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INTERNATIONAL STANDARD

NORME INTERNATIONALE

Magnetic materials –
Part 2: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of an Epstein frame

Matériaux magnétiques –
Partie 2: Méthodes de mesure des propriétés magnétiques des bandes et tôles magnétiques en acier au moyen d'un cadre Epstein

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CONTENTS

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MAGNETIC MATERIALS –

Part 2: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of an Epstein frame

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 60404-2 has been prepared by IEC technical committee 68: Magnetic alloys and steels.

This consolidated version of IEC 60404-2 consists of the third edition (2000) [documents 68/119/FDIS and 68/135/RVD] and its amendment 1 (2008) [documents 68/365/FDIS and 68/369/RVD].

The technical content is therefore identical to the base edition and its amendment and has been prepared for user convenience.

It bears the edition number 3.1.

A vertical line in the margin shows where the base publication has been modified by amendment 1.

This standard supersedes chapters I, II, IV and V of IEC 60404-2:1978.

The standard IEC 60404-11 supersedes chapter VIII of IEC 60404-2:1978.

The standard IEC 60404-13 supersedes chapters VI, VII and IX of IEC 60404-2:1978.

Chapter III of IEC 60404-2:1978 is cancelled.

The committee has decided that the contents of the base publication and its amendments will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

The contents of the corrigendum of March 2018 have been included in this copy.

MAGNETIC MATERIALS –

Part 2: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of an Epstein frame

1 Scope and object

This part of IEC 60404 is applicable to grain oriented and non-oriented electrical sheet and strip for a.c. measurements of magnetic properties at frequencies up to 400 Hz and for d.c. magnetic measurements.

The object of this part is to define the general principles and the technical details of the measurement of the magnetic properties of electrical steel sheet and strip by means of an Epstein frame.

The Epstein frame is applicable to test specimens obtained from electrical steel sheets and strips of any grade. The a.c. magnetic characteristics are determined for sinusoidal induced voltages, for specified peak values of magnetic polarization and for a specified frequency.

The measurements are to be made at an ambient temperature of (23 ± 5) °C on test specimens which have first been demagnetized.

Measurements at higher frequencies are to be made in accordance with IEC 60404-10.

NOTE Throughout this standard the term "magnetic polarization" is used as defined in IEC 60050(221). In some standards of the IEC 60404 series, the term "magnetic flux density" was used.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-221, *International Electrotechnical Vocabulary – Chapter 221: Magnetic materials and components*

IEC 60404-4, *Magnetic materials – Part 4: Methods of measurement of d.c. magnetic properties of magnetically soft materials*

IEC 60404-8-3, *Magnetic materials – Part 8-3: Specifications for individual materials – Cold-rolled electrical non-alloyed and alloyed steel sheet and strip delivered in the semi-processed state*

IEC 60404-8-4, *Magnetic materials – Part 8-4: Specifications for individual materials – Cold-rolled non-oriented electrical steel sheet and strip delivered in the fully-processed state*

IEC 60404-8-7, *Magnetic materials – Part 8-7: Specifications for individual materials – Cold-rolled grain-oriented electrical steel sheet and strip delivered in the fully-processed state*

IEC 60404-10, *Magnetic materials – Part 10: Methods of measurement of magnetic properties of magnetic sheet and strip at medium frequencies*

IEC 60404-13, *Magnetic materials – Part 13: Methods of measurement of density, resistivity and stacking factor of electrical steel sheet and strip*

3 General principles of a.c. measurements

3.1 Principle of the 25 cm Epstein frame method

The 25 cm Epstein frame which comprises a primary winding, a secondary winding and the specimen to be tested as a core, forms an unloaded transformer whose characteristics are measured by the method described in the following subclauses.

3.2 Test specimen

The strips to be tested are assembled in a square, having double-lapped joints (see figure 1), thus forming four branches of equal length and equal cross-sectional area.

The strips shall be sampled in accordance with the appropriate product standard in the IEC 60404-8 series.

They shall be cut by a method which will produce substantially burr-free edges and, if so specified, heat treated in accordance with the corresponding product standard. They shall have the following dimensions:

- width b = 30 mm ± 0,2 mm;
- length 280 mm ≤ l ≤ 320 mm.

The lengths of the strips shall be equal within a tolerance of ±0,5 mm.

When strips are cut parallel or normal to the direction of rolling, the edge of the parent sheet shall be taken as the reference direction.

The following tolerances shall apply for the angle between the specified and actual direction of cutting:

±1° for grain oriented steel sheet;

±5° for non-oriented steel sheet.

Only flat strips shall be used. Measurements shall be made without additional insulation.

The number of strips comprising the test specimen shall be a multiple of four and is specified in the corresponding product standard. However, the active mass of the test specimen (see equation (1)) shall be at least 240 g for strips 280 mm long.

