Magnetic Properties of Composite Soft Magnetic Materials with 2-D Fluxes

J.J. Zhong, J.G. Zhu, V.S. Ramsden, and Y.G. Guo

Faculty of Engineering, University of Technology, Sydney
P.O. Box 123 Broadway NSW 2007 Australia
Tel: +61 2 9514 2318 Fax: +61 2 9514 2435 Email: joe@eng.uts.edu.au

Abstract

Composite soft magnetic materials produced by powder metallurgy techniques can be very useful for construction of low cost motors. However, the rotational core losses and the corresponding **B-H** relationships of composite magnetic materials with two dimensional rotating fluxes have neither been supplied by the manufacturers nor reported in the literature. This paper reports the measurement of magnetic properties of a composite soft magnetic material, SOMALOY^{TM}500, Höganäs AB, Sweden, under two dimensional excitations. The principle of measurement, testing system, and power loss calculation are presented. The results are analyzed and discussed.

1. INTRODUCTION

Composite soft magnetic materials produced by powder metallurgical techniques have undergone significant development in the past a few years. The basic raw material for the manufacture of soft magnetic powder composites is iron powder of high purity and compressibility. Sometimes alloy powders such as Fe-Ni, Fe-Si, Fe3P, and Fe-Si-Al, which are of importance as admixtures or special application of these composites, can be used. Materials for injection moulding have also been commercially available recently. This leads to simpler construction methods for electrical machines and hence much lower cost.

In a rotating electrical machine, the magnetic flux rotates. Therefore, the magnetic properties of the core material with rotating fluxes need to be examined, and employed in the performance simulation and design of rotating electrical machines. A lot has been done on rotational core loss measurement and modeling of electrical sheet steels [1-5]. The rotational core losses and the corresponding B-H loci of composite magnetic materials with two dimensional rotating magnetic fluxes, however, have neither been supplied by the manufacturers nor reported in the literature.

This paper presents the measurement of magnetic properties of a composite soft magnetic material, SOMALOY^{TM} 500, Höganäs AB, Sweden, under two dimensional excitations. By cutting the samples in different orientations, quasi three dimensional information of magnetic properties can be obtained by two dimensional measurements. The principle of measurement, testing system, and power loss calculation will be presented and the experimental results will be analyzed and discussed. The results will be useful in the design and performance analysis of rotating electrical machines of composite soft magnetic cores.

2. PRINCIPLE OF MEASUREMENT

2.1 Testing System

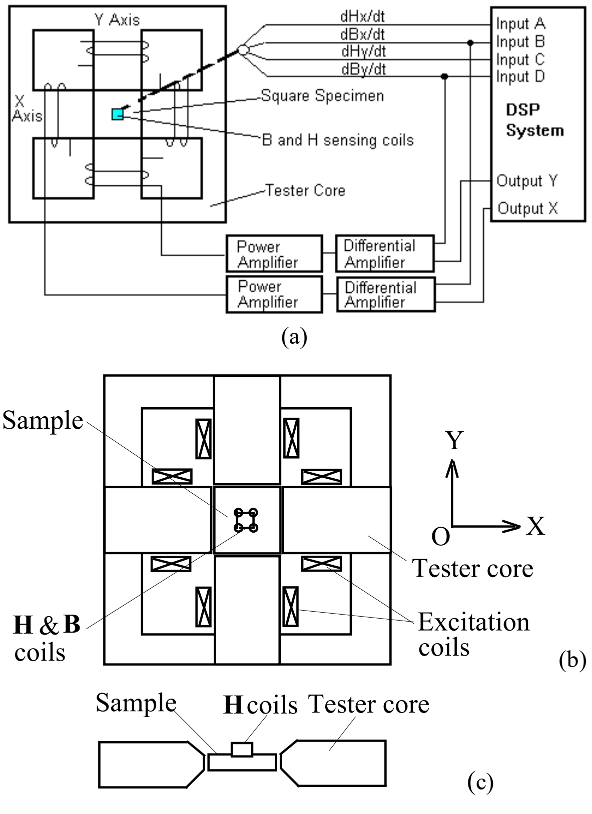
Since the rotational power losses in electrical steels were quantitatively measured for the first time by Baily in 1896 [1], a great number of measuring techniques and testing systems have been developed for rotational core loss measurement. In general, they fall into two categories:

(1) rotating a disk sample in a static magnetic field
(2) rotating the magnetic field while keeping the sample stationary.

