Research Article

Magnetic Behavior of Sintered NdFeB Magnets on a Long-Term Timescale

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Stable polarization of permanent magnets over the lifetime of the application is an important aspect in electrical machine design. Specification of the long-term stability of magnet material is difficult, since knowledge of the phenomenon is incomplete. To be able to optimize magnet material selection, the long-term magnetic behavior of the material must also be understood. This study shows that material with a very square JH curve is stable until a certain critical operating temperature is reached. Major losses are detected as the critical temperature is exceeded. Material with a rounder JH curve does not show a well-defined critical temperature, but increasing losses over a large temperature range. The critical temperature of a material is also dependent on the field conditions. Results differ whether the tests are performed in an open or closed magnetic circuit. In open-circuit tests, the opposing field is not homogeneously distributed throughout the volume of the magnet and thus the long-term behavior is different than that in closed-circuit conditions. Open-circuit tests seem to give bigger losses than closed-circuit tests in cases where the permeance coefficient of the open-circuit sample is considered to be the average permeance coefficient, calculated according to the dimensions of the magnet.

1. Introduction

During the last decade, the utilization of sintered NdFeB magnets in large motor and generator applications has become more common. The remanence of NdFeB material is superior in comparison to other types of magnet materials. The challenge is coercivity, which decreases rapidly as the temperature rises. Coercivity at elevated temperatures can be increased by partial substitution of Nd with Dy. Increasing Dy content, however, decreases the remanence and is therefore an unfavorable way of improving stability at elevated temperatures. In addition, dysprosium is not as abundant as neodymium in ores and thus it is much more expensive than Nd. A lot of effort has recently been put into development work for lower Dy content magnets with higher coercivities [1–3].

One way to avoid excess Dy additions in magnets is the optimization of the application by means of appropriate material selection. This requires, however, precise knowledge

of the magnetic behavior of the materials concerned. FE-modeling is an efficient way of designing the application. The optimization of the magnetic circuit is thus much easier today than a few decades ago. Irreversible polarization losses occurring in magnets during the operation of machines are difficult to estimate, detect, and compensate accurately. Consequently, it is more preferable to avoid any demagnetization.

Many studies have recently been published on the demagnetization risks of permanent magnets in different types of machines [4–10]. In [4–8], the behavior of the magnet material is represented by an idealized BH curve, meaning that the magnetic field density of the magnet is considered to decrease linearly with an increasing opposing external magnetic field, until a certain knee point is reached. If the opposing field exceeds the knee point, some irreversible losses will occur. The same principle, but utilizing the nominal BH curves given by the magnet producers, is used in [9, 10].

TABLE 1: Properties of the tested materials.

Material	Room temperature coercivity H_{ci} [kA/m]	Room temperature remanence B_r [T]	Temp. coeff. α of B_r (20–100°C) [%/°C]	Temp. coeff. β of H_{ci} (20–100°C) [%/°C]
1	1730	1.25	−0.11	−0.64
2	1680	1.21	−0.09	−0.62

In addition to FEM calculations, it is important to understand how to convert the knee point value that is used into the real material properties and especially into specifications when ordering magnets. The magnetic behavior of commercial permanent magnet material is not necessarily close to ideal. Usually BH curves are measured only for one sample in the production lot and there is always some variation in properties from sample to sample. There might also be some inhomogeneities inside the magnet, and the measured BH curve only shows the average behavior of the material. Locally, the response to the opposing magnetic field can differ from the measured response.

These effects can be taken into account by setting tolerances for the remanence and coercivity values and for the homogeneity of these properties. However, these parameters do not define the shape of the BH curve. To ensure similar magnetic behavior to that applied in the FE model, the JH curve of the applied material should be very square-like. A common way to quantify the shape of the curve is to use a parameter termed squareness factor (SF) (or in some papers squareness ratio SR):

$$SF = \frac{H_k}{H_{ci}}, \quad (1)$$

where H_k refers to the field at which 10% of the remanence is lost (= field at 90% of B_r) [11]. A squareness factor of 1 describes an ideal magnet material in which the magnetization of all domains is reversed in the same opposing field, the coercive field. In real materials this is almost impossible to achieve, but the closer the SF approaches unity, the better the homogeneity of the material. Consequently, SF is considered as the quality measure of a magnet material.

