Determination of 3-D magnetic reluctivity tensor of soft magnetic composite material

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Abstract

Soft magnetic composite (SMC) materials are especially suitable for construction of electrical machines with complex structures and three-dimensional (3-D) magnetic fluxes. In the design and optimization of such 3-D flux machines, the 3-D vector magnetic properties of magnetic materials should be properly determined, modeled and applied for accurate calculation of the magnetic field distribution, parameters and performance. This paper presents the measurement of 3-D vector magnetic properties and determination of 3-D reluctivity tensor of SMC. The reluctivity tensor is a key factor for accurate numerical analysis of magnetic field in a 3-D flux SMC motor.

Keywords: Soft magnetic composite (SMC); 3-D vector magnetic property; magnetic reluctivity tensor; numerical analysis of magnetic fields.

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1. Introduction

Soft magnetic composite (SMC) materials possess a number of unique properties such as magnetic and thermal isotropy, very low eddy current loss and relatively low total core loss, net shape fabrication with smooth surface and good finish (without need of further machining), and prospect of very low cost mass production of electromagnetic devices [1]. The basis of SMC materials is the bonded iron powder of high purity and compressibility. The powder particles are coated with an organic material, which produces an electrical insulation between particles. The coated powder is compressed in a die into a solid with the desired shape and dimensions, and the solid is then heat treated and annealed to cure the bond [2].

Because of the above unique properties, SMC materials and their application in electrical machines have attracted strong research interest in the past decade [1]. Typical examples are rotating machines with complex structures and three-dimensional (3-D) magnetic fluxes, such as claw pole and transverse flux motors [3]. In such a 3-D flux machine, when the rotor rotates, the **B** (magnet flux density) locus at a certain location can be very complicated. It can be an alternating (one-dimensional or 1-D), circularly or elliptically rotating within a two-dimensional (2-D) plane which may not be parallel to any coordinate axis, or even an irregular loop in a 3-D space, all with or without harmonics [4]. Therefore, the vector magnetic properties of the magnetic materials under different **B** vector patterns should be investigated and properly incorporated in the design and analysis of electrical machines [5, 6].

In a magnetic field analysis, **B** and **H** (magnetic field strength) are related by the magnetic reluctivity or permeability. The conventional measurement of magnetic properties is based on the assumption that **B** and **H** are parallel and hence the magnetic reluctivity in the specified orientation is a scalar. The reluctivity in an arbitrary direction is then modeled by using that of the easy axis and its perpendicular direction [7]. As the measurement assumption contradicts the fact that **B** and **H** are generally not in parallel in rotating machines, the conventional field analysis using the scalar reluctivity cannot accurately calculate the magnetic field distribution.

A huge amount of work has been done by various researchers on the measurement, understanding and modeling of magnetic properties under 2-D rotating field excitations, which are quite different from those under alternating ones [8, 9]. With a rotating flux, the magnetic reluctivity becomes a tensor of full matrix [10]. It is not correct to analyze rotating magnetic field problems by the traditional reluctivity tensor (with diagonal elements only).

Some work has been done with 2-D reluctivity tensor for analysis of laminated steel machines. For example, based on the measured 2-D data subjected to rotating field, Enokizono *et al.* calculated the 2-D magnetic tensor reluctivity (or permeability) [10, 11] and applied the tensor to 2-D finite element analysis (FEA) of the rotating magnetic field of a three-phase transformer core of oriented steel [12].

For accurate determination of magnetic field distribution of a 3-D flux rotating machine, FEA should be performed with a 3-D reluctivity tensor. However, this work has never been conducted or reported due to the lack of data, which can only be obtained by 3-D magnetic property measurements.

This paper presents the determination of 3-D magnetic reluctivity tensor of SOMAOLY™

500 [13], an SMC material specially developed for electrical machine application by Höganäs AB. The tensor elements are derived from a series of measurements on a cubic SMC sample by using a 3-D magnetic property tester [14].

2. 3-D Magnetic Property Measurement

2.1 3-D Magnetic Tester

In a magnetic material, the magnetic flux is 3-D even under a 1-D or 2-D magnetic field excitation because of the rotation of magnetic domains, without the need to mention the 3-D excitation in rotating machines. In order to understand and account for the effects of 3-D magnetic properties on the magnetic field distribution, machine parameters and performance, a 3-D magnetic testing system has been designed and constructed by the authors [15].

