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Results on the Magnetization of Ferromagnetic Substances Dependent on Temperature

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Abstract

This paper presents the study of the magnetization for the ferromagnetic substances depending on temperature. The Stoletov curves were obtained through three types of ferromagnetic materials, pointing out the modifications depending on temperature. The revealing of these variations can represent an experimental background for new theoretical models or, for the confirmation of theoretical models already proposed.

Key words: *magnetic permeability, Stoletov curve, hysteresis loop*

Theoretical Background

A substance introduced in magnetic fields is magnetized. The magnetization of the substance can be temporary (it is present only when the sample is introduced in magnetic field) or permanent (it is present also after the disappearance of exterior magnetic field). In macroscopic treatments it is admitted that the magnetism is caused by the stationary movement of electric charges from magnetic substances, producing a current with constant intensity. The electric current exists only at molecular and atomic level, appointed as bonded current. To bonded currents, with intensity I, there corresponds a magnetic moment

$$\vec{m} = I\vec{S} = IS\vec{n}\,, \tag{1}$$

where S is the contour of the area limited by the current and $\vec{n}$ is the unit vector attached to the approximately plane surface S.

To bonded currents we can attach a magnetic moment because they behave as a small magnet, named magnetic dipole. The acting forces on magnetic dipole placed in magnetic field has zero resultant in the case of uniform magnetic fields and non-zero in the non-uniform fields. The moment of forces couple is

$$\vec{C} = \vec{m} \times \vec{B}\,. \tag{2}$$

The current knowledge demonstrates that in practice the magnetic properties of the substances are based on the orbital and spin movement of the electrons and of the nucleons.

Afterwards we shall discuss the magnetic properties of the substances using the model of bonded current which offers a more intuitive and simple description. The magnetization of the substances is characterized through the magnetization vector (or magnetization intensity) whese value represents the magnetic moment of unit of volume

$$\vec{M} = \lim_{\Delta V \to 0} \frac{\Delta \vec{m}}{\Delta V} = \frac{\mathrm{d}\vec{m}}{\mathrm{d}V}. \tag{3}$$

Generally, with the exception of the group of ferromagnetic substances, the magnetization change proportionally with the intensity of the magnetizing field where the substance is placed

$$\overrightarrow{M} = \chi \overrightarrow{H}, \tag{4}$$

where χ represents the magnetic susceptibility, a material constant that depends on temperature.

As opposed to electric susceptibility that takes only positive values, the magnetic susceptibility can be both negative as positive. Depending on the sign and the value susceptibility, the substances can be classified as follows:

- diamagnetic substances with $\chi < 0$ (Bi, Hg, Cu, He, Ne, Ar),
- paramagnetic substances with $\chi > 0$ (Na, K, Ca, Mg, Al),
- ferromagnetic and ferrimagnetic substances with $\chi >> 0$ (Fe, Ni, Co, Gd).

All elementary magnetic moments of an ideal ferromagnetic substance are aligned. Though, analysing the entire sample, the total magnetic moment can be much less than the saturation moment and to obtain a saturated sample it is necessary to apply an exterior magnetic field. Weis explains this behavior presupposing that all real samples should be compounded of great number of small regions (domains) and only inside these domains the local magnetization is saturated. The magnetization directions of all these areas are parallel. The domains are formed in all types of crystals also in antiferromagnetic, ferroelectric, antiferroelectric, ferroelastic and sometimes in metals influenced by the strong Haas-van Alphen effect.

The magnetic moment of the sample placed in a magnetic field increases through two independent processes:

- for low intensity exterior fields the volume of Weiss domains orientated in field lines increases against the arbitrary oriented domains,
- for high intensity exterior fields these magnetization domains are rotated in the fields direction.

