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Magnetic materials –
Part 3: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of a single sheet tester

Matériaux magnétiques –
Partie 3: Méthodes de mesure des caractéristiques magnétiques des bandes et tôles magnétiques en acier à l'aide de l'essai sur tôle unique

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MAGNETIC MATERIALS –

Part 3: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of a single sheet tester

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IEC 60404-3 edition 2.2 contains the second edition (1992) [documents 68(CO)68+75 and 68(CO)77+79], its amendment 1 (2002) [documents 68/258/FDIS and 68/263/RVD], its amendment 2 (2009) [documents 68/389/CDV and 68/397/RVC] and its corrigendum of December 2009.

A vertical line in the margin shows where the base publication has been modified by amendments 1 and 2.

International Standard IEC 60404-3 has been prepared by IEC technical committee 68: Magnetic alloys and steels.

Annex A forms an integral part of this standard.

Annex B, C and D are for information only.

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MAGNETIC MATERIALS –

Part 3: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of a single sheet tester

1 Object and field of application

The object of this part is to define the general principles and the technical details of the measurement of the magnetic properties of magnetic sheets by means of a single sheet tester.

This part of IEC 60404 is applicable at power frequencies to:

a) grain oriented magnetic sheet and strip:

for the measurement between 1,0 T and 1,8 T of:

– specific total loss;

– specific apparent power;

– r.m.s. value of the magnetic field strength;

for the measurement up to peak values of magnetic field strength of 1 000 A/m of:

– peak value of the magnetic polarization;

– peak value of the magnetic field strength.

b) non-oriented magnetic sheet and strip:

for the measurement between 0,8 T and 1,5 T of:

– specific total loss;

– specific apparent power;

– r.m.s. value of excitation current;

for the measurement up to peak values of magnetic field strength of 10 000 A/m of:

– peak value of the magnetic polarization;

– peak value of the magnetic field strength.

The single sheet tester is applicable to test specimens obtained from magnetic sheets and strips of any quality. The magnetic characteristics are determined for a sinusoidal induced voltage, for specified peak values of magnetic polarization and for a specified frequency.

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

NOTE Throughout this part the quantity "magnetic polarization" is used as defined in IEC 60050(901). In some standards of the IEC 60404 series, the quantity "magnetic flux density" was used.

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2 Normative references

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

IEC 60404-2, *Magnetic materials – Part 2: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of an Epstein frame*

3 General principles

3.1 Principle of the method

The test specimen comprises a sample of magnetic sheet and is placed inside two windings:

- an exterior primary winding (magnetizing winding);
- an interior secondary winding (voltage winding).

The flux closure is made by a magnetic circuit consisting of two identical yokes, the cross-section of which is very large compared with that of the test specimen (see figure 1).

To minimize the effects of pressure on the test specimen, the upper yoke shall be provided with a means of suspension which allows part of its weight to be counterbalanced in accordance with 3.2.1.

Care shall be taken to ensure that temperature changes are kept below a level likely to produce stress in the test specimen due to thermal expansion or contraction.

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3.2 Test apparatus

3.2.1 Yokes

Each yoke is in the form of a U made up of insulated sheets of grain oriented silicon steel or nickel iron alloy. It shall have a low reluctance and a specific total loss not greater than 1,0 W/kg at 1,5 T and 50 Hz. It shall be manufactured in accordance with the requirements of annex A.

In order to reduce the effect of eddy currents and give a more homogeneous distribution of the flux over the inside of the yokes, the latter shall be made of a pair of C-cores or a glued stack of laminations in which case the corners shall have staggered butt joints (see figure 1).

The yoke shall have pole faces having a width of 25 mm ± 1 mm.

The two pole faces of each yoke shall be coplanar to within 0,5 mm and the gap between the opposite pole faces of the yokes shall not exceed 0,005 mm at any point. Also, the yokes shall be rigid in order to avoid creating mechanical stresses in the test specimen.

The height of each yoke shall be between 90 mm and 150 mm. Each yoke shall have a width of 500^{+5}_{-5} mm and an inside length of 450 mm ± 1 mm (see figure 2).

NOTE It is recognized that other yoke dimensions can be used provided that the comparability of the results can be demonstrated.

There shall be a non-conducting, non-magnetic support between the vertical limbs of the yokes on which the test specimen is placed. This support shall be centered and located in the same plane as the pole faces so that the test specimen is in direct contact with the pole faces without any gap.

The upper yoke shall be movable upwards to permit insertion of the test specimen. After insertion the upper yoke shall be realigned accurately with the bottom yoke. The suspension of the upper yoke shall allow part of its weight to be counterbalanced so as to give a force on the test specimen of between 100 N and 200 N.

