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The effect of surface grain reversal on the AC losses of sintered Nd–Fe–B permanent magnets

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ABSTRACT

Sintered Nd–Fe–B magnets are exposed to AC magnetic fields in many applications, e.g. in permanent magnet electric motors. We have measured the AC losses of sintered Nd–Fe–B magnets in a closed circuit arrangement using AC fields with root mean square-values up to 80 mT (peak amplitude 113 mT) over the frequency range 50 to 1000 Hz. Two magnet grades with different dysprosium content were investigated. Around the remanence point the low grade material (1.7 wt% Dy) showed significant hysteresis losses; whereas the losses in the high grade material (8.9 wt% Dy) were dominated by classical eddy currents. Kerr microscopy images revealed that the hysteresis losses measured for the low grade magnet can be mainly ascribed to grains at the sample surface with multiple domains. This was further confirmed when the high grade material was subsequently exposed to DC and AC magnetic fields. Here a larger number of surface grains with multiple domains are also present once the step in the demagnetization curve attributed to the surface grain reversal is reached and a rise in the measured hysteresis losses is evident. If in the low grade material the operating point is slightly offset from the remanence point, such that zero field is not bypassed, its AC losses can also be fairly well described with classical eddy current theory.

1. Introduction

In the last two decades there has been a rapid growth in the permanent magnet electric motor industry [1]. The permanent magnets provide excitation; creating the same effects as electromagnets excited with direct current. One key benefit of the magnet excitation system is that there are no ohmic losses, which means higher efficiencies can be achieved. When the magnet electric motors need to be small in weight and size, sintered Nd–Fe–B magnets are the material of choice as they have high energy densities [2,3]. In the laboratory the magnet achieves its full potential. On the other hand, the application environment in a permanent magnet electric motor is very complex and various stability issues require detailed consideration [4]. One is the exposure of sintered Nd–Fe–B magnets to AC magnetic fields during motor operation. AC losses in general lead to a temperature rise in the magnet material which in turn decreases the magnet performance. The electrical resistivity of sintered Nd–Fe–B magnets is low [5,6]; e.g. compared to ferrite magnets that have a many orders of magnitude greater resistivity [7]. This means eddy current losses in the Nd–Fe–B parts might be a challenge in motor applications. Hysteresis losses are present even when the field is swept in a quasi-static manner and are attributed to small successive rapid changes in the magnetization, the Barkhausen discontinuities [8,9]. Experimentally only few attempts have been taken to quantify and analyze AC losses in sintered Nd–Fe–B magnets. Fukuma et al. [10] and Kanazawa et al. [11] reported AC loss measurements on sintered Nd–Fe–B magnets in a closed-circuit experimental system for frequencies up to 150 Hz and AC field amplitudes up to 100 mT. Hysteresis losses (W_h) and eddy current losses (W_e) were separated by fitting the frequency (f) dependent curves assuming that W_e is proportional to f^2 and W_h is proportional to f [11]. They obtained hysteresis losses that were larger than the eddy current losses, but did not elaborate further about the origin of hysteresis losses in sintered Nd–Fe–B magnets at fairly low magnetic field amplitudes. The main source of such hysteresis losses will be identified in this paper. We have measured and compared the AC losses of two Nd–Fe–B sintered magnet grades with different dysprosium content. The magnet

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with the low dysprosium content is referred to as the low grade material and the material with the high dysprosium content as the high grade material. Dysprosium is usually added to Nd–Fe–B magnets because of the much increased anisotropy field of $Dy_2Fe_{14}B$ [12] which leads to a better magnet performance at elevated temperatures. We demonstrate that the AC losses differ significantly between the low and high grade material and clarify the origin of hysteresis losses by applying Kerr microscopy imaging and inductive AC loss measurements.

2. Experimental methods

The dysprosium content of the commercially purchased sintered Nd–Fe–B magnets was determined using inductively coupled plasma-optical emission spectrometry (iCAP 6500 Duo View, Thermo Fisher Scientific GmbH). Any surface protection coatings were removed by grinding the magnets with abrasive paper down to grit 2500 and cleaning the magnet surface with ethanol. The magnetic properties of the uncoated Nd–Fe–B samples (dimensions 5 (EA)x10 $\times$ 10 mm^3, EA: easy axis) were measured in a Magnet-Physik C-300 permagraph ($\mu_0 H_{max}$=2 T) with a temperature stage and a closed loop magnetic circuit to avoid demagnetizing effects. The coercive fields of the high grade magnet at lower temperatures (Θ_{min}=22 °C) were extracted from vibrating sample magnetometer (VSM) measurements on uncoated samples sized 3 $\times$ 3 $\times$ 3 mm^3. All sample magnetization took place in a 5 T pulsed magnetic field. The magnets′ electrical resistivity was measured with a standard four probe method. The thermally demagnetized magnet material was cut into thin stripes, parallel and perpendicular to the easy axis (cross section area 1 mm^2), placed on a hot plate, and carefully contacted with four very fine beryllium copper spring force pins. Two voltage readings from initial and reverse current excitation were averaged to eliminate thermoelectric electromotive force. A zirconium oxy-nitride thermocouple was placed next to the sample for temperature measurement.

