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Power losses of soft magnetic composite materials under two-dimensional excitation

J. G. Zhu, J. J. Zhong, V. S. Ramsden, and Y. G. Guo
Faculty of Engineering, University of Technology, Sydney, P.O. Box 123, Broadway NSW 2007, Australia

Soft magnetic composite materials produced by powder metallurgy techniques can be very useful for construction of low cost small motors. However, the rotational core losses and the corresponding **B**–**H** relationships of soft magnetic composite materials with two-dimensional rotating fluxes have neither been supplied by the manufacturers nor reported in the literature. This article reports the core loss measurement of a soft magnetic composite material, SOMALOY™ 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. © *1999 American Institute of Physics.* [S0021-8979(99)17508-X]

I. INTRODUCTION

In the last few years, a number of soft magnetic composite materials were developed using powder metallurgy techniques. The basic raw material of soft magnetic composites is iron powder of high purity and compressibility. For special applications, alloy powders such as Fe–Ni, Fe–Si, Fe3P, and Fe–Si–Al, can be used. The type of bonding between powder particles depends on the type of composite. In the case of a sintered core, it is a direct metallurgical bond, whereas in dielectromagnetics and magnetodielectrics bonding is effected by an additional substance, a dielectric, which also performs the function of insulating the ferromagnetic particles. Materials for injection moulding have also become commercially available. These materials can lead to simpler construction methods for small electrical machines and hence 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. 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 soft magnetic materials with two-dimensional rotating fluxes, however, have neither been supplied by the manufacturers nor reported in the literature.

This article presents the power loss measurement of a composite soft magnetic material, SOMALOY™ 500, recently developed by Höganäs AB, Sweden, under two-dimensional excitation. By cutting the samples in different orientations, quasi-three-dimensional information of magnetic properties can be obtained by two dimensional tests. 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 soft magnetic composite cores.

II. PRINCIPLE OF MEASUREMENT

Since the rotational power losses in electrical steels were quantitatively measured for the first time by Baily[1] in 1896, a great number of measuring techniques and testing systems have been developed for rotational core loss measurement.[2–5] Among these testers, the square specimen single sheet tester which was developed by Brix and Hempel[2] appears to be the most favorable one because it is

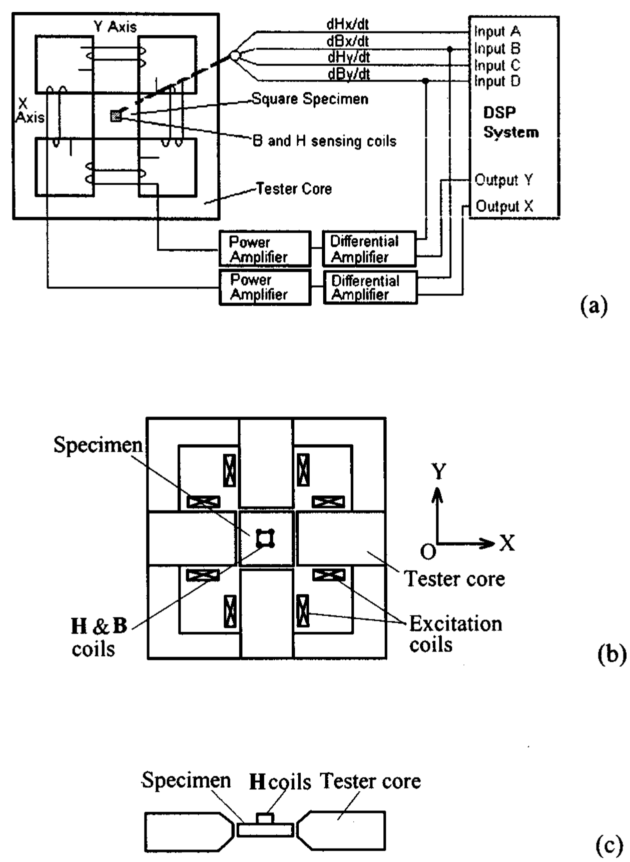

FIG. 1. Schematic illustration of (a) block diagram of the rotational core loss testing system, (b) square specimen single sheet tester, and (c) positions of specimen and **H** search coils.

