A PROBABILISTIC MODEL FOR SIMULATING MAGNETOACOUSTIC EMISSION RESPONSES IN FERROMAGNETS

J. P. Fulton and B. Wincheski
Analytical Services and Materials, Inc.
107 Research Drive
Hampton, VA 23666

M. Namkung
NASA, Langley Research Center
Hampton, VA 23681

INTRODUCTION

Magnetoacoustic emission (MAE) is a phenomenon where acoustic noise is generated due to the motion of non-180° magnetic domain walls in a ferromagnet with non-zero magnetostrictive constants. MAE has been studied extensively for many years [1-5] and has even been applied as an NDE tool for characterizing the heat treatment of high-yield low carbon steels [6-8]. A complete theory which fully accounts for the magnetoacoustic response, however, has not yet emerged.

The motion of the domain walls appears to be a totally random process, however, it does exhibit features of regularity which have been identified by studying phenomena such as “1/f flicker noise” and self-organized criticality (SOC) [9-11]. In this paper, a probabilistic model incorporating the effects of SOC has been developed to help explain the MAE response. The model uses many simplifying assumptions yet yields good qualitative agreement with observed experimental results and also provides some insight into the possible underlying mechanisms responsible for MAE.

We begin by providing a brief overview of magnetoacoustic emission and the experimental set-up used to obtain the MAE signal. We then describe a pseudo-probabilistic model used to predict the MAE response and give an example of the predicted result. Finally, the model is modified to account for SOC and the new predictions are shown and compared with experiment.

A BRIEF OVERVIEW OF THE MAGNETOACOUSTIC EMISSION TECHNIQUE

When an external magnetic field is applied to a ferromagnet a rearrangement of local lattice strain fields due to the motion of non-180° magnetic domain walls occurs and emits elastic energy. The interaction between domain walls and lattice defects creates a discontinuity in the domain wall motion causing a burst of energy called magnetoacoustic emission.

A typical experimental set-up is shown in Fig.1. Two electromagnets are oriented to direct the alternating magnetic field along the axis of the ferromagnetic test sample. The time rate of change in the net magnetic induction is measured indirectly by winding a pick-up coil around the sample. An acoustic emission is coupled to the sample to monitor the acoustic noise produced within the sample. The outputs of both the pick-up coil and the

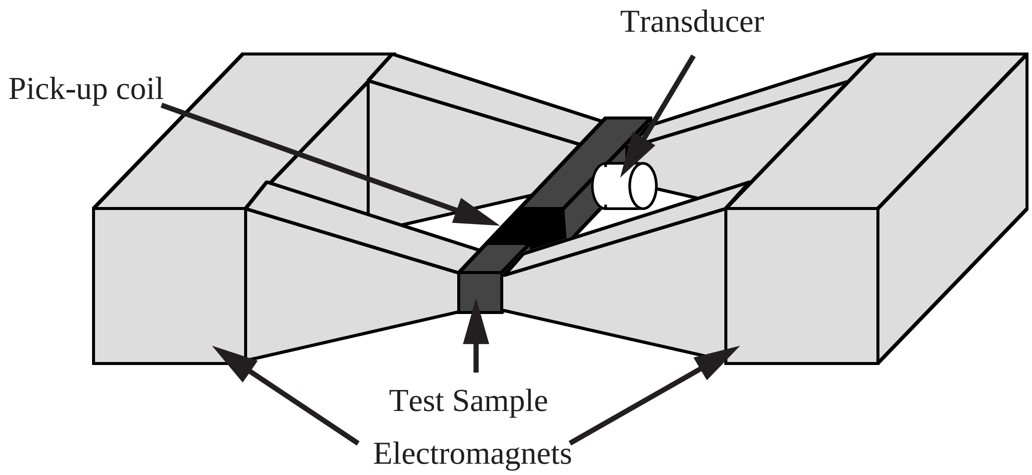


Fig. 1. Experimental set-up

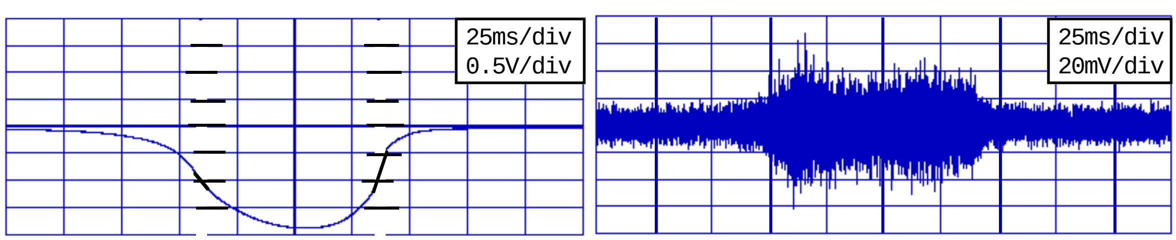
transducer are displayed on an oscilloscope and typical results are shown in Fig. 2.