NOTE The square shape of the yoke has been chosen in order to have only one test specimen for non-oriented material. By rotating the test specimen through 90° it is possible to determine the characteristics in the rolling direction and perpendicular to the rolling direction.

3.2.2 Windings

The primary and secondary windings shall be at least 440 mm in length and shall be wound on a non-conducting, non-magnetic, rectangular former. The dimensions of the former shall be as follows:

- length: 445 mm ± 2 mm;
- internal width: 510 mm ± 1 mm;
- internal height: $5^{\ 0}_{-2}$ mm;
- height: ≤15 mm.

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The primary winding can be made up of:

- either five or more coils having identical dimensions and the same number of turns connected in parallel and taking up the whole length (see figure 3). For example, with five coils, each coil can be made up of 400 turns of copper wire 1 mm in diameter, wound in five layers;
- or a single continuous and uniform winding taking up the whole length. For example this winding can be made up of 400 turns of copper wire 1 mm in diameter, wound in one or more layers.

The number of turns on the secondary winding will depend on the characteristics of the measuring instruments.

3.3 Air flux compensation

Compensation shall be made for the effect of air flux. This can be achieved, for example, by a mutual inductor. The primary winding of the mutual inductor is connected in series with the primary winding of the test apparatus, while the secondary winding of the mutual inductor is connected to the secondary winding of the test apparatus in series opposition.

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.

3.4 Test specimen

The length of the test specimen shall be not less than 500 mm. Although the part of the specimen situated outside the pole faces has no great influence on the measurement, this part shall not be longer than is necessary to facilitate insertion and removal of the test specimen.

The width of the test specimen shall be as large as possible and at its maximum equal to the width of the yokes.

For maximum accuracy, the minimum width shall be not less than 60 % of the width of the yokes.

The test specimen shall be cut without the formation of excessive burrs or mechanical distortion. The test specimen shall be plane. When a test specimen is cut, the edge of the parent strip is taken as the reference direction. The following tolerances are allowed for the angle between the direction of rolling and that of cutting:

- ±1° for grain oriented steel sheet;
- ±5° for non-oriented steel sheet.

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For non-oriented steel sheet, two specimens shall be cut, one parallel to the direction of rolling and the other perpendicular unless the test specimen is square, in which case one test specimen only is necessary.

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3.5 Power supply

The power supply shall be of low internal impedance and shall be highly stable in terms of voltage and frequency. During the measurement, the voltage and the frequency shall be maintained constant within ±0,2 %.

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In addition, the waveform of the secondary induced voltage shall be maintained as sinusoidal as possible. It is preferable to maintain the form factor of the secondary voltage to within ±1 % of 1,111. This can be achieved by various means, for example by using an electronic feedback amplifier.

4 Determination of the specific total loss

4.1 Principle of measurement

The single sheet tester with the test specimen represents an unloaded transformer the total loss of which is measured by the circuit shown in figure 4.

4.2 Apparatus

4.2.1 Voltage measurement

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

4.2.1.1 Average type voltmeter

The secondary rectified voltage of the test apparatus shall be measured by an average type voltmeter. The preferred instrument is a digital voltmeter having an accuracy of ±0,2 %.

NOTE Instruments of this type are usually graduated in average rectified value multiplied by 1,111.

The load on the secondary circuit shall be as small as possible. Consequently, the internal resistance of the average type voltmeter should be at least 1 000 Ω/V.

4.2.1.2 R.M.S. voltmeter

A voltmeter responsive to r.m.s. values shall be used. The preferred instrument is a digital voltmeter having an accuracy of ±0,2 %.

4.2.2 Frequency measurement

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

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

4.2.3 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 D.

The resistance of the voltage circuit of the wattmeter shall be at least 100 Ω/V for all ranges. If necessary, the losses in the secondary circuit shall be subtracted from the indicated loss value.

The ohmic resistance of the wattmeter voltage circuit 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 is adjusted and the losses are measured.

4.3 Measurement procedure of the specific total loss

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

4.3.1 Preparation of measurement

The length of the test specimen shall be measured with an accuracy of ±0,1 % and its mass determined within ±0,1 %. The test specimen shall be loaded and centred on the longitudinal and transverse axes of the test coil, and the partly counterbalanced upper yoke shall be lowered.

Before the measurement, the test specimen shall be demagnetized by slowly decreasing an alternating magnetic field starting from well above the value to be measured.

