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A Study on the Deperm Protocols Considering Demagnetizing Field of a Ferromagnetic Material

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Magnetic materials with large coercive force and high squareness ratio are currently developing to meet an industrial demand. Since a ferromagnetic material has hysteresis characteristics, it is hard to demagnetize a ferromagnetic material precisely. In this paper, we describe deperm processes and conduct an analysis of residual magnetization of ferromagnetic material using the Preisach modeling with a two-dimensional finite elements method (FEM). From the results, it was shown that an exponential decrement form of deperm protocol is more efficient than a linear decrement form because of the demagnetizing field in the ferromagnetic material.

Keywords : deperm, ferromagnetic material, preisach model, Anhysteretic Deperm, Deperm-ME, demagnetization effect, FEM

1. Introduction

Ferromagnetic material has been widely applied in the electric and electronics industries because soft magnetic material has a high permeability and hard magnetic material has a large coercive force. In the trend towards electrical machine miniaturization and high-efficiency, a rare-earth permanent magnet that has a higher magnetic property (ex. higher saturation magnetic flux density, larger coercive force, higher squareness ratio and etc) was developed. In order to adapt these ferromagnetic materials to industries such as permanent magnetic machines and hard disk drives, an appropriate magnetization and demagnetization system must be developed. In particular, to reduce a strong permanent magnetic field to zero, a precise demagnetization protocol is required. With the development of materials with a large coercive force and squareness ratio, like neodymium magnets and samarium cobalt, general deperm methods have limitations in demagnetization. Also, for national defense, research on precise deperm is required for demagnetization of underwater magnetic fields on warships in order to avoid detection by mines, torpedoes, and anti-submarine aircraft. There are conventional deperm protocols such as Anhysteretic Deperm, Deperm-ME and Flash-D Deperm [1-4], which were established from experience and experiments without theoretical approaches. Since they cannot reflect a ferromagnetic material's property, they are thought of as inefficient.

Residual magnetization of ferromagnetic material is caused by various factors such as domain wall pinning center, irreversible magnetization rotation and so on. And interaction between magnetic domains, that have spontaneous magnetization [5], also affected residual magnetization, so that reducing an individual small-sized region's residual magnetization is thought to be more important than reducing the object's external magnetization. In this matter, deperm magnetic field should be reached to inside the material. Since magnetic domains have different magnetization characteristics according to the external magnetic field [6, 7], a study on internal magnetization is needed. In order to carry out efficient deperm, a magnetic hysteresis curve should be considered and a suitable deperm adapted to each ferromagnetic material.

In this paper, we present a ferromagnetic property using the Preisach model and conduct a two-dimensional (2D) FEM analysis. In addition, we propose the efficient form of deperm protocol that reflects a ferromagnetic material's

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property through an internal magnetization distribution analysis according to the components of the deperm protocol.

2. Deperm of Ferromagnetic Material

As an efficient and reliable deperm protocol for ferromagnetic material, Preisach modeling, one of the hysteresis modeling methods to describe a magnetic material's property, is introduced in this section. Also, steps for deperm analysis are described.

2.1. Preisach Model

In order to analyze a magnetic material's complex hysteresis curve according to deperm protocols, a hysteresis modeling method that reflects the magnetic material’s property is required. The most widely utilized hysteresis analysis models based on properties of materials up to now have been the micromagnetics model [8, 9], the Stoner-Wohlfarth model [10, 11] and the Preisach model [12, 13]. The micromagnetics model has limitations when applied to magnetization on a macroscopic scale. Also the Stoner-Wohlfarth model cannot consider inter-particle interactions among magnetic domains. On the other hand, the Preisach model considers coercive force density distribution of magnetic domains as an input and remembers the process according to the change of input to consider magnetic hysteresis. Consequently, the Preisach model best describes the actual magnetic hysteresis characteristics and complex changes.

