completely. This measurement contains the change rate of the polarization in the sample due to hysteresis and eddy current effects. The time derivate of the magnetic flux density B_{Coil} in the field coil for the magnetization reversal induces an eddy current density J_{E}

$$J_{\text{E}} \propto \kappa \cdot \frac{\partial B_{\text{Coil}}}{\partial t} \tag{9}$$

due to the electrical conductivity κ of the sample. In turn, the induced eddy current density in the sample affects the magnetic flux density according to Ampère's law

$$\nabla \times B_{\text{PM}} \propto J_{\text{E}}\,. \tag{10}$$

Therefore, for obtaining the purely hysteretic behavior of the PM a separate post-measurement is made for evaluating the influence of eddy current effects and subtracted from the pre-measurement [7].

Figure 3 illustrates the polarization change rate as a function of the magnetic field strength due to induced eddy currents. Table 3 compares the resulting magnetic parameters obtained in the pre- and post-measurement.

Table 3. Evaluation of eddy current effects

Measurement	**Remanence B_r**	**Coercivity H_{cB}**	**Maximum Energy Product $(BH)_{\max}$**
Pre-measurement	1.234 T	952.9 kA/m	294.2 kJ/m^3
Post-measurement	1.225 T	948.9 kA/m	290.9 kJ/m^3

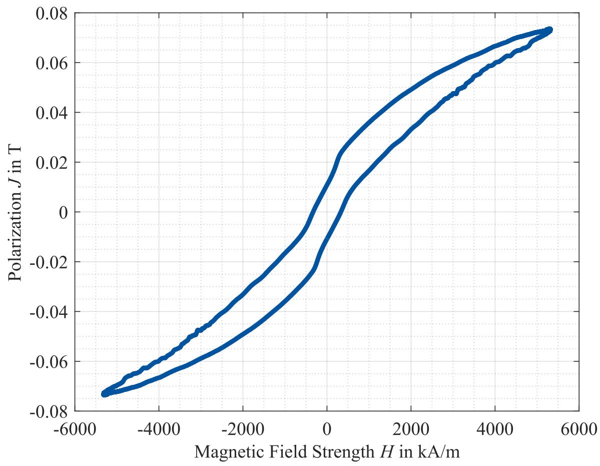

Fig. 3. Polarization change due to induced eddy currents in the sample

Moreover, the eddy current measurement can be further evaluated to determine the electric conductivity of the sample [7]. During one full hysteresis cycle in the time span T within the post-measurement the loss power can be determined with [9]

$$P_{\text{Measurement}} \propto \frac{1}{T} \cdot \int B_{\text{E}} \, \text{d}H, \tag{11}$$

where B_{E} is the magnetic flux density change due to induced eddy currents. The integral in (11) corresponds to the enclosed area of the hysteresis $B_{\text{E}}(H)$. A relation towards the measured loss power and the conductivity is given by [7, 9–11]

$$P_{\text{Measurement}} \propto \frac{1}{T} \cdot \int B_{\text{E}} \, \text{d}H \propto \frac{\kappa \cdot w_{\text{PM}}^2 \cdot \hat{B}^2}{T^2}. \tag{12}$$

The width of the PM is denoted by w_{PM} and $\hat{B}$ is the peak magnetic flux density during the hysteresis cycle. The prerequisite of (12) is that the eddy currents in the sample only flow in one direction perpendicular to the applied time varying magnetic flux density [10]. This assumption refers to a 2D-approximation for the calculation of induced eddy currents in electrically conductive bodies. Generally, the consideration of eddy current effects is a 3D-problem, whereas the 2D-approximation becomes applicable only in the case of axial very long samples compared to their width [12].

Figure 4 exemplarily shows the spatial resolution of the finite element simulated eddy current density in PM sample S1 for a sinusoidal, time varying magnetic flux density in y-direction. As the width and the length of sample S1 are comparable the 2D-assumption is not valid. The current density flows in the axial as well as in the tangential direction. Moreover, the length and the width of the sample are no distinct quantities when inserting the sample inside the field coil for the eddy current measurement.

