# E102. Study of the magnetic hysteresis

## 1. Introduction

Due to the behavior in a magnetic field, the materials can be divided into three groups: diamagnets (weakly repelled by a magnet), paramagnets (weakly attracted by a magnet) and ferromagnets (strongly attracted by a magnet). Diamagnetism is based on partial shielding of the magnetic field due to the movement of electrons in the atoms, induced by the magnetic field. It is present in all bodies, but may be offset by the presence of stronger phenomenon of paramagnetism or ferromagnetism. Paramagnetism occurs in bodies that have a permanent dipole magnetic moments of atoms or molecules, changing their orientation under the influence of a magnetic field. If these moments interact strongly then ordered localized structures are formed (called domains), which have a uniform direction of magnetization, and the material becomes ferromagnetic.

The resultant magnetic induction (B-field) $B$ in the medium is related to the intensity of the external magnetic field (H-field) $H$ by the following relationship:

$$\mathrm{B} = \mu_r \, \mu_0 \, H, \tag{1}$$

where$\mu_r$ is a relative magnetic permeability and $\mu_0$ the vacuum magnetic permeability ($\mu_0$ = 1,26 $\times 10^{-6}$ T m / A) For diamagnets $\mu_r$<1, for paramagnets $\mu_r$>1. In a hard magnet such as a ferromagnet, $B$ is not proportional to the H-field and is generally nonzero even when $H$ is zero. When an external magnetic field is applied to a ferromagnet such as iron, the atomic dipoles align themselves with it. Even when the field is removed, part of the alignment will be retained: the material has become magnetized. Once magnetized, the magnet will stay magnetized indefinitely. To demagnetize it requires heat or a magnetic field in the opposite direction. This is the effect that, for example, provides the element of memory in a hard disk drive.

The relationship between field strength (the H-field) $H$ and magnetic induction $B$ is not linear in such materials. If a magnet is demagnetized ($H$=$B$=0) and the relationship between $H$ and $B$ is plotted for increasing levels of field strength, $B$ follows the initial magnetization curve (Figure 1). This curve increases rapidly at first and then approaches an asymptote called magnetic saturation. At this stage, the whole material is uniformly magnetized. If the magnetic field is now reduced monotonically, *B* follows a different curve. At zero field strength, the magnetic induction is offset from the origin by an amount called the remanence. If the *B(H)* relationship is plotted for all strengths of applied magnetic field the result is a hysteresis loop called the main loop (Figure 1). The width of the middle section is twice the coercivity of the material.

