Magnetic Screening in Multidomain Material

Tom MOON and Ronald T. MERRILL

Geophysics Program AK-50, University of Washington, Seattle, Washington 98195, U.S.A.

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The screening of domain moments associated with the displacement and pinning of a single domain wall from an initial energy minimum position is investigated. The domain moment acquired by the pinning of a domain wall in this fashion is reduced (or screened) by the subsequent readjustment of the non-pinned, mobile domain walls within the magnetic material. Although only a simple, one-dimensional domain geometry is considered, the screening effects are quite variable depending on the grain size, the number of domains and which wall is pinned. In all cases, however, the screening in grains with a few mobile domain walls is generally very large. The results of these screening calculations have important consequences regarding the grain size dividing stable from unstable remanence in multidomain grains.

1. Introduction

The origins and properties of remanent magnetization in multidomain (MD) grains are not well understood. This lack of understanding is greatest in small MD grains where complicating factors include possible contributions to remanence from domain walls (e.g., STACEY and BANERJEE, 1974; DUNLOP, 1977), mechanisms and rates of nucleation and denucleation of domain walls (e.g., HALGEDAHL and FULLER, 1983; MOON and MERRILL, 1985) and magnetic screening effects (e.g., VERHOOGEN, 1959; STACEY, 1963). The amount and mechanism of screening of magnetization by surrounding soft magnetic material in a given grain has been very controversial. At one extreme, screening has been argued to be perfect (e.g., STACEY, 1963) while at the other extreme screening has been assumed to be completely negligible (e.g., VERHOOGEN, 1959). It is clearly important to resolve such differences. Recently domain wall resonance experiments indicate that grains could be very soft magnetically even though they contained very tightly pinned domain walls indicating screening effects may be strongly associated with stability (SMITH and MERRILL, 1984). In this paper the first microscopic domain calculations of magnetic screening effects are carried out and briefly compared to macroscopic continuum models of screening (STEPHENSON, 1976; MERRILL, 1981).

The approach used in this paper is to displace a domain wall from its equilibrium position to some new position where it is assumed to be pinned. (It is beyond the scope of this paper to determine the nature of the pinning defect.) After pinning, all other walls are allowed to relax to their new equilibrium positions. By comparison of the

moment produced by the initial displacement of the wall with the final equilibrium moment, one can determine the degree of screening. It will be shown that the amount of screening appears to be a major factor in separating so-called "pseudosingle domain (PSD)" behavior from "typical" MD behavior. PSD behavior involves stably magnetized grains in which the absolute energy minimum (AEM) state is characterized by non-uniform magnetization. "Typical" MD behavior is exhibited by large MD grains that manifest unstable magnetic behavior. (Stability is measured in a variety of ways, including various demagnetization methods and hysteresis loop classification, e.g., STACEY and BANERJEE, 1974.)

2. Screening Calculations: Methods and Results

Domain structures calculations are mostly based on pioneering contributions from KITTEL (1949), RHODES and ROWLANDS (1954) and AMAR (1958). With the development of computers, several rock magnetists have now returned to calculating equilibrium configurations of magnetization without making the restrictive assumption required by those pioneers (e.g., DUNLOP, 1983; ARGYLE and DUNLOP, 1984; VEITCH, 1984; MOON and MERRILL, 1984, 1985). Most calculations involve determining domain wall energies and moments separately from the overall domain structure. One exception is given by MOON and MERRILL (1984) who simultaneously minimize magnetostatic, E_m , exchange, E_e and magnetocrystalline anisotropy energies, E_k , for the entire grain providing only 180° domain walls are present and providing that the magnetocrystalline anisotropy is uniaxial. These last assumptions are identical to those made in all references given above. Although an important result coming from this more general approach was that the effective wall moment can be significantly less than previously thought, it also showed that essentially the "correct" domain structure (e.g., the correct number of domains and walls at equilibrium) was well approximated by much less rigorous methods (e.g., CHIKAZUMI, 1964; MOSKOWITZ and BANERJEE, 1979). Although the calculations in this paper are kept as simple as possible by considering uniaxial magnetocrystalline anisotropy and infinitesimally thin 180° (Bloch) walls, the calculations are still sufficiently complex that they must be carried out numerically on a computer. Moreover, usually there are more than one equilibrium domain state for a grain of a given size (MOON and MERRILL, 1985). For example, 3 to 10 domains are possible in equilibrium in zero external field for a $1\ \mu\text{m}$ "near" magnetite grain (MOON and MERRILL, 1985; "near" refers to the fact that uniaxial anisotropy was used in the calculations rather than cubic anisotropy). These accessible states are referred to as LEM (local energy minima) states. One of the LEM domain states (the 6-domain state in the last example) has the lowest absolute energy and is hereafter referred to as an AEM (absolute energy minimum) state.

