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Some notes about properties of magnetic materials

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1 Introduction

Magnets will be used in different parts of Einstein Telescope. The magnetization characteristics of several magnet families as a function of temperature have been discussed by [1]. In view of the impact on the performance of Einstein Telescope, in the following I will discuss some aspects of magnetic properties of materials: angular dependence of coercivity, texture and correlation effects, Barkhausen noise, with an accent on low temperature measurements.

The problem of Barkhausen noise effects in Virgo has been firstly addressed by [2] in the context of the magnets glued to test masses. The force applied by magnets on the mirrors could change because of the variation of the moment of magnets due to domain inversion. The author considered an applied force of $\sim 2\times 10^{-3}$ N, compared to a Riemann force of $\sim 10^{-12}$ N. If v is the domain volume and V the magnet volume, each domain flip event will be below shot noise if the ratio of the two volumes is lower than the ratio of the Riemann force to the applied force. For magnet volumes of about 6 cm^3 the domain volume was smaller than 3×10^{-15} m^3. The typical domain size in NdFeB magnets is about 10 μm^3. Test performed on NdFeB magnets [2] showed that each flip event involved a variation in magnetization of about 10^9 A m^2, with a rate of one per second, i. e. some hundreds events per second for the magnet size mentioned above. Large events involving many domains were not excluded. It was suggested that heating the magnets before installation could trigger premature domain flips and reduce their occurrence during operation.

The Barkhausen effect has been extensively studied by the LIGO collaboration [3]. A relevant part of the conversion noise in the range between 50 and 100 Hz was caused by the control coils of the end test masses [3]. The initial choice of magnet material was NdFeB. It was demonstrated that SmCo magnets with the same magnetic moment and geometry as NdFeB ones were less noisy by a factor 500. In addition, the magnetic permeability of SmCo magnets was very close to 1, while the value for NdFeB magnets was larger than 1, suggesting that still were unturned magnetic domains.

2 Angular dependence

The angular dependence of coercivity in sintered magnets has been studied by [4]. In these magnets the typical grain size is about 10 μm. It was assumed that there were no exchange interaction between the moments of different grains and each grain evolved independently. Magnetization reversal in each grain initially starts in a small volume, the activation volume v. The energy barrier that must be overcome to reverse magnetization in the small volume is the sum of magnetostatic energy feeded by the external field and of a contribution related to thermal activation energy. When the coercive field is much smaller than the anisotropy field, magnetization in the bulk is oriented along the easy axis, as does the magnetization in the activation volume. When the coercive field is not negligible, there is a rotation of magnetic moments apart from the easy direction. In the authors' model, if the grain easy magnetization axis is inclined by an angle θ with respect to the applied field (where θ=0 for antiparallel field and magnetization), magnetization reversal scales as $(\cos\theta)^{-1}$ [4], increasing with grain misalignment. The grains with easy axis parallel to the field are the first ones that undergo reversal. The authors have tested NdFeB and $SmCo_5$ magnet samples, applying magnetic fields at different angles from the preferential axis. The dependence of the ratio of coercive field to the value at zero angle is shown in Fig. 1, with the authors' model (full line) superimposed: the coercive field increases with increasing angle for both magnets, in agreement with the $(\cos\theta)^{-1}$ scaling.

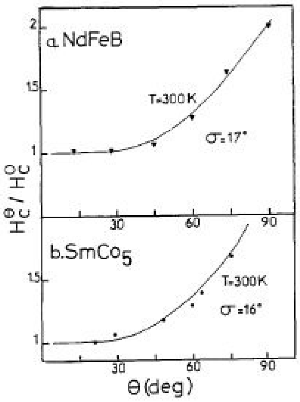

Figure 1: Angular dependence of the coercive field of NdFeB and $SmCo_5$ magnets [4]

Further investigations have been performed with NdFeB at 200 K and Sr ferrites at 300 K [4]. In both cases the coercive field increased with increasing angle, but the agreement with the $(\cos\theta)^{-1}$ law was less satisfactory at large angles (Fig. 2). When a magnetic field comparable to the coercive field is applied, the magnetostatic energy of the moments is comparable with the anisotropy energy. A coherent rotation of magnetization from the easy axis to the field occurs.