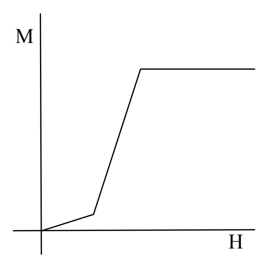

Fig. 1. Ideal primary magnetization curve

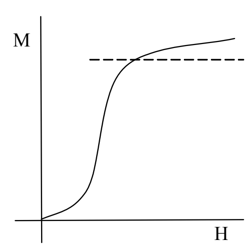

Fig. 2. Real primary magnetization curve

Two adjacent Weiss domains are separated by the Bloch wall where, the spin orientation doesn't change rapidly (discontinuity) but in graded ways across many atomic planes. Overall the exchange energy of successive spins couples, with small angles between them, overlaps the anisotropy energy that acts in the sense of the limitation of the Bloch walls thickness.

Conseqmentaly, in the case of very weak fields, the enlargement of the favorably orientated Weiss domains is done through reversible movements of the frontiers (Bloch walls) and in the case of relative strong fields these movements become irreversible. In the Fig. 1, there is presented the curve of primary magnetization for a ferromagnetic material that contains a profile with three different slopes. The first sector of the line presents the material behavior when the movements of the frontiers are reversible, the second sector of line is representative for irreversible movements of the frontiers and the last is characterized, by the saturation of the material when it is in progress the rotation of the Weiss domains, i.e. strong magnetic fields applied (also in this case appear the Barkhausen effect).

For real magnetic material the transition from a zone to another is done continuously (see Fig. 2). What is specific is the fact that the last zone indicates there slow inclination against the level from the Fig. 1.

From the derivative of the primary magnetization curves results the dependency of the magnetic permeability for a ferromagnetic material given magnetizing field intensity (the resulting curve is known under Stoletov curve name).

The Experimental Setup and Data Acquisition

To obtain the primary magnetization curve we used the block-scheme represented on Fig. 3. For an efficient analysis, the analogical signals obtained on Ox and Oy were digitalized. From the studied substances, through turning, we obtain toroidal samples (annular magnets) with two coil in a winding-ups report $N_{\text{prim.}} / N_{\text{sec.}} = 1$.

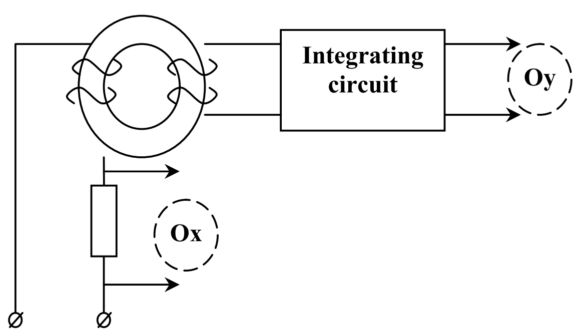

Fig. 3. Signal acquisition to oscilloscope

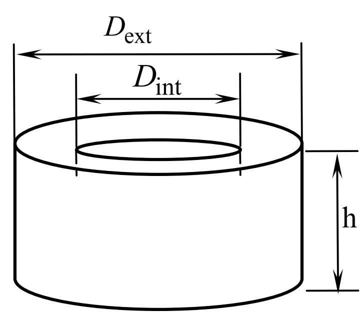

Fig. 4. Dimensions for the used samples

For the ferromagnetic cores there were selected the toroidal form where through amounts to an infinit long air coil with minimum loss of magnetic energy. Therefore the magnetic intensity can be expressed by expression $H = \mu N I / l_e$ where l_e is the effective length of the toroidal core. The effective length can be expressed through expression $l_e = \pi\left(D_{\text{ext}} + D_{\text{int}}\right)/2$, Fig. 4. A precise expression of the real length the toroidal core is

$$l_e = 2\pi \frac{\ln \dfrac{R_{\text{ext}}}{R_{\text{int}}}}{\dfrac{1}{R_{\text{ext}}} - \dfrac{1}{R_{\text{int}}}} \tag{4}$$

deviations from precedent can be neglected.

For the study of the dependency of ferromagnetic substances magnetization on temperature, the samples were placed in a calorimetric enclosure and the temperature was controlled by a computer interface. The toroidal coils dimensions are presented in Table 1.

