Dependence of Barkhausen pattern reproducibility on hysteresis loop size

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The Barkhausen pattern from the amorphous alloy $Fe_{21}Co_{64}B_{15}$ showed high sweep-to-sweep reproducibility for most sweeps when driven slowly over a minor hysteresis loop. Small changes in the maximum applied field led to completely different pulse patterns. When driven near saturation the sweep-to-sweep reproducibility was lost. Large features observed on rapid sweeps were also reproducible, but not when the sample was driven to fields about two orders of magnitude larger than the coercive field. [S1063-651X(97)09009-0]

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INTRODUCTION

The origins of the uneven temporal magnetization patterns known as Barkhausen noise remain obscure [1]. Perhaps the central question is the extent to which the magnetization patterns are directly determined by the underlying disorder in the material or by some collective effects among many domain-wall segments [2]. Although there have been occasional claims [3] that Barkhausen data can be explained by ''self-organized criticality'' (an extreme limit of the collective type of explanation, in which details of the quenched randomness become irrelevant), by far the most impressive fits to detailed statistical properties of Barkhausen noise in metals come from a model by Alessandro, Beatrice, Bertotti, and Montorsi (designated ABBM) which assumes only a single degree of freedom together with a coercive field which makes a random walk in space [2,4,5]. Many of the simpler properties (e.g., shapes of hysteresis loops) are often fit with a simple Preisach picture of a collection of independent two-state system [6].

The physical motivation for the spatial random walk pinning potential assumed in the ABBM model is obscure. Although it is known that the average pinning force affecting an entire domain wall shows long-range correlations as a function of the average position of the domain wall [7], it is not known whether these arise directly from spatial correlations in the pinning field or from effects of the domain-wall flexibility. In fact, the required extent of strong spatial correlations in the pinning field (several micrometers, as we shall see) seems very hard to justify in general.

Urbach, Madison, and Markert [8] proposed that long-range demagnetizing effects, unlike the short-range effects considered in typical pictures of self-organized criticality, might lead to critical depinning for flexible domain walls. Narayan [9] showed that the demagnetizing effects of the dipole-dipole interaction are in fact sufficiently long range for the Barkhausen problem with uncorrelated local pinning to map to a standard interface depinning problem (e.g., [10]) tuned to the critical depinning threshold. The predicted spectral exponent in two dimensions (2D) would roughly match observation [9], as would the pulse-size probability density function [8]. In this picture the long-range correlations arise because the domain wall is slightly flexible, and parts remain pinned to previous sites even when other parts have jumped to new sites. Thus this picture intrinsically relies on many coupled degrees of freedom to produce the long-time correlations of the noise. The possibility of some large number of coupled degrees of freedom resulting in a complicated free-energy landscape for Barkhausen effects was proposed long ago by Erber [11]. An explicit version of a many-degree-of-freedom Barkhausen picture appears in a recent theory [12].

The role of interactions among domains or among parts of a domain can lead to several qualitative effects which are inexplicable in the simpler ABBM and Preisach pictures. Although interacting models are, like the simpler pictures, in principle deterministic except for small thermal fluctuation effects (and thus can easily give the partially reproducible Barkhausen patterns often seen, e.g., [13]), they allow multiple pathways for the magnetization to change [11]. Complicated interacting models are intrinsically history dependent, since the fields affecting any one part of a domain wall depend on what has become of other parts of the same and other walls. Thus small changes in field sweep parameters have been found to completely change some Barkhausen patterns [14]. One then should be able to find particular field histories for which two dissimilar pathways are equally likely, i.e., symmetrically branching valleys in the complicated landscape [11]. Under these conditions, any tiny noise in the field sweep or even intrinsic thermal fluctuations will make the Barkhausen pattern switch randomly when the field is cycled, as has been found experimentally [14]. Finally, when the magnetization approaches saturation, information as to the previous domain configuration should be lost, leading to a loss of reproducibility of the Barkhausen pattern [15].