The system consists of a 3-D yoke to guide the magnetic fluxes along three orthogonal directions, a data acquisition system, three groups of excitation coils which are wound around the legs of the 3-D yoke, and a feedback control system comprising a control unit and three high power amplifiers. A cubic sample of the tested magnetic material is placed at the center of the yoke. For the materials with isotropic magnetic properties, e.g. SMC, the testing sample can be made of a solid cube. Fig. 1 shows a 3-D **H** sensor, and a sample with the **B** coils.

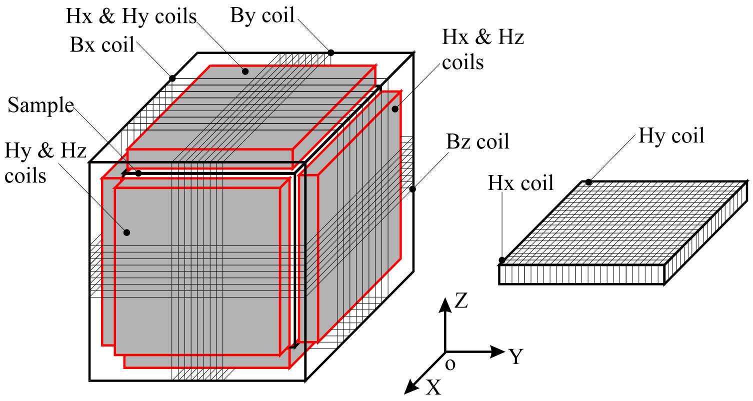


Fig. 1. A cubic sample and its **B** and **H** sensing coils for 3-D magnetic property measurement

2.2 Measurement of B-H Loop and Core Loss

Through careful design and construction, uniform **H** and **B** inside the cubic sample can be achieved. The X, Y, and Z components of the surface **H** and the cross sectional **B** are obtained by integrating the induced electromotive force (emf) of the sensing coils by

$$B_i = \frac{1}{K_{Bi}} \int V_{Bi}\, dt \tag{1}$$

$$H_i = \frac{1}{\mu_0 K_{Hi}} \int V_{Hi}\, dt \tag{2}$$

where i = X, Y, Z, $K_{Bi} = N_{Bi} h_{sp} w_i$ is the coefficient of the **B** sensing coil, N_{Bi} the number of turns of the **B** sensing coil, h_{sp} the height of the sample, w_i the width of sample, K_{Hi} the **H** sensing coil coefficient obtained by calibration, and V_{Bi} and V_{Hi} are terminal voltages of the **B** and **H** sensing coils, respectively.

The corresponding core losses can be calculated according to the Poynting's theorem by

$$P_t = \frac{1}{T\rho_m} \int_0^T \left(H_x \frac{dB_x}{dt} + H_y \frac{dB_y}{dt} + H_z \frac{dB_z}{dt}\right) dt \tag{3}$$

where P_t is the specific core loss (in W/kg) in the sample due to a time-varying 3-D **B** vector, $T=1/f$ is the time period, f the frequency of magnetization, and ρ_m the sample mass density.