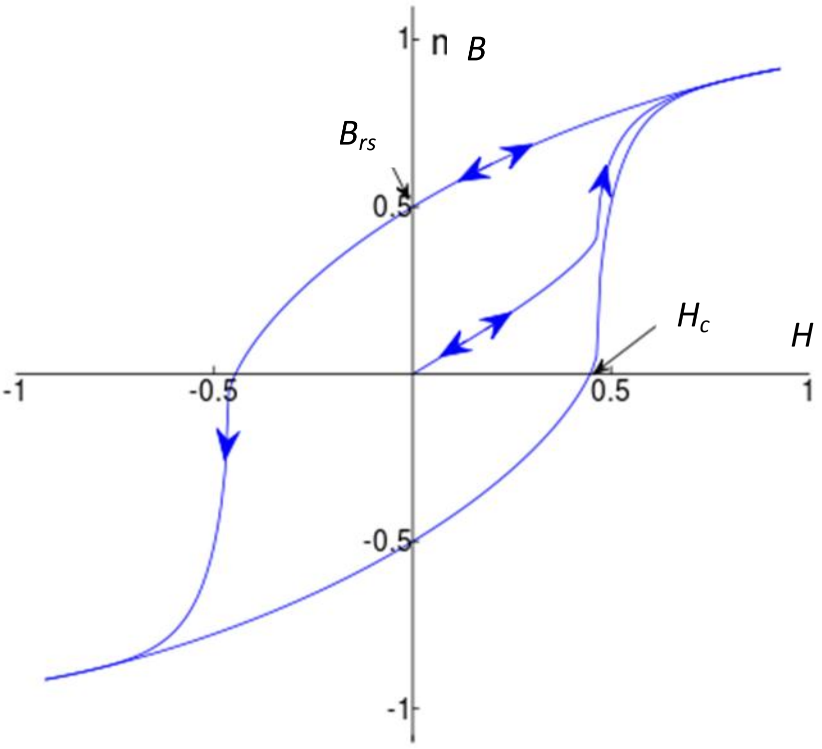


**Figure 1.**Magnetic hysteresis curve. Starting at the origin, the upward curve is the initial magnetization curve. The downward curve after saturation, along with the lower return curve, form the main loop. The intercepts $H_c$ and $B_{rs}$ are the coercivity and saturation remanence.

Ferromagnetic materials can be divided into hard (eg. some steel), where there is a large hysteresis loss and a large value of coercivity (up to 20 MA/m, eg. permanent magnets are made with them), and soft, with small values of coercivity (even 0.1 A/m, eg. ferrites). Ferrites are materials having a high magnetic permeability value at low current losses. They are widely used eg. as cores of transformers and radiation antennas.

## 2. Apparatus and measurements

The basic part of the measurement system (Figure 2) is the transformer consisting of two coaxial coils with a replaceable core where the samples are placed. Magnetizing coil is supplied with alternating current generator with a frequency of a few Hz. The current is controlled by the amplifier WZM and is measured by the voltage drop $U_1$ over the resistor $R_1$ (serially connected with the magnetizing coil). The intensity of the magnetic field $H$ in the magnetizing coil is proportional to the intensity of the current, and hence the voltage drop $U_1$ :

$$H = \frac{N_m\, U_1}{R_1\, d\, w_1}, \tag{2}$$

where$N_m$ is the number of turns of the coil, $d$ - its length, and $w_1$ - voltage gain value before sending it to the console channel no. 1 (*Kan.1*).

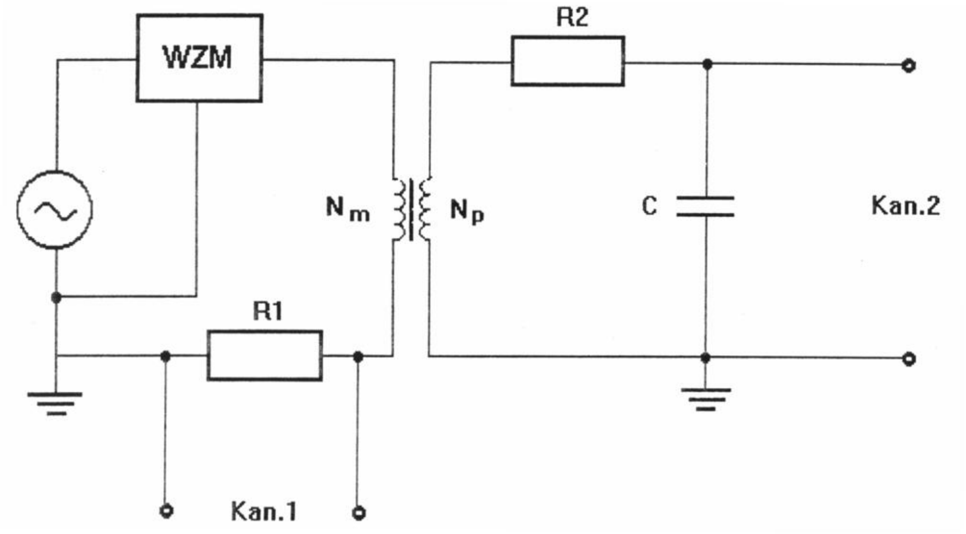


**Figure 2.**Scheme of the measurement setup.

Next, the voltage induced in the coil is proportional, according to Faraday's law, to the rate of temporal changes in flux of magnetic induction $B$. The signal from the probe coil is integrated by an RC circuit consisting of a resistor with a resistance $R_2$ and capacitor with capacity $C$. Induction magnetic B depends on the capacitor voltage $U_2$ in the following manner:

