Bulletin of the *Transilvania* University of Braşov
Series I: Engineering Sciences • Vol. 4 (53) No. 2 - 2011

INVESTIGATION PROCEDURE OF MAGNETIC PERFORMANCES OF NdFeB PERMANENT MAGNETS

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Abstract: *The permanent magnet applications based on carbon steel magnets, hard ferrites and AlNiCo magnets classes are renewed with new classes of advanced magnetic materials based on rare earth elements, the Sm-Co and NdFeB types. Performance increase of the hard magnetic materials and their use in specific applications impose also great advances in the field of magnetic measurement. New researches need to be validated in order to investigate the NdFeB permanent magnets performances, including their stability under different thermal operational regimes. In this paper a specific investigation procedure of magnetic performances of NdFeB permanent magnets in correlation with the range of operating temperature is proposed based on modern hysteresisgraph method and impulse magnetization technique.*

Key words: *Hard magnetic materials, magnetic measurements, magnetization process, NdFeB permanent magnets, temperature dependence.*

1. Introduction

Hard magnetic materials have been source of fascination for human perception for millennia. Their practical applications have begun with inventions such as magnetic compass that improved the accuracy of navigation and continued with new revelations in magnetism field. Today, these materials are used in a wide range of technical and social life applications. Relatively recent, the hard magnetic materials applications were imposed in electromagnetism field, in domains like communications, automation, medical treatment, automotive, aviation and spaceflight [12]. In the electrical machines they are used in magnetic circuit excitation.

Hard magnetic materials, known as permanent magnets, are widely extended due to their characteristics such as: large magnetization remanence, high coercive force and high storable magnetic energy density. After the classes of the carbon steel magnets, hard ferrites and AlNiCo magnets, the researches promote since 80's the permanent magnets based on rare earth metals, highlighted due their advantages like small sizes and high power density, which provide moreover compactness of the overall system in which are included. The advanced classes of hard magnetic materials based on rare earth metals are Samarium-Cobalt magnets (Sm-Co) and Neodymium-Iron-Boron (NdFeB) bonded magnets. The favourable interaction between

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inter-metallic phases of rare earth metals and transition metals, together with the evolution of hard magnetic material production technology - raw material preparation, melting casting, pulverizing, pressing, heating treatment, surface treating and coating - provide a positive impact on improving the permanent magnet properties. Permanent magnets with improved characteristics are the sintered NdFeB magnets [2], [10]. The sintered NdFeB have highest magnetic field strength know until present [5].

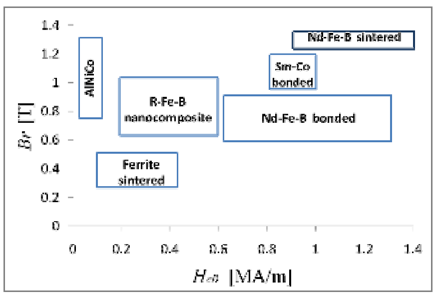

Fig. 1. *Diagram of hard magnetic materials performances*

In Figure 1 it is remarked that the magnetic parameters of sintered NdFeB magnets occupy the highest position, where B_r varying between 1.1…1.3 T and H_{cB} varying between 0.9…1.4 MA/m. New improvements of magnetic properties of NdFeB sintered magnets are done by addition and substitution of different elements in magnetic compound, optimizing the treatment process to provide a specific crystallographic texture and optimal grain size and using new coating techniques [4], [9], [15], [16].

The rare earth magnet classes provide a better efficiency in operation of electrical drives and promote the permanent magnet synchronous machines (PMSM) applied successfully in a large variety of low and medium power applications. Providing an optimal overall machine design oriented to required application, assuring an optimal geometry and an adequate distribution of magnetization in different magnetic circuit sections and using adequate grades of permanent magnet materials assure an efficient PMSM exploitation [1], [3], [14]. In addition, regarding the performances of PMSMs, an adequate range of operating temperature is imposed to be assured. Further, it is required the knowledge of magnetic materials characteristics and their variation with the operating temperature. New experimental data are required in order to improve thermal stability and modelling magnetic characteristics with temperature dependence of NdFeB permanent magnets.

The magnetic material performance imposes also adequate measuring devices. Measuring systems are required to be developed and/or improved correlated with new measurement procedures in order to reach the higher magnetic fields [13].

