High grade Sm(Co,Fe,Cu,Zr)$_z$ permanent magnets

Sm-Co magnets with higher residual (remanent) magnetic induction, Br, and density of magnetic energy or maximum energy product, $(BH)_{max}$, are of great benefit for many applications such as motors, generators, actuators, isolators, circulators, accelerometers and other magnetic devices. EEC has developed a superior 2:17 Sm(Co,Fe,Cu,Zr)$_z$ magnet grade with upper values of $(BH)_{max}$ exceeding 33 MGOe, Br > 11.8 kG and H_{ci} > 24 kOe, grade that can operate up to 300°C depending on the characteristics of the magnetic circuit design. The properties of EEC 2:17-34 grade exceed those of EEC 2:17-33 and EEC 2:17-31 grades as noted in Table 1 below.

Table 1. Top high grades of 2:17 Sm(Co,Fe,Cu,Zr)$_z$ permanent magnets.

Magnetic Properties of Sm-Co Magnets

Magnet Grade	Maximum Energy Product $(BH)_{max}$				Residual Induction B_r				Coercivity H_c				Intrinsic Coercivity $_iH_c$				RTC of B_r (1)	Max. Operating Temp.(2)
	MGOe		kJ/m³		kG		T		kOe		kA/m		kOe		kA/m		%/°C	°C
	typ	min	typ	min	typ	min	typ	min	typ	min	typ	min	typ	min	typ	min	typ	typ
Sm_2Co_{17} Magnets																		
EEC 2:17-34	34	32	271	255	11.9	11.70	1.19	1.17	11.1	10.8	884	860	20	18	1592	1432.8	-0.040	300
EEC 2:17-33	33	31	263	247	11.65	11.40	1.17	1.14	10.9	10.4	868	828	20	18	18	1433	-0.040	300
EEC 2:17-31	31	29	247	231	11.50	11.20	1.15	1.12	10.7	10.2	852	812	>24	24	20	1592	-0.035	300

What's the limit of the magnetic properties?

The theoretical limit of $(BH)_{max}$ is difficult to estimate as it depends on the specificity of the composition and structural morphology of the Sm(Co,Fe,Cu,Zr)$_z$ magnets. Maximizing Br, while maintaining a relatively high intrinsic coercivity H_{ci} and squareness of the demagnetization curve is the key towards reaching a higher $(BH)_{max}$. Sm(Co,Fe,Cu,Zr)$_z$ magnets have a very complicated subgranular microstructure consisting of Sm2(Co, Fe)17 nanocells with Sm(Co, Cu)5 cell boundaries, intersected by Zr-rich nanolamella. The composition, size and defects or strains of these microstructure features, along with the level of impurities (e.g. samarium oxide) and crystallographic texture (or alignment) are the main factors that influence the magnetic hysteresis parameters. The saturation magnetization of the Sm_2Co_{17} phase is about 12 kG. With the addition of Fe, the saturation magnetization increases to about 13.5 kG for $Sm_2(Co_{0.8}Fe_{0.2})_{17}$ [1]. Considering that the remanent magnetic induction (or remanent magnetization) equals the saturation magnetization and also with a very rough estimation [2] the amount of this high magnetization Sm2(Co, Fe)17 phase is about 90 vol% (note that Sm(Co, Cu)5 phase may also have a saturation magnetization above 7 kG), one can estimate that Br of Sm(Co,Fe,Cu,Zr)$_z$ magnets will never exceed 12.5 kG.

Table 2 summarizes the performance of the main rare earth based permanent magnet materials, as reported by the industry or in scientific articles. A great deal of effort has been put on the research on nanocomposite magnets containing besides the main hard (permanent) magnetic phase also a soft magnetic phase that allows for much higher Br values, but the theoretical predictions have not been achieved yet.

Table 2. Comparison of density of magnetic energy $(BH)_{max}$ for rare earth based permanent materials.

Permanent magnet		$(BH)_{max}$			
		$Nd_2Fe_{14}B$	$Sm_2(Co,Fe)_{17}$	$SmCo_5$	$Sm_2Fe_{17}N_x$
Conventional permanent magnets	In mass production	54	33-34	24	14
	Highest reported value	59.3[3]	34[4]	25[5]	47[6]
	Theoretical prediction (for single phase structures)	64[7]	52[8]	32.5[9]	59.3[10]
Nano-composite	Theoretical prediction	86[11]	N/A	65[12]	137[13]

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Comparison of temperature dependence of magnetic properties with other permanent magnets

Currently, the performance of Neo magnets at temperatures up to 150°C is superior, and, as long as the market still permits, and with the development of new grain boundary engineering technology that minimizes the needed amount of Dy for high temperature operation, these magnets will dominate their respective applications area. However, for applications at temperatures above 180°C, $Sm(Co,Fe,Cu,Zr)_z$ magnets become the best option. Fig. 1 and Table 3 below show a direct comparison between the magnetic hysteresis parameters of Nd-Dy-Fe-B and $Sm(Co,Fe,Cu,Zr)_z$ magnet grades with different maximum operating temperatures.

Figure 1. Comparison of the magnetic properties of selected sintered Nd-Fe-B and Sm-Co magnets at temperatures up to 250°C.

