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BRITISH STANDARD

BS 6404-13:
1996
IEC 404-13:
1995

Magnetic materials —

Part 13: Methods of measurement of density, resistivity and stacking factor of electrical steel sheet and strip

ICS 29.040.10

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Committees responsible for this British Standard

The preparation of this British Standard was entrusted to Technical Committee ISE/NFE/5, Magnetic alloys and steel, upon which the following bodies were represented:

Association of Manufacturers Allied to the Electrical and Electronic Industry (BEAMA Ltd.)
British Steel Industry
Department of Trade and Industry (National Physical Laboratory)
Electricity Supply Industry in England and Wales
Electronic Components Industry Federation
GAMBICA (BEAMA Ltd.)
Institute of Physics
Rotating Electrical Machines Association (BEAMA Ltd.)
Sunderland Polytechnic (Magnet Centre)
Transmission and Distribution Association (BEAMA Ltd.)
Wolfson Centre for Magnetics Technology
Co-opted members

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Contents

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National foreword

This British Standard has been prepared by Technical Committee ISE/NFE/5. It is identical with IEC 404-13:1996 *Magnetic materials — Part 13: Methods of measurement of density, resistivity and stacking factor of electrical steel sheet and strip*. It is based on the physical properties chapters of BS 6404-2:1985 which has been superseded by BS 6404-2:1996.

This Part of BS 6404 is the thirteenth in a series of British Standards based on the IEC 404 series, Magnetic materials. The Part numbers of the British Standards follow those of the IEC Publication. The following Parts of the British Standard have been published or will shortly be published.

— *Part 1: Classification;*

— *Part 2: Methods of measurement of magnetic, electrical and physical properties of magnetic sheet and strip;*

— *Part 3: Methods of measurement of the magnetic properties of magnetic sheet and strip by means of a single sheet tester;*

— *Part 4: Methods of measurement of the d.c magnetic properties of solid steels;*

— *Part 5: Permanent magnetic (magnetically hard) materials. Method of measurement of magnetic properties;*

— *Part 6: Methods of measurement of the magnetic properties of isotropic nickel-iron magnetic alloys, types E1, E3 and E4;*

— *Part 7: Method of measurement of the coercivity of the magnetic materials in an open magnetic circuit;*

— *Part 8: Individual materials;*

— *Section 8.1: Specification for magnetically hard materials;*

— *Section 8.2: Specification for cold-rolled, magnetic, non-oriented, alloyed steel strip delivered in the semi-processed state;*

— *Section 8.3: Specification for cold-rolled, magnetic, non-oriented, non-alloyed steel strip delivered in the semi-processed state;*

— *Section 8.4: Specification for cold-rolled, non-oriented, magnetic, steel sheet and strip delivered in the finally annealed state;*

— *Section 8.5: Specification for steel sheet and strip with specified mechanical properties and magnetic permeability;*

— *Section 8.6: Specification for soft magnetic metallic materials;*

— *Section 8.7: Specification for grain-oriented magnetic steel sheet and strip;*

— *Section 8.8: Specification for thin magnetic steel strip for use at medium frequencies;*

— *Section 8.9: Standard specification for sintered soft magnetic materials;*

— *Section 8.10: Specification for magnetic materials (iron and steel) for use in relays;*

— *Part 9: Methods for determination of the geometric characteristics of magnetic steel sheet and strip;*

— *Part 10: Methods of measurement of magnetic properties of magnetic steel and strip at medium frequencies;*

— *Part 11: Method of test for the determination of surface insulation resistance of magnetic sheet and strip;*

— *Part 12: Guide to the methods of assessment of temperature capability of interlaminar insulation coatings;*

— *Part 20: Resistance and temperature classification of insulation coatings.*

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Additional Parts and Sections of IEC 404 will be published and are expected to provide a basis for additional Parts of BS 6404.

