# The Role of Cobalt in NdFeB Permanent Magnets

Neodymium iron boron (“Neo”) permanent magnets, discovered in 1980 and commercialized by 1984, remain the strongest magnets known to man – at least near room temperature.

All magnets experience a change in properties as a function of temperature. As the Neo magnet temperature increases, both intrinsic coercivity, $H_{cJ}$, and magnetic field strength, $B_r$, decrease. Over a limited temperature range, these changes are non-destructive and reversible and are quantified by what are called Reversible Temperature Coefficients of Induction, $\alpha(B_r)$, and Intrinsic Coercivity $\alpha(H_{cJ})$. These coefficients are the average rate of change between temperature limits. The changes are non-linear so it is necessary to state the temperature range over which the coefficients are calculated.

To permit Neo magnets to operate at elevated temperatures, two composition changes are introduced.

1. The substitution of the heavy rare earth elements (HREEs) dysprosium and/or terbium for a portion of the neodymium increases the anisotropy field. This provides higher room temperature intrinsic coercivity and reduces the rate at which coercivity drops as temperature increases – smaller reversible temperature coefficient of (intrinsic) coercivity.
2. Substitution of cobalt for a portion of iron raises the magnet Curie temperature, Tc, and reduces the rate at which magnetic field strength, B, changes as a function of temperature.

This **TECH**Note focuses on the effects of cobalt on magnet Curie temperature, residual induction, intrinsic coercivity and corrosion resistance.

### Curie Temperature

Both ferro- and ferrimagnetic materials exhibit a phenomenon wherein their behavior changes from strongly magnetic to weakly magnetic (paramagnetic) above a certain temperature. This critical temperature is called the Curie point or Curie temperature, $T_c$. Exchange interaction that is responsible for strong spontaneous magnetism is diminished by thermal agitation with concomitant reduced magnetic field strength until $T_c$ at which point the strength is reduced to near zero. The naturally ferromagnetic elements iron, cobalt and nickel have Curie temperatures of 770, 1130 and 358 °C respectively. Figure 1 shows field strength as a function of temperature and illustrates how it increasingly declines as $T_c$ is approached.

While Figure 1 shows individual elements, Figure 2 shows the effect of adding cobalt to NdFeB. Figure 3 is a compilation of information from US patents (4975130; 4792368; 5110377; 5230749; 5645651) and industry data compiled by Arnold over a period of two decades.