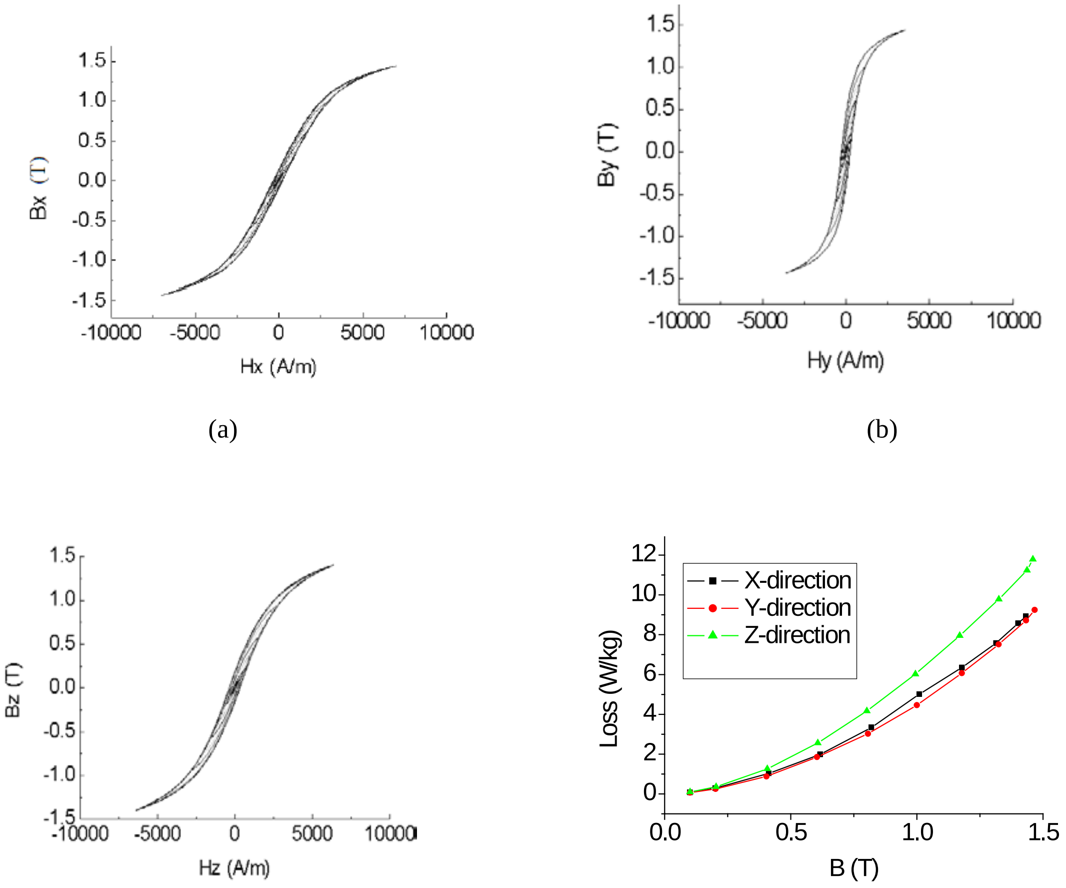
2.3 Measured Results on a Cubic SMC Sample

By using the 3-D magnetic tester, the magnetic properties of a SOMAOLY™ 500 sample cut from a cylindrical preform have been systematically measured with various **B** loci, e.g. 1-D alternating, 2-D rotating, and even a loop in the 3-D space. These measurements will provide the necessary data for modeling the reluctivity tensor and core loss. Fig. 2 shows the B-H loops and core losses when the **B** is controlled to be sinusoidally alternating at 50 Hz along the X, Y, and Z axis, respectively. It can be seen that the permeability along the Y axis is higher than that along the X or Z axis although the material is considered as magnetically isotropic. This is caused by the difference of mass densities of the SMC sample in the compressing and perpendicular directions. The preform was compacted in a cylindrical die with a high pressure along the Y-axis, i.e. the axis of the cylinder.

The difference among the core losses of three axes may be caused by the non-ideal symmetrical 3-D yokes of the tester and the mechanical stress induced during the sample preparation.

Fig. 3 illustrates the **B** and corresponding **H** loci when the **B** locus is controlled to be a series of ellipses with a fixed major axis of 1.2 T at 50 Hz in the XOY, YOZ and ZOX, respectively. Fig. 4 shows the core loss in the XOY plane with the circular **B** locus. The core losses in the YOZ and ZOX planes are similar.