In this paper, a new investigation procedure of magnetic performance of $Nd_2Fe_{14}B$ permanent magnets using the hysteresisgraph method and impulse magnetization technique is proposed. The sensitivity of permanent magnets with temperature is investigated in the range 25 °C to 120 °C, pertinent for electrical machines operation.

2. Material, Method and Measurement System

The magnetic materials are Φ20 x 15 mm cylindrical samples of sintered NdFeB permanent magnet of N38 type.

The method used in order to investigate permanent magnets performances is the hysteresisgraph method. It consists from determination of magnetic parameters and demagnetization curves of permanent magnets. After every measurement, the magnetic samples are remagnetized with an additional impulse magnetizer. The remagnetization process is required in order to reach the magnetic saturation of the permanent magnetic samples after each magnetic measurement.

The integrated magnetic measurement

system consist from the hysteresisgraph Permagraph with vertical electromagnet EP 3 type (Figure 2) and the impulse magnetizer IM-U-1420 with magnetizing fixture MF-1218 type (Figure 3).

Fig. 2. *Permagraph L with vertical electromagnet and NdFeB sample*

Fig. 3. *The impulse magnetizer system with magnetizing coil and NdFeB sample*

The magnetizing fixture is suitable for parallelepiped or circular magnetic samples with lengths up to 60 mm and diameter up to 30 mm.

2.1. Investigation procedure of magnetic characteristics by hysteresisgraph method

The main part of Permagraph measuring system is the electromagnet whose poles assure magnetization and demagnetization process of the magnetic samples. The maximum field strength generated is of range 2400-2500 kA/m, values over which the soft steel poles of electromagnet are being saturated. The control of electromagnet magnetic field is assured using a personal computer. The Permagraph system allows automatic acquisition and processing of the experimental data. The permanent magnet characteristics are obtained using PERMA soft. The system contains additional heating poles for measurements at higher temperatures. A thermocouple JH-T type is attached to power supply with afferent measuring probe placed inside to heating poles. The measuring process is assured by special measuring coils, type JH26-1 for ambient temperature, and type JHT40-4 for high temperatures in the range 40…200 ºC, rising the intrinsic magnetic field strength *H* [A/m] and magnetic polarization *J* [T].

2.2. Impulse magnetization technique description

Rising of second quadrant demagnetization characteristics using Permagraph system is accompanied by the sample demagnetization. In order to raise a new magnetic characteristic is required to reach the saturation state of magnetic sample.

An additionally impulse magnetizer system is used because the NdFeB permanent magnets require for saturation maximum field strength values more than 4000 kA/m. The magnetization process assured by impulse magnetizer involves large power absorption from the electrical grid. The power is absorbed in a specific bank capacitor C from a rectified power supply T (Figure 4).

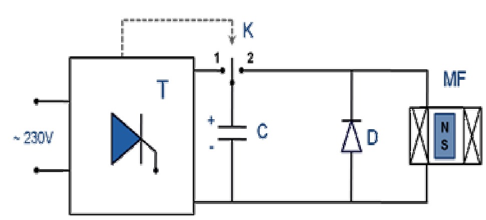

Fig. 4. *Scheme of the impulse magnetizer*

After the magnetic sample is introduced in the magnetization coil MF attached to the impulse magnetizer and the magnetizing voltage is set, a thyristor command discharge the energy stored from capacitor bank into the magnetization coil. The magnetization process in capacitor-discharge impulse magnetizer, in correlation with the location of the operating point of permanent magnet sample [6], [7], [8], [11], consists of:

- The permanent magnet sample is placed inside the magnetizing coil and capacitor C is charging with setting magnetization voltage (Figure 5a). The operating point of magnetic sample is placed between a' and a segment (Figure 6).
- The energy stored in capacitor is transferred in magnetizing coil by switching the breaker switch K on 2 positions (Figure 5b). The diode D is switched off. The operating point is found in b saturation point (Figure 6).
- The magnetization process of magnet sample is ended when the current that traverses MF coil attempts the maximum value and begin to decrease. The breaker switch K is switched on 1 position and the diode D is polarized again, the energy stored in MF coil being dissipate outside.

The sample is removed from the magnetizing coil and fixed between electromagnet poles in order to continue properties investigation (Figure 5c).

