IEC 60404-1

Edition 3.1 2025-07

INTERNATIONAL STANDARD

CONSOLIDATED VERSION

Magnetic materials -
Part 1: Classification

ICS 29.030

ISBN 978-2-8327-0621-3

IEC 60404-1:2016-10+AMD1:2025-07 CSV(en)

IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

About the IEC
The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications
The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

IEC publications search - webstore.iec.ch/advsearchform
The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee, …). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished
Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

IEC Customer Service Centre - webstore.iec.ch/csc
If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

IEC Products & Services Portal - products.iec.ch
Discover our powerful search engine and read freely all the publications previews, graphical symbols and the glossary. With a subscription you will always have access to up to date content tailored to your needs.

Electropedia - www.electropedia.org
The world's leading online dictionary on electrotechnology, containing more than 22 500 terminological entries in English and French, with equivalent terms in 25 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

Magnetic materials - Part 1: Classification

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) IEC draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). IEC takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, IEC had not received notice of (a) patent(s), which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at https://patents.iec.ch. IEC shall not be held responsible for identifying any or all such patent rights.

This consolidated version of the official IEC Standard and its amendment has been prepared for user convenience.

IEC 60404-1 edition 3.1 contains the third edition (2016-10) [documents 68/533/CDV and 68/555/RVC] and its amendment 1 (2025-07) [documents 68/780/CDV and 68/791A/RVC].

In this Redline version, a vertical line in the margin shows where the technical content is modified by amendment 1. Additions are in green text, deletions are in strikethrough red text. A separate Final version with all changes accepted is available in this publication.

International Standard IEC 60404-1 has been prepared by IEC technical committee 68: Magnetic alloys and steels.

This bilingual version (2017-12) corresponds to the monolingual English version, published in 2016-10.

This third edition cancels and replaces the second edition published in 2000 and constitutes a technical revision.

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

a) Removal of all tables and values describing typical properties of the material to be consistent with the aim of the document to be a classification and not a specification.
b) Enlargement of the Ni content for the classes E1 and E3.
c) Enlargement of the Co content for the classes F3.
d) Addition of a new class: U5 bonded rare earth-iron-nitrogen magnets.

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

CDV	Report on voting
68/533/CDV	68/555/RVC

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

The French version of this standard has not been voted upon.

This document 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 document and its amendment will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

1 Scope

This part of IEC 60404 is intended to classify commercially available magnetic materials.

The term "magnetic materials" denotes substances where the application requires the existence of ferromagnetic or ferrimagnetic properties.

In this document, the classification of magnetic materials is based upon the generally recognized existence of two main groups of products:

- soft magnetic materials (coercivity $\leq$1 000 A/m);
- hard magnetic materials (coercivity $>$1 000 A/m).

Within these main groups, the classification when appropriate recognizes the following characteristics:

- the main alloying element and the metallurgical state and physical properties of the material;
- when possible and convenient, the relationship between these characteristics is identified.

A classification by specific areas of application cannot be applied to all materials because different materials can very often be used for the same application depending on the characteristics required.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-121, *International Electrotechnical Vocabulary – Part 121: Electromagnetism*

IEC 60050-151, *International Electrotechnical Vocabulary – Part 151: Electrical and magnetic devices*

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

IEC 60401-3, *Terms and nomenclature for cores made of magnetically soft ferrites – Part 3: Guidelines on the format of data appearing in manufacturers catalogues of transformer and inductor cores*

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

IEC 60404-3, *Magnetic materials – Part 3: Methods of measurement of the magnetic properties of magnetic sheet and strip by means of a single sheet tester*

IEC 60404-4, *Magnetic materials – Part 4: Methods of measurement of d.c. magnetic properties of iron and steel*

IEC 60404-6, *Magnetic materials – Part 6: Methods of measurement of the magnetic properties of magnetically soft metallic and powder materials at frequencies in the range 20 Hz to 200 kHz by the use of ring specimens*

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

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

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

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

IEC 60404-8-5, *Magnetic materials – Part 8: Specifications for individual materials – Section Five: Specification for steel sheet and strip with specified mechanical properties and magnetic permeability*

IEC 60404-8-6, *Magnetic materials – Part 8-6: Specifications for individual materials – Soft magnetic metallic materials*

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

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

IEC 60404-8-9, *Magnetic materials – Part 8: Specifications for individual materials – Section 9: Standard specification for sintered soft magnetic materials*

IEC 60404-8-10, *Magnetic materials – Part 8-10: Specifications for individual materials – Magnetic materials (iron and steel) for use in relays*

IEC 60404-8-11, *Magnetic materials - Part 8-11: Specifications for individual materials - Fe-based amorphous strip delivered in the semi-processed state*

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

ISO 4948-1, *Steels – Classification – Part 1: Classification of steels into unalloyed and alloy steels based on chemical composition*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-121, IEC 60050-151, IEC 60050-221 and in the product standards of the IEC 60404-8 series apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

4 Magnetically soft materials (coercivity ≤1 kA/m)

4.1 Class A – Irons

4.1.1 Reference documents

These materials are covered by IEC 60404-8-6 and IEC 60404-8-10.

4.1.2 Chemical composition

The basic constituent of these materials is pure iron, and they are often referred to as "commercially pure" or "magnetically soft" irons. The material also contains unavoidable impurities that may affect magnetic properties. The amount of impurities that adversely affect the remanence, coercivity, saturation, magnetic polarization and stability of the magnetic properties are limited to produce the required magnetic properties for the proposed application. For information the most significant impurities when they are present in these materials are carbon (up to 0,03 %), silicon (up to 0,1 %), manganese (up to 0,2 %), phosphorus (up to 0,015 %), sulphur (up to 0,03 %), aluminium (up to 0,08 %), titanium (up to 0,1 %) and vanadium (up to 0,1 %).

NOTE For improved free machining capability, the amount of phosphorus and sulphur can be higher than indicated above.

4.1.3 Basis of subclassification

The recommended subclassification is based on coercivity values.

4.1.4 Available forms

These materials are available in a wide variety of forms. They may be supplied as slabs, billets, ingots or forgings; as hot-rolled bar in rectangular and square cross-sections; as hot-rolled wire rod in round, hexagonal and octagonal cross-sections; in cold-rolled and drawn forms as bar and wire; as hot- or cold-rolled sheet and strip.

4.1.5 Physical characteristics

In addition to the values of coercivity, a more complete definition of these materials can be based on the following characteristics:

- magnetic: saturation magnetic polarization, magnetic polarization at various values of magnetic field strength (from which permeability can be derived), stability of characteristics with time;
- mechanical: hardness, suitability for punching operations, free machining capability, deep drawing properties, tensile strength;
- metallurgical state: hot- or cold-worked, forged, deep drawn, fully processed state, i.e. final annealed.

NOTE For material not delivered in the fully processed state, subclassification is based on the coercivity measured after heat treatment according to the requirements of the product standard or the recommendations of the manufacturer.

Ranges of specified values for the above-mentioned magnetic characteristics in the fully processed state are given in the corresponding product specifications.

4.1.6 Main applications

The main applications are in DC relays, loudspeakers, electromagnets, magnetic clutches, brakes, parts for magnetic circuits in instruments and control apparatus, as well as for pole pieces and other DC parts for generators and motors.

4.2 Class B – Low carbon mild steels

4.2.1 Class B1 – Bulk material

4.2.1.1 Reference document

Some of these materials are covered by IEC 60404-8-10.

4.2.1.2 Chemical composition

The basic constituent of these materials is iron containing unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process. The amount of alloying elements is limited to that of a non-alloy steel as defined in ISO 4948-1, in particular silicon is less than 0,5 %.

4.2.1.3 Basis of subclassification

The recommended subclassification is based on the coercivity.

4.2.1.4 Available forms

These materials are normally supplied in the form of castings or forgings in a final heat-treated condition or partially machined to drawings supplied by the user or as bar, wire rod or wire in the hot-rolled, cold-rolled or cold-drawn condition.

4.2.1.5 Physical characteristics

In addition to the coercivity a more complete definition of these materials can be based on the following properties:

- magnetic: magnetic polarization at various values of magnetic field strength;
- mechanical: yield strength (or 0,2 % proof stress) elongation (L_o = 5 d_o), freedom from defects;
- metallurgical state: hot- or cold-worked, annealed to produce required magnetic characteristics.

Mechanical and non-destructive tests are made in accordance with the appropriate ISO standards. Coercivity shall be measured in accordance with IEC 60404-7, other magnetic properties in accordance with IEC 60404-4.