Figure 1 helps to illustrate the screening calculation where the grain dimensions a and c are taken constant and equal to $0.5\ \mu$, while b varies. Since our primary interest here is in the screening of domain moments, the walls are assumed to be infinitely thin, parallel planes. This allows the use of the RHODES and ROWLANDS (1954) result to

Fig. 1. Screening calculations are made by either displacing an outermost wall (e.g., wall #1) or an inside wall (e.g., wall #2) a small amount $\Delta y (= \pm 0.005 \mu\text{m})$ from an energy minimum position and "pinning" it. Initially the grains are in either AEM or LEM states—i.e., lowest or local minimum energy states in the absence of domain wall pinning. The grain dimensions along the x , y and z axes are a , b and c , respectively. Domain walls are assumed infinitely thin and arrows indicate the directions of domain magnetization. The odd-numbered domain magnetization is always taken as being "up" while the even-numbered domain magnetization is always taken as being "down".

calculate the magnetostatic energy, E_m . The general method of calculating E_m has been given in several places (e.g., MOSKOWITZ and BANERJEE, 1979; DUNLOP, 1983) and will not be repeated here. All calculations are done for magnetite at room temperature, except that the cubic magnetocrystalline anisotropy of magnetite is replaced by an uniaxial anisotropy. The wall energy, which is equal to the sum of the exchange energy, E_e , and the magnetocrystalline anisotropy energy, E_k , is approximated from the following result found in CHIKAZUMI (1964):

$$E_e + E_k = (n - 1)a^2 4\sqrt{AK} \quad (1)$$

where n is the number of domains, $K(=|K_1|=1.36 \times 10^4 \text{ J/m}^3)$ is the uniaxial magnetocrystalline anisotropy constant and $A(=0.67 \times 10^{-11} \text{ J/m})$ is the exchange constant (MOSKOWITZ and BANERJEE, 1974). The domain state energy is the sum of magnetostatic and wall energies. In this simple domain model the calculation of wall energies is necessary only in determining the lowest energy domain configuration with respect to the number of walls for a given grain dimension b . Only the calculation of E_m is actually required to determine equilibrium (or energy minimum) wall positions. Thus the accuracy of the wall energies is not crucial in determining the effects of screening under the assumptions of this model.

Only grains with an even number of domains are considered so that there is no net domain magnetization for a minimum energy configuration (in either AEM or LEM state) in zero external field and in the absence of domain wall pinning. One wall is then displaced from its AEM or LEM state position by an amount $\Delta y = +0.005 \mu\text{m}$ (or $-0.005 \mu\text{m}$ if indicated on the figure) and "pinned" from its equilibrium position. The ± 0.005 values were chosen for convenience: the values are large enough to produce significant effects in the calculated magnetic moments yet small enough that one need not worry about domain wall nucleation effects. At this point the grain moment is

$$m_0 = 2(-1)^{j+1} a^2 \Delta y M_s \quad (2)$$

where the j^{th} wall is being displaced and pinned (see Fig. 1) and $M_s (=480 \times 10^3 \text{ A/m})$ is the saturation magnetization. The factor 2 occurs because we are adding magnetization to one domain and subtracting an equal amount from the adjacent domain. The displaced wall is then held fixed while all other walls are allowed to find new positions which minimize the energy. (For minimization we used a steepest descent algorithm similar to that used by MOON and MERRILL, 1984.) Given that the moment of the i^{th} domain is

$$m_i = (-1)^{i+1} a^2 b_i M_s \quad (3)$$

where b_i is the width of the i^{th} domain in the y direction, then the resulting reduced grain moment, μ , is given by

$$\mu = \frac{m}{m_0} = \frac{1}{2\Delta y} \sum_{i=1}^n (-1)^{i+j} b_i \quad (4)$$

where

$$m = \sum_{i=1}^n m_i .$$

Note that the b_i are simply variables that are determined numerically by minimizing the energy. The difference between successive b_i s is linearly proportional to the domain moments as given by Eq. (4). In addition, by using the normalization procedures that lead to Eq. (4), one has that in all calculations the "initial" reduced moment being screened is equal to 1. The amount of screening is proportional to $1 - \mu$: in other words,

if $\mu = 1 \rightarrow$ no screening of m_0 ,

if $\mu = 0 \rightarrow$ perfect screening of m_0 .