The magnetic hysteresis property of each magnetic domain is represented as a unit hysteresis operator f defined in Fig. 1(a). Because α and β, the output transitions of magnetic domains, are different, the number of magnetic domains over the Preisach plane containing α and β axes can be expressed as a density function: $P(\alpha, \beta)$. Because magnetic domains having spontaneous magnetization compose the macroscopic magnetization configuration, the Preisach model evaluates the volume of magnetization by integrating the density of the unit hysteresis operator. In order to calculate the volume of magnetization, the hysteresis loop is computed according to the change of input on the Preisach plane. Fig. 1 (b) shows the changes of the unit hysteresis operator in direction A and B. In direction A, α is fixed, whereas β is getting bigger, and vice versa in direction B. Therefore, when the input is increased, the trace on the Preisach plane is increased perpendicularly, whereas when the input is decreased, the trace on the Preisach plane is decreased horizontally.

2.2. Deperm Process

In this paper, we assume that only strong magnetic anisotropy is considered. Consequently, only one component of the easy magnetization axis is applied to the scalar Preisach model. The analysis program we used is a 2D simulation tool that combines Preisach modeling method and a finite element method and performs electromagnetic analysis that reflects the changing hysteresis according to the deperm process. This analysis method is compared with the experimental result based on the magnetic treatment facility (MTF) and numerical accuracy of this analysis method is verified [14]. Steps for deperm analysis that examines the internal magnetization distribution according to the deperm protocol are as follows:

1) In order to build a deperm model, place the x-axis solenoid for horizontally applying the deperm magnetic field towards the targeted ferromagnetic material.

2) To represent the ferromagnetic material property, the

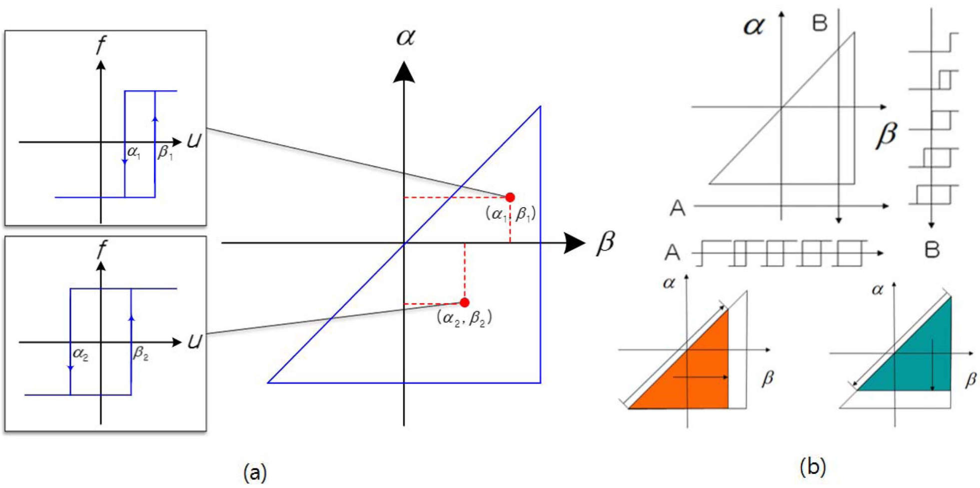


Fig. 1. (Color online) Preisach modeling: (a) unit hysteresis operator on the Preisach plane and (b) the movement of trace according to the variation of the input.

Gaussian distribution function in equation (1) is used to describe the density of the coercive force on the Preisach plane [15].

$$f(x, y, \theta_i, \theta_c) = \frac{1}{2\pi\theta_i\theta_c} e^{-\left(\frac{x^2}{2\theta_i^2}+\frac{y^2}{2\theta_c^2}\right)} \quad (1)$$

In equation (1), x and y are the grid points on the Preisach plane, θ_i is the density in the 45° direction, and θ_c is the density in the 135° direction.

3) Current is applied to the solenoid to magnetize the ferromagnetic material. After conducting electromagnetic analysis, compare the distribution of horizontal M_x with the ColorMap.

4) Configure the deperm protocol in terms of the current applied to the solenoid and apply it to the analysis. When the alternating magnetic field according to the demagnetization current is horizontally applied to the target object, the trace on the Preisach plane is generated according to the rise and fall of the supplied current, then it is integrated to calculate M_x.

5) To verify the result, compare the horizontal distribution of M_x with the ColorMap. After that, peaks of B_x, the horizontal magnetic field component and B_z, the vertical magnetic field component, which is 16 cm vertically apart from the center of the target object, are compared for numerical analysis.