The shape of the JH curve depends on the microstructure of the magnet material [11, 12], and the microstructure depends on the production process. Factors affecting the squareness include the mean grain size and its standard deviation and grain shape homogeneity [12]. In addition, all kinds of defects in the microstructure, especially that soft magnetic phases can easily deteriorate the squareness [11]. If there is roundness in the material's JH and BH curves, it can be treated by a partial demagnetization (also termed stabilization or preageing) by heat treatment or a reversal field pulse. If a slight demagnetization is performed in a closed circuit, the recoil curve will be close to linear one [13].

The most difficult property to take into account in the optimization of materials specifications is time-dependent demagnetization. Standard demagnetization curves are measured in a timescale of seconds and the so-called thermal aftereffect or ageing is not visible in the curves. This ageing is due to a phenomenon called magnetic viscosity. The

phenomenon in NdFeB magnets has been studied since the 1980's [14–16], but mostly from a theoretical point of view. Those measurements were performed in a timescale of seconds. The results are not necessarily applicable to a timescale of years. The magnitude of the thermal aftereffect in permanent magnets depends on the microstructure of the material but also on the external conditions like temperature and magnetic field [17].

The magnetic behavior of a magnetized permanent magnet is expected to be defined by the measured demagnetization curve. In our previous work [17–19], we have studied the time-dependent demagnetization of different types of NdFeB-based magnets to find some practical information and a clear connection between the demagnetization curve of a magnet material and the long-term magnetic behavior of a magnet produced from that material. The shape of the demagnetization curve was found to have an effect on time-dependent demagnetization [19]. In this paper we present a more detailed analysis of the effects of the JH curve squareness on the long-term magnetic behavior of two different sintered NdFeB materials. We also compare the measurement results obtained in open magnetic circuit and closed magnetic circuit conditions. Open-circuit measurement results always contain information not only about the behavior of the material but also about the effect of the geometry of the sample. The influence of the geometrical factors is also discussed.

2. Experimental Approach

The experimental procedure consists of two parts. At first, a comparison was made of the time-dependent demagnetization behavior of two materials with different types of BH curves. Properties of the materials are listed in Table 1. The exposures were applied in open-circuit conditions. In the second part, the time-dependent demagnetization behaviors in open- and closed-circuit exposures were compared.

The samples were commercial sintered NdFeB magnets produced by Neorem Magnets Oy. The rectangular samples were $10 \times 10 \times 4.9$ mm in size, leading to a permeance coefficient (P_c) value of 1.2, calculated according to (2). These samples were tested at temperatures from 100°C to 160°C.

Also, samples with dimensions of $10 \times 10 \times 4.1$ mm and $10 \times 10 \times 5.6$ mm were tested ($P_c = 1.0$ and 1.4, resp.), but only for material 2 at 120°C. The results of these measurements were compared to the closed-circuit measurements applied to material 2 at 120°C.

The JH and BH curves of the samples were measured with a Magnet Physik Permagraph C-300. The curves were measured at room temperature (20°C), at 100°C, and at 150°C

FIGURE 1: The BH and JH curves measured for the studied materials at 20°C, 100°C, and 150°C. The red line refers to material 1 and the blue line to material 2. A load line representing the geometry of the samples ($P_c = 1.2$) is also shown.

(also at 120°C for material 2). The measured BH curves are shown in Figure 1.

The samples were kept at different stable temperatures for at least 500 hours and their residual inductions were measured at logarithmic time intervals. A minimum of 10 measurements were carried out within the 500-hour period. In open-circuit exposure, six identical samples were studied for each temperature and the result is considered as the average loss from these six samples. The same method was also used in our previous studies [14–16]. Corrosion protection of the samples was provided by wrapping them in aluminum foil. In closed-circuit exposure, the results are for a single sample only.