Cross-references

International Standard	Corresponding British Standard
IEC 404-2:1978	BS 6404 *Magnetic materials* Part 2:1985 *Methods of measurement of magnetic, electrical and physical properties of magnetic sheet and strip* (Technically equivalent)
IEC 404-3:1992	Part 3:1992 *Methods of measurement of magnetic properties of magnetic sheet and strip by means of a single sheet tester* (Identical)
IEC 404-10:1988	Part 10:1989 *Methods of measurement of magnetic properties of magnetic sheet and strip at medium frequencies* (Identical)
ISO 1183:1987	BS 2782 *Methods of testing plastics* Part 6: *Dimensional properties* Methods 620A to 620D *Determination of density and relative density of non-cellular plastics* (Identical) BS 5600 *Powder metallurgical materials and products* Part 3: *Methods of testing sintered metal materials and products, excluding hardmetals*
ISO 2738:1987	Section 3.2:1988 *Determination of density, oil content and open porosity* (Identical)

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 10, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

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1 Scope and object

This part of IEC 404 specifies the methods used for determining the density, resistivity and stacking factor of electrical steel sheet and strip. These quantities are necessary to establish the magnetic characteristics of the material. In particular, the density is necessary to allow specified values of the flux density to be set without knowing the thickness of the test specimen.

For the determination of the density, the immersion method was earlier considered to be a fundamental method for use in cases of arbitration. However, experience has shown that this method is very difficult to use in the case of sheet samples with a relatively large surface area. This method is therefore not included. It is described in ISO 2738 and ISO 1183.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of IEC 404. At the time of publication, the editions indicated were valid. All normative documents are subject to revision, and parties to agreements based on this part of IEC 404 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 404-2:1978, *Magnetic materials — Part 2: Methods of measurement of magnetic, electrical and physical properties of magnetic sheet and strip.*

IEC 404-3:1992, *Magnetic materials — Part 3: Methods of measurement of magnetic properties of magnetic sheet and strip by means of a single sheet tester.*

IEC 404-10:1988, *Magnetic materials — Part 10: Methods of measurement of magnetic properties of magnetic steel sheet and strip at medium frequencies.*

ISO 1183:1987, *Plastics — Methods for determining the density and relative density of non-cellular plastics.*

ISO 2738:1987, *Permeable sintered metal materials — Determination of density, oil content and open porosity.*

3 Determination of the density

3.1 Field of application

The method of measurement of the density defined in this clause applies only to non-oriented iron-silicon electrical sheet and strip with or without insulation, with the following range of chemical composition by mass:

— silicon: $p(\mathrm{Si}) \leq 4$ %;

— aluminium: $0{,}17\, p(\mathrm{Si}) - 0{,}28 \leq p(\mathrm{Al}) \leq 0{,}17\, p(\mathrm{Si}) + 0{,}28$ and $p(\mathrm{Al}) \geq 0$;

— total of other alloy constituents: $p \leq 0{,}4$ %

where

$p(\mathrm{Si})$ is the percentage of Si by mass;

$p(\mathrm{Al})$ is the percentage of Al by mass.

NOTE If the chemical composition is not known, it should be verified before using this method.

The two methods of determination of density described in this standard are applicable to Epstein strips (method A) as specified by IEC 404-2 and IEC 404-10 and to sheets (method B) as specified by IEC 404-3.

For materials not meeting the above range of chemical composition, immersion methods of equivalent accuracy such as those defined in ISO 2738 or ISO 1183 shall be used.

The measurements shall be made at an ambient temperature of (23 ± 5) °C.

3.2 Test specimens

3.2.1 *Strip specimens*

The strip specimen used in method A (see **3.3.2**) shall have the following dimensions:

— width $b = (30 \pm 0{,}2)$ mm;

— length 280 mm $\leq l \leq$ 320 mm.

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It shall be cut with its longitudinal axis parallel to the direction of rolling.