Ranges of typical values of magnetic and mechanical properties are given in the corresponding product specification.

4.2.1.6 Main applications

The materials are used for large DC magnets where no mechanical strength is required, for example, in deflection magnets in elementary particle physics and for relay applications.

4.2.2 Class B2 – Flat material

4.2.2.1 Reference documents

These materials are covered by IEC 60404-8-3, IEC 60404-8-4 and IEC 60404-8-10.

4.2.2.2 Chemical composition

The basic constituent of these materials is iron containing unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process. The amount of alloying elements is limited to that of non-alloy steel as defined in ISO 4948-1, in particular silicon is less than 0,5 %. These materials can have an annealing treatment after punching to enhance their magnetic properties.

4.2.2.3 Basis of subclassification

The recommended subclassification is based either on the specific total loss which is a function of thickness and is normally measured at a magnetic polarization value of 1,5 T and at normal industrial power frequencies or (for relay application) on the coercivity.

4.2.2.4 Available forms

These materials are supplied in the form of cold-rolled coils or sheets or (for relay application) in the form of hot-rolled strip, sheet or plate.

4.2.2.5 Physical characteristics

In addition to specific total loss, a more complete definition of these materials can be based on the following properties:

- magnetic: magnetic polarization at various values of magnetic field strength;
- mechanical: suitability for punching operations, surface condition, stacking factor;
- metallurgical state: hot-rolled; hard state – i.e. cold-rolled; semi-processed state – i.e. annealed and finally cold-rolled;

  fully processed state – i.e. final annealed.

NOTE For material delivered in the hard or semi-processed state, subclassification is based on the total specific loss or coercivity measured after heat treatment according to the requirements of the product standard or recommendations of the manufacturer.

- dimensions: thickness, width and (as required) length.

Recommended nominal thicknesses for the cold-rolled materials are given in the corresponding product specifications.

Magnetic measurements are made in accordance with IEC 60404-2, IEC 60404-3 or IEC 60404-7.

Ranges of specified values of maximum specific total loss, after annealing, for the commonly used thicknesses are also shown in the corresponding product specifications.

The specified maximum value of coercivity for relay material ranges from 40 A/m to 240 A/m.

4.2.2.6 Main applications

The materials are used in the manufacture of laminated cores for electrical apparatus and especially small machines and for relay applications.

4.3 Class C – Silicon steels

4.3.1 Class C1 – Bulk material

4.3.1.1 Reference documents

Some of these materials are covered by IEC 60404-8-6 and IEC 60404-8-10.

4.3.1.2 Chemical composition

The basic constituent of these materials is iron in which the main alloying element is silicon with a content of up to approximately 5 %.

4.3.1.3 Basis of subclassification

The recommended subclassification is based on coercivity values or on electrical resistivity which is a function of silicon content.

4.3.1.4 Available forms

These materials are available as hot-rolled and cold-drawn bar, wire, ground bar and forging billets and require heat treatment after mechanical working to achieve the required magnetic properties.

4.3.1.5 Physical characteristics

In addition to the coercivity and the electrical resistivity, a more complete definition of these materials can be based on the following characteristics:

- magnetic: saturation magnetic polarization, magnetic polarization at various values of magnetic field strength, remanent magnetic polarization;
- mechanical: machinability, ductility, hardness;
- metallurgical state: hot- or cold-worked, annealed to produce required magnetic characteristics.

4.3.1.6 Main applications

The main applications are for the magnetic circuits of relays, magnetic clutches, magnetic pole pieces, stepping motors and gyro housings.

4.3.2 Class C2 – Flat material

4.3.2.1 Class C21 – Isotropic[1] (non-oriented) steels for use at power frequencies

4.3.2.1.1 Reference documents

These materials are covered by IEC 60404-8-3, IEC 60404-8-4, IEC 60404-8-6 and IEC 60404-8-10.

4.3.2.1.2 Chemical composition

The basic constituent of these materials is iron. The main alloying element is silicon, whose content may be up to approximately 5 %. Other alloying elements, for example aluminium, may also be present. The material also contains unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.3.2.1.3 Basis of subclassification

The recommended subclassification is based on the specific total loss which is a function of thickness and normally measured at a magnetic polarization value of 1,5 T and at power frequencies.

When the application demands it (for example relays), it may be more appropriate for the subclassification to be based on coercivity or permeability.

[1] This describes a material which is substantially isotropic and deliberately processed to be so.

4.3.2.1.4 Available forms

These materials are normally supplied in the form of cold-rolled coils or sheets.

4.3.2.1.5 Physical characteristics

In addition to the values of specific total loss, a more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, specific apparent power for different values of magnetic polarization anisotropy of loss;
- electrical: type of surface insulation and its resistance, resistivity;
- mechanical: suitability for punching operations, ductility, tensile strength, hardness, surface condition and finish, stacking factor, flatness, edge camber;
- metallurgical state: hard state, i.e. as cold rolled semi-processed state, i.e. annealed or annealed and temper rolled; fully-processed state, i.e. final annealed;

NOTE For material delivered in the hard or semi-processed state, the subclassification is based on the specific total losses measured after heat treatment according to the requirements of the product standard or the recommendations of the manufacturer.

- dimensions: thickness, width and (as required) length.

The values of nominal thickness are given in the corresponding product specifications.

Magnetic measurements are made in accordance with IEC 60404-2 or IEC 60404-3. The density values to be used for magnetic measurements should be as defined in the relevant product standard. In other cases, the density values should be the subject of agreement.

Ranges of specified values of specific total loss, after final annealing, for four commonly used thicknesses are shown in the corresponding product specifications.

4.3.2.1.6 Main application

These materials are used mainly in the magnetic circuits of electrical apparatus, particularly in the parts of rotating machines in which the flux is not unidirectional. They may also be used in electromagnetic relays, small transformers, chokes for fluorescent tubes, electrical meters, shielding and magnetic poles of electron and proton synchrotrons.

4.3.2.2 Class C22 – Anisotropic[2] (oriented) steels for use at power frequencies

4.3.2.2.1 Reference documents

These materials are covered by IEC 60404-8-6, IEC 60404-8-7 and IEC 60404-8-8.

4.3.2.2.2 Chemical composition

The basic constituent of these materials is iron and the main alloying element is silicon (approximately 3 %), together with unavoidable impurities and low levels of other elements which may arise from additions necessitated during the manufacturing process. This type of magnetic material possesses anisotropic properties (orientation) such that the direction parallel to the axis of rolling shows the lowest values of specific total losses and the highest permeability. These properties are sensitive to mechanical treatment, and stress relief annealing may be used to optimize the inherent properties.

---

[2] This describes a material which is substantially anisotropic and deliberately processed to be so.

4.3.2.2.3 Basis of subclassification

The recommended subclassification is based on the perfection of crystal orientation expressed by the magnetic polarization for a magnetic field strength of 800 A/m and on the specific total loss, which is a function of thickness and of the orientation, and is normally measured at magnetic polarization values of 1,5 T or 1,7 T and at power frequencies.

With the revision of IEC 60404-8-7 in 2020, an additional subclassification has been introduced in order to distinguish between high-permeability grades with and without magnetic domain refinement.

4.3.2.2.4 Available forms

These materials are normally supplied in the form of cold-rolled coils or sheets having an inorganic insulating coating.

4.3.2.2.5 Physical characteristics

In addition to the perfection of crystal orientation and to the values of specific total loss, a more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength;
- Domain Refined (DR) state: whether or not the material has been treated with a technology for magnetic domain refinement;
- electrical: type of surface insulation and its resistance, resistivity;
- mechanical: ductility, surface condition and finish, stacking factor, flatness, edge camber;
- metallurgical state: annealed and fully recrystallized;
- dimensions: thickness, width and (if required) length.

The values of nominal thickness normally used are given in the corresponding product specifications.

Magnetic measurements are made in accordance with IEC 60404-2 or IEC 60404-3. The density used for calculations is normally 7,65 kg/dm³ and test pieces are taken parallel to the axis of rolling and, before measurement, undergo stress relief annealing in accordance with the recommendations of the manufacturer.

Ranges of specified values of maximum specific total loss, after stress relief annealing, for the normally used thicknesses are also shown in the corresponding product specifications.

NOTE According to IEC 60404-8-7, the magnetic properties of non-heatproof magnetic domain refined high-permeability grades are determined according to IEC 60404-3 without applying a supplementary heat treatment, and in the case of heatproof magnetic domain refinement grades, these properties are determined in accordance with IEC 60404-2 after the required heat treatment.

In addition, materials which are not yet specified in IEC 60404-8-7 are available.