In this paper we examine whether the qualitative effects incompatible with Preisach and ABBM models, found previously in one magnetic metallic glass under rapid field sweeps [14], are also present in material which fits the statistical properties of the ABBM picture, and in the best-characterized range of sweep parameters, i.e., when the dimensionless parameter c used to characterize the sweep rate is between 0.2 and 5 [4]. We do find effects similar to those

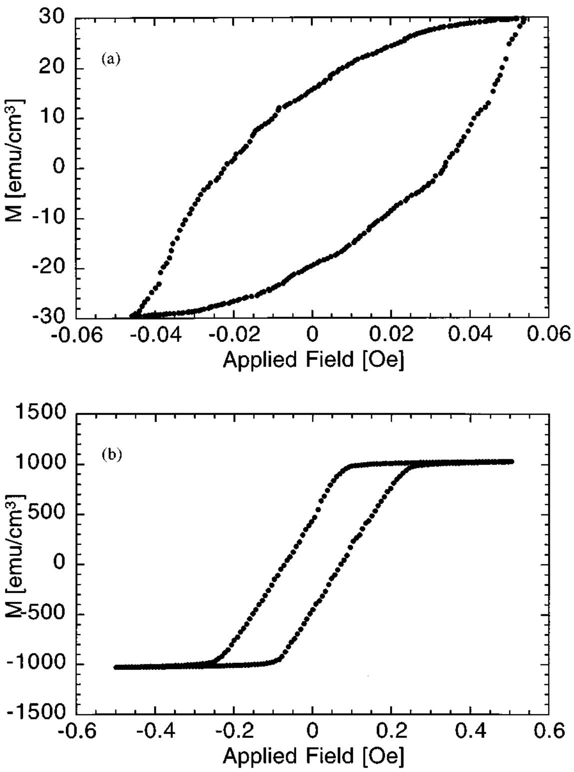

FIG. 1. (a) A minor hysteresis loop, typical for the sweep ranges investigated here, measured using a superconducting quantum interference device magnetometer. (b) A major hysteresis loop. The saturation magnetization of about 1000 emu/cm^3 is nearly reached at an applied field around 0.3 Oe, with a saturation magnetization of about 1000 emu/cm^3.

previously reported, as well as finding that for sweep ranges large enough to approach magnetic saturation, reproducibility is lost, a result already indicated by some previous sketchy data on FeSi [15]. We also further explore the fast-sweep regime, finding similar effects, but with surprisingly large fields required to scramble the Barkhausen patterns.

EXPERIMENT

The measurements were performed on a 30 cm$\times$0.9 cm$\times$25 μm ribbon of $Fe_{21}Co_{64}B_{15}$ amorphous alloy. The sample used was as-cast. This resulted in a domain structure with the domain walls parallel to the long axis of the sample and with roughly 50 domains/cm. This type of domain structure results in a rectangular hysteresis loop for fields along the long axis. Figure 1 shows the hysteresis loop of the sample. Saturation is approached at an applied field of about 0.25 Oe, with a saturation magnetization of about 1000 emu/cm^3. The width of the hysteresis loop is approximately 0.14 Oe. Previous characterization of this material has shown that the dimensionless parameter c used to characterize dH/dt in the ABBM model is given by (0.3 Oe/s) $c=dH/dt$ [16]. Values of $c<1$ correspond to slow sweeps, from which the probability density of the Barkhausen voltage peaks at $v=0$, while for $c>1$ the most probable value of v is finite [4]. This characterization has also shown that the distribution of v as a function of c follows the detailed predictions of the ABBM model in this alloy [16].

