

LOSSES IN SINTERED NdFeB MAGNETS

W. KAPPEL¹, M. M. CODESCU¹, D. POPA²

R&D Institute for Electrical Engineering – Advanced Research – ICPE – CA Splaiul

Unirii 313, sector 3, Bucharest - 74204, Romania

Tel. 01/346.72.35; 01/346.72.31, Fax: 01/346.82.99; 01/346.72.83

e-mail: kappel@icpe-ca.ro; mcodescu@yahoo.com

² South Airport Otopeni, e-mail: dragospopa@pcnet.ro

Abstract: The sintered and bonded NdFeB permanent magnets are very interesting for their high coercivity and magnetic specific energy, as well as by opening new applications domains leading to miniaturization and improvement of performances of magnetic conventional systems. Applications with permanent magnets used in aerospace industry and special industries that used special conditions, function about 213K/333K. The thermal stability can be increased by increasing the Curie temperature, the intrinsic coercivity and choosing an optimal working point (an optimum I/D rapport). The increasing of Curie temperature for the NdFeB can be done by a partial substitution of Fe by Co. The Co influences favorable the dependence of remanent induction from the temperature, having also a minor effect on the anisotropy field. The increase of intrinsic coercivity can be done by substituting partially Nd by Dy, as well as by adding transition elements like V, Mo, Al, Cr, elements that have influences on the microstructure.

Key words: NdFeB magnets, magnetic properties, losses at temperature

1. INTRODUCTION

The sintered and bonded NdFeB permanent magnets are very interesting for their high coercivity and magnetic specific energy [1,2], as well as by opening new applications domains leading to miniaturization and improvement of performances of magnetic conventional systems.

Despite their outstanding magnetic properties at room temperature, the use of the NdFeB magnets has been limited due to two essential reasons:

- the low temperature coefficient of the intrinsic coercivity leads to quite low maximum operating temperatures (around 120°C);
- the oxidation of the unavoidable Nd-rich phase, which plays a great role in the coercivity mechanism, leads to a bad corrosion resistance of these magnets.

For precision applications we need to know the amount of the change of open circuit flux with time and how this change is affectedly elevated or sub-zero temperatures.

The studies done until present deals with the increasing of thermal stability and corrosion resistance of these magnets, very important properties in developing industrial

applications. The thermal stability, characterized by the reversible and irreversible losses, can be increased by:

1. Increasing the Curie temperature, which can be done, in the case of NdFeB magnets, by a partial substitution of Fe with Co. The Co influences favorable the dependence of remanent induction from the temperature, having also a minor effect on the anisotropy field;
2. Increasing of the intrinsic coercivity, which can be done by substituting partially Nd by Dy, as well as by adding transition elements like V, Mo, Al, Cr, elements that have influences on the microstructure [3]. An other way to influence the intrinsic coercivity is the processing of permanent magnets from hydrogenated powders, fact that ensure fine grains [4];
3. Choosing an optimal working point (an optimum l/D rapport) [5].

2. EXPERIMENTAL

The NdFeB alloys, with/without-adding elements, were processed in the vacuum induction furnace, from industrial quality pre-alloys and pure Co. The powders, obtained by decrepitation, followed by grinding, were pressed in an exterior magnetic field, perpendicular to the pressing direction. The compacted were sintered and then treated in Ar.

Table 1
The magnetic characteristics for the NdFeB studied magnets

Code	Magnet composition	B_r (kGs)	B_{H_c} (kOe)	jH_c (kOe)	$(BH)_{max}$ (MGOe)
1	$Nd_{35.4}Fe_{62.3}B_{1.3}$	11.26	8.20	8.80	26.00
2	$Nd_{34.5}Dy_{1.5}Fe_{61.5}$ $Al_{1.2}B_{1.3}$	9.00	8.50	> 20.00	> 19.00
3	$Nd_{36}Fe_{58}Co_{3.5}Al_1$, $2B_{1.3} + 5\%$ Dy_2O_3	10.50	9.55	15.60	25.15

In Table 1 are presented the values of magnetic characteristics at room temperature for the investigated magnets and these evidenced the fact that the presence of Dy lead to obtain high coercivity, fact explained by the formation of fine dispersed constituents, stable from the chemical point of view, that influence the microstructure. Increases of coercivity are obtained also by using decrepitated powders.