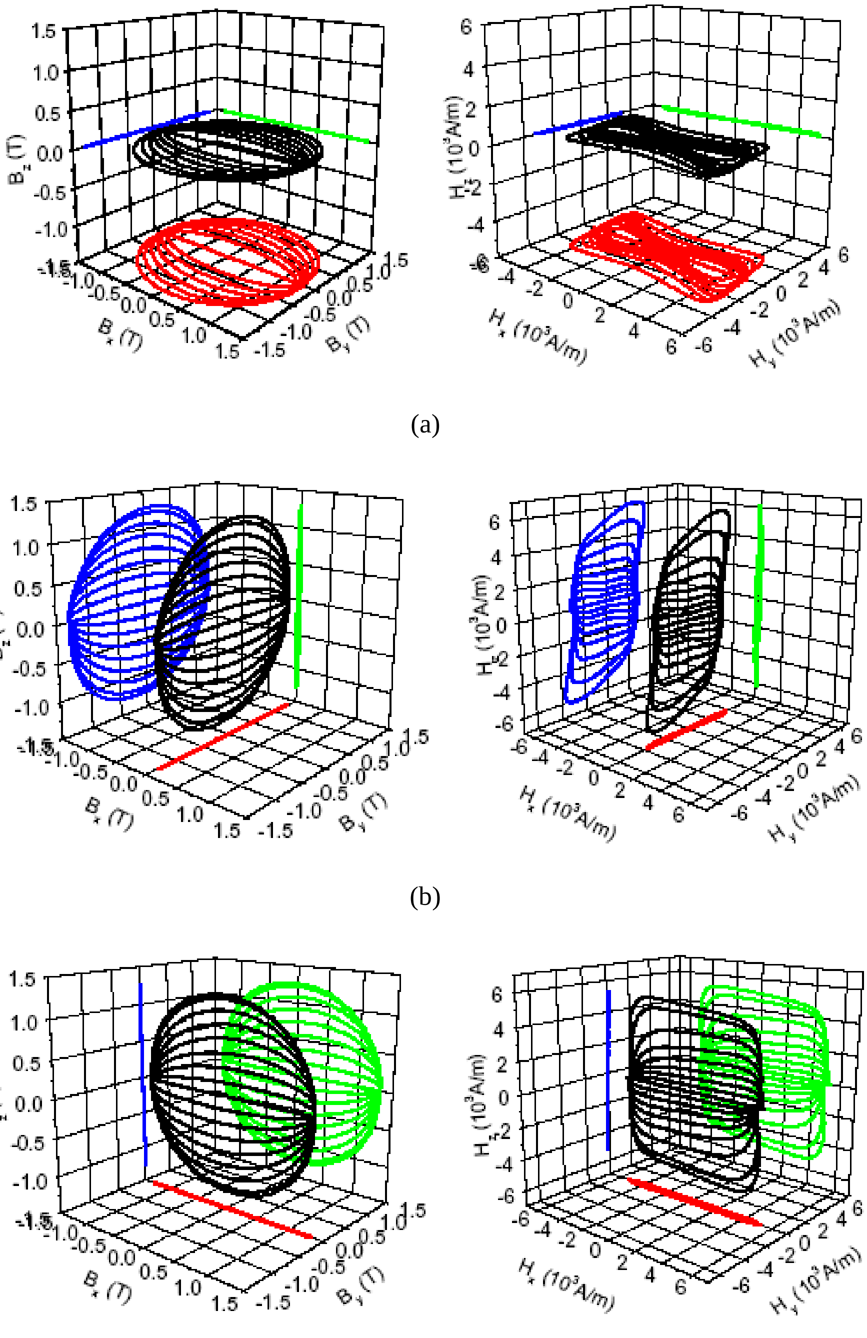
By controlling the magnetic excitations in three axes, the magnetic tester can also generate various 3-D patterns according to the testing requirement, e.g. the tip of **B** vector forms a spherical surface as shown in Fig. 5.



(a) (b)

(c) (d)

Fig. 2. B-H loops and core losses when **B** is sinusoidally alternating along one coordinate axis

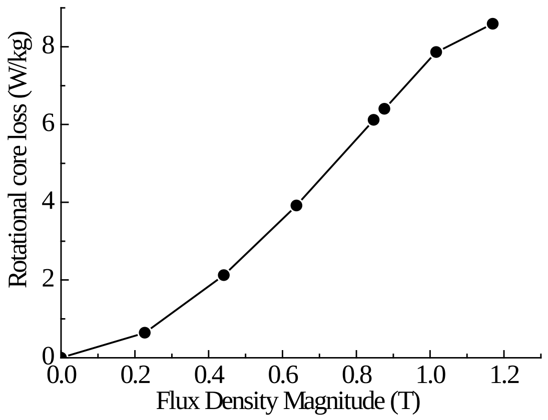


(a)