The unprocessed signal from the transducer is extremely difficult to analyze. Namkung et al. [8] found it advantageous to study the time-averaged envelope of the transducer output which is displayed in Fig.3. The envelope was obtained by averaging the absolute value of 50 consecutive acoustic bursts and then smoothing the final result. The envelope of the time-averaged MAE burst has a unique shape which has been shown to be dependent upon the magnitude and frequency of the applied field and also on factors affecting material properties such as embrittlement [5-8].

From Fig. 3b we can identify two distinct and qualitatively different peaks in the processed MAE signal. The peaks typically occur around the knees of the B-H curve and the first peak always tends to be very sharp and narrow while the second peak is more rounded and spread out.

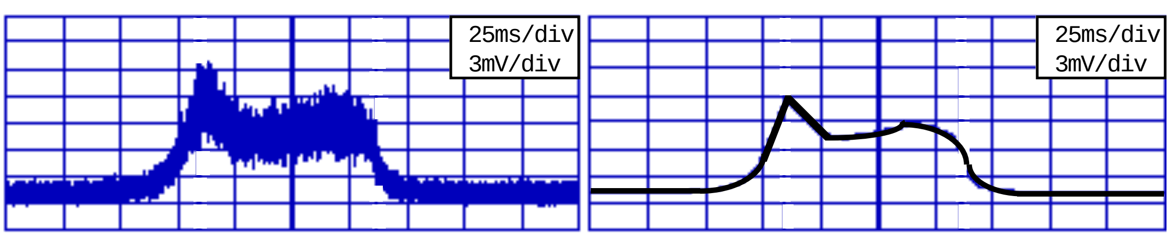
A PROBABILISTIC MODEL

A model was developed to try and explain the qualitative difference between the two peaks in the MAE burst. The model is essentially phenomenological, i.e. it is based on a priori knowledge of the experimental results and not on any governing equations. It does, however, incorporate some of the ideas developed by Goodenough[12]. In particular, we use the



(a) (b)

Fig. 2. Typical MAE results (a) pick-up coil output, (b) unprocessed transducer output



(a) (b)

Fig.3. Processed transducer output (a) averaged signal, (b) smoothed data

notion that as the magnetization is reduced from saturation, regions of reverse magnetization can form around non-magnetic inclusions. The sudden appearance of these regions also means that non-180° domain walls, which are 90° domain walls in steel, are being created and, hence, that elastic energy is being emitted. As the applied field increases in the opposite direction the walls move irreversibly and cause further acoustic noise to be generated. A more detailed explanation of domain wall creation and movement is given in a companion paper in this proceedings by Namkung et al. [13].

Assumptions of the model

The model was developed by incorporating the following assumptions:

1. The ferromagnetic sample can be discretized into a (i, j, k) grid of magnetization regions (as shown in Fig. 4) where domain walls are created and move, i.e. each region is a source of acoustic noise.

2. From the experimental results we observe two distinct peaks in the MAE signal as H is varied. We attribute one peak to the creation of regions of reverse magnetization which form 90° domain walls. The other peak is due to the irreversible motion of the 90° domain walls combined with the delayed motion of these domain walls through the sample due to the competing effects of the eddy currents generated by the changing magnetic field and the 180° domain walls [13]. We incorporate this into the model by assigning two distinct bursts of energy to each magnetization region. One corresponding to the formation of the domain walls and the other to the subsequent motion of the walls. Consequently, there are two critical values of H associated with each magnetization region.

3. The value of H at which regions of reverse magnetization are created will, following Goodenough's [12] notation, be denoted by H_{Nijk}. The critical values of H are assumed to be randomly distributed throughout the different regions with a gaussian distribution about a mean value of H corresponding to the first knee of the B-H curve. Similarly, the value of H at which the domains move irreversibly, H_{Wijk}, is also randomly distributed, but about a mean H corresponding to the second knee of the B-H curve. To assign the critical values of H to the individual magnetization regions a correlation is established between the area beneath the gaussian distribution and the total number of regions in the sample. The area is then discretized into a finite number of trapezoids and the number of regions corresponding to the area enclosed by the trapezoid is assigned the value of H as shown in Fig. 5. and is distributed randomly throughout the grid.

