# Magnetizability of Nd-Fe-B-type magnets with Dy additions

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Many alloying additions have been made into Nd-Fe-B-type magnets to alter their permanent magnet properties, in particular for applications above 100 °C. To this end, a common practice has been to add Dy, increasing $H_{ci}$ [M. Sagawa, S. Fujimura, H. Yamamoto, H. Matsuura, and K. Hiraga, IEEE Trans. Magn. **20**, 1584 (1984); M. Tokunaga, M. Meguro, M. Endoh, S. Tanigawa, and H. Harada, *ibid.* **20**, 1964 (1985)]. It is not unusual to find $H_{ci} > 20$ kOe in these substituted alloys. This approach has caused a dilemma. In some cases, increasing $H_{ci}$ above 20 kOe makes the alloy more difficult to magnetize and therefore less useful when the field available for magnetizing is 25 kOe or less. We have examined the effect of various alloying additions and heat treatment on the magnetizability of substituted Nd-Fe-B alloys. We show that high $H_{ci}$ at room temperature is not a necessary requirement to have $H_{ci} > 6$ kOe at 150 °C. We discuss the factors affecting the magnetizability of Nd-Fe-B-type magnets.

## INTRODUCTION

The applied field required to saturate a permanent magnet from the thermally demagnetized state is of some practical importance to users of permanent magnets. Most users of rare-earth–iron and rare-earth–cobalt materials would like to delay saturating a magnet until after final assembly of the magnet into the magnetic circuit. Unfortunately, saturation at this stage is more difficult for two reasons. First, a larger diameter coil is usually required to saturate after assembly because the assembly is usually larger than the individual magnet. Second, the assembly itself can act as a flux shunt, directing flux away from the magnet. Consequently, it is often not possible to saturate a magnet after assembly. It is desirable to know the minimum field to saturate a given alloy.

Normally one considers the field required to saturate a material as a property that is measured in the first quadrant of a complete $M$ vs $H$ curve. However, trying to measure the minimum field required to saturate a permanent magnet in this way creates three problems. First, the final approach to saturation is generally very gradual, making it difficult to accurately determine the minimum field required for saturating. Second, often large fields of over 100 kOe are necessary to see full saturation, which are not generally available. Third, from a practical point of view, the material is saturated when full second quadrant properties are developed. We have chosen to examine this problem by studying the second quadrant $M$ vs $H$ curves, after exposure to a given magnetizing field. The minimum field for saturation can be usually determined to ± 1–2 kOe.

## EXPERIMENT

The alloys and magnet samples used in this study were made by conventional vacuum melting and powder metallurgy techniques. The sintering and heat treating cycles used to prepare the samples have been previously reported.[1] Second quadrant magnetization curves were drawn after a thermally demagnetized sample was exposed to a given magnetizing field.

In a strict sense, we can say a material is saturated by a given field, when applying a larger field does not change the measured second quadrant properties. From a practical standpoint, saturation can be claimed when the measured properties are a significant percentage of their potential values. We have chosen 98% as this value for subsequent discussions.

## RESULTS

Data for a sample of $Nd_{0.86}Dy_{0.14}(Fe_{0.92}B_{0.08})_{5.5}$ are given in Table I and Fig. 1. The magnetic properties are given as a function of magnetizing field. The data show that, as the magnetizing field increases, $B_r$ develops rapidly, while $H_k$, $H_{ci}$, and $(BH)_{max}$ develop more slowly. We have concentrated on the measured $H_k$ as an indication of saturation. This sample is saturated at a field of 15 kOe.

In Fig. 2, the dependence of the measured $H_k$ on the applied magnetizing field for a series of

$$Nd_{1-x}Dy_x(Fe_{0.845}Co_{0.06}B_{0.08}Nb_{0.015})_{5.5}$$

samples is plotted. For $x$ up to 0.1, these samples saturate at 15 kOe. At higher levels of $x = 0.12$–$0.2$, 20 kOe is required

TABLE. I. Magnetic properties at 23 °C vs applied field for a sample of $Nd_{0.86}Dy_{0.14}(Fe_{0.92}B_{0.08})_{5.5}$.

| $H_{appl}$ (kOe) | $B_r$ (kG) | $H_c$ (kOe) | $H_k$ (kOe) | $H_{ci}$ (kOe) | $(BH)_{max}$ (MG Oe) |
|---|---|---|---|---|---|
| 5 | 10.3 | 5.0 | 0.75 | 15.8 | 11.6 |
| 7 | 11.25 | 8.9 | 3.4 | 19.5 | 23.9 |
| 10 | 11.7 | 10.8 | 15.0 | 20.5 | 31.4 |
| 15 | 11.8 | 11.3 | 19.9 | 20.6 | 33.4 |
| 20 | 11.8 | 11.3 | 19.5 | 20.4 | 33.4 |
| 25 | 11.8 | 11.4 | 19.8 | 20.5 | 33.5 |
| 80 (pulse) | 11.86 | 11.3 | 19.8 | 20.9 | 33.6 |

