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Abstract. – Both physical and phenomenological models are necessary to obtain good descriptions of coercivity in soft magnetic materials. The former models give insight into the processes involved, while the latter models compute quickly. The differences between modeling soft and hard materials are the parameters sizes and the importance of eddy currents.

Introduction

This paper reviews the problems involved in modeling coercivity of soft magnetic materials. The physical behavior of soft magnetic materials determines the nature of the coercivity and the resulting magnetic behavior. There are generally two types of soft materials: those that are essentially single crystal materials and those that are granular in nature. If the materials are also conducting, then the effect of eddy currents is also present. Eddy currents impede wall motion by shielding the interior of the material from the applied field. As a result, in these materials magnetization reversal tends to nucleate at the surface and then to propagate inward.

Essentially single crystal materials include amorphous materials and polycrystalline materials, if the crystallites are strongly exchange-coupled. In these materials, the magnetization reverses principally by domain wall motion. As the applied field is increased to a threshold value, such walls may nucleate at several points. There are several types of walls possible in magnetic materials that are principally classified by the angle between the magnetizations of adjacent domains and the nature of the rotation as one progresses through the wall from one magnetization direction to the other. They may not behave similarly depending upon the crystal structure of the material.

In granular materials, individual grains act as essentially independent magnetostatically-coupled entities. For small grains each entity is essentially single-domain, while for large grains they may be multidomain. Many different reversal modes are possible within a grain depending upon its size.

In both types of materials the change in magnetization is discontinuous. The wall's motion is erratic when it meets inclusions, dislocations, surface roughness, and other imperfections, both on the surface and in the interior, and this is the major source of coercivity in soft magnetic materials. The jumps in magnetization are referred to as the Barkhausen effect. In crystalline materials the boundary between the reversed regions is much more clearly defined than that in granular materials. In phenomenological modelling, this difference is the main distinction between the two types of materials.

Preisach modeling is one of the more effective tools used to compute the irreversible component of the magnetization. Recently, this technique has been modified so that it can also handle accommodation, noncongruency and vector problems. The interaction between reversible and irreversible components of the magnetization is also a topic of current interest.

Micromagnetism

Magnetic behavior can be modelled at the atomic level, the micromagnetic level, or the phenomenological level [1]. At the atomic level, one is concerned with the solution of Schrödinger's equation for the many electrons surrounding an atom in a crystal lattice. At the micromagnetic level, one uses either phenomenological or physically derived parameters to describe a continuous magnetization distribution. At the phenomenological level, one is not concerned with the physical nature of the magnetic phenomena, but simply the relationship between the magnetizaion and the applied field. Only the last two levels will be discussed here.

The parameters used to obtain a continuous magnetization distribution in the micromagnetic level of modeling could be derived from the atomic level of modeling; however, usually only the basic principles are utilized and the actual values of the parameters which are used are obtained experimentally. In addition to Maxwell's equations, the basic principles of micromagnetic modeling are: that at any point the magnitude of the magnetization is determined by the type of material and its temperature, but the direction of the magnetization is determined by the magnetizing process; that it takes additional exchange energy to reorient adjacent magnetic moments from their normal alignment, either parallel to each other (ferromagnetic materials) or antiparallel to each other (ferrimagnetic materials); and that it takes additional magnetocrystalline anisotropy energy to reorient the magnetization from the easy axis.

When calculating the magnetization, one uses the local field, which is the total field that an infinitesimal volume of material experiences. It is the sum of the applied field and the demagnetizing field. Computation of the demagnetizing field is a very time-consuming process, except for the degenerate case when it is uniform. This is the case only for grains the shape of uniformly-magnetized ellipsoids, which is seldom the case. Thus, the demagnetizing field has to be computed at all relevant points in the grain and is a function of the magnetization at all the other points. Therefore, if there are n points, then one has to perform at least n^2 calculations.