It is not necessary to remove the oxide or other insulating coating except from places where electrical contacts are made.

3.2.2 ***Sheet specimens***

The dimensions of the sheet used for method B (see **3.3.3**) shall be as follows:

— width b = 500 mm;

— length l = 500 mm.

These are the usual dimensions of a non-oriented test specimen for use in a single-sheet tester (SST) conforming with IEC 404-3. However, the dimensions of the rectangular sheets can vary within:

$300\ \text{mm} \le b \le 510\ \text{mm}$ and $500\ \text{mm} \le l \le 600\ \text{mm}$

3.3 Principles of measurement

3.3.1 ***General***

In the case of magnetic material as specified in clause **3**, both the density, ϱ_m, and the resistivity, ρ, are functions of the silicon and aluminium contents. Experience has shown that the relationship between the density ϱ_m and the easy-to-measure product $\varrho_m\,\rho$ (see **3.3.2** and **3.3.3**) is a simple, almost linear one, as shown in Figure 1. Thus, it is possible to determine the density by substituting its direct measurement by the measurement of the product $\varrho_m\,\rho$.

The linear function shown in Figure 1, obtained by linear regression from experimental data, follows the empirical relation:

$$\varrho_m = \varrho_o - k_s\,\varrho_m\,\rho \qquad (1)$$

where

k_s = 89 200 $(\Omega\cdot m)^{-1}$;

ϱ_m is the density, in kilograms per cubic metre;

ϱ_o = 7 973 $kg\cdot m^{-3}$;

ρ is the resistivity, in ohm metres.

This relationship has been established by careful and statistical application of the immersion method [1][1)] taking the usual impurities of non-oriented material into account.

For the two different types of test specimen used for the Epstein and single-sheet test (SST) method, respectively, two methods of determination of the product $\varrho_m\,\rho$ are applied, described in **3.3.2** and **3.3.3**.

3.3.2 ***Method of measuring the product $\varrho_m\cdot\rho$ using Epstein strips (method A)***

If an electric current flows homogeneously through the test specimen the resistance R of a length of an Epstein strip between two point contacts can be easily measured.

The relationships

$$R = \frac{\rho\cdot l_e}{b\cdot d} \qquad (2)$$

and

$$m = l\cdot b\cdot d\,\varrho_m \qquad (3)$$

give

$$\varrho_m\,\rho = \frac{R\cdot m}{l_e\cdot l} \qquad (4)$$

where

b is the width of the test specimen, in metres;

d is the thickness of the test specimen, in metres;

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

l_e is the electrical path length (distance between the potential contacts), in metres;

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

ϱ_m is the density of the test specimen without insulation, in kilograms per cubic metre;

R is the electrical resistance, in ohms;

ρ is the resistivity, in ohm metres.

1) The figures in square brackets refer to Annex A (Bibliography).