To study the stability at high temperature we used the followings l/D ratio: 0.2, 0.5, 1. The measurements for the reversible and irreversible losses were done at the temperatures: 50°C, 80°C, 100°C, 130°C and 150°C.

3. RESULTS AND DISCUSSIONS

The results obtained for the reversible and irreversible losses and the coefficients for the variation of induction with the temperature are presented in Table 2 and Fig. 1 ... 6.

Table 2

The coefficients of reversible variation of remanence with the temperature, $\alpha(B_r)$

Magnet composition	T = 100°C		$\alpha(B_r)$	T = 150°C		$\alpha(B_r)$
	P_{rev} (%)	P_{irev} (%)	20 ... 100°C (%/°C)	P_{rev} (%)	P_{irev} (%)	20 ... 100°C (%/°C)
$Nd_{35.4}Fe_{62.3}B_{1.3}$	25.92	22.22	0.32	64.28	59.21	0.49
$Nd_{34.5}Dy_{1.5}Fe_{61.5}Al_{1.2}B_{1.3}$	6.59	0.65	0.08	12.61	0.88	0.09
$Nd_{36}Fe_{58}Co_{3.5}Al_{1.2}B_{1.3} + 5\% Dy_2O_3$	6.47	0.95	0.08	11.83	2.04	0.09

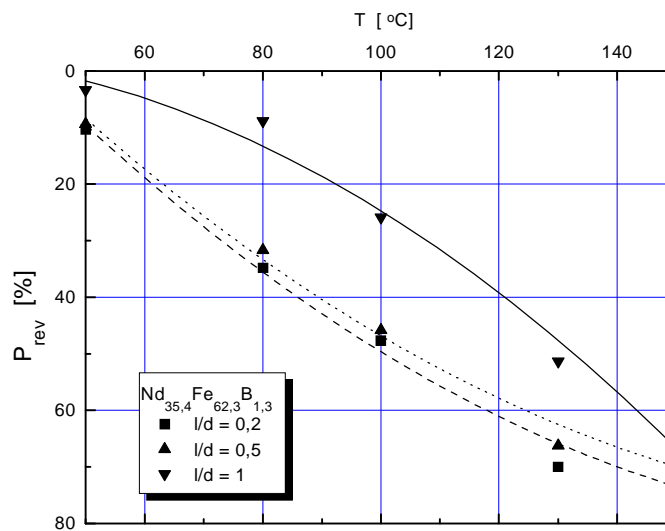


Fig. 1 - Reversible losses vs. temperature at different l/D ratios and temperatures for the $Nd_{34.5}Fe_{62.3}B_{1.3}$ magnets

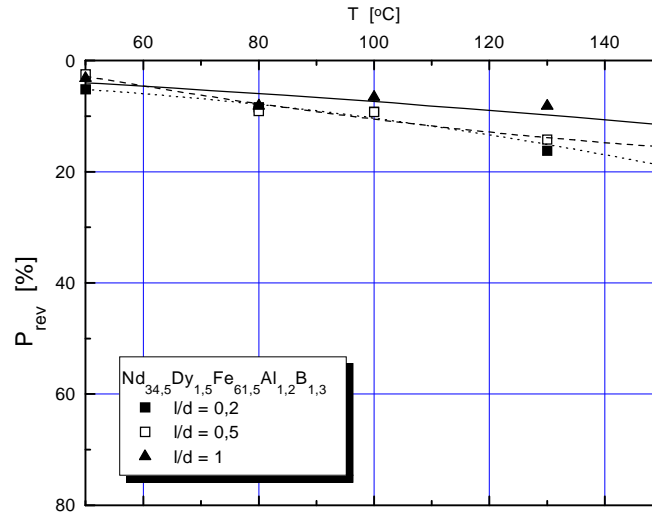


Fig. 2 - Reversible losses vs. temperature at different l/D ratios and temperatures for the $Nd_{34.5}Dy_{1.5}Fe_{61.5}Al_{1.2}B_{1.3}$ magnets