4. The problem is then discretized in time and a time-varying H field is applied. We assume that H is seen simultaneously and uniformly throughout all the regions (This is a feature that could be altered to account for eddy current effects, but was not done at this time). The applied H is sinusoidal and at each time step the grid is first searched to determine if H is above the critical value, H_{Nijk}, associated with each region. If the preceding condition is met, then an acoustic burst is considered to have occurred and is accounted for by adding a value to an array which counts the number of such bursts at each time step. After an acoustic burst has occurred for that particular region and value H_{Nijk}, the region is not searched at future time steps. Instead, we monitor the regions second H critical value, H_{Wijk}. Again, if H

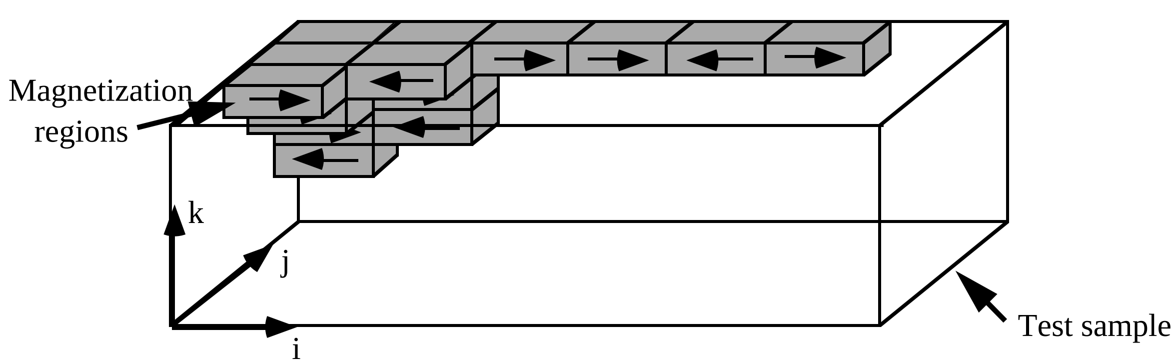


Fig. 4. Modeling discretization scheme

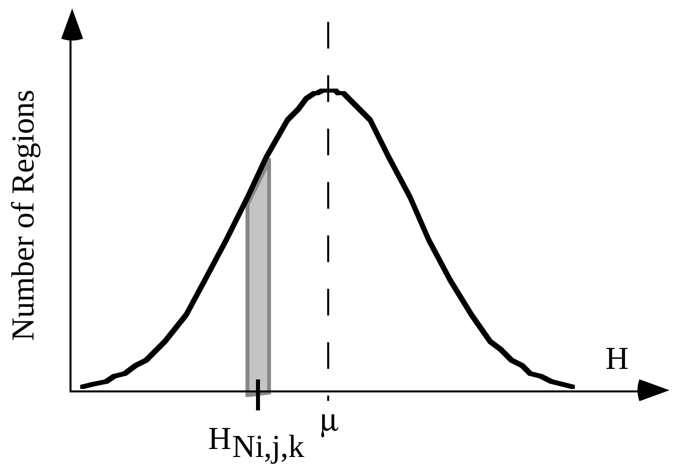


Fig. 5. H critical distribution procedure for model

is sufficiently large to cause the second burst to occur it is added to the burst array for that particular time step. This procedure is followed for all magnetization regions at each of the specified time steps. The end result is an array which contains the number of acoustic bursts occurring at each instant of time. The results are shown and discussed below.

MODELING RESULTS

The model was implemented using a grid of (20,24,120) regions for a total of 57,600 magnetization elements. An applied H field with an amplitude of 300 Oe and a frequency of 0.7 Hz with a time step of approximately 3 msec was used. The results are shown in Fig. 6 below. The modeling results obtained are not a good match, even qualitatively, for the experimental signals. We do see two distinct peaks, however, this is to be expected since we based our model on their occurrence. The main feature of interest to us was why the first peak was much sharper than the subsequent peak in the experimental results of Fig. 3b and no indication of this was found in our results. Obviously, there is some underlying process that is not accounted for in the model.

