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Studies on the Time-Dependent Demagnetization of Sintered NdFeB Permanent Magnets

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Temperature Stability and Flux Losses Over Time in Sintered Nd-Fe-B Permanent Magnets

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It is important to ensure that no permanent flux losses occur in permanent magnets during their use in industrial applications. Demagnetization occurring with time in a constant temperature is often assumed to be negligible, provided that the operating point of the magnet is above the knee of the BH curve. There is, however, a clear need to demonstrate these time dependent losses. In this study, losses over time were measured for four commercial sintered Nd-Fe-B magnet grades at five different temperatures (23°C - 150°C). Samples with three different permeance coefficient (Pc) values were tested for each material. The time-dependent losses measured fitted the logarithmic law of magnetic viscosity well. It was demonstrated that the total flux loss in a lifetime of 30 years can be estimated according to the temperature, coercivity of the material and the permeance coefficient of the magnet. With the proper selection of the magnet material, in accordance with the designed Pc of the application, the total flux loss in 30 years can be minimized almost to zero even at 150°C.

Index Terms— **Permanent magnets, Losses, Neodymium compounds, Stability**

I. Introduction

The number of sintered Nd-Fe-B magnets used in industrial machine applications has increased in recent years. Driving forces towards the permanent magnet technology are the higher achievable power densities and higher efficiencies [1]. This technology requires however a fairly stable magnetic polarization in the permanent magnets through the whole lifetime of the application, typically 20 to 30 years. For this reason, it is important to control the operating environment of magnets.

In rotating machines, induced eddy currents cause a temperature rise, which could be detrimental to the commonly used Nd-Fe-B magnets. Studies of more precise eddy current calculations [2-3] and of the effects of overheating in fault conditions [4] are attempts towards a better understanding of the operation of these machines. An accurate simulation of the application is required to assist in the selection of the proper magnet material.

Demagnetization effects in Nd-Fe-B magnets occurring in temperature cycling are quite well studied [5-7] and documented [8]. In temperature cycling, magnets are at a maximum temperature only for a short time, which represents the overload condition. If the coercive force of the material decreases too much due to the temperature rise and the operating point of the magnet falls below the knee of the demagnetization curve, some permanent flux loss will appear. The term used by the machine designers for the temperature where irreversible losses start to occur is the "critical temperature of the magnet" [9-11]. Critical temperature is a characteristic of an application with a certain permeance coefficient (operating point).

Demagnetization curves measured for materials are commonly used in defining the critical temperature of a magnet system. Demagnetization curves, however, consider only the demagnetization occurring immediately. Losses over time are usually assumed to be negligible. The assumption is reasonable when the temperature rise is only temporary. However, continuous eddy currents maintain the operating temperature close to the critical temperature of the magnets, which causes a time-dependent demagnetization through the so-called magnetic viscosity effect.

There are not many published studies on the time-dependent flux losses in commercial sintered Nd-Fe-B magnets. Clegg et al. [12] and Mildrum et al. [13] have shown that temperature, permeance coefficient (Pc) and coercivity of a magnet affects its time dependent losses. However, in [12] only one temperature and two Pc values were tested for 200 hours and in [13], samples were exposed to elevated temperatures in air with a clear effect of oxidation. If proper corrosion protection is applied, the losses with time are only due to the magnetic viscosity.

Magnetic viscosity is known to be a statistical relaxation phenomenon due to thermal fluctuation in the non-equilibrium state of the material [14]. Time dependence of the magnetization (M) as a function of time (t) and magnetic field (H) is described by a logarithmic law [11]:

$$M(t,H) = M(t_0,H) - S(H)\ln\frac{t}{t_0} \qquad (1)$$

Where S is a phenomenological magnetic viscosity constant and t_0 is a reference time. Wohlfarth et al. [15] have determined the magnetic viscosity constant as:

$$S = \frac{kT}{\upsilon K} f(H,T) M_S \qquad (2)$$

Where kT represents the temperature dependency (k is Bolzmann constant, T is temperature), υK (υ is the activation volume, K is the anisotropy constant) depends on the material and its microstructure and $f(H,T)$ is a complicated function, which describes the precise nature of the magnetization process. Thus, magnetization losses over time in permanent

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B. Effect of Temperature

Fig. 2 shows the magnetization losses for material 2 (see Table I) samples with three different Pc values at three different temperatures. When Pc = 3.3, time dependent losses are very small even at 150°C. No significant differences between samples in different temperatures. The total loss after 30 years is expected to be less than 3 %. When Pc = 1.1, clear losses start to occur at 150°C. However, at 120°C and 80°C, losses stay under 3 % in 30 years' time. When Pc = 0.33, clear losses occur at as low as 120°C.

