IEC 60404-5

Edition 3.0 2015-04
REDLINE VERSION

# INTERNATIONAL STANDARD

colour inside

## Magnetic materials –
## Part 5: Permanent magnet (magnetically hard) materials – Methods of measurement of magnetic properties



IEC 60404-5:2015-04 RLV(en)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 17.220.20; 29.030

ISBN 978-2-8322-2643-8

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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International Standard IEC 60404-5 has been prepared by IEC technical committee 68: Magnetic alloys and steels.

This third edition cancels and replaces the second edition published in 1993 and Amendment 1:2007. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- adaption of the measurement methods and test conditions to newly introduced magnetically hard materials with coercivity values $H_{cJ}$ higher than 2 MA/m;
- update of the temperature conditions to allow the measurement of new materials with high temperature coefficients.

The text of this standard is based on the following documents:

| FDIS | Report on voting |
|---|---|
| 68/497/FDIS | 68/505/RVD |

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 60404 series, published under the general title *Magnetic materials*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability 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- withdrawn,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.

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# INTRODUCTION

The previous edition of IEC 60404-5 was issued in October 1993 and amended in 2007. Since then, new applications of NdFeB sintered magnetic materials with intrinsic coercivity, $H_{cJ}$, higher than 2 MA/m for hybrid electric vehicles and fully electric vehicles have appeared. Thus, IEC TC68 decided in 2011 at their meeting in Ghent to revise IEC 60404-5.

For the measurement of the coercivity relating to polarization, $H_{cJ}$, at values higher than 2 MA/m and the measurement of magnetic properties at elevated temperatures, the methods described in the non-normative Technical Reports IEC TR 61807 and IEC TR 62331 can be considered.

The ambient temperature previously recommended was (23 ± 5) °C. However, for permanent magnet materials such as NdFeB and hard ferrites that have large temperature coefficients, it is strongly recommended that the ambient temperature should be controlled within this range to ± 1 °C or better. It is desirable to apply this temperature recommendation for other hard magnet materials. This recommendation was already included in IEC 60404-5:1993/AMD1:2007.

# MAGNETIC MATERIALS –

## Part 5: Permanent magnet (magnetically hard) materials – Methods of measurement of magnetic properties

## ~~1 General~~

## 1 Scope

The purpose of this part of IEC 60404 is to define the method of measurement of the magnetic flux density, magnetic polarization and the magnetic field strength and also to determine the demagnetization curve and recoil line of permanent magnet materials, such as those specified in IEC 60404-8-1 [1][1], the properties of which are presumed homogeneous throughout their volume.

The performance of a magnetic system is not only dependent on the properties of the permanent magnet material but also on the dimensions of the system, the air-gap and other elements of the magnetic circuit. The methods described in this part of IEC 60404 refer to the measurement of the magnetic properties in a closed magnetic circuit ~~simulating a ring~~.

## 2 Normative references

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

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at http://www.electropedia.org)

## 3 Terms and Definitions

For the purposes of this document, the terms and definitions given in IEC 60050-121, IEC 60050-151 and IEC 60050-221 apply.

## 4 Electromagnet and conditions for magnetization

### 4.1 General

For permanent magnet materials, this part of IEC 60404 deals with both the coercivity $H_{cB}$ (the coercivity relating to the magnetic flux density) and the intrinsic coercivity $H_{cJ}$ (the coercivity relating to the magnetic polarization).

The measurements specified in this part of IEC 60404 are for both the magnetic flux density, $B$, and the magnetic polarization, $J$, as a function of the magnetic field strength, $H$. These quantities are related by the following equation:

[1] Numbers in square brackets refer to the Bibliography.

$$B = \mu_0 H + J \quad (1)$$

where

$B$ is the magnetic flux density, in teslas;

$\mu_0$ is the magnetic constant = $4\pi \times 10^{-7}$, in henry per metre;

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

$J$ is the magnetic polarization, in teslas.

Using this relationship ~~$H_{cJ}$~~ $H_{cB}$ values can be obtained from the $B(H)$ hysteresis loop and ~~$H_{cB}$~~ $H_{cJ}$ values from the $J(H)$ hysteresis loop. The point represented by $H_a$ and $B_a$ at which the modulus of the product $BH$ has a maximum value is called the ~~working~~ point of maximum energy product for $(BH)_{max}$ (see Figure 1).

The term "squareness" of the demagnetization curve described in this part of IEC 60404 specifies roughly the characteristic shape of the demagnetization curve between the remanent flux density and the coercivity relating to the magnetic polarization in the $J$-$H$ curve.

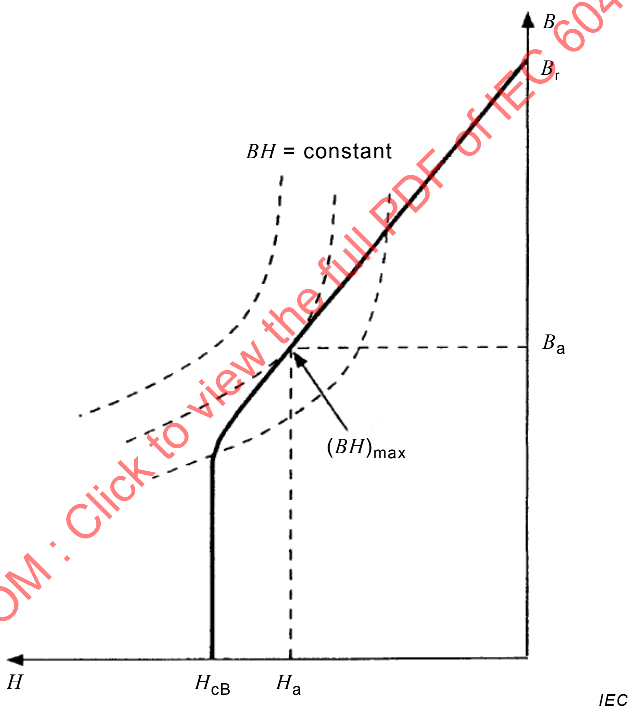



**Figure 1 – Demagnetization curve showing $(BH)_{max}$ point**

The measurements are carried out in a closed magnetic circuit consisting of an electromagnet made of soft magnetic material and the test specimen. The construction of the yokes shall be symmetrical; at least one of the poles shall be movable to minimize the air-gap between the test specimen and the pole pieces (see Figure 2). The end faces of both pole pieces shall be ground as nearly as possible parallel to each other and as nearly as possible perpendicular to the pole axis to minimize the air-gap (see Figure A.1).

NOTE For certain measurements, the yoke and the poles can be laminated to decrease eddy currents. The coercivity of the material ~~should~~ is normally ~~be~~ not more than 100 A/m.

To obtain a sufficiently uniform magnetizing field in the space occupied by the test specimen, the conditions described in 4.2 and 4.3 below shall be fulfilled simultaneously.

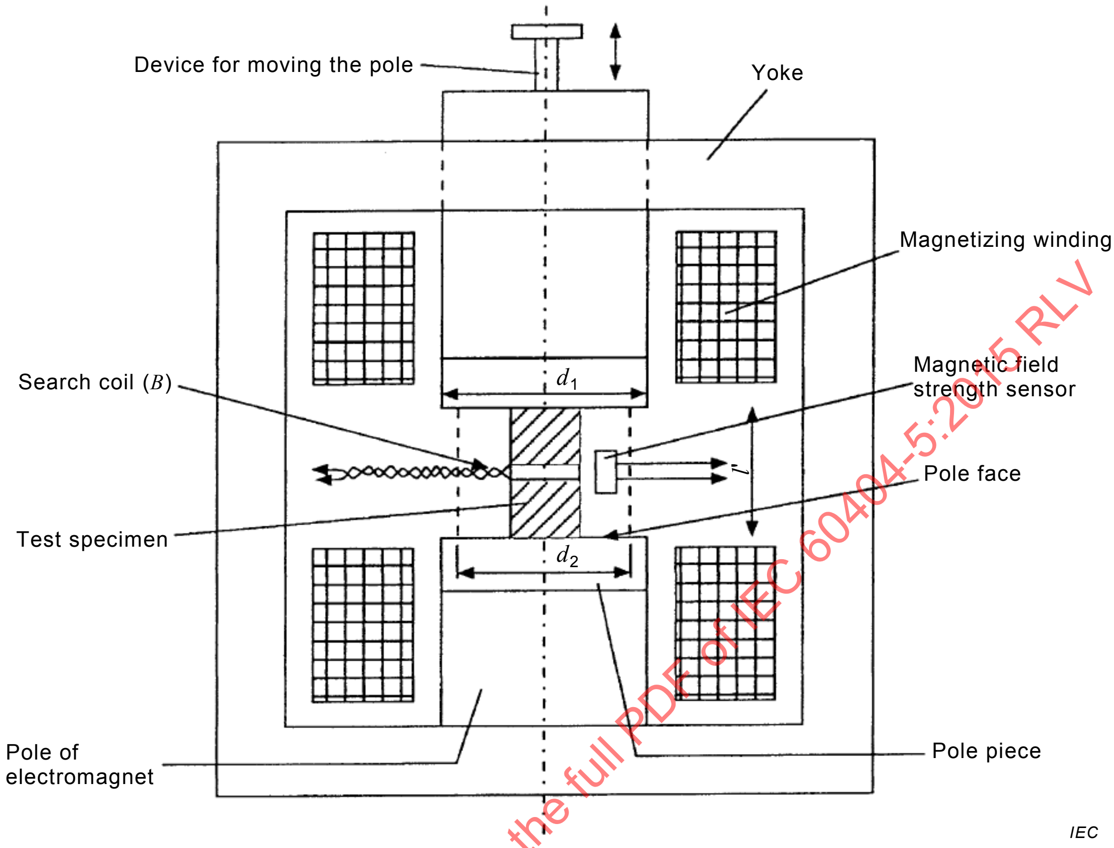



**Figure 1 – Schematic diagram of electromagnet**



### 4.2 Geometrical conditions

Referring to Figure 2;

$$d_1 \geq d_2 + 1{,}2\ l' \tag{2}$$

$$d_1 \geq 2{,}0\ l' \tag{3}$$

where

$d_1$ is the diameter of a circular pole ~~piece~~ or the dimension of the smallest side of a rectangular pole piece, in millimetres;

$l'$ is the distance between the pole pieces, in millimetres;

$d_2$ is the maximum diameter of the cylindrical volume with a homogeneous field, in millimetres.

With reference to the magnetic field strength at the centre of the air-gap, condition (2) ensures that the maximum field decrease at a radial distance of $d_2/2$ is 1 % and condition (3) ensures that the maximum field increase along the axis of the electromagnet at the pole faces is 1 %.

### 4.3 Electromagnetic conditions

During the measurement of the demagnetization curve, the flux density in the pole pieces shall be kept substantially lower than the saturation magnetic polarization so that the pole faces shall be brought as near as possible to an equipotential. In practice, the magnetic flux density shall be less than 1 T in iron and less than 1,2 T in iron alloy containing 35 % to 50 % cobalt.

