Using Permanent Magnets at Low Temperature

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 Hci 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 Br 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, Hci increases, except notably with hard ferrite. This effect can be far more dramatic; Hci can double or triple between room temperature and absolute zero. Behind the increase in Hci is a corresponding increase in the anisotropy with falling temperatures.

Magnetizing

The field required to saturate a magnet increases as the Hci 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 Hci 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 Hci. In addition, Parker and Studders [1] report a mild irreversible loss of flux after exposure to -60 ºC, presumably brought on by the reduced Hci at that temperature. Therefore, using ferrite magnets below -60 ºC is not usually recommended.

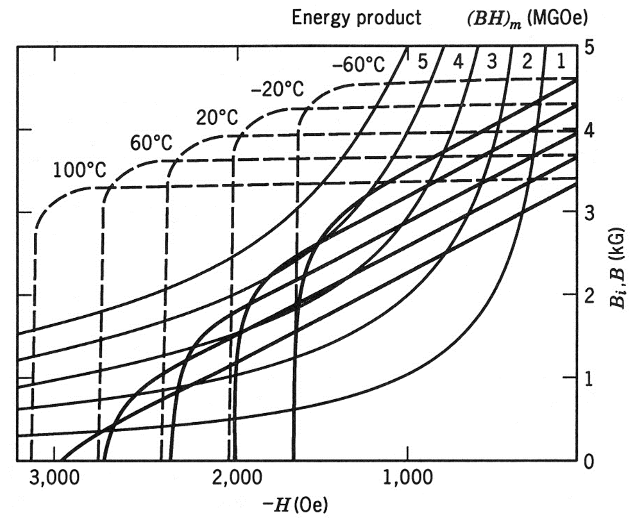

Figure 1. Demagnetization Curves for Ceramic 5 at Various Temperatures

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%,

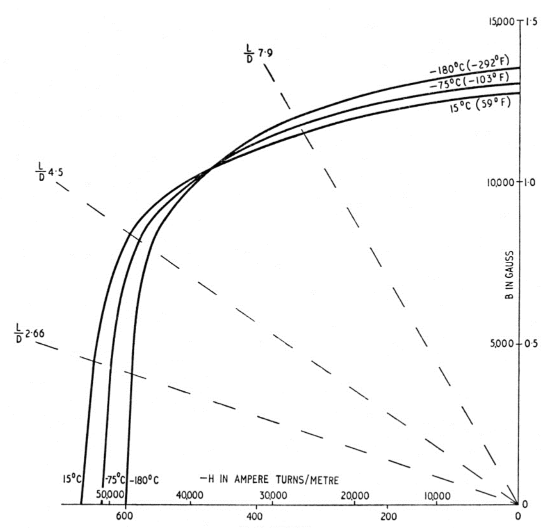

Fig. 10.4. BH curves for Alcomax III measured at 15°C (59°F), −75°C (−103°F) and −180°C (−292°F) showing also permeance lines for bars of Fig. 10.3. (After A. G. Clegg, Brit. J. Appl. Phys., 6, 120 (1955))

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

after exposure to -190 ºC (83 K, -310 °F). Besides temperature, this loss 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 Hci increases significantly as shown in Figure 3. The Br increases modestly. Numerous references report the successful use of samarium cobalt to temperatures as low as 2 K [3,4,5,6].

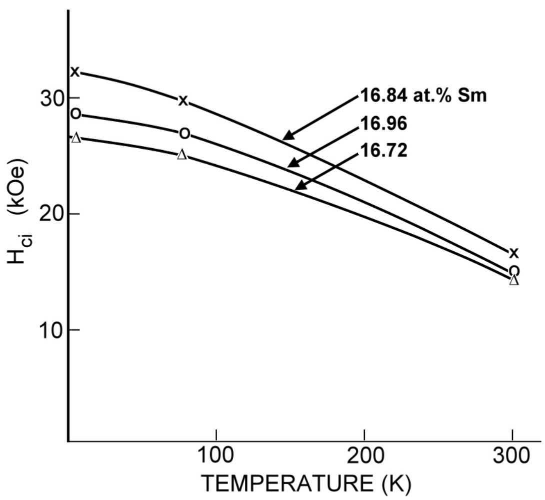

Figure 3. A Plot of H_{ci} vs. Temperature for Three $SmCo_5$ Samples. [3]

Neodymium-Iron-Boron (NdFeB, "Neo")
Like SmCo, NdFeB magnets increase in flux output and in Hci 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.

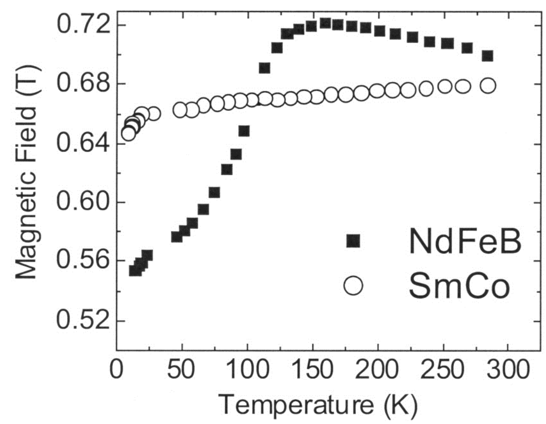

Figure 4. Magnetic Field as a Function of Temperature for NdFeB and SmCo. [6]

Generally, easy-cone anisotropy is considered less desirable for a permanent magnet because the magnet is easier to demagnetize.