In the open-circuit exposure, the demagnetizing field is only due to the self-field of the magnet. The self-field is determined by the permeance coefficient, the magnitude of which depends on the dimensions of the magnet. The permeance coefficients of the samples were calculated according to the following formula [20]:

$$P_c = 1.77 \frac{h}{lw} \sqrt{h(l+w) + lw}, \quad (2)$$

where h is the height (in the direction of magnetization), l is the length, and w is the width of the magnet. The calculated P_c gives an average value of $-B/\mu_0 H$ (μ_0 is used to change the units of H from kA/m to T [21]) for the magnet. In reality, the value of $-B/\mu_0 H$ in open circuit conditions is not a constant but varies inside the magnet. The variation of $-B/\mu_0 H$ was studied using FEM. The software used was Opera by Vector Fields.

To achieve a uniform demagnetizing field, a closed-circuit exposure system was developed. The system consists of an iron yoke, a bias magnet, and coils to adjust the field. Figure 2 shows the system. The yoke is manufactured from lamellar electric steel and in the middle of the yoke there is a bias magnet made from NdFeB with high coercivity, producing a bias field of about 400 kA/m in the air gap. Two coils are wound on the yoke to produce an excess field up to 560 kA/m. The magnetic field strength in the air gap is measured by a transversal Hall sensor, fixed to the pole.

FIGURE 2: The iron yoke for testing materials in homogenous magnetic field conditions.

The yoke was placed in an oven to get the desired elevated temperature of 120°C for the exposure. At the same time, the field was adjusted to the desired level by feeding current to the coils. The exposure time was considered to start when the field reached the set level. After the exposure, the yoke was taken out of the oven to cool down. The sample was detached from the yoke when it had cooled down close to room temperature. When the sample had reached room temperature, the magnetic flux was measured with a Helmholtz coil. The exposure was continued by placing the yoke in the oven to heat up and the sample was attached to the yoke again after it had reached the target temperature.

Demagnetization trends as a function of time were determined for all test series. The trends were assumed to follow the logarithmic decay law:

$$M(t) = M(t_0) - S \ln \frac{t}{t_0}, \quad (3)$$

where t_0 is the reference time (1 h in our measurements) and S is the magnetic viscosity coefficient.

3. Results and Discussion

3.1. Squareness of the JH Curves. The squareness factors for the JH curves measured at 100°C for both materials were determined according to (1) and the results are listed in Table 2. The curves and their H_k values are presented in Figure 3. The shape of the curves measured at room temperature is affected by the saturation of the hysteresis-graph poles and therefore the curves are unsuitable for SF determination.

The squareness factors are 0.98 and 0.90 at 100°C and are 0.98 and 0.89 at 150°C for materials 1 and 2, respectively. Thus, the SF of these materials is not sensitive to changes in temperature, which is in line with [18].

TABLE 2: Properties of the materials at 100°C.

Material	Coercivity H_{ci} [kA/m]	Remanence B_r [T]	H_k [kA/m]	Squareness factor SF
1	889	1.14	875	0.98
2	845	1.12	758	0.90

FIGURE 3: JH curves measured at 100°C for materials 1 and 2 with an elucidation of the squareness factor determination.

FIGURE 4: Polarization losses as a function of time at different temperatures in material 1 magnets.

3.2. Polarization Losses in Open-Circuit Exposures. The detected polarization losses as a function of time for open-circuit exposures are presented in Figures 4 and 5. The magnets produced from material 1 do not show losses greater than 0.7% during the period of measurements at 130°C and 140°C. Even after 30 years, the loss is estimated to remain below 1%. However, when the temperature was raised to 150°C, a clear loss of about 2.6% was detected after 1 hour and the following loss trend would increase the estimated loss to about 6.8% in 30 years. At 160°C the loss after 1 hour was as much as 8.5%. The slope of the loss trend at 160°C is very similar to that at 150°C. Small losses were detected in magnets produced from material 2, even at 100°C. The loss after 1 hour

FIGURE 5: Polarization losses as a function of time at different temperatures in material 2 magnets.

was only 0.4%, but following the trend it will result in about 1.3% in 30 years. However, raising the temperature by 10°C does not increase the loss very much. The temperature has to be raised to 130°C, to detect losses over 2% after 1 hour.

