Magnetic core test stand for energy loss and permeability measurements at a high constant magnetization rate and test results for nanocrystalline and ferrite materials

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A test stand was developed to measure the energy losses and unsaturated permeability of toroidal magnetic cores, relevant to applications of magnetic switching requiring a constant magnetization rate of the order of 1–10 T/μs. These applications in pulsed power include linear induction accelerators, pulse transformers, and discharge switches. The test stand consists of a coaxial transmission line pulse charged up to 100 kV that is discharged into a magnetic core load. Suitable diagnostics measure the voltage across and the current through a winding on the magnetic core load, from which the energy losses and unsaturated permeability are calculated. The development of the test stand is discussed, and test results for ferrite CN20 and the nanocrystalline material Finemet FT-1HS are compared to demonstrate the unique properties of a nanocrystalline material. The experimental data are compared with published data in a similar parameter space to demonstrate the efficacy of the experimental methods. © 2008 American Institute of Physics.

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I. INTRODUCTION

Ferrimagnetic and ferromagnetic toroidal cores are commonly used as switches for pulsed power applications requiring magnetization time scales as low as tens of nanoseconds and switch voltages as high as hundreds of kilovolts.1–3 For example, the pulse durations requisite to heavy-ion induction generators operating at hundreds of kilovolts.2 It is the rational times of hundreds of nanoseconds for kilojoule pulse generation, magnetic cores are used as discharge switches at saturation times of hundreds of nanoseconds for kilojoule pulse generators operating at hundreds of kilovolts.4 In another application, magnetic cores are used as discharge switches at saturation times of hundreds of nanoseconds for kilojoule pulse generators operating at hundreds of kilovolts.5 It is the recent emergence of the nanocrystalline magnetic materials, which are thought to operate with lower energy losses and higher unsaturated permeability than conventional magnetic materials,3–5 that motivates this present experimental study of the switching properties of ferrite and nanocrystalline magnetic materials at a high constant magnetization rate.

Several past and recent studies have examined the energy losses and permeability of magnetic cores, however, they have been limited to sinusoidal magnetization rates, magnetization rates below 1 T/μs, or were conducted before the availability of the nanocrystalline magnetic materials such as Finemet.2–6 In the present experimental study, the test stand generates a square voltage pulse across the winding on the magnetic core under evaluation, i.e., a linear magnetic induction and a constant magnetization rate, that replicates the magnetic excitation inherent to the pulsed power applications discussed previously. The magnetization rates achieved in the present study vary from approximately 5 to 50 T/μs, which are faster than those of any previous studies located by the authors. Our data are quantitatively similar to those of others working at lower magnetization rates, as will be shown subsequently.

II. BACKGROUND

The magnetization of a toroidal magnetic core with a \( N_t \)-turn winding, cross-sectional area \( A_t \), and magnetic path length \( l_p \) can be described by relating the electrical quantities of the winding to the field quantities of the core,

\[
B(t) = \frac{1}{N_t A_t} \int_0^t v(t) dt, \tag{1}
\]

\[
H(t) = \frac{N_t}{l_p} i(t), \tag{2}
\]

where \( v(t) \) is the voltage across the winding, \( i(t) \) is the current through the winding, \( B(t) \) is the magnetic induction, \( H(t) \) is the magnetic field strength, and SI units are used throughout. The field quantities \( B \) and \( H \) are related through the magnetization vector \( M \),

\[
\vec{B} = \mu_0 (\vec{H} + \vec{M}) = \mu \vec{H}, \tag{3}
\]

where \( \mu_0 \) is the permeability of free space and \( \mu \) is the total permeability that defines the slope of the BH curve.

The energy dissipated in the core is partitioned into three components known as the hysteresis loss, classical eddy-current loss, and anomalous loss.7,8 The total energy loss \( E_{\text{loss}} \) can be calculated from electrical or magnetic quantities,

\[
E_{\text{loss}} = \int_0^t v(t) i(t) dt = A_t l_p \int H dB. \tag{4}
\]

The mechanisms of the hysteresis loss and the classical eddy-current loss are well known.7,8 The anomalous loss
arises due to magnetic domain wall dynamics, and is the dominant loss mechanism at high frequencies. Experimentally, the anomalous loss has been shown to be the dominant loss mechanism in nanocrystalline magnetic materials for sinusoidal driving field frequencies above 10 kHz. The domain wall motion and hence the anomalous loss is dependent on the form of the driving field, and will vary for constant and sinusoidal magnetization rates. Hence, any experiment that accurately measures energy losses in magnetic cores at high frequencies must replicate the form of the magnetic excitation inherent to the application.