3.3 The 25 cm Epstein frame

The 25 cm Epstein frame (hereinafter referred to as the Epstein frame) shall consist of four coils into which the strips making up the test specimen are inserted (see figure 2).

A mutual inductor for air flux compensation is included with the Epstein frame.

The winding formers supporting the coils are made of hard insulating material, such as phenolic paper. They have a rectangular cross-section with 32 mm inner width. A height of approximately 10 mm is recommended.

The coils shall be fixed to an insulating and non-magnetic base in such a way as to form a square (see figure 2). The length of the sides of the square formed by the internal edges of the strips of the test specimen shall be 220 $^{+1}_{-0}$ mm (see figure 2).

Each of the four coils shall have two windings:

– a primary winding, on the outside (magnetizing winding);

– a secondary winding, on the inside (voltage winding).

NOTE An electrostatic screen may be provided between these windings.

The windings shall be distributed uniformly over a minimum length of 190 mm, each coil having one quarter of the total number of turns.

The individual primary windings of the four coils shall be connected in series, as shall be the secondary windings. The number of primary and secondary turns may be adapted to the particular conditions prevailing with regard to the power source, measuring equipment and frequency.

NOTE The total number of turns generally used and recommended is 700 or 1 000.

In order to reduce the effect of the impedances of the windings as much as possible, the following requirements shall be met:

$$\frac{R_1}{N_1{}^2} \leq 1{,}25 \cdot 10^{-6}\ \Omega \qquad \frac{R_2}{N_2{}^2} \leq 5 \cdot 10^{-6}\ \Omega$$

$$\frac{L_1}{N_1{}^2} \leq 2{,}5 \cdot 10^{-9}\ \text{H} \qquad \frac{L_2}{N_2{}^2} \leq 2{,}5 \cdot 10^{-9}\ \text{H}$$

where

R_1 and R_2 are the resistances of the primary and secondary windings, respectively, in ohms;

L_1 and L_2 are the inductances of the primary and secondary windings, respectively, in henrys;

N_1 and N_2 are the total number of turns of the primary and secondary windings, respectively.

NOTE These requirements are satisfied, for example, if windings with the following characteristics are used:

– total number of turns: $N_1 = 700$, $N_2 = 700$;

– primary (outer) winding: each of the four coils carries 175 turns of two copper wires connected in parallel, each with a nominal cross-sectional area of approximately 1,8 mm^2, wound side by side in three layers;

– secondary winding: each of the four coils carries 175 turns of one copper wire with a nominal cross-sectional area of 0,8 mm^2 wound in one layer.

The effective magnetic path length, l_m, of the magnetic circuit shall be conventionally assumed to be equal to 0,94 m. Therefore, the active mass, m_a, that is the mass of the test specimen which is magnetically active, is given by:

$$m_a = \frac{l_m}{4\,l}\,m \qquad (1)$$

where

l is the length of a test specimen strip, in metres;

l_m is the conventional effective magnetic path length, in metres (l_m = 0,94 m);

m is the total mass of the test specimen, in kilograms;

m_a is the active mass of the test specimen, in kilograms.

3.4 Air flux compensation

The mutual inductor for air flux compensation shall be located in the centre of the space enclosed by the four coils, its axis being directed normal to the plane of the axes of these coils. The primary winding of the mutual inductor shall be connected in series with the primary winding of the Epstein frame, and the secondary winding of the mutual inductor shall be connected to the secondary winding of the Epstein frame in series opposition (see figure 3).

The adjustment of the value of the mutual inductance shall be made so that, when passing an alternating current through the primary windings in the absence of the specimen in the apparatus, the voltage measured between the non-common terminals of the secondary windings shall be no more than 0,1 % of the voltage appearing across the secondary winding of the test apparatus alone.

Thus the average value of the rectified voltage induced in the combined secondary windings is proportional to the peak value of the magnetic polarization in the test specimen.

3.5 Power supply

The power supply shall have a low impedance and a high stability of voltage and frequency. During measurements, the voltage and frequency variations shall not exceed ±0,2 % of the required value.

For the determination of the specific total loss, the specific apparent power and the r.m.s. value of the magnetic field strength, the form factor of the secondary voltage shall be 1,111 ± 1 %.

NOTE This is possible in several ways: for example by using an electronically controlled power supply or a negative feedback power amplifier. The form factor of the secondary voltage is the ratio of its r.m.s. value to its average rectified value.

Two voltmeters, one responsive to r.m.s. values and the other responsive to average rectified values shall be used to determine the form factor.

NOTE The waveform of the secondary induced voltage should be checked with an oscilloscope to ensure that only the fundamental component is present.

3.6 Voltage measurement

The secondary voltage of the Epstein frame shall be measured by means of appropriate voltmeters having an input impedance greater than or equal to 1 000 Ω/V.