The yoke is excited by magnetizing coils which are arranged symmetrically as near as possible to the test specimen (see Figure 2). The axis of the test specimen shall be coincident with the axis of the ~~magnetizing coils~~ pole pieces.

Before measurement, the test specimen shall be magnetized in a magnetic field $H_{max}$ intended to bring the test specimen ~~close~~ to saturation ~~(see the following note)~~. The determination of the demagnetization curve shall then be made in a magnetic field ~~in~~ with the direction opposite to that used for the initial magnetization.

If it is not possible to magnetize the test specimen to near saturation within the yoke (for instance if the ~~conditions in the following note~~ requirements of formulae (4) and (5) cannot be met), the test specimen shall be magnetized outside the electromagnet in a superconducting coil or pulse magnetizer.

Recommended values for $H_{max}$ for various permanent magnet materials can be found in IEC TR 62517 [2].

~~NOTE~~ Where the product standard or the manufacturer does not specify the value of the magnetizing field strength, $H_{max}$, it is recommended that before the measurement of the demagnetization curve, the test specimen ~~should be~~ is magnetized to saturation. The test specimen will be considered to be saturated if the following relationships hold for two values of ~~magnetic~~ magnetizing field strength $H_1$ and $H_2$:

$$\cancel{P_2 \leq P_1\, e^{0{,}024\,54 \ln(H_2/H_1)}} \qquad \cancel{(4)}$$

~~or~~

$$\cancel{P_2 \leq P_1\, 10^{0{,}024\,54 \ln(H_2/H_1)}} \qquad \cancel{(5)}$$

$$P_2 \leq P_1 \cdot (H_2/H_1)^{0{,}02454} \qquad (4)$$

and

$$H_2 \geq 1{,}2\, H_1 \qquad (5)$$

where

$P_2$ is the maximum attainable value of $(BH)_{max}$ in joules per cubic metre, or of coercivity $H_{cB}$, in amperes per metre;

$P_1$ is the lower value of $(BH)_{max}$, in joules per cubic metre or of coercivity $H_{cB}$, in amperes per metre;

$H_2$ is the ~~magnetic~~ magnetizing field strength corresponding to $P_2$, in amperes per metre;

$H_1$ is the ~~magnetic~~ magnetizing field strength corresponding to $P_1$, in amperes per metre.

In the special case of $H_2/ H_1$=1,5, relationship (4) becomes $P_2 \leq 1{,}01\, P_1$.

In all cases, the magnetization process shall not cause the test specimen to be heated excessively.

## 5 Test specimen

The test specimen shall have a simple shape (for example a right cylinder or parallelepiped). The length $l$ of the test specimen shall be not less than 5 mm and its other dimensions shall be a minimum of 5 mm and shall be such that the test specimen and the sensing devices shall be within the diameter $d_2$ as defined in 4.2.

NOTE As a consequence of the high $(BH)_{max}$ values exhibited by rare earth permanent magnet materials, the length $l$ in the direction of magnetization can be less than 5 mm. When measuring test specimens with such a length, the homogeneity of the magnetic field between the pole pieces of the electromagnet deteriorates. The effect of this on the measurements was reported by Chen et al. [3]. It can be considered when evaluating the results and, if necessary, a contribution included in the measurement uncertainty. At these thicknesses, the influence of air-gap is also increased. Therefore the air-gap is carefully minimized. Since the magnetic properties of machined surfaces of sintered REFeB have poorer properties, the magnetic properties of specimens that have a thickness of less than 5 mm and/or higher $S/V$ ratio are carefully evaluated (where $S$ is the surface area of the test specimen and $V$ is the volume). In this case, a poor squareness of the demagnetization curves is usually observed.

The end faces of the test specimen shall be made as nearly as possible parallel to each other and perpendicular to the test specimen axis to reduce the air-gap (see Annex A).

The cross-sectional area of the test specimen shall be as uniform as possible along its length; any variation shall be less than 1 % of its minimum cross-sectional area. The mean cross-sectional area shall be determined to within 1 %.

The test specimen shall be marked with the direction of magnetization.

## 6 Determination of the magnetic flux density

The changes in magnetic flux density in the test specimen are determined by integrating the voltages induced in a search coil.

The search coil shall be wound as closely as possible to the test specimen and symmetrical with respect to the pole faces. The leads shall be tightly twisted to avoid errors caused by voltages induced in loops in the leads.

The total error of measuring the magnetic flux density shall be not greater than ± 2 %.

The variation of the apparent magnetic flux density $\Delta B_{ap}$ uncorrected for air flux, between the two instants $t_1$ and $t_2$ is given by:

$$\Delta B_{ap} = B_2 - B_1 = \frac{1}{AN}\int_{t_1}^{t_2} U\mathrm{d}t \qquad (6)$$

where

$B_2$ is the magnetic flux density at the instant $t_2$, in teslas;

$B_1$ is the magnetic flux density at the instant $t_1$, in teslas;

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

$N$ is the number of turns on the search coil;

$\int_{t_1}^{t_2} U\mathrm{d}t$ is the integrated induced voltage, expressed in webers, for the time interval of integration $(t_2 - t_1)$, in seconds.

This change in the apparent magnetic flux density $\Delta B_{ap}$ shall be corrected to take into account the air flux included in the search coil. Thus, the change in magnetic flux density $\Delta B$ in the test specimen is given by:

$$\Delta B = \Delta B_{ap} - \mu_0 \Delta H \frac{(A_t - A)}{A} \qquad (7)$$

where

$\mu_0$ is the magnetic constant = $4\pi \times 10^{-7}$, in henry per metre;

$\Delta H$ is the change in the measured magnetic field strength, in amperes per metre;

$A_t$ is the average cross-sectional area of the search coil, in square metres.

## 7 Determination of the magnetic polarization

The changes in magnetic polarization in the test specimen are determined by integrating the induced voltages at the terminals of a two-search-coil device composed of COIL 1 and COIL 2 where the test specimen is contained in ~~only one of these coils~~ COIL 2, while COIL 1 is empty. If each of the individual coils has the same product of cross-sectional area and the number of turns, and if both are connected electrically in opposition, the output of COIL 1 compensates for the output of COIL 2 except the magnetic polarization $J$ of the test specimen. The change of magnetic polarization $\Delta J$ in the test specimen is given by:

$$\Delta J = J_2 - J_1 = \frac{1}{AN}\int_{t_1}^{t_2} U\mathrm{d}t \qquad (8)$$

where

$J_2$ is the magnetic polarization at the instant $t_2$, in teslas;

$J_1$ is the magnetic polarization at the instant $t_1$, in teslas;

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

$N$ is the number of turns on the search coil;

$\int_{t_1}^{t_2} U\mathrm{d}t$ is the integrated induced voltage, expressed in webers, for the time interval of integration ($t_2 - t_1$), expressed in seconds.

Thus, the output of COIL 1 compensates for the output of COIL 2 except for $J$ within the test specimen.

Because no individual air flux correction is needed, test specimens having a range of cross-sectional areas may be measured with the same two-search-coil device.

The two-search-coil device shall ~~lie~~ be located totally within ~~the homogeneous field defined by conditions (2) and (3)~~ the area limited by the diameter $d_2$. Referring to conditions (2) and (3), this will provide the required field homogeneity.

The integrator and $B$ coil (or $J$ coil) used for the determination of the magnetic flux density (or the magnetic polarization) shall be calibrated using a traceable source of magnetic flux.

The total error of measuring the magnetic polarization shall not be greater than ± 2 %.

## 8 Measurement of the magnetic field strength

The magnetic field strength at the surface of the test specimen is equal to the magnetic field strength inside the test specimen only in that part of the space where the magnetic field strength vector is parallel to the side surface of the test specimen. Therefore, a magnetic field strength sensor is placed in the homogeneous field zone as near as possible to the test specimen and symmetrical with respect to the end faces (see Figure 2).

To determine the magnetic field strength, a flat search coil, a magnetic potentiometer or a Hall probe is used together with suitable instruments. The dimensions of the magnetic field sensor and its location shall be such that it shall be within the area limited by the diameter $d_2$ (see conditions (2) and (3)).

To reduce the measurement error, the air-gap between the test specimen and the pole pieces shall be small. The influence of the air-gap is considered in Annex A.

The magnetic field strength measuring system shall be calibrated. The effective area turns, $NA$ ($N$ is the number of turns and $A$ the effective area), of the flat search coil shall be calibrated. For the magnetic potentiometer the length of the potential coil is also required. The Hall probe shall be calibrated using a suitable method such as NMR (Nuclear Magnetic Resonance).

The total measuring error shall be not greater than ± 2 %.

NOTE The pole faces of ~~the poles of~~ the electromagnet ~~should be~~ are normally magnetically equipotential surfaces (see Clause 4). In some permanent magnet materials with high ~~remanence~~ remanent flux density, high coercivity, or both, magnetic flux densities higher than 1,0 T or 1,2 T can occur. These can then ~~generate unacceptably high~~ cause magnetic ~~flux densities~~ saturation in parts of the pole pieces adjacent to the test specimen. In such cases the pole faces are no longer equipotential surfaces and increased errors can occur.

## 9 Determination of the demagnetization curve

### 9.1 General

The demagnetization curve can be ~~obtained or plotted~~ produced as a $B(H)$ or a $J(H)$ graph. Conversion of an originally obtained $B$-signal into a $J$-signal and vice versa can be performed electrically or numerically by subtracting or adding, respectively, $\mu_0 H$ according to Equation (1).

The determination of $B(H)$ curves is described in 9.2 and 9.3. In the case of $J(H)$ curves, an analogous reasoning holds if the magnetic flux density $B$ is replaced by the magnetic polarization $J$ in the relevant formulae and curves.

The measurements shall be carried out at an ambient temperature of (23 ± 5) °C. For permanent magnet materials that are known to have a significant temperature coefficient $\alpha(H_{cJ})$, a specimen temperature of 19 °C to 27 °C shall be controlled within this range to ± 1 °C or better during the measurements (see Annex B). The temperature of the test specimen shall be measured by a non-magnetic temperature sensor affixed to the pole pieces of the electromagnet. Any temperature dependence of the measuring instruments (e.g. Hall probe) shall be taken into account.

NOTE 1 For measurement of $H_{cJ}$ ≥ 1,6 MA/m, saturation effects in the pole pieces can lead to significant measurement errors.

NOTE 2 Further information about the method (non-normative) of measurements at elevated temperatures is provided in IEC TR 61807 [4].

### 9.2 Principle of determination of the demagnetization curve, test specimen magnetized in the electromagnet

The search coil device to be used for measuring $B$ or $J$ is connected to a calibrated flux integrator which is adjusted to zero. The test specimen is inserted into the search coil and assembled into the electromagnet and magnetized to saturation. The magnetizing current is then reduced to a very low level, zero, or reversed if necessary, to produce zero magnetic field strength. The corresponding value of magnetic flux density or polarization is recorded (see Figure 3).