4.3.2.2.6 Main applications

These materials are used mainly for the manufacture of magnetic cores in which the magnetic flux paths are substantially parallel to the direction of cold-rolling, as for example in transformer cores.

4.3.2.3 Class C23 – Thin silicon steels

4.3.2.3.1 Reference document

These materials are covered by IEC 60404-8-8.

4.3.2.3.2 Chemical composition

The basic constituent of these materials is iron. The main alloying element is silicon, whose content may be between 2 % and 4 %. Other alloying elements, namely aluminium, may also be present. The material also contains unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.3.2.3.3 Basis of subclassification

The recommended subclassification is based on the magnetic anisotropy and the specific total loss which is a function of thickness, magnetic polarization value and test frequency.

4.3.2.3.4 Available forms

These materials are normally supplied in the form of cold-rolled coils or sheets.

4.3.2.3.5 Physical characteristics

In addition to the values of specific total loss, a more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength;
- electrical: type of surface insulation and its resistance, resistivity;
- mechanical: ductility, stacking factor, flatness, edge camber;
- metallurgical state: annealed and fully recrystallized;
- dimensions: thickness, width and (if required) length.

The specified values of maximum specific total loss for the commonly used thicknesses are shown in the corresponding product specification.

The magnetic properties are determined in accordance with IEC 60404-10 and the test specimens are prepared as described in the specification.

4.3.2.3.6 Main applications

These materials are mainly used in magnetic circuits of transformers and rotating machines operating at frequencies above 100 Hz.

4.3.2.4 Class C24 – Steels with specified mechanical properties and specific total loss

4.3.2.4.1 Reference document

These materials are not covered by an IEC publication.

4.3.2.4.2 Chemical composition

The basic constituent of these materials is iron. The main alloying element is silicon whose content may be between 2 % and 5 %. Other alloying elements, such as aluminium, manganese, may be added to increase strength and improve magnetic properties. The material also contains unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.3.2.4.3 Basis of subclassification

The recommended subclassification is based on the yield strength.

4.3.2.4.4 Available forms

These materials are normally supplied in the form of cold-rolled and final annealed coils or sheet.

4.3.2.4.5 Physical characteristics

In addition to the yield strength, a more complete definition of these materials can be based on the following characteristics:

- magnetic: specific total loss, magnetic polarization at various values of magnetic field strength;
- electrical: surface insulation and its resistance, resistivity;
- mechanical: tensile strength, elongation, hardness, stacking factor;
- metallurgical state: fully processed, i.e. final annealed;
- dimensions: thickness, width and (if required) length.

4.3.2.4.6 Main applications

These materials are generally used under conditions of alternating flux for the stressed parts of magnetic circuits such as rotors of high-speed rotating electric machines.

4.3.2.5 Class C25 – 6,5 % silicon steels

4.3.2.5.1 Reference document

These materials are not covered by an IEC publication.

4.3.2.5.2 Chemical composition

The basic constituent of these materials is iron. The main alloying element is silicon whose content may be between 6 % and 7 %. Other alloying elements may also be present. The material also contains unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.3.2.5.3 Basis of subclassification

The recommended subclassification is based on the specific total loss which is a function of thickness, magnetic polarization value and test frequency. Specific total loss is determined in accordance with IEC 60404-10, using sheared specimens consisting of half the strip taken parallel and half taken perpendicular to the axis of rolling.

4.3.2.5.4 Available forms

These materials are normally supplied in the form of cold-rolled coils or sheets.

4.3.2.5.5 Physical characteristics

In addition to the values of specific total loss, a more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength;
- electrical: type of surface insulation and its resistance, resistivity;
- mechanical: stacking factor, flatness, edge camber;
- metallurgical state: fully processed, i.e. final annealed;
- dimensions: thickness, width and (if required) length.

As an information, particular features of this material are:

- a nearby zero magnetostriction of almost 1 x 10^{-7} at 1 T and 400 Hz when measured with an optical fiber displacement meter.
- the losses measured according to IEC 60404-10 for a material of 0,10 mm thickness at 1 T and 400 Hz is around 6 W/kg and at 0,05 T and 20 kHz around 7 W/kg.

4.3.2.5.6 Main applications

These materials are generally used in magnetic circuits of the electrical apparatus operating at frequencies above 100 Hz, which require low noise output and low core loss at higher frequency, such as high-frequency transformers, reactors and the motors used in portable electrical apparatus.

4.4 Class D – Other steels

4.4.1 Class D1 – Bulk material

4.4.1.1 Class D11 – Cast solid steels

4.4.1.1.1 Reference document

These materials are not covered by an IEC publication.

4.4.1.1.2 Chemical composition

The basic constituent of these materials is iron containing unavoidable impurities. The main alloying elements are carbon, whose content is lower than 0,45 %, and other elements (namely chromium, nickel, manganese, molybdenum and silicon) which may be necessary to develop the required properties.

4.4.1.1.3 Basis of subclassification

The recommended subclassification is based on the yield strength or 0,2 % proof stress, which are a function of chemical composition and heat treatment.

4.4.1.1.4 Available forms

These materials are usually supplied in the form of castings in a final heat-treated condition or partially machined to drawings supplied by the user.

4.4.1.1.5 Physical characteristics

In addition to the values of yield strength, a more complete definition of the material may be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, coercivity;
- electrical: resistivity;
- mechanical: tensile strength, elongation, impact properties, freedom from defects;
- metallurgical state: either normalized and tempered or quenched and tempered.

Mechanical and non-destructive tests are made in accordance with the appropriate ISO standards. Coercivity is measured in accordance with IEC 60404-7, other magnetic properties in accordance with IEC 60404-4.

4.4.1.1.6 Main applications

The materials are used in the magnetic circuits of electrical apparatus, where a certain mechanical strength is required, particularly in parts of rotating machinery such as rotors, pole pieces, pressure plates and magnet frames.

4.4.1.2 Class D12 – Forged solid steel

4.4.1.2.1 Reference document

These materials are not covered by an IEC publication.

4.4.1.2.2 Chemical composition

The basic constituent of these materials is iron. The main alloying elements are carbon whose content may vary from 0,15 % to 0,5 % and other alloying elements such as nickel (up to 4 %), chromium (up to 1,8 %), molybdenum (up to 0,5 %), vanadium (up to 0,12 %) and manganese (up to 1,9 %), depending on the mechanical properties required and the size of the forgings. The material also contains unavoidable impurities together with a low content of other elements (Si, Al) which may arise from additions necessitated during the manufacturing process.

4.4.1.2.3 Basis of subclassification

The recommended subclassification is based on the yield strength or 0,2 % proof stress which are normally a function of chemical composition and heat treatment.

4.4.1.2.4 Available forms

The materials are usually supplied in the form of forgings in a finally heat-treated and partially machined condition to drawings supplied by the user.

4.4.1.2.5 Physical characteristics

In addition to the values of yield strength, a more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength;
- electrical: resistivity;
- mechanical: tensile strength, elongation, impact properties, bend test, freedom from defects;
- metallurgical state: either normalized and tempered or quenched and tempered;
- dimensions: according to drawings supplied by the user.

Mechanical and non-destructive tests are made in accordance with the appropriate ISO standards. Magnetic properties are measured in accordance with IEC 60404-4.

4.4.1.2.6 Main applications

These materials are used in magnetic circuits of electrical apparatus, particularly in the stressed parts of rotating machines such as shafts for rotating machines, pole shoes, pole bodies and pole endplates.

4.4.2 Class D2 – Flat material

4.4.2.1 Class D21 – High strength steels – Steel with specified mechanical properties and permeability

4.4.2.1.1 Reference document

These materials are covered by IEC 60404-8-5.

4.4.2.1.2 Chemical composition

The basic constituent of these materials is iron. Alloying elements may be carbon or others, for example silicon. The material also contains unavoidable impurities and a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.4.2.1.3 Basis of subclassification

The recommended subclassification is based on the 0,2 % proof stress value.

4.4.2.1.4 Available forms

The materials are normally supplied in the form of coils or sheet.

4.4.2.1.5 Physical characteristics

In addition to the proof stress values, a more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, from which the relative permeability can be derived;
- electrical: resistivity;
- mechanical: tensile strength, elongation, surface condition, suitability for punching operations, flatness, edge camber;
- metallurgical state: hot-rolled, hot-rolled and temper-rolled, cold-rolled and final annealed, cold-rolled, annealed and temper-rolled;
- dimensions: thickness, width and (if required) length.

The values of nominal thickness normally recommended lie in the range from 0,5 mm to 4,5 mm.

