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Magnetic Characterization of the Nd Based Permanent Magnet by Newly-Developed Bipolar Pulse-Type Hysteresis Loop Tracer

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By applying an alternate pulsed magnetic field – generated by using a sequential ignition circuit and a magnet exciting circuit – with peak value of about 10 T to the rod type Nd based magnet $Nd_2Fe_{12.7}Cr_{1.3}B$ with length of 5 mm and diameter of 3.6 mm, the basic magnetic properties such as saturation magnetization, residual magnetization, coercivity, maximum energy products, magnetic anisotropy and anisotropic field are investigated with obtaining the major and minor *J-H* loops of the magnet. The increase in coercivity due to eddy currents in ac measurement of coercivity is calculated considering eddy current loss by analyzing a wave of generating magnetic field. The average coercivity calculated for the magnet is about 12.2 kOe, anisotropy magnetic field and anisotropic constant are measured as 60 kOe and 2.43 Mj/m^3, respectively.

1. Introduction

It is difficult to measure, over the four quadrant range, the magnetic properties of rare earth based magnets with the coercivity on the order of 20 kOe by using a conventional iron core electromagnet which usually generated magnetic fields up to 20 kOe [1, 2]. To get through the problems, the user-friendly and economical hysteresis loop tracers, which are able to measure four quadrant ***J-H*** loop of Nd based high coercivity magnet with a single experimental run, were constructed in our laboratory [3, 4].

In the latter one of two loop tracers, an alternate pulse magnetic field with peak value of about 10 T is generated by a way of connecting 3 monopolar pulse generators to an air solenoid magnet. Fig. 1. shows time variation of the voltage and current of the solenoid magnet operated with the sequential ignition unit and magnet exciting circuits at room temperature.

In this work, using the loop tracer, basic magnetic properties such as the major and minor ***J-H*** loops with initial magnetization curves, magnetic anisotropy and anisotropic field of rod type Nd based magnet $Nd_2Fe_{12.7}Cr_{1.3}B$ with length of 5 mm and diameter of 3.6 mm, are investigated.

2. Experiment

2.1. Air Solenoid Geometry and Generated Field

Inner and outer diameter and length of the solenoid magnet of bipolar pulse-type loop tracer [4] that permits measurement of four quadrant ***J-H*** loop during a single experiment, is 8.4, 40 and 26 mm, respectively. A pulsed high magnetic field with the maximum amplitude of 81.5 kOe, the maximum current of 812 A, and the heavily damped oscillation of half period 13.7 ms is generated by discharging a 12 mF capacitor charged with 450 V into the air solenoid magnet operated with the sequential ignition unit and magnet exciting circuits.

2.2. Hysteresis Loop of NdFeB Magnet

The saturation magnetization is calibrated by using standard Ni sample, and showed good agreement with the known values. Major ***J-H*** curve for the rod type $Nd_2Fe_{12.7}Cr_{1.3}B$ magnet (supplied from Daebo magnetics Korea Co.) with dia. of 3.6 mm and length of 5 mm is

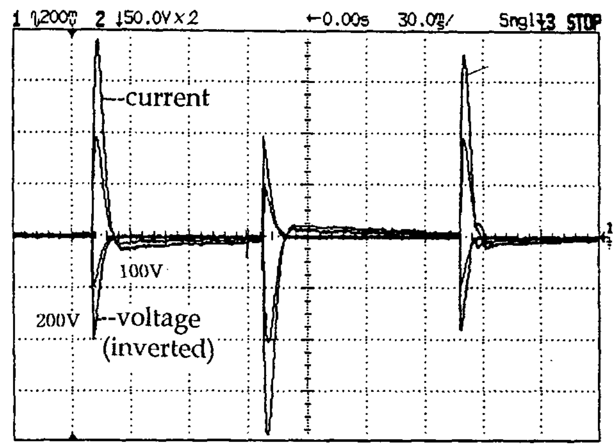

Fig. 1. Experimental time variation of current *I* and voltage *V* of the solenoid magnet operated with sequential ignition unit. Charged voltages are 100 V and 200 V; real sweep with speed of 30 ms/div..