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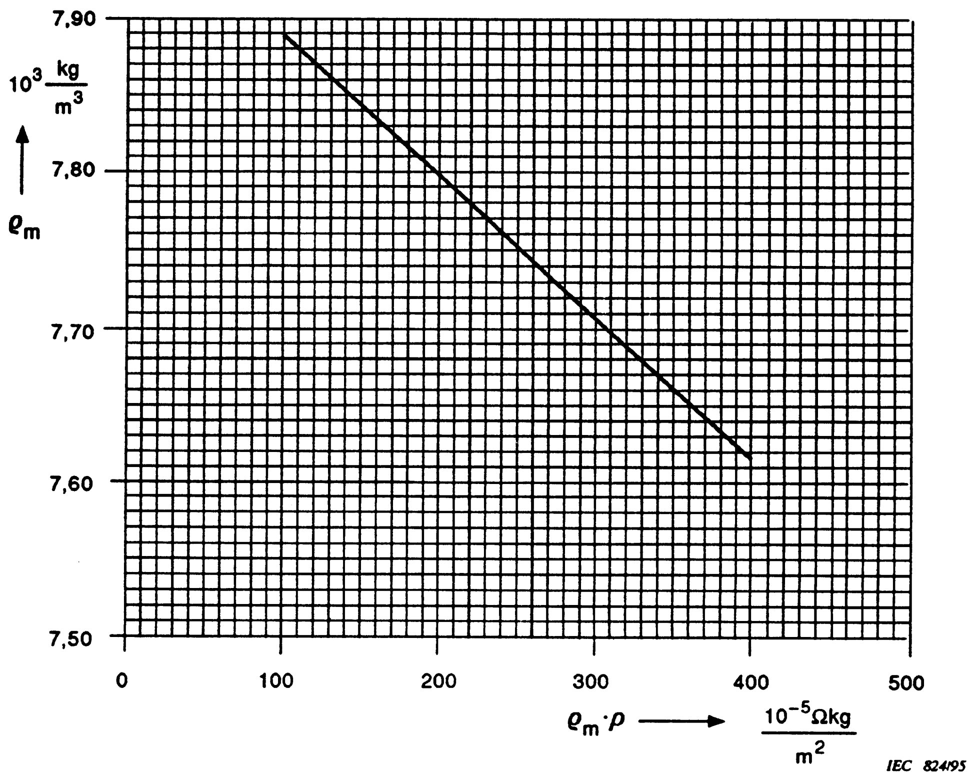

Figure 1 — Density ϱ_m as a function of the product $\varrho_m \cdot \rho$, for alloyed electrical sheet steel

The value of ϱ_m shall be determined by reading from Figure 1 the value corresponding to the value of the product $\varrho_m\,\rho$ determined from equation (4). It can also be calculated using equation (1).

3.3.3 ***Method of measuring the product $\varrho_m \cdot \rho$ using sheet specimens (method B)***

On the basis of the theory of conformal mapping of two-dimensional fields, it has been shown [2] that, for a body of uniform thickness and arbitrary shape, the following relationship holds:

$$\rho = \frac{\pi d}{\mathrm{In}\ 2} \cdot \frac{R_{AB,CD} + R_{BC,DA}}{2} \cdot F_p \qquad (5)$$

where

- ρ is the resistivity, in ohm metres;
- F_p is a function of the ratio $\frac{R_{AB,CD}}{R_{BC,DA}}$ only;
- $R_{AB,CD}$ is the resistance obtained from the potential difference $V_C - V_D$ between the contacts C and D per unit current through the contacts A and B, the contacts A, B, C and D being as small as possible and randomly distributed over the specimen edge, in ohms;
- $R_{BC,DA}$ is, correspondingly, the resistance obtained from the potential difference between contacts D and A per unit current through the contacts B and C, in ohms;
- d is the thickness of the test specimen, in metres.

If the ratio $\frac{R_{AB,CD}}{R_{BC,DA}}$ is close to unity, the function F_p becomes 1 so that it can be omitted [2].

To ensure that this ratio is close to unity, the contacts shall be arranged symmetrically at the mid-points of the edges of the square or rectangular test specimen as shown in Figure 2.

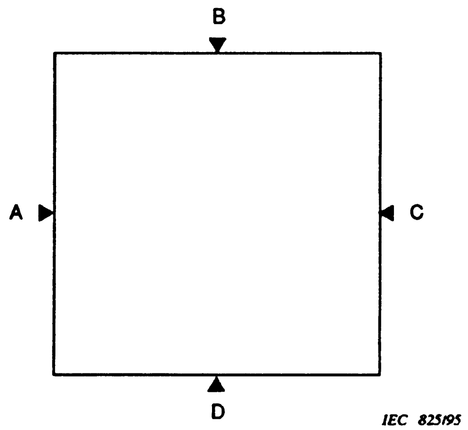

Figure 2 — Arrangement of contacts on the test specimen for method B

Again the relationship is obtained for the determination of the product $\varrho_m \rho$, which is independent of the thickness d, from equation (5) using equation (3):

$$\varrho_m \cdot \rho = \frac{\pi \cdot m}{l \cdot b \cdot \ln 2} \cdot \frac{R_{AB,CD} + R_{BC,DA}}{2} \qquad (6)$$

The value of ϱ_m shall be determined by reading it off from Figure 1 corresponding to the value of the product $\varrho_m \rho$ determined from equation (6). It can also be calculated using equation (1).