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.

$$\cos \Phi \geq \cos 30^{o} = 0.866$$

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.

Praseodymium has been substituted for part or all of neodymium in Neo magnets creating a material with lower magnetization (flux output) at room temperature but avoiding the spin reorientation. 80% substitution by praseodymium provides magnets that perform successfully down to at least 10 Kelvin [8]. These formulations are being produced by a limited number of companies for use in Cryogenic Permanent Magnet Undulators (CPMUs) [9].

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

1. *Permanent Magnets and Their Application*, Rollin J. Parker and Robert J. Studders, John Wiley & Sons, New York, 1962.
2. *Advances in Permanent Magnetism*, Rollin J. Parker, John Wiley & Sons, New York, 1990.
3. *High Field Magnetic Measurements on Sintered $SmCo_5$ Permanents*, S.R. Trout and C.D. Graham, Jr., AIP Conference Proceedings, vol. 29, p.608, 1975.
4. *A New Small Nano-Kelvin Resolution Thermometer for Low-Temperature Experiments,* Paul Welander, Martin Barmatz, and Insoeb Hahn, IEEE Transactions on Instrumentation and Measurement, vol. 49, no. 2, April 2000.
5. *High Field p-Ge Laser Operation in Permanent Magnet Assembly*, C.J. Fredricksen, E.W. Nelson, A.V. Muravjov, R.E. Peale, Infrared Physics and Technology, July 2002.
6. *High and Low Temperature Properties of Sintered Nd-Fe-B Magnets*, K.J. Strnat, D. Li, and H. Mildrum, Paper no. VIII-8 at the 8th International Workshop on Rare Earth Magnets and Their Applications, Dayton, OH, 6-8 May, 1985.
7. *Orbital Magnetic Moment Instability at the Spin Reorientation Transition of $Nd_2Fe_{14}B$*, L.M. Garcia, J. Chaboy, F. Bartolomé and J. B. Goedkoop, Physical Review Letters, vol. 85, p. 429, 2000.
8. *Sintered (Pr,Nd)-Fe-B permanent magnets with (BH)max of 520 kJ/m3 at 85 K for cryogenic applications*, Uestuener et al, REPM 2008
9. *Praseodymium iron-boron undulators with textured dysprosium poles for compact X-ray FEL applications*, Agustsson et al, Proceedings of IPAC2012, MOPPP086

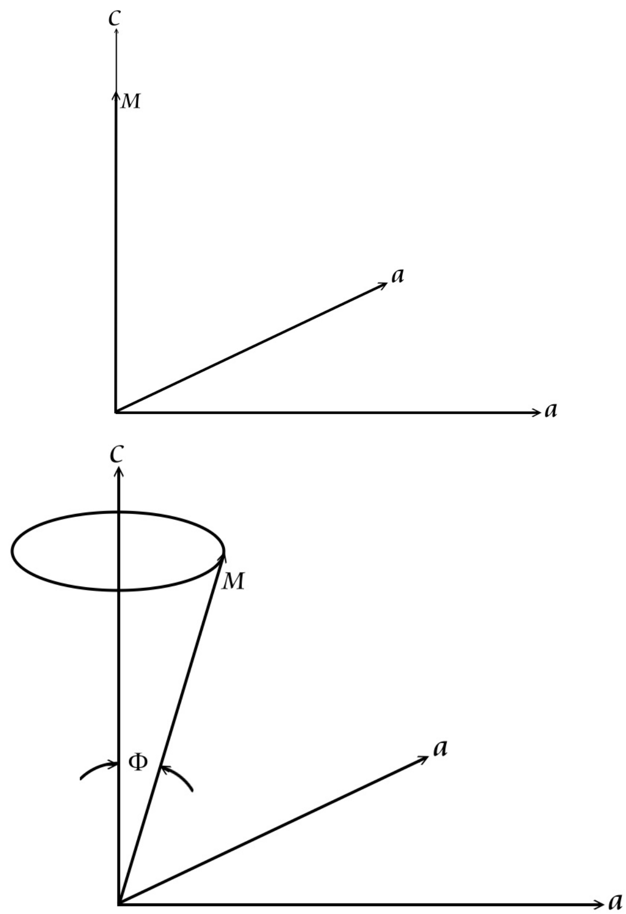

Figure 5. Orientation of the Magnetization for an Easy Axis or Uniaxial Anisotropy (top); Easy Cone Anisotropy with a Canting Angle Φ (bottom)

Written in 2003 for Arnold by Stanley R. Trout, Ph.D, P.E.
strout@ieee.org • www.spontaneousmaterials.com
Revised and updated in 2015 by Steve Constantinides

ARNOLD® MAGNETIC TECHNOLOGIES

770 Linden Avenue • Rochester • NY 14625 USA
800-593-9127 • (+1) 585-385-9010 • Fax: (+1) 585-385-9017
E-mail: infoNA@arnoldmagnetics.com
www.arnoldmagnetics.com