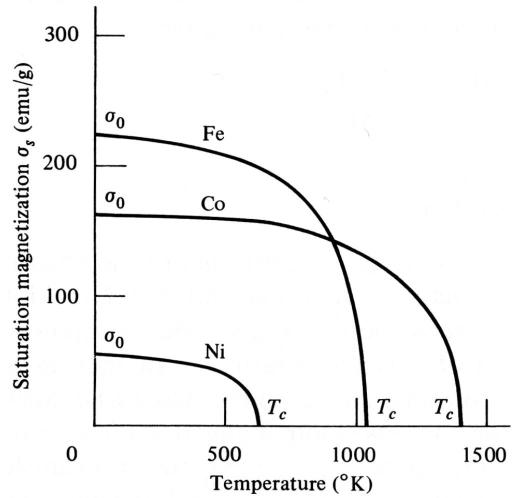


**Figure 1.** Magnetic field strength of iron, cobalt and nickel as a function of temperature. [1]

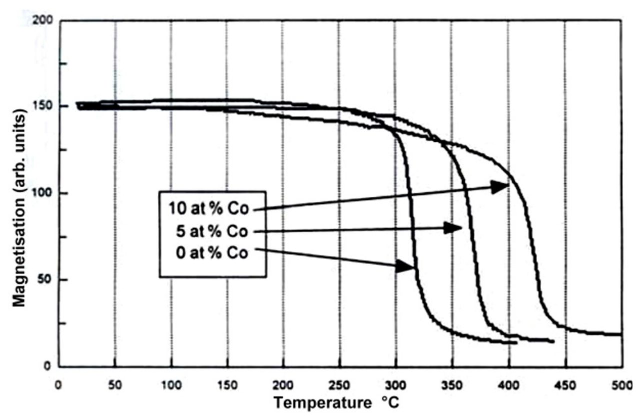


**Figure 2.** Magnetization versus magnetic field strength for NdFeB magnets with three levels of cobalt. [2]

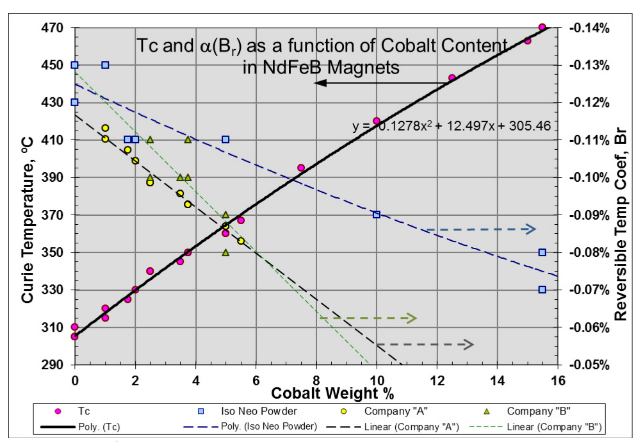


**Figure 3.** Curie temperature and reversible temperature coefficient as a function of cobalt content. Data from US patent 4975130 and industry sources.

 

Included in Figure 3 are data from three industry sources for reversible temperature coefficient of induction, $\alpha(B_r)$, showing that as the cobalt content increases and the Curie temperature rises, the $\alpha(B_r)$ becomes smaller indicating reduced loss of induction with rising temperature. Values shown are for temperature change from 20 to 150 °C.

**Cobalt and Coercivity**
Although cobalt has been successful at reducing $\alpha(B_r)$ in both sintered and bonded magnets, in sintered magnets it was found to reduce coercivity. In the early 1990s experiments determined that adding a small percentage of copper (about 0.2 to 0.3 weight percent) resulted in measurably improved intrinsic coercivity with negligible reduction of $B_r$ despite the presence of cobalt.

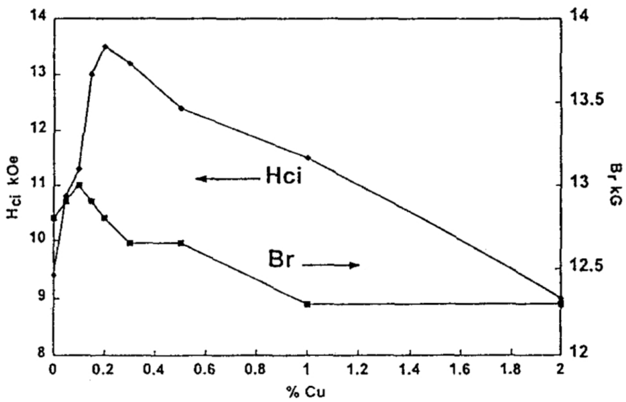


**Figure 4.** Cobalt plus copper addition effect on residual induction ($B_r$) and intrinsic coercivity ($H_{cJ}$). [3]

**Corrosion Resistance**
Cobalt has also been found to reduce the corrodibility of Neo magnets as measured by irreversible loss after exposure to elevated temperatures. The irreversible loss is reduced by the inclusion of copper and by the combination of copper and cobalt as per Figure 5.

