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Circular magnetisation measurement in ferromagnetic wires

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Abstract. The difficulties involved for the measurement of the circular magnetisation as a function of the circular magnetic field in ferromagnetic wires are discussed. An experimental arrangement which allows the study of the M_ϕ–H_ϕ hysteresis loops is shown.

1. Introduction

Ferromagnetic wires can be macroscopically magnetised either in a longitudinal (M_z) or in a circular (M_ϕ) way much easier than in a radial one. If isotropic samples are considered, the tensor of susceptibilities has two diagonal terms which can be expressed in cylindrical coordinates as

$$\begin{pmatrix} M_z \\ M_\phi \end{pmatrix} = \begin{pmatrix} \chi_{zz} & 0 \\ 0 & \chi_{\phi\phi} \end{pmatrix} \begin{pmatrix} H_z \\ H_\phi \end{pmatrix}. \tag{1}$$

In tubular-shaped samples having thin walls, the magnetisation curves M_z–H_z and M_ϕ–H_ϕ can be obtained by conventional methods using the appropriate windings. However, in cylindrical samples such as thin wires, the determination of the M_ϕ–H_ϕ curves involves some difficulties which can be summarised as follows:

(1) The applied field H_ϕ must be produced by a current flowing through the wire. Such a field is not homogeneous; it increases radially.
(2) Field inhomogeneity leads to differences in the magnetisation of cylindrical shells with differing radii, so producing interactions among them and a magnetostrictive gradient.
(3) In order to pick up the magnetisation changes no windings can be used and the wire itself must be used as a secondary, thus, if quantitative measurements have to be done, it is necessary to know the equivalent ns, n being the total number of turns and s the area threaded by the magnetic flux.
(4) Because the induced EMF is small compared with the applied EMF, some special arrangement must be used to eliminate the latter.

Measurements of M_ϕ have great interest for determining magnetoelastic properties, particularly those related to torsion and giving rise to the non-diagonal terms $\chi_{z\phi}$ and

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$\chi_{\phi z}$ in the expression (1) (Hernando and Barandiarán 1975), as well as for understanding the magnetisation process in ferromagnetic whiskers having grown in a hard direction (Hernando 1973).

In the present paper an expression relating the M_ϕ variation with the EMF induced in the wire is derived. We also describe the experimental method for obtaining the M_ϕ–H_ϕ curves, showing some results for iron and nickel samples. Further work is being carried out at this moment in order to investigate the characteristics of the circular magnetisation processes in ferromagnetic wires, by means of the results mentioned above.

2. Calculation of the equivalent *ns* of a wire

Let $\boldsymbol{M}$ be the magnetisation of a wire having a radius a. The electric field produced at any given point of the wire may be expressed as

$$E(r) = -\frac{\partial A}{\partial t} \tag{2}$$

A being the vector potential of the magnetisation and related to it by

$$\text{curl curl } A = \text{curl } \mu_0 \boldsymbol{M}. \tag{3}$$

Because of the symmetry of the problem, cylindrical coordinates are suitable and then equation (3) can be written as

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial A_z}{\partial r}\right) = -\mu_0 \frac{1}{r}\frac{\partial}{\partial r}(rM_\phi) \qquad r \leqslant a \tag{4}$$

considering only the circular magnetisation and provided that A satisfies div $A = 0$.

Solutions of equation (4) with the requirement that A_z vanishes at $r = a$ can be easily found. So if M takes a constant value in the wire

$$A_z = \mu_0 M_\phi (a - r) \tag{5}$$

and for $M_\phi = \lambda r$

$$A_z = \frac{\mu_0 \lambda}{2}(a^2 - r^2). \tag{6}$$

Now the EMF between two points separated by a distance l along the wire is

$$V = \langle E_z \rangle \, l \tag{7}$$

$\langle E_z \rangle$ being the average electric field given by equation (2) in the cross-section of the wire, which can be calculated as

$$\langle E_z \rangle = \frac{1}{\pi a^2}\int_0^{2\pi}\int_0^a E_z(r, \phi) r \, \mathrm{d}r \, \mathrm{d}\phi. \tag{8}$$

Two particular cases are

$$V = \frac{al}{3}\mu_0\left(\frac{\partial M_\phi}{\partial t}\right) \qquad \text{for } M_\phi = \text{const} \tag{9}$$

and

$$V = \frac{3al}{8}\mu_0\left(\frac{\partial \langle M_\phi \rangle}{\partial t}\right) \qquad \text{for } M_\phi = \lambda r \tag{10}$$

where M stands for the average circular magnetisation.

To avoid this discrepancy we can take a value of 0·35 al for the proportionality factor between the induced voltage and the magnetisation changes (being within 7% of error, for any magnetisation sharing between the two considered cases).