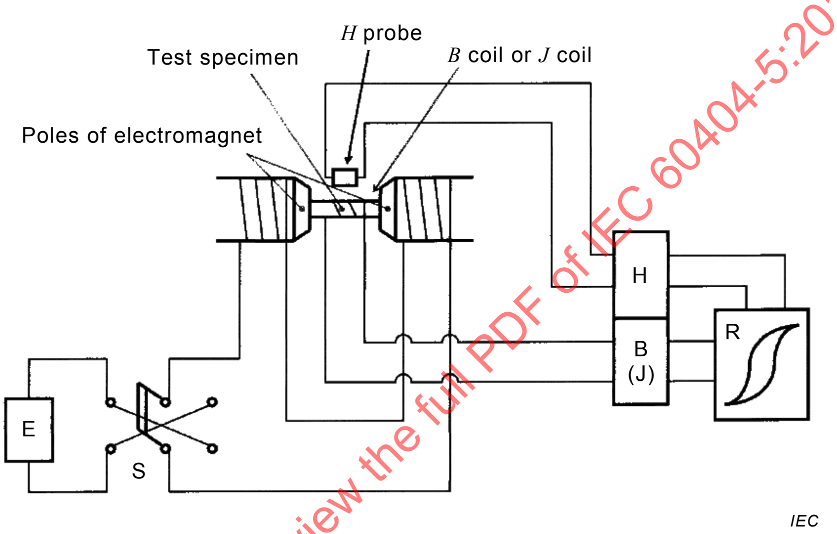
With the current in the reverse direction to that used for magnetization, the current level is slowly increased until the magnetic field strength has passed the coercivity $H_{cB}$ or $H_{cJ}$. ~~The speed of variation of the magnetic field strength shall be sufficiently slow to avoid the~~

~~production of a phase difference between $H$ and $B$ or of eddy currents in the test specimen.~~ With some materials there is a significant delay between the change in the magnetic flux density and the change in magnetic field strength. In this case, the time constant of the flux integrator shall be long enough and the zero drift sufficiently low to ensure accurate integration.

The speed of variation of the magnetic field strength during the reversal of the polarization shall be sufficiently slow to avoid significant magnetic viscosity and eddy current effects.

Corresponding values of $H$ and $B$ or $H$ and $J$ on the demagnetization curve shall be obtained either from a continuous curve produced by a recorder connected to the outputs of the magnetic field strength measurement device and the ~~magnetic~~ flux integrator or from point-by-point measurements of the magnetic field strength and the magnetic flux density or magnetic polarization.






**Key**

H $H$ measuring equipment
B $B$ measuring equipment
J $J$ measuring equipment
R X-Y recording equipment
E power supply to magnetize the specimen
S switching equipment

**Figure 3 – Measuring circuit (schematic)**

### 9.3 Principle of determination of the demagnetization curve, test specimen magnetized in a superconducting coil or pulse magnetizer

The test specimen is magnetized to saturation in either a superconducting coil or by using a pulse magnetizer in accordance with Clause 4. The magnetic field strength required for saturation depends on the magnetization process involved. For more information see IEC TR 62517 [2].

The search coil device to be used for measuring $B$ or $J$ is connected to a calibrated flux integrator which is adjusted to zero. The test specimen is inserted into the search coil and assembled into the electromagnet and magnetized towards saturation in the same direction as previously magnetized in the superconducting coil or pulse magnetizer.

The magnetizing current is then reduced to a very low level, zero or reversed if necessary, to produce zero magnetic field strength. The corresponding value of magnetic flux density or magnetic polarization is recorded.

The current in the electromagnet is then slowly increased further in the reverse direction in accordance with 9.2 until the magnetic field strength has passed the coercivity $H_{cB}$ or $H_{cJ}$.

The magnetic field strength that can be achieved using an electromagnet may not be sufficient to measure very high values of the coercivity relating to the polarization, $H_{cJ}$. In such a case, the measurement can be carried out using other methods such as a superconducting solenoid or a pulsed field magnetometer (for the latter see IEC TR 62331 [5]). Generally, to determine the magnetic properties of permanent magnet materials with a coercivity higher than 2 MA/m, the method described in this standard is used for $B_r$, $H_{cB}$ and $(BH)_{max}$, and a magnetometer that uses a superconducting solenoid or a pulsed field is used for $H_{cJ}$. However, these methods are not normative.

Corresponding values of $H$ and $B$ or $H$ and $J$ on the demagnetization curve shall be obtained in accordance with 9.2.

## 10 Determination of the principal characteristics

### 10.1 ~~Magnetic remanence~~ Remanent flux density

The ~~magnetic remanence~~ remanent flux density is given by the intercept of the demagnetization curve with the $B$ or $J$ axis.

### 10.2 $(BH)_{max}$ product

The $(BH)_{max}$ product is the maximum value of the modulus of the product of corresponding values of $B$ and $H$ for the demagnetization curve.

The following are examples of methods by which it can be determined:

a) evaluation by direct reading or interpolation from a family of curves of $B \times H$ = constant (see Figure 1);
b) calculation of the $B \cdot H$ for a number of points of the demagnetization curve and ensuring that the maximum value has been covered;
c) evaluation by multiplying $B$ and $H$ electronically and plotting the product as a function of $H$ or $B$.

### 10.3 Coercivities $H_{cB}$ and $H_{cJ}$

The coercivity $H_{cB}$ is given by the intercept of the demagnetization curve with the straight line $B = 0$. The coercivity $H_{cJ}$ is given by the intercept of the demagnetization curve with the line $J = 0$.

### 10.4 Determination of the recoil line and the recoil permeability

For the starting point $B_{rec}$, $H_{rec}$ of the recoil line (Figure 4), the test specimen shall be previously magnetized by a magnetic field strength $H_{max}$. Operating in the second quadrant of the hysteresis loop, the ~~demagnetizing~~ demagnetization current is increased to the value corresponding to $H_{rec}$. Then, the magnetic field strength is reduced by a value $\Delta H$ and the corresponding change in magnetic flux density $\Delta B$ is measured. The relative recoil permeability $\mu_{rec}$ is calculated from the equation:

$$\mu_{rec} = \frac{1}{\mu_0} \frac{\Delta B}{\Delta H} \qquad (9)$$

where

$\mu_{rec}$ is the recoil permeability;

$\Delta B$ is the change in magnetic flux density corresponding to the change $\Delta H$, in teslas;

$\Delta H$ is the change in magnetic field strength from $H_{rec}$, in amperes per metre;

$\mu_0$ is the magnetic constant = $4\pi \times 10^{-7}$, in henry per metre.

Since the recoil permeability is not usually constant along the demagnetization curve, the values $H_{rec}$, $B_{rec}$, and $\Delta H$ shall be indicated.

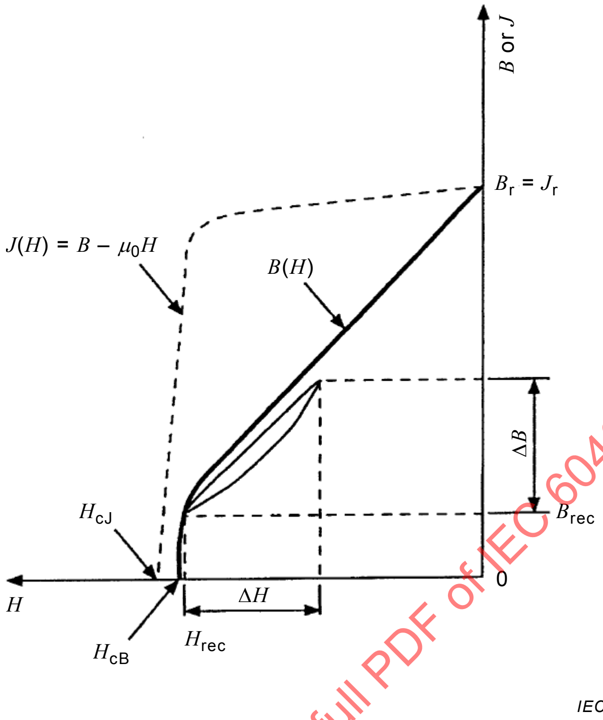





**Figure 2 – Demagnetization curve and recoil loop**

## 11 Reproducibility

The reproducibility of the measurements is characterized by a standard deviation given in the following Table 1.

**Table 1 – Reproducibility of the measurement of the magnetic characteristics of permanent magnet~~ic~~ materials**

| Quantity | AlNiCo | Hard ferrites~~, RE magnet~~, RECo, REFeB |
|---|---|---|
| $B_r$ | 1 % | 2 % |
| $H_{cB}$ | 1 % | 2 % |
| $H_{cJ}$ | 1 % | 2 % |
| $(BH)_{max}$ | 1,5 % | 3 % |

## 12 Test report

The test report shall contain, as applicable:

– type and identification mark of the material;

– shape and dimensions of the test specimen;

~~– type of yoke used (single or double yoke);~~

– temperature of the test specimen during measurement;

– the ambient temperature;

– the value of the magnetizing field strength $H_{max}$;
– demagnetization curve;
– ~~magnetic remanence~~ remanent flux density $B_r$ or $J_r$;
– coercivity $H_{cB}$ and $H_{cJ}$;
– $(BH)_{max}$ product;
– values of $B$ and $H$ for $(BH)_{max}$, that is $B_a$ and $H_a$ (see Figure 1);
– recoil permeability $\mu_{rec}$ and the values $B_{rec}$, $H_{rec}$ and $\Delta H$;
– in the case of anisotropic material: the direction of magnetization with respect to the preferred axis of the material if this angle differs from zero degrees;
– estimated uncertainty of the measurement~~s~~;
– type of $H$, and $B$ or $J$ sensor;
– statement of SI traceability of the measuring system.

# Annex A
(normative)

## Influence of the air-gap between the test specimen and the pole pieces

The relative maximum error of the measurement of the magnetic field strength, $\Delta H/H$, due to the air-gap, can be calculated approximately from the equation:

$$\frac{\Delta H}{H} = \frac{2dB}{\mu_0 lH} \quad \text{(A.1)}$$

where

$B$, $H$ are the values of magnetic flux density (expressed in teslas) and magnetic field strength (expressed in amperes per metre), respectively, at a given point of the demagnetization curve;

$l$ is the length of the test specimen, in metres (Figure A.1);

$d$ is the length of the air-gap between the face of the test specimen and the pole piece, in metres;

$\mu_0$ is the magnetic constant = $4\pi \times 10^{-7}$, in henry per metre.

For example, near the $(BH)_{max}$ point, the error is 1 % for the ~~following~~ $d/l$ ratios given in Table A.1.