3 Texture effects

The texture of the magnets has an influence on the magnetization behavior, as shown by [5] with sintered $Nd_{16}Fe_{78}B_6$ magnets. The curves of sintered $Nd_{16}Fe_{78}B_6$ magnets with different textures are reported in Fig. 3. A magnetizing field of 1 T was enough to achieve full remanence in a sample with good texture, but a field as large as 5.5 T was required for an isotropic sample. The initial susceptibility of thermally demagnetized samples is large for all alignments. The saturation field strongly increases with decreasing level of texture, since the misalignment of local magnetization produces stray fields that perturb the removal of domain walls from the grains. The curve of field magnetized samples has a weaker dependence on the texture level.

The increase of remanence at small magnetizing fields is large for all alignments (Fig. 4). The saturation field is sensitive to the texture.

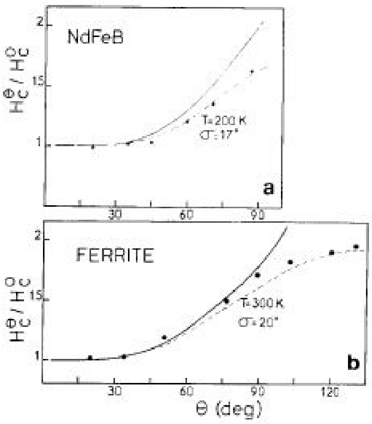

Figure 2: Angular dependence of the coercive field of NdFeB at 200 K and Sr ferrites at 300 K [4]

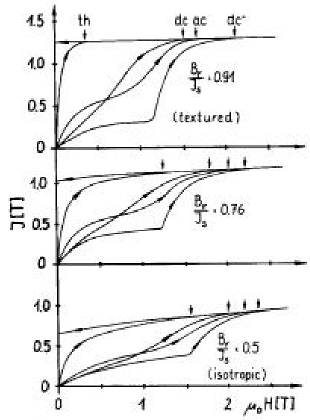

Fig. 1. Initial magnetization curves of sintered $Nd_{16}Fe_{78}B_6$ with different degrees of texture B_r/J_s. J: polarization, H: applied internal field, B_r: remanence, J_s: saturation polarization, th: thermally demagnetized state, dc: direct-field demagnetized state, dc+: direct field demagnetized state with previous polarization opposite to the applied field, ac: alternating field demagnetized state. The arrows indicate the saturation fields.

Figure 3: Initial magnetization curves of sintered $Nd_{16}Fe_{78}B_6$ magnets with different textures [5]

4 Correlation effects

Measurements performed by [6] on sintered $Nd_{15}Fe_{77}B_8$ magnets showed that the occurrence of correlated grain switching is not negligible, since the volume fraction of multiple Barkhausen jumps is relevant for fields approaching the coercive field. The demagnetization curve is shown in Fig. 5.

Several type of jumps were observed: multiple jumps were less frequent than single ones, but nevertheless were not negligible (Fig. 6). Most jumps lasted a few microseconds at most. Multiple jumps are probably caused by the correlated reversal of close and coupled grains. The integrated area of pulses was correlated with the grain size. The volume fraction of multiple jumps ranged from 20 to 50 % (Fig. 6).

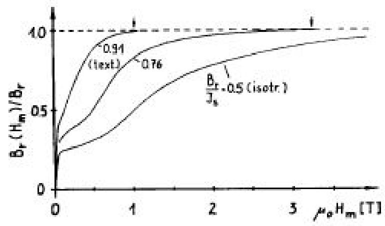

Fig. 2. The increase of remanence $B_r(H_m)$ of thermally demagnetized sintered $Nd_{16}Fe_{78}B_6$ in a magnetizing process. H_m: maximum applied internal field, J_s: saturation polarization, B_r: remanence (saturated value). The arrows indicate the saturation fields. The saturation field of the isotropic sample is about 5.5 T.