Determining the AC losses was based on applying an homogeneous AC magnetic field and accurately measuring the flux density B(t) in the sample and the applied magnetic field strength $H(t)$. The AC losses then correspond to the area enclosed in the B (H) curve. The closed circuit arrangement for measuring the AC losses has been adapted from Kanazawa et al. [11] and is schematically shown in Fig. 1.

An amplified sinusoidal AC current was passed through excitation coils creating an AC magnetic field which was transposed and increased in a laminated stainless steel split tape core. The strength of the AC magnetic field was determined using a Hall probe. (The probe measured the root mean square (rms)-value, which is the AC field amplitude divided by $\sqrt{2}$ for a sinusoidal wave.) AC fields with rms-values up to 80 mT were attained over the frequency range 50 to 1000 Hz. Between the two core parts an iron piece was placed on one side and the magnet sample on the other side which led to a closed magnetic circuit arrangement. A coaxial double coil for picking up the induced voltages was fitted around the sample. The two single-layered coils were wound parallel with 23 turns each on reels that could be inserted in each other. One coil was placed closely around the magnet (coil 1) and the second farther away (coil 2). The time-dependent flux density $B(t)$ in the sample and the magnetic field strength $H(t)$ can be deduced from the induced voltages in coils 1 and 2 using Maxwell equations. Since the relative permeability of magnetized Nd–Fe–B magnets is about 1.05 [13] homogenous magnetic field distribution in the sample was assumed. An area-turn calibration of the double coil with a Hall probe was performed to ensure good measurement accuracy. The voltage signals were recorded with an oscilloscope. To minimize noise-related errors a low pass filter was applied and each voltage trace was averaged 4096 times. Phase shifts induced by the electronic equipment were accounted for by measuring a ceramic block as reference and deducting any phase shift not induced by the magnetic sample. The AC-field was applied parallel to the magnet's easy axis (EA). The sample dimensions were 4.8 (EA)x5.7 $\times$ 5.7 mm^3, which was set by the geometries of the steel split tape core and the double coil. The investigated sintered Nd–Fe–B magnets weighed ~1.2 g.

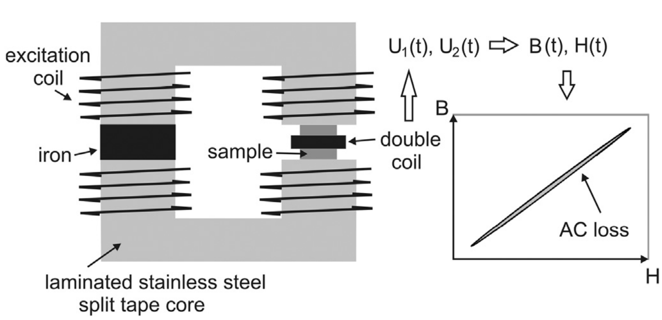

Fig. 1. Schematic of magnet yoke for AC loss measurements.

Domain structure investigations were carried out in the magnetized state using a Kerr microscope (evico magnetics GmbH) in transversal magneto-optic contrast. The sensitivity direction was parallel to the easy-axis of magnetization. Electromagnetic coils and an iron yoke provided a demagnetizing field DC_{Kerr} up to −400 mT parallel to the easy axis. The pole faces of the magnet touched the poles of the iron yoke leaving only a very small air gap. The observed surface was parallel to the easy axis (not the pole faces) and was polished shortly before the measurement using standard metallographic techniques (down to 1 μm suspension) to ensure good picture quality. Afterwards the sample was magnetized. In the Kerr microscope a background image was taken to capture the initial magnetized state (DC_{Kerr}=0). Subsequently a demagnetizing field DC_{Kerr} was applied to the sample for a few seconds, the DC field was switched off and another image was taken at DC_{Kerr}=0. The initial background image was subtracted from the latter image to clearly emphasize changes in the surface's domain structure. The procedure was repeated with a larger demagnetizing field values. Black and white contrast in the images can be referred to as changes in the domain structure compared to its initial state.

3. Results and discussion

The dysprosium content was determined to 1.7 ± 0.1 wt% in the low grade magnet material and 8.9 ± 0.1 wt% in the high grade material. Table 1 shows the magnetic properties of the uncoated sintered Nd–Fe–B magnets. As expected the high grade material

Table 1
Temperature dependent magnetic properties of uncoated low grade and high grade magnets from permagraph measurement. (*VSM values).

Temperature (°C)	22	60	100	130	150	180
Low grade						
$\mu_0 {}_J H_C$ (T)	1.416	0.945	0.598	0.426	0.336	0.232
BH_{max} (kJ/m^3)	376	343	294	242	199	141
B_R (T)	1.391	1.331	1.259	1.209	1.161	1.095
High grade						
$\mu_0 {}_J H_C$ (T)	3.703 (*)	2.892 (*)	2.263	1.851	1.575	1.220
BH_{max} (kJ/m^3)	247	229	208	192	183	163
B_R (T)	1.121	1.083	1.038	1.00	0.977	0.928