In all calculations, no domain wall nucleation or denucleation is allowed; a

reasonable expectation since Δy is small compared to b . In addition, the external field is taken to be zero throughout.

All grains would also have a net wall moment, because there is an odd number of walls in all the domain configurations considered, except the walls here are assumed to be infinitesimally thin. One complication that occurs when considering walls of finite width is that adjacent wall moments need not alternate in sign as do the individual domain moments. The lowest energy state does occur when they alternate in sign, but there are local energy minimum states in which one or more adjacent walls have net moments in the same direction. This added complication makes the general treatment of wall moment interaction or "screening" far more messy. In an attempt to obtain some physical insight into screening and to obtain a zeroth order microscopic model of screenings, wall moments have been neglected. This is certainly justified in the minimum energy case in which Bloch wall moments alternate in sign, because those moments are perpendicular to the moments in the magnetic domains (see MOON and MERRILL, 1985, for further discussion).

Figure 2 shows the number of domains versus size when given grains occupy AEM states (recall that the absence of domain wall pinning is implicit in this term). These are taken to be the initial states before wall displacement occurs. These values differ somewhat from the values given by MOON and MERRILL (1985) because in these previous calculations $a=b=c$ and here $a=c=0.5\text{ }\mu\text{m}$ and b is the only varying grain dimension. In addition, the walls in the previous calculations were of finite width. Figures 3 and 4 show the reduced moments versus the number of domains n (or, equivalently, size as given by Fig. 2 and Table 1). Figure 3 is for the case when an outermost wall is displaced and pinned and Figure 4 applies to the case when a wall initially in the middle of the grain is displaced and pinned (referred to as the mid-wall in the figure). The smallest number of domains calculated is four, because the 4-domain grain is the smallest *even* number domain grain in which screening can occur. Figure 5 shows the reduced moment of a 12-domain grain initially in an AEM

Fig. 2. AEM state distribution for "near" magnetite grains as a function of grain dimension b of Fig. 1. Dimensions a and c are held constant and equal to $0.5\text{ }\mu\text{m}$.

Fig. 3. Reduced moment, μ , as a function of domain number, n , for grains initially in their AEM states. In this case, wall #1 has been displaced and pinned a distance Δy from its AEM state position.

Fig. 4. Reduced moment, μ , as a function of domain number, n , for grains initially in their AEM states. In this case the mid-wall ($\#n/2$) has been displaced and pinned a distance Δy from its AEM state position.

state. The reduced moment is shown as a function of the wall initially chosen to be displaced and pinned.

Figures 6 and 7 show screening when the initial state is a LEM state. In these cases, the grain is constrained to remain in a 4-domain state. That this is not generally the AEM state is illustrated by the fact that for $b = 1.5 \mu\text{m}$ there would be 12 domains in an AEM state, even though 4 domains are allowed following similar calculations to those given in MOON and MERRILL (1985).

Table 1. Grain dimension b with respective AEM state domain number, n , for the five grains of Fig. 3 and 4.

b (μm)	n
0.42	4
0.68	6
0.95	8
1.20	10
1.50	12

Fig. 5. Reduced moment, μ , as a function of wall pinned, i , for a 12-domain AEM state grain ($b \sim 1.5 \mu\text{m}$). The reduced moment after pinning wall #1 has not been plotted, but is equal to 0.31 (0.29) for $\Delta y = +0.005 \mu\text{m}$ ($-0.005 \mu\text{m}$).

The above calculations show the high variability in magnetic screening, a variability that depends on the initial equilibrium state (LEM or AEM), and on which wall is chosen to be displaced and pinned. Physical insight into why such variations occur is given in the next section.

3. Interpretations

Reference to Fig. 5 helps gain insight into the complex nature of screening. Screening in grains with an even number of domains conveniently divides into two subclasses depending on whether or not one is dealing with an even- or odd-numbered pinned wall (see Fig. 1). For the odd-numbered walls, screening increases mono-

Fig. 6. Reduced moment, μ , as a function of grain dimension, b , for grains in a 4-domain LEM state. In this case the mid-wall (#2) has been displaced and pinned an amount Δy from its LEM state position.

