Drag force measurement: A means for determining hysteresis loss

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A method for determining hysteresis losses in thin strips of soft magnetic materials is described. It is based on the measurement of a drag force which arises with the movement of the sample through the strong field existing in the space near a permanent magnet. Not associated with macro eddy currents, the force is shown to originate from the magnetic hysteresis of the material, having, in fact, an amplitude equal to the product of hysteresis loss and the area of the sample cross section. Correlation within 18% with the measurements made by conventional methods is shown for a wide range of experimental materials. © 2006 American Institute of Physics. [DOI: 10.1063/1.2172583]

I. INTRODUCTION

Hysteresis loss is a defining characteristic of electrical steels. It strongly influences the energy efficiency and functionality of the products in which such materials are used. Hysteresis loss varies greatly with composition, with the thermal and mechanical fabrication processes, and with the direction of magnetization.\(^1\) Hysteresis loss measurement, therefore, is routinely practiced both during the development of such materials and in ensuring the consistent quality of the finished products.

Although varying significantly in detail,\(^2,3\) conventional methods determine the hysteresis loss from the enclosed area of a sample’s \(B-H\) loop. This is typically obtained by concurrent measurements of an applied field, \(H\), slowly varying between desired limits, and the resulting induction, \(B\), in a sample of known cross sectional area, \(A\). In contrast, the method described here, while also requiring knowledge of \(A\), depends only on the measurement of a mechanical force. As will be seen, the described method, in addition to its applicability to standard strip samples, offers an opportunity for the continuous measurement of hysteresis loss, in real time, during the manufacture of product in wire, strip, sheet, and possibly even in bar form.

II. THEORY

A schematic arrangement of the apparatus needed to practice the method is shown in Fig. 1. The specimen under test (SUT) is maintained at a small, fixed distance, \(G\), from a magnetic dipole of moment, \(m\), typically a permanent magnet (PM). Both the SUT and the PM are constrained to disallow the mutual attractive force, \(F_a\), to bring them into contact. The SUT is made to move in a direction parallel to \(m\) at some convenient, not necessarily constant, velocity, but slowly enough to avoid the corrupting influence of eddy currents. In the analysis which follows, it will be shown that the motion of the SUT will be resisted by a “drag” force, \(F_d\), originating from the magnetic hysteresis of the material.

Since the SUT may be large, is in motion, and subjected to a variety of associated forces, the measurement of \(F_d\) is more conveniently made by its reaction on the PM, which therefore is supported in such a manner as to both rigidly resist \(F_a\) and provide for the measurement of \(F_d\).

To simplify the analytical treatment, the PM is assumed to be a single dipole. Also, the SUT, though having a finite cross sectional area (\(A\)), is assumed to have negligible dimensions normal to \(m\) and, in the plane of its surface, normal to the direction of motion. By thus implying that the distance to the dipole is large compared to these SUT dimensions, the intensity of the dipole field, \(H\), at points within the SUT effectively varies only with the longitudinal position. The SUT is also assumed to extend far enough in both longitudinal directions that its ends are situated in regions of vanishingly small \(H\). Although \(H\) includes components normal to \(m\), the shape anisotropy of the SUT limits the effects of these components on the magnetization orientation. (It is nevertheless recognized that \(F_a\) derives from the normal component of magnetization.) Thus, the longitudinal component of \(H\) and the history of exposure to this component are the significant determinants of the intensity and polarity of the local magnetization, \(M\), within the SUT. Following from Cullity’s\(^4\) derivation, \(H\) at a point \(P\) within the SUT, at a distance \(Gx\) from the central location of \(m\), is readily shown to be

\[
H = \frac{m}{G^3(1+x^2)^{3/2}} \left( \frac{3x^2}{1+x^2} + 1 \right)^{1/2},
\]

directed at an angle, \(\beta = \tan^{-1}(0.5/x) + \tan^{-1}(1/x)\), to \(m\). Its longitudinal component is then found from

![Drag force measurement: A means for determining hysteresis loss](https://example.com/drag-force.png)

FIG. 1. Schematic arrangement of the apparatus.

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Several features of this plot should be noted.

(1a) and (1b) show \(H_L\) to depend only on \(m, G\), and the normalized distance, \(x\), to \(P\). Figure 2(a) shows \(H_L\), normalized against its maximum value at \(x=0\), plotted against \(x\). Several features of this plot should be noted.

1. \(H_L\) is symmetrical around \(x=0\).
2. The peak negative \(H_L\) is 20.2% of its peak positive value and occurs at \(x=\pm 1.225 G\).
3. \(H_L\) crosses zero at \(x=\pm 0.707 G\).
4. \(H_L\) at \(x=\pm 6G\) < 0.01 of its peak value; thus significant changes in \(M\) are limited to locations between \(\pm 5G\), a region hereinafter called the active zone (AZ).

