Using Permanent Magnets at Low Temperatures

The performance of permanent magnets generally deteriorates as the temperature increases; a fact we usually learn early in our experience with permanent magnets. And with the exception of the H_{ci} in hard ferrites, this is an accurate generalization. But what happens below room temperature? What is important to know, if we plan to use magnets at low temperatures? Let's first review the general situation and each of the popular permanent magnet materials.

Two generally beneficial changes occur in permanent magnets as the temperature decreases. First, the B_r increases, as is typical with most ferromagnetic materials. The effect is usually small, just a few percent, as the temperature decreases to absolute zero, but it improves $(BH)_{max}$ about twice as much. Second, H_{ci} increases, except notably with hard ferrite. This effect can be far more dramatic; H_{ci} can double or triple between room temperature and absolute zero. Behind the increase in H_{ci} is a corresponding increase in the anisotropy with falling temperatures.

Magnetizing

The field required to saturate a magnet increases as the H_{ci} increases, although the relationship is not well defined. For this discussion, we will assume that any magnets are magnetized at room temperature, before exposure to cryogenic temperatures. This is not to say that magnetizing at cryogenic temperatures is impossible, just that it requires extra care to assure the magnets are saturated.

Hard Ferrite (Ceramic)

Ferrites have a unique characteristic: the H_{ci} decreases as the temperature decreases. By the time a ceramic magnet has cooled to –60 ºC/213 K/-76 ºF, it has already lost about one-third of its room temperature H_{ci}. In addition, Parker and Studders [1] report a mild irreversible loss of flux after exposure to –60ºC, presumably brought on by the reduced H_{ci} at that temperature. Therefore, using ferrite magnets below –60 ºC is not usually recommended.

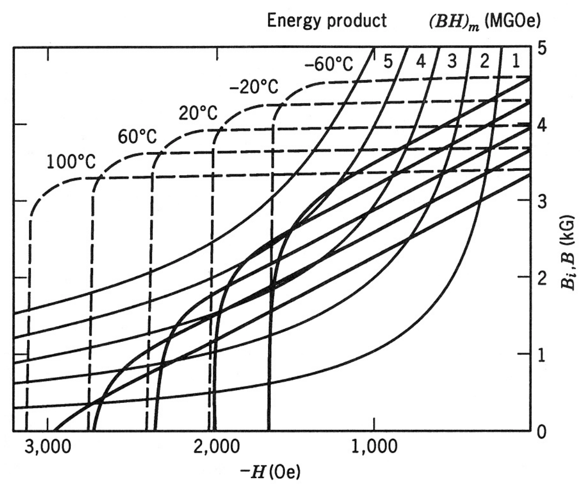

Figure 1. Demagnetization Curves for Ceramic 5 at Various Temperatures

Alnico

As shown in Figure 2, Alnico magnets do not show much sensitivity to temperature, in terms of their demagnetization characteristics. However, Parker and Studders [1] report an irreversible loss in magnetization, up to 10%, after exposure to –190 ºC/ 83 K/ -310°F. Besides temperature, this loss

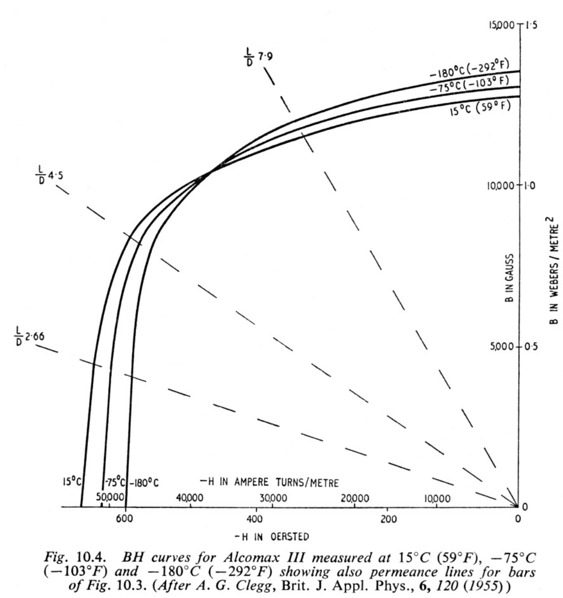

Figure 2. Demagnetization Curves for Alnico 5 at Various Temperatures. [1]

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depends strongly on the self-demagnetizing stress seen by the magnet as a function of its geometry and the magnetic circuit. Without specific and detailed evaluation, -75 ºC/198 K/-103 ºF is a reasonable lower limit for alnico.

Samarium Cobalt

Both the $SmCo_5$ and the Sm_2Co_{17} types of samarium cobalt magnets do quite well at cryogenic temperatures. The H_{ci} increases significantly as shown in Figure 3. The B_r increases modestly. Numerous references report the successful use of samarium cobalt to temperatures as low as 2 K [3 4,5,6].