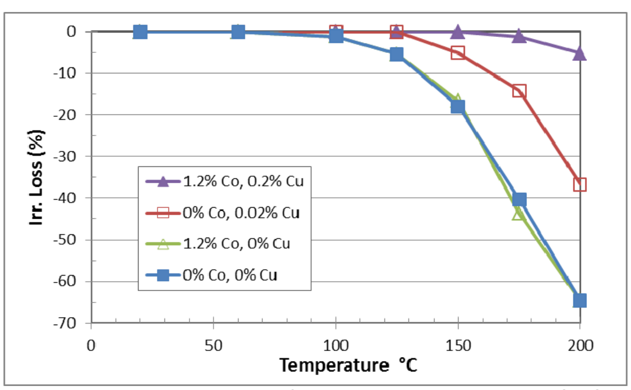


**Figure 5.** Irreversible losses of 30.5Nd-2.5Dy-1.1B-bal(Fe,Co,Cu) magnets as a function of Cu and Co content. [3]

Another measure of corrodibility is the bulk corrosion test wherein unmagnetized magnets are placed in a steam autoclave at elevated temperature and pressure for periods of up to 96 hours. Kim and Camp report the following results (see Table 1).

**Table 1.** Corrosion rates (weight losses) of 33Nd-1.1B-xCo-yCu-Bal Fe magnets after autoclave tests at 110-115 °C for 96 hours. [3]

| % Co | % Cu | Wt. Loss ($mg/cm^2$) |
|---|---|---|
| 0 | 0 | 203.3 |
| 5.0 | 0 | 17.5 |
| 0 | 0.15 | 18.3 |
| 1.2 | 0.15 | 0.15 |

Cobalt in Neo magnets can also be successfully combined with aluminum [4, 5], used in combinations of Pr and Co [6], combinations of Co, Cu, and Al [7], and more complex alloys such as Pr-Fe-Co-Cu-Nb-B [8].

**Summary**
Cobalt use by itself in Neo magnets results in a higher Curie temperature and reduced reversible temperature coefficient of induction, $\alpha(B_r)$. When combined with selected elements, additional benefits include better corrosion resistance and reduced irreversible loss at elevated temperatures.

**References**
1. *Introduction to Magnetic Materials*, B.D. Cullity; Addison-Wesley Publishing Company, 1972, ISBN: 0-201-01218-9; p.122
2. *Magnetic Properties, Curie Temperature and Microstructures of RFeB Based Magnets with Additives by Blending*, A. Ahmad, I.R. Harris; 2007; a variation of this paper was published in *Magnetics Business & Technology*, Spring 2006
3. *Effect of Minor Grain Boundary Additives on the Magnetic Properties of NdFeB Magnets*, A.S. Kim, F.E. Camp; IEEE Transactions on Magnetics, Vol. 31, No. 6, November 1995
4. *Magnetic Properties of Nd-Fe-B Magnets with both Co and Al Addition*, T. Mizoguchi, I. Sakai, H. Niu, K. Inomata; IEEE Transactions on Magnetics, Vol. MAG-23, No. 5, September 1987
5. *Coercive Force of Co added Nd-Fe-B Based Powders Prepared by Crushing Sintered Magnets*, I. Sakai, A. Tsutai, M. Sahashi, K. Inomata; IEEE Transactions on Magnetics, Vol. 26, No. 5, September 1990
6. *Improvement of the thermal stability of sintered Nd-Fe-B magnets by intergranular addition of $Pr_{34.4}Co_{65.6}$*, C. Jin, R. Chen, W. Yin, X. Tang, Z. Wang, A. Yan, D. Lee; INTERMAG 2015, AS-04
7. *Dysprosium Diffusion Behavior and Microstructure Modification in ?Sintered Nd-Fe-B Magnets via Dual-Alloy Method*, C. Lin, S. Guo, W. Fu, R. Chen, D. Lee, A. Yan; IEEE Transactions on Magnetics, Vol. 49, No. 7, July 2013
8. *The Influence of Cobalt Content on the Magnetic Properties and Corrosion of PrFeCoCuNbB Sintered Magnets*, J.D. Angelo, H. Takiishi, I. Costa, R.N. Faria, C. Motta; 18th Workshop on High Performance Magnets & Their Applications, Annecy, France, 2004; P. 159

 

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**