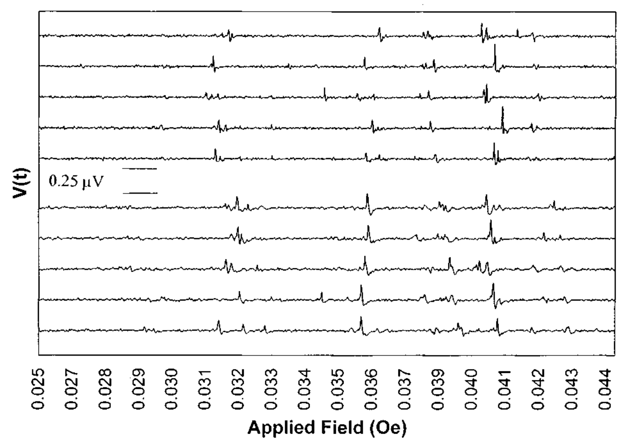

FIG. 2. Ten Barkhausen sweeps taken at a peak applied field ± 0.053 Oe. The first five sweeps were recorded at $c=0.35$ and the next five sweeps at $c=0.7$.

The sample was placed in a long solenoid which applies an external magnetic field along the long axis of the sample. The solenoid is driven with a triangle wave. Typical driving frequencies range from 0.01 to 100 Hz. The Barkhausen noise was detected via a small pickup coil, 1 mm wide, of 50 turns of enameled copper wire wrapped around the center of the sample. The signal from the pickup coil was amplified with standard low noise preamps, passed through an antialias filter, and then sampled with a 12-bit analog to digital converter. The antialias filter avoids artifacts from pulses or pickup at frequencies above half the sampling rate, but distorts the pulse shape, producing negative tails. All of the data here will simply be presented in the form of time series. The sample, coils, and first preamplifier (a Stanford model 552) were placed in a μ-metal box to reduce effects from stray magnetic fields.

Figure 2 shows Barkhausen patterns taken at fixed sweep conditions, for values of the sweep rate parameter $c=0.35$ and 0.7, in the range where the most detailed statistical characterizations of the sample have been performed. The sweeps extend over only ± 0.052 Oe, less than the nominal saturation value of 0.3 Oe. Most of the larger features of the patterns are reproducible sweep to sweep. The group of sweeps with $c=0.7$ give qualitatively similar results. We will see that for $c \gg 1$ the shape of a Barkhausen event is very different from those shown in Fig. 2.

In order to obtain the observed statistical properties, a single-degree-of-freedom model must assume that the pinning field makes a random walk in space over distances larger than the typical domain-wall jump. A typical identifiable Barkhausen event from a slow sweep ($c=0.7$) is circled in Fig. 2. The pulse has a duration on the order of 1.6 msec and of magnitude 0.18 μV, corresponding to a domain-wall velocity of approximately 0.14 cm/sec with our setup. Thus a typical domain-wall jump distance is about 2.2 μm, averaged over the 1 mm or so of the domain wall within the pickup coil. A similar calculation for identifiable jumps in fast sweeps ($c=11$) gives a jump distance of 5 μm.

We investigated how the patterns changed as a function of sweep range. Figure 3 shows 15 Barkhausen sweeps all taken at $c=0.7$ illustrating the typical change of a pattern as the maximum applied field is increased. The first five sweeps

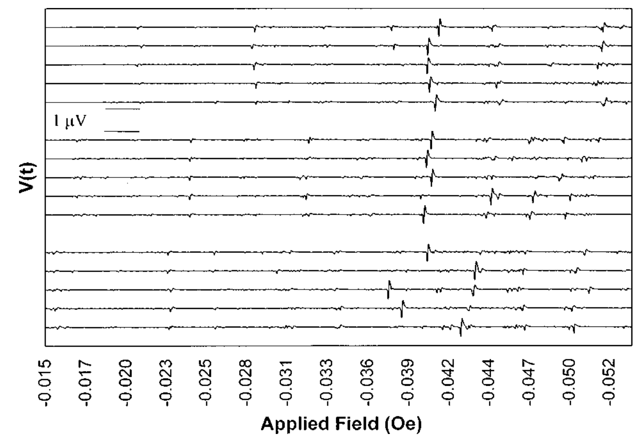

FIG. 3. Fifteen Barkhausen sweeps recorded at $c=0.7$. Three groups of sweeps were recorded, at peak fields of ± 0.053, 0.055, and 0.057 Oe, in order of increasing magnitude. These are plotted using a common field axis. A change in sweep range of less than 5% is enough to completely scramble the smaller events. A change in field of less than 10% begins to alter the largest of the events.

