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CURIE TEMPERATURE IN FERROMAGNETIC MATERIALS AND VISUALIZED MAGNETIC DOMAINS.

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Abstract: The Curie temperature is a physical constant and refers to a characteristic property of ferromagnetic materials. Above the Curie temperature, a material loses its ferromagnetic properties. In a ferromagnetic material, elementary dipoles are aligned into the so – called domains and the domains – through their arrangement – bring about the internal magnetic field of the material – magnetization. At temperatures above the Curie point the ordered state is destroyed, magnetic dipoles become chaotically disordered and the material no more exhibits ferromagnetic properties. This change comes about in an abrupt manner at reaching the Curie temperature.

The paper describes a laboratory experiment intended for undergraduate students of Electrical Engineering as part of a general 1st year physics course. In the course of the measurement, students determine the Curie temperature of iron. In order to facilitate the understanding of this phenomenon, domains are visualized and observed in a microscope under variable external magnetic field.

Keywords; students laboratory experiment, Curie temperature, visualized magnetic domains

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1. INTRODUCTION

Undergraduate students of Electrical Engineering at Brno University of Technology pass the basic course of general physics in first and second semester, i.e. at the beginning of their studies. Their previous knowledge and experience in mathematics and physics are very small. Explication of the magnetic properties of materials can not start from their quantum nature. Only the description of macroscopic behavior of diamagnetism, paramagnetism and ferromagnetism is possible. Several textbooks are available. At the Brno University of Technology the textbook Halliday et al., (1997) is used.

In laboratory exercises which are a part of basic course of general physics the students experiment usually with ferromagnetic materials. They study the behavior of these materials near the Curie temperature or the effects of saturation and hysteresis during the magnetization of a ferromagnetic material. The explanation of these phenomena is not possible without understanding of the concept of magnetic domain.

Magnetic domains and their behavior under action of an external magnetic field belong to frequent questions of students. For better understanding of magnetic domains, the experiment was completed with a tool which makes the domains visible and enables to observe their behavior under changes of an external magnetic field.

2. CURIE TEMPERATURE

2.1. Magnetic Domains

Atoms have magnetic moments that determine the magnetic properties of materials. Electrons orbit around the nucleus. The orbital motions may be regarded as flows of electric current within the atom, and these currents give rise to magnetic moments. Besides of them electrons have their intrinsic spin magnetic moments.

The net magnetic moment of the atom with more electrons can equal zero. These atoms or molecules form the diamagnetic materials. The external magnetic field does not act on the material as the whole but it influences the motion of individual electrons.

The atoms of paramagnetic materials have permanent magnetic moments. By influence of thermal motion these magnetic moments are randomly oriented and their magnetic fields average to zero. In an external magnetic field B_{ext} the magnetic moments tend to align with the field. According to the experimental *Curie law* the value of the magnetization M is

$$M = B_{\mathrm{ext}} \frac{C}{T} . \tag{1}$$

C is called the *Curie constant*, it depends on the quantum model of respective material, and T is the temperature. Increasing external magnetic field B_{ext} increases the parallel alignment of atomic magnetic moments, and the magnetization of the material increases. When the temperature increases, the alignment is disturbed by thermal motion and the magnetization of the material decreases. This law is some approximation and it is valid only for weak fields and higher temperatures.

The atomic magnetic moments can align also without an external magnetic field. Analogous to the loops of wires with currents, the magnetic moments of atoms act each other and tend to align to be parallel. This interaction is small in paramagnetic materials. The situation differs in ferromagnetic materials. The influence of mutual interaction of atomic magnetic moments can be considered as acting of internal magnetic field that aligns these moments. The internal magnetic field B_{int} reaches great values that cannot be produced by external electric currents. According to quantum mechanics this interaction is created by spin – spin forces between neighboring atoms. Due to these forces the alignment of atomic magnetic moments arises in small regions of the material even without an external magnetic field. Microscopic magnetized regions (sizes 10^{-3} mm^3 – 10 mm^3), called *magnetic domains*, arise at this spontaneous magnetization. But the domains are oriented at random, and the material is found in a nonmagnetic state. The domains are separated from each other by thin boundary layers with the thickness of several hundreds of atomic planes where the vector of magnetization rotates from the direction of one domain to the direction of the neighboring domain. The internal energy of such arrangement is less than the internal energy of the state of complete alignment.