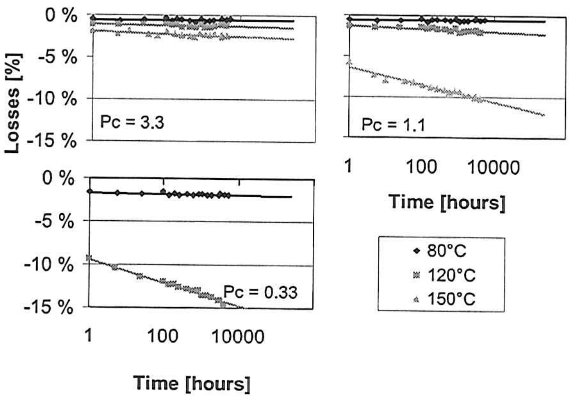

Fig. 2. Flux losses as a function of time for material 2 with room temperature coercivity of 1600 kA/m when Pc = 3.3, 1.1 and 0.33.

C. Effect of Coercivity

Fig. 3 compares the losses of different materials at 150°C. When the Pc = 3.3 all three materials are fairly stable. Losses in 30 years are less than 3 % for all these materials. When the Pc = 1.1, losses in material 2 increase to about 12 % in 30 years. The two other materials show very small losses. When the Pc = 0.33, the total loss after 30 years in material 2 drops to about 32 % and it falls outside the scale. The initial loss in the other two materials is minor. In any event, losses over time in material 3, increases the total loss to approximately 6 %.

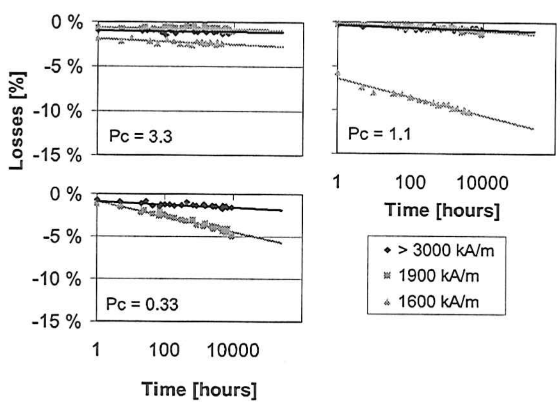

Fig. 3. Flux losses at 150°C as a function of time for materials 2-4 with different room temperature coercivities when Pc = 3.3, 1.1 and 0.33.

D. Effect of Stabilization Heat Treatment

Fig. 4 compares the loss behavior of stabilized and unstabilized samples at 80°C. The Pc of the samples was 0.33. The trend curve for losses in stabilized samples is more horizontal, but the difference between these curves is very small. Losses over 2 % for both stabilized and unstabilized samples measured after 9 000 hours of exposure indicates, however, that horizontal loss trend of stabilized samples will change in some point to the downward trend.

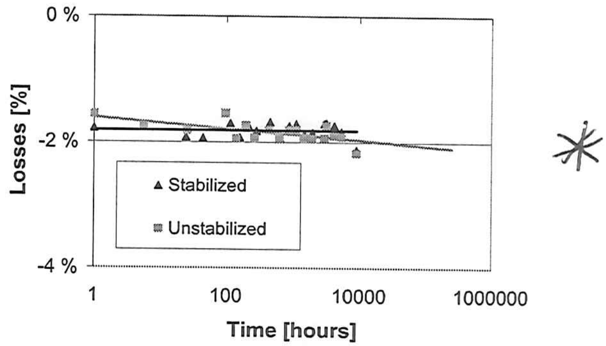

Fig. 4. Loss trends for unstabilized and stabilized samples of material 2 at 80°C when Pc = 0.33.

IV. Discussion

The obtained trend curves for flux losses show clearly the division of the irreversible losses into two categories. The intersection point of the trend curve with the loss axis represents the loss occurring immediately at a certain temperature, term $M(t_0)$ in (1). The following trend curve defines the losses over time, $S*ln(t/\ t_0)$ in (1). Both terms depend on the coercivity of the material, the permeance coefficient of the magnetic circuit and the temperature. The results also show that when an immediate loss occurs, there will also be losses over time. However, if the immediate loss is negligible, the following losses with time are not necessarily negligible: for example, in fig. 3 the losses with time in material 3 (at 150°C when Pc = 0.33) will exceed 5 % in 30 years time.