Figure 4: Increase of remanence of thermally demagnetized sintered $Nd_{16}Fe_{78}B_6$ magnets [5]

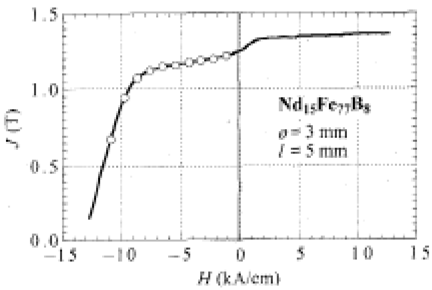

Figure 5: Demagnetization curve of $Nd_{15}Fe_{77}B_8$ [6]

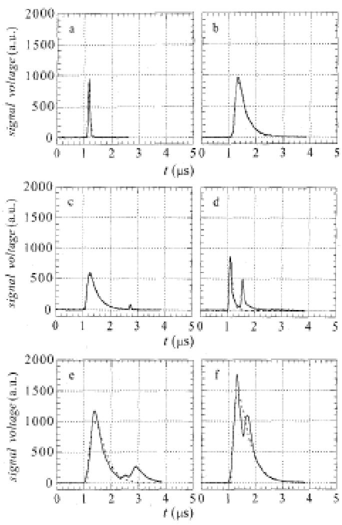

Figure 6: Barkhausen jumps involving single (top row) and multiple (middle and bottom rows) grain switching; the dashed line shows the fit for a single jump [6]

The mean size of grains that undergo reversal for a given applied magnetic field increases near coercivity. Smaller grains are reversed at smaller fields, since they have a higher probability of being misaligned compared to large ones.

The work by [7] on sintered $Nd_{15}Fe_{77}B_8$ (S4) and melt quenched $Nd_2Fe_{14}B_8$ (MP3) magnets showed that the Barkhausen signal during magnetic viscosity (temporal dependence of magnetization at constant field) is correlated with changes in bulk magnetization. The demagnetization curves of sintered $Nd_{15}Fe_{77}B_8$ (S4) and melt quenched $Nd_2Fe_{14}B_8$ (MP3) magnets is shown in Fig. 7. The authors make a distinction between the activation volume and the Barkhausen volume. The former is the volume associated to the beginning of magnetization reversal, while the latter is the total volume of material that undergoes magnetization as a consequence of a single activation process. In NdFeB the magnetization occurs via nucleation and propagation of domain walls. The field needed for nucleating the domain walls is higher than the field needed to propagate them. Thus the Barkhausen volume linked to a single magnetization step in principle can involve several grains, not necessarily a single one.

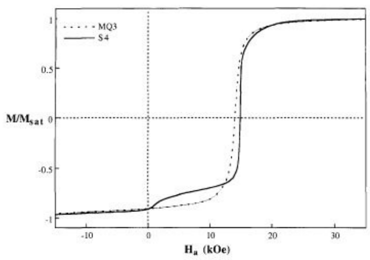

Figure 7: Demagnetization curves of sintered $Nd_{15}Fe_{77}B_8$ (S4) and melt quenched $Nd_2Fe_{14}B_8$ (MP3) magnets [7]

The authors estimated an activation volume of about (7 nm)^3 for both samples. The Barkhausen volume is about (4-20 μm)^3, correlated to the grain size. The distribution of Barkhausen pulse amplitudes had a long tail toward high values, pointing to the occurrence of collective reversal of grains in sintered samples. Barkhausen volumes are as large as (100 μm)^3, i. e. of the order of 10^3 grain volumes, well above the activation volume by several orders of magnitudes. The work suggests that interaction between grains must be included and that correlated reversal can include a large number of grains, even thousands.

5 Magnetic behavior at low temperatures

The work by [8] has investigated the reversal in magnetization of the chemically disordered alloy $SmCo_{3.5}Cu_{1.5}$ at different temperatures. The demagnetization curve at different temperatures is reported in Fig. 8. A staircase behavior was observed below a few Kelvin.

When the magnetic field is slowly varied, adiabatic jumps and isothermal plateaus occur. Above 50 K, magnetization reversal occurs by kink creation and annihilation. There is an anomaly of the mean activation energy below 50 K [9]. The primary motion of domain walls is caused by microscopic tunneling events between defects. Initial demagnetization reversal induces local heating that favors domain wall propagation with a speed up to a few meters per second. The hysteresis loop of the material between 4 and 50 K is continuous, but below 4 K a large discontinuity appears. At 1.8 K, the discontinuities in magnetization appear as discrete jumps with a staircase appearance. The authors showed that the most part of the jumps needed about 2 ms, with a long tail extending up to 10 ms. The magnetization jumps at 1.8 K were explained by a group of domain walls motion occurring almost at the same time through the sample. When a sweeping field is applied, wall motion occurs firstly via microscopic tunneling, leading to local heating and local trigger of wall motion via thermal activation. The effect propagates in the sample via an avalanche, appearing as the series of jumps. The jumps stop when the magnetization achieves an hysteresis loop for the new temperature, that can be as high as 20 K; later, the sample cools below 2 K.