**Table A.1 – $d/l$ ratios**

| Material | $d/l$ |
|---|---|
| AlNiCo 37/5 | 0,000 25 |
| Hard ferrite 25/14 | 0,003 |
| RECo ~~120/96~~ 180/150 | 0,005 |
| REFeB 340/130 | 0,005 |

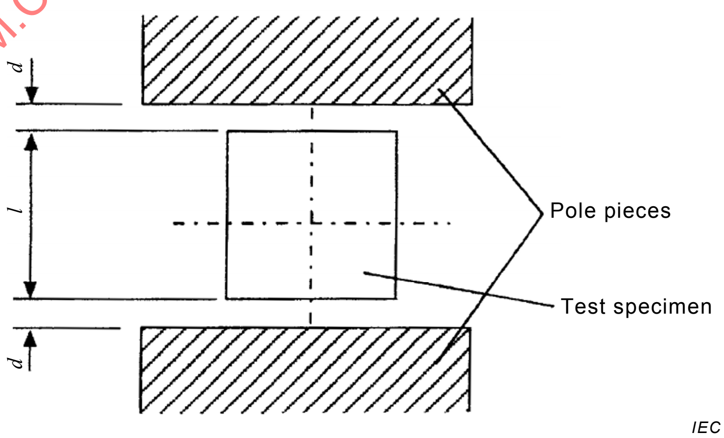



**Figure A.1 – Air-gap**

# Annex B
(informative)

## Influence of the ambient temperature on measurement results

Table B.1 shows the temperature coefficients of $B_r$ and $H_{cJ}$ of various kinds of permanent magnet materials.

**Table B.1– Temperature coefficients of $B_r$ and $H_{cJ}$ of permanent magnet materials**

| Material | $\alpha(B_r)$ %/°C | $\alpha(H_{cJ})$ %/°C |
|---|---|---|
| AlNiCo | −0,02 | −0,07 to +0,03 |
| CrFeCo | −0,05 to −0,03 | −0,04 |
| FeCoVCr | −0,01 | 0 |
| RECo | −0,04 to −0,03 | −0,3 to −0,25 |
| REFeB | −0,12 to −0,09 | −0,6 to −0,45 |
| Hard ferrite | −0,2 | +0,11 to +0,40 |

The ambient temperature recommended in this standard is (23 ± 5) °C. This temperature range is considered to be adequate in the case of AlNiCo, CrFeCo and FeCoVCr permanent magnet materials because the absolute value of temperature coefficient of $H_{cJ}$ of these materials is smaller than 0,1 %/°C.

However, in the case of temperature sensitive magnet materials such as REFeB and hard ferrites, a temperature variation within the range of ± 5 °C may change the measured results significantly. For example, in the case of REFeB 240/200, the difference in the measured $H_{cJ}$ values for a temperature of 18 °C (the lowest temperature in the range) to 28 °C (the highest temperature in the range) is estimated to be 0,1 MA/m assuming a $H_{cJ}$ of 2 MA/m and a temperature coefficient of $H_{cJ}$ of −0,50 %/°C.

When measuring magnet materials that are sensitive to temperature, it is strongly recommended that a test specimen temperature of 19 °C to 27 °C should be controlled within ± 1 °C or better.

# Bibliography

[1] IEC 60404-8-1, *Magnetic materials – Part 8-1: Specifications for individual materials – Magnetically hard materials*

[2] IEC TR 62517, *Magnetizing behaviour of permanent magnets*

[3] CHEN, C.H., et al. Verification by finite element modeling for the origin of the apparent image effect in closed-circuit magnetic measurements. *Journal of Magnetism and Magnetic Materials*. 2011, 323(1), 108-114

[4] IEC TR 61807, *Magnetic properties of magnetically hard materials at elevated temperatures – Methods of measurement*

[5] IEC TR 62331, *Pulsed field magnetometry*

IEC 60404-5

Edition 3.0 2015-04

# INTERNATIONAL STANDARD

# NORME INTERNATIONALE



**Magnetic materials –**
**Part 5: Permanent magnet (magnetically hard) materials – Methods of measurement of magnetic properties**

**Matériaux magnétiques –**
**Partie 5: Aimants permanents (magnétiques durs) – Méthodes de mesure des propriétés magnétiques**

IEC 60404-5:2015-04(en-fr)

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

# MAGNETIC MATERIALS –

## Part 5: Permanent magnet (magnetically hard) materials – Methods of measurement of magnetic properties

## FOREWORD

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International Standard IEC 60404-5 has been prepared by IEC technical committee 68: Magnetic alloys and steels.

This third edition cancels and replaces the second edition published in 1993 and Amendment 1:2007. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- adaption of the measurement methods and test conditions to newly introduced magnetically hard materials with coercivity values $H_{cJ}$ higher than 2 MA/m;
- update of the temperature conditions to allow the measurement of new materials with high temperature coefficients.

The text of this standard is based on the following documents:

| FDIS | Report on voting |
|---|---|
| 68/497/FDIS | 68/505/RVD |

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 60404 series, published under the general title *Magnetic materials*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability 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.

# INTRODUCTION

The previous edition of IEC 60404-5 was issued in October 1993 and amended in 2007. Since then, new applications of NdFeB sintered magnetic materials with intrinsic coercivity, $H_{cJ}$, higher than 2 MA/m for hybrid electric vehicles and fully electric vehicles have appeared. Thus, IEC TC68 decided in 2011 at their meeting in Ghent to revise IEC 60404-5.

For the measurement of the coercivity relating to polarization, $H_{cJ}$, at values higher than 2 MA/m and the measurement of magnetic properties at elevated temperatures, the methods described in the non-normative Technical Reports IEC TR 61807 and IEC TR 62331 can be considered.

The ambient temperature previously recommended was (23 ± 5) °C. However, for permanent magnet materials such as NdFeB and hard ferrites that have large temperature coefficients, it is strongly recommended that the ambient temperature should be controlled within this range to ± 1 °C or better. It is desirable to apply this temperature recommendation for other hard magnet materials. This recommendation was already included in IEC 60404-5:1993/AMD1:2007.

# MAGNETIC MATERIALS –

## Part 5: Permanent magnet (magnetically hard) materials – Methods of measurement of magnetic properties

## 1 Scope

The purpose of this part of IEC 60404 is to define the method of measurement of the magnetic flux density, magnetic polarization and the magnetic field strength and also to determine the demagnetization curve and recoil line of permanent magnet materials, such as those specified in IEC 60404-8-1 [1][1], the properties of which are presumed homogeneous throughout their volume.

The performance of a magnetic system is not only dependent on the properties of the permanent magnet material but also on the dimensions of the system, the air-gap and other elements of the magnetic circuit. The methods described in this part of IEC 60404 refer to the measurement of the magnetic properties in a closed magnetic circuit.

## 2 Normative references

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

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at http://www.electropedia.org)

## 3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-121, IEC 60050-151 and IEC 60050-221 apply.

## 4 Electromagnet and conditions for magnetization

### 4.1 General

For permanent magnet materials, this part of IEC 60404 deals with both the coercivity $H_{cB}$ (the coercivity relating to the magnetic flux density) and the intrinsic coercivity $H_{cJ}$ (the coercivity relating to the magnetic polarization).

The measurements specified in this part of IEC 60404 are for both the magnetic flux density, $B$, and the magnetic polarization, $J$, as a function of the magnetic field strength, $H$. These quantities are related by the following equation:

$$B = \mu_0 H + J \qquad (1)$$

[1] Numbers in square brackets refer to the Bibliography.

where

$B$ is the magnetic flux density, in teslas;

$\mu_0$ is the magnetic constant = $4\pi \times 10^{-7}$, in henry per metre;

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

$J$ is the magnetic polarization, in teslas.

Using this relationship $H_{cB}$ values can be obtained from the $B(H)$ hysteresis loop and $H_{cJ}$ values from the $J(H)$ hysteresis loop. The point represented by $H_a$ and $B_a$ at which the modulus of the product $BH$ has a maximum value is called the point of maximum energy product for $(BH)_{max}$ (see Figure 1).

The term "squareness" of the demagnetization curve described in this part of IEC 60404 specifies roughly the characteristic shape of the demagnetization curve between the remanent flux density and the coercivity relating to the magnetic polarization in the $J$–$H$ curve.

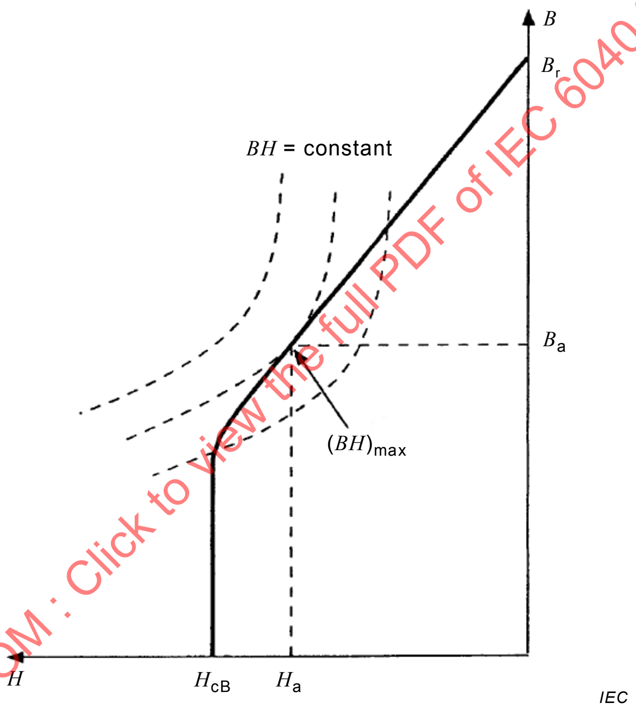



**Figure 1 – Demagnetization curve showing $(BH)_{max}$ point**

The measurements are carried out in a closed magnetic circuit consisting of an electromagnet made of soft magnetic material and the test specimen. The construction of the yokes shall be symmetrical; at least one of the poles shall be movable to minimize the air-gap between the test specimen and the pole pieces (see Figure 2). The end faces of both pole pieces shall be ground as nearly as possible parallel to each other and as nearly as possible perpendicular to the pole axis to minimize the air-gap (see Figure A.1).

NOTE For certain measurements, the yoke and the poles can be laminated to decrease eddy currents. The coercivity of the material is normally not more than 100 A/m.

To obtain a sufficiently uniform magnetizing field in the space occupied by the test specimen, the conditions described in 4.2 and 4.3 below shall be fulfilled simultaneously.