A dramatic difference in the loss behavior of different sized magnets (i.e. different Pc values) can be detected. Near the closed circuit condition (Pc = 3.3), losses stay within 3 % in material 1 (Hci = 1240 kA/m at room temperature) until 120°C and in other materials until 150°C. When the Pc is reduced to 1.1, materials with lower coercivities start to show severe losses at temperatures over 120°C. With a Pc = 0.33, losses occur at as low as 80°C.

Trout [16] has pointed out that there is a lack of clear definition of the term "maximum operating temperature" for permanent magnets at the moment. Maximum working temperature values given for different materials might be misleading, since the amount of flux loss also depends strongly on the permeance coefficient of the circuit. One expects no losses at the given maximum working temperature. For example, for Chinese magnet grade M, with a minimum coercivity of about 1200 kA/m, the maximum working

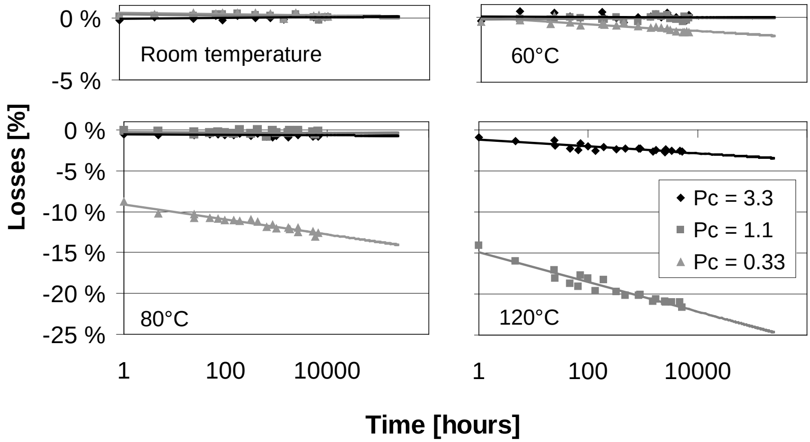

Figure 20. Flux losses as a function of time at room temperature, 60°C, 80°C and 120°C for material I (1) with a room temperature coercivity of 1240 kA/m. *(Publication I, © 2009 IEEE)*

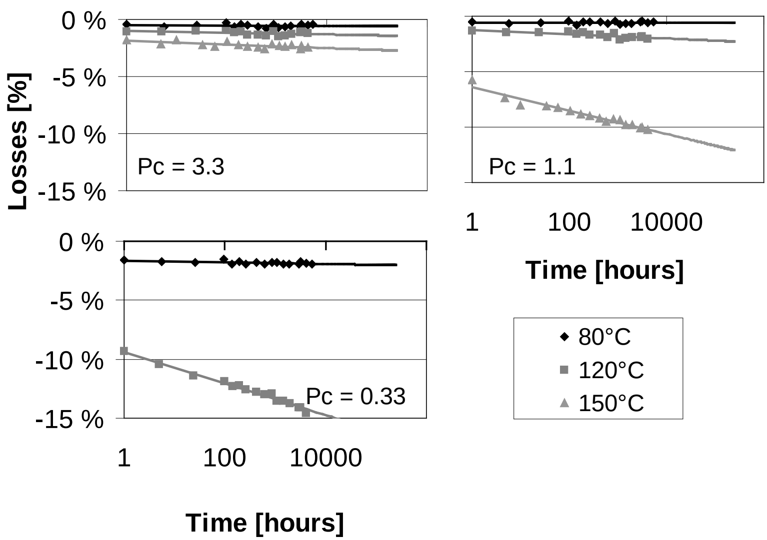

Figure 21. Flux losses as a function of time for material I (2) with a room temperature coercivity of 1600 kA/m in samples with P_c = 3.3, 1.1 and 0.33. *(Publication I, © 2009 IEEE)*