SELF-ORGANIZED CRITICALITY

In 1987 Bak, Tang, and Weisenfeld [9] introduced the concept of self-organized criticality (SOC) to provide a consistent explanation of 1/f flicker noise and fractal structures observed in dynamical systems. This phenomenon is related to the “domino effect” where many dynamical systems tend to organize themselves into a barely stable state where small perturbations can cause catastrophic changes throughout the system. Shortly thereafter, Babcock, and Westervelt [11] observed the phenomenon in magnetic domain patterns in garnet films.

The effect was incorporated into the model by allowing a change in one region to have an effect on regions which directly border it. The bordering magnetization regions can, in turn, have an effect on regions they border. Consequently, the disturbance can propagate throughout the sample. Physically, what we are saying is that the sudden emission of elastic energy by one domain wall will, momentarily, change the critical H value at which domain

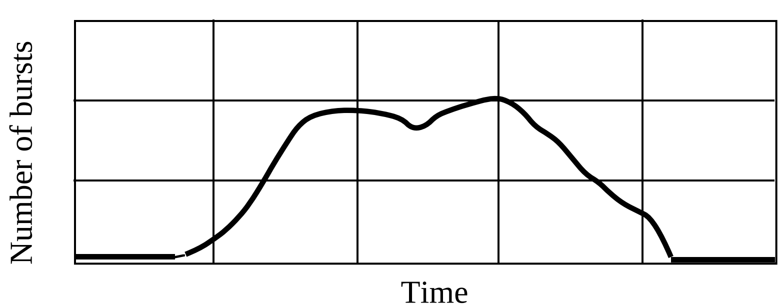


Fig. 6. Modeling results for a 57,600 region grid with H = 300 Oe sin [(2 π) 0.7 t]

walls are created or move at the other regions.

MODIFIED MODEL RESULTS

The changes were implemented into the algorithm and the model was run using the same parameters that produced Fig. 6 and the results are shown in Fig. 7 below. The first observation is that the results are a fairly good qualitative match for the smoothed MAE signal obtained experimentally (Fig. 7b). The modeling supports the assertion that the first peak in the MAE burst is due to the sudden formation of regions of reverse magnetization. Furthermore, we feel that these results, along with the work of Babcock, and Westervelt [11], provide a strong argument for suggesting that SOC plays a significant role in the creation of regions of reverse magnetization.

We also observe that the second peak is not as spread out as the corresponding peak obtained from experiments (Fig. 7 (b)). As stated earlier, this probably can be accounted for if we include the delaying effects of eddy currents. The eddy currents tend to inhibit the ability of the magnetic field to penetrate into the sample and, as a result, would move the response to a later time.

All of the modeling results were obtained by supplying a particular seed number to the computers built in random number generator. To study the reproducibility of the results, the random seed was varied and typical results are shown in Fig. 8. The results are clearly consistent with one another, ruling out the possibility that the results are unique to a particular starting random seed. The model also proved to be fairly robust with respect to the number of regions used. Even with a relatively small number of magnetization regions, the model still produced the same qualitative shape. In Fig. 9 we show results taken at different random seeds using the same parameters as above, except that now a grid of (10,12,6), or a total of 7,200 magnetization regions, was used.

SUMMARY

Although the model we propose is rather simplistic, it still provides reasonable qualitative results and also offers insight into some of the underlying features responsible for magnetoacoustic emission. The first peak in the MAE burst is probably caused by the sudden creation of regions of reverse magnetization in the sample. Furthermore, the sharpness of this peak seems to be directly related to the phenomenon of self-organized criticality, i.e. the