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4.3.2 Source setting

The source shall be adjusted so that the average value of the secondary rectified voltage is:

$$\left|\overline{U_2}\right| = 4\, f\, N_2\, \frac{R_i}{R_i + R_t}\, A\hat{J} \qquad (1)$$

where

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

f is the frequency, in hertz;

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

R_t is the series resistance of the secondary windings of the test apparatus and mutual inductor, in ohms;

N_2 is the number of turns of the secondary winding;

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

$\hat{J}$ is the peak value of magnetic polarization, in tesla.

The cross-sectional area A is given by the equation:

$$A = \frac{m}{l\,\rho_m} \qquad (2)$$

where

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

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

ρ_m is the density of the test material, in kilograms per cubic metre.

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4.3.3 Measurements

4.3.3.1 The ammeter, if any, in the primary circuit shall be observed to ensure that the current circuit of the wattmeter is not overloaded. The ammeter shall then be short-circuited and the secondary voltage readjusted.

After checking the waveform of the secondary voltage, the wattmeter shall be read. The value of the specific total power loss shall then be calculated from the equation:

$$P_s = \left[P \frac{N_1}{N_2} - \frac{(1{,}111 \overline{|U_2|})^2}{R_i} \right] \frac{l}{m\, l_m} \qquad (3)$$

where

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

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

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

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

l_m is the conventional magnetic path length, in metres (l_m = 0,45 m);

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

N_1 is the number of turns of the primary winding;

N_2 is the number of turns of the secondary winding;

R_i is the combined resistance of instruments in the secondary circuit, in ohms.

NOTE 1 Studies* have shown that the inside length of the yokes is an appropriate mean value for the effective magnetic path length l_m for different materials and polarization values.

NOTE 2 A long established practice in a few countries is to calibrate the test apparatus by determination of the effective magnetic path length based on specific total power loss measurements made in an Epstein frame. The details of the calibration procedure are described in annex B. This practice is permitted only for the evaluation of magnetic sheet and strip intended for consumption in those countries.

4.3.3.2 In the case of non-oriented material, for values of the specific total loss specifid in the product standards for magnetic materials, the reported value of the specific total loss shall be calculated as the average of the two measurements made for the directions parallel and perpendicular to the direction of rolling. For other purposes the values of the specific total loss parallel and perpendicular to the direction of rolling shall be reported separately.

4.3.4 Reproducibility

The reproducibility of this method using the test apparatus defined above is characterized by a relative standard deviation of 1 % for grain oriented steel sheet and 2 % for non-oriented steel sheet.

5 Determination of magnetic field strength, excitation current and specific apparent power

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

– r.m.s. value of the excitation current $\tilde{I}_1$;

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

– specific apparent power S_s.

* J. D. Sievert, Determination of AC Magnetic Power Loss of Electrical Steel Sheet: Present Status and Trends, IEEE Trans. Mag. Vol. 20, No. 5 (1984) 1702-1707.

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5.1 Principle of measurement

5.1.1 Peak value of magnetic polarization

The peak value of magnetic polarization shall be derived from the average value of the rectified secondary voltage measured as described in 4.2.1.

5.1.2 R.M.S. value of the excitation current

The r.m.s. value of the excitation current shall be measured by an r.m.s. ammeter in the circuit shown in figure 5.

5.1.3 Peak value of the magnetic field strength

The peak value of the magnetic field strength shall be obtained from the peak value $\hat{I}$ of the primary current. This shall be determined by measuring the voltage drop across a known precision resistor R_n using a peak voltmeter as shown in figure 6.

5.2 Apparatus

5.2.1 Average type voltmeter

The secondary rectified voltage of the test apparatus shall be measured by an average type voltmeter. The preferred instrument is a digital voltmeter having an accuracy of ±0,2 %.

NOTE Instruments of this type are usually graduated in average rectified value multiplied by 1,111.

The load on the secondary circuit shall be as small as possible. Consequently, the internal resistance of the average type voltmeter should be at least 1 000 Ω/V.

5.2.2 Current measurement

The r.m.s. value of the primary current shall be measured either by means of an r.m.s. ammeter of low impedance of class 0,5 or better (see figure 5), or by using a precision resistor and r.m.s. electronic voltmeter (see figure 6).

5.2.3 Peak current measurement

The measurement of the peak voltage across resistor R_n (see figure 6) shall be achieved either by means of an electronic voltmeter of high sensitivity indicating the peak value, or by means of a calibrated oscilloscope.

The full scale error of the device used shall be ±3 % or better.

5.2.4 Power supply

The power supply shall be in accordance with 3.5.

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