extend over only ± 0.053 Oe, the next five sweeps show an increase in sweep range of 5%, and the last five sweeps another increase of 5%. The presentation keeps the different patterns aligned as a function of field, not time. Although the data are taken at slightly different sweep rates (only 4%), that does not affect the patterns much, as discussed below. Most of the reproducible fine structure of the patterns becomes unrecognizably different on changes of sweep range of less than 5%. An increase in sweep range of 10% is enough to substantially change the largest of the events. Such data are inconsistent with a fixed set of barriers in a given field range, a central qualitative feature of the simpler models, including ABBM.

It has previously been shown that for $c \gg 1$ the Barkhausen pattern can alternate between two different patterns for fixed driving parameters [14]. It is also possible to obtain a switching pattern for much lower driving rates. Figure 4 shows ten consecutive Barkhausen sweeps taken at $c=2.5$, with a peak applied field of 0.038 Oe. The majority of the Barkhausen events are reproducible, but the large event

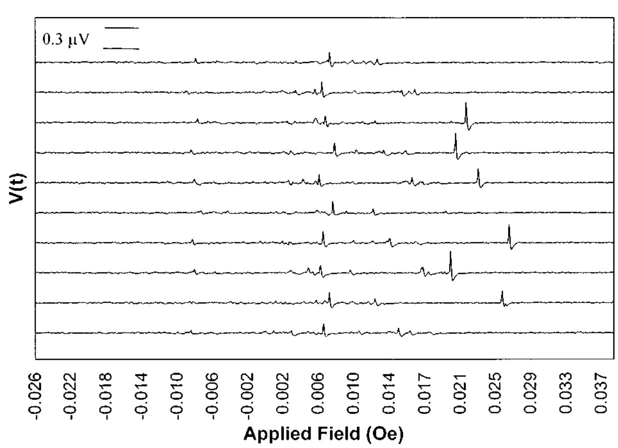

FIG. 4. Ten consecutive Barkhausen sweeps recorded at $c=2.5$ with a peak applied field of ± 0.038 Oe. The event near 0.042 Oe switches among different field values and is absent from some sweeps.

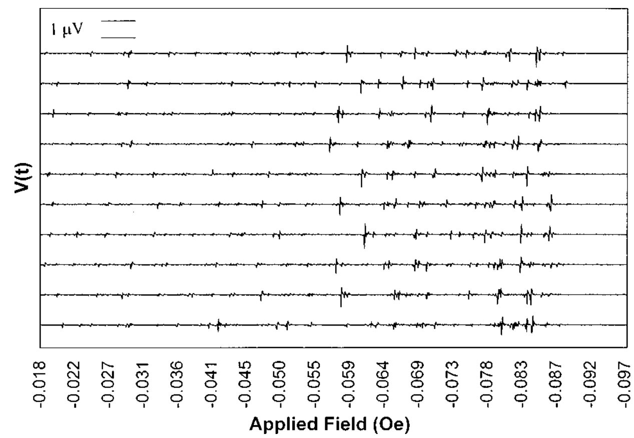

FIG. 5. Ten consecutive Barkhausen sweeps recorded at a driving frequency of 1 Hz with a peak applied field of ± 0.12 Oe. Even though the applied field is well below nominal saturation it is much harder to find reproducible patterns than in the data taken at lower applied fields.

near 0.022 Oe is not present in 40% of the sweeps, and shows unusual large variation in the field at which it occurs.