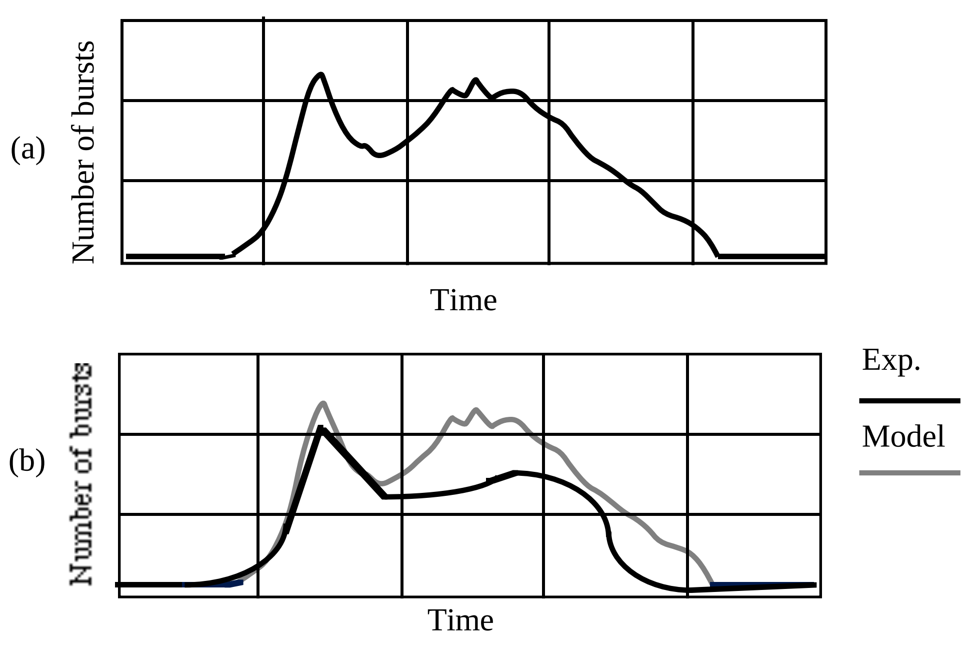


Fig. 7. (a) Modeling results obtained by incorporating SOC into the model, (b) a comparison of experimental and modeling results.

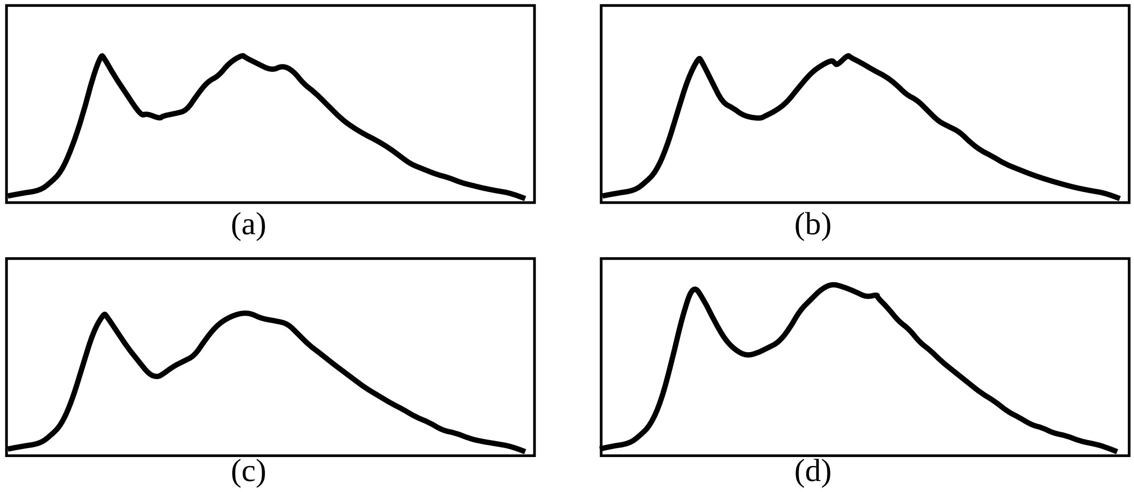


Fig. 8. (a)-(c) Modeling results obtained for different random seeds, (d) is the average of signals (a)-(c).