Fig. 7. Reduced moment, μ , as a function of grain dimension, b , for grains in a 4-domain LEM state. In this case wall #1 has been displaced and pinned an amount Δy from its LEM state position.

tonically the closer the pinned wall is to the center of the grain. For example, in the 12-domain grain of Fig. 5, the moment resulting from the displacement and pinning of wall #5 is the most efficiently screened ($\mu \approx 0.05$). In contrast, the moment resulting from the displacement of wall #1 shows the least amount of screening ($\mu \approx 0.30$). In the case when an even-numbered wall is displaced and pinned, however, a quite unexpected result is obtained: the reduced moment is less than zero. (The reduced moments shown in Fig. 5 for even-numbered walls are approximately -0.031 , -0.017 and -0.016 for walls numbered 2, 4 and 6, respectively.) If the percent of m_0 screened is taken to be equal to $(1 - \mu) \times 100\%$, then the screening of the moments from pinned even-numbered wall is over 100% efficient. In other words, not only is m_0 completely screened, but the resulting moment is reversed. This result is independent of whether or not the grain is initially in an AEM or LEM state.

The reason for the different screening effects with regards to even- or odd-numbered walls seems as follows. In general, for any given even number of domains there are an odd number of domain walls and always one more odd-numbered wall than even-numbered wall. (For example, in the screening calculations of Fig. 5 there are 6 odd-numbered walls and 5 even-numbered walls.) Since displacement and pinning of any given wall produces a displacement of the mobile walls in the *same* direction, the individual contributions to the moment from the displacement of each even-numbered wall have the same sign, and likewise for the odd-numbered walls. Consequently, the number of positive contributions to μ when an odd- (even-) numbered wall is displaced and pinned is always one greater (less) than the number of negative contributions. Thus one should expect at least different degrees of screening on whether one initially displaces and pins an odd- or even-numbered wall.

Physical insight into the origin of the reversed moment is similar in some respects to that for the origin of the net moment in a 3-domain grain in equilibrium in zero external field (DUNLOP, 1983). Intuitively, it has been felt that the remanences should be zero to make the average demagnetization field zero when in a minimum energy state. The reason this does not occur seems to arise from the asymmetry in the domain configuration: the central domain has two nearest neighbor domains with opposite magnetization, while the two outermost domains each have one nearest neighbor domain with opposite magnetization. As it turns out, the magnitude of the net outermost domain moment is greater than the magnitude of the central domain moment (DUNLOP, 1983). A similar effect occurs in the 4-domain situation of Figure 8a-c where screening occurs by displacement of the two outside walls in response to the moment produced by the displacement of the one central wall. In a sense, the net moment produced by the displacement and pinning of the mid-wall in the 4-domain grain is analogous to the single central domain of the 3-domain grain: the two outermost walls are displaced in the same direction to produce oppositely directed magnetization to the “central moment” and, in analogy with the 3-domain case, produce a larger net “outermost moment”. Similar analogies can be seen between the screening effects in higher even-number domain configurations and the intrinsic moments of odd-number domain configurations.

As a brief aside, it is useful to point out that the above is not expected to be a mechanism by which a rock might undergo self-reversal. As will be discussed in detail later, the amount of screening obtained in the calculations given above is likely an upper limit. In the case illustrated in Fig. 4 for the 4-domain AEM state grain ($b=0.42\ \mu\text{m}$), only a 7% decrease in the net displacement of walls #1 and #3 would be required to eliminate the small reversed moment altogether. Even if this upper limit were reached, there would have to be a very unusual grain size distribution, one with a very large predominance of even-number domain grains, to produce the possibility of a net reversed moment. It would require a larger percentage of pinned even-numbered walls to pinned odd-numbered wall, as $|\mu|$ is generally larger when an odd-numbered wall is displaced and pinned than when the adjacent even-numbered wall is displaced (an equivalent amount) and pinned. Hence, it is unlikely for self-reversal to occur under natural conditions from this effect.