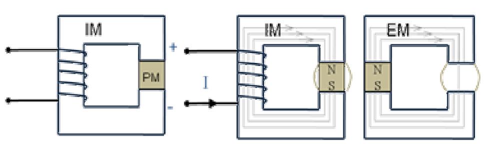

Fig. 5. *The magnetization process*

The operating point of magnetic sample is now placed in c remanence point, and after the introduction in electromagnet EM, is find between c and c' segment (Figure 6).

The operating point is dependent on magnetic state of permanent magnet.

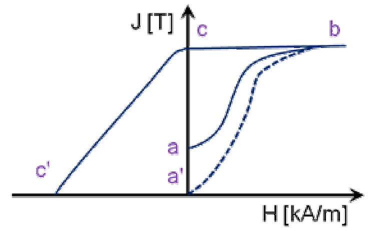

Fig. 6. *The locations of the operating point of permanent magnet sample*

The investigation procedure of magnetic characteristics of NdFeB magnets based on hysteresisgraph method and additional impulse magnetization technique benefit of flexibility and modularity measurement system and assures a high accuracy of magnetic measurements.

3. Experimental Data, Results and Discussion

The magnetic measurements are performed according to IEC 60404-5 standard, that defines the measurement method of the magnetic flux density, the magnetic polarization and the magnetic field strength. The demagnetization curve and recoil line of samples are obtained, with presumption that the magnetic properties are homogeneous throughout their volume.

3.1. Optimal operating parameters of impulse magnetizer

The impulse magnetizer operates in the magnetization voltage range of 100-2000 V. For protection to excessive stresses of impulse magnetizer and for increasing the lifetime of capacitor bank, an optimal value of magnetization voltage should be established and set for each type of magnetic sample.

The specific steps in finding the optimal magnetization level of impulse magnetizer are:

- setting the lower level (100 V) of magnetization voltage and performing a magnetizing operation;

- measuring the degree of sample magnetization using Permagraph system and noting the intrinsic value of magnetic field generated by sample;
- consecutive magnetizing with increased voltage step of 100 V and noting the degree of magnetization at every step, until the difference between the intrinsic magnetic field generated by previous and present magnetized sample is less than 1%. This value correspond to saturation magnetization voltage;
- determining the optimal magnetization voltage, which is 10% increased value of saturation magnetization voltage.

In Figure 7 are shown the results of the process of magnetization and demagnetization of sample with the magnetization voltage values of 600 V, 700 V, ..., 1000 V. After every sample remagnetization the measurement with Permagraph is performed.

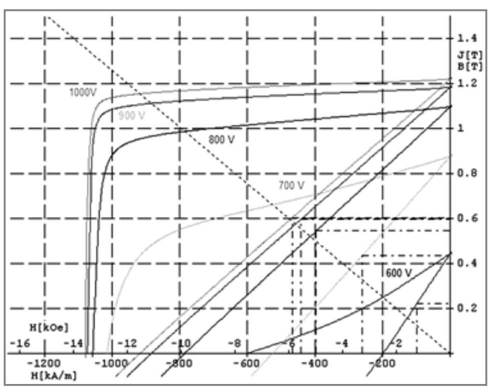

Fig. 7. *Demagnetization curves for NdFeB sample at different discharge voltages in the range 600-1000 V at 25 °C*

The obtained experimental data of the demagnetization curves, at discharged voltage of 600…1000 V, show that the magnetic sample saturation is not yet reach.

The optimal magnetization voltage for NdFeB permanent magnet N38 type was reached at the value of 1300 V, corresponding to an impulse current released by specific bank capacitor of 2.96 kA (Table 1).

Table 1

Successive measurements effectuated on magnetizer in correlation with Permagraph measurements

Impulse magnetizer measurements		**Permagraph measurements**			
U [V]	I [kA]	H_{cJ} [kA/m]	H_{cB} [kA/m]	B_r [T]	$(BH)_{max}$ [kJ/m^3]
100	0.35	0.91	0.52	0.002	0.1
200	0.59	11.57	6.55	0.018	0.1
300	0.79	14.54	8.89	0.025	0.1
400	1.01	17.23	10.95	0.034	0.1
500	1.23	37.44	20.16	0.052	0.3
600	1.40	601.3	198.3	0.444	21.8
700	1.64	1015	525.3	0.877	113
800	1.87	1058	785.4	1.097	216
900	2.10	1073	884.3	1.183	263
1000	2.29	1079	918.1	1.220	282
1100	2.53	1079	931.1	1.237	290
1200	2.76	1079	933.6	1.240	292

It is observed that at discharged voltages of 1200 V the magnetic saturation is reached. Successive measurements effectuated on magnetizer in correlation with Permagraph measurements are illustrated in Figure 8.