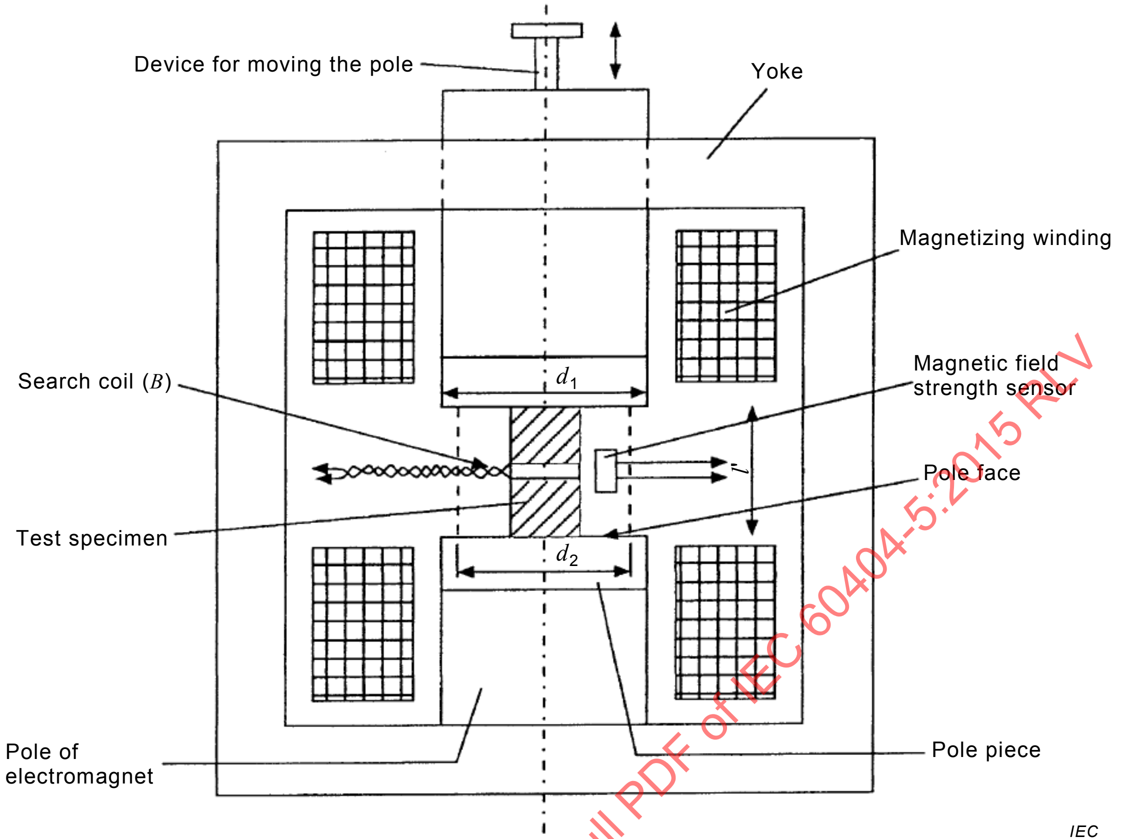



**Figure 2 – Schematic diagram of electromagnet**



## 4.2 Geometrical conditions

Referring to Figure 2;

$$d_1 \geq d_2 + 1{,}2\, l' \tag{2}$$

$$d_1 \geq 2{,}0\, l' \tag{3}$$

where

$d_1$ is the diameter of a circular pole or the dimension of the smallest side of a rectangular pole piece, in millimetres;

$l'$ is the distance between the pole pieces, in millimetres;

$d_2$ is the maximum diameter of the cylindrical volume with a homogeneous field, in millimetres.

With reference to the magnetic field strength at the centre of the air-gap, condition (2) ensures that the maximum field decrease at a radial distance of $d_2/2$ is 1 % and condition (3) ensures that the maximum field increase along the axis of the electromagnet at the pole faces is 1 %.

## 4.3 Electromagnetic conditions

During the measurement of the demagnetization curve, the flux density in the pole pieces shall be kept substantially lower than the saturation magnetic polarization so that the pole faces shall be brought as near as possible to an equipotential. In practice, the magnetic flux density shall be less than 1 T in iron and less than 1,2 T in iron alloy containing 35 % to 50 % cobalt.

The yoke is excited by magnetizing coils which are arranged symmetrically as near as possible to the test specimen (see Figure 2). The axis of the test specimen shall be coincident with the axis of the pole pieces.

Before measurement, the test specimen shall be magnetized in a magnetic field $H_{max}$ intended to bring the test specimen to saturation. The determination of the demagnetization curve shall then be made in a magnetic field with the direction opposite to that used for the initial magnetization.

If it is not possible to magnetize the test specimen to near saturation within the yoke (for instance if the requirements of formulae (4) and (5) cannot be met), the test specimen shall be magnetized outside the electromagnet in a superconducting coil or pulse magnetizer.

Recommended values for $H_{max}$ for various permanent magnet materials can be found in IEC TR 62517 [2].

Where the product standard or the manufacturer does not specify the value of the magnetizing field strength, $H_{max}$, it is recommended that before the measurement of the demagnetization curve, the test specimen is magnetized to saturation. The test specimen will be considered to be saturated if the following relationships hold for two values of magnetizing field strength $H_1$ and $H_2$:

$$P_2 \leq P_1 \cdot (H_2/H_1)^{0,02454} \tag{4}$$

and

$$H_2 \geq 1,2\ H_1 \tag{5}$$

where

$P_2$ is the maximum attainable value of $(BH)_{max}$ in joules per cubic metre, or of coercivity $H_{cB}$, in amperes per metre;

$P_1$ is the lower value of $(BH)_{max}$, in joules per cubic metre or of coercivity $H_{cB}$, in amperes per metre;

$H_2$ is the magnetizing field strength corresponding to $P_2$, in amperes per metre;

$H_1$ is the magnetizing field strength corresponding to $P_1$, in amperes per metre.

In the special case of $H_2/H_1$=1,5, relationship (4) becomes $P_2 \leq 1,01\ P_1$.

In all cases, the magnetization process shall not cause the test specimen to be heated excessively.

## 5 Test specimen

The test specimen shall have a simple shape (for example a right cylinder or parallelepiped). The length $l$ of the test specimen shall be not less than 5 mm and its other dimensions shall be a minimum of 5 mm and shall be such that the test specimen and the sensing devices shall be within the diameter $d_2$ as defined in 4.2.

NOTE As a consequence of the high $(BH)_{max}$ values exhibited by rare earth permanent magnet materials, the length $l$ in the direction of magnetization can be less than 5 mm. When measuring test specimens with such a length, the homogeneity of the magnetic field between the pole pieces of the electromagnet deteriorates. The effect of this on the measurements was reported by Chen et al. [3]. It can be considered when evaluating the results and, if necessary, a contribution included in the measurement uncertainty. At these thicknesses, the influence of air-gap is also increased. Therefore the air-gap is carefully minimized. Since the magnetic properties of machined surfaces of sintered REFeB have poorer properties, the magnetic properties of specimens that have a thickness of less than 5 mm and/or higher $S/V$ ratio are carefully evaluated (where $S$ is the surface area of the test specimen and $V$ is the volume). In this case, a poor squareness of the demagnetization curves is usually observed.

The end faces of the test specimen shall be made as nearly as possible parallel to each other and perpendicular to the test specimen axis to reduce the air-gap (see Annex A).

The cross-sectional area of the test specimen shall be as uniform as possible along its length; any variation shall be less than 1 % of its minimum cross-sectional area. The mean cross-sectional area shall be determined to within 1 %.

The test specimen shall be marked with the direction of magnetization.

## 6 Determination of the magnetic flux density

The changes in magnetic flux density in the test specimen are determined by integrating the voltages induced in a search coil.

The search coil shall be wound as closely as possible to the test specimen and symmetrical with respect to the pole faces. The leads shall be tightly twisted to avoid errors caused by voltages induced in loops in the leads.

The total error of measuring the magnetic flux density shall be not greater than ± 2 %.

The variation of the apparent magnetic flux density $\Delta B_{ap}$ uncorrected for air flux, between the two instants $t_1$ and $t_2$ is given by:

$$\Delta B_{ap} = B_2 - B_1 = \frac{1}{AN} \int_{t_1}^{t_2} U \mathrm{d}t \tag{6}$$

where

$B_2$ is the magnetic flux density at the instant $t_2$, in teslas;

$B_1$ is the magnetic flux density at the instant $t_1$, in teslas;

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

$N$ is the number of turns on the search coil;

$\int_{t_1}^{t_2} U \mathrm{d}t$ is the integrated induced voltage, expressed in webers, for the time interval of integration $(t_2 - t_1)$, in seconds.

This change in the apparent magnetic flux density $\Delta B_{ap}$ shall be corrected to take into account the air flux included in the search coil. Thus, the change in magnetic flux density $\Delta B$ in the test specimen is given by:

$$\Delta B = \Delta B_{ap} - \mu_0 \Delta H \frac{(A_t - A)}{A} \tag{7}$$

where

$\mu_0$ is the magnetic constant = $4\pi \times 10^{-7}$, in henry per metre;

$\Delta H$ is the change in the measured magnetic field strength, in amperes per metre;

$A_t$ is the average cross-sectional area of the search coil, in square metres.

## 7 Determination of the magnetic polarization

The changes in magnetic polarization in the test specimen are determined by integrating the induced voltages at the terminals of a two-search-coil device composed of COIL 1 and COIL 2 where the test specimen is contained in COIL 2, while COIL 1 is empty. If each of the individual coils has the same product of cross-sectional area and the number of turns, and if both are connected electrically in opposition, the output of COIL 1 compensates for the output of COIL 2 except the magnetic polarization $J$ of the test specimen. The change of magnetic polarization $\Delta J$ in the test specimen is given by:

$$\Delta J = J_2 - J_1 = \frac{1}{AN}\int_{t_1}^{t_2} U\mathrm{d}t \tag{8}$$

where

$J_2$ is the magnetic polarization at the instant $t_2$, in teslas;

$J_1$ is the magnetic polarization at the instant $t_1$, in teslas;

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

$N$ is the number of turns on the search coil;

$\int_{t_1}^{t_2} U\mathrm{d}t$ is the integrated induced voltage, expressed in webers, for the time interval of integration $(t_2 - t_1)$, expressed in seconds.

Thus, the output of COIL 1 compensates for the output of COIL 2 except for $J$ within the test specimen.

Because no individual air flux correction is needed, test specimens having a range of cross-sectional areas may be measured with the same two-search-coil device.

The two-search-coil device shall be located totally within the area limited by the diameter $d_2$. Referring to conditions (2) and (3), this will provide the required field homogeneity.

The integrator and $B$ coil (or $J$ coil) used for the determination of the magnetic flux density (or the magnetic polarization) shall be calibrated using a traceable source of magnetic flux.

The total error of measuring the magnetic polarization shall not be greater than ± 2 %.

## 8 Measurement of the magnetic field strength

The magnetic field strength at the surface of the test specimen is equal to the magnetic field strength inside the test specimen only in that part of the space where the magnetic field strength vector is parallel to the side surface of the test specimen. Therefore, a magnetic field strength sensor is placed in the homogeneous field zone as near as possible to the test specimen and symmetrical with respect to the end faces (see Figure 2).

To determine the magnetic field strength, a flat search coil, a magnetic potentiometer or a Hall probe is used together with suitable instruments. The dimensions of the magnetic field sensor and its location shall be such that it shall be within the area limited by the diameter $d_2$ (see conditions (2) and (3)).

To reduce the measurement error, the air-gap between the test specimen and the pole pieces shall be small. The influence of the air-gap is considered in Annex A.

The magnetic field strength measuring system shall be calibrated. The effective area turns, $NA$ ($N$ is the number of turns and $A$ the effective area), of the flat search coil shall be calibrated. For the magnetic potentiometer the length of the potential coil is also required. The Hall probe shall be calibrated using a suitable method such as NMR (Nuclear Magnetic Resonance).

