Issues with Micromagnetic Numerical Simulations of Magnetic Structures of Soft Magnetic Materials for Electric Vehicles

F. Akagi[1]
[1]Dept. of Applied Physics, Kogakuin Univ., Shinjuku 163-8677, Japan

1. Introduction

Ferromagnetic materials are used in the drive motors of electric vehicles. NdFeB magnets are used on the rotating part (or “rotor”) of drive motors and electrical steel is used on the stationary part (or “stator”). In terms of magnetic properties, NdFeB magnets are classified as hard magnetic material and electrical steel as soft magnetic material. Electrical steel has two magnetic characteristics. One is that iron loss (sum of hysteresis and eddy current losses) is low during transformation between electrical and magnetic energies. The other is that high magnetic flux densities are obtained even if low magnetic fields are applied to the soft magnetic materials. We previously reported that we performed micromagnetic numerical simulations of magnetic domain structures in electrical steel 1). Calculation models were assumed to be grain-oriented electrical steel (GOES) for transformer cores with an anisotropy field at 20 kA/m. Magnetization reversal in the GOES occurred by applying a DC magnetic field of 8 kA/m. This DC magnetic field was less than half of the anisotropy field but experimentally equals zero, which corresponds to the coercivity (H_c) of the GOES. Therefore, the DC magnetic field used for the micromagnetic numerical simulations was larger than expected. In this report, we describe issues with using electrical steel in simulation models, and we compare MH-loops between soft and hard magnetic materials to clarify what the issues with the micromagnetic numerical simulations for soft magnetic materials are.

2. Micromagnetic numerical simulation

In this simulation, a dynamic magnetic reversal process was calculated using the Landau–Lifshitz–Gilbert equation as follows:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\gamma(M \times H_{eff}\ ) + \frac{\alpha}{M_s}\left(M \times \frac{dM}{\mathrm{d}t}\right), \tag{1}$$

where, M is magnetization and M_s is saturation magnetization 2). H_{eff} is an effective field, which is the sum of an external, static, anisotropy, and exchange fields. γ is the gyromagnetic ratio and α is the damping factor.

In our calculations of MH-loops, a model of magnetic material contained $16\times16\times16$ cubic cells that were 3 nm long. The M_s was 1.0 T, the intercell exchange stiffness constant was assumed to be 1.0×11^{-11} J/m, and the damping constant was 0.02. The cells have uniaxial magnetic anisotropy, which aligned in one direction. The anisotropy field (H_k) was changed from 10–300 kA/m. The external field was defined by a cosine function, of which the frequency was 25 MHz.

3. Results and discussions

Table 1 compares the magnetic characteristics of soft and hard magnetic materials. Magnetic domain wall width (σ) and exchange length (ρ) are given as

$$\sigma = \pi\sqrt{\frac{A}{K_u}}, \qquad \rho = \sqrt{\frac{A}{K_u}}, \tag{2}$$

where A is the exchange stiffness constant and K_u is the anisotropy constant. The soft magnetic materials are referred to as GOES and non-GEOS; the hard magnetic materials are referred to as NdFeB for motors and CoCr alloy for hard disk drives. The cell sizes of simulation models are defined by exchange length; the cell sizes must be equal to or less than the exchange length for the NdFeB and CoCr alloy. We must consider the cell size and magnetic domain width for

GOES or non-GEOS. The exchange length cannot be calculated and the cell size cannot be determined because the magnetic domain wall width and the exchange stiffness constant are unknown. If the magnetic domain wall width is on the order of 10 nm—which equals 100–150 atoms—the intercell exchange stiffness constant is 2×10^{-13} J/m and the exchange length is about 4.5 nm. Therefore, the cell size should be smaller than 4.5 nm. However, the number of the cell is needed more than 20,000 in the direction of magnetic domain width, because the magnetic domain width is over 100 µm for GEOS. Therefore, simulations of GEOS are very difficult because they are time-consuming and require a lot of memory. As the cell increases in size, simulations of the motions of the magnetic moments in the magnetic domain wall are not precise.

Next, we compared MH-loops between soft and hard magnetic materials to clarify what the issues with the micromagnetic numerical simulations of the soft magnetic materials are. The magnetic materials were assumed to be small, as mentioned in Chapter 2. Figure 1 shows the relationship between H_k and H_c, calculated from MH-loops. The graph in Fig. 1 shows that when the H_k was higher than or equal to 100 kA/m, the H_c was proportional to the H_k. When the H_k was lower than 100 kA/m, the H_c was about 30–40 kA/m. In particular, when the H_k was lower than 20 kA/m, the H_c was larger than H_k. This might be due to the equilibrium between the exchange and static magnetic fields.

We have to solve the above issues in order to simulate soft magnetic materials using a micromagnetic numerical simulation.

Table 1 Comparison of magnetic characteristics of soft and hard magnetic materials.

Magnetic material		Grain size	Magnetic domain width	Magnetic domain wall width (nm)	M_s (T)	K_u (J/m^3)	H_k (kA/m)	Exchange stiffness constant (J/m)	Exchange length (nm)	Cell size (nm)
Soft	GOES	1−2 cm	> 100 µm	unknown	2	2×10^4	20	unknown	-	-
	Non-GOES	(∼10 µm)	> 10 µm							
Hard	Nd-Fe-B	200−1000 (nm)	-	4.4	1.6	5×10^6	6000	1×10^{-11}	1.4	2
	CoCr alloy	< 10 (nm)	-	10.0	< 1.0	$> 1 \times 10^6$	2000	1×10^{-11}	3.2	1−10

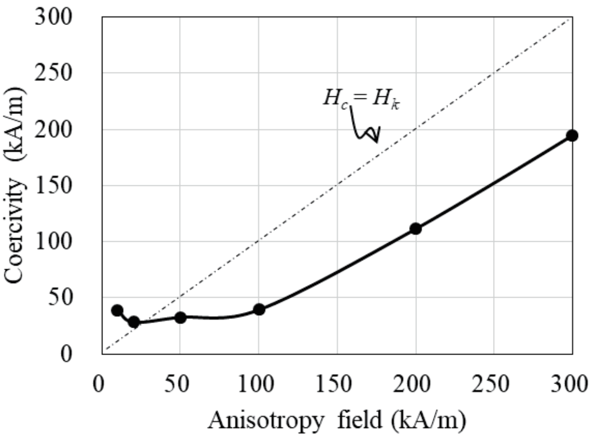

Fig. 1 Anisotropy field dependence of coercivity.

Acknowledgments

We thank Hitachi Corp. for providing us with the use of this simulator.

References

1) F. Akagi, K. Fujisaiki, The Papers of Joint Technical Meeting on “Rotating Machinery” and “Linear Drives” RM-17-045, LD-17-026, 2017, p. 19.

2) F. Akagi, J. Ushiyama, A. Ayano, and H. Miyamoto, “Head and Granular Media for Thermally Assisted Magnetic Recording for Recording Density of 6 Tb/in^2,” *IEEE Trans. on Magn.*,Vol. 49, Issue 7, 2013, p. 5667 .