Ranges of specified values of mechanical and magnetic properties are shown in the corresponding product specification.

4.4.2.1.6 Main applications

These materials are generally used under conditions of DC magnetization for the stressed parts of the magnetic circuits of rotating electrical machines, particularly spiders, rims and poles.

4.4.3 Class D3 – Stainless steels

4.4.3.1 Reference document

These materials are presently not covered by an IEC publication.

4.4.3.2 Chemical composition

The basic constituent of these materials is iron. The main alloying element is chromium in the range of 11 % to about 20 %. Other alloying elements, for example silicon and manganese, may also be present. The material also contains unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process, to improve machinability for example sulphur, selenium or lead or to enhance corrosion resistance for example molybdenum, titanium or niobium. As compared to conventional stainless steels, grades developed for magnetic applications have more stringent chemical and processing limits to yield more consistent magnetic performance.

4.4.3.3 Basis of subclassification

The recommended subclassification is based on chromium content and fabrication characteristics. Grades D31-01, D31-03 and D31-05 are intended for applications requiring good cold forming characteristics and weldability. Grades D31-02, D31-04 and D31-06 are intended for applications requiring improved machinability. Grades D31-01 and D31-02 have reduced chromium contents for reduced alloy cost and higher saturation polarization. They are, however, only suitable for moderately corrosive environments. Grades D31-03 and D31-04 are intended for use in more corrosive environments, while grades D31-05 and D31-06 are intended for use in the most corrosive environments though with some reduction in magnetic performance.

4.4.3.4 Available forms

The materials are normally supplied as billet, bar, rod, wire, sheet or strip.

4.4.3.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: saturation magnetic polarization, maximum permeability, remanent magnetic polarization, coercivity;
- electrical: resistivity;
- mechanical: machinability, cold formability, weldability, hardness;
- chemical: corrosion resistance.

Although the chromium content influences the magnetic polarization and electrical resistivity, it does not have a pronounced effect on maximum permeability and coercivity.

4.4.3.6 Main applications

These materials are used in magnetic cores and other parts requiring a high-permeability stainless steel having low coercive force and low residual magnetism: magnetic solenoid valves and automotive electromechanical devices such as fuel injectors and anti-lock braking systems.

4.5 Class E – Nickel-iron alloys

4.5.1 Class E1 – Nickel content 70 % to 85 %

4.5.1.1 Reference document

These materials are covered by IEC 60404-8-6.

4.5.1.2 Chemical composition

The basic constituents of these materials are iron and nickel whose content is in the range of 70 % to 85 %. Alloying elements such as molybdenum, copper, manganese, chromium or silicon may be added to increase resistivity and improve magnetic properties. The materials also contain unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.5.1.3 Basis of subclassification

The recommended subclassification is based on the coercivity or the amplitude permeability at a magnetic field strength of 0,4 A/m and the shape of the hysteresis loop: round, flat or rectangular.

4.5.1.4 Available forms

The materials are available as hot-rolled sections and strip, forgings, cold-drawn wire and cold-rolled sheets, strip. They are commonly supplied in the semi-processed state, but a number of materials, particularly those with flat or rectangular hysteresis loop, are available in the final heat-treated state for example as toroidal strip wound cores.

4.5.1.5 Physical characteristics

A more complete definition of the material can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, saturation magnetic polarization, coercivity, maximum amplitude.

Magnetic measurements are made in accordance with either IEC 60404-4 or IEC 60404-6 according to product form.

4.5.1.6 Main applications

The materials are used where high permeability at low magnetic field strength in combination with high remanent or saturation magnetic polarization is required.

- Round hysteresis loop: measuring instruments, current transformers, low-power transformers, relay parts, transducers, protective ground-fault circuit breakers, rotor and stator laminations, magnetic shielding;
- Flat hysteresis loop: pulse transformers, thyristor protective chokes, protective ground-fault circuit-breakers;
- Rectangular hysteresis loop: magnetic amplifiers, AC/DC converters, saturable inductors, pulse transformer cores.

4.5.2 Class E2 – Nickel content 54 % to 68 %

4.5.2.1 Reference document

These materials are covered by IEC 60404-8-6.

4.5.2.2 Chemical composition

The basic constituents of these materials are iron and nickel whose content is in the range of 54 % to 68 %. In some instances, part of the nickel may be replaced by cobalt. Additionally, molybdenum, copper, manganese, chromium or silicon may be present to increase resistivity and improve magnetic properties. The materials also contain unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.5.2.3 Basis of subclassification

A possible basis is the shape of the hysteresis loop: round or flat (magnetic field annealed).

4.5.2.4 Available forms

The materials are available as semi-processed cold-rolled strip or fully processed strip-wound cores.

4.5.2.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: maximum amplitude permeability, saturation magnetic polarization, remanent magnetic polarization, coercivity;
- electrical: resistivity;
- mechanical: suitability for winding operations;
- metallurgical state: semi-processed state, i.e. cold-rolled or fully processed state, i.e. final annealed (with or without magnetic field).

Typical values for magnetic properties in the fully processed state are given in the corresponding product specification.

Magnetic measurements are made in accordance with IEC 60404-6.

4.5.2.6 Main applications

The materials are used where high permeability at low magnetic field strength is required.

- Round hysteresis loop: protective ground-fault circuit-breakers, transducers, measuring transformers;
- Flat hysteresis loop: protective ground-fault circuit-breakers, pulse transformers, thyristor protective choke.

4.5.3 Class E3 – Nickel content 40 % to 51 %

4.5.3.1 Reference document

These materials are covered by IEC 60404-8-6.

4.5.3.2 Chemical composition

The basic constituents of these materials are iron and nickel whose content is in the range of 40 % to 51 %. Alloying elements such as molybdenum, manganese, copper, chromium or silicon may be added to increase resistivity and improve magnetic properties. The materials also contain unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.5.3.3 Basis of subclassification

The recommended subclassification is based on the amplitude permeability at a magnetic field strength of 0,4 A/m or the shape of the hysteresis loop: round (isotropic), flat (magnetic field annealed) or rectangular (anisotropic).

4.5.3.4 Available forms

The isotropic materials are available as hot-rolled sections and strip, forgings, cold drawn wire and cold-rolled sheet and strip.

The materials with flat hysteresis loop are available as strip-wound core.

The anisotropic materials are available as cold-rolled strip or tape.

4.5.3.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, saturation magnetic polarization, coercivity, remanence ratio;
- electrical: resistivity;
- mechanical: suitability for punching or deep drawing operation;
- metallurgical state: the materials require a heat treatment to develop their full magnetic properties.

Values for magnetic properties in the fully processed state are given in the corresponding product specification.

Magnetic measurements are made in accordance with either IEC 60404-4 or IEC 60404-6, according to product form.

4.5.3.6 Main applications

The materials are used where high permeability at low magnetic field strength in combination with high remanent or saturation magnetic polarization is required.

- Round hysteresis loop: measuring instruments, current transformers, low-power transformers, relay parts, transducers, protective ground-fault circuit-breakers, rotor and stator laminations, magnetic shielding, sensors;
- Flat hysteresis loop: pulse transformers, thyristor protective chokes, protective ground fault circuit breakers;
- Rectangular hysteresis loop: magnetic amplifiers, AC/DC converters, saturable inductors, pulse transformer cores.

4.5.4 Class E4 – Nickel content 35 % to 40 %

4.5.4.1 Reference document

These materials are covered by IEC 60404-8-6.

4.5.4.2 Chemical composition

The basic constituents of these materials are iron and nickel whose content is in the range of 35 % to 40 %. Alloying elements such as molybdenum, manganese, copper, chromium or silicon may be added to increase resistivity and improve magnetic properties. The materials also contain unavoidable impurities, together with a level of other elements which may arise from additions necessitated during the manufacturing process.

4.5.4.3 Basis of subclassification

The recommended subclassification is based on the coercivity or the amplitude permeability at a magnetic field strength of 1,6 A/m.

4.5.4.4 Available forms

The materials are available as hot-rolled sections and strips, forgings, cold-drawn wire and cold-rolled sheet and strip. It is commonly supplied in the semi-processed state, but a number of materials are available in the fully processed state.

4.5.4.5 Physical characteristics

A more complete definition of the material can be based on the following characteristics:

- magnetic: coercivity, magnetic polarization at various values of magnetic field strength;

- electrical: resistivity;
- mechanical: suitability for punching and deep drawing operations;
- metallurgical state: the materials require a heat treatment to develop their full magnetic properties.

Specified values for magnetic properties of materials in the fully processed state are given in the corresponding product specification.