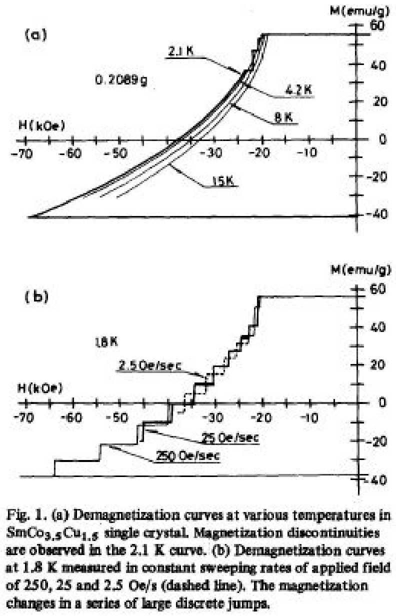

Figure 8: Demagnetization curve of $SmCo_{3.5}Cu_{1.5}$ at different temperatures [8]

Large Barkhausen jumps have been observed in sintered $Nd_{15}Fe_{77}B_8$ magnets below 50 K [10], [11]. A staircase pattern appeared in the hysteresis loop for temperatures below 11 K (Fig. 9). The domain walls will jump the pinning site barrier if the effective field is larger than the unpinning field. When there is a sharp decrease of magnetization as a consequence of growth of reversed domains, the effective magnetic field decreases leading to the pinning of domain walls to a different place. Thus the jumps can be explained by the increase of reversed magnetic domains pinned to defects. The jumps in magnetization were clustered around a coercive field of about 5.5 T.

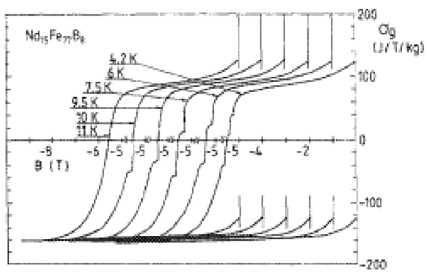

Figure 9: Hysteresis loop of $Nd_{15}Fe_{77}B_8$ for temperatures in the range from 4.2 to 11 K [11]

The authors investigated a sample of 2x2x2 mm^3 and found that each jump corresponded to a magnetization reversal of about 5% of the volume. The number of jumps varied with decreasing temperature, suggesting that cryogenic operation could be helpful in reducing Barkhausen noise. Jumps were more probable during beginning of the magnetization reversal than later. Each magnetization step around the coercive yield produced a temperature rises up to a few K, see Fig. 10.

A local heating model, operating near coercive field, was proposed for pulse trigger and propagation, starting

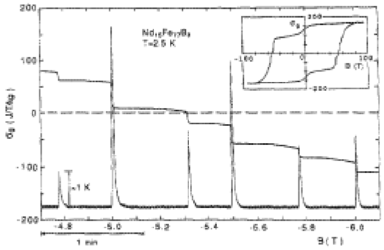

Figure 10: Pulses observed at 2.5 K [11]

from an activation volume $V \sim \delta^3$, where δ is the domain wall thickness; for the above material in the investigated temperature range, the volume is about 1.6×10^{-26} m^3. A temperature increase can shrink the propagation field of the domain wall within a volume of about $100\delta^3$ and trigger the subsequent magnetization reversal, until the process becomes self sustained and thermal spikes are observed. The avalanche is finally stopped, since the effective magnetic field acting on the domain wall decreases at each jump and magnetization is thus decreased.

6 Conclusions

The physical characteristics of a magnet, such as the texture, have a strong impact on its performances. Correlation between grains is not negligible, often. In addition, peculiar behavior at cryogenic temperatures can occur.

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