When one formulates a discrete problem for numerical calculations, it is necessary to include a sufficient number of points in any region to describe the variation in magnetization. Due to the detail that is involved in these calculations, even with the use of supercomputers, it is impractical to model engineering devices by this technique. It is usually assumed that the magnetization derived from this level of modeling of isolated grains or domain walls is valid for assemblies of such magnetostatically interacting entities. This is a very questionable assumption in some cases.

Domain wall structure

In a bulk sample of magnetic material the usual wall structure between two oppositely-magnetized domains is a Bloch wall. Since the magnetizaion rotates about an axis normal to the domain wall when one moves from one domain to the next, there are no poles induced in the wall, and hence, no demagnetizing field is generated by the wall. In thin films, on the other hand, less energy is required to form a Néel wall, since the poles induced at the surfaces of the film would produce a larger demagnetizing field than that induced in the slowly varying magnetization of the domain wall.

A calculus of variation calculation [2] has shown that the angle of the magnetization in a Bloch wall rotates continuously from one domain to the other, and as it approaches either domain the magnetization approaches the domain magnetization asymptotically. The structure of a wall in a thin film varies continuously from that of a Néel wall at the surface asymptotically towards that of a Bloch wall in the interior. The Néel wall has more energy and is wider than a Bloch wall. Thus, the wall flares out at the surface of the film [3]. Other complex structures are also possible in thin films, such as cross-ties where two walls of opposite chirality meet. Furthermore, if the walls separate domains whose magnetization makes an angle of other than 180°, or if the walls bend, then the walls will also have different parameters from the 180° Bloch wall. Thus, one should not characterize all domain walls similarly.

Domain wall motion

In a perfect crystal a domain wall can move with practically no applied field at zero velocity. Any imperfection in the crystal will impede the wall motion and is the main cause of hysteresis. Also, the wall has viscosity, so that an additional field proportional to the wall's velocity is necessary to move it. The constant of proportionality is called the wall's mobility. At high velocities, the field's velocity relationship becomes nonlinear, and there is some question as to whether it is possible to move a wall faster than a certain maximum velocity without breaking up the wall. This has been investigated extensively in conjunction with the design of magnetic bubble devices. A theory for wall viscosity was developed by Walker and was extended by Thiele [4]. Furthemore, the wall also has mass; therefore, an additional field is required proportional to its acceleration.

The Walker equation for the motion of a domain wal can be derived from the Landau-Lifshitz equation for a spinning charged particle. This equation has a phenomenological damping constant in it. The nature of this damping power loss is thought to be radiation at the precession frequency of the moment. Whether this would fully account for the loss is still an open question.

An important unanswered question is the source of coercivity in soft materials. No mechanism for coercivity has yet been proposed for large perfect single-crystals, and in fact it has not been established experimentally that a perfect crystal does have any intrinsic coercivity.

Two mechanisms have been proposed for inclusions, vacancies, and other imperfections in crystals: the Kersten-Néel model [5], that assumes that the wall "hangs up" on the imperfections because it takes energy to reform it just after it has moved past these imperfections, and a model that assumes that in a uniformly-magnetized region, an imperfection will have surface poles induced on it which will repel an approaching wall. Computations have been performed using the latter model for walls that are very thin compared to the diameter of a spherical imperfection [6] and for walls that are comparable in size with the imperfections [7]. Comparison with experiment indicates that the latter model gives more realistic results in certain garnets. For materials with a combination of lower magnetization and higher wall energy, the former model should give better results.

Surface roughness, stress, change in composition, such as surface doping, and similar effects are also a source of coercivity. These are usually important only in thin films where surface effects can make an appreciable contribution to the coercivity. Like the bulk effects, the source of the coercivity could be a magnetic interaction or a reduction in the wall energy, which trap the wall at isolated points.

Both of these mechanisms imply that the wall motion will not be smooth, but rather will jump from imperfection to imperfection. This erratic motion is the source of the Barkhausen effect. It was first observed experimentally as noise generated during the magnetizing process [8].