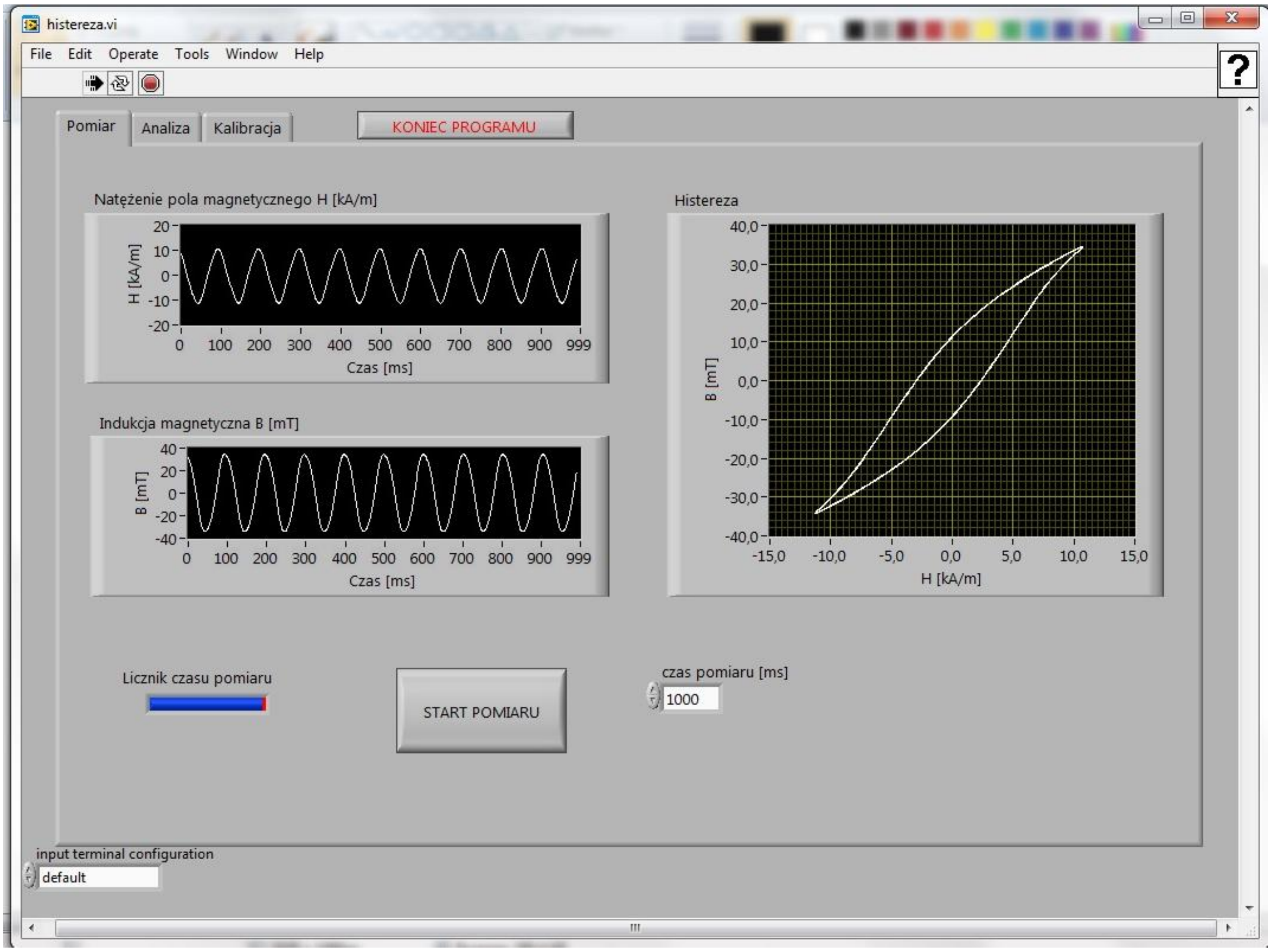
$$B = \frac{U_2\, R_2\, C}{N_p\, S\, w_2}, \tag{3}$$

where$N_p$ is the number of turns of the probe coil, $S$ is the cross-sectional area of the coil, and $w_2$ - voltage gain value before sending it to the console channel no. 2 (*Kan.2*).

