CONSIDERATIONS ON THE MAGNETIZATION CHARACTERISTICS OF SOFT MAGNETIC MATERIALS

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Key words: Hysteresis loop, Initial magnetization curve, Static normal curve, Dynamic normal curve, Soft magnetic materials.

In the design of several types of electromagnetic devices with magnetic core, electrical machines included, an essential problem is which characteristics have to be used. If adequate characteristics are not available even computer programs of high accuracy cannot allow results of high precision. In the present paper the following characteristics will be examined: static and dynamic normal characteristics, as well as the first (initial) magnetization curve. A theoretical and several detailed measurements are presented that have not been found in literature.

1. INTRODUCTION

The experimental determination of the technical characteristics of materials is of outstanding importance for any practical application. An example is represented by the experimental determination of the magnetization curves, also called magnetization characteristics [1–11]. In fact, its value may be considered more important than that of the methods of modelling because even the modelling methods have to be validated by experiments. Moreover, in many practical applications the modelling methods are avoided in the favour of the direct usage of the magnetic characteristics, stored by a great number of point data, using computer programs.

The methods of measuring the magnetic properties of soft magnetic materials (magnetically soft materials) specimens refer especially to their determination in a closed magnetic circuit including the specimen, using either the ring or the Epstein frame method. The ring method is suitable for use with laminated or solid ring test specimens as well as ring specimens produced by sintering.

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It is important to emphasize that several firms produce apparatus for determining the magnetic characteristics of magnetic materials by using advanced data acquisition and processing systems. Such apparatus are at present constructed in several countries among which Germany, Italy, USA, China. At the same time, it is important to be noted that each of these apparatus has to be in accordance with the international standards of the IEC (International Electrotechnical Commission). For this reason, below, the principles of experimentally determining the characteristics of magnetic materials will be presented in agreement with the data found in literature and in the international standards mentioned in References.

The measurements have in view two cases: measurements in d.c. current and in a.c. current, respectively. For each case, the measurements show certain particularities. The experimental analyses we have carried out [12] have shown that the Epstein frame procedure is to be preferred to the ring one for d.c. measurements as well as for a.c. measurements. The Epstein frame may be used for magnetic field strengths in the interval 1–200 kA/m.

It is worth noting that the description of the procedures for measurement are not clearly or detailed enough explained in many books and even in some International Standards, because some important detail have not been presented without ambiguity and in accordance with the capability of the measurement devices now in use. For instance, on the known web-sites, for the normal magnetization curve is given the definition of the first magnetization curve, hence something different. In several other works, like [5, p. 93], a more precise definition is given, but there has not been specified if it concerns the static or dynamic case, which require different definitions.

In the work [7, p. 324], there is mentioned that the normal magnetization curve is considered the basic characteristic of magnetic materials. The reason is that it fulfils the requirements for good reproducibility and is largely used in describing the behaviour of materials.

For the first (initial) magnetization, the definitions found in literature are consistent, except confusion with another characteristic as above mentioned.

2. **THE OBJECT AND DEFINITIONS**

2.1. THE OBJECT TO BE STUDIED

The aim of the ring and Epstein frame methods includes the obtaining of several types of curves: initial magnetization curve, hysteresis loop, normal magnetization curve. Some terms have to be recalled since they are not to be found in usual standards and books. The first should be the term of *normal magnetic induction and magnetization* (Magnetic Testing Theory and Nomenclature, American Society for Testing and Materials, 1916, Race St. Philadelphia 3, Pa.

ASTM Special Technical Publication no. 371, by American Society for Testing and Materials 1964. Library of Congress Catalog Card Numbers C4-8524). The IEC International Standards give not a definition of this curve, but recommendations explaining how to carry out the experimental determination of this curve, which seems to be in accordance with the mentioned work. However, certain recommendations are not in complete accordance with the procedures used in several actual measuring apparatus (devices).