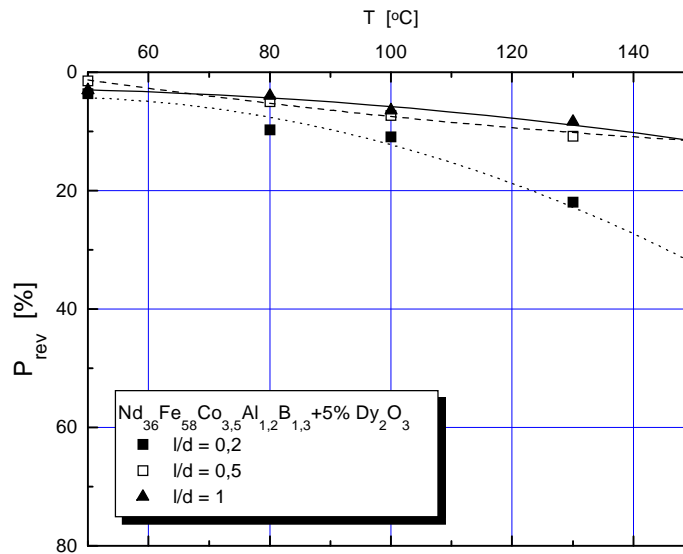


Fig. 3 - Reversible losses vs. temperature for the magnets at different l/D ratios and temperatures $Nd_{36}Fe_{58}Co_{3.5}Al_{1.2}B_{1.3} + 5\% Dy_2O_3$

The lower losses were obtained for a ratio $l/D = 1$. One can observe that the alloy with the higher coercivity ($JH_c \approx 20$ kOe) has the lowest losses.

Losses in sintered NdFeB magnets

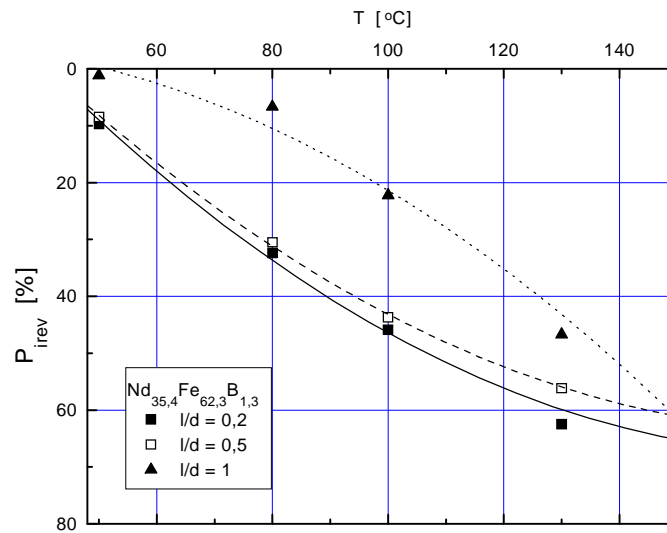


Fig. 4 - Irreversible losses vs. temperature at different l/D ratios and temperatures for the $N_{34,5}Fe_{62,3}B_{1,3}$ magnets