In the second category, the sample can be a disk (or a stack of disks), a stack of annular rings, a cross, an Epstein strip, a square (or a stack of squares), or a large sheet. Among these testers, the square sample single sheet tester which was initiated by Brix and Hempel [2] appears to be the most favorable one because it is more flexible to control the rotating magnetic flux pattern and the magnetic field in the sample is more uniform and hence higher accuracy of measurement.

A square sample single sheet tester was developed at the University of Technology, Sydney (UTS) in 1992 [5] and used to measure the magnetic properties of composite soft magnetic materials under two dimensional magnetic excitations. This tester is supported by a computerised digital signal processing system, and can measure B-H relationships and core losses with either alternating fluxes in any specified orientation or circular or elliptical rotating fluxes with any specified axis ratio. Fig.1 illustrates schematically the square sample single sheet tester and the whole testing system.

The two dimensional magnetic field in the sample is generated by two groups of excitation coils arranged on the X and Y axes, respectively. The excitation voltages and currents are supplied by two identical power amplifiers. By controlling the waveforms, magnitudes, and phase angles of the excitation voltages on the X and Y axes, any complex one or two dimensional magnetic flux density vector, such as an alternating magnetic flux density inclined at a specified angle from the X or Y axis, a purely circular or elliptical rotating magnetic flux density, or a rotating magnetic flux density of any specified locus, can be generated. For the feedback control of the magnetic flux density components on the X and Y axes, two specially designed differential amplifiers with low and high pass filters are used. An IBM/PC based digital signal processing system is used for both function generation and data acquisition.



(a)

(b)

(c)

Fig.1 Schematic illustration of (a) block diagram of the rotational core loss testing system at UTS, (b) the square specimen single sheet tester, and (c) position of the sample between the magnetization poles

2.2 Measurement of 2D Magnetic Field

To determine the total core loss and **B-H** relationship in two dimensions in a sample, the flux density inside the sample and the surface field strength should be measured accurately. The flux density inside the sample can be measured in two ways: **B**-tips or **B**-coils. The former requires the material to be conductive and a good contact surface between the probe and the sample. On the other hand, the **B**-coils method is more generally applicable to samples of any materials. In the testing presented in this paper, **B**-coils are employed. As shown in Fig.2, twenty turns of enamel insulated fine wire are threaded through four small holes of about 1 mm in diameter and 10 mm apart to form a **B**-coil on each axis. The flux density on one axis can be calculated by

$$B = \frac{1}{N_B A_B} \int V_B dt$$

(1)

where N_B is the number of turns, A_B the cross sectional area, and V_B the induced terminal voltage of the **B**-coil on the axis.

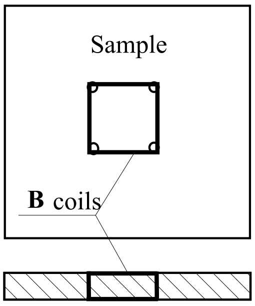


Fig.2 Two dimensional **B** coil arrangement

For the measurement of two dimensional magnetic field strength, Hall elements, surface **H** coils and Rogowski-Chattock **H** coils can be used. Because of the physical size, it is difficult to install Hall elements very close to the sample surface. Surface **H** coils can be made very thin and are linear. However, the distance between the surface and the coil has significant impact on the signal induced in the coil. To correct the signal, a number of compensation methods were developed. A special sandwich arrangement [5] was implemented by the authors. This method can effectively improve the accuracy of measurement of field strength. This arrangement, however, requires two pieces of samples to be aligned carefully. This is especially important for core loss measurement of grain oriented sheet steels. To overcome this short-coming, the Rogowski-Chattock coils are employed. Fig.3 is a photograph of two dimensional Rogowski-Chattock coils. Since the coils can be installed right on the sample surface, the correct value of the surface field strength can be picked up. The surface field strength component on one axis can be calculated from the output voltage of the coil which is aligned with that axis by

$$H = \frac{1}{\mu_o K_H} \int V_H dt$$

(2)

where V_H is the output voltage of the coil, and K_H the coil coefficient, which is determined by calibration.

