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NORME INTERNATIONALE

Magnetic materials –
Part 4: Methods of measurement of d.c. magnetic properties of magnetically soft materials

Matériaux magnétiques –
Partie 4: Méthodes de mesure en courant continu des propriétés magnétiques des matériaux magnétiquement doux

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IEC 60404-4 edition 2.2 contains the second edition (1995) [documents 68(CO)95 and 68/117/RVD], its amendment 1 (2000) [documents 68/215/FDIS and 68/217/RVD] and its amendment 2 (2008) [documents 68/363/CDV and 68/375/RVC].

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

International Standard IEC 60404-4 has been prepared by IEC technical committee 68: Magnetic alloys and steels.

Annex A forms an integral part of this standard.

Annexes B and C are for information only.

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- withdrawn,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.

MAGNETIC MATERIALS –

Part 4: Methods of measurement of d.c. magnetic properties of magnetically soft materials

1 Scope and object

This part of IEC 60404 specifies the methods of measuring the d.c. magnetic properties of magnetically soft materials in a closed magnetic circuit using either the ring or the permeameter methods. The ring method is suitable for use with laminated or solid ring specimens as well as ring specimens produced by sintering.

Two methods are used:

a) the ring method, particularly for magnetic field strengths of up to 10 kA/m;

b) the permeameter method for magnetic field strengths in the range 1 kA/m to 200 kA/m.

NOTE The measurement of coercivity in an open magnetic circuit is specified in IEC 60404-7.

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 60404-7:1982, *Magnetic materials – Part 7: Method of measurement of the coercivity of magnetic materials in an open magnetic circuit*

IEC 60404-8-2:1985, *Magnetic materials – Part 8: Specifications for individual materials – Section Two: Specification for cold-rolled magnetic alloyed steel strip delivered in the semi-processed state*

IEC 60404-8-3:1985, *Magnetic materials – Part 8: Specifications for individual materials – Section Three: Specification for cold-rolled magnetic non-alloyed steel strip delivered in the semi-processed state*

IEC 60404-8-4:1986, *Magnetic materials – Part 8: Specifications for individual materials – Section Four: Specification for cold-rolled non-oriented magnetic steel sheet and strip*

IEC 60404-8-6:1986, *Magnetic materials – Part 8: Specifications for individual materials – Section Six: Soft magnetic metallic materials*
Amendment 1 (1992)

IEC 60404-8-7:1988, *Magnetic materials – Part 8: Specifications for individual materials – Section Seven: Specification for grain-oriented magnetic steel sheet and strip*
Amendment 1 (1991)

IEC 60404-8-8:1991, *Magnetic materials – Part 8: Specifications for individual materials – Section 8: Specification for thin magnetic steel strip for use at medium frequencies*

3 Determination of the magnetic characteristics by the ring method

3.1 Object

This clause describes the ring method used to obtain the normal magnetization curve and the hysteresis loop.

3.2 General

This method is used particularly for magnetic field strengths of up to 10 kA/m. However, if care is taken to avoid heating the test specimen, this method may be used at higher magnetic field strengths.

3.3 Effect of temperature on the measurements

Care shall be taken to avoid unduly heating the test specimen. The measurements shall be made at an ambient temperature of (23 ± 5) °C. The temperature of the test specimen shall not exceed 50 °C which shall be monitored by means of a temperature sensor.

For materials which are particularly temperature sensitive, product standards may define lower or higher test specimen temperatures.

3.4 Test specimen

The test specimen is a homogeneous unwelded ring of rectangular or circular cross-section. The cross-sectional area of the ring is determined by the product dimensions, uniformity of magnetic properties, instrumentation sensitivity and space required for the test windings. Usually the cross-sectional area is in the range of 10 mm^2 to 200 mm^2.

Care shall be taken in the preparation of the test specimen to avoid work hardening or heating of the material which might affect the magnetic characteristics. The test specimen can be prepared by turning and finished by light grinding with sufficient coolant to prevent heating the material. The edges of the rings shall be deburred.

To reduce the effect of radial variation of the magnetic field strength, the ring shall have dimensions such that the ratio of the outer to inner diameter shall be no greater than 1,4 and preferably less than 1,25. If the ratio approaches the value 1,4, there will be a greater radial variation in the magnetic field strength.