(b)

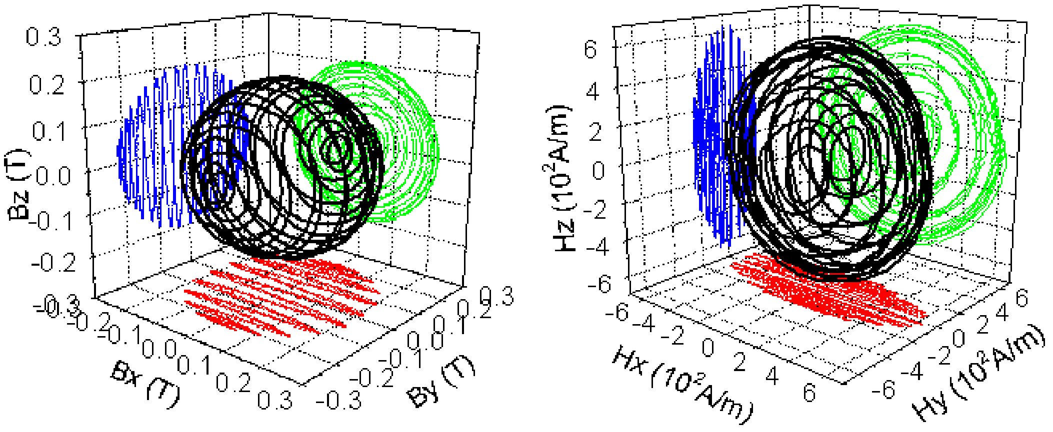
(c)

Fig. 3. **B** and **H** loci when the **B** locus is controlled to rotate elliptically in a plane: (a) XOY, (b) YOZ, (c) ZOX



(d)

Fig. 4. Core losses when **B** is circularly rotating in XOY plane



(a)

(b)

Fig. 5. (a) **B** locus and (b) corresponding **H** locus when **B** is controlled to form a spherical surface

3. Determination of 3-D Reluctivity Tensor

3.1 Reluctivity Tensor

When **B** and **H** are in the same direction, the constitutive equation is usually expressed as

$$H = \nu B \tag{4}$$

where ν is the magnetic reluctivity, which is a scalar. If there is a phase difference between **B** and **H**, e.g. **B** lags **H** by an angle, the constitutive equation should be written as

$$H_i = \sum_j \nu_{ij} B_j \tag{5}$$

where ν_{ij} is the reluctivity tensor. The magnetic properties with tensor reluctivity are called vector magnetic properties.

It has been known that the **B** and **H** loci at different positions in the magnetic core of a rotating electrical machine can take very different patterns, when the rotor rotates. Because any types of **B** or **H** locus can be transformed into a Fourier series, and each of the harmonics basically forms a circular or elliptical locus [4], it might be sufficient to investigate the magnetic properties of ferromagnetic materials under the excitations of elliptical **B** vectors.

The B-H curves and core losses of SMC are measured under a series of **B** vectors, which are controlled to be elliptical loci on different planes, different orientations, different peak flux densities, different axis ratios (the ratio between the minor and major axes of an elliptical **B** locus), and different frequencies. Some examples of measurement are given in Fig. 5.

It should be noted that the measurements under 1-D alternating and 2-D rotating magnetic fluxes by using the 3-D tester are substantially different from those obtained from conventional measurements, as the latter cannot detect the 3-D effect.

From these measurements, the reluctivity tensor in the relationship between the **B** and **H** vectors (5) can be deduced.

3.2 Numerical Modeling of 3-D Magnetic Properties

The vector magnetic properties of material and the tensor expression of the reluctivity in the constitutive equation have been discussed. In a 3-D magnetic field, the X, Y, and Z components of magnetic field strength can be expressed as:

$$\begin{pmatrix} H_x \\ H_y \\ H_z \end{pmatrix} = \begin{bmatrix} \nu_{xx} & \nu_{xy} & \nu_{xz} \\ \nu_{yx} & \nu_{yy} & \nu_{yz} \\ \nu_{zx} & \nu_{zy} & \nu_{zz} \end{bmatrix} \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} \tag{6}$$