In granular materials, the individual grains are either uncoupled or very lightly coupled by exchange, and thus can act as more or less independent magnetostatically coupled entities. Each grain could be single- or multi-domain, depending upon its cross-sectional diameter. The multi-domain grains switch by propagating a local domain wall and thus have a low coercivity. The coercivity can be related to the energy required to nucleate this domain wall.

For these materials, the domain walls cannot propagate from grain to grain. In fact, different grains will have different domains. Each grain may be single-domain if it is sufficiently small; however, larger grains may be multi-domain and switch by domain-wall motion. A single-domain grain has to overcome both shape and magnetocrystalline anisotropy in order to switch. For cubic crystals with low shape anisotropy this barrier may be very low.

It is not necessary for the grain to switch to have a low coercivity. For example, an acicular grain perpendicularly oriented to the magnetizing direction will have a very small coercivity, but may also have a small permeability. In this case, it is necessary to distinguish between the switching field, the field at which the grain changes its remanent state, and the coercivity, the field which reduces the magnetization to zero along a given direction. The switching field of grains varies only at most by a factor of two, but the coercivity decreases essentially monotonically to zero as the angle of the major axis of the grain with respect to the applied field is increased from 0° to 90°.

The classic model for an isolated grain was proposed by Stoner and Woflfarth [9]. It is valid for ellipsoidally shaped grains, or for very small grains, or for materials with very high exchange energy. Other analytical models have been proposed for these shapes that led to the curling and buckling modes. Also a model that approximated a finite length rod by a chain of spheres produced the fanning mode. These results are summarized in [10].

Traditionally odd-shape grains are approximated by ellipsoids when trying to explain experimental results. Due to the complexity of realistic grain shapes, it is possible to obtain only numerical solutions for their magnetization processes. The results of some of these models have been recently reported [11]. The principal cause for their complex behavior is that the demagnetizing field varies dramatically over the grain.

In small grains the magnetization process is controlled principally by the shape of the grain. This effect enters into the model through the demagnetizing field. It is noted that the effect of non-uniformity in the grain's composition has not been examined by any calculation model as yet. In particular, since the grain is separated from adjacent grains by a variation in its composition, even its surface may not be clearly defined.

Eddy currents

In conducting materials, a changing field will induce electric currents. If the material is magnetic, its change in magnetization will enhance these currents. These currents generate a magnetic field that opposes the change in the applied field, and thus they attempt to shield the interior of the material from these changes.

Hard materials require large fields to change their magnetization; thus, the effect of eddy currents is usually negligible. Furthermore, many of these materials, such as ferrites, are insulators, and, therefore, the size of these currents is negligible, if not zero. Since ferrites are ferrimagnetic, they have a lower magnetic moment than ferromagnetic materials, so for the same material conductivity, they would induce smaller currents.

The process of nucleation is also not well understood as to whether it is deterministic or not. There might be some points in the crystal at which it is easier to nucleate a reversed domain. Then, a wall would always nucleate at these points and proceed by the same path through the crystal each time it is magnetized. Thus, for these deterministic process, a negatively saturated material will be magnetized positively by the same sequence of magnetization changes if the external field is applied in the same way; otherwise, domains will be nucleated at different points each time, and a different magnetization path will be taken each time.

The geometry can be manipulated to reduce the effect of the eddy currents. In particular, using thin laminations will increase the resistance of the path by which they have to flow, thereby reducing their magnitude.

Preisach modeling

The oldest example of phenomenological modeling in magnetic materials is to fit the materials behavior with a $B-H$ curve. This curve could be either linear or nonlinear, depending upon the strength of the field involved. If this curve is single-valued, such modeling is limited to nonhysteretic effects. This technique could be extended to include hysteresis loops, for example, by requiring that minor loops be parallel to the major loop; however, this technique does not compute resulting magnetizations accurately. The problem with modeling in the $B - H$ plane is that the state of the system can be characterized by only one parameter, the magnetization. Thus, it is difficult to devise a simple algorithm for creating different minor loops starting from the same point in the $B - H$ plane. A given point inside the major hysteresis loop could be attained by many magnetizing processes, and consequently when the applied field is increased, the increase in magnetization depends upon the path by which one had arrived at tha point.