Magnetic measurements are made in accordance with either IEC 60404-4 or IEC 60404-6, according to product form.

4.5.4.6 Main applications

The materials are used for high-frequency and pulse applications, telecommunication translators, high-frequency filters or transformers, blocking transformers, pulse transformers, magnetic shields.

4.5.5 Class E5 – Nickel content 29 % to 33 %

4.5.5.1 Reference document

These materials are not covered by an IEC publication.

4.5.5.2 Chemical composition

The basic constituents of these materials are iron and nickel. The Curie temperature is strongly dependent on the nickel content. Alloying elements such as copper may be added to improve magnetic performance. The materials also contain unavoidable impurities together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.5.5.3 Basis of subclassification

A possible basis of subclassification is the maximum service temperature.

4.5.5.4 Available forms

The materials are supplied as cold-rolled strip or cold-drawn wire usually in the fully processed condition.

4.5.5.5 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: change of magnetic polarization with temperature for a given magnetic field strength and a given range of temperature;
- electrical: resistivity;
- metallurgical state: semi-processed, i.e. cold-rolled or cold-drawn;
  fully processed, i.e. final annealed.

4.5.5.6 Main applications

Temperature compensators (magnetic shunts) for permanent magnet measuring devices especially for electric current (watt-hour) meters and automotive voltage regulators.

4.6 Class F – Iron-cobalt alloys

4.6.1 Class F1 – Cobalt content 47 % to 50 %

4.6.1.1 Reference document

These materials are covered by IEC 60404-8-6.

4.6.1.2 Chemical composition

The basic constituents of these materials are iron and cobalt whose content is in the range of 47 % to 50 %. Alloying elements such as vanadium, chromium, zirconium, niobium or tantalum may be added to improve ductility.

4.6.1.3 Basis of subclassification

The recommended subclassification is based on the coercivity.

4.6.1.4 Available forms

The materials are supplied as hot-rolled rectangular and round bars, cold-drawn wire, strip and sheet, forgings and cold-rolled strip.

4.6.1.5 Physical characteristics

A more complete definition of the material can be based on the following characteristics:

- magnetic: maximum relative permeability, saturation magnetic polarization, magnetic polarization for various values of magnetic field strength, remanence, coercivity, specific total loss;
- mechanical: suitability for punching operations in the cold-worked state, machinability in the hot-worked or heat-treated state, yield strength;
- metallurgical state: the materials require a heat treatment to develop their full magnetic properties.

Magnetic measurements are made in accordance with either IEC 60404-4 or IEC 60404-6, according to product form.

Values for magnetic properties of final annealed material are given in the corresponding product specification.

4.6.1.6 Main applications

The materials are used in applications involving extremely high magnetic polarizations in low or medium magnetic fields such as motors and generators with highest power density, actuators, transformers, relays, electromagnetic and electro-mechanical devices for aeronautical or aerospace equipment, pole pieces for electromagnets, magnetic lenses and magnetic bearings.

4.6.2 Class F2 – Cobalt content 35 %

4.6.2.1 Reference document

These materials are covered by IEC 60404-8-6.

4.6.2.2 Chemical composition

The basic constituents of these materials are iron and cobalt the content of which is approximately 35 %. Alloying elements such as vanadium or chromium may be added to improve ductility.

4.6.2.3 Basis of subclassification

The recommended subclassification is based on the coercivity.

4.6.2.4 Available forms

The materials are available as hot-rolled strip and sheet, forgings and castings.

4.6.2.5 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, saturation magnetic polarization;
- mechanical: machinability in the hot-worked or heat-treated state;
- metallurgical state: semi-processed state, i.e. hot-rolled or hot-worked; the material requires a heat treatment to develop its full magnetic properties.

Magnetic measurements are made in accordance with either IEC 60404-4 or IEC 60404-6, according to product form.

Specified values for magnetic properties of the final annealed materials are given in the corresponding product specification.

4.6.2.6 Main applications

The materials are mainly used for applications involving either extremely high magnetic polarizations or unusually high temperatures and as pole pieces for electromagnets.

4.6.3 Class F3 – Cobalt content 23 % to 30 %

4.6.3.1 Reference document

These materials are covered by IEC 60404-8-6.

4.6.3.2 Chemical composition

The basic constituents of these materials are iron and cobalt of which the content is in the range of 23 % to 30 %. Alloying elements such as vanadium, niobium, molybdenium or chromium may be added to improve ductility.

4.6.3.3 Basis of subclassification

The recommended subclassification is based on the coercivity.

4.6.3.4 Available forms

The materials are available as hot-rolled round bars, hot-rolled sheet and strip, forgings, cold-drawn wire and cold-rolled strip and tape.

4.6.3.5 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, saturation magnetic polarization;
- mechanical: ductility; suitability for punching operations in the cold-worked state and machinability in the hot-worked or heat-treated state;
- metallurgical state: semi-processed state, i.e. hot-rolled, cold-rolled, forged, cast or cold-drawn. The material requires a heat treatment to develop its full magnetic properties.

Magnetic measurements are made in accordance with either IEC 60404-4 or IEC 60404-6, according to product form.

Specified values for the magnetic properties of final annealed material are given in the corresponding product specification.

4.6.3.6 Main applications

These materials are mainly used for applications involving either extremely high magnetic polarizations or particularly high temperatures, such as for electromagnetic and electro-mechanical devices for aeronautical or aerospace equipment, especially when subjected to mechanical load in service such as liquid metal pumps and magnetic bearings. They are also used for pole pieces for electromagnets.

4.7 Class G – Other alloys

4.7.1 Class G1 – Aluminium-iron alloys

4.7.1.1 Reference document

These materials are not covered by an IEC publication.

4.7.1.2 Chemical composition

The basic constituents of these materials are iron and aluminium whose content may be between 12 % and 16 %, together with unavoidable impurities. These materials may contain additions of chromium and rhenium to improve the magnetic properties of the alloy.

4.7.1.3 Basis of subclassification

The recommended subclassification is based on the aluminium content.

4.7.1.4 Available forms

The materials are normally supplied in the form of hot-rolled bars, strips and sheets or cast or sintered structural parts.

4.7.1.5 Physical characteristics

In addition to aluminium content, a more complete definition can be based on the following properties:

- magnetic: initial and maximum permeability, coercivity, saturation magnetic polarization, magnetostriction;
- mechanical: hardness, suitability for punching operations, surface condition;
- metallurgical state: hot-rolled, cast, sintered;
- dimensions: thickness, width (as required), diameter.

4.7.1.6 Main applications

The materials are used in the manufacture of laminated cores for magnetic heads and ultrasonic transducers or as structural parts of magnetic circuits.

4.7.2 Class G2 – Aluminium-silicon-iron alloys

4.7.2.1 Reference document

These materials are not covered by an IEC publication.

4.7.2.2 Chemical composition

The basic constituents of these materials are iron, aluminium, the content of which may be between 5 % to 6,5 %, and silicon, the content of which may be between 7 % and 9,5 %, together with unavoidable impurities. These alloys may contain additions of titanium, cerium, niobium and vanadium to improve magnetic and mechanical properties.

4.7.2.3 Basis of subclassification

The recommended subclassification is based on the initial permeability.

4.7.2.4 Available forms

The materials are normally supplied in the form of castings or of semi-processed products, for example, powder.

4.7.2.5 Physical characteristics

In addition to the initial permeability, a more complete definition can be based on the following characteristics:

- magnetic: saturation magnetic polarization, coercivity, initial permeability, maximum permeability;
- electrical: resistivity;
- mechanical: hardness;
- metallurgical state: as cast;
- dimensions: determined by application.

4.7.2.6 Main applications

The materials are used for the parts of magnetic circuits, magnetic heads and as semi-processed products, for example, powder.

4.8 Class H – Magnetically soft materials made by powder metallurgical techniques

4.8.1 Class H1 – Soft ferrites

4.8.1.1 Reference document

These materials are covered by IEC 60401-3.

4.8.1.2 Chemical composition

The majority of commercially available soft ferrites are polycrystalline ceramics having a cubic crystal structure and a typical formula MFe_2O_4 where M usually represents one or more of the divalent transition metals. In the most common materials, M is either a combination of manganese and zinc, or of nickel and zinc.

4.8.1.3 Basis of subclassification

The recommended subclassification is based on the initial permeability.

4.8.1.4 Available forms

Magnetically soft ceramics are generally supplied in the form of magnetic components, for which the raw materials are made into powder, formed to the required shape, sintered and mechanically finished. Only a very small proportion is supplied as a material in the form of a (fully sintered) magnetic powder.