3. Experimental procedure and results

Experimental arrangement is shown in figure 1. A simple bridge is used to compensate the voltage appearing across the wire (A), due to the current flowing through it. The apparatus is operated at 50 Hz. When compensation is reached by means of the variable resistor R, the signal in the centre (points P and P′) is proportional to $B_\phi = \mu_0 (H_\phi + M_\phi)$. The $\mu_0 H_\phi$ contribution may also be eliminated by putting a non-ferromagnetic wire (B), in the arm containing R.

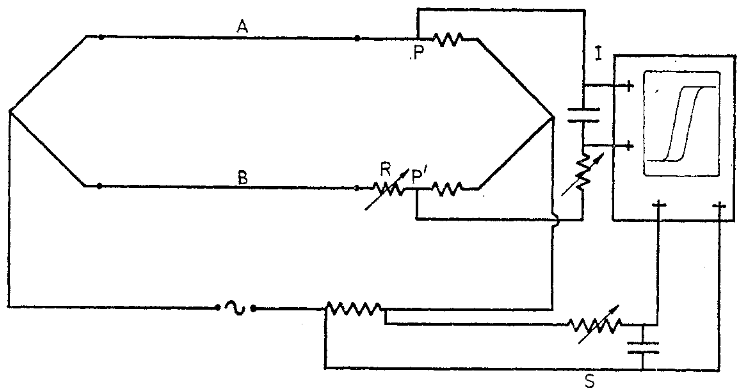

Figure 1. Scheme of the device used for the measurement of the M–H curves. (A) ferromagnetic wire, (B) compensating wire, (R) compensating resistor, (I) integrator, and (S) phase-shifter.

The signal so obtained is then integrated and displayed in an oscilloscope, applying to the x-axis a signal proportional to the applied field.

Figure 2 (plate) shows the results obtained with Fe and Ni samples of purity 99·5 and 99·8 respectively. The upper pictures are the derivatives of the circular magnetisation. When the bridge is accurately compensated they must start and end in a horizontal line, as shown. The M–H curves in the lower part were obtained by passing a current of 1 and 1·5 A (RMS) for iron and nickel respectively, and the coercive force corresponds to a maximum field in the wire of 280 and 620 A m^{-1}. On the other hand, the average circular magnetisation in the saturated part of the curves was about $7{\cdot}6 \times 10^5$ A m^{-1} for iron and 4×10^5 A m^{-1} for Ni.

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(*a*) (*b*)

(*c*) (*d*)

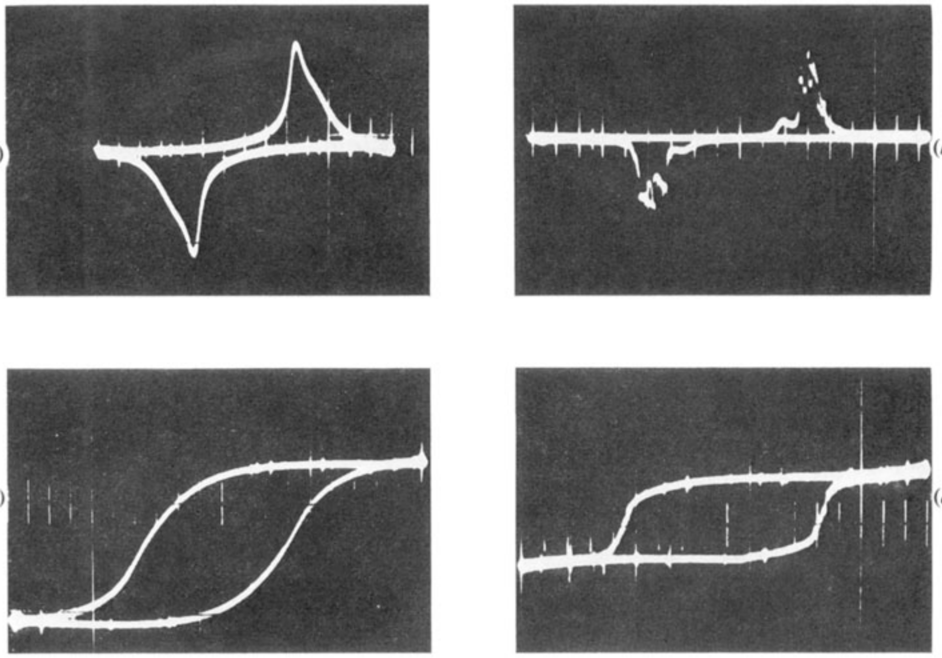

Figure 2. M–H curves, and their derivatives for iron and nickel wires of 0·5 mm in diameter and 1 m long. (*a*) derivative for iron, (*b*) derivative for nickel, (*c*) magnetisation curve for iron, (*d*) magnetisation curve for nickel.