For a stack of laminations or a toroidal wound core, the cross-sectional area of the test specimen shall be calculated from the mass, density and the value of the inner and outer diameter of the ring. The density can be the conventional density for the material supplied by the manufacturer. The cross-sectional area shall be calculated from the following equation:

$$A = \frac{2m}{\rho\,\pi(D+d)} \qquad (1)$$

where

- A is the cross-sectional area of the test specimen, in square metres;
- D is the outer diameter of the test specimen, in metres;
- d is the inner diameter of the test specimen, in metres;
- m is the mass of the test specimen, in kilograms;
- ρ is the density of the material, in kilograms per cubic metre.

The dimensions of the test specimen shall be determined by measuring the outside and inside diameters of the ring together with the height or diameter using a suitable micrometer or vernier gauge. The mean cross-sectional area shall be calculated with an uncertainty of ±0,5 % or better.

The mean magnetic path length of the test specimen shall also be calculated with an uncertainty of ±0,5 % or better from the relationship:

$$l = \pi \frac{D + d}{2} \qquad (2)$$

where

l is the mean magnetic path length of test specimen, in metres.

3.5 Windings

Before winding, a connection shall be made to the core in order to check subsequently the insulation of the windings, a temperature sensor shall be attached to the test specimen and then the ring shall be overlaid with a thin layer of insulating material.

Firstly, a secondary winding of insulated copper wire shall be wound evenly round the core. The dimensions of the secondary winding shall be determined and the mean cross-sectional area, A_c, of the secondary winding shall be calculated.

A magnetizing winding of wire capable of carrying the maximum magnetizing current and of a sufficient number of turns to produce the maximum required magnetic field strength shall be evenly wound in one or more layers on the core. The magnetizing winding can consist of:

a) a large number of turns of a single conductor applied closely and uniformly round the whole ring, or

b) a smaller number of turns of a multicore cable applied closely and uniformly round the whole ring, the ends of the conductor in the individual cores being interconnected to give the effect of one multilayer winding, or

c) an arrangement of rigid, or part rigid and part flexible, conductors which can be opened to admit the ring (carrying the secondary winding and insulation) and then closed to form a uniformly wound toroid round the ring.

If necessary, the wound ring is immersed in an oil bath or subjected to an air blast in order to cool it.

NOTE If the above arrangements are used with a uniformly distributed secondary winding, an error, which may be present in any ring test, is liable to be magnified and to become of considerable importance. This error arises because, in winding a ring specimen toroidally, an effective circular turn of diameter equal to the mean diameter of the ring is produced.

The flux between the effective mutually inductive circular turns of the magnetizing winding and secondary winding, associated with flux parallel to the axis of the ring, is added to, or subtracted from the circumferential flux. When a multiconductor cable is used for the magnetizing winding, the number of turns in the primary of the supplementary mutual inductance is increased in proportion to the number of cores, and the error from this source, particularly at high field-strengths where the permeability of the test specimen is reduced, may amount to several per cent. To eliminate this error a turn should be wound back on the secondary winding along the mean circumference of the ring, or, preferably, the magnetizing cable should be wound in pairs of layers, alternate layers being wound clockwise and anti-clockwise around the ring.

3.6 Methods of measurement by the ring method

3.6.1 Magnetic field strength

The magnetizing current shall be measured with an uncertainty of ±0,5 % or better. The magnetic field strength shall be calculated from the following relationship:

$$H = \frac{N_1 I}{l} \quad (3)$$

where

H is the magnetic field strength, in amperes per metre;

N_1 is the number of turns of magnetizing winding of the ring;

l is the mean magnetic path length, in metres;

I is the magnetizing current, in amperes.

3.6.2 Magnetic flux density

The secondary winding N_2 (B coil) shall be connected to a flux integrator (electronic integrator, ballistic galvanometer or fluxmeter) the calibration of which shall be established in accordance with one of the procedures given in annex B with an uncertainty of ±1 % or better.