The two dimensional Rogowski-Chattock coils were calibrated in a solenoid as shown in Fig.4. The solenoid was excited with sinusoidal voltage. The flux density in the center of the solenoid was calculated from the magnitude of the excitation current and double checked by a high precision Gauss meter. The sensing unit of two coils to be calibrated is mounted on a small turn table. When the output voltage signal of a coil, which is proportional to the excitation frequency and the flux density in the center of the solenoid, reaches the maximum, the axis of this coil is aligned with the solenoid axis. The coil coefficient can be determined by averaging the results of a number of measurements. If the axes of the two coils are not perpendicular to each other, the error can be picked up by measuring the output voltage of the coil whose axis is not aligned with the axis of the solenoid, and can be eliminated by an axis transform.

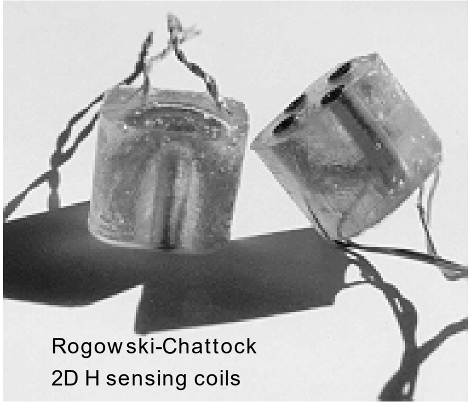
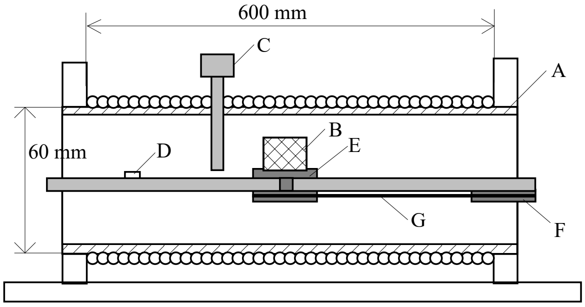


Fig.3 Two dimensional Rogowski-Chattock **H** coils



Solenoid: N=695 (turns), and H/I=1150.21 (1/m)

Fig.4 Solenoid for calibration of **H** sensing coils, where A is the solenoid frame, B the **H** coils to be calibrated, C the Gauss meter probe, D the connector for the sending coil output terminals, E the turn table for mounting the coils, and F and G are the wheel rubber band for adjusting the coil orientation.

2.3 Measurement of Rotational Core Loss

For measurement of rotational core loss, there are four methods: (a) torque-metric method, (b) thermometric method, (c) Field-metric method, and (d) Watt-metric method.

The torque-metric method is usually used in apparatus using disk or ring samples. The torque due to rotational core loss occurring in the sample is measured by using mechanical torque meters, or calculated from the variation of sample angular speed. The advantages of this method are the direct reading of the torque corresponding to rotational core loss from the torque meter, and the ability to measure rotational core loss with high flux density. The disadvantage is the difficulty of torque meter construction owing to the complicated mechanics.

In the thermometric method, the temperature of the sample is determined by thermocouples, thermistors, or thermoviewers. The rotational core loss is proportional to the initial rate of the sample temperature rise if no cooling process is involved. This is a very versatile method, which has been widely used in apparatus using various types of samples, such as disk, cross, and square, with various types of rotating magnetic fields. The major shortcomings of this method are the difficulties of installation and calibration of thermosensors, and isolation against the surrounding. It is, therefore, being more and more replaced by the field-metric method.

In the field-metric method, rotational core loss is calculated from the measured magnetic field strength **H** at the sample surface and flux density **B** inside the sample. This method features high accuracy and great versatility. Moreover, the measured instantaneous **H** and **B** values can yield more desirable information, such as various loss contributions, the loci of **H** and **B** vectors, and harmonics etc. The main disadvantages are the difficulties of manufacture, calibration, and installation of **B** and **H** sensors, and the sensitivity to preamplifier phase angle errors.