III. TEST STAND, DATA ACQUISITION AND ANALYSIS, AND MATERIAL PROPERTIES

The test stand was designed to saturate magnetic cores at a constant magnetization rate, in time scales from 10 to 100 ns. The test stand voltage was designed to be variable up to 100 kV in order to saturate magnetic cores of varying cross-sectional area and with varying saturation induction at the requisite time scales. Accordingly, a coaxial transmission line pulse charged by a variable-voltage Marx bank, and discharged by a self-break spark gap into a magnetic core load was used as the pulse generator; the circuit schematic is shown in Fig. 1.

The pulse-charge section consisted of a four-stage Marx bank and a charge inductor connected to a 1.8 nF, 43 Ω, and 80 ns high-voltage transmission line. The resonant period of the pulse-charge waveform was set by the values of $C_{\text{Marx}}$ and $L_0$ to equal 2 μs, approximately one order of magnitude greater than the transit time of the transmission line. The peak voltage on the transmission line was variable from 40 to 100 kV, and thus energy storage varied from approximately 1 to 10 J. The discharge section of the test stand consisted of a self-break SF6-filled, variable pressure spark gap switch connected to the magnetic core load.

The pulsed power diagnostics used to monitor the current through and the voltage across the winding on the magnetic core load were a current-viewing-resistor shunt with ±1% measurement error and a passive RC compensated high-voltage probe with ±2% measurement error, respectively.

The magnetic core under evaluation was set at the negative remnant induction on the $BH$ curve prior to each magnetization cycle to utilize the maximum change in induction, $\Delta B$, before saturation. A dc magnetic core reset circuit was used, with circuit schematic shown in Fig. 2. The inductor and the capacitor in the dc circuit were used to prevent transient currents and voltages induced in the reset circuit during the main pulse from damaging the reset power supply. The 2.6 Ω resistor and the stray circuit resistance limited the output current of the reset circuit to 9.2 A, which was sufficient to reset all the magnetic cores evaluated on the test stand.

Typical voltage and current waveforms as measured on the test stand are shown in Fig. 3. The overshoot seen in the voltage waveform is a result of the load being highly resistive as well as highly inductive. A complete model of a magnetic core using nonlinear lumped circuit elements is described by Zhu et al., and identifies the mechanisms of the resistive and inductive components of the magnetic core. The resistance of a magnetic core load is due to the winding resistance, which increases with frequency due to the skin effect, and the equivalent resistance from eddy-current and anomalous losses, which are the significant loss mechanisms at the high frequencies of these experiments. The oscillations seen concurrently near the end of the current and voltage
waveforms occur after two transit times of the transmission line, and are a result of reflections due to the impedance mismatch of the transmission line and magnetic core.

The $BH$ curve was generated using Eqs. (1) and (2), and a typical waveform is shown in Fig. 4. Only the first half-cycle could be generated because reflections in the transmission line occurred before reverse magnetization. The current diagnostic was susceptible to ringing, as seen in Fig. 3, which is manifested in the unsaturated segment of the $BH$ curve, as seen in Fig. 4. Due to significant voltage breakdown jitter in the spark gap switch $S_0$, the discharge voltage of the transmission line was slightly variable pulse to pulse and hence multiple waveforms could not be averaged to correct the ringing. Instead, a high-order curve fit procedure was used in the data analysis to fit the $BH$ curve, as shown in Fig. 4.

The total unsaturated permeability $\mu$ of a magnetic core is calculated from the slope of the $BH$ curve, as given by Eq. (3). However, the transition from the unsaturated state to the saturated state is not well defined, as seen in Fig. 4. Therefore, the unsaturated permeability was calculated by averaging the position of a large number of points along the unsaturated segment of the $BH$ curve, thus generating a straight line curve fit to those points.

The saturation time of a magnetic core may be loosely defined as the interval over which the winding on the core supports a high voltage. However, for the square-pulse voltage waveforms utilized in our experiments, the transitions between zero voltage and high voltage at both ends of the voltage pulse are not well defined, as seen in Fig. 3. In addition, the points in the current waveform concurrent to those voltage transitions are also not well defined. Accordingly, a B-dot probe, which is sensitive to changes in the slope of the current pulse, was used to measure the saturation interval, and a typical waveform of the B-dot response is shown in Fig. 5. The data analysis found the point at 5% of the initial peak value of the B-dot waveform to define the start of the saturation interval, and the point at 10% of the peak value of the B-dot waveform to define the end of the saturation interval, and this definition was consistent throughout the data analysis.

Two materials evaluated in the experiments that represent a conventional and emerging magnetic material are ferrite CN20 and the nanocrystalline material Finemet FT-1HS, respectively. The relevant material properties of these magnetic cores are summarized in Table I. Ferrite is an oxide whereas the nanocrystalline core is a conductor, hence the four order of magnitude difference in resistivity. In addition, the lamination thickness for the nanocrystalline core was measured experimentally, as this value could not be found accurately in the manufacturer’s data and was important for comparisons with the published data; a sample micrograph is shown in Fig. 6.