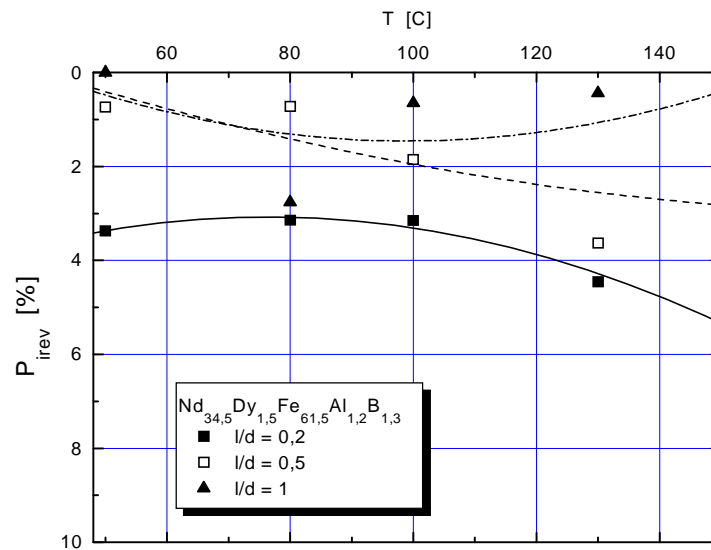


Fig. 5 - Irreversible losses vs. temperature at different l/D ratios and temperatures for the $Nd_{34,5}Dy_{1,5}Fe_{61,5}Al_{1,2}B_{1,3}$ magnets

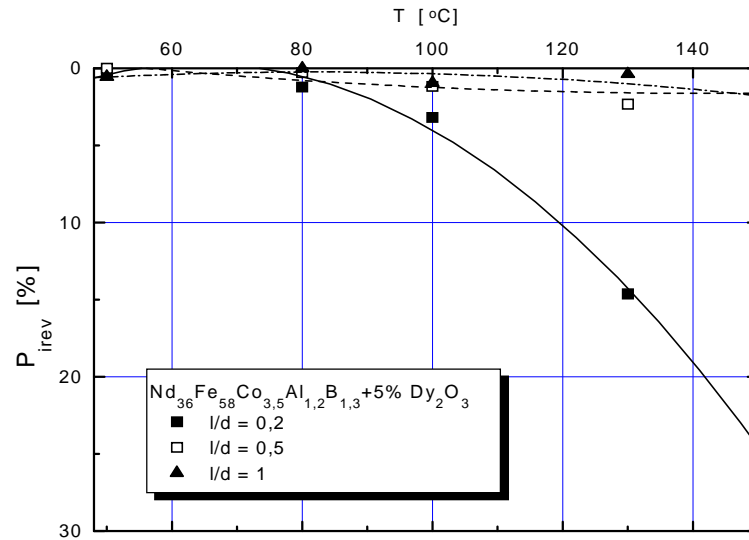


Fig. 6 - Irreversible losses vs. temperature at different l/D ratios and temperatures for the $Nd_{36}Fe_{58}Co_{3,5}Al_{1,2}B_{1,3} + 5\% Dy_2O_3$ magnets

Fig. 7 presents the irreversible losses for two samples, made from the same material - $Nd_{34,5}Dy_{1,5}Fe_{61,5}Al_{1,2}B_{1,3}$ - but with different values for the intrinsic coercivity field. One can observe that the irreversible losses increase with the decreasing of the l/D ratio, fact that must be taken into account when designing magnetic circuits and decrease with the increasing of the intrinsic coercivity of the magnets.

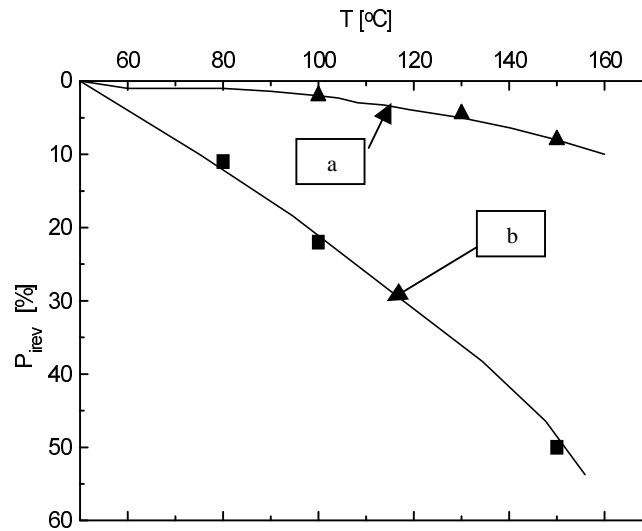


Fig. 7 - Irreversible losses for two $Nd_{34,5}Dy_{1,5}Fe_{61,5}Al_{1,2}B_{1,3}$ magnets:
a) $jH_c = 15.50$ kOe; b) $jH_c = 13.50$ kOe

