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TITLE RADIATION-INDUCED CHANGES IN MAGNETIC PROPERTIES OF
Nd-Fe-B PERMANENT MAGNETS

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RADIATION-INDUCED CHANGES IN MAGNETIC PROPERTIES OF Nd-Fe-B PERMANENT MAGNETS

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Abstract

The high remanence and intrinsic coercivity of Nd-Fe-B magnets make them desirable for use in the accelerators. Use in the radiation environment of an accelerator requires that the sensitivity of these magnets to radiation be determined and the mechanisms responsible be understood. We present results comparing the relative radiation sensitivity of a number of commercially available Nd-Fe-B magnets. Small samples of these magnets were irradiated at the Omega West Reactor in a neutron flux of 2×10^{13} n/cm²s at a temperature of 350 K (77°C). At various time intervals during the irradiation, samples were removed from the reactor and the open circuit remanence measured. We also measured the second quadrant dc magnetization curve of samples before and after neutron irradiation to monitor changes in remanence and intrinsic coercivity. Our results show that the sensitivity to radiation varies widely among magnets from different vendors. In general, these samples showed a decrease in the remanence and an increase in the intrinsic coercivity. We present results showing that the rate of remanence decay decreases monotonically with increasing length to diameter (L/D) ratio for samples of the same material. Thus, it is important to compare decay rates corrected to some constant L/D ratio.

Introduction

Permanent magnets must remain magnetically stable under irradiation if they are to be useful in accelerator environments. Such environments may involve exposure to neutron fluences of 10^{15} n/cm² in a 50-MeV proton accelerator. Sm-Co magnets have been shown¹⁻⁴ to have very good radiation resistance at even higher fluence levels. The Nd-Fe-B magnets have high magnetization and intrinsic coercivity, although they are not as stable at high temperatures as Sm-Co magnets, suggesting that they might have inferior radiation resistance. Prior to our earlier work,^{5,6} only one study had been made of radiation effects on Nd-Fe-B magnets.⁴ Our previous work has shown that they decay more rapidly than Sm-Co when irradiated using fast neutrons. We also showed that different Nd-Fe-B materials exhibit different rates of magnetization decay, as was illustrated by the slow decay rate of Hitachi Nd94EB compared to the decay rates for Crumax 282 and NeIGT2/H.⁶

In this paper, we extend our previous studies of radiation-induced magnetization decay to a number of other commercially available Nd-Fe-B magnet materials. We report changes in intrinsic coercivity due to irradiation, and investigate effects of specimen geometry showing that the magnetic operating point of the sample being irradiated is an important factor in determining the decay curve of the magnetization.

Experimental Procedure

Sample preparation

Magnet samples were purchased from the manufacturers listed in Table I and cut into smaller pieces to minimize radiation induced activation. Samples were of square cross section, typically just less than 1.0 mm on a side. An equivalent diameter was defined, such that the area was unchanged. The length was cut to give the desired L/D ratios. All of the samples were cut using a low-speed diamond saw with ample coolant. Most of the samples were received in the uncharged condition. Following cutting, the samples were charged using a pulse charger.

Measurements

The intrinsic coercivity of the samples was measured during the charging operation prior to irradiation. Samples were placed in a holder which held the sample axis parallel to the charging solenoid axis and kept one end of the sample against the face of a Hall probe, while a coil located in the bore of the solenoid, but below the sample, measured the applied pulsed field. The measurement was necessarily of lower accuracy than obtainable from other techniques, however, measurement of the intrinsic coercivity, defined by the change in sign of the sample induction, could be repeated to within a few percent.

The open-circuit remanent induction was measured by moving the samples through a coil whose output voltage was sampled at 1-ms intervals. The resulting voltage samples were then numerically integrated to obtain a measure of the open-circuit remanence. Measurements were taken prior to and at intervals during the irradiation. This allowed us to determine the remanence as a function of fluence.

Irradiation

The irradiations were run at the Omega West Reactor at Los Alamos, with the samples inserted in the north epithermal port. This port is shielded with cadmium, which attenuates the thermal neutron flux by a factor of approximately 10^4 in order to avoid the high-cross section reaction between thermal neutrons and boron. The neutron flux ($E > 0.1$ MeV) in the north epithermal port is approximately 2×10^{13} n/cm²s. Samples were placed in polyethylene bits and irradiated in helium, which flowed slowly through the port. Sample temperatures were checked by placing 0.25 mm diameter thermocouples inside samples during irradiation. We found that during irradiation with the reactor at its maximum power of 8 Mw, the sample temperature was about 78°C.