Thus, losses increase more gradually with temperature in material 2 magnets, but they also start at lower temperatures than in material 1 magnets. Estimated losses after 1 hour and after 30 years are plotted as a function of temperature in Figure 6. When examining this figure, it can be concluded that the control of losses will be easier in practice when the JH curve of the magnet material is squarer in shape. There is a clear limiting temperature under which losses are negligible. The amount of losses at higher temperatures is irrelevant as long as the temperature is kept under the limit.

3.3. Polarization Losses in Closed Circuit Exposures. The detected polarization losses as a function of time for closed-circuit exposures are presented in Figure 7. Individual samples of material 2 were exposed to a temperature of 120°C in five different static magnetic fields from 400 kA/m to 540 kA/m. At 400 kA/m, an initial loss of about 1.2% appears after 1 hour of exposure, but the subsequent trend is horizontal. At 540 kA/m, the initial loss is about 4.6% with a further loss trend increasing the total loss to about 24% in 30 years. The variation in the initial loss is fairly small and the losses detected after one hour at 480 kA/m, 500 kA/m, and 520 kA/m are within the limit of error, which is due to differences between the samples. In the open circuit tests, a variation of about 1% units was found in the initial loss of

FIGURE 6: Estimated polarization losses after 1 hour and after 30 years as a function of exposure temperature in open-circuit exposures. The curves on the left refer to material 2 and the curves on the right to material 1.

FIGURE 7: Polarization losses as a function of time at different demagnetizing fields in material 2 magnets at 120°C.

the samples exposed to 120°C. The variation of the initial loss in closed-circuit samples exposed to fields from 480 to 520 kA/m was only 0.9% units.

Although the initial losses are fairly small in all the closed-circuit exposures, the slopes of further time-dependent demagnetizations decrease strongly with increasing field strength. Thus, the time dependence of the demagnetization is stronger than in the open-circuit exposures.

3.4. Comparison of the Results from the Open- and Closed-Circuit Exposures. Only an ellipsoidal magnet with uniform magnetization has a uniform self-demagnetization field [22]. In this special case the P_c is constant throughout the sample

volume. When the sample shape differs from the ellipsoid, the P_c also varies inside the sample. The P_c calculated according to (2) describes only the average demagnetizing condition in the magnet.

The result of the simulation of the field conditions inside the rectangular sample is presented in Figure 8. The figure illustrates the variation of the P_c at 120°C inside the $10 \times 10 \times 4.9$ mm sample produced from material 2 (only the field component in the direction of magnetization is considered). The minimum value for $-B_z/\mu_0 H_z$ is about 0.5 at the center of the top and bottom surfaces of the magnet. In most of the volume of the magnet the P_c is under the average value of 1.2.

Figure 9 shows the BH and JH curves of material 2 measured at 120°C. Load lines describing the average and the minimum operating points of the open circuit samples ($P_c = 1.2$ and 0.5) are also included. The maximum and the minimum field strengths used in closed circuit tests ($H = 540$ kA/m and 400 kA/m) are marked in blue. The demagnetization in the open circuit tests is likely to be concentrated on the areas where the operating point is below 1.0 ($H > 400$ kA/m). The volume fraction of the sample that experiences a reversal field of 500 kA/m or more is 8.3%. This area is demonstrated in Figure 8 with a P_c line of 0.62. Line 0.55 represents a field of 520 kA/m. Most of the demagnetization is likely to occur in this small volume of the sample during exposure tests in open circuit conditions.

The estimated losses after 1 hour and after 30 years in open- and closed-circuit exposures are presented in Figure 10 as a function of P_c . The P_c values of the open-circuit samples are the average values calculated according to the dimensions of the samples. The comparison reveals that the time-dependent losses in open-circuit exposures do not match the results from closed-circuit exposure. This is understandable, since the demagnetization behavior of the open-circuit sample is more like the sum of the different behaviors in different field conditions. At operating point $P_c = 1.0$ the closed-circuit exposures give smaller values for losses. This means that, in reality, the measurements in open-circuit conditions give conservative results at $P_c = 1.0$.

There is also a slight variation in the properties of individual samples. This is easily visible in the closed-circuit test results, since they are based on measurements on individual samples. In open-circuit tests, the effect of sample variation is minimized by showing the average results for six equivalent samples.