The total measuring error shall be not greater than ± 2 %.

NOTE The pole faces of the electromagnet are normally magnetically equipotential surfaces (see Clause 4). In some permanent magnet materials with high remanent flux density, high coercivity, or both, magnetic flux densities higher than 1,0 T or 1,2 T can occur. These can then cause magnetic saturation in parts of the pole pieces adjacent to the test specimen. In such cases the pole faces are no longer equipotential surfaces and increased errors can occur.

# 9 Determination of the demagnetization curve

## 9.1 General

The demagnetization curve can be produced as a $B(H)$ or a $J(H)$ graph. Conversion of an originally obtained $B$-signal into a $J$-signal and vice versa can be performed electrically or numerically by subtracting or adding, respectively, $\mu_0 H$ according to Equation (1).

The determination of $B(H)$ curves is described in 9.2 and 9.3. In the case of $J(H)$ curves, an analogous reasoning holds if the magnetic flux density $B$ is replaced by the magnetic polarization $J$ in the relevant formulae and curves.

The measurements shall be carried out at an ambient temperature of (23 ± 5) °C. For permanent magnet materials that are known to have a significant temperature coefficient $\alpha(H_{cJ})$, a specimen temperature of 19 °C to 27 °C shall be controlled within this range to ± 1 °C or better during the measurements (see Annex B). The temperature of the test specimen shall be measured by a non-magnetic temperature sensor affixed to the pole pieces of the electromagnet. Any temperature dependence of the measuring instruments (e.g. Hall probe) shall be taken into account.

NOTE 1 For measurement of $H_{cJ} \geq 1,6$ MA/m, saturation effects in the pole pieces can lead to significant measurement errors.

NOTE 2 Further information about the method (non-normative) of measurements at elevated temperatures is provided in IEC TR 61807 [4].

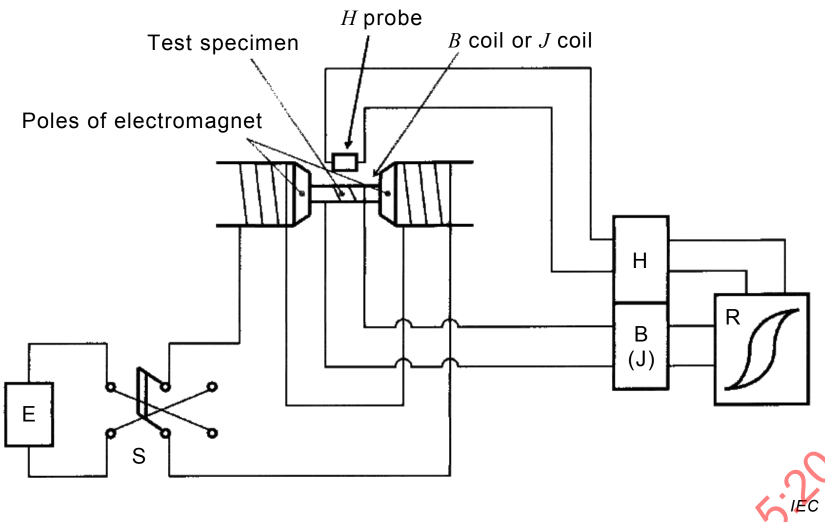
## 9.2 Principle of determination of the demagnetization curve, test specimen magnetized in the electromagnet

The search coil device to be used for measuring $B$ or $J$ is connected to a calibrated flux integrator which is adjusted to zero. The test specimen is inserted into the search coil and assembled into the electromagnet and magnetized to saturation. The magnetizing current is then reduced to a very low level, zero, or reversed if necessary, to produce zero magnetic field strength. The corresponding value of magnetic flux density or polarization is recorded (see Figure 3).

With the current in the reverse direction to that used for magnetization, the current level is slowly increased until the magnetic field strength has passed the coercivity $H_{cB}$ or $H_{cJ}$. With some materials there is a significant delay between the change in the magnetic flux density and the change in magnetic field strength. In this case, the time constant of the flux integrator shall be long enough and the zero drift sufficiently low to ensure accurate integration.

The speed of variation of the magnetic field strength during the reversal of the polarization shall be sufficiently slow to avoid significant magnetic viscosity and eddy current effects.

Corresponding values of $H$ and $B$ or $H$ and $J$ on the demagnetization curve shall be obtained either from a continuous curve produced by a recorder connected to the outputs of the magnetic field strength measurement device and the flux integrator or from point-by-point measurements of the magnetic field strength and the magnetic flux density or magnetic polarization.




**Key**

| | | | |
|---|---|---|---|
| H | $H$ measuring equipment | E | power supply to magnetize the specimen |
| B | $B$ measuring equipment | S | switching equipment |
| J | $J$ measuring equipment | | |
| R | X-Y recording equipment | | |

**Figure 3 – Measuring circuit (schematic)**



### 9.3 Principle of determination of the demagnetization curve, test specimen magnetized in a superconducting coil or pulse magnetizer

The test specimen is magnetized to saturation in either a superconducting coil or by using a pulse magnetizer in accordance with Clause 4. The magnetic field strength required for saturation depends on the magnetization process involved. For more information see IEC TR 62517 [2].

The search coil device to be used for measuring $B$ or $J$ is connected to a calibrated flux integrator which is adjusted to zero. The test specimen is inserted into the search coil and assembled into the electromagnet and magnetized towards saturation in the same direction as previously magnetized in the superconducting coil or pulse magnetizer.

The magnetizing current is then reduced to a very low level, zero or reversed if necessary, to produce zero magnetic field strength. The corresponding value of magnetic flux density or magnetic polarization is recorded.

The current in the electromagnet is then slowly increased further in the reverse direction in accordance with 9.2 until the magnetic field strength has passed the coercivity $H_{cB}$ or $H_{cJ}$.

The magnetic field strength that can be achieved using an electromagnet may not be sufficient to measure very high values of the coercivity relating to the polarization, $H_{cJ}$. In such a case, the measurement can be carried out using other methods such as a superconducting solenoid or a pulsed field magnetometer (for the latter see IEC TR 62331 [5]). Generally, to determine the magnetic properties of permanent magnet materials with a coercivity higher than 2 MA/m, the method described in this standard is used for $B_r$, $H_{cB}$ and $(BH)_{max}$, and a magnetometer that uses a superconducting solenoid or a pulsed field is used for $H_{cJ}$. However, these methods are not normative.

Corresponding values of $H$ and $B$ or $H$ and $J$ on the demagnetization curve shall be obtained in accordance with 9.2.

## 10 Determination of the principal characteristics

### 10.1 Remanent flux density

The remanent flux density is given by the intercept of the demagnetization curve with the $B$ or $J$ axis.

### 10.2 $(BH)_{max}$ product

The $(BH)_{max}$ product is the maximum value of the modulus of the product of corresponding values of $B$ and $H$ for the demagnetization curve.

The following are examples of methods by which it can be determined:

a) evaluation by direct reading or interpolation from a family of curves of $B \times H$ = constant (see Figure 1);

b) calculation of the $B \cdot H$ for a number of points of the demagnetization curve and ensuring that the maximum value has been covered;

c) evaluation by multiplying $B$ and $H$ electronically and plotting the product as a function of $H$ or $B$.

### 10.3 Coercivities $H_{cB}$ and $H_{cJ}$

The coercivity $H_{cB}$ is given by the intercept of the demagnetization curve with the straight line $B = 0$. The coercivity $H_{cJ}$ is given by the intercept of the demagnetization curve with the line $J = 0$.

### 10.4 Determination of the recoil line and the recoil permeability

For the starting point $B_{rec}$, $H_{rec}$ of the recoil line (Figure 4), the test specimen shall be previously magnetized by a magnetic field strength $H_{max}$. Operating in the second quadrant of the hysteresis loop, the demagnetization current is increased to the value corresponding to $H_{rec}$. Then, the magnetic field strength is reduced by a value $\Delta H$ and the corresponding change in magnetic flux density $\Delta B$ is measured. The relative recoil permeability $\mu_{rec}$ is calculated from the equation:

$$\mu_{rec} = \frac{1}{\mu_0} \frac{\Delta B}{\Delta H} \tag{9}$$

where

$\mu_{rec}$ is the recoil permeability;

$\Delta B$ is the change in magnetic flux density corresponding to the change $\Delta H$, in teslas;

$\Delta H$ is the change in magnetic field strength from $H_{rec}$, in amperes per metre;

$\mu_0$ is the magnetic constant = $4\pi \times 10^{-7}$, in henry per metre.

Since the recoil permeability is not usually constant along the demagnetization curve, the values $H_{rec}$, $B_{rec}$, and $\Delta H$ shall be indicated.

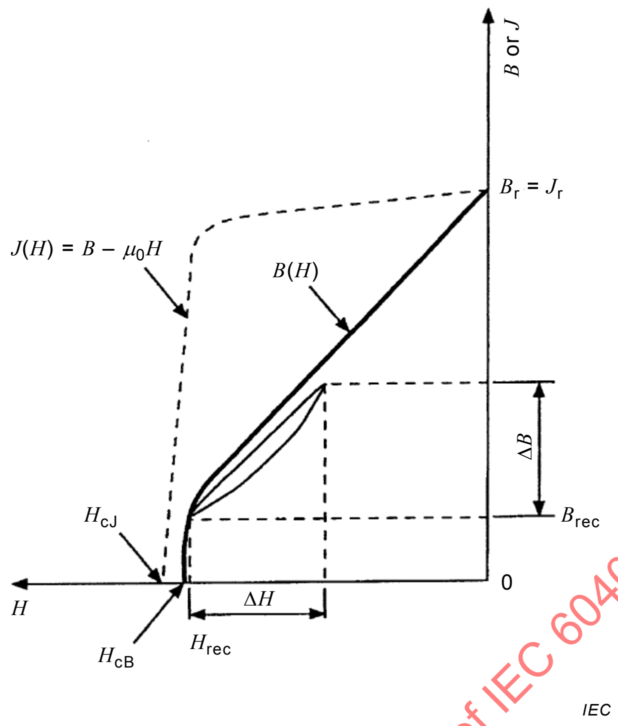



**Figure 4 – Demagnetization curve and recoil loop**



## 11 Reproducibility

The reproducibility of the measurements is characterized by a standard deviation given in the following Table 1.

**Table 1 – Reproducibility of the measurement of the magnetic characteristics of permanent magnet materials**

| Quantity | AlNiCo | Hard ferrites, RECo, REFeB |
|---|---|---|
| $B_r$ | 1 % | 2 % |
| $H_{cB}$ | 1 % | 2 % |
| $H_{cJ}$ | 1 % | 2 % |
| $(BH)_{max}$ | 1,5 % | 3 % |

## 12 Test report

The test report shall contain, as applicable:

– type and identification mark of the material;
– shape and dimensions of the test specimen;
– temperature of the test specimen during measurement;
– the ambient temperature;
– the value of the magnetizing field strength $H_{max}$;
– demagnetization curve;
– remanent flux density $B_r$ or $J_r$;
– coercivity $H_{cB}$ and $H_{cJ}$;

– $(BH)_{max}$ product;
– values of $B$ and $H$ for $(BH)_{max}$, that is $B_a$ and $H_a$ (see Figure 1);
– recoil permeability $\mu_{rec}$ and the values $B_{rec}$, $H_{rec}$ and $\Delta H$;
– in the case of anisotropic material: the direction of magnetization with respect to the preferred axis of the material if this angle differs from zero degrees;
– estimated uncertainty of the measurement;
– type of $H$, and $B$ or $J$ sensor;
– statement of SI traceability of the measuring system.