Modeling in the $B - H$ plane, when applied to nonhysteretic materials, satisfies two important criteria of phenomenological modeling: the basic information used in the model is experimentally derived, in this case the $B - H$ curve, and the method is able to predict the desired behavior for certain restricted cases. The Preisach model was introduced as a systematic method for describing both major and minor lopps. The state of the system is contained in the assignment of different polarities to different regions of the Preisach plane; thus, a given point on the $M - H$ plane has many different interpretations, since the same magnetizations can be obtained for many different partitions of the Preisach plane.

This technique also has its limitations. It was shown by Mayergoyz [12] that all minor hysteresis loops between the same pair of applied fields are congruent. By generalizing the Preisach function to $P(H_+, H_-, H)$ that is not only a function of the positive and negative field extrema, but also the applied field at that instant, he showed that the loops do not have to be congruent, but only have to have the same height for all cross-sections.

Much greater freedom could be obtained in describing minor loops, instead, by using a Preisach function of $P(H_+, H_-, M)$, that is a function of the current magnetization. This approach produced minor loops of different heights dependidng upon the magnetization, which is much more realistic. Two such models are the product model [13] and the moving model [14].

An effect that cannot be described by any of the models above is accommodation. This effect is evident when cycling between a pair of applied fields. In this case, the hysteresis loop approaches a stable loop asymptotically. In was described experimentally by Nguyen-Van-Dang [15] and theoretically by Néel [16]. Two phenomenological models for accommodation have been introduced that are compatible with the product model and the moving model respectively [17]. Basically these models assume that there is a stable loop that can be attained only asymptotically.

The original Preisach model is one-dimensional. Several attempts have been made to generalize it to more than one dimension [18]. These models are purely phenomenological and as yet no convincing physical mechanism has been proposed to justify them. These vector effects are important in modelling both tape recording and rotating machines, where the applied field changes direction during the magnetizing process.

It is especially important in soft materials to be able to model the reversible component of the magnetization as well as the irreversible component, which can be modelled increasingly accurately using the modifications of the Preisach approach discussed above. It is not desirable to simply add a reversible compnent, since the resulting magnetization may not be physically realizable. For example, it may calculate magnetizations larger than the saturation value.

The energy supplied to the material is stored by the reversible component during one part of a magnetizing cycle and returned to the source during the other part of the cycle. The energy supplied to the irreversible component, on the other hand, is dissipated. The Preisach function can be used to calculate, not only the total hysteresis loss [19] per cycle, but also the partial loss for an incomplete cycle [20].

Geometrical effects

It is noted that even if the material is well characterized, the overall behavior of the device can have some unusual effects due to its geometry. For example, Roberts and Van Nice [21] have shown that even a rectangular loop material in the shape of a toroid can appear to have a non-rectangular loop simply because the applied at the inner radius of a toroid is larger than at the outer radius. Furthermore, the phenomena of loop shearing occurs when measuring the loops of an element in its own demagnetizing field.

Numerical solutions have been attempted for these problems by both the finite element method and the finite difference method. The former method is preferred for engineering devices because of its ability to define arbitrary shapes accurately. The latter method is also useful for its simplicity in programming, especially when modeling simple shapes.

The question of how to account for grain interaction in numerical models is very complex. The Preisach model is the only mechanism which can explain adequately the complex behavior of anhysteretic magnetizing processes. Attempts to justify it for physical reasons have indicated that the Preisach function is unstable. This instability, which has led to the moving model, is probably also the cause of accommodation.

Conclusion

This paper has briefly reviewed some of the problems involved in characterizing the coercivity of soft magnetic materials. There are still many unanswered questions in modeling these materials. Some of these questions will be answered as the capability of computers increases to the point that detailed investigations of these processes can be made.

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