Figure 5 shows data from repeated sweeps with the sweep range extended to ± 0.12 Oe, still below nominal saturation. Some pulses appear to be usually reproducible, such as the one at about 0.58 Oe. Overall, the pattern clearly is much less reproducible than ones taken with smaller sweep range. The irreproducibility is not due to thermal jitter in the timing of barrier crossings, which would also be present on smaller sweeps. Nonetheless, we checked this thermal jitter time by abruptly stopping the sweep in the midst of the Barkhausen regime, and looking for the subsequent pulses, finding values of less than 7 msec (1.6 mOe) under the conditions of these sweeps, not enough to account for the irreproducibility.

All these data obviously point toward a role for interactions among domain-wall segments, although whether these are segments of the same wall or different ones cannot be determined by inspection. For any picture of flexible domain-wall segments, questions arise as to whether the time scales for reequilibration of the domain-wall internal configuration (or of the positions of some pinning defects) occurs on the same time scale as the Barkhausen pulses (e.g., [7,17]), which would complicate comparison with interface depinning models. If there were substantial rearrangement on the relevant time scale, the detailed effective pinning pattern would depend on sweep rate. Returning to Fig. 2, one finds that the detailed Barkhausen patterns for these slow sweeps are a function of the sweep rate for fixed sweep ranges. However, the most prominent pulses are little changed by a factor of 2 change in c, in contrast to the much stronger sensitivity to the sweep range.

At much faster sweep rates (similar to the conditions of our previous work [14]) we also found reproducible features in the Barkhausen patterns. For some values of the sweep parameters, the Barkhausen pulses randomly switched between distinct patterns [14]. Figure 6 shows a section of ten Barkhausen sweeps taken consecutively at a driving frequency of 100 Hz with a peak field of 0.217 Oe. There is perfect correlation between the event near 0.13 Oe and a subsequent large event near -0.05 Oe, indicating that the available magnetization changes are highly dependent upon

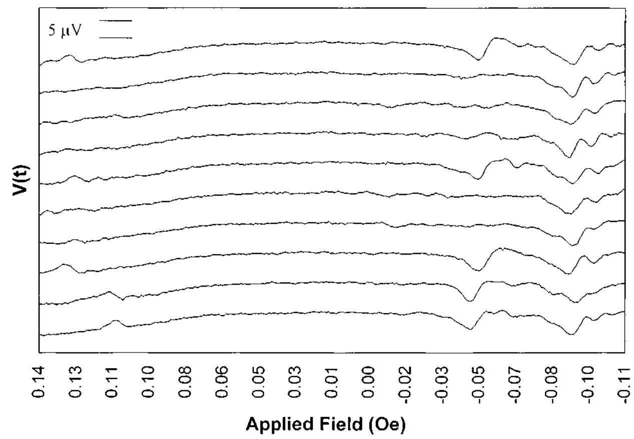

FIG. 6. Ten Barkhausen sweeps taken consecutively at a driving frequency of 100 Hz with a peak field of ± 0.207 Oe. There is perfect correlation between an event near 0.12 Oe and a large event near -0.05 Oe, indicating that the sample magnetization changes are highly dependent upon the magnetization path taken at earlier fields.

the magnetization path taken at previous fields.

In the high-c regime, we also find that large changes in the driving frequency, greater than by a factor of 2, have little effect on the structure of the larger Barkhausen events. Figure 7 shows nine Barkhausen sweeps taken at a peak applied field of ± 0.08 Oe. Three sweeps were taken at 10-, 15-, and 20-Hz driving frequencies (corresponding to c of 10, 15, and 20, respectively), in order of increasing frequency, and sampled such that the bin width corresponds to the same change in the applied field. The large event near -0.048 Oe occurs at roughly the same field value, regardless of driving frequency.

