Three-dimensional hysteresis of soft magnetic composite

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Abstract

Hysteresis phenomenon is one of the important characteristics of soft magnetic materials. A three-dimensional (3-D) magnetic properties measurement system has been developed. This system can effectively control the locus of the time-varying magnetic flux density vector **B** and measure the corresponding magnetic field strength vector **H** in a cubic sample of soft magnetic material. The sample involved in this study is a soft magnetic composite sample made of highly pure iron powder. This paper investigates **B** and **H** loci in 3-D space, and power loss when the **B** loci are controlled to be circles and ellipses lying in three orthogonal planes. It is found that the **B** and **H** loci lie in the same magnetization plane, but the **H** loci and losses depend strongly on the orientation, position, and process of magnetization. On the other hand, the **H** vectors evolve into a unique locus pattern, and the power losses approach to a unique value when the **B** vectors evolve into the same loci through either a series of small circles or ellipses.

I. INTRODUCTION

Applications of magnetic materials largely rely on the hysteresis characteristics. The hysteresis curves of a material, as a valuable means connecting the magnetization mechanisms and applications of the material, are determined by complex interplay of magnetic domain wall motion and rotation of local magnetization vectors. Studying the curves is of great benefit to build general theories to interpret the hysteresis phenomenon, and also to develop practical models for optimum design of innovative electromagnetic devices, for example, electric machines. However, there are very few experiments investigating three-dimensional (3-D) characteristics of soft magnetic materials though great efforts have been made to study one- and two-dimensional magnetic properties.[1-4] This paper studies 3-D experimental results of time-varying magnetic flux density vector **B** loci and magnetic field strength vector **H** loci, and the power losses when the **B** loci are controlled to be circles with increasing amplitudes and ellipses evolving from a straight line into a circle in three orthogonal planes, respectively.

II. EXPERIMENTAL SETUP

A 3-D magnetic properties measurement system has been developed.[5,6] This system can effectively control the **B** locus and measure the corresponding **H** locus in a cubic sample of soft magnetic materials. The system consists of a 3-D orthogonal yoke system, a control system, a data acquisition system, and particular sensors for **B** and **H** vectors. Six thin H sensors with 0.5 mm thickness were immediately attached to the sample surfaces to measure the tangential component of **H** field and normal component of **B** field. The sample with dimensions of $22 \times 22 \times 22$ mm^3 is a soft magnetic composite material made of highly pure iron powder with surface coating. It has high resistivity to ensure low

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eddy current loss. In particular, the sample was enclosed by six guard pieces cut from sample material in order to uniform the magnetic field inside the sample.

III. RESULTS AND DISCUSSION

The alternating hysteresis properties of the sample were studied firstly, and then, 3-D properties, that is, **B** vectors with circular and elliptical loci controlled to lie in the three orthogonal planes and the corresponding **H** vectors, were investigated. Figure 1 plots the hysteresis loops with the **B** magnitude up to 1.3 T when the sample was magnetized at 50 Hz along the *x*-, *y*-, and *z*-axes, respectively. It is noticed that the loops for the *x*- and *z*-axes are similar while the *y*-axis seems to be the easy axis though the sample are expected to be isotropic. Figure 2 plots the alternating power loss versus flux density. The results are agreement with the data provided by Höganas AB, Sweden.

The controlled circular **B** loci and the corresponding **H** loci were measured at 50 Hz when the amplitude of **B** increases up to 1.3 T in the *xoy*-, *yoz*-, and *zox*-planes, respectively. Figure 3 plots the **B** and **H** loci when the amplitude of **B** reaches 1.3 T. It is found that the **B** and **H** loci lie in the same magnetization planes. The **H** loci in the *xoy*- and *yoz*-planes evolve from ellipses into rectangle-like loops while the **H** loci in the *zox*-plane changes from circles into square-like loops. This phenomenon is consistent with the alternating hysteresis loops since the easy magnetization is along the y-axis.

Figure 4 plots the **B** and **H** loci at 50 Hz when the **B** loci evolve gradually from a straight line into a circle with amplitude of 1.3 T via a series of ellipses in the *xoy*-, *yoz*-, and *zox*-planes, respectively. Note that the ultimate **B** circles evolve from two directions in each plane. It is found that the **H** loci also evolve from two directions, but the ultimate **H** loci are similar. In the *xoy*-plane, for example, there are two series of elliptical **B** loci, whose major

axes are along the *x*- or *y*-axis individually, but the ultimate **H** loci in respect to the **B** loci with the amplitude of 1.3 T are similar. In addition, both ultimate **H** loci are similar to the **H** locus when **B** locus is circle with amplitude of 1.3 T, shown in figure 3. Similar to figure 3, the **H** loci, shown in figure 4, in the *xoy*-, and *yoz*-planes evolve into rectangle-like loops while the loci in the *zox*-plane into square-like loops.

Figure 5 plots the power losses when the **B** loci evolve from a series of circles and from a straight line into a circle in different planes. The similarity of ultimate **H** loci can also be approved by power losses. For example, the losses approach to 7.4 W/kg when the **B** locus approaches to the circle with amplitude of 1.3 T in the *xoy*-plane, 14.1 W/kg in the *yoz*-plane, and 12.3 W/kg in the *zox*-plane. However, the losses depend strongly on the direction of the major axis, magnetization plane, and process.

IV. Conclusion

3-D magnetic properties of a cubic soft magnetic composite material made of pure iron powder with insulation coating have been studied by measuring the alternating hysteresis loops and 3-D spatial **B** and **H** loci when the **B** loci are controlled. It is found that the shape and orientation of the corresponding **H** loci and power losses depend strongly on the magnetization plane, direction and process. However, the ultimate **H** vectors have similar pattern, and the corresponding power losses are similar when the **B** vectors evolve into the same loci through either a series of small circles or ellipses.

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Figure captions:

FIG. 1. Alternating hysteresis loops when the sample was magnetized along the *x-*, *y-*, *z-*axes, respectively.

FIG. 2. Dependence of power losses on flux densities when the sample was magnetized along the *x-*, *y-*, *z-*axes, respectively.

FIG. 3. **B** (top) and **H** (bottom) loci when amplitude of circular **B** reaches 1.3 T in three orthogonal planes.

FIG. 4. **B** (row 1 and 3) and **H** (row 2 and 4) loci when **B** loci evolve from a line to a circle with amplitudes of 1.3 T in the *xoy-* (left column), *yoz-* (middle column), and *zox*-planes (right column).

FIG. 5. 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).

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

(i)

(j)

(k)

(l)