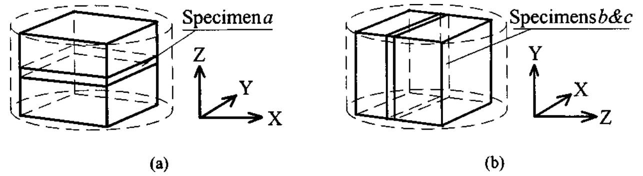

FIG. 2. Positions of specimen types *a, b,* and *c* in SOMALOY™ 500 preforms.

more flexible to control the rotating magnetic flux pattern and the magnetic field in the specimen is more uniform and hence higher measurement accuracy can be obtained.

Figure 1 illustrates schematically a square specimen single sheet tester developed by the authors in 1992.[5] This tester was used for the power loss measurement of soft magnetic composite materials with rotating fluxes. Supported by a PC based digital signal processing system, this tester can measure **B**–**H** relationships and core losses with either alternating fluxes in any specified orientation or circular/elliptical rotating fluxes with any specified axis ratio.

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. Among them, the field-metric method features high accuracy and great versatility. Moreover, the measured instantaneous **H** and **B** values can yield additional information, such as various loss contributions, the loci of **H** and **B** vectors, and harmonics, etc. In the work for this article, the field-metric method was employed. By the Poynting's theorem, the total core loss P_t in the specimen can be calculated by

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

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

III. EXPERIMENTAL RESULTS

In order to get three-dimensional information of magnetic properties by two-dimensional tests, $50\times 50\ \mathrm{mm}^2$ specimens of different thickness were cut in different orientations from cylindrical SOMALOY™ 500 preforms (80 mm in diameter and 50 mm in height). These preforms had been compacted in a cylindrical die at 800 MPa and 500 °C. Three types of specimens were prepared. As shown in Fig. 2, type *a* specimens were cut with their normals parallel to the axis of the cylinder and type *b* and *c* specimens were cut with their normals perpendicular to the axis of the cylinder, whereas type *c* specimens were further annealed at 500 °C for 48 h in order to diminish the mechanical stress created in the manufacturing of the preform and the specimen.

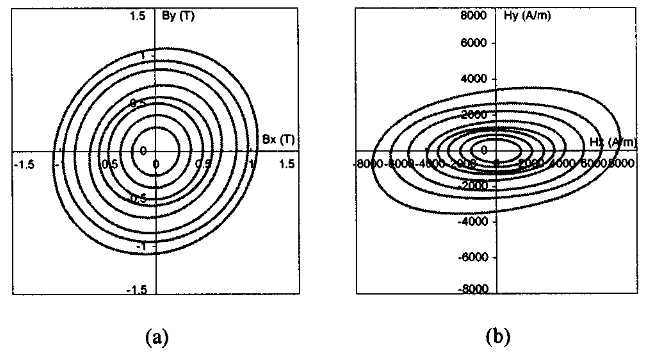

FIG. 4. Loci of (a) **B** and (b) **H** vectors in the 2 mm type *b* specimen with circular rotating magnetic flux density vectors at 10 Hz.

Figures 3–5 illustrate the **B** and **H** loci in three 2 mm thick type *a, b,* and *c* specimens with circular rotating fluxes at 10 Hz, respectively. A slight difference in anisotropy is observed between type *a* and *b* specimens. This could be partially due to the nonuniform distribution of iron particles and the stress produced in the preform compaction. This anisotropy, however, is not reduced much by annealing as shown in Fig. 5. Figure 6 plots the corresponding total core losses in the three specimens. It is shown that although there is a small anisotropy, the total core losses in type *a* and *b* specimens are close. However, the total core loss in type *c* specimen is higher than that in type *a* and *b* specimens. This might be due to the increase in eddy currents as a result of the degradation of the insulation between particles resulting from the annealing process.