Watt-metric method differs from the field metric method in that the magnetic field strength H is determined from the magnetization current, and is widely used in the Epstein frames and single sheet testers for alternating core loss measurement. Initially, magnetic field strength, flux density, and core loss were measured by ammeters, voltmeters, and wattmeters, respectively. That is why this method is known as the watt-metric method. An outstanding advantage of this method is the simplicity of the H determination. When this method is used for rotational core loss measurement, however, excessive systematic error in magnetic field strength measurement would occur by applying the Ampere's law, since the magnetic flux paths in the sample and the yoke system of the rotational core loss tester are not well defined.

In the work for this paper, the field-metric method was employed. By the Poynting's theorem, the total core loss P_t in the sample can be calculated by

$$P_t = \frac{1}{T\rho_m}\int_0^T \mathbf{H} \bullet \frac{d\mathbf{B}}{dt}dt \tag{3}$$

where T is the time period of magnetization and ρ_m the mass density of sample.

3. EXPERIMENTAL RESULTS

3.1 Samples

Three 50×50×2 mm samples of composite soft magnetic material SOMALOY^{TM} 500 by Höganäs AB, Sweden, were cut in different orientations from cylindrical preforms of 80 mm in diameter and 50 mm in height. These preforms were compacted in a cylindrical die at 800 MPa and 500°C. As shown in Fig.5, sample *a* was cut with its normal parallel to the axis of the cylinder and samples *b* and *c* were cut with their normal perpendicular to the axis of the cylinder. Sample *c* was further annealed at 500°C for 48 hours in order to diminish the mechanical stress created in the manufacturing of the preform and sample.

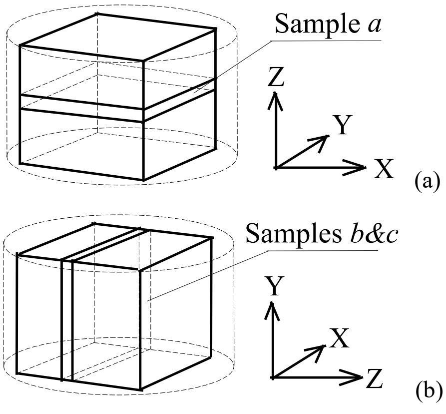


Fig.5 Positions of samples *a*, *b*, and *c* in SOMALOY^{TM} 500 preforms

3.2 B-H Loops with Alternating Fields

Figs.6-8 illustrate the B-H loops of samples *a*, *b*, and *c* under 5 Hz sinusoidal excitations on the X and Y axes, respectively. The difference between the B-H loops on the X and Y axes in Fig.6 is very small. This means that the material is almost isotropic in the transversal directions which are perpendicular to the axis of the cylindrical preform. However, in the longitudinal direction, which is parallel to the axis of the preform, the magnetic property is different from that in the transversal direction as shown in Fig.7 by the B-H loops in the X and Y axes. This could be partially due to the non-uniform distribution of iron particles and the stress produced in the preform compaction. This anisotropy is not reduced much by annealing as shown in Fig.8.

3.3 B & H Loci and Core Loss with Circular Flux

Figs.9-11 plot the **B** and **H** loci in samples *a*, *b*, and *c* with circular rotating flux density vectors at 10 Hz. The anisotropy observed in the last section by alternating measurement appears again as shown by the H loci corresponding to the circular B loci in Figs.10 and 11. Figs.12(a) and (b) plot the total core loss and its X and Y components in samples *a*, *b*, and *c* versus the magnitude of circular rotating flux density at 10 Hz and 5 Hz, respectively. It is shown that although there is a small anisotropy, the total core losses in samples *a* and *b* are close. However, the total core loss in sample c is higher than that in samples a and b. This might be due to the increment of eddy currents as a result of the damage to the insulation between particles in the annealing process.

4. CONCLUSION

Core losses in different samples of a composite soft magnetic material SOMALOY^{TM} 500 manufactured by Höganäs AB, Sweden, have been measured with alternating magnetic fields of different orientations and circular rotating magnetic fields at 5 and 10 Hz. By cutting the samples in different orientations, quasi three dimensional information of magnetic properties can be obtained by two dimensional tests. Despite the slight anisotropy, the **B**-**H** relationships and core losses in the longitudinal and transversal directions are very close. Therefore, this material can be considered as isotropic and suitable for application in electrical machines with three dimensional fluxes.

ACKNOWLEDGMENT

The authors want to thank Höganäs AB, Sweden, for supplying the preforms of SOMALOY^{TM} 500.