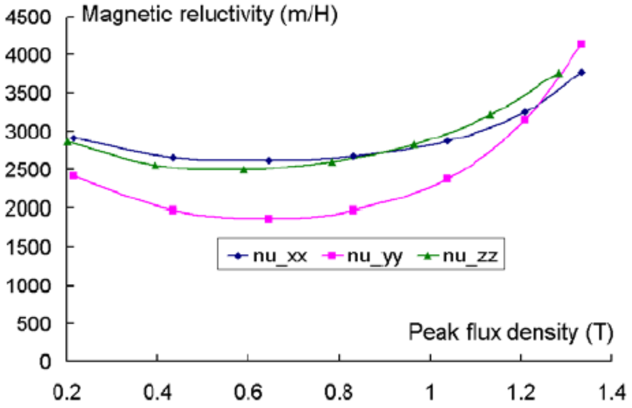
The vector magnetic properties are defined by three parameters including the maximum flux density, orientation and axis ratio of the elliptical **B** locus [16, 17]. The orientation is defined by the direction of major axis of the **B** ellipse, which is given by the angles between the major axis and the three coordinate axes [18, 19]. Theoretically, SMC is magnetically isotropic and its magnetic properties should be independent of the orientation of **B** vector. Hence, the terms of the reluctivity tensor are a function of the flux density magnitude and the axis ratio only.

When the measured components of **B** and **H** are substituted into (6), three equations are obtained. But the reluctivity tensor cannot be solved yet as it contains nine elements. Because each tensor element is a constant on one loop (with fixed maximum flux density and axis ratio) [10], the following equations can be obtained if three different points of the loop are considered.

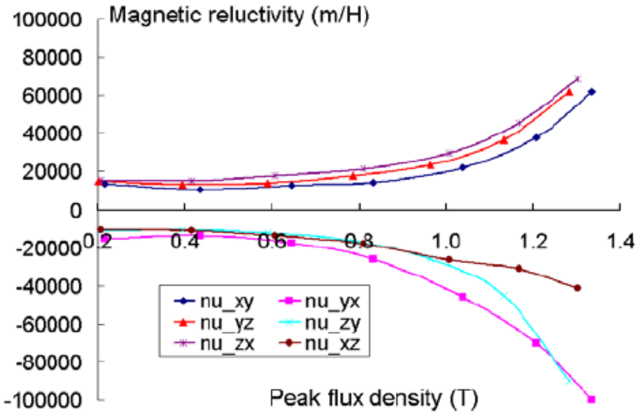
$$\begin{aligned} H_x(a) &= \nu_{xx} B_x(a) + \nu_{xy} B_y(a) + \nu_{xz} B_z(a) \\ H_x(b) &= \nu_{xx} B_x(b) + \nu_{xy} B_y(b) + \nu_{xz} B_z(b) \\ H_x(c) &= \nu_{xx} B_x(c) + \nu_{xy} B_y(c) + \nu_{xz} B_z(c) \end{aligned} \tag{7}$$

By solving (7) simultaneously, ν_{xx}, ν_{xy}, and ν_{xz} can be obtained. Similarly, ν_{yx}, ν_{yy}, ν_{yz}, ν_{zx}, ν_{zy}, and ν_{zz} can be acquired. Fig. 6 shows the measured reluctivity against the magnitude of a circularly rotating flux density (the axis ratio is equal to 1) in a cubic SMC sample. It is shown that the Y-axis is the easy direction although the SMC material is claimed as 3D isotropic.

This is because the sample preform is compressed along the Y-axis and it has a higher mass density in this axis than that of the other two axes.



(a)



(b)

Fig. 6. Magnetic reluctivity tensor: (a) diagonal terms; (b) off-diagonal terms

4. Conclusion and Discussion

This paper presents the measurement of 3-D vector magnetic properties and determination of 3-D reluctivity tensor of an SMC material, which are crucial for accurate magnetic field analysis of 3-D flux SMC motors. It was found that the SMC shows somewhat magnetically anisotropic. The magnetic reluctivity tensor becomes a full matrix under 3-D vector excitations, and is anti-symmetric when the rotating flux density is precisely circular. The off-diagonal elements of the tensor are due to the rotating magnetic flux.

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