Calcined powders for component production cannot be considered as ferrite material for the purpose of this classification.

4.8.1.5 Physical characteristics

A more complete definition of these materials may be based on the following characteristics:

- magnetic: initial permeability, saturation magnetic flux density, remanent flux density, coercivity, relative loss factor at low flux density, hysteresis material constant, relative temperature factor, disaccommodation factor, total harmonic distortion factor, power loss (volume) density, amplitude permeability;
- mechanical: density;
- thermal: Curie temperature;
- electrical: resistivity, normalized impedance;
- shapes: rods, tubes, screw and drum cores, balun cores, multi-hole bead, ring cores, EP, E, EFD, PQ, pot, PM, RM and U cores.

Where material values are quoted, these are normally measured on ring cores of stated dimensions and identical characteristics cannot always be realized on a component of differing geometry.

Typical ranges of properties for the Mn-Zn- and the Ni-Zn-ferrites are given in the corresponding product specification.

The properties depend strongly on the exact composition, i.e. the metal ions and their proportion. The heat treatment including atmosphere and cooling rate are critical factors in developing the properties.

Variation of one property normally influences the value of various other properties. This situation gives rise to the existence of many separate materials, each intended for a relatively small group of applications.

4.8.1.6 Main applications

Among the most important applications are the following:

- cores for inductors and transformers operating at frequencies in the range from audio frequency to several hundred MHz;
- cores for pulse transformers up to several hundred MHz;
- aerial rods;
- cores for power transformers operating at frequencies in the range from about 5 kHz to about 30 MHz;
- ring cores and multiaperture cores for data storage devices;
- cores for recording heads;
- cores for deflection coils on cathode-ray tubes;
- cores for reciprocal and non-reciprocal microwave devices;
- beads for RF decoupling and attenuation of unwanted signals.

4.8.2 Class H2 – Magnetically soft sintered materials

4.8.2.1 Reference document

These materials are covered by IEC 60404-8-9.

4.8.2.2 Chemical composition and manufacturing method

Magnetically soft sintered materials are produced by the powder metallurgical (PM) technique. This manufacturing technology allows the economical manufacture of structural parts. An additional heat treatment is necessary if the structural parts have to be machined to keep the prescribed tolerances or to complete the final shape.

Besides plain iron FeP-alloys containing 0,3 % to 0,8 % P, FeNi-alloys containing 30 % to 85 % Ni, FeCo-alloys containing 40 % to 55 % Co and FeSi-alloys containing 0,3 % to 3,5 % Si are usual.

4.8.2.3 Basis of subclassification

For each alloy the recommended subclassification is based on the coercivity.

4.8.2.4 Available forms

Magnetically soft sintered materials are generally supplied as structural parts.

4.8.2.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, saturation magnetic polarization, maximum permeability;
- mechanical: density, porosity, hardness;
- electrical: resistivity.

Physical and magnetic properties are given in the corresponding product specification.

4.8.2.6 Main application

The materials are used as structural parts in magnetic circuits.

4.8.3 Class H3 – Powder composites

4.8.3.1 Reference document

These materials are not covered by an IEC publication.

4.8.3.2 Chemical composition and manufacturing method

Powder composite materials consist of a basic magnetic powder and inorganic or organic electrically insulating additives and binders.

Pure iron (Fe), iron-silicon (FeSi, FeSiAl) and nickel-iron (FeNi, FeNiMo) powder composites are in use. Powder metallurgical techniques such as cold-isostatic pressing, die pressing or injection moulding are used for manufacturing.

4.8.3.3 Basis of subclassification

For each material the recommended subclassification is based on the initial permeability. A possible basis of subclassification is the composition of the alloying elements.

4.8.3.4 Available forms

Powder composite materials are supplied as structural parts (powder cores) or cold isostatic pressed blanks. In the case of organic bound composites, shaping by machining is possible.

4.8.3.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: initial permeability, saturation magnetic polarization, total loss density;
- mechanical: density;
- electrical: resistivity.

4.8.3.6 Main application

The materials are used as ring-shaped powder cores for inductive components (storage chokes) and as structural parts in motor applications.

4.9 Class I – Amorphous soft magnetic materials

4.9.1 General

Amorphous alloys are non-crystalline materials which are produced via rapid solidification by casting as thin sheets, wires and powders. Due to the lack of long-range atomic order, they have no magneto-crystalline anisotropy. Interesting soft magnetic properties are found in Fe-based alloys with relatively high saturation magnetic polarization and in Co-based alloys with near-zero magnetostriction.

4.9.2 Class I1 – Iron-based amorphous alloys

4.9.2.1 Reference document

These materials are ~~not~~ covered by ~~an IEC publication~~ IEC 60404-8-11.

4.9.2.2 Chemical composition

The basic constituents of these materials are iron and metalloids (mainly silicon and boron) the content of which is commonly in the range of 16 % by atoms to 30 % by atoms. These alloys may further contain additions of titanium, vanadium, chromium, zirconium, niobium, manganese, carbon or molybdenum to improve magnetic and mechanical properties. Part of the iron may be substituted by nickel or cobalt.

4.9.2.3 Basis of subclassification

The recommended subclassification is based on the saturation magnetic polarization and the shape of the hysteresis loop.

4.9.2.4 Available forms

The materials are normally supplied in the form of rapidly solidified thin ribbons of typical thickness 20 µm to 50 µm and in the form of tape wound cores.

4.9.2.5 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: specific total loss as a function of magnetic polarization and frequency, specific apparent power, saturation magnetic polarization, magnetostriction, coercivity, initial permeability, reversible permeability at various values of magnetic field strength, squareness of the *B-H* loop, remanence;
- electrical: resistivity;
- thermal: Curie temperature, crystallization temperature;
- dimensions: thickness, width;
- mechanical: ductility, stacking factor;
- metallurgical state: semi-processed state, i.e. as cast. The magnetic properties are developed by the heat treatment in a magnetic field.

The properties depend strongly on the exact composition of the material and on the heat treatment.

4.9.2.6 Main applications

Variation of one property normally influences the value of various other properties. This situation gives rise to the existence of many different materials, each intended for a relatively small group of applications.

The most important ones are:

- core material for distribution transformers at power frequency,
- cores for inductors and transformers operating at frequencies up to several hundred kHz, and
- theft detection tags.

4.9.3 Class I2 – Cobalt-based amorphous alloys

4.9.3.1 Reference document

These materials are not covered by an IEC publication.

4.9.3.2 Chemical composition

The basic constituents of these materials are cobalt and iron or manganese whose content is commonly in the range of 2 % by atoms to 10 % by atoms and metalloids (silicon and boron mainly) whose content is in the range of 18 % by atoms to 30 % by atoms. Cobalt may be partly substituted by nickel. These alloys may contain additions of titanium, vanadium, chromium, zirconium, niobium, molybdenum, ruthenium, hafnium, tantalum and tungsten to improve magnetic and mechanical properties.

4.9.3.3 Basis of subclassification

The recommended subclassification is based on the saturation magnetic polarization and the shape of the hysteresis loop.

4.9.3.4 Available forms

The materials are normally supplied in the form of rapidly solidified thin strips with a typical thickness of 10 μm to 50 μm and in the form of tape wound cores.

4.9.3.5 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: magnetostriction, initial permeability, reversible permeability at various values of magnetic field strength, specific total loss as a function of frequency, squareness of the B-H loop, coercivity;
- electrical: resistivity;
- thermal: Curie temperature, crystallization temperature;
- dimensions: thickness, width;
- metallurgical state: semi-processed state, i.e. as cast.

The properties depend strongly on the exact composition of the material and on the heat treatment. Some magnetic properties can be developed by further heat treatment with or without a magnetic field.

4.9.3.6 Main applications

Variation of one property normally influences the value of various other properties. This situation gives rise to the existence of many different materials, each intended for a relatively small group of applications.

The most important ones are

- cores for inductors and transformers operating at frequencies in the range from 50 Hz to several MHz,
- cores for pulse transformers,
- cores for recording heads, and
- flexible magnetic shielding.

4.9.4 Class I3 – Nickel-based amorphous alloys

4.9.4.1 Reference document

These materials are not covered by an IEC publication.

4.9.4.2 Chemical composition

The basic metallic constituents of these materials are nickel and iron in approximately equal amounts by weight and which form about 90 % of the alloy by weight. In some alloys molybdenum can be present. The principal metalloid is boron although phosphorus and silicon can also be present.

4.9.4.3 Basis of subclassification

The recommended subclassification is based on the shape of the hysteresis loop.