2.2. DEFINITION OF THE STATIC NORMAL CURVE

According to the recommended ASTM, the *normal magnetic induction* results when placing the considered specimen in a symmetrically magnetized condition, abbreviated as SCM and below specified. Then, consider this specimen submitted to a successively reversal of equal positive and negative values of the magnetic field strength H, hence symmetric conditions. The normal magnetic induction B is taken as the half of the measured changes in induction B, which occur on reversal of the considered d.c. value of the magnetic field strength H. There is to be added that after each reversal, the pause should be greater than 2 seconds. The definition of the normal value of B is extended to the normal value of magnetization M and implicitly of the magnetic polarization J also denoted $M_j = \mu_0 H$.

The static normal magnetization curve is that obtained starting from the demagnetized state of the specimen and increasing the value of H with a certain quantity, and then recording the value of the normal induction value of B or M defined above. Hence this value of B or M cannot be directly obtained, but may be got only by the procedure described below, in Section 3.

2.3. DEFINITION OF THE DYNAMIC NORMAL CURVE

The dynamic normal curve (characteristic) is the continuous line which links the peaks of all symmetric hysteresis loops, usually only for the positive values of the magnetic induction and magnetization.

3. **THE EXPERIMENTAL DRAWING UP OF THE NORMAL CURVES**

3.1. CONSTRUCTION OF THE STATIC NORMAL CURVE

In the IEC Standards there has been described the general procedure for obtaining experimentally this curve. Here, we shall describe the manner in which this curve is obtained in the actual devices and used for this purpose. In order to carry out the procedure, certain programs have been prepared for the existing devices. Firstly, a certain small magnetic field strength is introduced by applying any positive small step representing say 1/100 of the maximum value of the current linkage (ampere-turns) we need for obtaining the greatest required value for instance for to obtain the saturation state.

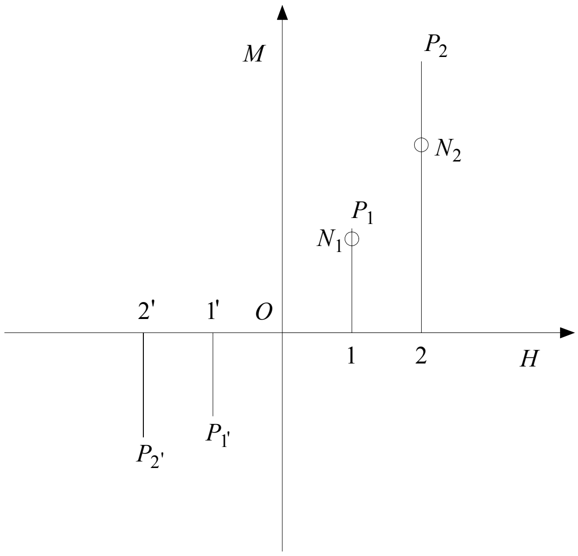

Fig. 1 – Explanatory for the experimental construction of the static normal curve.

Let $F_1 = O1$ be this step, corresponding to the magnetic field strength, H_1, as shown in Fig. 1, a positive quantity. For this value, we shall obtain a certain magnetization M_1, at point P_1. Then, we shall commute the sense of the magnetization by introducing the step $F_{1'} = O1'$. For this value, we shall obtain the magnetization $M_{1'}$, at point $P_{1'}$, hence a negative quantity, and generally $-M_{1'} \neq M_1$. As assumed, the positive quantity:

$$M_{1\,\text{normal}} = \frac{M_1 - M_{1'}}{2}, \tag{1}$$

will represent the normal value of the magnetization for the magnetic field strength H_1. The absolute value of $M_{1\,\text{normal}}$ is the half the sum of the absolute values of M_1 and $M_{1'}$.