# Annex A
(normative)

## Influence of the air-gap between the test specimen and the pole pieces

The relative maximum error of the measurement of the magnetic field strength, $\Delta H/H$, due to the air-gap, can be calculated approximately from the equation:

$$\frac{\Delta H}{H} = \frac{2dB}{\mu_0 lH} \quad \text{(A.1)}$$

where

$B$, $H$ are the values of magnetic flux density (expressed in teslas) and magnetic field strength (expressed in amperes per metre), respectively, at a given point of the demagnetization curve;

$l$ is the length of the test specimen, in metres (Figure A.1);

$d$ is the length of the air-gap between the face of the test specimen and the pole piece, in metres;

$\mu_0$ is the magnetic constant = $4\pi \times 10^{-7}$, in henry per metre.

For example, near the $(BH)_{max}$ point, the error is 1 % for the $d/l$ ratios given in Table A.1.

**Table A.1 – $d/l$ ratios**

| Material | $d/l$ |
|---|---|
| AlNiCo 37/5 | 0,000 25 |
| Hard ferrite 25/14 | 0,003 |
| RECo 180/150 | 0,005 |
| REFeB 340/130 | 0,005 |

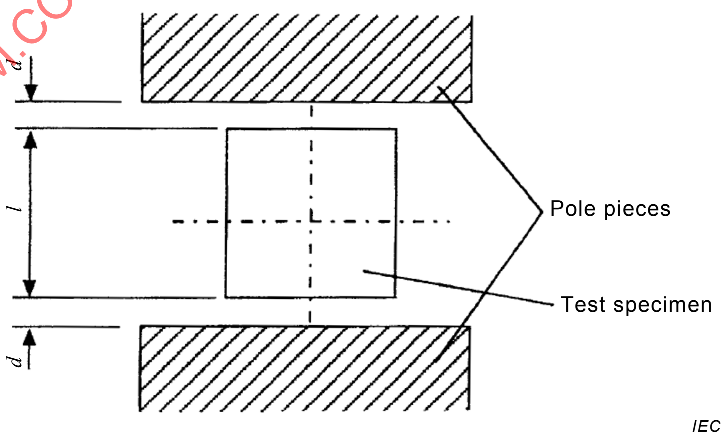



**Figure A.1 – Air-gap**

# Annex B
(informative)

## Influence of the ambient temperature on measurement results

Table B.1 shows the temperature coefficients of $B_r$ and $H_{cJ}$ of various kinds of permanent magnet materials.

**Table B.1 – Temperature coefficients of $B_r$ and $H_{cJ}$ of permanent magnet materials**

| Material | $\alpha(B_r)$ %/°C | $\alpha(H_{cJ})$ %/°C |
|---|---|---|
| AlNiCo | −0,02 | −0,07 to +0,03 |
| CrFeCo | −0,05 to −0,03 | −0,04 |
| FeCoVCr | −0,01 | 0 |
| RECo | −0,04 to −0,03 | −0,3 to −0,25 |
| REFeB | −0,12 to −0,09 | −0,6 to −0,45 |
| Hard ferrite | −0,2 | +0,11 to +0,40 |

The ambient temperature recommended in this standard is (23 ± 5) °C. This temperature range is considered to be adequate in the case of AlNiCo, CrFeCo and FeCoVCr permanent magnet materials because the absolute value of temperature coefficient of $H_{cJ}$ of these materials is smaller than 0,1 %/°C.

However, in the case of temperature sensitive magnet materials such as REFeB and hard ferrites, a temperature variation within the range of ± 5 °C may change the measured results significantly. For example, in the case of REFeB 240/200, the difference in the measured $H_{cJ}$ values for a temperature of 18 °C (the lowest temperature in the range) to 28 °C (the highest temperature in the range) is estimated to be 0,1 MA/m assuming a $H_{cJ}$ of 2 MA/m and a temperature coefficient of $H_{cJ}$ of −0,50 %/°C.

When measuring magnet materials that are sensitive to temperature, it is strongly recommended that a test specimen temperature of 19 °C to 27 °C should be controlled within ± 1 °C or better.

# Bibliography

[1] IEC 60404-8-1, *Magnetic materials – Part 8-1: Specifications for individual materials – Magnetically hard materials*

[2] IEC TR 62517, *Magnetizing behaviour of permanent magnets*

[3] CHEN, C.H., et al. Verification by finite element modeling for the origin of the apparent image effect in closed-circuit magnetic measurements. *Journal of Magnetism and Magnetic Materials*. 2011, 323(1), 108-114

[4] IEC TR 61807, *Magnetic properties of magnetically hard materials at elevated temperatures – Methods of measurement*

[5] IEC TR 62331, *Pulsed field magnetometry*

SOMMAIRE

COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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# MATÉRIAUX MAGNÉTIQUES –

## Partie 5: Aimants permanents (magnétiques durs) – Méthodes de mesure des propriétés magnétiques

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La Norme internationale IEC 60404-5 a été établie par le comité d'études 68 de l'IEC: Matériaux magnétiques tels qu'alliages et aciers.

Cette troisième édition annule et remplace la deuxième édition parue en 1993 et l'Amendement 1:2007. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

- adaptation des méthodes de mesure et des conditions d'essai aux matériaux magnétiquement durs récemment introduits possédant un champ coercitif $H_{cJ}$ supérieur à 2 MA/m;

- mise à jour des conditions de température, afin de permettre la mesure de nouveaux matériaux avec des coefficients de température élevés.

Le texte de cette norme est issu des documents suivants:

| FDIS | Rapport de vote |
|---|---|
| 68/497/FDIS | 68/505/RVD |

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à l'approbation de cette norme.

Cette publication a été rédigée selon les Directives ISO/IEC, Partie 2.

Une liste de toutes les parties de la série IEC 60404, publiées sous le titre général *Matériaux magnétiques,* peut être consultée sur le site web de l'IEC.

Le comité a décidé que le contenu de cette publication ne sera pas modifié avant la date de stabilité indiquée sur le site web de l'IEC sous "http://webstore.iec.ch" dans les données relatives à la publication recherchée. A cette date, la publication sera

- reconduite,
- supprimée,
- remplacée par une édition révisée, ou
- amendée.

# INTRODUCTION

L'édition précédente de l'IEC 60404-5 a été publiée en octobre 1993 et modifiée en 2007. Depuis, de nouvelles applications des matériaux magnétiques au NdFeB fritté présentant un champ coercitif intrinsèque, $H_{cJ}$, supérieur à 2 MA/m destinés aux véhicules électriques hybrides et aux véhicules entièrement électriques sont apparues. Ainsi, lors de la réunion de Gand en 2011, le CE 68 de l'IEC a décidé de réviser l'IEC 60404-5.

Pour la mesure du champ coercitif se rapportant à la polarisation, $H_{cJ}$, de valeur supérieure à 2 MA/m et pour la mesure des propriétés magnétiques à des températures élevées, on peut utiliser les méthodes décrites dans les rapports techniques non normatifs IEC TR 61807 et IEC TR 62331.

Auparavant, la température ambiante recommandée était (23 ± 5) °C. Toutefois, pour les matériaux pour aimants permanents tels que le NdFeB et les ferrites dures de coefficients de température élevés, il est fortement recommandé que la température ambiante soit contrôlée dans les limites de cette plage avec une précision de ± 1 °C ou plus. Il est souhaitable d'appliquer cette recommandation de température pour d'autres matériaux pour aimants durs. Cette recommandation figurait déjà dans l'IEC 60404-5:1993/AMD1:2007.

# MATÉRIAUX MAGNÉTIQUES –

## Partie 5: Aimants permanents (magnétiques durs) – Méthodes de mesure des propriétés magnétiques

## 1 Domaine d'application

La présente partie de l'IEC 60404 a pour objectif de définir la méthode de mesure de l'induction magnétique, de la polarisation magnétique et l'intensité du champ magnétique, mais aussi de déterminer la courbe de désaimantation et la droite de recul des matériaux pour aimants permanents, comme ceux qui sont spécifiés dans l'IEC 60404-8-1 [1][1], dont les propriétés sont supposées homogènes dans tout leur volume.

Les performances d'un système magnétique ne dépendent pas seulement des propriétés du matériau pour aimant permanent, mais aussi des dimensions du système, de l'entrefer et des autres éléments du circuit magnétique. Les méthodes décrites dans la présente partie de l'IEC 60404 se rapportent aux mesures des propriétés magnétiques en circuit magnétique fermé.

## 2 Références normatives

Les documents suivants sont cités en référence de manière normative, en intégralité ou en partie, dans le présent document et sont indispensables pour son application. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60050 (toutes les parties), *Vocabulaire Électrotechnique International* (disponible sous: www.electropedia.org)

## 3 Termes et définitions

Pour les besoins du présent document, les termes et définitions de l'IEC 60050-121, l'IEC 60050-151 et l'IEC 60050-221 s'appliquent.

## 4 Electroaimant et conditions d'aimantation

### 4.1 Généralités

Concernant les matériaux pour aimants permanents, la présente partie de l'IEC 60404 distingue le champ coercitif $H_{cB}$ (représentatif de la coercitivité de l'induction magnétique) et le champ coercitif intrinsèque $H_{cJ}$ (représentatif de la coercitivité de la polarisation magnétique).

Les mesures spécifiées dans la présente partie de l'IEC 60404 sont relatives à la fois à l'induction magnétique, $B$, et à la polarisation magnétique, $J$, en fonction de l'intensité du champ magnétique, $H$. Ces grandeurs sont reliées par l'équation suivante:

$$B = \mu_0 H + J \tag{1}$$

[1] Les chiffres entre crochets se réfèrent à la Bibliographie.

où

$B$ est l'induction magnétique, en teslas;

$\mu_0$ est la constante magnétique = $4\pi \times 10^{-7}$, en henry par mètre;

$H$ est l'intensité du champ magnétique, en ampères par mètre;

$J$ est la polarisation magnétique, en teslas.

Compte tenu de cette relation, les valeurs de $H_{cB}$ peuvent être déduites du cycle d'hystérésis $B(H)$ et les valeurs de $H_{cJ}$ peuvent être déduites du cycle d'hystérésis $J(H)$. Le point représenté par $H_a$ et $B_a$ pour lequel le module du produit $BH$ atteint sa valeur maximale est appelé point du produit d'énergie maximale pour $(BH)_{max}$ (voir Figure 1).

