Three-dimensional Magnetic Properties of Soft Magnetic Composite Materials

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This paper studies the relationship between the **B** and **H** loci, and the power losses features of a soft magnetic composite in 3-D space when the **B** loci are controlled to be circles with increasing magnitudes and ellipses evolving from a straight line to a circle in three orthogonal planes. It is found that the **B** and **H** loci lie in the same magnetization plane, but the **H** loci and power losses strongly depend on the orientation, position, and process of magnetization. On the other hand, the **H** vector evolves into a unique locus, and the power loss approaches a unique value, respectively, when the **B** vector evolves into a round locus with the same magnitude from either a series of circles or ellipses.

1. Introduction

Magnetic hysteresis is a key feature of soft magnetic materials, and is determined by the complex interplay of magnetic domain wall motion and rotation of local magnetization vectors [1]. The conventional magnetization techniques examine the overall hysteresis under one- (alternating) or two-dimensional (rotational) [2] magnetization. The investigation of three-dimensional (3-D) properties of soft magnetic materials is strongly demanded by physicists to gain a deep insight into the physical mechanisms. In fact, the nature of the magnetization process suggests that hysteresis properties should be studied in three-dimensions, and 3-D hysteresis models should be developed to predict magnetic properties for design. This paper will present a series of 3-D hysteresis loci under various experimental conditions.

2. Experiment

A 3-D magnetic property measurement system, shown in figure 1, has been successfully built [3,4]. Briefly, the system consists of a 3-D yoke to guide the magnetic fluxes along the orthogonal *x*-, *y*-, and *z*- axes, 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. As a result, various loci of the flux density **B** vector in 3-D space, for example, circular or elliptical, can be obtained. A cubic sample is located at the center of the system.

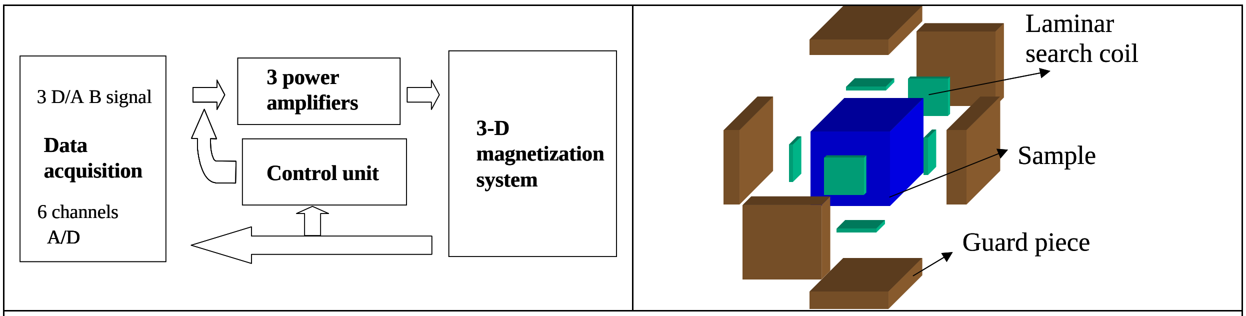

Figure 1. Schematic diagram of 3-D magnetic property measurement system and sample arrangement.

Six laminar 3-D coils, which were calibrated in a long solenoid, were attached to the sample surface. Six guard pieces which were cut from the sample material enclose the sample tightly in order to improve the accuracy, shown in figure 1. Each 3-D coil comprises two **H** coils and one planar **B** coil. The **H** coils measure the tangential component of field strength at the sample surface, for example, H_x and H_y in the *xoy*-plane while the **B** coil is used to measure the normal component of flux density, B_z. A group of equations has been derived to calculate the **H** and **B** vector in the sample by considering the superposition of components of emf induced by normal and tangential components of field [4].

The sample involved in this study was a soft magnetic composite made of highly pure iron powder with surface coating to ensure low eddy current loss. A cubic sample of 22 × 22 × 22 mm^3 and six guard pieces of 22 × 22 × 5 mm^3 were cut from a large cylindrical block.