Table 1. Characteristic dimensions of the used samples

Samples	D_{ext} (mm)	D_{int} (mm)	h(mm)
Sample 1	10	5	5
Sample 2	10	5	4,7
Sample 3	10	5	5,1

Were necessary we performed the isolation of the samples because they have electricall conducting proprieties. For this, the samples were immersed in Duco type paint. After drying and appling a very thin Teflon foil the samples were coiled as follows:

- a layer of cupriferous emailed wire with diameter of 0,6 mm whose layer represents the primary coil,
- a layer of cupriferous wire turns with diameter of 0,1 mm, fan out with silk. This layer represents the second coil.

The primary coil was adjusted to a variable alternative voltage source with the 50 Hz frequency. The voltage inducted is proportional the magnetic induction that is also dependent on the core magnetic proprietary, according to, the fundamentall law of the magnetism theory.

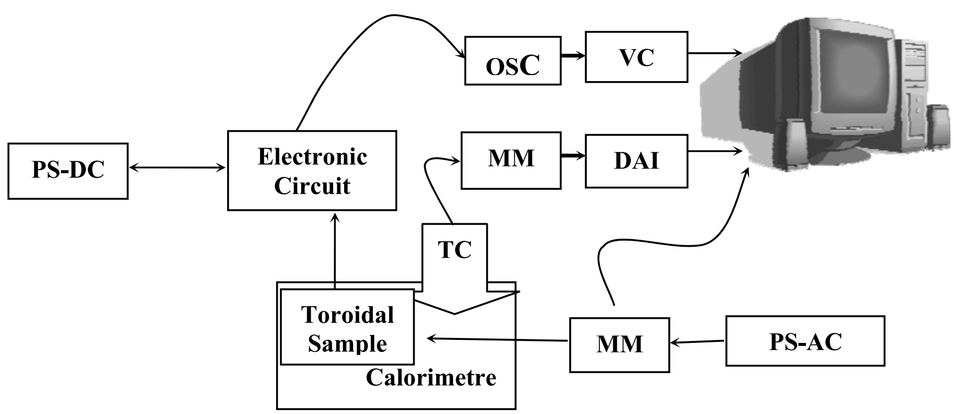

Fig. 5. The schematic experimental setup

The dataset experimentally obtained were digitized and processed with a proper software. The connections between these apparatuses are represented in Fig. 5, where the significations of the abbreviations are:

- PS-AC – Power supply (AC - Alternating Current)
- PS-DC – Power supply (DC - Direct Current)
- OSC – Osciloscope
- TC – Thermocouple
- MM – Multimeter
- DAI – Data acquisition interface
- VC – Video camera