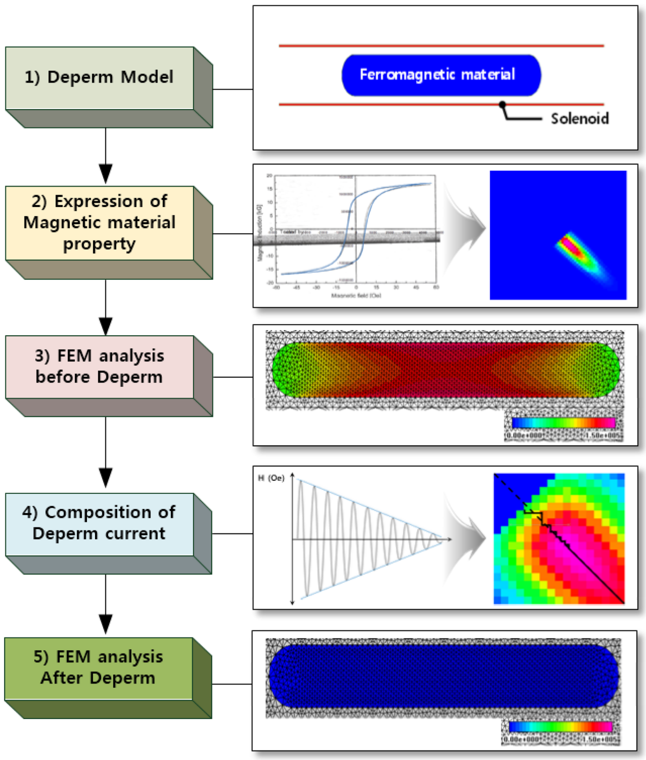


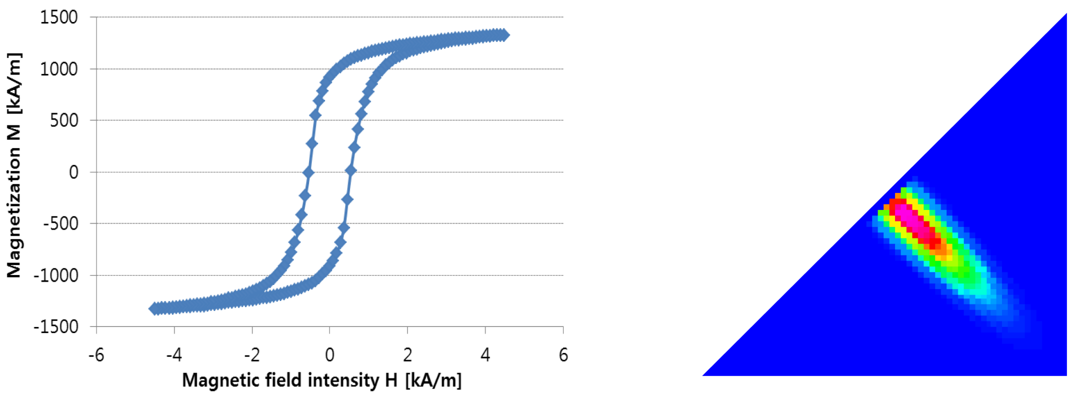
Fig. 2. (Color online) Schematic diagram of the deperm process.

3. Deperm Results and Discussion

Through the deperm analysis using SM45C, which is a carbon steel magnetic material, internal magnetization distributions are compared and analyzed. We present deperm analysis results of Anhysteretic Deperm, which have linear decrease ratios, and Deperm-ME, which have exponential decrease ratios. We also analogize the correlation of hysteresis characteristics and deperm results. Finally, we propose an efficient form of deperm protocol according to the relationship.

3.1. Effect of demagnetization field on Anhysteretic Deperm protocol

To represent the magnetic property, we used the major M-H curve of SM45C as seen in Fig. 3. According to the coercive force density of SM45C's magnetic domains, the Preisach plane is represented as seen in Fig. 3(b). As a



(a) (b)

Fig. 3. (Color online) Magnetic property of SM45C: (a) M-H curve and (b) expression on the Preisach plane.