The magnetic core under evaluation was installed on the test stand using a dual-winding configuration, as shown in

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Ferrite CN20</th>
<th>Finemet FT-1HS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation induction (T)</td>
<td>0.3</td>
<td>1.35</td>
</tr>
<tr>
<td>Resistivity ($\mu\Omega$ cm)</td>
<td>$10^6$</td>
<td>110</td>
</tr>
<tr>
<td>Lamination thickness ($\mu$m)</td>
<td>N/A</td>
<td>18</td>
</tr>
</tbody>
</table>

FIG. 4. (Color online) Typical $BH$ curve generated in the experiments.

FIG. 5. (Color online) Waveform showing the B-dot probe response. The left boundary of the saturation interval is defined at 5% of the initial peak value of the B-dot waveform, and the right boundary is defined at 10% of the peak value of the B-dot waveform.

FIG. 6. Sample micrograph of the tape-wound structure of a Finemet FT-1HS magnetic core.
The current in each winding generates a magnetic flux that points in the same direction throughout the volume of the core, and the energy loss of a core in the dual-winding configuration would be the same as that for a core having a single winding with half the number of total windings in the dual-winding configuration. The purpose of the dual-winding configuration was to accommodate the installation of the cores on the test stand, and also to ensure uniform magnetization of the entire core volume at the fast time scales of the experiments.

The variable parameters of the test stand for each magnetic core evaluated were charge voltage, spark gap switch pressure, and the number of turns in the winding. By varying these parameters, we could obtain a range of saturation times for each core evaluated from approximately 40 to 100 ns, and consequently a magnetization rate from approximately $5 \times 10^7$ to $5 \times 10^8$ T/s, dependent on the magnetization rate of the magnetic core.

IV. EXPERIMENTAL RESULTS

The experimental results are first discussed through plots of energy loss per core volume and unsaturated permeability as a function of the saturation time, as shown in Figs. 8 and 9, respectively. The unsaturated permeability calculation was discussed previously, and the energy loss was calculated using Eq. (4), where the interval of integration was the saturation time. Each data point in the figures represents a single shot on the test stand, and the error bars result from the inaccuracies of the voltage and current probes.

The ferrite magnetic core has a much lower energy loss per core volume than the nanocrystalline core in the parameter space of these experiments. An empirical formula for the classical eddy-current loss is given by Chen,$^7$

$$E_{\text{eddy-current}} \propto f^2 \rho,$$

where $f$ is the frequency of magnetization and $\rho$ is the resistivity, which is four orders of magnitude larger for the ferrite magnetic core. Therefore, at the high frequencies of these experiments the classical eddy-current loss must be a substantial loss mechanism. The data in Fig. 9 show that the nanocrystalline core has much higher unsaturated permeability than the ferrite core in the parameter space of these experiments. Several models are available in the literature to predict the permeability of a single magnetic domain of a known geometry in a constant applied field.$^7$ However, models are generally not available to explain the unsaturated permeability for the bulk domain structure of a toroidal magnetic core in terms of basic material properties, such as those described in Table I. Instead, permeability is shown to be a strong function of the chemical composition, temperature, and magnetocrystalline anisotropy.$^10,11$

The data in Fig. 8 are not sufficient for relative core-to-core comparisons because the saturation induction, which is an important material parameter relevant to any magnetic
switching application, is not taken into account. From Table I, the saturation induction for the nanocrystalline core and the ferrite core differ by approximately 2 T. A figure of merit known as the loss factor has been used in past studies of energy losses in magnetic cores to make relative core-to-core comparisons, and the same figure of merit will be used here. The loss factor is given by

$$L_f = \frac{E_{loss}}{V_{eff}(\Delta B^2)},$$

where $V_{eff}$ is the core volume scaled by the packing factor. The packing factor is the ratio of the volume of magnetic material to the total core volume, and is unity for the solid ferrite core. The plot of loss factor as a function of saturation time for the two materials is given in Fig. 10, showing the nanocrystalline core to operate with the lower loss factor in the parameter space of these experiments.

V. COMPARISONS TO PREVIOUS DATA

The measured data previously discussed were also compared with data found in the literature in a similar parameter space to verify the efficacy of the experimental methods. The energy loss and permeability of the nanocrystalline alloy Finemet FT-1H has been investigated by Molvik and Faltens at a constant magnetization rate. The present work has examined the FT-1HS alloy, where the only difference in these alloys is the lamination thickness, which for the FT-1H alloy is 22 µm, and for the FT-1HS alloy is 18 µm. As eddy-current losses are directly proportional to the lamination thickness, higher energy losses and lower permeability should be expected for the studies of the FT-1H alloys when compared to the present research. The comparison of energy loss per core volume is shown in Fig. 11, and the comparison of unsaturated permeability is shown in Fig. 12.