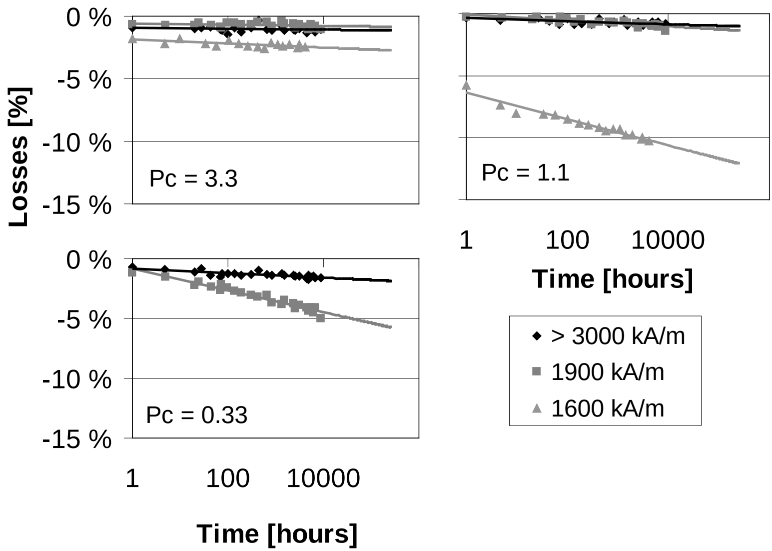

Figure 22. Flux losses at 150°C as a function of time for materials I (2, 3 and 4) in samples with P_c = 3.3, 1.1 and 0.33. *(Publication I, © 2009 IEEE)*

5.1.1 Effect of temperature

Material I (1) was further tested at 90°C, 100°C and 110°C to get more detailed information about the effect of temperature on the time-dependent losses. In Fig. 23, loss trends at five different exposure temperatures are presented. Fig. 24 shows the development of the initial loss and the magnetic viscosity coefficient *S* according to Equation (1) as a function of temperature. The Figure reveals that the time-dependent losses start at a lower temperature than the immediately occurring losses. Coefficient *S* grows fast as the temperature rises but seems to saturate to a certain level at higher temperatures.

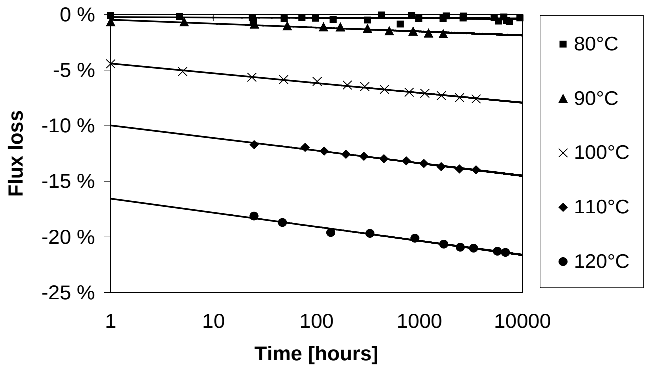

Figure 23. Flux losses as a function of time at different temperatures. Material II, P_c of the samples is 1.1. *(Publication II, © 2010 IEEE)*

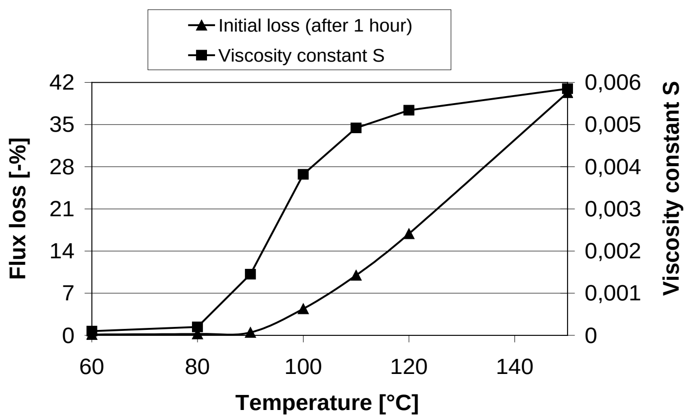

Figure 24. Comparison of the changes in the immediate loss and the viscosity coefficient S as a function of temperature. *(Publication II, © 2010 IEEE)*

The estimated losses after different exposure times can be calculated from the trend curves shown in Fig. 23. In Fig. 25, the estimated losses after 30 years, after 1 hour, after 1 second, and after 10 milliseconds are presented as a function of temperature. At 100°C there are losses of about 5 % after 1 hour exposure, and after 30 years these losses can be estimated to be almost 10 %. If the same trend is expected to continue also to the time scale of seconds or even milliseconds, one can notice that after 10 ms the losses would be negligible.

The magnetic properties of permanent magnet materials are measured typically by a hysteresis-graph, in which the reverse field is increased and the measurements are performed at about 10 ms time intervals. This suggests that even though there is no demagnetization detected at certain conditions in the *BH* curve measurement, there might occur significant time-dependent demagnetization in the magnet in the long run. If the expected losses at a certain temperature are calculated only according to the measured *BH* curves as in [97], it includes an assumption that the duration of the fault condition of the application is limited to a millisecond range. The calculations are not valid for longer exposures.