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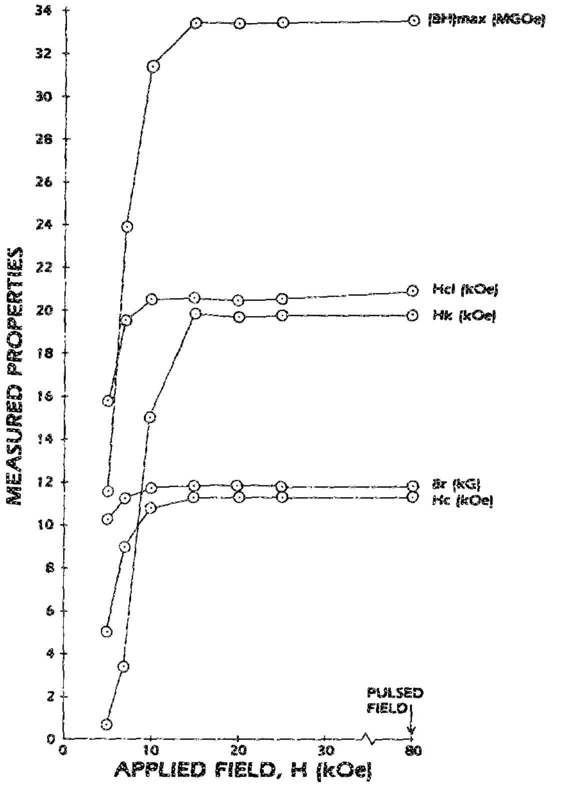

FIG. 1. Measured magnetic properties vs applied field for a sample of $Nd_{0.86}Dy_{0.14}(Fe_{0.92}B_{0.08})_{5.5}$.

for saturation. As $x$ varies from 0 to 0.2, the field required to saturate increases only slightly, while $H_k$ more than doubles.

The field required for saturation also depends on heat treatment. In Fig. 3, the dependence of $H_{appl}$ and the measured $H_k$ on final heat treatment temperature $T_2$ is shown for a sample of

$$Nd_{0.8}Dy_{0.2}(Fe_{0.851}Co_{0.06}B_{0.08}Nb_{0.009})_{5.5}.$$

Demagnetization curves as a function of temperature, from 23 up to 200 °C are shown in Fig. 4 for a sample with $T_2 = 580$ °C. This sample is remarkable in that it has $H_{ci} = 6.7$ kOe at 150 °C and can still be saturated by an applied field of 20 kOe.

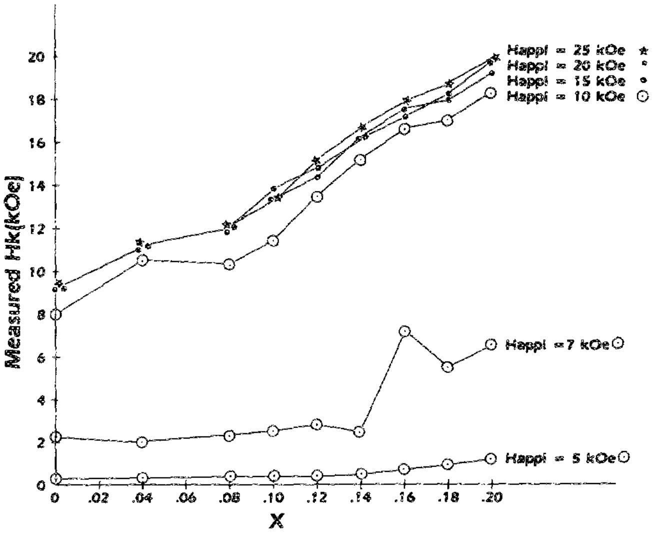

FIG. 2. Measured $H_k$ at indicated applied field levels vs dysprosium content for $Nd_{(1-x)}Dy_x(Fe_{0.845}Co_{0.06}B_{0.08}Nb_{0.015})_{5.5}$.

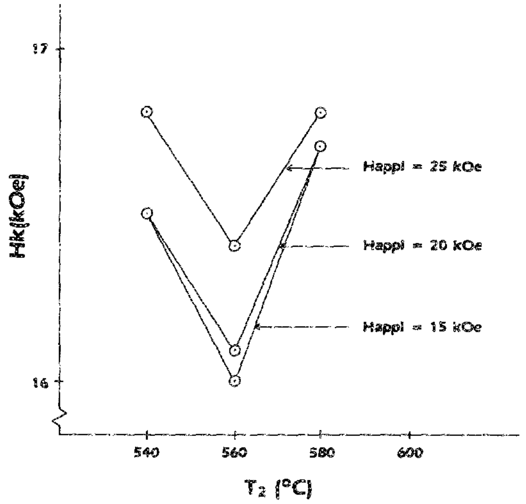

FIG. 3. Measured $H_k$ at indicated applied field levels vs $T_2$ heat treating temperature for a sample of $Nd_{0.8}Dy_{0.2}(Fe_{0.851}Co_{0.06}B_{0.08}Nb_{0.009})_{5.5}$.