The changes of the magnetic flux density shall be calculated from the following relationship:

$$\Delta B = \frac{K_b \alpha_b}{N_2 A} \quad (4)$$

where

ΔB is the measured change of the magnetic flux density, in teslas;

K_B is the flux integrator calibration constant, in volts seconds;

α_B is the reading of the flux integrator;

N_2 is the number of turns on the secondary winding of the ring;

A is the cross-sectional area of the ring, in square metres.

For direct reading of the ΔB, the flux integrator may be adjusted so that $K_B/(N_2 A)$ becomes a power of 10.

Provided that the secondary winding is wound closely on the test specimen, the air flux included in the secondary winding over the range of magnetic field strength 0 to 4 kA/m will be insignificant and no correction need be applied. At higher values of magnetic field strength, an air flux correction shall be applied in accordance with equation (8).

3.6.3 Connection of apparatus

The apparatus is connected as shown in figure 1.

A source of direct current E (stabilized d.c. supply with a ripple content of less than 0,1 %, or a battery) is connected through a current-measuring device A and a reversing switch S_1 to the magnetizing winding N_1 on the ring specimen. If a bipolar current source is used, reversing switch S_1 is not required. With switch S_2 closed, the current in the magnetizing circuit is controlled by resistor R_1. If a stabilized supply with a continuously controllable output is used, resistor R_1 is not required. This is the arrangement of the magnetizing circuit for the determination of the normal magnetization curve and for the measurement of the tip points of hysteresis loops. Switch S_2, together with resistor R_2 are necessary in some arrangements for the determination of the complete hysteresis loop. The secondary circuit comprises the secondary winding N_2 (B coil) connected to the flux integrator.

3.6.4 Determination of normal magnetization curve

The test specimen shall be carefully demagnetized from a magnetic field strength of not less than 5 kA/m by the repeated reversals of a gradually reducing demagnetizing field. Test specimens which have been subjected to a higher magnetic field strength shall be demagnetized from a suitably high field before test (for example, when machined using a magnetic chuck).

NOTE In order that the magnetic field may completely penetrate the test specimen, the dwell time after each reversal should be greater than 2 s for a cross-section 10 mm × 10 mm, and 10 s for a cross-section 20 mm × 20 mm.

The flux integrator shall be calibrated by one of the methods described in annex B. With S_2 closed, the normal magnetization curve shall then be determined by one of the following methods.

Method A: continuous recording method

To utilize this method, the output from the flux integrator shall be connected to the Y axis of an X-Y recorder, plotter or computer interface. A low value (e.g. 0,1 Ω or 1 Ω) calibrated resistor with two current and two voltage terminals shall be connected in series with the magnetizing winding. The potential terminals of this resistor shall be connected to the X axis of the recorder, plotter or computer interface. The system can be calibrated overall to give direct readings of magnetic flux density and magnetic field strength on the recorder, plotter or computer interface.

The magnetizing current shall be steadily increased from zero to the value to produce the required maximum magnetic field strength. The magnetization curve is then produced on the X-Y recorder, plotter or computer interface.

Method B: point-by-point method

A low current corresponding to a low magnetic field strength (see equation 3) shall be passed through the magnetizing winding N_1. The current shall be reversed about 10 times by means of reversing switch S_1 to bring the material into a steady cyclic state. Switch S_3 shall be closed during this operation to maintain the flux integrator at zero. With switch S_3 open, the flux integrator reading corresponding to the reversal of the magnetizing field shall be recorded and the corresponding magnetic flux density calculated.

By successively increasing the magnetizing current and repeating this procedure, corresponding values of magnetic field strength and magnetic flux density are obtained from which the normal magnetization curve can be plotted.

The magnetizing current shall never be decreased during the measurements, otherwise the test specimen shall be demagnetized before resuming measurements.

3.6.5 Determination of a complete hysteresis loop

The test specimen shall be demagnetized in accordance with 3.6.4 and the hysteresis loop shall be determined by one of the following methods.

Method A: continuous recording method

The additional equipment specified in method A of 3.6.4 is required. The flux integrator shall be zeroed and then a current of value sufficient to produce the maximum magnetic field strength required shall be passed through the magnetizing winding N_1. This current shall be slowly reduced to zero, reversed, increased to its maximum negative value, reduced to zero, reversed again and increased to its maximum positive value.