The quantities F_1 or H_1 and $M_{1\,\text{normal}}$ represent the pair of co-ordinates of the first point N_1 after the origin, of the static normal curve. Now, we shall apply the next step of ampere-turns namely say $F_2 = 2F_1 = O2$ and we shall obtain the magnetization M_2. After a commutation, as above, we shall obtain the quantities $M_{2'}$ and:

$$M_{2\ \mathrm{normal}} = \frac{M_2 - M_{2'}}{2}, \tag{2}$$

which will represent the normal value of the magnetization for F_2, for a certain magnetic field strength H_2.

Similarly as above, the quantities F_2 or H_2 and $M_{2\ \mathrm{normal}}$ represent the pair of co-ordinates of the next point N_2 of the static normal curve. The procedure is carried out till F_n is equal or very close to the maximum assumed value.

3.2. CONSTRUCTION OF THE DYNAMIC NORMAL CURVE

As already mentioned, the dynamic normal curve (characteristic) is the continuous line which links the peaks of all symmetric hysteresis loops. Because usually one considers only the superior branch, for the continuous line, only the positive value of the magnetic induction and magnetization may be taken into consideration. In principle, this curve is relatively simpler to be drawn up. In this case, we start from a small value of an alternating linkage current and we draw up the hysteresis loop which corresponds to this. Finally we obtain a dynamic hysteresis curve with $H_{\max 1}$ and $M_{\max 1}$.

We continue these constructions for increasing values of one of the quantities $H_{\max}$ or $M_{\max}$ until we shall reach the saturation value $M_{\max\ \mathrm{sat}}$. By linking with a continuous line the peaks of the all built hysteresis curves, the locus obtained is called the dynamic normal curve (characteristic).

In order to avoid too high values of the measured electromotive force to be introduced in the Epstein frame device that could damage the device, it is recommendable the experiment be carried out to a smaller value of the frequency say 10 Hz. The results obtained may be seen in Fig 2.

We could remark that the two types of curves give results relatively near each other, but the dynamic curve is obviously under the static one.

For to have a larger understanding, we should add that the initial magnetization curve is over the static magnetization curve but very near to it. However the static normal magnetization curve shows a surer repeatability.

Remarks

1º The static normal curves we have constructed on the base of experimental data for sheets of the grade M 700–50 A have shown that the peaks of the symmetric hysteresis loops are not placed on the static normal curve what is not stated in the known literature. A reason could be that the actual measuring apparatus (devices) build the symmetric hysteresis loops only with a single tracking (a single commutation), hence without reaching the commutation state achieved for the static normal curve.

2º The ring method is particularly used for magnetic field strengths up to 10 kA/m. However, if measures are taken in order to avoid the heating of the test specimen, this method may be used at higher magnetic field strengths.

3º The influence of the temperature on the measurement results should be considered. There is recommended to avoid a relatively important heating of the test specimen. If no other requirement exists, the measurements have to be performed at an ambient temperature of (23 ± 5) °C. If no special mention is made, the temperature of the test specimen shall not exceed 50 °C. The temperature of the specimen has to be monitored by means of a temperature sensor.

For the case of materials which are particularly sensitive to temperature, the standards concerning these materials may specify the lower and higher limits of the accepted temperature interval.

4. **MEASURING TECHNOLOGY FOR SOFT MAGNETIC MATERIALS**

For the experimental proofs of the present work, the used apparatus has been of the type **MPG 100 D Measuring Unit** produced by the Brockhaus firma.

Measuring categories: specific hysteresis loss; maximum polarization; effective (r.m.s.) polarization; maximum values for field strength; effective (r.m.s.) field strength; remanence; coercive field strength; permeability; specific apparent output; hysteresis display; form factor; $J(H)$ or $M = f(H)$ graphic display.

4.1. OPERATING PRINCIPLE

In a measuring coil, a material sample, *i.e.*, a proof specimen, say a steel sheet, is submitted to a defined magnetic field and a magnetic flux is created in the steel sheet. The electric current required is supplied by a power amplifier. The current is measured by means of a temperature-stable, induction-free precision resistor (shunt) or via field coils.