REFFERENCE

[1] F.G. Baily, "The hysteresis of iron and steel in a rotating magnetic field", Phil. Trans. Royal Soc. A, 1896, pp715-746

[2] W. Brix, "Verlust und Anisotropie von nichtorientiertem Elektroblech in magnetschen Drehfeldern", Von der Fakultät für Elektrotech-nik der Rheinisch-Westfälischen Technischen Grades eines Doktor-Ingenieurs genehmigte Dissertation, 1983

[3] M. Enokizono, T. Suzuki, J. Sievert, and J. Xu, "Rotational power loss of silicon steel sheet", IEEE MAG-26, No.5, Sept. 1990, pp2562-2564

[4] J. Sievert, J. Xu, L. Rahf, M. Enokizono, and H. Ahlers, "Studies on the rotational power loss measurement problem", Anales de Fisica Serie B, Vol.86 (1990), pp35-37

[5] J.G. Zhu and V.S. Ramsden, "Two dimensional measurement of magnetic field and core loss using a square specimen tester", IEEE MAG-29, No.6, November 1993, pp2995-2997

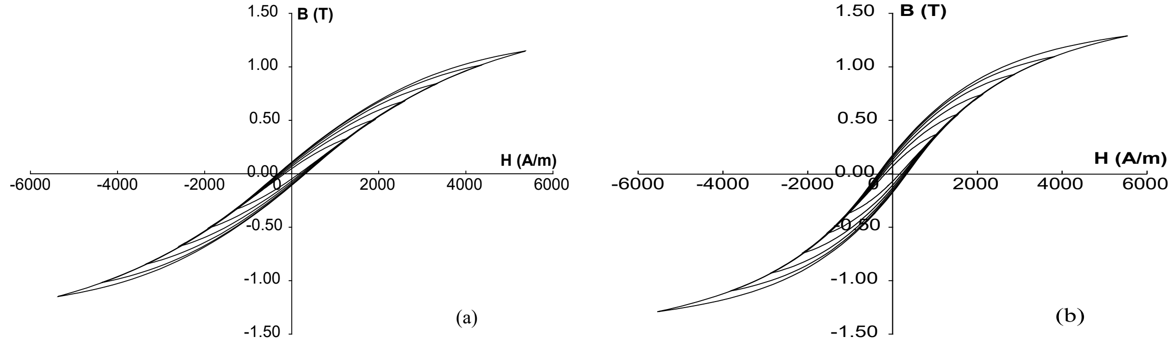


Fig.6 B-H loops of specimen *a* with 5 Hz sinusoidal flux density on (a) X and (b) Y axes

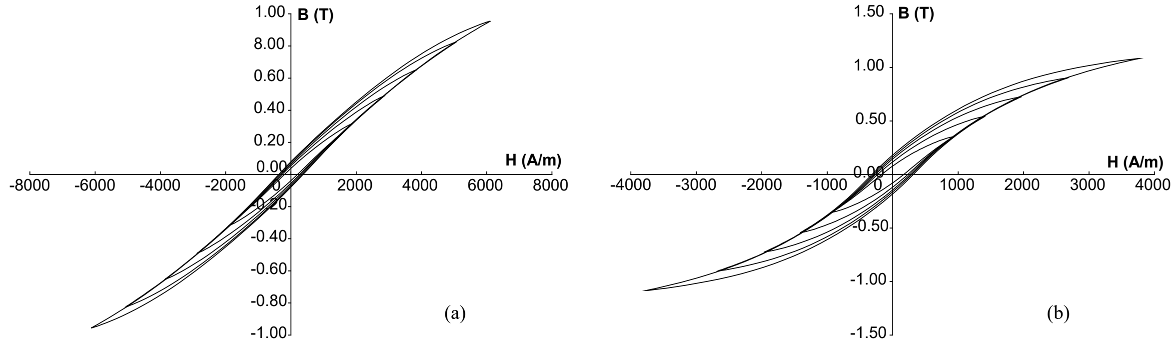


Fig.7 B-H loops of specimen *b* with 5 Hz sinusoidal flux density on (a) X and (b) Y axes