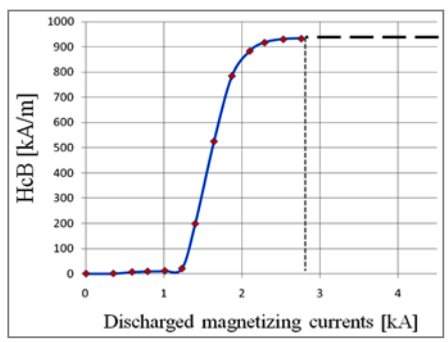

Fig. 8. *Coercive magnetic field strength variation with discharged currents*

It is remarked that the magnetic saturation of NdFeB sample is initiated at 933 kA/m.

The related procedure establishes the optimum magnetization level for a type of NdFeB permanent magnets, minimizing the negative impact of superior voltages on performance and lifetime of specific bank capacitor.

3.2. Temperature Influence on NdFeB Magnetic Characteristics

J-H and *B-H* demagnetization curves are raised in 10 °C steps up to 120 °C (Figures 9 and 10).

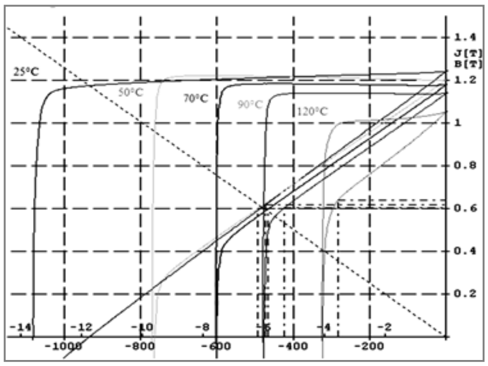

Fig. 9. *J-H demagnetization curves in the temperature range of 25…120 ºC*

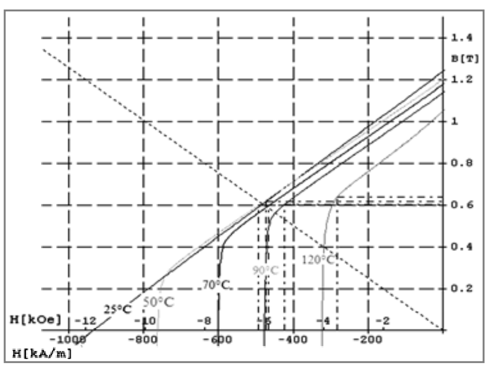

Fig. 10. *B-H demagnetization curves in the temperature range of 25…120 ºC*

The temperature dependence of NdFeB parameters was graphically raised using program Excel. The strong influence of temperature on operating point of NdFeB sample is graphically performed. The magnetic properties are changing with the temperature: remanent magnetic induction varies between 1.241…1.050 T (Figure 11) and coercive magnetic field strength varies between 1082…325 kA/m (Figure 12). The linearity of demagnetization curves is better at ambient temperature, but occupies smaller range with temperature increasing, from 0.3 T at 50 °C and 0.6 T at 120 °C. The maximum energy product varies with the temperature between 295…180 kJ/m^3 (Figure 13).

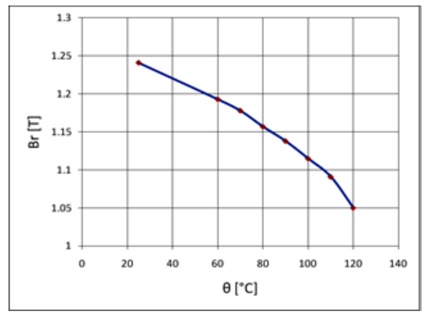

Fig. 11. *Dependence with the temperature of NdFeB magnetic remanent flux density*