NOTE The cycle should be completed in a time between 30 s to 60 s, although some materials, e.g. pure iron, may require longer, in order to allow time for the magnetization of the test specimen to follow the applied magnetic field and yet avoid significant drift of the flux integrator zero with time.

Method B: point-by-point method

The test specimen shall be demagnetized and a current sufficient to produce the maximum magnetic field strength required shall be passed through the magnetizing winding N_1. The tip points of the hysteresis loop shall be determined by measuring the corresponding values of magnetic field strength and magnetic flux density in accordance with method B of 3.6.4.

Portion PQ of the hysteresis loop (see figure 2) is then determined with switch S_1 closed in position 1, by opening switch S_2, and measuring the corresponding magnetic field strength and change in magnetic flux density. By adjusting resistor R_2 a number of points on the curve PQ can be obtained. The point Q is obtained with switch S_2 closed and measuring the change in magnetic flux density when opening switch S_1.

The value of the magnetic field strength at each point is calculated from the corresponding measured value of current flowing (see equation (3)).

The value of the magnetic flux density at each point is calculated from the following relationship:

$$B_{P'} = B_P - \Delta B \tag{5}$$

where

$B_{P'}$ is the flux density at the point P′ of curve PQ, in teslas;

B_P is the magnetic flux density at tip of hysteresis loop, in teslas;

ΔB is the change in magnetic flux density measured when switch S_2 is opened, switch S_1 being closed in position 1, in teslas.

Portion QS of the hysteresis loop is determined, with switch S_2 open, by closing switch S_1. Changes in magnetic field strength and magnetic flux density are measured starting with switch S_1 in the open position and closing it to position 2.

The value of the magnetic field strength at each point is calculated from the measured value of the current flowing when S_1 is closed in position 2 (see equation (3)).

The value of the magnetic flux density at each point is calculated from the following relationship:

$$B_{Q'} = B_Q - \Delta B \qquad (6)$$

where

$B_{Q'}$ is the magnetic flux density at the point Q′ on curve QS, in teslas;

B_Q is the magnetic flux density at the point Q, in teslas;

ΔB is the change in magnetic flux density measured when switch S_1 is closed in position 2 with the switch S_2 open, in teslas.

To obtain the complete hysteresis loop, the switching sequence shall be in accordance with the arrangement given in table 1 to maintain the test specimen in a steady cyclic state.

Table 1 – Switching sequence to maintain the test specimen in a steady cyclic state

	Switch- S_1	**Switch S_2**	**Point on loop**
1	Closed (1)	Closed	P
2	Closed (1)	Open	P′
3	Open	Open	Q
4	Closed (2)	Open	Q′
5	Closed (2)	Closed	S
6	Closed (2)	Open	S′
7	Open	Open	T
8	Closed (1)	Open	T′
9	Closed (1)	Closed	P

Resistors R_1 and R_2 respectively are adjusted to obtain:

– resistor R_1: values of magnetic field strength $+H$ or $-H$, that is point P or point S on the loop (figure 2);

– resistor R_2: values of magnetic field strength $+H'$ or $-H'$, that is points P′ and T′ or points Q′ and S′ on the loop (figure 2).

It is desirable to make measurements on the complete hysteresis loop, to eliminate drift errors in the flux integrator. However, since portion STUP of the loop is symmetrical with portion PQRS, measurements may be made for only one-half of the hysteresis loop.

3.6.6 Determination of remanent flux density

For a given hysteresis loop, the remanent flux density of the material is the value of the magnetic flux density, in teslas, when the magnetic field strength is zero. It shall be determined from the position of point Q on the hysteresis loop or the symmetrical point T.

3.6.7 Determination of coercive field strength

For a given hysteresis loop, the coercive field strength of the material is the value of the magnetic field strength, in amperes per metre, when the magnetic flux density is zero. It shall be determined from point R on the hysteresis loop or the symmetrical point U.

3.7 Uncertainty by the ring method

The total uncertainty in the measurement of the magnetic flux density or the magnetic field strength normally expected is less than or equal to, ±2 % when using measuring instruments