The physical origin of open recoil loops in nanocrystalline permanent magnets

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The numerical simulation of the open recoil loops has been carried out using micromagnetic finite element method. By giving an example for this issue, the magnetization behaviors during the recoil processes of nanocomposite Pr2Fe14B/α-Fe magnets have been analyzed. It is the strong intergrain exchange coupling that results in the magnetization reversal in some hard grains during the recoil processes, which leads to the large opening of recoil loops. The magnetization reversal of α-Fe grain follows that of its neighboring hard grains. Consequently, the opening of recoil loops is enhanced due to the presence of α-Fe grains. © 2008 American Institute of Physics.

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After a magnet saturated in a positive field and the field reduced to zero or some negative value, recoil loops are recorded by cycling the magnetic field between zero or the negative value and some larger negative field. In practice, the recoil loops represent the variation in working point in the application of permanent magnets, such as in a permanent magnet motor or generator. The recoil loops are open and the area enclosed by recoil loops shows energy loss after one cycle. Usually, the energy loss is very small for traditional permanent magnets. Therefore, the open recoil loops are well known but rarely discussed. Besides magnetic hysteresis, the same case is encountered in ferroelectric hysteresis, mechanical hysteresis, superconducting hysteresis, etc. Recently, however, it has been found that the area enclosed by recoil loops largely increases for nanocrystalline or nanostructured permanent magnets, especially for nanocomposite (hard/soft) permanent magnets.1–12 Therefore, it is fundamentally and practically important to fully understand the nature of the open recoil loops. Much effort has been paid to investigate the origins of open recoil loops in nanocrystalline or nanostructured permanent magnets.7–12

Normally, the origins of open recoil loops can be composed of a time-dependent component and a time-independent one. The time-dependent component is contributed by magnetic viscosity, i.e., thermal relaxation.1,13 In nanocrystalline or nanostructured materials, it is found that the open recoil loops are mainly determined by the time-independent component.7–11 In the following parts, we will focus on the time-independent component. For an assembly of noninteracting single-domain particles, i.e., the Stoner–Wohlfarth model, the recoil loops are not open. Based on the Preisach model, a kind of black-box theory, the open recoil loops can be produced when there are biased hysterons (asymmetrical rectangular) elements in a magnet. The biased hysterons elements are caused by the magnetic interaction between particles.4,14,15 However, the dependence of the interaction on particular states of magnetization, shapes, and location of the particles is not presented in the Preisach model at all.14 So, this model is purely descriptive and its physical basis is not clear.

Recently, for nanocomposite permanent magnets, the presence of open recoil loops is attributed to a manifestation of breakdown in the exchange coupling and the enclosed area is associated with the decoupled volume in the soft phase.7,8 Using a simple mean field model, McCallum10 pointed out that the area enclosed in the recoil loops is a function of the mean field interaction strength, the distribution of particle coercivities, and volume fraction of the soft phase. However, from the experimental results measured by x-ray resonant magnetic scattering magnetometry (XRMS), it is found that the open recoil loops are not a consequence of exchange coupling breakdown between the soft and hard phases.11 The open recoil loops are thought to originate from the anisotropy variations in the hard phase. Therefore, the exploration of microphysical origin of open recoil loops is far from its final ending. A deep understanding of the relations between intergrain exchange coupling, microstructural features, and demagnetization behaviors is necessary to the clarification of the physical origin of open recoil loops.

The issue of the physical origin of open recoil loops can be solved by understanding how the magnetization configuration varies with the external field. Although the variation in magnetization configuration with the external field can be observed by some experimental techniques, such as magnetoforce microscopy (MFM) or XRMS, only the magnetization configuration of the surface of sample (by MFM) (Ref. 16) or element-specific aggregate magnetization (XRMS) (Ref. 11) can be obtained. In other words, it is impossible to give a direct observation of magnetization reversal to reveal the physical origin of open recoil loops based on the present experimental techniques. Fortunately, the variation in magnetization configuration with the field can be obtained by numerical simulations. Up to now, it is believed that micromagnetic finite element method is powerful to simulate the magnetization behavior in a magnet.17–20 Therefore, in this work, the mechanism of open recoil loops for nanocrystalline permanent magnets is investigated using micromagnetic finite element method.

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Micromagnetics is a continuum theory to describe magnetization processes by a continuous magnetization vector. In this work, the total magnetic Gibbs free energy is composed of the exchange energy, anisotropy energy, dipolar interaction energy and the Zeeman energy under an external field H. By the energy minimization with respect to the direction of magnetic polarization, the state of magnetization can be calculated. A more detailed description of the used simulation method is given in Refs. 17 and 18.