The domain structure of ferromagnetic materials is resistant to disruptive influence of the thermal motion. However, above a certain critical temperature T_{C}, called the *Curie temperature*, the spin – spin forces cannot maintain the alignment of magnetic moments in domains and the material becomes paramagnetic. As soon as the temperature decreases below the critical temperature, the domain structure rebuilds. The Curie temperature for iron is 1043 K which is closer to 770 °C.

Under subjecting of an increasing magnetic field two processes are caused. The magnetic domains that already are aligned with the field tend to grow in size at the expense of their neighbors and, furthermore, some domains will rotate their dipoles in the direction of the field. If all the magnetic dipoles align with the field, the domain structure disappears. The material is magnetically saturated.

2.2 Students laboratory experiment

The measured material is the transformer metal plate twisted in the form of a pipe. The temperature is measured by means of a thermocouple inserted in the pipe. The sample with alternating current I_s is placed inside of the measuring coil in its axis. The alternating current heats the sample and simultaneously produces a variable magnetic field. This field itself does not induce the electromotive force (emf) in the measuring coil because its field lines are parallel to the coil plane. However, the field induces changes in alignment of magnetic domains in the sample. It results in changes of the magnetic flux in the measuring coil, and in this way the induced emf U_i rises. The experimental setup is shown in Fig. 1.

By means of properly placed permanent magnet, the magnetic domains can be aligned for the voltage induced in the measuring coil to be as high as possible. Gradual increases in the supply current induce increase of the temperature and the resistance of the sample, and the change of induced emf, too. The emf induced in the measuring coil increases slowly until the temperature of the sample reaches the Curie temperature T_C. At that moment the domain structure disappears and the magnetic flux in the measuring coil together with the induced emf decrease rapidly. From the variation $U_i = f(T)$, the value of Curie temperature T_C can be taken at the point of rapid decreasing of the induced emf U_i. The variation is shown in Fig. 2, the temperature is in °C.

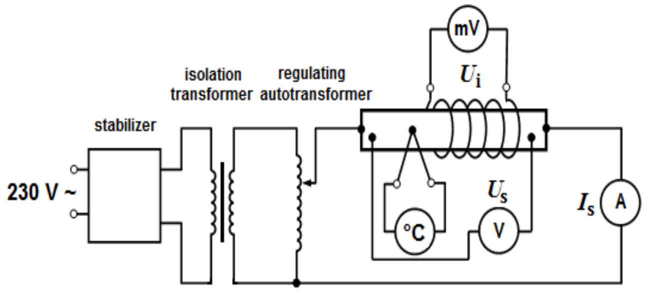


Figure 1 Determination of Curie temperature. The experimental setup.

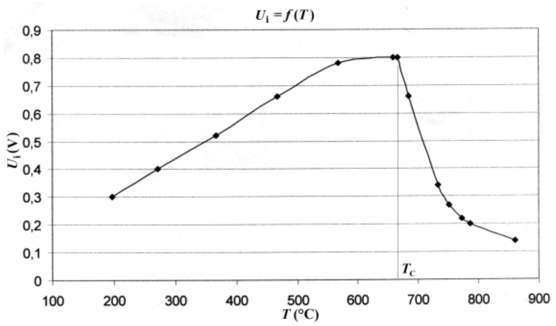


Figure 2 Temperature dependence of the induced emf U_i.

During the described measurement the students chart also the values of the current I_s in the sample and of the corresponding voltage U_s. They calculate values of the sample resistance R_s, plot the graph of the temperature dependence of the sample resistance $R_s = f(T)$, and discuss the results for the iron sample.