The measurements of $B(t)$ and $H(t)$ and the analysis of the results is performed in program "Histereza" written in LabView environment. The amplifiers on channels 1 and 2, the generator (the frequency of a sinusoidal signal of a few Hz, usually 10 Hz) and the amplifier WZM should be all turn on. The latter should be set so as to obtain a sufficient amplitude of the measured signals (in the range of 1.5 to 2.0 A). Before measurements, make sure that the measuring system parameters correspond to those which are listed in the *Kalibracja* fold of the program - otherwise the calibration (conversion of voltages into H- and B- field) is wrong.

When the studied material is placed inside the transformer, the measurement starts by pressing the button *START POMIARU* in the fold *Pomiar* (Figure 3). The computer then begins to collect data from channels 1 and 2 for a specified duration of time (*czas pomiaru*). During the data acquisition the horizontal slide indicates the accumulation time, and when it finishes the graphs $B(t)$ and $H(t)$ are refreshed, showing periodic variation in time of magnetic field strength $H$ and magnetic induction $B$, as well as plot of $B$ versus $H$ showing the hysteresis curve (see Figure 3). The aim of the lab is to observe the $B(H)$ plots for air and different materials and determine which of them are hard and soft ferromagnets. The hysteresis curves can be also measured for varying the amplification of the current (and thus maximum of the H-field inside the transformer) and for different number of steel rods and sheets inside the transformer to observe the saturation effects.

The fold *Analiza* is used to carry out the analysis of the results. The most recently measured $B(H)$ plot is shown in black (Figure 4). The program automatically calculates the area under the hysteresis loop (value in the field *POLE WEWNĄTRZ HISTEREZY*) which determines the energy losses on the magnetization, being an important parameter for ferromagnetic materials. The dimension of the area is the product of the energy and volume. The area is averaged over a whole number of periods of waveforms $B(t)$ and $H(t)$. This period is determined automatically, and its value is given as *Zmierzony okres [ms]*. If the designated period is different than what is set at frequency generator (eg. for a frequency of 10 Hz the determined period should be approx. 100 ms), then the calculated area is invalid and the measurements must be repeated.