NOTE It has been shown that the method described in this subclause is equivalent to method A for strips described in **3.3.2**, within limits which are smaller than the dispersion between individual strip samples of one grade of material, when method A is applied [3].

3.4 Apparatus

3.4.1 *Requirements for methods A and B*

The following equipment is required:

— a balance, capable of measuring the mass, m, of the test specimen to within ± 0,1 g;

— a length measuring device, capable of measuring the length l and the width b of the test specimen to within ± 0,5 %;

— a power supply consisting of a stable low voltage d.c. current source capable of supplying a current of the order 1 A to 10 A (unless a 4-terminal ohm meter is used, see next paragraph);

— a resistance measuring device (e.g. standard resistor and digital voltmeter of accuracy 0,1 % or better or a Kelvin bridge or a 4-terminal ohm meter of corresponding accuracy) capable of measuring the resistance, R, of the test specimen to within ± 1 %;

— an apparatus for making contact to the test specimen consisting of a base plate carrying contacts (see **3.4.2** and **3.4.3**) and, between the contacts, a supporting flat plate smaller than the test specimen (on sides where contacts are arranged) but not by more than 5 mm (10 mm for sheet specimens) on each side. The thickness of the support shall allow the contacts to touch the specimen lying on the support.

3.4.2 *Requirements for method A*

The apparatus for making electrical contact with the strip specimen employs four contacts: two potential contacts (tips) arranged on a removable bridge and two current contacts fixed to the base plate. The four contacts are arranged so that the two potential contacts lie between the current contacts and are on the axis of the strip. The current contacts consist of two leaf springs making contact with the test specimen over the whole width. The distance between the potential contacts shall exceed 200 mm. The minimum distance between the potential contacts and the current contacts shall be not less than the width of the test specimen (the distance l_e between the tips shall be determined once and for all within ± 0,5 mm).

It is not necessary to remove the oxide or other insulating coating except from places where electrical contact is made.

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3.4.3 *Requirements for method B*

For method B four contacts with a relatively sharp edge (e.g. with a radius of curvature of 1 mm) shall each be mounted on a holder which is fixed to the base plate. The contacts shall be arranged symmetrically about the sample axes, within ± 1 mm (see Figure 2).

The position of one pair of these contacts, arranged opposite each other, should be able to be changed in such a way that the distance between them can be changed but they remain symmetrical about the axis between the other two contacts. This allows for the varying length of the test specimens, which might possibly involve the need to vary the size of the supporting plate. Tapped holes at different points or adjustment slots enable the contact holders to be placed in different positions. The contacts shall be elastically pressed against the test specimen with the help of springs. The edge of the contacts shall be perpendicular to the specimen's edges. This can be achieved by means of a small contact block which can slide relative to its holder and which is pressed against the test specimen by a spring placed between the holder and the contact block. The movable contact shall be connected to the holder, or a plug-in socket on it, by means of a flexible conductor welded to both. (See Figure 3.)

NOTE Other methods such as soldering may be used to provide good electrical contact.