3. DISPLAYING OF MAGNETIC DOMAINS

To obtain the idea of magnetic domains and their behavior in variable external magnetic field, a special apparatus for displaying of magnetic domains can be used. It has appeared at European market round about 2000 in offer of the company PHYWE under the name Live Magnetic Domain. Nowadays it is possible to meet it at several websites. The University of Iowa (2010) presents the Magnetic domain apparatus including MPEG Movie. The Harvard University (2010) and the Arizona State University (2010) launch the apparatus among scientific demonstrations as the Magnetic bubbles apparatus. It can be found under the same name at the website of the TEL–Atomic, Incorporated company (2010). The apparatus of this company are used in the student laboratory at the Brno University of Technology. Made in Ireland by Lennox is given at the apparatus but it is not mentioned at the website of this company.

To observe the magnetic domains, very thin (one – atomic) layer of ferromagnetic material has been used. It is the compound with garnet structure consisting of Bi, Tm, Ga, Fe, and O. The thickness of the transparent layer is 8 μm. Due to small thickness of the layer and its composition only the magnetic domains of two types aroused. The direction of the magnetic moment in domains of both types is perpendicular to the layer surface. Both possible orientations are present, i.e. the magnetic moments of different domain types are anti – parallel.

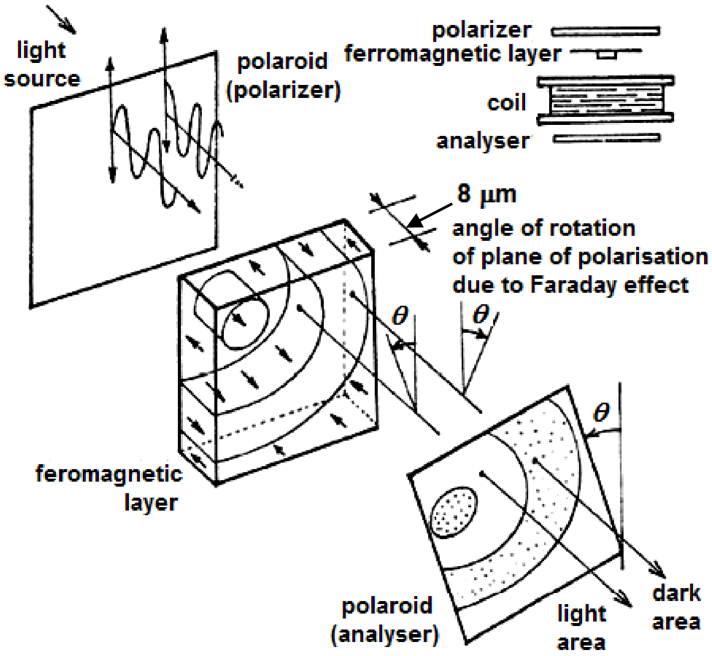
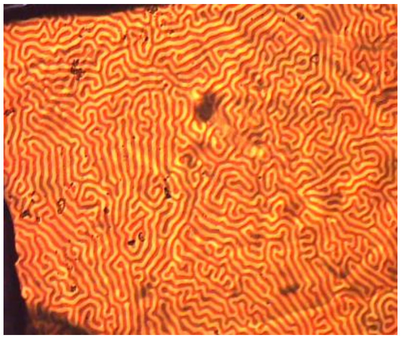


Figure 3 The geometry of the magnetic domain apparatus.