The SUT is assumed to have arrived at the position shown in Fig. 1 by motion from left to right, and that in so doing, at least the portion shown, passed under a second, identical PM (PM2—not shown), also separated from the SUT by \(G\) and located >12G to the left of PM. An element of material of infinitesimal length, \(dx\), at position 1 in Fig. 2(a), while presently located where the fields from both PMs are near zero, has been previously exposed to the peak negative field, \(H_{p-}\), from PM2, assumed to be sufficient to result in technical saturation. Thus, when reaching position 1, the start of the AZ, this element of material will be at (negative) remanence, \(-M_r\), indicated as point 1 on the hysteresis loop in Fig. 2(b), and transcribed to a plot of \(M\) vs \(x\) in Fig. 2(c).

During further rightward motion of the SUT, a distance sufficient for the element originally at 1 to arrive at 2, the location of \(H_{p-}\), \(M\) within this element will grow along the path indicated 1 → 2 in Figs. 2(b) and 2(c). During further motion to the right, \(H_L\) falls to zero and \(M\) returns to \(-M_r\) along path 2 → 3 [Figs. 2(a)–2(c)], thereby completing the traversal of a minor hysteresis loop. The continuously moving element then experiences a steep growth in \(H_L\) of opposite polarity, reaching \(H_{p+}\) at 4, relaxing to zero at 5, a growth to \(H_{p+}\) at 6, and again approaching zero at 7, the end of the AZ. If moved slowly enough for quasistatic conditions to prevail, \(M\) within the element will follow these field variations, reaching positive saturation at 4, \(+M_r\) at 5, negative saturation at 6, and return to its starting value of \(-M_r\), at 7, thereby completing the traversal of a major hysteresis loop.

At each position within the AZ, the element will have a magnetic moment, \(MA dx\), and by virtue of the field gradient, \(dH/dx\) at that location, it will experience a longitudinal force \(dF=MA dx dH/dx\). Variation in \(dH/dx\) with position is shown in Fig. 2(d); variation in \(dF\) (plotted as \(dF/\text{dx}\)) is shown in Fig. 2(e). Since, at any one instant, there are elements of like size at every location in the AZ, the sum of these elemental forces will comprise a net force acting on the SUT,

\[
F = \int dF = \int MA dx \frac{dH}{dx} = A \int MdH. \tag{2}
\]

Since within the AZ there are elements having magnetizations representative of the traversal of both the minor loop 1 → 2 → 3 and the major loop 3 → 4 → 5 → 6 → 7, \(F\) in (2) clearly derives from the total area of both loops. Figure 2(f) shows the cumulative sum of the elemental forces to the left of each point within the AZ. The existence of a finite final sum, \(F\), clearly seen in this figure, reflects the asymmetry of the plots in Figs. 2(c) and 2(e), asymmetries which arise from the hysteretic \(M-H\) functions of the SUT material. \(F\) is seen to be a repulsive force, acting to resist the motion of the SUT. The reaction on the PM is in the opposite direction, tending to drag it along in the direction of the motion, hence its appropriate appellation, “drag force,” \(F_d\).