Pr$_2$Fe$_{14}$B and α-Fe are chosen as the magnetically hard and soft phases, respectively. The parameters of room-temperature magnetic saturation polarization, anisotropy and exchange constant are used as 1.569 T, 5.567 MJ/m$^3$, and 7.7 × 10$^{-12}$ J/m, respectively, for Pr$_2$Fe$_{14}$B, and 2.15 T, 0.046 MJ/m$^3$, and 25 × 10$^{-12}$ J/m, respectively, for α-Fe. The sample is composed of 125 irregular shape grains. According to the results in Ref. 17, the mean grain size is chosen as 20 nm. The easy magnetization direction of each hard grain is distributed randomly. There are about 120 000 finite elements for each sample.

Figure 1 shows the demagnetization curves with a selection of recoil loops for the samples with (a) 0, (b) 10, and (c) 30 vol % α-Fe. Vertical bars represent recoil loop areas.

30 vol % α-Fe, respectively, which is comparable with the values reported in Refs. 7–9, 11, and 12.

Figure 3 shows vector plots of magnetization distribution, the magnetization configuration, along a cut through the sample with 0 vol % α-Fe. The vector plots of magnetization distribution as shown in Figs. 3(a)–3(d) correspond to points a–d on the recoil loop as given in Fig. 1(a). Attention should be paid to magnetization direction in the grain labeled by a dashed circle. During the recoil process of a-b-c, the magnetization direction in the circled grain changes from the negative field direction to the positive field direction under the field approaching zero. During the process of c-d-a, the magnetization direction in the circled grain is changed to the negative direction under the field approaching to the field at point a. The nearly same cases can be found in the vector plots of magnetization distribution along other cuts through the sample. Therefore, it is clear that the recoil loop a-b-c-d-a as shown in Fig. 1(a) is mainly contributed by the magnetization reversal in some grains.

As shown in Fig. 3(a), it is noted that in the core of the circled grain the magnetization direction, close to the given easy axis, is opposite to those of its most neighboring grains. Similar cases can be easily found in other cuts. Considering the strong intergrain exchange coupling in a magnet with 20 nm averaged grains, it is easy to understand that the magnetization direction near the grain boundaries of the circled grain deviates somewhat in the direction in the grain core as shown in Fig. 3(a). Therefore, as the field varies along a-b-c,
the magnetization state of the core of the circled grain becomes less and less stable. As a result, the magnetization direction suddenly reverses as shown in Fig. 3(c). During the c-d-a process, due to the uniaxial anisotropy, a larger field is needed to resume the magnetization state in the circled grain as shown in Figs. 3(d) and 3(a). That is, the open recoil loops are mainly contributed by the magnetization reversal in some grains. Because of strong intergrain exchange coupling, the reversal of magnetization during recoil processes in some grains is suggested to be a characteristic of isotropic nanocrystalline magnets. Thus, the area enclosed by open recoil loops for nanocrystalline magnets is larger than that for traditional magnets in which the intergrain exchange coupling is not so strong.

Figure 4 shows vector plots of magnetization distribution along a cut through the sample with 10 vol% α-Fe. The plots (a)–(d) shown in Fig. 4 represent points a-d on the recoil loop as given in Fig. 1(b), respectively. Similar case of the samples with 5, 20, and 30 vol% α-Fe is omitted here. Gray grains in Fig. 4 denote α-Fe. When we focus on the magnetization distribution of hard grains only, the same result, the magnetization reversal in some grains takes place during recoil process in single-phase nanocrystalline magnet, can be further confirmed in nanocomposite magnets. It is noted that the magnetization reversal of α-Fe as circled in Fig. 4 is almost simultaneous with those of its neighboring hard grains, which is consistent with the XRMS results reported in Sm-Co/Fe exchange spring magnets. Due to very weak anisotropy and large exchange coupling constant of α-Fe, α-Fe grain acts as a “glue” sticking the magnetizations of its neighboring hard grains together. Compared with the case in a single-phase magnet, the opening of recoil loop is amplified by the presence of α-Fe. In the past, the open recoil loops in nanocomposite magnets was assumed to be caused by the internal hysteresis loops of α-Fe grains. However, after checking the plots along a lot of cuts through the nanocomposite magnets, we find that no magnetization reversal of α-Fe grains is unaccompanied by the magnetization reversal of a neighboring hard grain, which is similar to the results in Ref. 17.

In summary, during the recoil process the occurrence of magnetization reversal in some grains is caused by the strong intergrain exchange coupling in a nanocrystalline magnet, which leads to the obviously open recoil loops. In nanocomposite magnets, the magnetization of α-Fe grains cannot reverse solitarily. In other words, the magnetization reversal of some α-Fe grains is the concomitant of that of its neighboring hard grains. As a result, the opening of recoil loop is amplified by the presence of α-Fe in nanocomposite magnets. Therefore, we should be careful about the application of nanocrystalline magnets in the case of varying working point, such as in permanent magnet motor or generator.

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