As with the very different sorts of Barkhausen patterns found for $c<1$, these high-c patterns were scrambled after exposure to large fields. The characteristic field for eliminating the fast-sweep reproducibility was not, however, close to

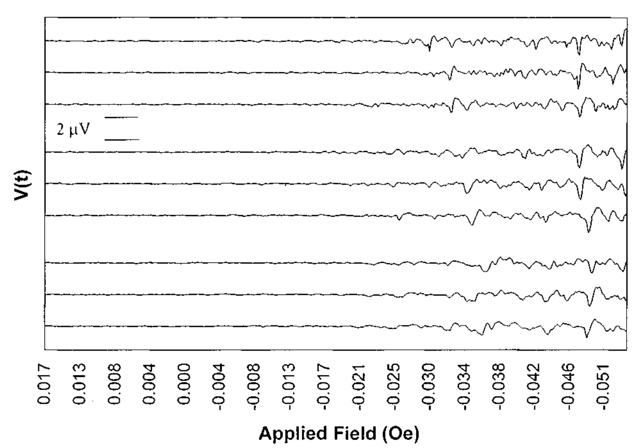

FIG. 7. Nine Barkhausen sweeps taken at a peak applied field of 0.08 Oe. Three sweeps were taken at 10-, 15-, and 20-Hz driving frequencies, in order of increasing frequency, with the digital sampling rate kept proportional to the sweep rate. The largest event, near -0.048 Oe, occurs at roughly the same field value, regardless of driving frequency, suggesting that the domain walls are affected by a similar effective pinning field regardless of large changes in the driving frequency.

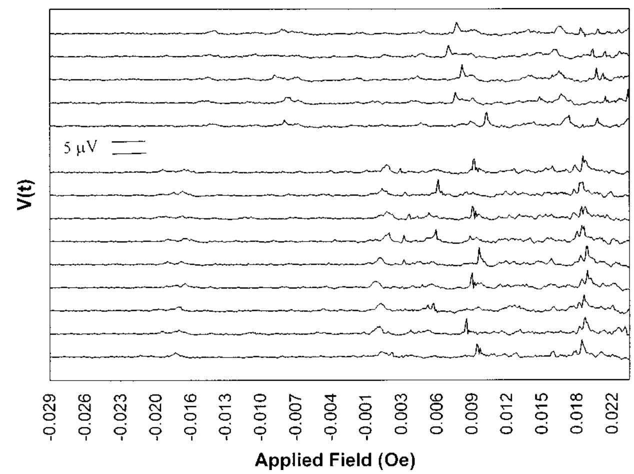

FIG. 8. An example of how a sweep past the saturation field alters the Barkhausen pattern on successive sweeps. The first five sweeps were taken consecutively at a driving frequency of 10 Hz with a peak field of 0.075 Oe. The Barkhausen pattern shows sweep-to-sweep reproducibility. The separation denotes a sweep up to 65 Oe and back to 0 Oe. The next ten sweeps were taken with exactly the same sweep parameters as the first five sweeps. The Barkhausen pattern is completely altered after the sweep past saturation, but still exhibits clear sweep-to-sweep reproducibility.

the nominal saturation field, but nearly two orders of magnitude larger. Figure 8 shows a section of 15 Barkhausen sweeps taken at a 10-Hz driving frequency with a peak applied field of 0.08 Oe. The first five sweeps, taken consecutively at fixed driving parameters, gave highly reproducible patterns. The applied field was then increased by hand to 65 Oe and lowered to 0 Oe, over a time on the order of 10 sec. Ten more consecutive sweeps were then recorded with exactly the same driving parameters as the first five sweeps. The new pattern is again reproducible, but entirely distinct from that shown before sweeping to saturation. One pulse, located near 9 mOe, switches its location between two different field values from sweep to sweep, again indicating the occasional sweep-to-sweep irreproducibility found for some sweep parameters. We checked to make sure that the change in pattern was not an artifact of simply delaying or interrupting the sweep pattern by simply interrupting the sweep, without loss of reproducibility.