## DISCUSSION

The data show that saturation can be achieved at fields that are generally less than $H_{ci}$. Earlier data indicated that fields at least comparable to $H_{ci}$ are necessary for saturation.[2–4] All the samples studied were saturated at 20 kOe or less. The measured values of $H_k$ and $H_{ci}$ compared to their maximum values, are excellent indicators of saturation. Heat treatment also influences slightly the field required for saturation. The sample in Figs. 3 and 4 demonstrates that it is possible to have a material that saturates at 15–20 kOe and that it is not necessary to have $H_{ci}$ over 25 kOe at room temperature to have a useful permanent magnet at elevated temperatures. Other processing parameters also influence the ease of saturation in these materials, such as degree of alignment, particle size and shape, which have been held as constant as possible for this study.

Because several processing parameters as well as composition affect the ease of saturation, it is difficult to model this behavior in a meaningful way. From a fundamental point of view, changes in magnetization are controlled by the relative ease of domain wall motion in a thermally demagnetized sample. In contrast, $H_{ci}$ is controlled by the field

TABLE. II. Magnetic properties at various temperatures for a sample of $Nd_{0.8}Dy_{0.2}(Fe_{0.851}Co_{0.06}B_{0.08}Nb_{0.009})_{5.5}$.

| Temp. (°C) | $B_r$ (kG) | $H_c$ (kOe) | $H_k$ (kOe) | $H_{ci}$ (kOe) | $(BH)_{max}$ (MG Oe) |
|---|---|---|---|---|---|
| 23 | 11.4 | 10.9 | 17.1 | 20.1 | 31.1 |
| 50 | 11.0 | 10.6 | 14.8 | 16.6 | 29.9 |
| 75 | 11.0 | 10.3 | 12.2 | 13.55 | 28.4 |
| 100 | 10.75 | 9.85 | 10.2 | 11.0 | 27.1 |
| 125 | 10.5 | 8.55 | 8.25 | 8.8 | 25.8 |
| 150 | 10.2 | 6.6 | 6.4 | 6.7 | 24.0 |
| 175 | 9.8 | 5.0 | 4.9 | 5.0 | 21.9 |
| 200 | 9.45 | 3.6 | 3.6 | 3.6 | 19.0 |

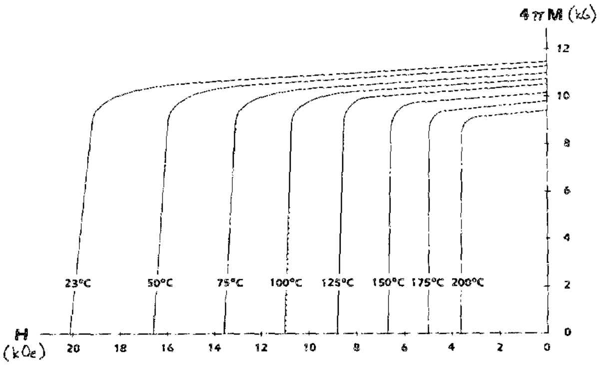

FIG. 4. Second quadrant magnetization curves for a sample of $Nd_{0.8}Dy_{0.2}(Fe_{0.851}Co_{0.06}B_{0.08}Nb_{0.009})_{5.5}$ at various temperatures.

required to nucleate or unpin domain walls. Saturation can be thought of as the removal of all domain walls. The final act in the process of saturation is to sweep all domain walls into the grain boundary. Our data indicate that the field required to remove a domain wall is less than the field required to nucleate or unpin a domain wall. It seems that alloying additions influence ease of saturation by controlling the motion of domain walls at or near grain boundaries.

## CONCLUSION

We have shown that the field required to saturate Nd-Fe-B-type magnets is a function of composition and heat treatment. Looking at the second quadrant magnetization curve is a practical method for determining the minimum field to saturate a sample. Dy additions tend to increase the field required for saturation slightly. The value of $H_{ci}$ at room temperature does not predict the field required for saturation, yet the relative value of $H_k$ or $H_{ci}$ at a given applied field be used to determine saturation. Also the $H_{ci}$ at room temperature cannot generally be used to predict $H_{ci}$ at an elevated temperature.

This information can be useful to users of these magnets, provided the data are used as the basis for additional studies to determine the actual requirement for a given alloy, process, and magnetic circuit.

[1] M. Tokunaga, M. Meguro, M. Endoh, S. Tanigawa, and H. Harada, IEEE Trans. Magn. **21**, 1964 (1985).
[2] M. Sagawa, S. Fujimura, N. Togawa, H. Yamamoto, and Y. Matsuura, J. Appl. Phys. **55**, 2083 (1984).
[3] F. E. Pinkerton and D. J. Van Wingerden, J. Appl. Phys. **60**, 3685 (1986).
[4] E. Adler and W. Fernengel, paper GC-07, Intermag 1986 (unpublished).