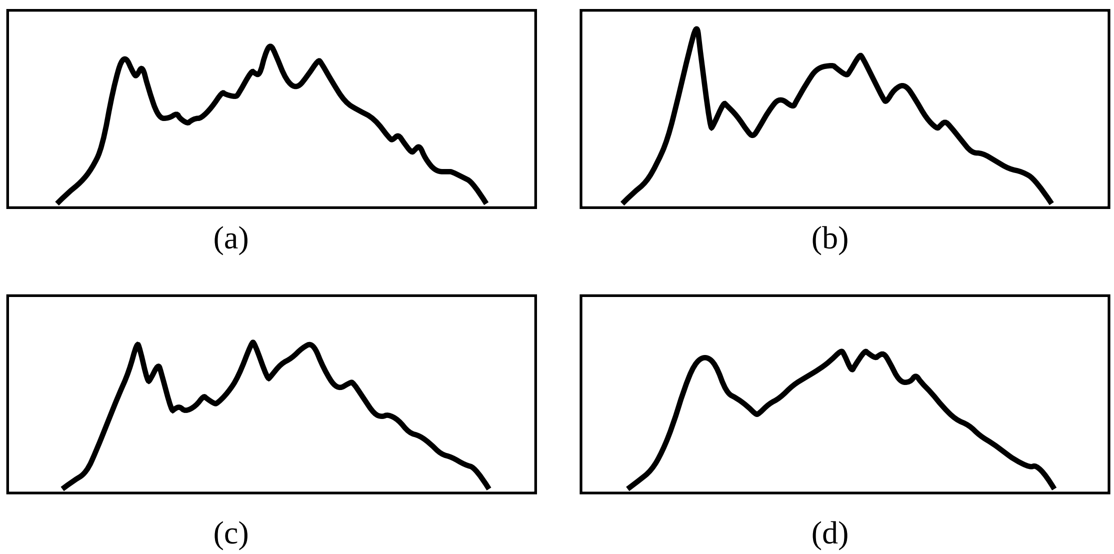


Fig. 9. (a)-(c) Modeling results for different random seeds with 7,200 magnetization regions, (d) is the average of signals (a)-(c).

sudden movement of domains alters the critical value of H required to create other regions of reverse magnetization in neighboring areas.

The model still needs to be modified further to accurately reproduce the shape of the second peak. The characteristics of this peak are probably caused by the competing effects of domain wall motion and the eddy currents generated on the surface of the sample by the changing magnetic field.

REFERENCES

1. A.E. Lord, in *Physical Acoustics*, edited by W. P. Mason and R. Thurston (Academic Press, New York, 1975), Vol. XI, p. 324.
2. H. Kusangi, H. Kimura, and H. S. Sasaki, “Acoustic emission characteristics during magnetization of ferromagnetic materials,” *J. Appl. Phys*., Vol. 50, pp. 2985-2987, 1976.
3. S. Tyagi, J. Steinberg, A. E. Lord, Jr., and P. M. Anderson, *Phys. Status Solidi*, Vol. 64, (1981), p. 443.
4. M. M. Kwan, K. Ono, and M. Shibata, *J. Acoust. Emission*, Vol. 3, (1984), p. 144.
5. M. Namkung, W. T. Yost, D. Utrata, and R. DeNale, “Effects of uniaxial stress on magnetoacoustic emission and magnetoacoustic responses in steels,” *Review of*

Progress in Quantitative NDE, Vol. 9B, edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York, 1989), pp. 1911-1919.

6. S. G. Allison, W. T. Yost, J. H. Cantrell, Jr., and D. F. Hasson, "Nondestructive evaluation of temper embrittlement in HY80 steel," *Review of Progress in Quantitative* NDE, Vol. 7B, edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York, 1988), pp. 1463 - 1470.
7. M. Namkung, W. T. Yost, J. L. Grainger, and P. W. Kushnick, "Detection of temper embrittlement in steel by magnetoacoustic emission technique," *Review of Progress in Quantitative* NDE, Vol. 8B, edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York, 1988), pp. 2075-2080.
8. M. Namkung, B. Wincheski, J. P. Fulton, and R. Denale, "AC magnetic field frequency dependence of magnetoacoustic emission," *Proc. IEEE Ultrasonics Symposium*, Vol. 2, edited by B. R. McAvoy, pp. 867-870.
9. P. Bak, C. Tang, and K. Wiesenfeld, "Self-organized criticality: an explanation of 1/f noise," *Phys. Rev. Lett.*, Vol. 59, No. 4, (1987), pp.381-384.
10. P. Bak, C. Tang, and K. Wiesenfeld, "Self-organized criticality," *Phys. Rev. A*, Vol. 38, No. 1, (1988), pp. 364-374.
11. K. L. Babcock and R. M. Westervelt, "Avalanches and self-organization in cellular magnetic-domain patterns," *Phys. Rev. Lett.*, Vol. 64, No. 18, (1990), pp. 2168-2171.
12. J. B. Goodenough, "A theory of domain creation and coercive force in polycrystalline ferromagnets," *Phys. Rev.*, Vol. 95, No. 4, (1954), pp. 917-932.
13. M. Namkung, B. Wincheski, J. P. Fulton, and R. Todhunter, "Characteristics of magnetoacoustic emission related to structural properties of ferromagnets, "Review *of Progress in Quantitative NDE*, (this volume), edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York, 1993)