Table 1. Parameters of anhysteretic deperm protocol.

Parameter	Anhysteretic Deperm
Shots [Number]	50
The first amplitude of magnetization current [A]	4
The first amplitude of demagnetization current [A]	4
The last amplitude of demagnetization current [A]	0.01
Deperm protocol	The decrement: 0.08 [A]

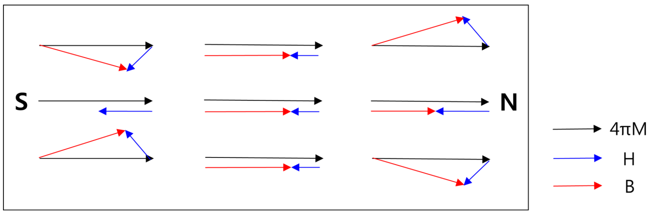


Fig. 5. (Color online) Effect of a demagnetization field.

soft magnetic material, the Preisach plane of SM45C has low scale coercive force density and wide distribution from the large interaction between magnetic domains.

In this phase, the applied deperm protocol is Anhysteretic Deperm. And the magnetization current and the first amplitude of the demagnetization current are approximately 8 times the coercive force H_c of SM45C. Each decrement is 0.08 A by configuring 50 shots of the current number and the detailed specifications of the deperm protocol, as represented in Table 1.

From the analysis results, the current component, which is applied horizontally to the target object through the X-axis solenoid, has linear decrement characteristics, as seen in Fig. 4(a). However, in the interior of ferromagnetic material, the trace on the Preisach plane, which is integrating density of the unit hysteresis, has nonlinear decrements as seen in Fig. 4(b). In order to analyze the reasons for these results, we evaluated the horizontal magnetic

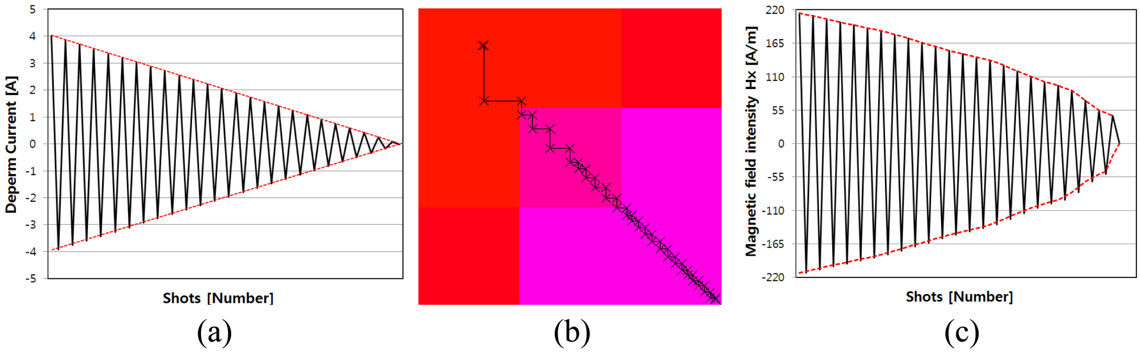


Fig. 4. (Color online) Anhysteretic deperm protocol and deperm results: (a) deperm current, (b) the trace on the Preisach plane and (c) total magnetic field strength applied to SM45C.