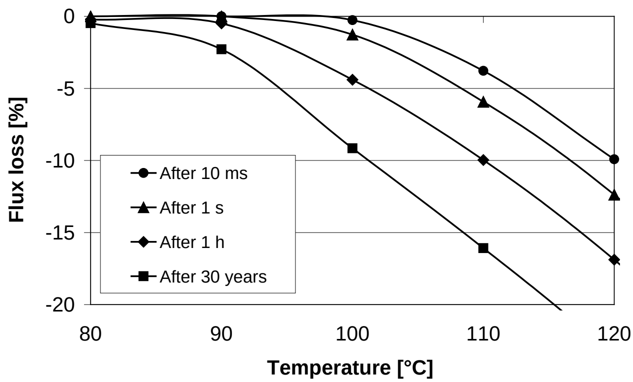

Figure 25. Estimated flux losses as a function of temperature in material II magnets with a room temperature coercivity of 1240 kA/m and permeance coefficient of 1.1. *(Publication II, © 2010 IEEE)*

5.1.2 Effect of the coercivity of the material

The previous Section describes the behavior of one material with one sample shape at different temperatures. To find out whether this type of behavior is typical for other NdFeB materials as well, similar exposure tests were performed for three materials having different coercivities. The trend curves of the detected losses are presented in Fig. 26. For each material there is a maximum temperature at which the total loss even after 30 years is expected to be negligible. This temperature is here denoted by T_0. The T_0 temperatures for the tested materials are listed in Table 3.

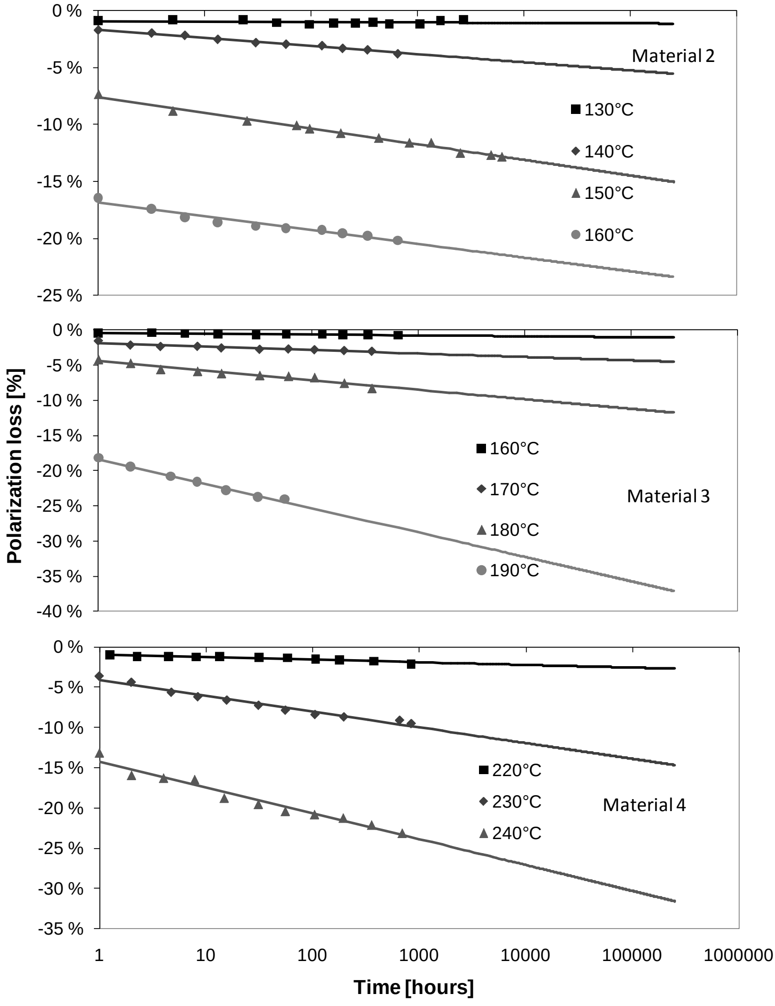

Figure 26. Polarization losses measured as a function of time in magnets with a permeance coefficient of 1.1 produced from materials III (2, 3, and 4). *(Publication III, © 2010 IEEE)*