APPLICATION OF THE ANISOTROPIC EXTENSION OF THE THEORY OF HYSTERESIS TO THE MAGNETIZATION CURVES OF CRYSTALLINE AND TEXTURED MAGNETIC MATERIALS

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Abstract—**The existing isotropic model equations of hysteresis in magnetic materials have been extended to include the effects of anisotropy and texture. This has proved particularly important as the model is been used to describe an increasing range of magnetic materials in which anisotropy plays a significant role, for example hard magnetic materials. It has been found that anisotropy and texture in polycrystalline magnetic materials can be adequately described by modifying the equation for the anhysteretic curve to account for these effects.**

I. INTRODUCTION

Previous Investigations have shown that the theory of hysteresis[1] works well in describing a wide range of ferromagnetic materials. However, the original model is isotropic in nature, which makes it ultimately unsuitable for many real magnetic materials, especially hard materials, which in most cases are anisotropic and textured. However the physical basis of this model makes it easily generalizable so that these additional effects can be incorporated into the model equations.

In the model, the differential magnetic susceptibility depends on the displacement of the prevailing magnetization from the anhysteretic. The anhysteretic magnetization of a material is a function of the energy of the moments in a domain. To include anisotropic effects into the model, the anisotropy energy must be incorporated into the total energy of the moments. Although Sablik et al.[2] incorporated an additional field term to take care of applied uniaxial stress, the extension of anisotropy to the anhysteretic function using the procedure adopted here, by describing the anisotropy energy surface for particular types of crystal symmetry, and calculating the probability of occupancy, was first proposed by Ramesh, Jiles and Roderick[3]. This approach considered a two dimensional description of magnetic materials and limited the application of the model to anisotropy in uniaxially anisotropic materials. Later, a more generalized extension[4] was made, in which the energy of a magnetic moment with anisotropic perturbation was calculated in three dimensions and therefore different kinds of anisotropic materials could be described. In the present work, it has been shown that texture can also be incorporated into the model using the anisotropically generalized anhysteretic equation. This has proved particularly important as the model is being used to describe an increasing range of magnetic materials in which anisotropy and texture play a significant role, for example hard magnetic materials[5].

Manuscript received Apr. 30, 1997.
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This work was supported by the US Department of Energy, Office of Basic Energy Sciences through the Center for Excellence in Synthesis and Processing, Program on tailored Microstructures in Hard Magnets.

Extension of the model:

Following the development of the generalized anhysteretic function described previously[4]:

$$M_{aniso} = M_s \frac{\sum_{all\ moments} e^{-E/k_B T} \cos\theta}{\sum_{all\ moments} e^{-E/k_B T}} \qquad (1)$$

where θ is the angle between the direction of the magnetic moment and the direction of the applied field, and

$$E = \mu_0 \langle m \rangle (H + \alpha M) + E_{aniso} \qquad (2)$$

and E_{aniso} is the anisotropy energy which depends on the anisotropic structure of material. For example, in the case of cubic anisotropy,

$$E_{aniso} = K_1 \sum_{i \neq j}^{3} \cos^2\theta_i \cos^2\theta_j \qquad (3)$$

with the normal convention on symbols. In the present description, we only used the first anisotropy coefficient. It has been shown that this approximation is in most case sufficient to provide an accurate description of the different magnetization curves along different directions.

A material is said to possess texture when the grains in the material are preferentially oriented along certain directions. In such a case, the anisotropy of these grains plays a important role in the magnetization behavior of the material. As a result, the anhysteretic magnetization of the material can be considered to be composed of both isotropic and anisotropic contributions. Here we consider "fiber" texture which implies that only one portion of the grains have their easy directions oriented at a specific angle to the field axis, and the rest of the domains are oriented in a completely random fashion. To incorporate the texture effect into the model, we introduce texture coefficient t, which is a statistical evaluation of the fraction of the textured portion of

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the material. Then the anhysteretic magnetization can be given as:

$$M_{an} = t \cdot M_{aniso} + (1-t) \cdot M_{iso} \qquad (4)$$

where M_{aniso} is given by (1) and M_{an} is the isotropic anhysteretic magnetization which can be directly obtained from the original isotropic model.

For more complicated textured materials, there may be several different texture orientations such that each particular direction has a proportion of the grains oriented along it. In these cases the anisotropic contribution of each part must be calculated separately and the net anisotropic portion of the anhysteretic magnetization is the weighted sum of the components of magnetization of these orientations along the direction of the applied field. In some cases, the anisotropic effects of these parts cancel each other and therefore the overall material can be treated as isotropic, for which the original isotropic model can applied.