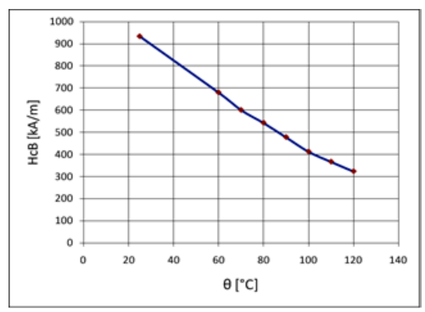

Fig. 12. *Dependence with the temperature of NdFeB magnetic coercively*

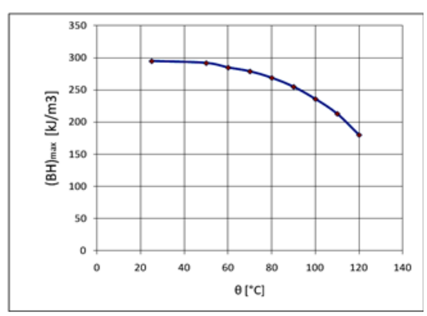

Fig. 13. *Dependence with the temperature of NdFeB maximum magnetic energy*

The magnetic properties deteriorate with temperature rising (Table 2).

Table 2
Dependence with the temperature of NdFeB magnetic parameter

Measuring temperature [°C]	*Br* [T]	H_{cB} [kA/m]	H_{cJ} [kA/m]	$(BH)_{max}$ [kJ/m^3]
25	1.241	934.3	1082	295
50	1.201	763.2	770.2	292
60	1.193	680.2	689.5	285
70	1.178	600.9	603.8	279
80	1.157	542.5	544.5	269
90	1.138	477.6	480.3	255
100	1.115	412.4	414.4	236
110	1.091	366.5	367.8	213
120	1.050	322.9	325.2	180

A set of coefficients measured in [%/K] or [1/K] can be further defined to characterize the temperature dependence of NdFeB magnetic parameters:

- the temperature variation coefficient of the remanent induction:

$$\alpha_{Br} = \frac{1}{B_r} \cdot \frac{\Delta B_r}{\Delta T} \cdot 100\% ; \quad (1)$$

- the temperature variation coefficient of the coercive magnetic field:

$$\alpha_{Hc} = \frac{1}{H_c} \cdot \frac{\Delta H_c}{\Delta T} \cdot 100\% ; \quad (2)$$

- the temperature variation coefficient of the maximum energy density:

$$\alpha_{(BH)\max} = \frac{1}{(BH)_{\max}} \cdot \frac{\Delta (BH)_{\max}}{\Delta T} \cdot 100\% . \quad (3)$$

With the reference values taken at 25 °C, the dependence of magnetic remanence on the temperature is linear, expressed by:

$$B_r(\theta) = -0.0019 \cdot T + 1.305 , \quad (4)$$

where $T = \theta + 273.15$ ºC is temperature [K].

The average coefficient of the remanent induction is $\overline{\alpha_{Br}}[\%/\mathrm{K}] = -0.126$.

The dependence of magnetic field strength as a function of temperature is linear expressed by:

$$H_{cB}(\theta) = -6.495 \cdot T + 1073.9 . \quad (5)$$

The average coefficient of the magnetic field strength is $\overline{\alpha_{HcJ}}[\%/\mathrm{K}] = 1.773$.

The dependence of magnetic energy density with the temperature is polynomial expressed by:

$$(BH)_{\max} = -0.0177 \cdot T^2 + 1.4163 \cdot T + 268.66 . \quad (6)$$

The average coefficient of the magnetic energy density is $\overline{\alpha_{BH\max}}[\%/\mathrm{K}] = 1.769$.

The experimental processed data are useful for the study of temperature influence on magnetic performances of NdFeB permanent magnets with application in electrical drives.

4. Conclusion

Sintered NdFeB permanent magnets are the new generation of high-tech materials.

The researches regarding the investigation of NdFeB permanent magnets stability under different thermal conditions have the opportunity to be validated with new and efficient measurement systems, in correlation with new measurement procedures, in order to improve thermal models of new permanent magnet behaviour.

To achieve that challenges, an extension of magnetic excitation field was done using an impulse magnetizer. It was proposed a procedure to establish the optimal operating point of impulse magnetizer. The dependence with the temperature of demagnetization characteristics of NdFeB permanent magnets was performed. Research engineers and others potential users of NdFeB permanent magnets will benefit by the proposed investigation procedure of NdFeB performances based on modern, fast and accuracy hysteresisgraph method and impulse magnetization technique.

Acknowledgment

This paper is supported by the Sectoral Operational Programme Human Resources Development (SOP HRD), financed from the European Social Fund and by the Romanian Government under the contract number POSDRU/6/1.5/S/6.

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