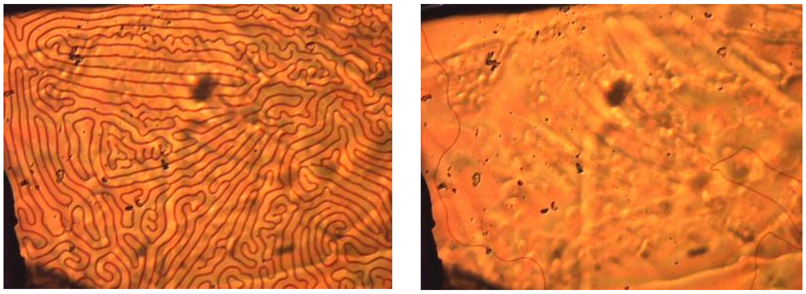
The sample of the ferromagnetic layer is placed on the coil head. It makes possible to apply the external magnetic field parallel to one or to the other orientation of the domains magnetic moment, respectively. The coil with the ferromagnetic sample is closed between two polarizing filters. The geometry of the apparatus can be seen in Fig. 3 (TEL – Atomic Inc., 2009). This figure illustrates also the principle of the magnetic domains display. The light passing the first polarizing filter (polarizer) is linearly polarized. Passing the ferromagnetic material the polarizing plane rotates at an angle θ to one or to the other side due to influence of the internal magnetic field. This rotating of the polarizing plane is called the *Faraday Effect*. The second polarizing filter (analyzer) is rotated just at the angle θ with respect to the polarizer. Passing the analyzer the intensity of polarized light passing one of the domains type decreases, the intensity of the light passing the other domain type remains unchanged. The domains appear like bright and dark areas. All parts mentioned above are closed in a metal container of cylindrical form with diameter of 50 mm (see Fig. 4)

Figure 4 Magnetic domain apparatus.

Figure 5 The experimental set up with magnetic domain apparatus.

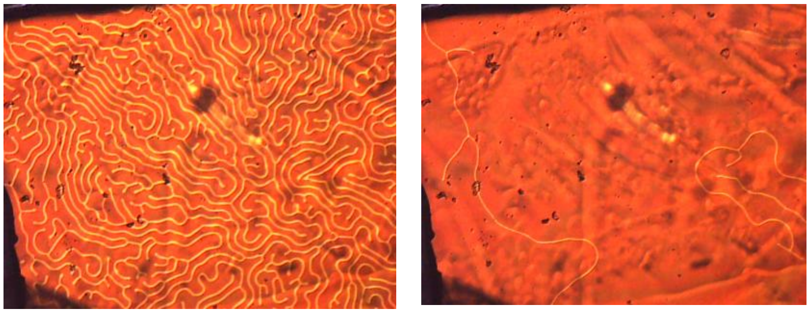


(a) The state with equal areas (light and dark) of each domain. Field 0.00 B_{sat}



(b) Increasing light area. Field + 0.50 B_{sat}

(c) No domains. Field + 0.99 B_{sat}



(d) Increasing dark area. Field – 0.50 B_{sat}

(e) No domains. Field – 0.99 B_{sat}

Figure 6 Views as seen through a microscope x100 magnification.

The picture is enlarged by means of a microscope, recorded by a camera and displayed at the PC monitor. For increasing external magnetic field the area of domains with parallel internal magnetic field grows in size at the expense of the area of domains with anti–parallel internal field. Fig. 3 shows the situation in case the area of dark domains increases. On the other hand, after changing the magnetic field orientation the domains with bright area increase. The experimental set up in the laboratory is shown in the Fig. 5; the shots taking from the PC monitor for different values of magnetic saturation of the sample are shown in Fig. 6.

To operate the coil creating the external magnetic field, the source of controllable direct voltage 0 – 6 V, the current no more that 1A is needed. The fuse of 1A is recommended by producer. According to our experience, the coil can be damaged by long – term current close to the maximal allowed value. To secure the current limiting to the allowed value electronically and to allow passing the current only for the time necessary to follow the phenomena is very useful.

4. CONCLUSION

Teachers and students of a general 1st year physics course working in laboratories discuss the running experiment, teachers monitor if students understand the studied effect. By experiments with ferromagnetic properties of materials, teachers often find that students do not understand what the magnetic domains means. The laboratory set was completed with a tool that makes the domains visible and enables to observe their behavior under changes of an external magnetic field. Students appreciate this new possibility, and teachers find out increased student’s interest in the issue of magnetic properties of materials and better understanding of the concept of magnetic domains.

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