4.9.4.4 Available forms

The materials are normally supplied in the form of rapidly solidified thin strips with a typical thickness of 15 µm to 50 µm.

4.9.4.5 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: magnetostriction, initial permeability, reversible permeability at various values of magnetic field strength, specific total loss as a function of frequency, squareness of the B-H loop, coercivity, shielding attenuation ratio;
- electrical: resistivity;
- thermal: Curie temperature, crystallization temperature;
- dimensions: thickness, width;
- metallurgical state: semi-processed state, i.e. as cast.

The properties depend strongly on the exact composition of the material and on the heat treatment. Some magnetic properties can be developed by further heat treatment with or without a magnetic field.

4.9.4.6 Main applications

The main applications are for article surveillance sensors and magnetic EMI shielding.

4.10 Class J – Nano-crystalline soft magnetic materials

4.10.1 Reference document

These materials are not covered by an IEC publication.

4.10.2 Production process

Iron-based nano-crystalline alloys are produced via rapid solidification by casting as thin sheets, wires or powders. After this casting process the material is in the amorphous state. The desirable nano-crystalline state is achieved by annealing at temperature between 500 °C and 600 °C. Nano-crystalline alloys exhibit a high saturation magnetic polarization and an almost zero magnetostriction due to their nano-crystalline microstructure.

4.10.3 Chemical composition

The basic constituents of these materials are iron, copper typically around 1 % by atoms, niobium around 3 % by atoms and metalloids (mainly silicon and boron) typically in the range of 16 % by atoms to 28 % by atoms. These alloys may further contain additions of zirconium, molybdenum, tantalum, titanium, vanadium, phosphorus, chromium, manganese and carbon to improve the magnetic and mechanical properties.

4.10.4 Basis of subclassification

The recommended subclassification is based on the saturation magnetic polarization and the shape of the hysteresis loop.

4.10.5 Available forms

The materials can be supplied in the amorphous state in the form of rapidly solidified thin ribbons of typical thickness 12 μm to 30 μm and in the nanocrystalline state in the form of tape wound cores.

4.10.6 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: specific total loss as a function of magnetic polarization and frequency, specific apparent power, saturation magnetic polarization, magnetostriction, coercivity, initial permeability, reversible permeability at various values of magnetic field strength, squareness of the B-H loop, remanence;
- electrical: resistivity;
- thermal: Curie temperature, crystallization temperature of the nanocrystalline grains, crystallization temperature of the amorphous matrix;
- dimensions: thickness, width;
- mechanical: ductility, stacking factor;
- metallurgical state: semi-processed state, i.e. as cast. The magnetic properties are developed by the heat treatment above the crystallisation temperature. Magnetic fields can be used to support the formation of induced anisotropies.

The properties depend strongly on the exact composition of the material and on the heat treatment.

4.10.7 Main applications

Variation of one property normally influences the value of various other properties. This situation gives rise to the existence of many different materials, each intended for a relatively small group of applications.

The most important ones are

- magnetic cores,
- inductive components like current transformers and yokes,
- shielding foils.

5 Magnetically hard materials (coercivity > 1 kA/m)

5.1 Class Q – Magnetostrictive alloys – Rare earth iron alloys (Class Q1)

5.1.1 Reference document

These materials are not covered by an IEC publication.

5.1.2 Chemical composition

The basic constituents of these materials are iron, terbium and dysprosium. In $Tb_xDy_{(1-x)}Fe_y$ compounds, the value of x determines the Tb/Dy ratio and y is the Fe/(Tb + Dy) ratio. The optimum values of x are close to 0,3, where high magnetostriction is obtained without excessive hysteresis losses. The stoichiometric value for y = 2,0 produces optimum magnetostrictive properties but the resulting materials are very brittle. As y is decreased from 2, the material becomes less brittle and the value of y = 1,95 provides a good compromise.

5.1.3 Basis of subclassification

There is no recognized subclassification.

5.1.4 Available forms

Grain-oriented, round bars of different sizes are available manufactured by free stand zone melting or modified Bridgeman solidification processes. The cylinder axis is the easy direction of magnetization.

5.1.5 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: magnetostrictive strain at saturation, Curie temperature, magneto-elastic coupling factor k_{33}, d-constant ($\mathrm{d}\lambda/\mathrm{d}H$), relative permeability, magnetic specific acoustic impedance, energy density;
- mechanical: density, modulus of elasticity, sound speed, tensile strength, compressive strength;
- thermal: thermal expansion coefficient;
- electrical: resistivity;
- metallurgical state: grain-oriented and heat-treated

The machinability is limited due to their brittleness. The materials can be ground or cut by means of a spark cutter or a diamond wheel.

5.1.6 Main applications

The materials are of prime interest for applications involving large forces and fast, high-precision motion at high power levels. Such applications are in high-power sound projectors in sonars and defence systems, for oil field logging and oceanography studies.

Other applications being developed are as active elements in electromechanical applications.

5.2 Class R – Magnetically hard alloys

5.2.1 Class R1 – Aluminium-nickel-cobalt-iron-titanium (AlNiCo) alloys

5.2.1.1 Reference document

These materials are covered by IEC 60404-8-1.

5.2.1.2 Chemical composition and manufacturing method

These alloys consist of 8 % to 13 % aluminium, 13 % to 28 % nickel, 5 % to 42 % cobalt, 0 % to 9 % titanium, 2 % to 6 % copper, 0 % to 3 % niobium, 0 % to 0,8 % silicon and the balance iron. They may contain other additions.

They are made by casting or a powder metallurgical process. The magnetic performance of alloys with a cobalt content higher than 20 % can be increased in a preferred direction by applying a magnetic field during heat treatment producing magnetic anisotropy. The best performances of cast magnets are achieved with alloys of columnar or single crystal structure, the magnetic field being applied parallel to the columnar axis.

5.2.1.3 Basis of subclassification

The subclassification is based on the magnetic degree of anisotropy and the manufacturing method.

5.2.1.4 Available forms

The magnets are mainly produced in the form of rings, prisms, cubes, cylinders or arc segments. Cast magnets with columnar or single crystal structure are subject to limitations of form and dimensions.

5.2.1.5 Physical characteristics

In addition to the degree of anisotropy and the manufacturing method, a more complete definition can be based on the following characteristics:

- magnetic: maximum BH product, remanent flux density, coercivity, recoil permeability;
- thermal: temperature coefficients of remanent flux density and of coercivity, and Curie temperature;
- mechanical: density, machinability;
- metallurgical state: cast or sintered and heat-treated;
- dimensions: determined by application.

Ranges of specified values of magnetic properties and density for isotropic and anisotropic AlNiCo alloys are given in the corresponding product specification.

5.2.1.6 Main applications

These materials are used in measuring devices and loudspeakers.

5.2.2 Class R3 – Iron-cobalt-vanadium-chromium (FeCoVCr) alloys

5.2.2.1 Reference document

These materials are covered by IEC 60404-8-1.

5.2.2.2 Chemical composition and manufacturing method

These materials consist of 49 % to 54 % cobalt, 4 % to 13 % vanadium plus chromium and the balance being iron.

The FeCoVCr alloys are manufactured by casting and subsequent hot and cold rolling or drawing to produce strips or wires, respectively.

5.2.2.3 Basis of subclassification

The recommended subclassification is based on the coercivity H_{cJ}.

5.2.2.4 Available forms

The material is generally available in the form of wires and bars with diameter < 20 mm or strips with a thickness < 6 mm.

5.2.2.5 Physical characteristics

A more complete definition of these magnetically anisotropic materials can be based on the following characteristics:

• magnetic:	maximum BH product, remanent flux density, coercivity;
• thermal:	temperature coefficients of remanent flux density and of coercivity, and Curie temperature;
• mechanical:	machinability before hardening;
• metallurgical state:	hot- and cold-rolled, heat-treated to develop magnetic properties;
• dimensions:	determined by application.

Specified values of magnetic properties and density for final annealed anisotropic FeCoVCr alloys are given in the corresponding product specification.

5.2.2.6 Main applications

These materials are used for compass needles, hysteresis motors, speedometers and sensors, and actuators for electromechanical displays.

5.2.3 Class R5 – Rare earth cobalt (RECo) alloys

5.2.3.1 Reference document

These materials are covered by IEC 60404-8-1.

5.2.3.2 Chemical composition and manufacturing method

Two main types of RECo magnet material are available; they are based on the compounds $SmCo_5$ and Sm_2Co_{17}. The $SmCo_5$ alloys consist of 33 % to 36 % samarium and the balance cobalt. The Sm_2Co_{17} alloys consist of 24 % to 26 % samarium, 10 % to 20 % iron, 4,5 % to 12 % copper, other elements (e.g. zirconium, hafnium or titanium) and the balance cobalt.