NOTE For the application of digital sampling methods, see Annex A.

3.6.1 Average type voltmeter

A voltmeter responsive to average rectified values having an accuracy of ±0,2 % or better shall be used.

NOTE The preferred instrument is a digital voltmeter.

3.6.2 RMS voltmeter

A voltmeter responsive to r.m.s. values having an accuracy of ±0,2 % or better shall be used.

NOTE The preferred instrument is a digital voltmeter.

3.6.3 Peak voltmeter

A voltmeter responsive to peak values having an accuracy of ±0,5 % or better shall be used.

3.7 Frequency measurement

A frequency meter having an accuracy of ±0,1 % or better shall be used.

NOTE For the application of digital sampling methods, see Annex A.

3.8 Power measurement

The power shall be measured by a wattmeter having an accuracy of ±0,5 % or better at the actual power factor and crest factor.

NOTE For the application of digital sampling methods, see Annex A.

The resistance of the voltage circuit of the wattmeter shall be at least 5 000 times its reactance, unless the wattmeter is compensated for its reactance.

If a current measuring device is included in the circuit it shall be short-circuited when the secondary voltage has been adjusted and the loss is being measured.

4 Procedure for the measurement of the specific total loss

NOTE For the application of digital sampling methods, see Annex A.

4.1 Preparation for measurement

The Epstein frame and measuring equipment shall be connected as shown in figure 3.

The test specimen shall be weighed and its mass determined to within ±0,1 %. After weighing, the strips shall be stacked into the coils of the Epstein frame with double lapped joints at the corners and with the same number of strips in each branch of the frame such that the length of the internal side of the square so formed is 220^{+1}_{-0} mm. Where strips are cut half parallel and half perpendicular to the direction of rolling, the strips cut in the direction of rolling shall be inserted in two opposite branches of the frame and those cut perpendicular to the direction of rolling inserted in the other two branches. Care shall be taken to ensure that the air gap between the strips in the overlapping portions is as small as possible. It is permissible to apply a force of about 1 N to each corner, normal to the plane of the overlapping strips.

The test specimen shall then be demagnetized in a decreasing alternating magnetic field of an initial level higher than used in previous measurements.

4.2 Adjustment of power supply

The power supply output shall be slowly increased, whilst observing the ammeter in the primary circuit to ensure that the wattmeter current circuit is not overloaded, until the average rectified value of the secondary voltage $\overline{|U_2|}$ of the Epstein frame has reached the required value. This is calculated from the desired value of magnetic polarization by means of:

$$\overline{|U_2|} = 4\, f\, N_2 \frac{R_\mathrm{i}}{R_\mathrm{i} + R_\mathrm{t}}\, A\, \hat{J} \qquad (2)$$

where

$\overline{|U_2|}$ is the average value of the rectified voltage induced in the secondary winding, in volts;

A is the cross-sectional area of the test specimen, in square metres;

f is the frequency, in hertz;

$\hat{J}$ is the peak value of magnetic polarization, in teslas;

N_2 is the total number of turns of the secondary winding;

R_i is the total resistance of the instruments in the secondary circuit, in ohms;

R_t is the series resistance of the secondary windings and mutual inductor, in ohms.

The cross-sectional area of the test specimen is given by the equation:

$$A = \frac{m}{4\, l\, \rho_m} \tag{3}$$

where

A is the cross-sectional area of the test specimen, in square metres;

m is the total mass of the test specimen, in kilograms;

l is the length of a test specimen strip, in metres;

ρ_m is the conventional density, or the value determined in accordance with IEC 60404-13, of the test material, in kilograms per cubic metre.

4.3 *Measurement of power*

The ammeter in the primary circuit shall be short circuited and the secondary voltage readjusted if necessary. The form factor of the secondary voltage shall be determined in accordance with 3.5 and then the wattmeter reading shall be recorded.

4.4 Determination of the specific total loss

The power, P_m, measured by the wattmeter includes the power consumed by the instruments in the secondary circuit. The total loss, P_c, of the test specimen shall therefore be calculated using the equation:

$$P_c = \frac{N_1}{N_2}\, P_m - \frac{\left(1{,}111\, \overline{|U_2|}\right)^2}{R_i} \tag{4}$$

where

P_c is the calculated total loss of the test specimen, in watts;

N_1 is the total number of turns of the primary winding;

N_2 is the total number of turns of the secondary winding;

P_m is the power measured by the wattmeter, in watts;

R_i is the total resistance of the instruments in the secondary circuit, in ohms;

$\overline{|U_2|}$ is the average value of the rectified voltage induced in the secondary winding, in volts.