Figure 7 depicts the **B** and **H** loci in a 1.27 mm thick type *a* specimen. It can be seen that the anisotropy is reduced and tends to disappear when the specimen approaches saturation. Figure 8 plots the total core losses with circular rotating fluxes at 50 Hz. For comparison, the core losses with

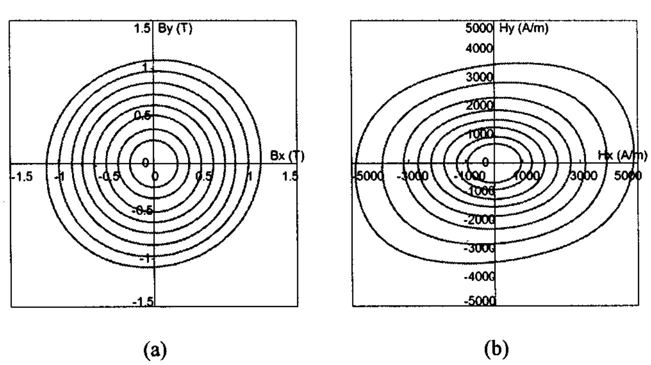

FIG. 3. Loci of (a) **B** and (b) **H** vectors in the 2 mm type *a* specimen with circular rotating magnetic flux density vectors at 10 Hz.

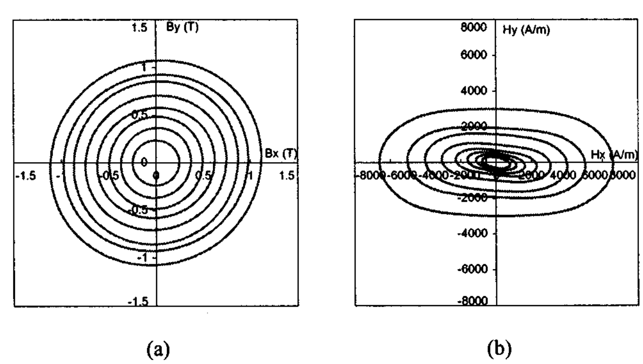

FIG. 5. Loci of (a) **B** and (b) **H** vectors in the 2 mm type *c* specimen with circular rotating magnetic flux density vectors at 10 Hz.

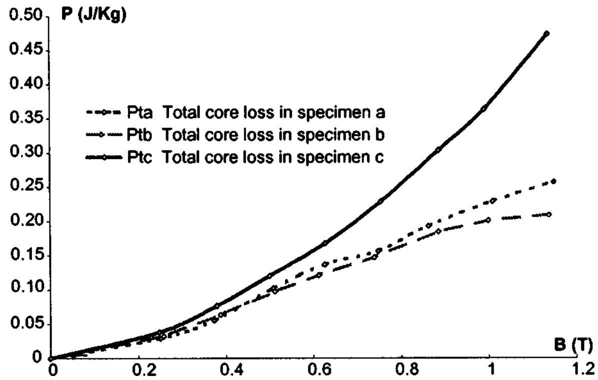

FIG. 6. Total core losses in the 2 mm type *a, b,* and *c* specimens with circular rotating fluxes at 10 Hz.

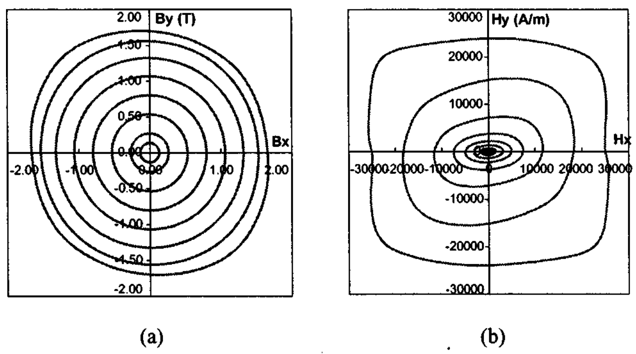

FIG. 7. Loci of (a) **B** and (b) **H** vectors in the 1.27 mm type *a* specimen with circular rotating magnetic flux density vectors at 50 Hz.