4. MAGNETIC CIRCUITS WITH PERMANENT MAGNETS IN AERONAUTICAL INDUSTRY

Devices with permanent magnets (Magnetic plugs with or without electrical sensor, super speed detection - magnetic tachometer with signalization, starter generators, special tachometer for transmission and receive, drive in c.c. with permanent magnet for special installation, magnetic compass for navigation, booster (pump) for fuel; gyroscope, close assurance systems, magnetometers, SQUID, magnetic record in "black box") used in aerospace industry who work in special conditions, need correction for any type of device. For more than that in lower or higher temperature case, it's necessarily to acclimatisation.

For magnetic circuits calculations and design in special condition of work it's necessarily to take in considerations the behaviour of this, represented by the variation coefficient of magnetic properties at low or higher temperature who deter the stability in function.

For describe the stability of permanent magnet it's necessarily to analyse next process:

1. **Reversible modifications of induction**, caused by the dependence with temperature from spontaneous magnetization, M_s .
2. **Irreversible losses**. The magnets with rectangular histeresys loops, in case of more 1000 h ageing, present smaller initial irreversible losses. These losses were caused, essentially, by the temperature coercitivity modifications. Irreversible ageing depends on the demagnetisation curve that means from the manufacturing process. If demagnetisation curve is more rectangular and coercitive fields are higher, then the demagnetization losses were smaller.
3. **Structural ageing** is caused by the modifications of surface and/or microstructure because of corrosion.

5. CONCLUSIONS

- (i) The use of Dy as adding elements for the NdFeB alloys lead to significant increases of the intrinsic coercive field and also the utilization of the hydrogenated powders for the permanent magnets manufacturing.
- (ii) As well as the value of the intrinsic coercive field increases the level of irreversible loss decrease.
- (iii) For the same material, the irreversible losses increase with the decreasing of the l/D ratio.
- (iv) For application in aeronautical industry is necessarily for NdFeB sintered alloys to know: the values of magnetic energy product, (BH) max, the profile of the demagnetisation curves $B = B(H)$ and the working conditions (temperature, medium), because the level of losses depends on this parameters.

REFERENCES

1. M. SAGAWA, S. FUJIMURA, H. YAMAMOTO, Y. MATSUURA, S. HIROSAWA, K. HIRAGA, *Magnet Properties and Microstructure of Rare-Earth-Iron-Boron Permanent Magnet Materials*, Proc. of the 4th Int. Symp. on Magn. Anisotropy and Coercivity in Rare-Earth – Transition Metal Alloys, 587 – 611 (1985)
2. J. F. HERBST, J. J. CROAT, W. B. YELON, *Structural and Magnetic Properties of Nd₂Fe₁₄B*, J. Appl. Phys. 57 4086 - 4090 (1985)
3. ST. ALEXANDRU, W. KAPPEL, I. IVAN, M. M. CODESCU, *The Effect of Vanadium Addition on Microstructure and Coercivity of NdFeB Based Magnets*, Romanian Reports in Physics 47, 8-9-10, 767 – 772 (1995)
4. M. M. CODESCU, I. IVAN, W. KAPPEL, *Magnetic Properties of the Hydrogenated NdFeB Powders*, "Romanian Reports in Physics 47 8-9-10, 773 – 778 (1995)
5. M. M. CODESCU, A. PASCALE, A. RUSU-PETROAIA, W. KAPPEL, *Losses in sintered NdFeB magnets with different adding elements*, Proc. of the 3rd Balkanian Physics Union 517 - 520 Cluj-Napoca (1997)