The measured specific total loss, P_s, is obtained by dividing P_c by the active mass m_a of the test specimen.

$$P_s = \frac{P_c}{m_a} = \frac{P_c\, 4\, l}{m\, l_m} \tag{5}$$

where

P_s is the specific total loss of the test specimen, in watts per kilogram;

l is the length of a test specimen strip, in metres;

l_m is the conventional effective magnetic path length, in metres (l_m = 0,94 m);

m is the total mass of the test specimen, in kilograms;

m_a is the active mass of the test specimen, in kilograms;

P_c is the calculated total loss of the test specimen, in watts.

4.5 Reproducibility of the specific total loss measurement

The reproducibility of the results obtained from the procedures described in this subclause is characterized by a relative standard deviation of 1,5 % for measurements on grain oriented material at magnetic polarizations up to 1,7 T and for measurements on non-oriented material up to 1,5 T.

For measurements at higher magnetic polarizations, it is expected that the relative standard deviation will be increased.

5 Procedure for the determination of the peak value of magnetic polarization, r.m.s. value of magnetic field strength, peak value of magnetic field strength and specific apparent power

This clause describes measuring methods for the determination of the following characteristics:

– peak value of magnetic polarization $\hat{J}$;

– r.m.s. value of magnetic field strength $\tilde{H}$;

– peak value of magnetic field strength $\hat{H}$;

– specific apparent power S_s.

5.1 Test specimen

The test specimen shall comply with 3.2.

5.2 Principle of measurement

5.2.1 Peak value of magnetic polarization $\hat{J}$

The peak value of magnetic polarization shall be determined from the average value of the secondary rectified voltage measured as described in clause 4 and calculated from equation 2.

5.2.2 RMS value of magnetic field strength

The r.m.s. value of the magnetic field strength shall be calculated from the r.m.s. value of the current, measured by an r.m.s. ammeter in the circuit shown in figure 4. Alternatively a precision resistor, of value typically in the range 0,1 Ω to 1 Ω of an accuracy of 0,1 %, shall be connected in place of the ammeter and the voltage developed across this resistor shall be measured using a voltmeter responsive to r.m.s. values conforming to the requirements of 3.6. The frequency shall be set to the desired value. The peak value of the magnetic polarization shall be set by adjusting the secondary voltage of the Epstein frame to the required value calculated from equation 2. The r.m.s. value of the current shall then be determined and recorded. The r.m.s. value of the magnetic field strength shall be calculated from the equation:

$$\tilde{H} = \frac{N_1}{l_m} \tilde{I}_1 \qquad (6)$$

where

$\tilde{H}$ is the r.m.s. value of magnetic field strength, in amperes per metre;

$\tilde{I}_1$ is the r.m.s. value of magnetizing current, in amperes;

l_m is the conventional effective magnetic path length, in metres (l_m = 0,94 m);

N_1 is the total number of turns of the primary winding.

5.2.3 Peak value of magnetic field strength

The peak value of the magnetic field strength shall be derived from the peak value of the magnetizing current $\hat{I}_1$ which is obtained by measuring the voltage drop across a known precision resistor R of an accuracy of 0,1 %, using a peak voltmeter as shown in figure 5. For this measurement, the form factor of the secondary voltage is allowed to exceed the specified value (see 3.5).

The peak magnetic field strength shall be calculated from the equation:

$$\hat{H} = \frac{N_1}{l_m}\,\hat{I}_1 \qquad (7)$$

where

$\hat{H}$ is the peak value of magnetic field strength, in amperes per metre;

$\hat{I}_1$ is the peak value of magnetizing current $\left(\hat{I}_1 = \frac{\hat{U}}{R}\right)$ in amperes;

l_m is the conventional effective magnetic path length of test specimen (l_m = 0,94 m);

N_1 is the total number of turns of the primary winding of the Epstein frame.

Alternatively, the peak value of the magnetizing current $\hat{I}_1$ can be determined by measuring the average rectified value of the voltage appearing across the secondary winding of a mutual inductor M_D of an accuracy of 0,5 %, the primary winding of which is connected in series with the primary winding of the Epstein frame. With this method it is necessary to ensure (e.g. by observing the waveform on an oscilloscope) that there are no more than two zero crossings per cycle of the voltage waveform of the secondary winding of the mutual inductor. The circuit is given in figure 6. The voltmeter can be the same instrument as is used for measuring the secondary voltage of the Epstein frame. With this method, the peak value of the magnetic field strength shall be calculated from the equation:

$$\hat{H} = \frac{N_1}{4\,f\,M_D\,l_m} \cdot \frac{R_v + R_m}{R_v} \cdot \overline{U}_m \qquad (7a)$$

where

M_D is the mutual inductance in the circuit given in figure 6, page 35, in henrys;

R_m is the resistance of the secondary winding of M_D, in ohms;

R_v is the internal resistance of the average type voltmeter, in ohms;

$\overline{U}_m$ is the average rectified value of the voltage induced in the secondary winding of M_D, in volts.