The polarization is determined by the measurement of the induced voltage, and then conversion and integration by means of a 16-bit processor. Parallel recording of the H and J or M values by separate recording systems guarantees absolutely simultaneous measurement. Faults in measurement caused by phase displacement are thereby avoided. From the differentiated and integrated parameters the processor system can calculate all the above-mentioned values.

There are no sources of faults such as analogue multipliers and integrators.

The a.c. measurement is performed by means of sinusoidal polarization. By using a control algorithm the secondary voltage can be checked and controlled sinusoidally. The rated (nominal) voltage is supplied by a highly stable, quartz-controlled digital sinus generator. Amplitude and frequency are set by the processor unit according to the sample data entered (weight, specific mass, desired frequency, nominal polarization, etc.).

There are used Epstein frame for frequencies up to 400 Hz, (50 Hz and 60 Hz included) as well as for d.c. measurements, according to IEC 60404-2. The recommendations are valid for both: magnetic steel sheets and strips with oriented and non-oriented grains.

4.2. OPERATION, MEASUREMENTS AND EVALUATION

The MPG Expert software for simple operations of the instruments enables completely free parametering and structuring of the measuring processes under Windows.

4.3. TECHNICAL DATA

Repeatability : 0.2 %.
Comparability of the measured results : according to IEC 60404.
Setting accuracy of the nominal value : according to IEC 60404.
Maximum current : ± 20 A (± 40 A optional).
Maximum voltage : ± 125 V.
Coil connectors : 3–6.
Operating mode : PC / software.
Model : table or cabinet version.
Measuring frequency : 3 Hz to 10 kHz, DC with adjustable rise time for primary signals and flux alteration control $d\Phi/dt$.
Power supply voltage : 105–125 V AC / 220 V AC.
Frequency : 50/60 Hz.

5. EXPERIMENTS CARRIED OUT AND RESULTS OBTAINED IN THIS WORK

In order to make evident the properties of the magnetization curves, we have determined by measurement the following curves: static normal curve, dynamic normal curve, initial curve, also called static fundamental curve, dynamic fundamental curve, initial (first) magnetization curve. The curves have been drawn up using the apparatus described above, hence using an Epstein frame, and the specimen (sample) has been bundles of sheet grade M 700–50 A, 8 sheets per frame branch. In Fig. 2, there are the following characteristics: initial, static, dynamic (to 10 Hz). Fig. 3 shows the hysteresis loop (with an interruption necessary because of the relatively far positions of the positive and negative peaks). On the same figure, there are represented the static normal curve, the initial curve and two minor loops. This representation is useful for emphasizing the relative positions of the loops and curves. The static and dynamic curves have been obtained as in Sub-sections 3.1 and 3.2.

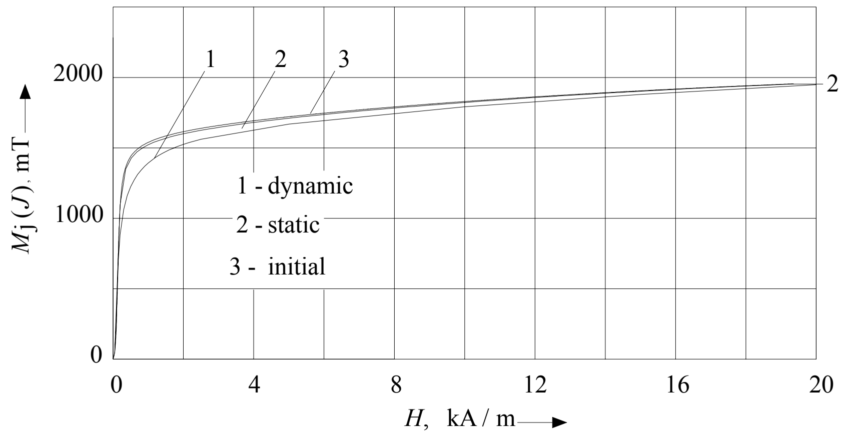

Fig. 2 – The initial (first magnetization) curve, having the greatest values, the static normal curve, and the dynamic normal curve (smaller values) drawn up to 10 Hz.