Comparison of open- and closed-circuit loss trends (Figures 5 and 7) reveals that in closed-circuit exposures the initial loss does not dominate as much as in the open-circuit exposures. Time-dependent demagnetization, however, seems to be stronger in closed-circuit exposures. This suggests that changes in the self-field occur during the initial demagnetization of the open-circuit samples, which affects the subsequent time-dependent behavior. Due to local changes in field conditions, the local minimum of the P_c in the open-circuit samples is expected to rise. For this reason, it is difficult to apply the open-circuit test results in the formulation of any universal theories about material-specific time-dependent demagnetization. The geometrical effect might be too strong.

FIGURE 8: Variation of $-B_z/\mu_0 H_z$ inside the sample with dimensions $10 \times 10 \times 4.9$ mm. The model includes one eighth of the sample. The upper right corner is the actual corner of the magnet and the lower left corner is the center of the magnet. The model depicts the sample produced from material 2 at 120°C .

FIGURE 9: JH and BH curves measured for material 2 at 120°C . Load lines of 0.5 and 1.2 are also shown.

4. Conclusions

A comparison was made of the time-dependent demagnetization behavior of two different sintered NdFeB magnet materials showing different types of demagnetization curves. In magnets produced from a material with a very square JH curve, the losses are negligible until a certain critical temperature is reached. As the temperature exceeds the critical, substantial losses occur. For this type of material, it is possible to determine a critical temperature under which the polarization losses even after 30-years exposure will remain under 1%.

For magnets made from material with rounder JH curve, small losses occur over a wide range of temperatures. It is more difficult to determine a critical temperature for this type of material. There is a need to set more limiting values like the amount of losses that are acceptable after how long an exposure time.

FIGURE 10: Estimated polarization losses as a function of P_c in closed- and open-circuit exposures in material 2 magnets at 120°C .

If specifications concerning time-dependent demagnetization behavior are used and quality control is performed in open-circuit exposure tests, the difference between the open-circuit results and the closed-circuit behavior also needs to be understood. The findings of this study suggest that the open-circuit tests give higher loss estimates, in cases where the limiting permeance coefficient is considered to be the average P_c of the sample, determined according to its dimensions. This is valid at least in rectangular samples with P_c values close to 1.

A universal theory about material-specific, long-term time-dependent demagnetization is impossible to formulate based on measurements performed in open-circuit conditions. Many more measurements in closed-circuit conditions

are required. This type of study is, however, very time-consuming and would need a long-term research plan in the future.

Conflict of Interests

Authors of this paper do not have any financial relations with the commercial providers of the research facilities like measurement equipment or the modeling software.