Le terme “rectangularité” de la courbe de désaimantation décrite dans la présente partie de l'IEC 60404, spécifie grossièrement la forme de la caractéristique de la courbe de désaimantation entre l'induction rémanente et la coercitivité de la polarisation magnétique de la courbe $J(H)$.

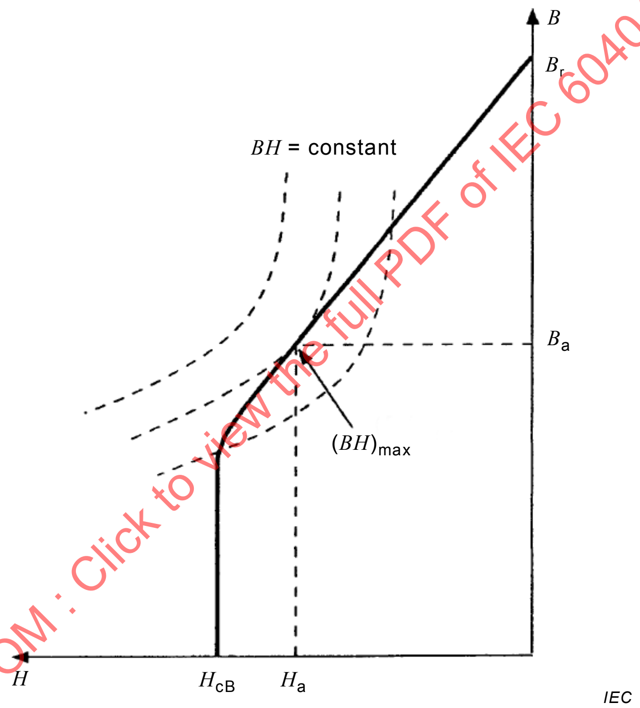


**Figure 1 – Courbe de désaimantation montrant le point $(BH)_{max}$**



Les mesures sont effectuées dans un circuit magnétique fermé constitué d'un électroaimant réalisé en matériau magnétique doux et du spécimen soumis aux essais. La culasse doit être de forme symétrique par construction, un des pôles au moins doit être mobile afin de réduire l'entrefer à sa valeur minimale entre le spécimen soumis aux essais et les pièces polaires (voir Figure 2). Les faces d'extrémité des deux pièces polaires doivent être rectifiées aussi parallèles que possible l'une à l'autre et aussi perpendiculaires que possible à l'axe des pôles, afin de réduire l'entrefer à sa valeur minimale (voir Figure A.1).

NOTE Pour certaines mesures, la culasse et les pôles peuvent être feuilletés afin de diminuer les courants de Foucault. La coercitivité du matériau ne dépasse normalement pas 100 A/m.

Pour obtenir un champ d'excitation magnétique suffisamment uniforme dans l'espace occupé par le spécimen soumis aux essais, les conditions décrites en 4.2 et 4.3 ci-dessous doivent être satisfaites simultanément.

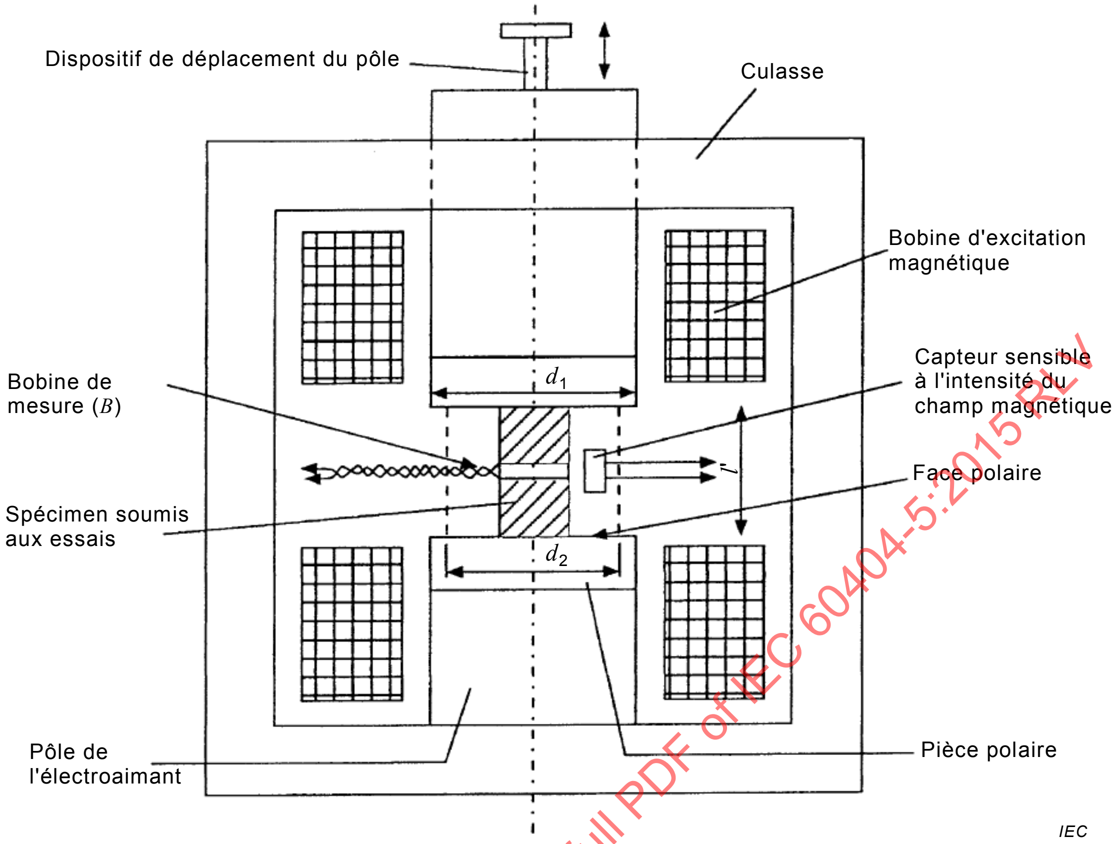


**Figure 2 – Schéma de principe de l'électroaimant**



### 4.2 Conditions géométriques

En se référant à la Figure 2;

$$d_1 \geq d_2 + 1{,}2\ l' \tag{2}$$

$$d_1 \geq 2{,}0\ l' \tag{3}$$

où

$d_1$ est le diamètre d'un pôle circulaire, ou la dimension du plus petit côté d'une pièce polaire rectangulaire, en millimètres;

$l'$ est la distance entre les pièces polaires, en millimètres;

$d_2$ est le diamètre maximal du volume cylindrique où le champ est homogène, en millimètres.

Par rapport à l'intensité du champ magnétique existant au centre de l'entrefer, la condition (2) garantit que la décroissance du champ magnétique atteint au plus 1 % sur une distance radiale égale à $d_2/2$ et la condition (3) garantit que la croissance du champ atteint au plus 1 % au contact des faces polaires, le long de l'axe de l'électroaimant.

### 4.3 Conditions électromagnétiques

Pendant la mesure de la courbe de désaimantation, l'induction dans les pièces polaires doit être maintenue à des valeurs notablement inférieures à la polarisation magnétique à saturation, de telle sorte que les faces polaires doivent être assimilables autant que possible à des surfaces équipotentielles. En pratique, l'induction magnétique ne doit pas dépasser 1 T dans le fer et 1,2 T dans un alliage de fer contenant 35 % à 50 % de cobalt.

La culasse est pourvue de bobines d'excitation magnétique disposées symétriquement, aussi près que possible du spécimen soumis aux essais (voir Figure 2). L'axe du spécimen soumis aux essais doit coïncider avec celui des pièces polaires.

Préalablement à la mesure, le spécimen soumis aux essais doit être aimanté dans un champ magnétique $H_{max}$ pour l'amener à la saturation. La détermination de la courbe de désaimantation doit alors être faite en appliquant un champ magnétique de direction opposée à celui utilisé pour l'aimantation initiale.

S'il n'est pas possible d'aimanter le spécimen soumis aux essais au voisinage de l'état saturé à l'intérieur de la culasse (par exemple si les exigences des formules (4) et (5) ne peuvent pas être satisfaites), alors le spécimen soumis aux essais doit être aimanté à l'extérieur de l'électroaimant, dans une bobine supraconductrice ou un banc d'aimantation à impulsion.

Les valeurs recommandées pour $H_{max}$ pour différents matériaux pour aimants permanents sont données dans l'IEC TR 62517 [2].

Si la norme de produit ou le fabricant ne spécifie pas la valeur de l'intensité du champ magnétique d'excitation $H_{max}$, il est recommandé d'aimanter le spécimen soumis aux essais à saturation avant d'effectuer la mesure de la courbe de désaimantation. Le spécimen soumis aux essais sera considéré comme étant saturé si les relations suivantes sont satisfaites pour deux valeurs $H_1$ et $H_2$ de l'intensité du champ magnétique d'excitation:

$$P_2 \leq P_1 \cdot (H_2/H_1)^{0,02454} \tag{4}$$

et

$$H_2 \geq 1,2\,H_1 \tag{5}$$

où

$P_2$ est la valeur maximale pouvant être atteinte de $(BH)_{max}$ en joules par mètre cube, ou celle du champ coercitif $H_{cB}$ en ampères par mètre;

$P_1$ est la valeur la moins élevée de $(BH)_{max}$, en joules par mètre cube, ou celle du champ coercitif $H_{cB}$, en ampères par mètre;

$H_2$ est l'intensité du champ magnétique d'excitation correspondant à $P_2$, en ampères par mètre;

$H_1$ est l'intensité du champ magnétique d'excitation correspondant à $P_1$, en ampères par mètre.

Dans le cas particulier où $H_2/H_1$ = 1,5, la relation (4) entraîne $P_2 \leq 1{,}01\ P_1$.

Dans tous les cas, le processus d'aimantation ne doit pas entraîner un échauffement exagéré du spécimen soumis aux essais.

## 5 Spécimen soumis aux essais

Le spécimen soumis aux essais doit être de forme simple (par exemple un cylindre droit ou un parallélépipède). La longueur $l$ du spécimen soumis aux essais ne doit pas être inférieure à 5 mm et ses autres dimensions doivent être d'au moins 5 mm et doivent être telles que le spécimen soumis aux essais et les dispositifs de détection doivent être inclus dans le diamètre $d_2$ défini en 4.2.

NOTE En raison des valeurs élevées de $(BH)_{max}$ des matériaux pour aimants permanents à terres rares, la longueur $l$ dans la direction d'aimantation peut être inférieure à 5 mm. Lorsque des spécimens soumis aux essais d'une telle longueur sont mesurés, l'homogénéité du champ magnétique entre les pièces polaires de l'électroaimant se détériore. L'effet de cette détérioration sur les mesures a été rapporté par Chen et al. [3] et peut être pris en compte lors de l'évaluation des résultats et, si nécessaire, une contribution peut être incluse dans l'incertitude de mesure. A ces épaisseurs, l'influence de l'entrefer augmente également. Par conséquent, l'entrefer est réduit à sa valeur minimale avec précaution. Puisque les propriétés magnétiques des surfaces usinées du REFeB fritté sont