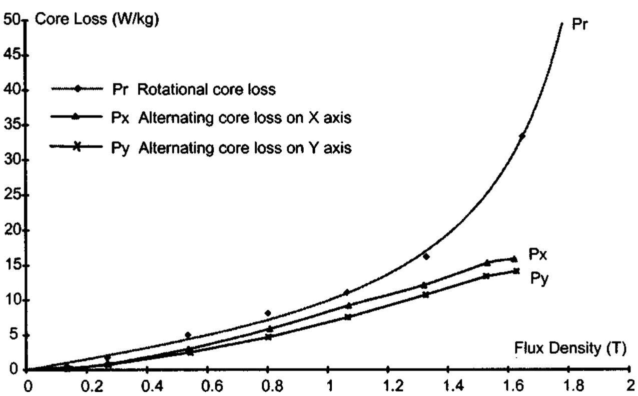

FIG. 8. Total core losses in the 1.27 mm type *a* specimen with circular rotating fluxes at 50 Hz.

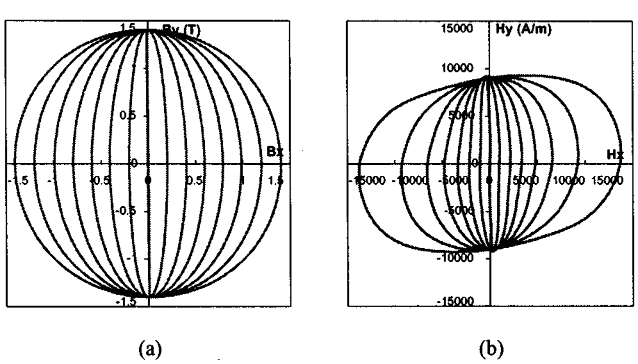

FIG. 9. Loci of (a) **B** and (b) **H** vectors in the 1.27 mm type *a* specimen with elliptical rotating magnetic flux density vectors at 50 Hz.

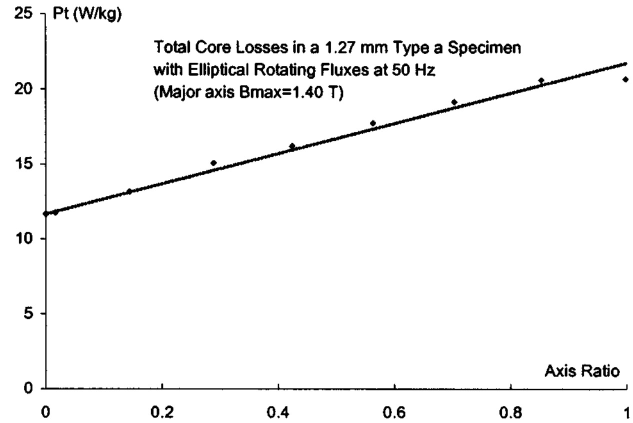

FIG. 10. Total core losses in the 1.27 mm type *a* specimen with elliptical rotating fluxes at 50 Hz.

alternating fluxes in the *X* and *Y* axes are also plotted. It is shown that the major component of power loss in SOMALOY™ 500 composite can be attributed to magnetic hysteresis because the classical eddy current loss caused by a circular rotating flux is twice as much as that due to an alternating flux. When the specimen approaches saturation, the rotational core loss increases much more rapidly than alternating core losses.

Figures 9 and 10 plot the **B** and **H** loci and total core losses against the axis ratio in the 1.27 mm type *a* specimen with elliptical rotating fluxes at 50 Hz, where the axis ratio is defined as the magnitude of flux density in the minor axis divided by the magnitude of flux density in the major axis and the magnitude of flux density in the major axis is fixed at 1.4 T. Interestingly, the total core loss against the axis ratio is almost linear.

IV. CONCLUSION

Core losses in different specimens of a soft magnetic composite material SOMALOY™ 500 developed by Höganäs AB, Sweden, have been measured with circular and elliptical rotating magnetic fields at different frequencies. By cutting the specimens in different orientations, quasi-three-dimensional information on magnetic properties can be obtained by two dimensional tests. Despite the slight anisotropy caused by nonuniform iron powder distribution and the mechanical stress generated by compaction, the **B**–**H** relationships and core losses in the longitudinal and transverse directions are very similar. Therefore, this material can be considered as isotropic and suitable for application in electrical machines with three dimensional fluxes.

ACKNOWLEDGMENT

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