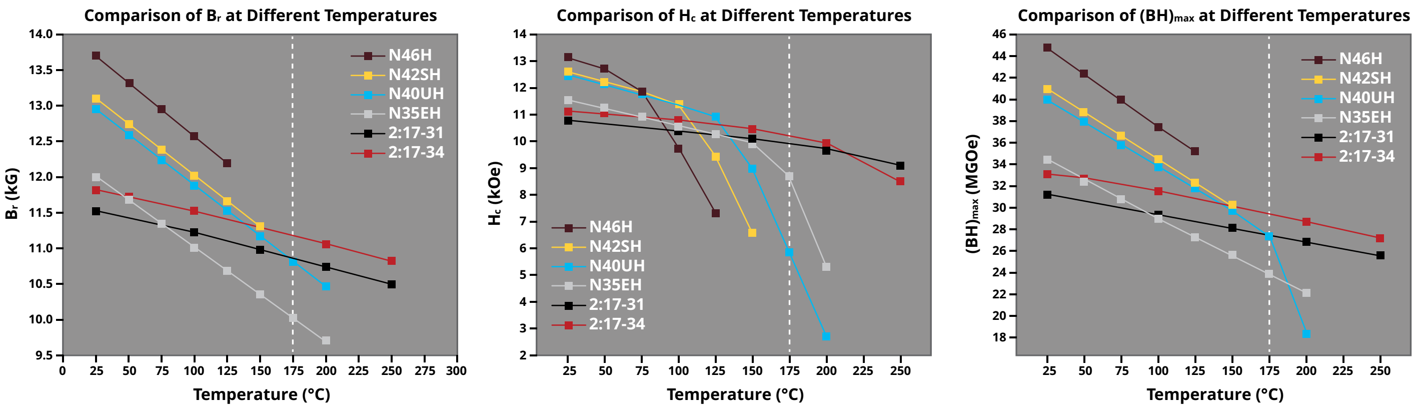

Table 3. Summary of the magnetic properties of selected sintered Nd-Fe-B and Sm-Co magnets at 25°C and elevated temperatures.

Temperature (°)	B_r(kG)			H_{ci}(kOe)			$(BH)_{max}$ (MGOe)		
	25	200	240 - 250	25	200	240 - 250	25	200	240 - 250
N28EH	10.8	9	8	>30	7	4	28	<20	<16
N35EH	12	9.69	N/A				34.7	22.15	N/A
SmCo 2:17-31	11.52	10.74	10.5	>25	14.33	11.25	31.45	26.95	25.65
SmCo 2:17-34	11.81	10.95	10.63	>18	10.74	8.16	33.25	27.88	26.12

References

[1] A. E. Ray and K. J. Strnat, Research and development of rare earth – transition metal alloys as permanent magnet materials, Technical Report AFML-TR-72-202, 1972

[2] M.F. de Campos et al., Magnetic characterization of the (Zr,Sm)Co3 phase in $Sm(CoFeCuZr)_z$ magnets, Journal of Applied Physics 101, 09K101, 2007

[3] 1. Y. Matsuura, "Recent development of Nd-Fe-B sintered magnets and their applications," J. Magn. Magn. Mater. 303 (2006) 344.

[4] S. Liu and A.E. Ray, " $Sm_2(Co,Fe,Cu,Zr)_{17}$ magnets with higher Fe content," IEEE Trans. Magn. 25 (1989) 3785.

[5] 3. S. Foner, E.J. McNiff, D.L. Martin, M.G. Benz, "Magnetic properties of Cobalt-Samarium with a 24-MGOe energy product" Appl. Phys. Lett. 20 (1972) 447.

[6] 4. R. Arlot, H. Izumi, K. Machida, D. Fruchart, G. Adachi, " Particle size dependence of magnetic properties for zinc-coated $Sm_2(Fe_{0.9}Co_{0.1})_{17}N_{2.9}$ powders," J. Magn. Magn. Mater. 172 (1997) 119.

[7] K.H.J. Buschow, "New developments in hard magnetic materials," Reports on Progress in Physics 40 (1991) 1179.

[8] K.J. Strnat, "Rare earth - cobalt permanent magnets," In Ferromagnetic Materials, E.P. Wohlfarth and K.H.J. Buschow (Eds.), North-Holland, Amsterdam, vol. 4 (1988) 131.

[9] A.V. Korolev, A.S. Yermolenko, A.Y.Yermakov, A.V. Antonov, L.M. Magat, G.M. Makarova, "Influence of deviation from stoichiometric composition on the magnetic properties of the compounds YCo_5 and $SmCo_5$," Fiz. Met. Metalloved. 39 (1975) 1107.

[10] J.M.D. Coey, H. Sun, "Improved magnetic properties by treatment of iron-based rare earth intermetallic compounds in amonia," J. Magn. Magn. Mater. 87 (1990) L251.

[11] H. Fukunaga, "Computer simulation of magnetic properties of anisotropic nanocomposite magnets," IEEE Trans. Magn. 36 (2000) 3285.

[12] R.F. Sabiryanov, S.S. Jaswal, "Magnetic properties of hard/soft composites: $SmCo_5/Co_{1-x}Fe_x$" Phys. Rev. B 58 (1998) 12 071.

[13] R. Skomski and J.M.D. Coey, "Giant energy product in nanostructured two-phase magnet," Phys. Rev. B, 48 (1993) 15812.

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