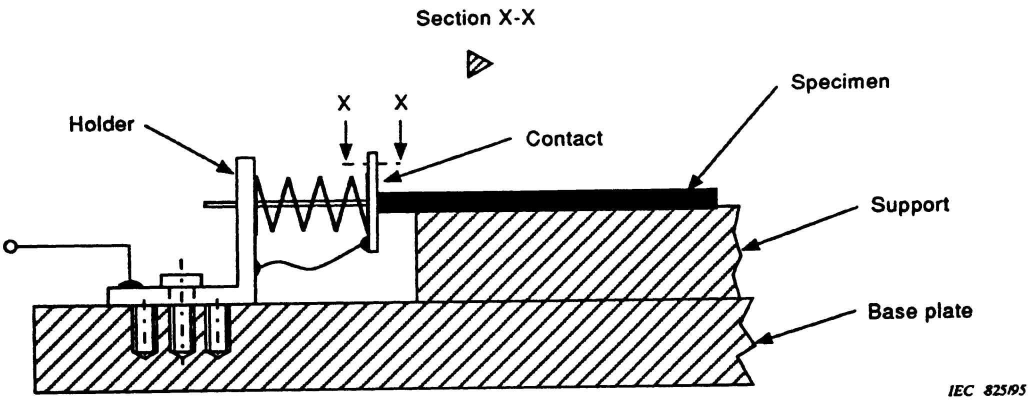

Figure 3 — Schematic cross-sectional view of the arrangement of the contact holder

3.5 Procedure

3.5.1 ***General***

The test specimen shall be weighed. The length and width of the test specimen shall be determined using the length measuring device. Measurements shall be made at an ambient temperature of (23 ± 5) °C. The temperature shall be kept constant throughout the measurement.

3.5.2 ***Procedure with strip specimens (method A)***

The circuit connections shall be made, and a current having a value between 1 A and 5 A depending on the thickness of the material and the material properties, shall be fed through the test specimen. If a 4-terminal ohm meter having the same accuracy of measurement is used, a lower value of the current is permitted. The voltage and the current shall be read. The current shall then be reversed and set to the same value, and the voltage read again. The resistance R is then calculated from the average of the two voltages divided by the current value.

The product $\varrho_m\,p$ shall be calculated using equation (4).

3.5.3 ***Procedure with sheet specimens (method B)***

The circuit connections shall be made as shown in Figure 4. A current having a value between 2 A and 10 A sufficient to give a voltage reading of the specified accuracy shall be fed via the contacts A and B through the test specimen. If a 4-terminal ohm meter having the same accuracy of measurement is used, a lower value of the current is permitted. The voltage and the current shall be read. The current shall then be reversed and set to the same value, and the voltage read again. The resistance $R_{AB,CD}$ is then calculated from the average of the two voltages divided by the current value. After exchanging connections to the two opposite contacts A and C, the resistance $R_{BC,DA}$ is similarly determined.

The product $\varrho_m\,p$ shall be calculated using $R_{AB,CD}$ and $R_{BC,DA}$ and equation (6).

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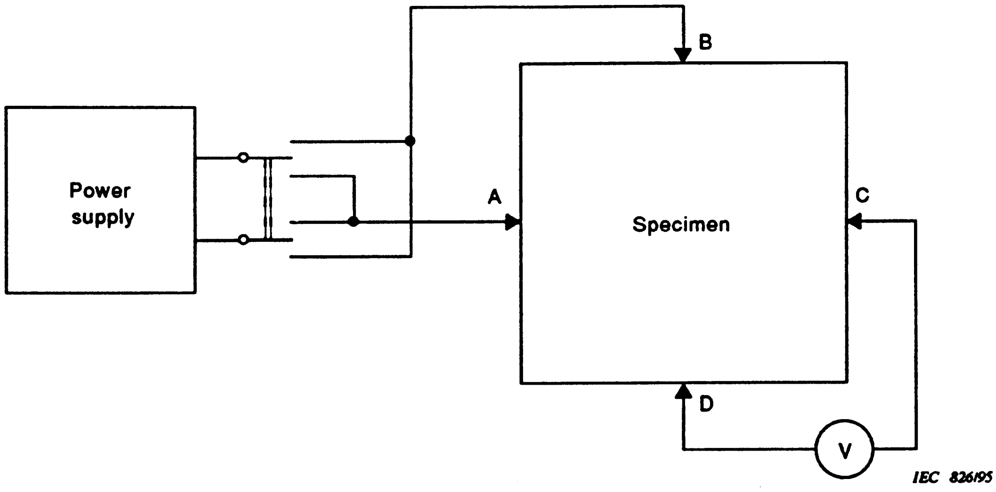