The general equation of hysteresis that has been described previously[6] can now be solved with the incorporation of the anisotropic and textured anhysteretic magnetization M_{an} given above to obtain the magnetization curves along particular directions,

$$\frac{dM}{dH} = (1-c)\frac{M_{an} - M_{irr}}{k\delta - \alpha(M_{an} - M_{irr})} + c\frac{dM_{an}}{dH} \quad (5)$$

The principal advantage here is that the other terms in the equation remain the same as in the isotropic hysteresis equation. It should be mentioned here that the resulted magnetization M is parallel to the direction of the applied field because, for anhysteretic magnetization in (1), only the components along field direction are calculated. As a result, although the model equation for hysteresis remains basically the same there is a significant difference in the modeled magnetic properties along different field directions.

II. RESULTS AND DISCUSSION

The extended model has been used to fit two sets of measured curves of $Nd_2Fe_{14}B$ materials which have uniaxial anisotropy. The first set of curves are die-upset (MQ-3) $Nd_{13.75}Fe_{80.25}B_6$ material and sintered $Nd_{15}Fe_{78.5}B_{6.5}$ material obtained from Brookhaven National Laboratory. The experimental data were obtained in the following manner: A sample was heated to 800°K and then zero-field cooled to 375°K. A small field was applied and cycled back, to create a minor loop. The sample was again heated to 800°K, zero-field cooled, and then a slightly larger field was applied and cycled. In these two figures, only the cycles which reached saturation are selected. The modeled and measured curves are shown in Figs. and 2. The modeled curves show good agreement with the experimental results.

The other set of data are from two other samples. In this case, the samples were made of the same material but prepared by different compacting methods and therefore resulted in different anisotropic properties. One sample was prepared by compacting small $Nd_2Fe_{14}B$ powders without applying external field, so all the particles in the sample were completely randomly distributed and the overall material can be considered isotropic. The other sample was prepared similarly, except in this case a constant external field was applied during compacting. As a result, some particles in the sample were oriented along a preferred direction and therefore the sample can be treated as a fiber textured material. The modeled and measured curves of these two samples are shown in Figs.3 and 4. For the anisotropic sample, the field was applied along its hard axis, as shown in Fig.4. The modeled texture level is t = 0.32, which means statistically 32 per cent of the sample was oriented along a specific direction and the rest was randomly oriented. It is also shown that most hysteresis coefficients are unchanged except the coupling coefficient α because of the different mean interaction field experienced by the domains due to different compacting processes.

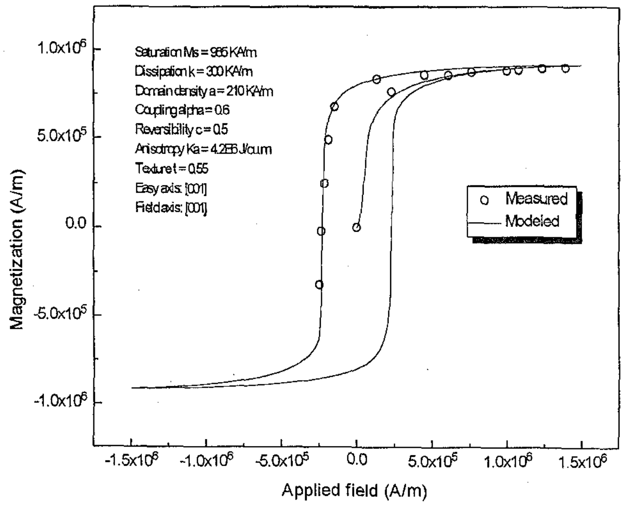

Fig.1. Modeled and measured curves of Die-upset (MQ-3) $Nd_{13.75}Fe_{80.25}B_6$ material

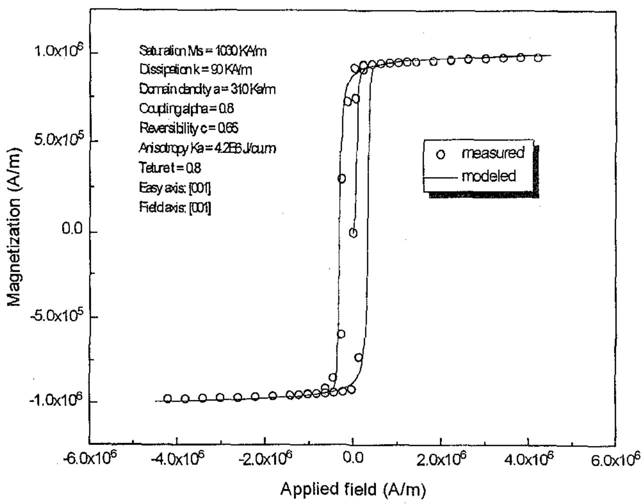

Fig.2. Modeled and measured curves of sintered $Nd_{15}Fe_{78.5}B_{6.5}$ material