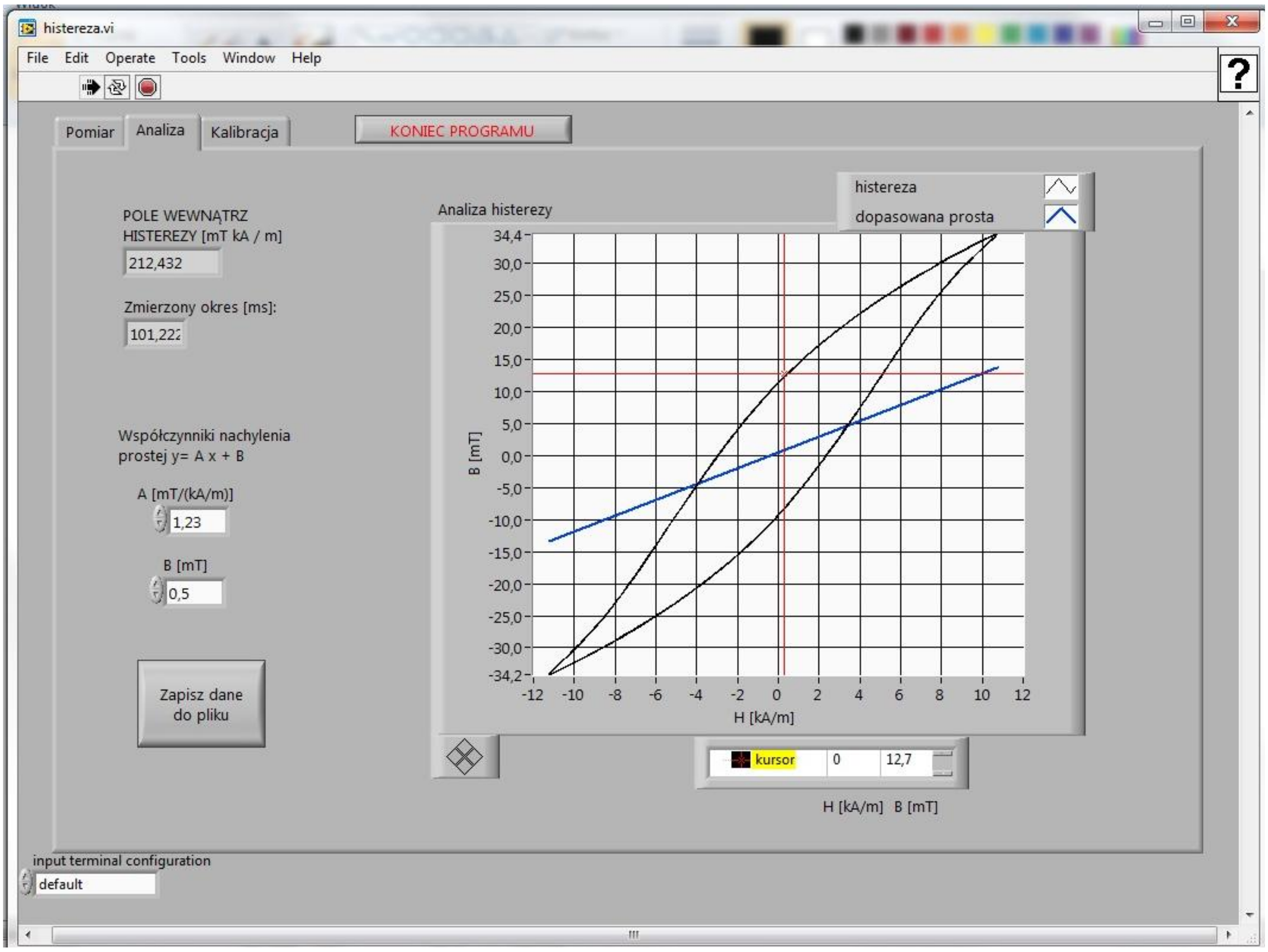


czas pomiaru [ms]: 1000

input terminal configuration: default

**Figure 3.**Measurement panel of the program *Histereza*.

The cursor (in red) position can be used to determine the coercivity and saturation remanence. If the hysteresis curve is symmetrical relative to the origin of the coordinate system, the values of remanence and coercivity are the coordinates of points of intersection of the hysteresis with the x and y axes. Finally, for linear relationship between *B* and *H* (diamagnets and paramagnets with no hysteresis curve) a linear function y = A x + B (blue line) can be fitted by changing the values of the parameters A and B (Figure 4). Cascade change in the value of 0.1 is obtained by clicking on the arrows to the left of the corresponding fields. The value of the slope A is equal to the coefficient $\mu_r \mu_0$ (see formula (1)). In particular, for measurements with an empty transformer ($\mu_r$=1), the coefficient A should be compared with the value of the magnetic permeability of vacuum $\mu_0$. The data can be saved in the text file by pressing the button *Zapisz dane do pliku*.



POLE WEWNĄTRZ HISTEREZY [mT kA / m]: 212,432

Zmierzony okres [ms]: 101,22

Współczynniki nachylenia prostej y= A x + B

A [mT/(kA/m)]: 1,23

B [mT]: 0,5

kursor: 0 | 12,7

H [kA/m] B [mT]

input terminal configuration: default

**Figure 4.**Analysis panel of the program *Histereza*.