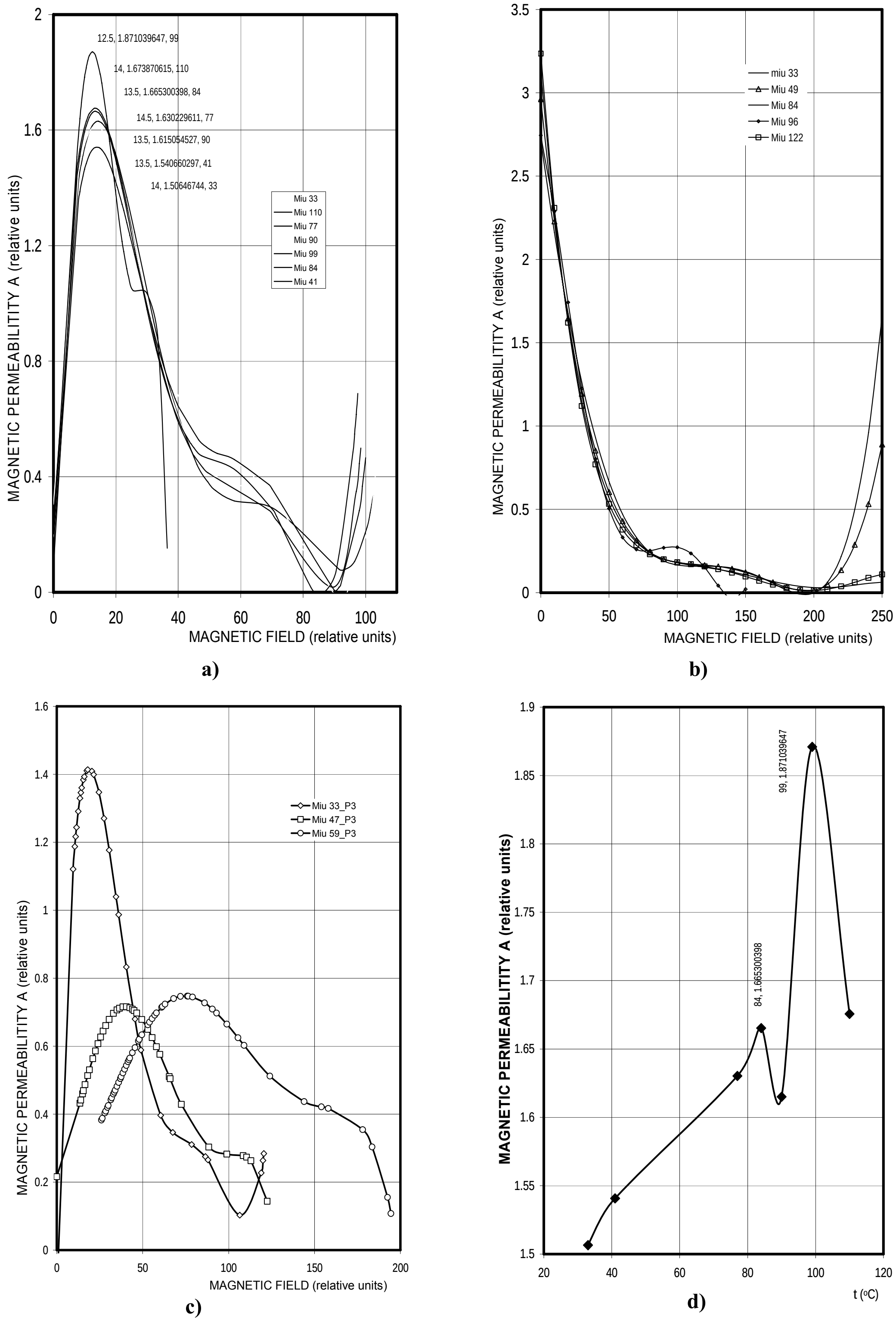

Fig. 6. The Stoletov curves dependency by the temperature for studied samples

The Fig. 6a, 6b and 6c represents the Stoletov curves for samples 1, 2 and 3 for temperatures contained in the interval $20 \div 120^{\circ}C$. As observed, sample 2 doesn't present a specific reversible area of the frontiers movements (the Bloch walls). In this case, the dependency of the magnetic permeability by temperature points out two peaks. We consider that these peaks are connected to the Bloch walls size and the temperature of the samples. For sample 3 we observe a strong dependency of the primary magnetization curve by temperature. On Fig. 6d there is represented the maximum value of the magnetic permeability (the peak value of the Stoletov curve) depending on the temperature for sample 1.

Conclusions

The magnetization dependency on temperature can be emphasized using the Stoletov curve. In the area of selected temperatures, a modification of the magnetic permeability of the material from the selected samples depending on temperature is observed. For sample 1 we get two maximum values, see Fig. 6d, at $84°C$ and $99°C$ for magnetic permeability. There must be noticed, as seen on the Fig. 6b, that sample 2 is composed by a magnetic material that don't presents the zone with reversible modifications the Bloch walls from the primary magnetization curve. For sample 3, Fig.6c, the dependency on temperature is reflected also through the modification of Stoletov curves maxim's width. This experimental data can be used for theoretical interpretations.

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Rezultate privind dependența magnetizării substanțelor feromagnetice de temperatură

Rezumat

În această lucrare se urmăreşte studiul dependenţei de temperatură a magnetizării substanţelor feromagnetici în funcţie de temperatură. În urma analizelor efectuate au fost obţinute curbele Stoletov pentru trei tipuri de materiale feromagnetice, relevând modificarea acestora în funcţie de temperatură. Evidenţierea acestor variaţii poate reprezenta punctul de plecare în propunerea unor noi modele sau confirmarea unor modele teoretice deja propuse.