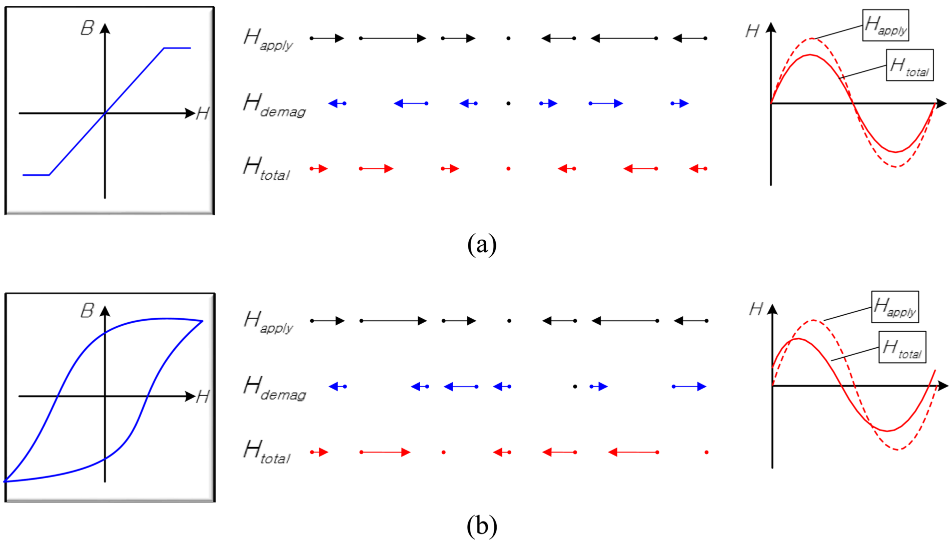


Fig. 6. (Color online) Schematic of magnetic field strength distribution: (a) in the case of non-hysteresis and (b) in the case of hysteresis.

field strength H_x values actually applied to the target object which is considered by not only the externally magnetic field but also the demagnetization field. And consequentially the variation of the magnetic field is nonlinear and has bell-shaped reduced characteristics, as seen in Fig. 4(c), that cause the nonlinear trace on the Preisach plane.

From the physical perspective of the magnetic field distribution, the demagnetization field, which is caused by the internal dipole, affects the formation of a magnetic field, as seen in Fig. 5. Therefore, the total magnetic field, H_{total}, that is really applied to the target object is represented by equation (2), which is considered to be externally applied magnetic field H_{apply} and demagnetization field H_{demag}.

$$H_{total} = H_{apply} + H_{demag} \tag{2}$$

In addition, magnetization M affects not only the magnetic field H at time t_0 but also magnetic field H at time $t \le t_0$, as in equation (3) [16, 17]

$$H_{total}(t_0) = H_{apply}(t_0) - NM[H_t \le t_0)] \tag{3}$$

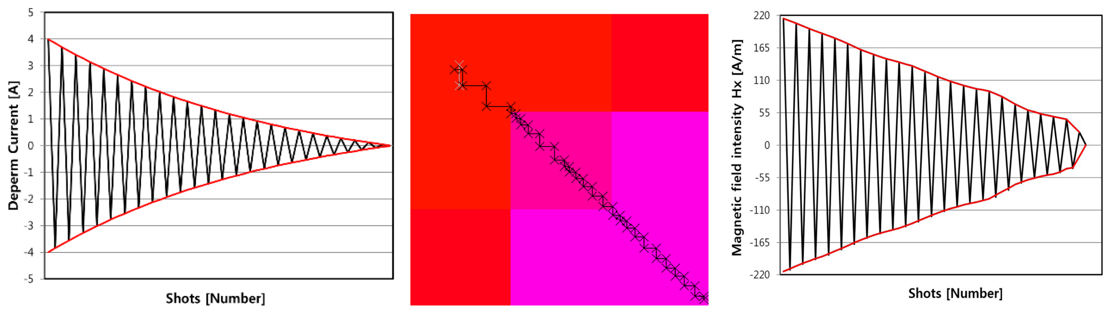
Table 2. Parameters of Deperm-ME protocol.

Parameter	Deperm-ME
Shots [Number]	50
The first amplitude of magnetization current [A]	4
The first amplitude of demagnetization current [A]	4
The last amplitude of demagnetization current [A]	0.01
Deperm protocol	The reduced form: $e^{-0.03x}$

where N is the demagnetizing factor. Fig. 6 is a schematic of magnetic field strength distribution. In case of non-hysteresis, such as Fig. 6(a), demagnetization field H_{demag} is not affected by externally applied magnetic field H_{apply}. On the other hand, in the case of hysteresis, such as Fig. 6 (b), total magnetic field H_{total} has a different magnitude and phase due to demagnetization field H_{demag} that is affected by externally applied magnetic field H_{apply}.