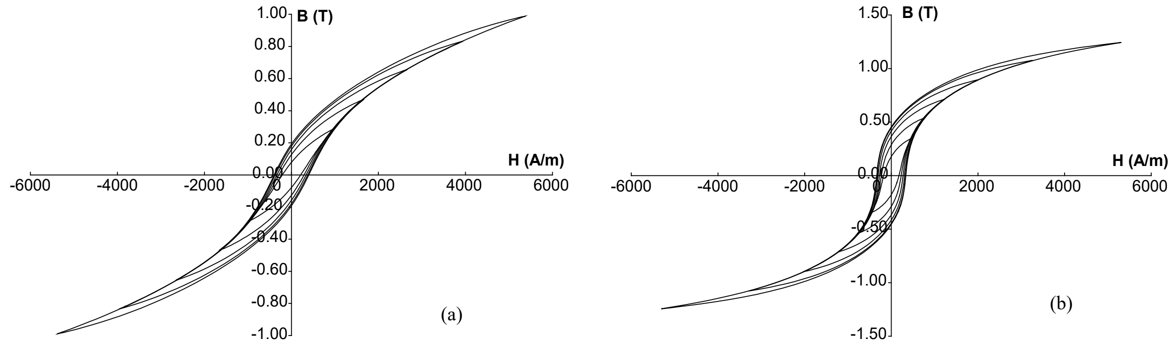


Fig.8 B-H loops of specimen *c* with 5 Hz sinusoidal flux density on (a) X and (b) Y axes

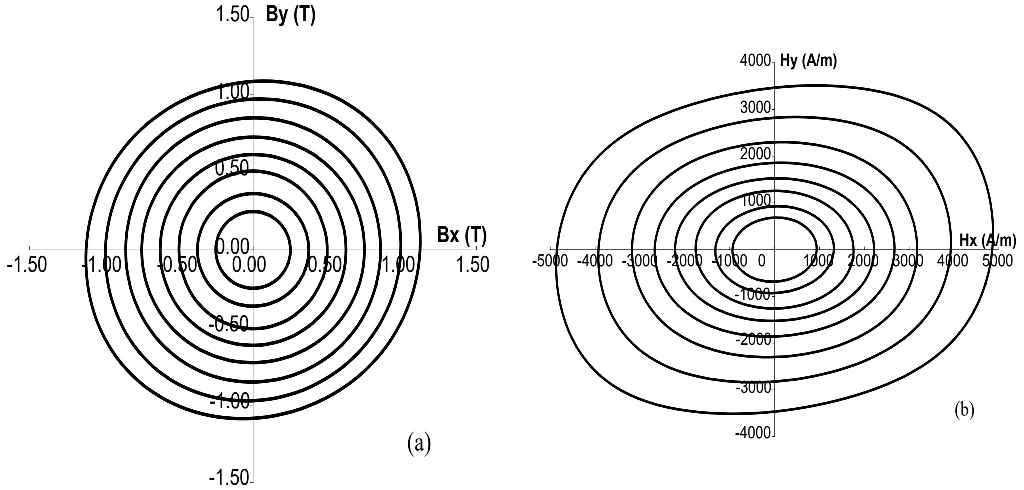


Fig.9 Loci of (a) **B** and (b) **H** vectors in sample *a* with circular rotating magnetic flux density vectors at 10 Hz