Figure 3 shows that screening of remanence in an outermost domain (i.e., displacement and pinning of wall #1) increases with increase in the number of domains and grain size. Figure 4 shows that for odd-numbered walls, inside domains are more effectively screened than outermost ones while the opposite trend is apparent for even-numbered walls. Again, in Fig. 5 the same trends exist as in the previous two figures with regards to the displacement and pinning of even- and odd-numbered walls and their proximity to the center of the grain. All grains in these figures are initially in their AEM states. The results shown in Fig. 3 and 4 can be attributed to the decrease in the "average" contribution to the reduced moment for the individual wall displacements with the increase in the number of walls. In other words, since the ratio of even-numbered to odd-numbered walls is approaching 1 with increasing domain numbers, the relative difference between the number of negative contributions and the number of positive contributions from individual wall displacements of the reduced moment is approaching zero. Consequently, regardless as to whether an even- or odd-numbered wall is displaced and pinned, μ approaches zero with increasing domain numbers as indicated in Fig. 3 and 4.

The situation for grains initially in their LEM states as depicted in Fig. 6 and 7 requires a somewhat different explanation. In these cases, as the grain size, b , is increased the number of domains, 4, is held constant. For both figures, as grain size increases the relative distance between walls increases resulting in a decrease in the magnetostatic interaction between the walls and thus a decrease in the mobile wall displacements. Consequently, the increasing trend in μ with increasing b shown in Fig. 6 where the mid-wall is displaced and pinned is consistent with Eq. (7) and the expected decrease in mobile wall displacements. In Fig. 7 where wall #1 is displaced and pinned, the trend in μ is as expected from the above argument: that is, as the displacement in the mobile walls decreases, μ should approach 1 (i.e., no screening).

4. Discussion and Conclusions

We have seen that screening is very complex, depending on which wall is pinned and the particular LEM state characterizing the initial domain state of the grain. The reasons for this have been discussed in the previous section. However, in general screening is more effective than might be expected from previous non-domain calculations (e.g., STEPHENSON, 1976; MERRILL, 1981), which suggested that the upper limit for the screening of a hard dipole in a spherical shell of soft magnetite is near 50%. One reason for the difference in screening estimates can be traced to the grain shape and domain geometry. Consider a lattice made up of uniformly magnetized cubes as shown in Fig. 8. This is an artificial, but insightful, example in which regions are not coupled by exchange and domain walls but are treated as separate entities. If we take the magnetization in the central cube to be fixed and allow the nearest neighbor cubes (there are 6, only 4 are shown) to rotate to reach a minimum energy state, the configuration shown in Fig. 8 is obtained. (This can be seen directly by drawing in the field lines of the dipole field associated with the central cube.) The cubes above and below the central cube are magnetized in the same

Fig. 8. A hard magnetized cube (center) will induce magnetizations in surrounding magnetically soft nearest neighbor cubes in the directions shown by the dotted arrows. Two cubes, one above and one below the page, are not shown but are magnetized upward.

direction, while the 4 cubes on the same plane as the central cube are magnetized in the opposite direction. Thus screening is probably less effective in a three-dimensional array of domain walls rather than the one-dimensional array assumed here.

Another major difference between the calculations presented here and those given previously involves the use of experimental data. The calculations of MERRILL (1981) used experimental values from natural magnetites to obtain estimates for magnetite's permeability. In practice, defects will impede the motion of domain walls. The effect of having such defects present is to reduce the amount of screening; consequently, estimates given in this paper are upper limit values of screening of the cases considered.

In spite of the large variations discussed above that are applicable to the "simple" one-dimensional microscopic screening model considered in this paper, it appears that screening in grains with a few mobile domain walls is generally very large. In the cases considered here, $1 - \mu$ ranges from about 0.45 to 1.07, and approaches 1, i.e., perfect screening with increasing domain numbers. Although these values should be considered as upper limits for screening for reasons given above, the calculations indicate nevertheless that most of the stable remanence in rocks probably resides in single domain or small number domain grains. However, because of the existence of LEM states, there may be a far wider number of grains with few domains than expected from analyses of grain sizes and AEM states alone. For example, grains can exist in single domain states over a much larger size range than has been traditionally accepted (MOON and MERRILL, 1985), a conclusion supported strongly by domain observational evidence (HALGEDAHL and FULLER, 1980, 1983) and by magnetic measurements (DUNLOP, 1986).

The main conclusions of this paper are: (1) that although magnetic screening is very complex, it is probably much larger than generally accepted; (2) screening is probably a major factor separating stable remanence in small grains from unstable remanence in large grains; and (3) there will not be a precise size dividing stable from unstable remanence because of the existence of LEM states and because of the large variability of screening effects.

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