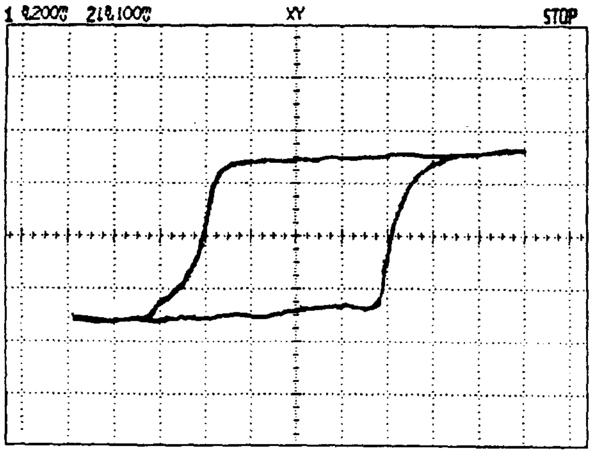

Fig. 2. ***J-H*** curve of NdFeCrB magnet (3.6 mm dia., 5 mm length), $J_s = 1.03$ T, $H_c = 19.7$ kOe, $H_p = 47.2$ kOe (y-scale: 0.70 T/div., x-scale: 9.50 kOe/div.).

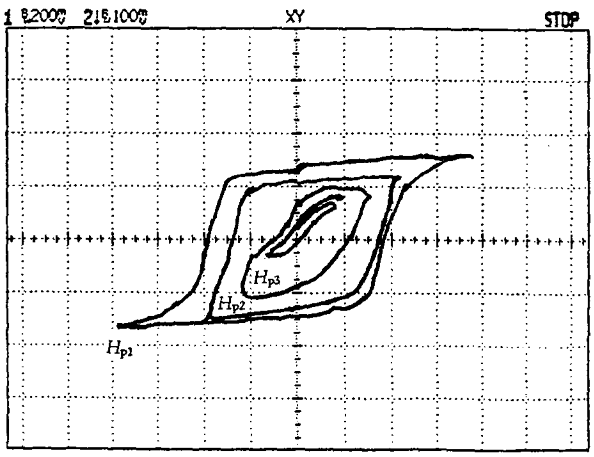

Fig. 3. ***J-H*** minor loops of the NdFeCrB magnet. $H_{p1} = 34.7$ kOe, $H_{p2} = 17.4$ kOe, $H_{p3} = 12.3$ kOe, $H_{p4} = 6.85$ kOe (y-scale: 0.70 T/div., x-scale: 9.50 kOe/div.).

shown in Fig. 2. Fig. 3. presents ***J-H*** minor loops of the NdFeCrB magnet to be measured lowering successively the peak value of applied magnetic field $\boldsymbol{H}_{p1} = 34.7$ kOe. The results are summarizd in Table 1. When $\boldsymbol{H}_p$ is 6.85 kOe, the magnet is almost demagnetized and relative susceptibility χ_r for initial magnetization is about 2.7.

The values of $\boldsymbol{J}_s$ are obtained when the applied field is over 17 kOe and these are in fairly good agreement with

Table 1. Parameters for NdFeCrB Magnet of 3.6 mm dia

H_P (kOe)	J_s (T)	J_r (T)	$H_{c(app)}$ (kOe)	J_rH_{max} (kj/m^3)
47.2	1.03	0.78	19.7	1,043
34.7	1.03	0.78	16.9	923
17.4	0.92	0.69	14.7	653
12.3	–	0.24	–	–
6.85	0.40	0.096	1.47	χ_r=2.7

H_p : peak value of applied field, J_s : saturation magnetization, J_r : residual magnetization, $H_{c(app)}$: apparent coercivity, J_rH : maximum energy product, χ_r : relative susceptibility

that reported in the literature [5]. However the valus of $\boldsymbol{H}_c$ shows higher from the known value 12.5 kOe [6].

The increase of coercivity due to the eddy current effect can be calculated equating the density of power loss by the classical model for eddy current, with power loss as calculated by the area of the hysteresis loop [7]. To consider the eddy current effect as done in Ni standard rod [4], the experimental time variation of magnetization $\Delta J/\Delta t$ which can be obtained experimentally under $\boldsymbol{H}_p$ of 17.4 kOe is shown in Fig. 4. As $2\Delta t$ in the present paper corresponds to pulse duration from Table 2, errors in the coercivity due to eddy currents in the magnet are in fairly good agreement with results of Grossinger *et al.* [8]. Therefore, the real

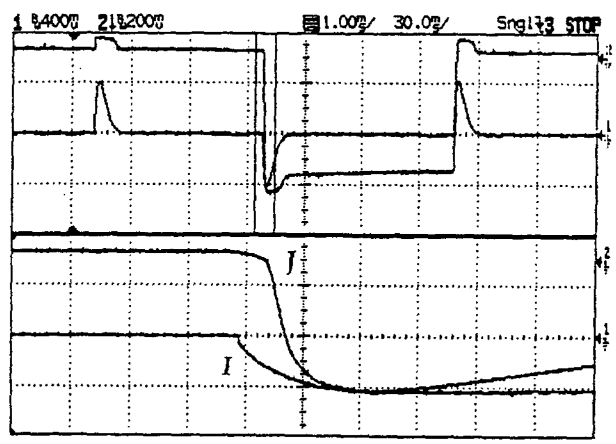

Fig. 4. Time variation of ***J***, ***I*** for *dJ/dt* of the same magnet, lower half curves (delayed sweep 1.0 ms/div.) are enlarged of two parallel cursor lines of upper half (real sweep with speed of 30 ms/div.), $H_p = 17.4$ kOe.