### TABLE I. Identification of materials tested together with the measurement results and correlation assessment.

<table>
<thead>
<tr>
<th>ID</th>
<th>Material</th>
<th>Condition</th>
<th>Thickness (mm)</th>
<th>Major (J/m²)</th>
<th>Minor (J/m²)</th>
<th>Minor/Major (%)</th>
<th>Major+Minor (J/m²)</th>
<th>By (F_d) (J/m²)</th>
<th>Diff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Black nickel</td>
<td>As received</td>
<td>0.254</td>
<td>992.8</td>
<td>80.6</td>
<td>8.11</td>
<td>1073.4</td>
<td>1037.0</td>
<td>−3.4</td>
</tr>
<tr>
<td>B</td>
<td>AISI1010 steel</td>
<td>Cold rolled</td>
<td>0.127</td>
<td>5450.4</td>
<td>698.0</td>
<td>12.81</td>
<td>6148.4</td>
<td>6356.2</td>
<td>3.1</td>
</tr>
<tr>
<td>C</td>
<td>AISI1010 steel</td>
<td>Annealed</td>
<td>0.125</td>
<td>1450.1</td>
<td>285.2</td>
<td>19.67</td>
<td>1735.3</td>
<td>1952.3</td>
<td>12.5</td>
</tr>
<tr>
<td>D</td>
<td>AISI1010 steel</td>
<td>Cold rolled</td>
<td>0.254</td>
<td>6317.3</td>
<td>492.1</td>
<td>7.79</td>
<td>6809.4</td>
<td>6798.6</td>
<td>−0.2</td>
</tr>
<tr>
<td>E</td>
<td>AISI1010 steel</td>
<td>Annealed</td>
<td>0.250</td>
<td>1240.1</td>
<td>59.7</td>
<td>4.81</td>
<td>1299.8</td>
<td>1324.9</td>
<td>1.9</td>
</tr>
<tr>
<td>F</td>
<td>AISI1010 steel</td>
<td>Cold rolled</td>
<td>0.381</td>
<td>6745.1</td>
<td>744.8</td>
<td>11.04</td>
<td>7489.9</td>
<td>7137.0</td>
<td>−4.7</td>
</tr>
<tr>
<td>G</td>
<td>AISI1010 steel</td>
<td>Annealed</td>
<td>0.370</td>
<td>1439.8</td>
<td>198.2</td>
<td>13.77</td>
<td>1638.0</td>
<td>1393.6</td>
<td>−14.9</td>
</tr>
<tr>
<td>X</td>
<td>FeSi NO</td>
<td></td>
<td>0.500</td>
<td>505.5</td>
<td>124.7</td>
<td>24.67</td>
<td>630.2</td>
<td>518.2</td>
<td>−17.8</td>
</tr>
<tr>
<td>Y</td>
<td>FeSi GO 75 deg</td>
<td></td>
<td>0.235</td>
<td>372.4</td>
<td>173.3</td>
<td>46.54</td>
<td>545.7</td>
<td>531.9</td>
<td>−2.5</td>
</tr>
<tr>
<td>Z</td>
<td>FeSi GO 0 deg</td>
<td></td>
<td>0.288</td>
<td>155.3</td>
<td>39.2</td>
<td>25.24</td>
<td>194.5</td>
<td>199.5</td>
<td>2.6</td>
</tr>
</tbody>
</table>
was a 50.8 mm long tal direction at speeds ranging from 1.6 to 7 mm/s. The PM tor and driving rollers for moving the SUT in either horizon-

mal mounted PM, and equipped with a small gear head mo-

The samples were first moved back and forth such that the central 250 mm passed once in each direction under the magnet. By this means, all portions of the strip not in the AZ were placed in the (negative) remanent state without the need for a second PM. The SUT was then positioned to allow the central 80 mm to pass once in each direction under the PM while the horizontal force on the magnet was recorded. Forward and reverse motions were used to eliminate the effect of possible components of the attractive force due to imperfect parallelism between \( m \) and the motion. The pendulum was biased to always exert a force in one direction on the load cell; \( F_t \) then being taken as \( 0.5 \times \) the difference between the average forces measured in each direction. Limiting the measurements to a relatively small central region of the SUT prevented its ends from getting close enough to the PM to develop significant parasitic forces.

Quasistatic hysteresis loss associated with both major and minor loops was measured in a double yoke, small size single sheet tester\(^6\) (SST) using a current mode excitation with a constant \( dH/dt \) of 1 (kA/m)/s.

Major and minor \( B-H \) loops for the three Si-steel samples are shown in Fig. 3, with similar loops for the black-

ed nickel and a low carbon steel, in both cold rolled and annealed conditions, shown in Fig. 4. The results of both conventional and drag force measurements are listed in Table I.

Figure 5 shows the effect of varying the spacing between the PM and SUT. The drag forces initially increase with a decreasing gap for all of the test specimens, with all except strip Z reaching limiting values near 1 mm gaps. The data scatter seen for this strip seems to indicate that the accurate measurement of very low drag forces (\( \approx \)1.1 mN) is beyond the capability of the load cell (5 N range) utilized.

IV. DISCUSSION

Hysteresis loss by drag force measurement is seen to match within 18\% those determined by a more conventional method. This unexpectedly close correlation for materials having a wide range of magnetic and geometric characteristics seems to indicate that neither normal field components nor the demagnetizing fields arising from the large values of \( dM/dx \) [Fig. 2(c)] existing within some portions of the AZ have significant effects. The latter was expected on the basis of qualitative reasoning but it has not yet been rigorously proven. The apparent sluggish dependence on the gap is also not unexpected, since peak field excursions of just a few times the coercivity are usually sufficient to develop the major portion of the major loop areas. These encouraging results recommend that this work will be continued, including the examination of the use of magnets with moments oriented normal to the SUT travel. This is expected to allow separation of the major and minor loop losses. Apparatus variations including magnet placement on both sides of the SUT could substantially reduce the normal force and allow this method to be applied to thicker samples. The results of these investigations will be presented in future reports.