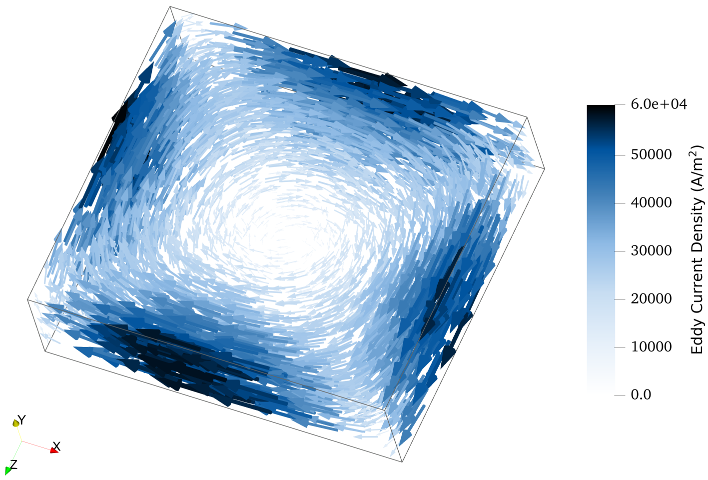

Fig. 4. Finite element simulated eddy current density in PM sample S1

4. Conclusions and outlook

The accurate measurement of the magnetic properties of hard magnetic materials requires a careful consideration of the magnetically active sample volume. In a PFM the measured hysteresis is scaled by the assumed sample's volume. The magnetic characteristic values of a PM sample change almost proportionally with deviations in its volume.

The sensitivity study regarding theoretically varied coating thicknesses points out that for measuring the magnetic properties of hard magnetic materials accurately the thickness of the coating layer has to be considered since it wrongly enlarges the magnetically active material volume. The inaccuracy of the measurement is approximately proportional the product of the coating thickness and the surface area of the sample. In this context, a thin cylindrical sample is preferable to a cubic shaped sample under the assumption of equal volumes.

The consideration of polarization changes due to eddy current effects is specially related to the usage of a PFM. The loss power during the eddy current measurement is proportional to the electric conductivity of the PM sample.

In future work, eddy current measurements are evaluated in order to determine the electric conductivity of PM samples by additional simulative consideration of geometry related 3D-effects.

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References

[1] Orefice M., Eldosouky A., Škulj I., Binnemans K., *Removal of metallic coatings from rare-earth permanent magnets by solutions of bromine in organic solvents*, RSC Advances, vol. 9, no. 26, pp. 14910–14915 (2019), DOI: 10.1039/C9RA01696A.

[2] Chen Z., Ng A., Yi J., Chen X., *Multi-layered electroless Ni–P coatings on powder-sintered Nd–Fe–B permanent magnet*, Journal of Magnetism and Magnetic Materials, vol. 302, no. 1, pp. 216–222 (2006), DOI: 10.1016/j.jmmm.2005.09.008.

[3] Gao Y., Bai Y., Zhu H., Liang W., Liu Q., Dong H., Jia R., Ma W., *Corrosion Resistance, Mechanical and Magnetic Properties of Cold-Sprayed Al Coating on Sintered NdFeB Magnet*, Journal of Thermal Spray Technology, vol. 30, no. 8, pp. 2117–2127 (2021), DOI: 10.1007/s11666-021-01266-z.

[4] Campbell P., *Permanent magnet materials and their application*, Cambridge University Press (1996).

[5] Cheng C.W., Man H.C., Cheng F.T., *Magnetic and corrosion characteristics of Nd-Fe-B magnet with various surface coatings*, IEEE Transactions on Magnetics, vol. 33, no. 5, pp. 3910–3912 (1997), DOI: 10.1109/20.619612.

[6] Fliegans J., Delette G., Dobrynin A.N., Dempsey N.M., Givord D., *Closed-Circuit Versus Open-Circuit Characterization of Hard Magnets*, IEEE Transactions on Magnetics, vol. 55, no. 2, pp. 1–5 (2019), DOI: 10.1109/TMAG.2018.2883917.

[7] Dinca C., *Motor design for maximum material exploitation and magnetization procedure with in-line quality check for mass production*, PhD Thesis, Faculty of Electrical Engineering, TU Berlin, Berlin (2017).

[8] Fiorillo F., Beatrice C., Bottauscio O., Patroi E., *Measuring the Hysteresis Loop of Permanent Magnets with the Pulsed Field Magnetometer*, IEEE Transactions on Magnetics, vol. 43, no. 7, pp. 3159–3164 (2007), DOI: 10.1109/TMAG.2007.893536.

[9] Tellinen J., *A simple scalar model for magnetic hysteresis*, IEEE Transactions on Magnetics, vol. 34, no. 4, pp. 2200–2206 (1998), DOI: 10.1109/20.703856.

[10] Polinder H., Hoeijmakers M.J., *Eddy-current losses in segmented surface-mounted magnets of a PM machine*, IEE Proceddings-Electric Power Applications, vol. 146, no. 3, pp. 261–266 (1999), DOI: 10.1049/ip-epa:19990091.

[11] Jiles D.C., *Modelling the effects of eddy current losses on frequency dependent hysteresis in electrically conducting media*, IEEE Transactions on Magnetics, vol. 30, no. 6, pp. 4326–4328 (1994), DOI: 10.1109/20.334076.

[12] Steentjes S., Boehmer S., Hameyer K., *Permanent Magnet Eddy Current Losses in 2-D FEM Simulations of Electrical Machines*, IEEE Transactions on Magnetics, vol. 51, no. 3, pp. 1–4 (2015), DOI: 10.1109/TMAG.2014.2362551.