Table 2. Increase of Coercivity H_c Due to Eddy Current Effect for NdFeCrB Magnet of 3.6 mm dia

H_P (kOe)	ΔJ (T)	Δt (ms)	ΔH_c (Oe)	$H_{c(app)}$ (Oe)	$H_{c(app)}$-DH_c (Oe)	2Δt (ms)	Error (%)	*pulse duration	*Error (%)
47.2	1.98	0.16	7,600	19,700	12,100	0.32	60.8	0.33	39.7
34.7	1.98	0.20	4,870	16,900	12,030	0.40	38.9	0.50	27.0
17.4	1.98	0.29	2,310	14,700	12,390	0.58	18.4		
–	–	–	–	–	–	–	–	1.2	12.0
–	–	–	–	–	–	–	–	3.0	5.0
								4.8	3.5

$H_{c(app)}$: apparent coercivity, *Grossinger *et al.* data

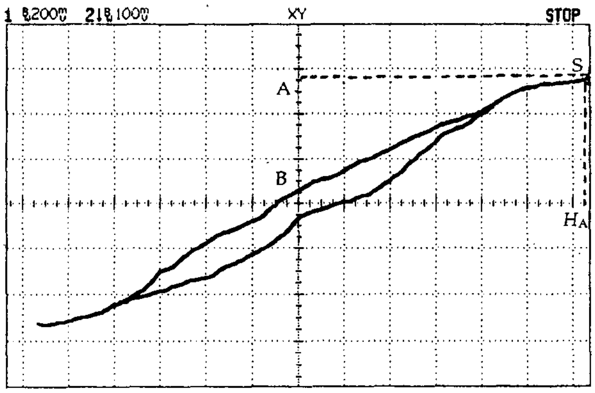

Fig. 5. ***J-H*** curve of the NdFeCrB magnet. Applied magnetic field direction is perpendicular to long axis of the sample. $\boldsymbol{H}_A$: anisotropy magnetic field, $\boldsymbol{t}$ = 1 ms. (y-scale: 0.40 T/div., x-scale: 9.50 kOe/div.).

coercivity is $\boldsymbol{H}_{c(app)}$-$\Delta\boldsymbol{H}_c$, which is in fairly agreement with that reported [8]. The skin depth calculated for the NdFeCrB magnet is 10.5 mm, which is larger than the radius of the rod (3.6 mm dia.). Thus, the magnetization should be uniform.

2.3. Uniaxial Anisotropic Constant

When the applied magnetic field is perpendicular to the long axis of the rod type NdFeCrB magnet, ***J-H*** curve is shown as Fig. 5. In the figure, anisotropy magnetic field $\boldsymbol{H}_A$ in which the magnet is saturated, is 60 kOe. As anisotropic constant $\boldsymbol{K}_u$ equals to area of ΔABS, so $\boldsymbol{K}_u$ = 2.43 Mj/m^3, where magnetization of point A and B are 1.13 T and 0.12 T, respectively. This value is smaller than the reported value in the literature [9]. It is likely that the result is caused by two reasons; one reason is that $\boldsymbol{H}_A$ value was considered as small because point S was not saturated enough as shown in the Fig. 5. The other is that saturation magnetization of 1.6 T in reported value is larger than this sample.

3. Conclusions

1. The increase of coercivity due to the eddy current in ac measurement of coercivity is calculated considering eddy current loss by analyzing a wave of generating magnetic field.

2. Saturation magnetization, residual magnetization, coercivity and relative susceptibility for rod type Nd based magnet $Nd_2Fe_{12.7}Cr_{1.3}B$ of 3.6 mm diameter and 5 mm length are determined by using the user-friendly and economical hysteresis loop tracer with the new circuit and devices.

3. By using ***J-H*** curve, anisotropy magnetic field and anisotropic constant for the magnet are measured as 60 kOe and 2.43 Mj/m^3, respectively.

Acknowledgement

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