Figure 4 — Circuit for the measurement of resistance $R_{AB,CD}$ on sheet specimen of square shape

3.5.4 ***Determination of the density***

From the straight line in Figure 1, the density ϱ_m corresponding to the product $\varrho_m\,\rho$ is read. It can also be calculated using equation (1).

3.6 Test report

The test report shall refer to this standard and give the following details:

a) the type or grade of material, its nominal thickness and its identity;

b) the sampling method;

c) the width b and total length l in metres, the mass m of the test specimen in kilograms;

d) the density ϱ_m, in kilograms per cubic metre, rounded to the nearest 10 kg/m^3;

e) the ambient temperature at which the measurement was made.

3.7 Reproducibility

The reproducibility of each of the two methods described in **3.3.2** and **3.3.3** and the difference between the result of the two methods is characterized by a relative standard deviation of the density of 0,1 %.

4 Determination of the resistivity

4.1 Object

The object of this clause is to define a method for measuring resistivity.

4.2 Field of application

The method of determination of the resistivity ρ, based on the determination of the product $\varrho\,\rho$ as described in clause **3**, can be applied to sheet and strip specimens. However, it is restricted to the materials specified in **3.1**. The method based on the measurement of the geometric dimensions of the sample, including the thickness can be applied to all types of material.

Because the resistivity is a function of temperature, the curve in Figure 1 [or equation (1)] shall only be used for measurements at (23 ± 5) °C. If measurements at temperatures outside this range are required the method described in **4.4.2** shall be used.

4.3 Test specimen

The test specimen shall be in accordance with **3.2**.

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4.4 Principle of measurement

4.4.1 ***Method based on the determination of the product*** $\varrho_m \cdot \rho$

When using the electrical method for measuring density described in **3.3** to **3.5**, with the relationship ϱ_m against $\varrho_m\ \rho$, the resistivity is automatically obtained by dividing the abscissa by the ordinate of the values in Figure 1. Because of the difficulty of measuring thickness with sufficient accuracy, this method is to be preferred.

4.4.2 ***Method based on the determination of thickness d***

For the determination of the resistivity of products not falling within the scope of **3.1** the thickness d shall be determined using the value of density ϱ_m of the product obtained from tables of physical properties published in the literature or supplied by manufacturers. The mass m, width b and length l of the test specimen shall be determined with an accuracy of 0,1 %, and the thickness d determined from the following equation:

$$d = \frac{m}{\varrho_m \cdot b \cdot l} \tag{7}$$

where

- d is the thickness of the test specimen, in metres;
- m is the mass of the test specimen, in kilograms;
- ϱ_m is the density of the test specimen, in kilograms per cubic metre;
- b is the width of the test specimen, in metres;
- l is the length of the test specimen, in metres.

NOTE If it is not possible to obtain the actual value of density (as distinct from conventional values of density ϱ_m from reference literature or from the manufacturer), then the density should be determined by the immersion method. It will be necessary to remove any insulating coating before the test. (A less accurate assessment of density can be obtained by measuring the thickness at a number of places with a high-resolution micrometer, but the reproducibility given in **4.6** is not likely to be achieved.)

4.4.2.1 *Measurements using a strip specimen*

A strip specimen in accordance with **3.2.1** shall be used.

The width of the strip and the resistance shall be measured following the procedures described in **3.5.1** and **3.5.2** using the devices described in **3.4.1** and **3.4.2**. The resistivity shall then be determined using equation (2).