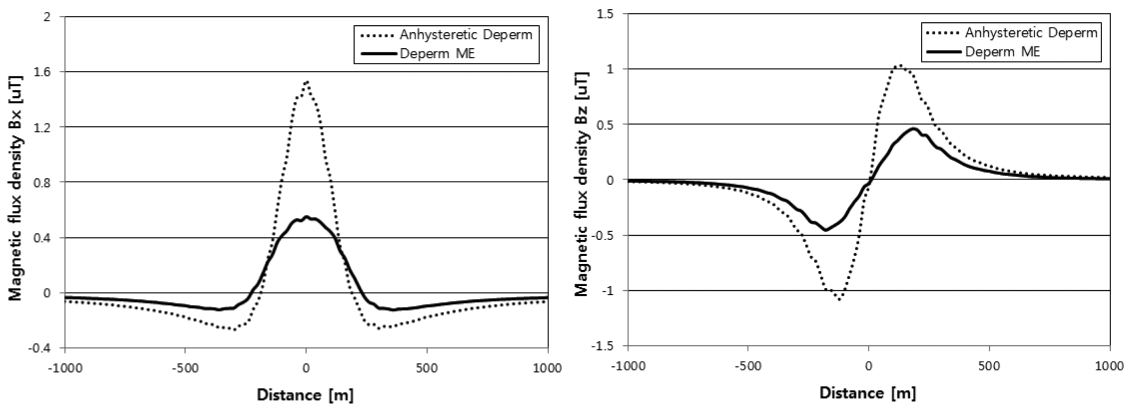
3.2. Considering the demagnetization effect on Deperm-ME protocol

The total magnetic field of the target object has a



(a) (b) (c)

Fig. 7. (Color online) Deperm-ME protocol and deperm results: (a) deperm current, (b) the trace on the Preisach plane and (c) total magnetic field strength applied to SM45C.



(a) (b)

Fig. 8. Comparing the results of the deperm protocol: (a) magnetic flux density B_x, and (b) magnetic flux density B_z.

different decrement ratio from the applied magnetic field because of the demagnetization effect. In this phase, the applied deperm protocol is Deperm-ME. Parameters of Deperm-ME are described in Table 2, which has all the same parameters as Anhysteretic Deperm except for the form of decrement.

From the analysis result of Deperm-ME, the current has an exponential decrement characteristic, as seen in Fig. 7(a), but the trace is more uniform than the trace of the Anhysteretic Deperm in Fig. 4(b), as seen in Fig. 7(b). Furthermore, horizontal total magnetic field strength H_x of Deperm-ME has more uniform decrement characteristics compared with Anhysteretic Deperm.

3.3. Comparing deperm results of Anhysteretic Deperm and Deperm-ME

Deperm results between Anhysteretic Deperm and Deperm-ME are compared by the values of magnetic flux density B. Fig. 8 shows the results at 160 [mm] apart from the target object, and we see that Deperm-ME is more efficient than Anhysteretic Deperm as the deperm protocol.

This result is related to the linearity of H_{total} applied to the target object. In the case of Anhysteretic Deperm, the decrement of early current is small, but gradually the decrement is bigger because of the bell-shaped reduced characteristics of H_{total}. On the other hand, with Deperm-ME, the decrement is more linear, having a small decrement ratio compared with Anhysteretic Deperm. Therefore, since the number of magnetic domains is increased due to the small decrement ratio, Deperm-ME is thought to be more efficient than Anhysteretic Deperm.

4. Conclusion

In this paper, we conducted deperm analysis by using Preisach modeling combined with 2D FEM. For an efficient demagnetization, Anhysteretic Deperm and Deperm-ME protocols are compared and analyzed for a ferromagnetic material. Followings are summarized results.

It is total magnetic field H_{total}, instead of applied field H_{apply}, which is applied on the target object, because of a demagnetization effect of a ferromagnetic material.

The total magnetic field strength of the target object has a different decrement ratio from the applied magnetic field strength because of the demagnetization effect.

Uniformity of the trace on the Preisach plane and decrement of H_{total} according to Anhysteretic Deperm and Deperm-ME are analyzed and result shows that an exponential decrease form of deperm protocol is more efficient because of a demagnetizing field of a ferromagnetic material.

In this paper, it is shown that a deperm protocol should consider a demagnetizing field in the material, and for a ferromagnetic material, exponential decrease form of deperm protocol produces more linearly decrement field which makes more efficient demagnetization.

Acknowledgments

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