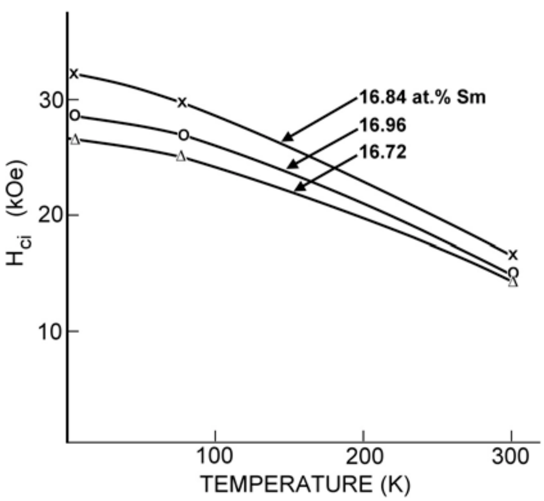

Figure 3. A Plot of H_{ci} vs. Temperature for Three $SmCo_5$ Samples. [3]

Neodymium-Iron-Boron (NdFeB, "Neo")

Like SmCo, NdFeB magnets increase in flux output and in H_{ci} as temperature decreases, with one important distinction: NdFeB undergoes a spin reorientation as temperature falls. Most reports put this transition temperature at –138 ºC/135 K/-216 ºF. Spin reorientation refers to a change in the preferred direction of the magnetization. NdFeB changes from a uniaxial or easy-axis material to an easy-cone material, as shown in Figures 4 and 5. The transition is due to an unusual combination of anisotropy constants and other factors. Generally, easy-cone anisotropy is considered less desirable for a permanent magnet because the magnet is easier to demagnetize.

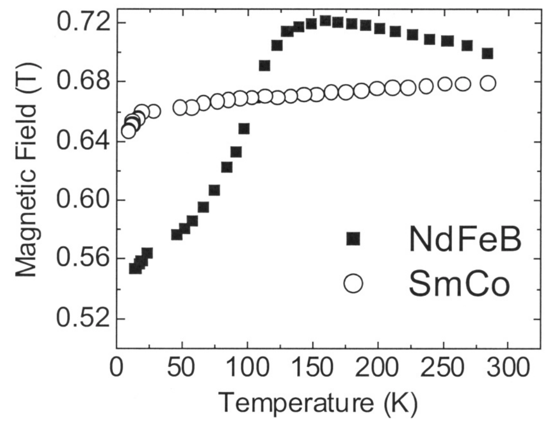

Figure 4. Magnetic Field as a Function of Temperature for NdFeB and SmCo. [6]

Does spin reorientation disqualify the use of NdFeB at low temperatures? It probably does not. While the transition from easy-axis to easy-cone anisotropy is an interesting theoretical phenomenon, it is not as important in a practical sense. Most researchers find that the canting angle Φ of the easy cone is never more than 30º [7]. The component of flux parallel to the c-axis is reduced by the cosine of the canting angle, i.e.

$$\cos \Phi \geq \cos 30^\circ = 0.866$$

meaning the flux is reduced by no more than 14%. Furthermore, the flux loss is recovered when the magnet warms up, so it is not a permanent loss. In most cases, spin reorientation would appear to be a minor concern. However, anyone planning to use NdFeB at cryogenic temperatures should be aware of this effect and design accordingly. See Figure 5.

Conclusion

While using permanent magnets below room temperature is much less troublesome that using them at elevated temperatures, it is still important to understand how materials behave in the temperature range of the application to avoid unpleasant surprises.

References

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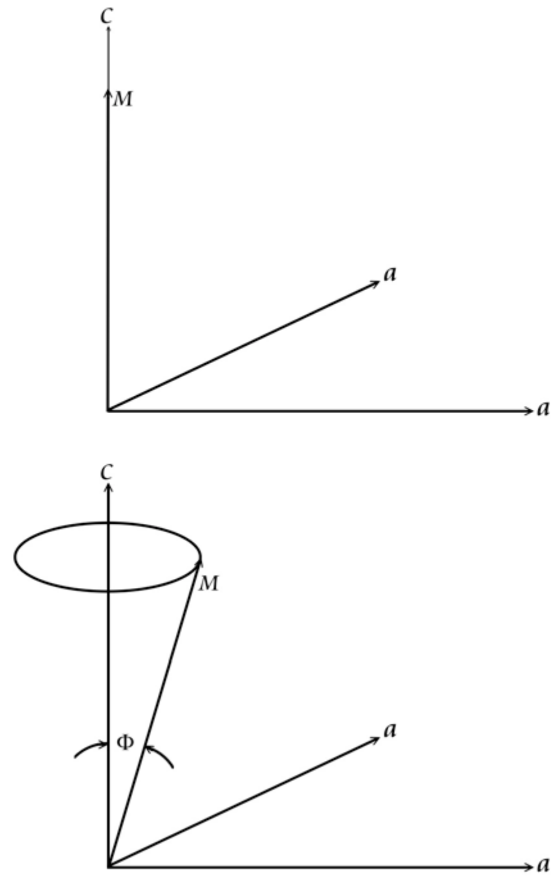

Figure 5. Orientation of the Magnetization for an Easy Axis or Uniaxial Anisotropy (top); Easy Cone Anisotropy with a Canting Angle Φ (bottom)

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