3. Results

Figure 2 plots a series of **B** and **H** loci when the **B** loci were controlled to be circles with increasing magnitudes up to 1.3 T at 50 Hz in the *xoy*-, *yoz*-, and *zox*-planes, respectively. Their projections are also plotted. It is clear that the **B** loci are well controlled to form the round loci, and the **B** and **H** loci lie in the same magnetization planes. The **H** loci in the *xoy*- and *yoz*-planes change from ellipses to rectangle-like loops with increasing magnitudes of **B** while the **H** loci in the *zox*-plane change from circles to square-like loops. At low flux densities, **H** is linear with **B**, so the **H** loci are circles (or ellipses). However, at high **B** values the **B** is nonlinear with **H** fields. The **H** loci become rectangle-like (or square-like).

Figure 3 plots the **B** and **H** loci at 50 Hz when the **B** loci were controlled to be a series of ellipses, whose major axis is along the x- (A series) and z- (B series) axes, respectively, in the *zox*-plane. The axis ratio, R, of the minor axis to the major axis (fixed at 1.3 T) varies

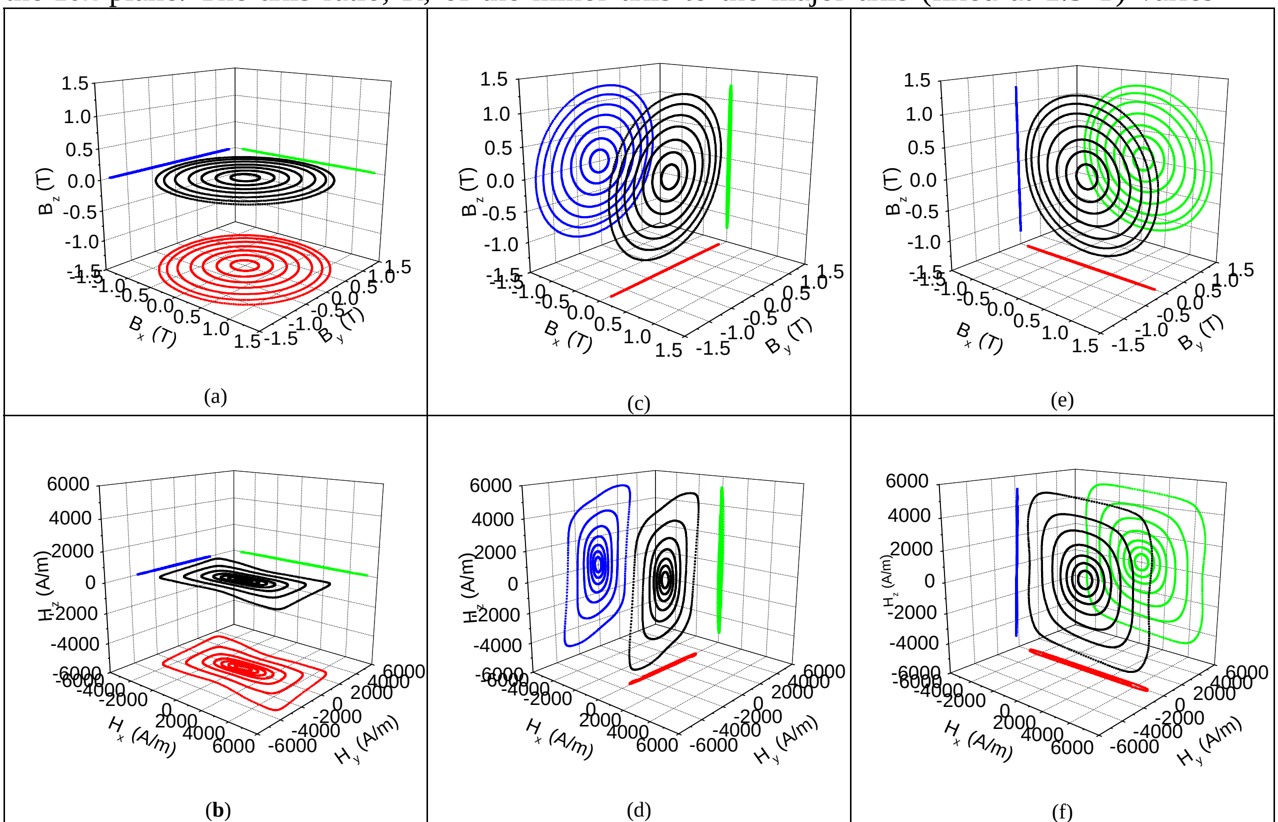

Figure 2. Round **B** loci (top row) and corresponding **H** loci (bottom row) in *xoy*- (left column), *yoz*- (middle column), and *zox*-planes (right column). (a): round **B** loci in the *xoy*-plane. B = 0.22, 0.43, 0.65, 0.83, 1.04, 1.20, 1.32 T. (**b**): **H** loci for round **B** loci in the *xoy*-plane. (c): round **B** loci in the *yoz*-plane. B = 0.20, 0.39, 0.59, 0.79, 0.96, 1.13, 1.29 T. (d): **H** loci for round **B** loci in the *yoz*-plane. (e): round **B** loci in the *zox*-plane. B = 0.21, 0.42, 0.61, 0.81, 1.00, 1.16, 1.29. (f): **H** loci for round **B** loci in the *zox*-plane.

from 0 to 1. It is seen that when the axis ratio increases, the **B** loci evolve from a straight line at R = 0 into a circle at R = 1 via a series of ellipses (1 > R > 0) while the **H** loci evolve from a straight line at R = 0 into a square-like loop at R = 1. Two series of **B** and **H** loci lie in the same *zox* plane. At R = 1, two series of **B** loci evolve into the same circle. Interestingly, the **H** loci of A and B series are the same as well. In addition, this ultimate shape of **H** loci is similar to that corresponding to the round **B** locus with the magnitude of 1.3 T in the *zox* plane shown in figure 2. This phenomenon is also observed for the **B** and **H** loci lying in the *xoy*- and *yoz*-planes.

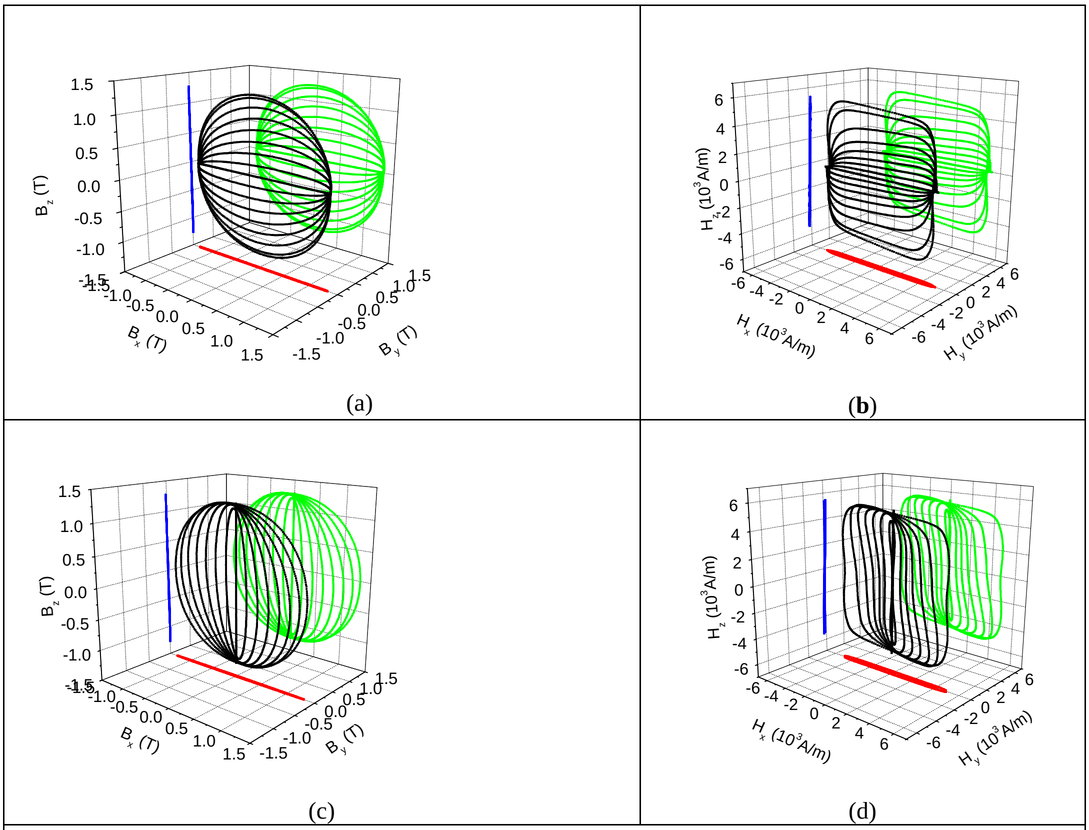

Figure 3. Elliptical **B** and **H** loci in the *zox*-plane. (a): elliptical **B** loci whose major axis is along the *x*-axis in the *zox*-plane, and R = 0, 0.14, 0.28, 0.42, 0.57, 0.70, 0.83, 0.93, 1.0, respectively. (**b**): **H** loci corresponding to the **B** loci in (a). (c): elliptical **B** loci whose major axis is along the *z* axis in the *zox*-plane, and R = 0, 0.17, 0.34, 0.5, 0.66, 0.81, 0.93, 1.0, respectively. (d): **H** loci corresponding to the **B** loci in (c).