The degree to which the fast-sweep Barkhausen pattern is scrambled is dependent upon how high the intervening field is raised. For intervening fields of about 60 Oe as shown in Fig. 8 events of all sizes are scrambled. For intervening fields of about 30 Oe, the smaller events still appear to be mostly scrambled while the larger events persist. Figure 9, which shows ten Barkhausen sweeps taken at a driving frequency of 100 Hz with a peak applied field of 0.30 Oe, gives a typical example of this effect. The first five sweeps, taken consecutively at fixed driving parameters, exhibit a largely reproducible pattern. The applied field was then increased to 30 Oe and lowered to 0 Oe. Five more consecutive sweeps were then recorded with the same driving parameters as the first five sweeps. The new pattern is again reproducible, but the large pulse near -0.24 Oe remains while the smaller events, e.g., around 0 Oe, are mostly changed.

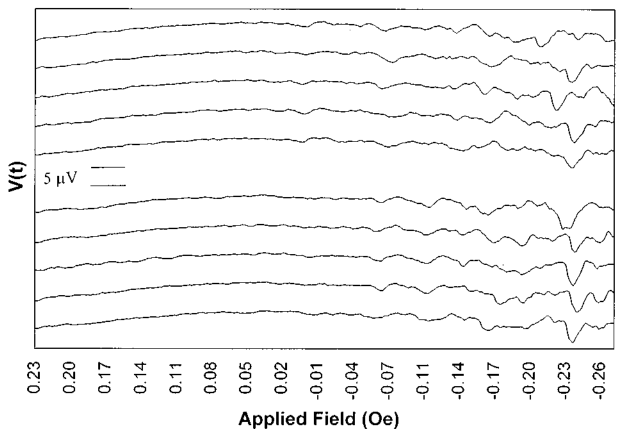

FIG. 9. Ten Barkhausen sweeps taken at a driving frequency of 100 Hz with a peak applied field of 0.30 Oe. The first five sweeps, taken consecutively at fixed driving parameters, exhibit the same overall structure. The applied field was then increased to 30 Oe and lowered to 0 Oe. Five more consecutive sweeps were then recorded with exactly the same driving parameters as the first five sweeps. The new pattern is again reproducible, but the event near -0.24 Oe remains after the sweep to saturation while the smaller events; i.e., around 0 Oe, are completely scrambled.

CONCLUSION

There is a prior case against single-degree-of-freedom models. If the pinning were to come from pointlike defects or from composition fluctuations in an amorphous material, the spatial correlations for any isolated rigid segment would be limited to distances of about a domain-wall thickness, some two orders of magnitude smaller than the typical jump distance. Of course, in any one particular material it would be possible to invoke some extended defects to account for long-range correlations in the pinning field, but it would be hard to argue that such effects account for the general behavior of Barkhausen noise in metals. It is particularly hard to invoke extended defects to explain results in amorphous materials.

Within the well-characterized regime, Barkhausen noise shows qualitative features not possible in simple models but expected for models with multiple interacting variables. Most strikingly, slight changes in the field sweep range completely change the detailed Barkhausen pattern. These effects are well beyond those from ordinary thermal jitter in the time for individual pulses to occur. The obvious interpretation would be that the random field affecting any segment of domain wall depends strongly on other segments of domain wall, producing complicated history dependence. Very small fluctuations can lead to the collective domain-wall state following different pathways. Such effects were essentially anticipated many years ago [18], and are intrinsic to models involving flexible advancing fronts [9].

The behavior of the discernible large pulses in fast sweeps provides an interesting puzzle. These large pulses show reproducible patterns until the sweep range is extended to some two orders of magnitude larger than the coercive field. We may speculate that the grossest features of the domain-wall motions remain deterministic until the field becomes so large that the nuclei of the domain walls are eliminated. At any rate, it is remarkable that these features, with a characteristic field scale so different from that involved in the low-*c* Barkhausen features, still show similar qualitative dependences on sweep parameters.

We conclude that the Barkhausen noise in a metal exhibiting many statistical properties of the single-degree-of-freedom ABBM model nevertheless exhibits other statistical properties requiring many interacting degrees of freedom. It remains to be seen whether such a model can correctly reproduce subtle features such as the sweep-rate dependence of the form of the voltage distribution which have been correctly predicted by the elegant ABBM model [2].

ACKNOWLEDGMENT

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