Results and Discussion

To determine the effect of L/D ratio on the radiation induced decay of the open circuit remanence, samples with constant cross section were

cut to several different lengths. Samples having L/D ratios from 2.0 to 8.9 were irradiated. Fig. 1 shows that the decay was most rapid for the smallest L/D ratios. The effect is not unexpected, as the shortest samples have the highest demagnetizing fields. The radiation-induced decay of a given sample thus depends on the local value of B. This has also been demonstrated by Zeller⁷, who measured the local variation in B across the pole faces of samples using a fine probe. Zeller irradiated the samples with deuterons and separately with gamma radiation. Portions of the sample with the highest demagnetizing fields showed the largest radiation induced losses.

Analysis of the decay curves shown in Fig. 1 showed that they could be fairly well fit by an exponential decay function. (It should be noted, however, that extended irradiation⁵ shows marked deviation from first-order kinetics.) When the time constants for exponential decay were plotted as a function of the L/D ratio, we observed a monotonic increase with increasing L/D ratio. The present data cover too narrow a L/D range to allow the proper quantitative relationship to be determined. Hopefully, additional work should allow us to determine the relationship. Results shown in previous papers^{5,6} for radiation-induced decay of NeIGT2/H and CRUMAX 282 were for a L/D ratio of 3.1.

To determine differences among various Nd Fe B materials, one sample of each material having L/D of 4.4 was irradiated. The decay curves in Figs. 2(a) and 2(b) show that some of the materials, particularly those supplied by Sumitomo, showed relatively high resistance to

radiation-induced decay. It must be remembered that the Sm-Co magnets show even greater irradiation resistance. Sm-Co samples that we previously irradiated⁶ showed less than 0.5% decay after 41 hours of irradiation at the flux used here. The observation that different materials exhibit different rates of radiation-induced decay is important. Since composition was typically the same for the different magnets, this suggests that the microstructures resulting from different processing play an important role in determining resistance to radiation damage. Efforts are now underway to examine the microstructure of these materials. It will be of interest to determine whether there are similarities in the microstructures of radiation-resistant magnets such as the Sumitomo S30H and the Crumax 322.

In addition to measuring the decay of open-circuit remanence, we also measured the increase in intrinsic coercivity following the highest radiation fluence received by a given sample. Since this measurement involves magnetically charging the sample, it could not be made until the remanence decay measurement had been completed. Table II shows the change in coercivity for several samples. Changes in intrinsic coercivity are expected to reflect changes in the ease with which domains can be pinned. An increase in coercivity indicates that the radiation damage increases the strength of this pinning, presumably through the addition of radiation-produced defect clusters. Decreases in coercivity may mean that the material in question already possessed a high density of pinning centers, and that the immediate effect of the radiation was to allow consolidation of some of these centers, resulting in a decrease in domain pinning.

Conclusions

Fast neutron irradiation of Nd-Fe-B permanent magnets shows that different magnet materials show different rates of radiation-induced decay. These differences may be due to changes in microstructure resulting from materials processing. Studies are now underway to investigate the microstructure and hopefully allow improvement of the radiation resistance through processing. One must be careful to conduct these irradiations on samples having the same L/D ratio, as the radiation-induced decay curve is strongly dependent on the local induction inside the magnet.

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Figure Captions

Fig. 1. The normalized open-circuit remanence is plotted vs irradiation time for several samples having L/D ratios between 2.0 and 8.9.

Fig. 2. The (a) graph shows the decay of open-circuit remanence vs irradiation time for four of the more radiation resistant samples. The (b) graph shows the decay of open-circuit remanence for four of the less radiation resistant samples. All samples had a L/D ratio of 4.4.

Table 1

Vendor	Magnet Material	Residual Induction (G)	Intrinsic Coercivity (Oe)
Indiana General	NeIGT27H	10200	17000
Crucible Magnetics	Crumax 261	10100	20000
	Crumax 315	11300	13800
	Crumax 322	11400	13000
Electron Energy	NEO 30H	11000	13000
	NEO32	-----	-----
Sumitomo Special	Neomax S30H	11500	17000
Metals			
Vacuumschmeltze	Vacomax 370H	12000	17000
Hitachi Magnetics	Hicorex Nd94EB	9400	15000

Table I lists the magnet manufacturers, the material grades which we purchased, and gives manufacturers' values for the residual induction and the intrinsic coercivity.

Table II

Material	L/D	Coercivity
		Change %
NeIGT27H	2.0	2.1
NeIGT27H	4.4	1.8
Hicorex Nd94EB	4.4	4.8
Neomax S30H	4.4	4.2
Crumax 322	4.4	3.5
Vacomax 370	4.4	3.1

Table II lists the change in intrinsic coercivity following irradiation, together with L/D ratios for several magnet samples.

Figure 1.

Figure 2a.

Figure 2b.