In order to obtain comparable results, it is necessary to test at least four test specimens and to average the results.

4.4.2.2 *Measurements using a sheet specimen*

A sheet specimen in accordance with **3.2.2** shall be used. The resistance values $R_{AB,CD}$ and $R_{BC,DA}$ (see **3.3.3**) of the test specimen shall be measured following the procedure described in **3.5.1** and **3.5.3** using the devices described in **3.4.1** and **3.4.3**.

The resistivity shall then be determined using the following equation:

$$\rho = \frac{\pi d}{\ln 2} \cdot \frac{R_{AB,CD} + R_{BC,DA}}{2} \tag{8}$$

where

- ρ is the resistivity, in ohm metres;
- $R_{AB,CD}$ is the resistance obtained from the potential difference $V_C - V_D$ between the contacts C and D per unit current through the contacts A and B, the contacts A, B, C and D (see Figure 2) being as small as possible and symmetrically distributed over the specimen's edges, in ohms;
- $R_{BC,DA}$ is, correspondingly, the resistance obtained from the potential difference between contacts D and A per unit current through the contacts B and C, in ohms;
- d is the thickness of the specimen, in metres.

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4.5 Test report

The test report shall refer to this standard and give the following details:

a) the type or grade of material, its nominal thickness and its identity;

b) the sampling method;

c) the width *b* and total length *l* in metres, the mass *m* of the test specimen in kilograms;

d) the resistivity ρ, in ohm metres, rounded to the nearest $0,1 \cdot 10^{-8}\ \Omega \cdot m$;

e) the ambient temperature at which the measurement was made.

4.6 Reproducibility

The reproducibility of the methods described in **4.4** is characterized by a relative standard deviation of the resistivity of 1,0 %.

5 Determination of the stacking factor

5.1 Object

The object of this clause is to define a method for measuring stacking factor.

5.2 Field of application

The method of determination of the stacking factor may be applied to all types of sheet material.

5.3 Measuring procedure

The test shall be made on sufficient samples of identical size to give a stack of minimum height 6 mm.

NOTE The test specimen can conveniently be derived from an Epstein sample.

The test specimens shall be weighed and their mean length and width measured with an error of ± 0,33 % or better. The test specimens, deburred before the test, are stacked and placed between the rams of a press; the surface area of the rams shall be sufficient to cover completely the stack of test specimens which is subjected to a pressure of (1,00 ± 0,05) N/mm^2. With this pressure applied, the distance *h* between the rams next to the four edges of the stack, or if not possible, in the middle of the two shorter sides is measured with an accuracy of ± 0,3 % or better.

NOTE If there is difficulty in achieving the specified accuracy for the measurement of the distance between the rams, the height of the stack may have to be increased.

By special agreement, the determination of stacking factor can be made with rams smaller than the size of the test specimens but not less than 25 mm × 12 mm. In this case, it is not necessary to deburr the test specimens. The distance *h* between the rams is measured at the middle of the stack.

The stacking factor *f* is calculated according to the relationship:

$$f = \frac{m}{\varrho_m \cdot h \cdot b \cdot l} \qquad (9)$$

where

f is the stacking factor;

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

b is the mean width of test specimen, in metres;

ϱ_m is the density of the test specimen, in kilograms per cubic metre;

h is the height of the stack, in metres;

m is the total mass of test specimens, in kilograms.

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5.4 Test report

The test report shall refer to this standard and give the following details:

a) the type or grade of material, its identity, its nominal thickness and the type of coating (if any);

b) the mean value of the width b and length l in metres, the total mass m of test specimen in kilograms;

c) the height of the stack, in metres;

d) the stacking factor f, rounded to the nearest 0,005.

5.5 Reproducibility

The reproducibility of the method described in **5.3** is characterized by a relative standard deviation of the stacking factor of 0,7 %.

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Annex A (informative) Bibliography

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List of references

See national foreword.

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