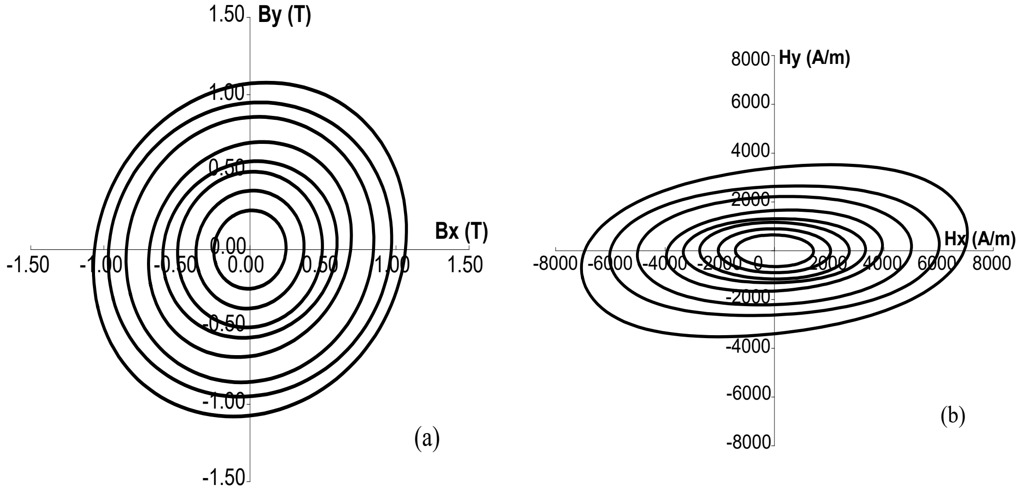


Fig.10 Loci of (a) **B** and (b) **H** vectors in sample *b* with circular rotating magnetic flux density vectors at 10 Hz

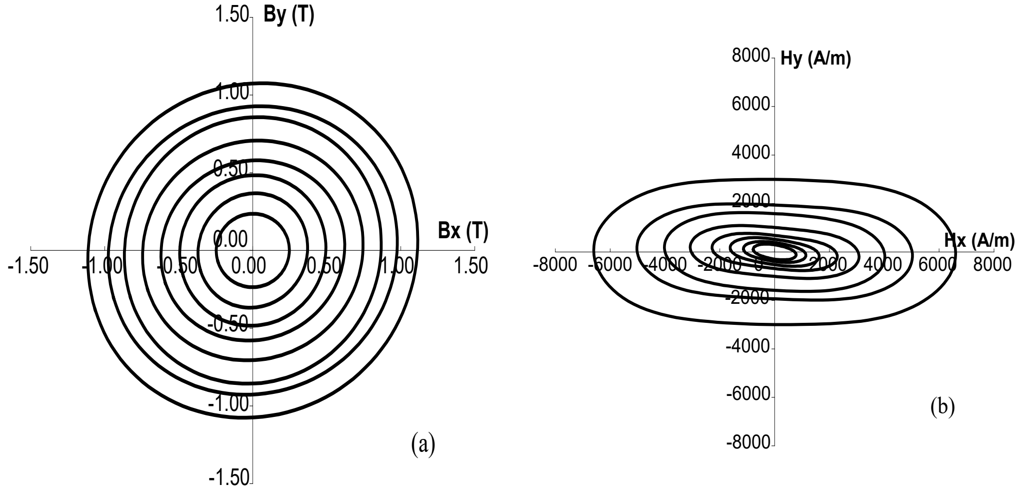
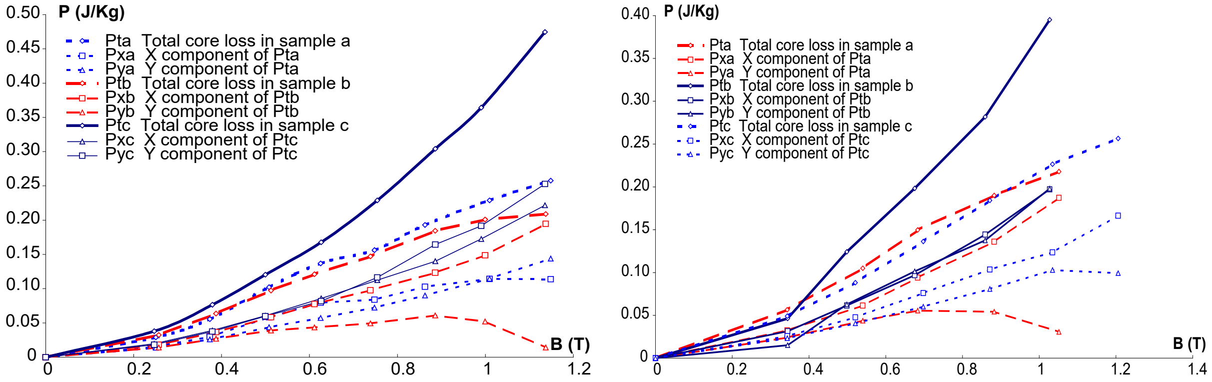


Fig.11 Loci of (a) **B** and (b) **H** vectors in sample *c* with circular rotating magnetic flux density vectors at 10 Hz



(a) (b)

Fig.12 Total core losses in samples *a*, *b*, and *c* with (a) 10 Hz and (b) 5 Hz circular rotating flux density