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References

- [1] H. Sepehri-Amin, Y. Une, T. Ohkubo, K. Hono, and M. Sagawa, "Microstructure of fine-grained Nd-Fe-B sintered magnets with high coercivity," *Scripta Materialia*, vol. 65, no. 5, pp. 396–399, 2011.
- [2] R. Goto, M. Matsuura, S. Sugimoto et al., "Microstructure evaluation for Dy-free Nd-Fe-B sintered magnets with high coercivity," *Journal of Applied Physics*, vol. 111, no. 7, Article ID 07A739, 2012.
- [3] K. Morimoto, N. Katayama, H. Akamine et al., "Coercivity enhancement of anisotropic Dy-free NdFeB powders by conventional HDDR process," *Journal of Magnetism and Magnetic Materials*, vol. 324, no. 22, pp. 3723–3726, 2012.
- [4] H. Kim, J. Jin-Hur, B. Kim, and G. Kan, "Characteristic analysis of IPM type BLDC motor considering the demagnetization of PM by stator turn fault," in *2nd IEEE Energy Conversion Congress and Exposition (ECCE '10)*, pp. 3063–3070, Atlanta, Ga, USA, September 2010.
- [5] C. Kral, R. Sprangers, J. Waarma, A. Haumer, O. Winter, and E. Lomonova, "Modeling demagnetization effects in permanent magnet synchronous machines," in *19th International Conference on Electrical Machines (ICEM '10)*, pp. 1–6, Rome, Italy, September 2010.
- [6] J. D. McFarland and T. M. Jahns, "Investigation of the rotor demagnetization characteristics of interior PM synchronous machines during fault conditions," in *Energy Conversion Congress and Exposition (ECCE '12)*, pp. 4021–4028, Raleigh, NC, USA, September 2012.
- [7] P. Guglielmi, B. Boazzo, E. Armando, G. Pellegrino, and A. Vagati, "Magnet minimization in IPM-PMASR motor design for wide speed range application," in *3rd Annual IEEE Energy Conversion Congress and Exposition (ECCE '11)*, pp. 4201–4207, San Jose, Calif, USA, September 2011.
- [8] H. Shin, T. H. Kim, and C. Kim, "A study on irreversible permanent magnet demagnetization in flux-reversal machines," in *International Conference on Electrical Machines and Systems (ICEMS '11)*, pp. 1–4, Beijing, China, August 2011.
- [9] P. Zhou, D. Lin, Y. Xiao, N. Lambert, and M. A. Rahman, "Temperature-dependent demagnetization model of permanent magnets for finite element analysis," *IEEE Transactions on Magnetics*, vol. 48, no. 2, pp. 1031–1034, 2012.
- [10] J. Wang, W. Wang, K. Atallah et al., "A linear permanent-magnet motor for active vehicle suspension," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 1, pp. 55–63, 2011.
- [11] D. J. Branagan, M. J. Kramer, Y. L. Tang, and R. W. McCallum, "Maximizing loop squareness by minimizing gradients in the microstructure," *Journal of Applied Physics*, vol. 85, no. 8, pp. 5923–5925, 1999.
- [12] E. A. Périgo, H. Takiishi, C. C. Motta, and R. N. Faria, "Microstructure and squareness factor: a quantitative correlation in (Nd, Pr)FeB sintered magnets," *Journal of Applied Physics*, vol. 102, no. 11, Article ID 113912, 4 pages, 2007.
- [13] S. Ruoho, E. Dlala, and A. Arkkio, "Comparison of demagnetization models for finite-element analysis of permanent-magnet synchronous machines," *IEEE Transactions on Magnetics*, vol. 43, no. 11, pp. 3964–3968, 2007.
- [14] D. Givord, A. Lienard, P. Tenaud, and T. Viadieu, "Magnetic viscosity in Nd-Fe-B sintered magnets," *Journal of Magnetism and Magnetic Materials*, vol. 67, no. 3, pp. L281–L285, 1987.
- [15] H. Nishio, "Magnetic aftereffect of Nd-Fe-B sintered magnets," *IEEE Transactions on Magnetics*, vol. 24, no. 6, pp. 3188–3192, 1988.
- [16] J. Shi, O. Yamada, H. Maruyama, M. Sagawa, and S. Hiroswawa, "Magnetic aftereffect in rare earth-iron-boron magnets," *IEEE Transactions on Magnetics*, vol. 23, no. 5, pp. 3122–3124, 1987.
- [17] M. Haavisto and M. Paju, "Temperature stability and flux losses over time in sintered NdFeB permanent magnets," *IEEE Transactions on Magnetics*, vol. 45, no. 12, pp. 5277–5280, 2009.
- [18] M. Haavisto, S. Tuominen, H. Kankaanpää, and M. Paju, "Time dependence of demagnetization and flux losses occurring in sintered Nd-Fe-B permanent magnets," *IEEE Transactions on Magnetics*, vol. 46, no. 9, pp. 3582–3584, 2010.
- [19] M. Haavisto, H. Kankaanpää, and M. Paju, "Estimation of time-dependent polarization losses in sintered Nd-Fe-B permanent magnets," *IEEE Transactions on Magnetics*, vol. 47, no. 1, pp. 170–174, 2011.
- [20] B. D. Cullity and C. D. Graham, *Introduction to Magnetic Materials*, pp. 478–484, John Wiley & Sons, 2009.
- [21] E. A. Perigo, H. Takiishi, C. C. Motta, and R. N. Faria, "On the squareness factor behavior of RE-FeB (RE = Nd or Pr) magnets above room temperature," *IEEE Transactions on Magnetics*, vol. 45, no. 10, pp. 4431–4434, 2009.
- [22] R. J. Parker, *Advances in Permanent Magnetism*, John Wiley & Sons, 1990.