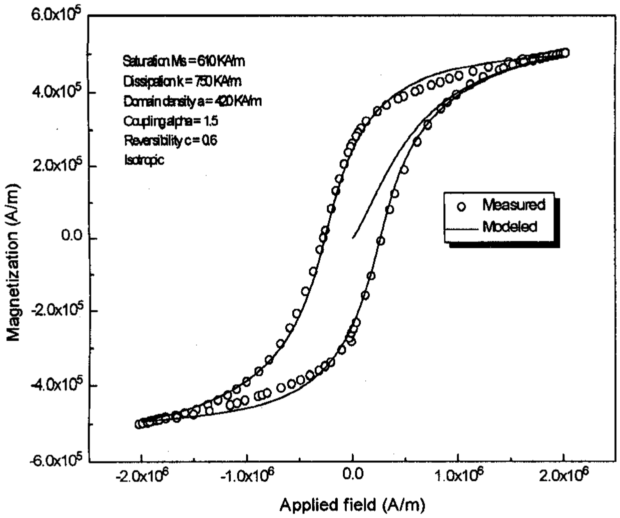

Fig.3. Modeled and measured curves of isotropic $Nd_2Fe_{14}B$ material

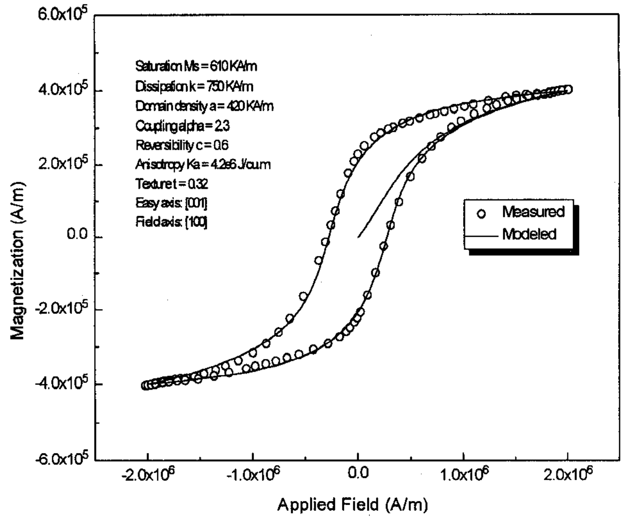

Fig.4. Modeled and measured curves of textured $Nd_2Fe_{14}B$ material

III. Conclusion

In magnetic materials anisotropy and texture play a major role in determining the magnetization. In some materials the anisotropy can be effectively ignored and reasonable model predictions of the magnetization curves can be obtained with the original isotropic model. However in a more general sense the anisotropy and texture effects determine the details of the magnetization curve and these need to be included in the model. This paper shows where anisotropy and texture arise in the model equations for hysteresis in order to provide a more general theory.

Acknowledgments

The authors wish to acknowledge the cooperation of Dr. Laura Henderson Lewis of Brookhaven National Laboratory for providing data on specimens.

This work was supported by the US Department of Energy, Office of Basic Energy Sciences through the Center for Excellence in Synthesis and Processing, Program on tailored Microstructures in Hard Magnets.

References

[1] D.C. Jiles and D.L. Atherton, "Theory of ferromagnetic hysteresis", *J. Mag. Mag. Mater.*, vol. 61, pp. 48, 1986.

[2] M.J. Sablik, S.W. Rubin, L.A. Riley, D.C. Jiles, D.A. Kaminski, and S.B. Biner, "A model for hysteretic magnetic properties under the application of noncoaxial stress and field", *J. Appl. Phys.*, vol. 74, pp. 480, 1993.

[3] A. Ramesh, D.C. Jiles and J. Roderick, "A model of anisotropic anhysteretic magnetization", *IEEE Trans. Mag.*, vol. 32, pp. 4234, 1996.

[4] A. Ramesh, D.C. Jiles and Y. Bi, "Generalization of hysteresis modeling to magnetization", to be published.

[5] L. Henderson Lewis, D.O Welch, Z. Gao and D.C. Jiles, "Modeling of permanent magnets: interpretation of parameters obtained from the Jiles-Atherton hysteresis model", *J. Appl. Phys.*, vol. 79, pp. 6470, 1996.

[6] Jiles, J.B. Thoelke and M.K. Devine, "Numerical determination of hysteresis parameters for the modeling of magnetic properties using the theory of ferromagnetic hysteresis", *IEEE Trans. Mag.*, vol. 28, pp. 27, 1992.