Figure 4 plots the power losses when the elliptical (with the major axis fixed at 1.3 T) and circular **B** loci lie in the *xoy*-, *yoz*-, and *zox*-planes, respectively. The losses at R = 0 agree with the alternating loss at **B** = 1.3 T. The loss is about 6.0 W/kg for the x-axis magnetization in the *xoy*- and *zox*-planes, 7.4 W/kg for y-axis in the *yoz*- and *xoy*-planes, and 8.8 W/kg for z-axis in the *zox*- and *yoz*-planes. When the axis ratio approaches 1, the losses for both series of elliptical **B** loci whose major axes are orthogonal in one of the *xoy*-, *yoz*-, and *zox*-planes approach the same value, and this value is also the same as that corresponding to the round **B** locus with the magnitude of 1.3 T. At R = 1 in the *zox*-plane, for example, the loss is 12.3 W/kg for the round **B** locus evolving from ellipse with the major axis on the z-axis, and 12.5 W/kg on the x-axis, whereas the loss is 12.2 W/kg for the round **B** locus in the *zox*-plane with the magnitude of 1.3 T. Similarly, 14.1 W/kg is for the *yoz*-plane, and 12.3 W/kg for the *zox*-plane. In spite of the agreement of losses at R = 1, the loss for 1 > R > 0 depends strongly on the orientation of major axis and the axis ratio.

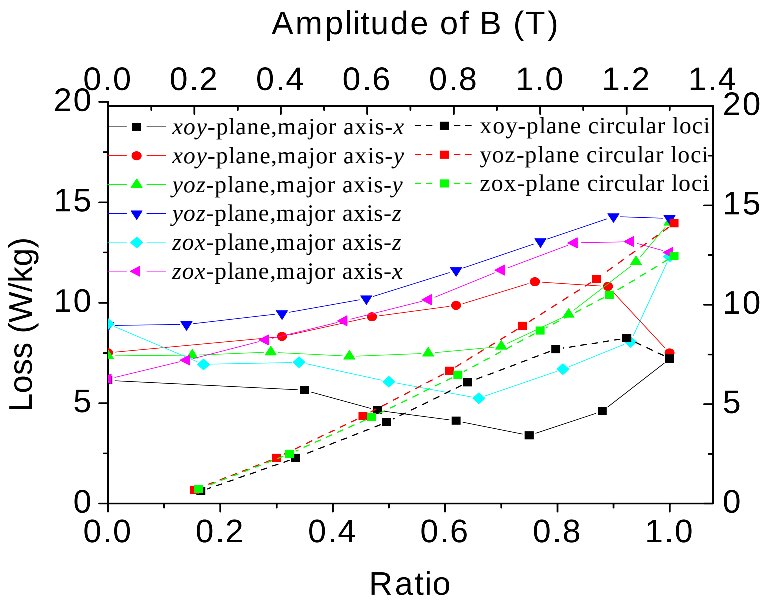

Figure 4. Power losses versus ratios of minor axis to major axis (bottom axis) of elliptical **B** loci evolving from lines to circles via ellipses, and versus amplitudes of circular **B** loci (upper axis).

4. Conclusion

A 3-D magnetic property measurement system has been developed and calibrated to characterize 3-D vector hysteresis of a soft magnetic composite. The **B** and **H** loci in 3-D space, as well as the power losses for alternating, circular, and elliptical rotating magnetizations have been presented and discussed. Although the **B** and **H** loci lie in the same magnetization plane, the shape of the **H** loci and the power losses depend strongly on the position, orientation, and process of magnetization. On the other hand, there is a unique shape of **H** loci and loss value when the corresponding **B** loci evolve into a circle with the same magnitude near the saturation value through a series of smaller circles or ellipses.

References

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