6. THE GRAPHICAL REPRESENTATION OF HYSTERESIS CURVES

There are many standard procedures for representing the hysteresis curves starting from acquired data. For instance, the Brockhaus system includes a specific procedure. The Excel, MathLab, Wolfram Mathematica, Apple and many other firma software types present various other procedures. In the present case, we have developed a procedure started by A. Nicolaide in paper [4] because it is adapted for the representation of curves using just the data stored by the Brockhaus device systems, and moreover permits to the user to apply any format he wishes, without any limitation, and to emphasize possible errors, and if possible, repair them.
The steps of this graphical representation are the following:

The acquired data delivered in xls form (Excell) are obtained from the device in the forms of two columns sets for abscissae and ordinates of points, respectively. These sets will be transformed into an array containing two columns, the former for abscissae and the latter for ordinates, in a form accessible for an AutoLISP program (the fixed point form corresponds to this aim).

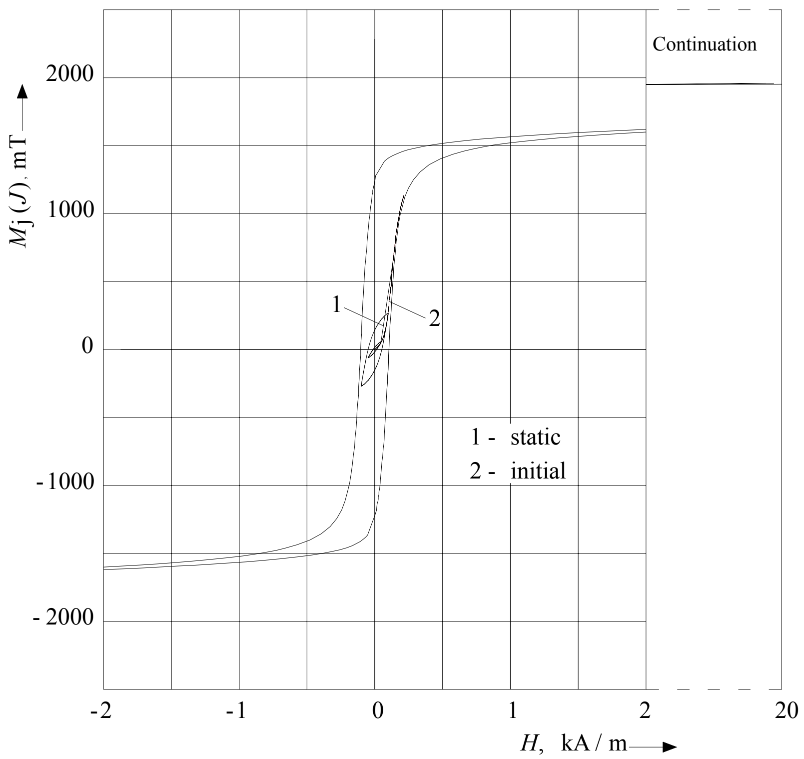

Fig. 3 – The hysteresis loop, the static normal curve, the initial curve and two minor loops.

7. **CONCLUSION**

In the experimental and theoretical analysis the authors have had in view that in the design of several types of electromagnetic devices with magnetic core, electrical machines included, an essential problem is which magnetization curves have to be used. If adequate characteristics are not available even computer programs of high accuracy cannot allow results of high precision, and a well founded comparison between various solutions is not possible. The authors had examined the main magnetization characteristics and have studied the following curves: general hysteresis, initial, static normal, dynamic normal. They have pointed out that the various test methods lead to different results due to the form of the test specimen. Several non founded statements of literature have been remarked removing various possible confusions.

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