Magnets may be formed by compacting the powder in a magnetic field and sintering the compacted body followed by heat treatments.

5.2.3.3 Basis of subclassification

The recommended subclassification is based on chemical composition and manufacturing method.

5.2.3.4 Available forms

The materials are typically available in the form of blocks, cylinders, rings and arc segments.

5.2.3.5 Physical characteristics

All RECo magnetic materials are normally magnetically anisotropic.

A more complete definition can be based on the following characteristics:

- magnetic: maximum BH product, remanent flux density, coercivity, recoil permeability, uniformity field strength;
- thermal: temperature coefficients of remanent flux density and of coercivity, and Curie temperature;
- mechanical: density, machinability;
- metallurgical state: sintered;
- dimensions: determined by application.

Sintered materials are brittle but machinable by grinding.

Ranges of specified values of magnetic properties and density for anisotropic sintered RECo alloys are given in the corresponding product specification. In addition, materials with improved magnetic properties, especially H_{cJ}, are available.

5.2.3.6 Main applications

These materials are mainly used in rotating machines and many other motor applications, transducers, separators, magnetic clutches and for medical applications. They find particular application where miniaturization is a requirement.

5.2.4 Class R6 – Chromium-iron-cobalt (CrFeCo) alloys

5.2.4.1 Reference document

These materials are covered by IEC 60404-8-1.

5.2.4.2 Chemical composition and manufacturing method

The materials consist of 25 % to 35 % chromium, 7 % to 25 % cobalt, 0,1 % to 3 % other elements (e. g. silicon, titanium, molybdenum, aluminium and vanadium) and the balance iron.

The CrFeCo alloys can be manufactured by casting, followed by hot and cold rolling and drawing to produce strips and wires. The magnets can also be formed by a powder metallurgical process. The magnetic performance of the cast as well as sintered material can be increased in a preferred direction by applying a magnetic field during heat treatment.

5.2.4.3 Basis of subclassification

The recommended subclassification is based on the degree of magnetic anisotropy and the manufacturing method (cast or sintered).

5.2.4.4 Available forms

The materials are generally available in the form of wire, strip and rod. They are also available in the form of cast shapes.

5.2.4.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: maximum BH product, remanent flux density, coercivity, recoil permeability;
- thermal: temperature coefficients of remanent flux density and of coercivity, and Curie temperature;
- mechanical: machinability and workability;
- metallurgical state: cold-rolled or drawn, cast, sintered;
- dimensions: determined by application.

Ranges of specified values of magnetic properties and density for final annealed isotropic and anisotropic CrFeCo alloys are given in the corresponding product specification.

5.2.4.6 Main applications

These materials are used for measuring devices, loudspeakers, rotating machines (including hysteresis motors), speedometers and theft detection labels and tags.

5.2.5 Class R7 – Rare earth-iron-boron (REFeB) alloys sintered magnets

5.2.5.1 Reference document Void

These materials are covered by IEC 60404-8-1.

5.2.5.2 Chemical composition and manufacturing method

The alloys sintered magnets are based on the compound $RE_2Fe_{14}B$. RE is mainly neodymium, which may be partially substituted by dysprosium, praseodymium or other rare earths. Iron may be partially substituted by cobalt. The alloys consist of 28 % to 35 % total rare earth, 0 % to 15 % cobalt., 0,85 % to 1,2 % boron, 0 % to 10 11 % dysprosium, and terbium and , 0 % to 15 % praseodymium, cerium (Ce), etc., 0 % to 1 % vanadium, niobium, aluminium, gallium and copper, and the balance iron. Magnets of this type can be divided into two main groups:

- The first group is sintered magnets are prepared by compacting milled alloy powder in a magnetic field and sintering the compacted body for densification followed by a heat treatment, resulting in a magnet with anisotropic magnetic properties;.
- the second group uses rapidly solidified flakes prepared by the melt-spinning process. Three different products are obtained by processing the flakes into an isotropic resin-bonded magnet (see 5.5.4), an isotropic hot-pressed magnet and a magnet with anisotropic magnetic properties achieved by hot die upset forging or extrusion.

A metallic or resinous layer on the surface of the magnet may be applied to resist corrosive attacks.

5.2.5.3 Basis of subclassification

The recommended subclassification is based on the degree of magnetic anisotropy of the material and the manufacturing method.

5.2.5.4 Available forms

The materials are typically available in the form of blocks, cylinders, rings and arc segments.

5.2.5.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: maximum BH product, remanent flux density, coercivity, recoil permeability, demagnetization field strength;
- thermal: temperature coefficients of remanent flux density and of coercivity, and Curie temperature;
- mechanical: density, machinability;
- dimensions: determined by application.

Sintered or hotpressed materials are brittle, but machinable by grinding.

Ranges of specified values of magnetic properties and density for anisotropic sintered REFeB alloys are given in the corresponding product specification.

5.2.5.6 Main applications

The materials are mainly used for traction motors for hybrid electric vehicles (HEV) and electric vehicles (EV), direct drive type generators for wind turbines, voice coil motors and many other electrical motors, electroacoustical applications, separators, magnetic resonance imaging (MRI).

5.2.6 Class R8 - Rare earth-iron-boron (REFeB) hot deformed magnets

5.2.6.1 Reference document

These materials are covered by IEC 60404-8-1.

5.2.6.2 Chemical composition and manufacturing method

The hot deformed magnets are based on the compound $RE_2Fe_{14}B$. The composition of the magnets are the same as the REFeB sintered magnets (Class R7).

The hot deformed magnets use rapidly solidified flakes prepared by the melt-spinning process. After obtaining isotropic pressed bodies, the pressed bodies are consolidated and subsequently hot deformed at elevated temperatures. Alignment of grains is obtained along compression stress during die-upsetting or extrusion.

5.2.6.3 Basis of subclassification

The recommended subclassification is based on the degree of magnetic anisotropy and chemical compositions of the material.

5.2.6.4 Available forms

The materials are typically available in the form of rings and plates.

5.2.6.5 Physical characteristics

The physical characteristics of REFeB hot deformed magnets are the same as REFeB sintered magnets (Class R7).

5.2.6.6 Main applications

The main applications of REFeB hot deformed magnets are the same as REFeB sintered magnets (Class R7).

5.3 Class S – Magnetically hard ceramics – Hard ferrites (Class S1)

5.3.1 Reference document

These materials are covered by IEC 60404-8-1.

5.3.2 Chemical composition and manufacturing method

The composition of the hard ferrites can be described by the formula $\mathrm{MO}\cdot n\ \mathrm{Fe_2 0_3}$ (where M is barium ~~or~~, strontium and calcium). The value of n can vary from 4,5 to 6,5. The magnetic properties may be improved by special substitutions. This is particularly so with substitutions of ~~up to 9 % of~~ lanthanum for strontium or calcium and ~~up to 4 %~~ of cobalt for iron. The hard ferrites have a hexagonal crystal structure ~~crystal~~ with magnetic anisotropy.

Compacting of the powder is carried out with or without a magnetic field, thus obtaining anisotropic or isotropic magnets. The pressed bodies are sintered.

5.3.3 Basis of subclassification

The recommended subclassification is based on the degree of magnetic anisotropy and the manufacturing method.

5.3.4 Available forms

Magnetic isotropic and anisotropic sintered hard ferrites are mainly produced as rings, prismatic blocks, cylinders and arc segments.

5.3.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: maximum BH product, remanent flux density, coercivity, recoil permeability;
- thermal: temperature coefficients of remanent flux density and of coercivity, and Curie temperature;
- mechanical: density, machinability, mechanical strength;
- dimensions: determined by application.

Sintered materials are brittle, but machinable by grinding. Sintered magnets have usually large transverse dimensions compared with their length.

Ranges of specified values of magnetic properties and density for isotropic and anisotropic hard ferrites are given in the corresponding product specification.

5.3.6 Main applications

The materials are mainly used in rotating machines, loudspeakers, holding devices and toys.

5.4 Class T – Other magnetically hard materials – Martensitic steels (Class T1)

5.4.1 Reference document

These materials are not covered by an IEC publication.

5.4.2 Composition

These materials have a tetragonal structure which is achieved by water quenching from the austenitic phase. This structure combines mechanical with magnetic hardness. In addition to carbon, alloying elements such as cobalt or chromium are present.

5.4.3 Basis of subclassification

The recommended subclassification is based on the cobalt content.

5.4.4 Available forms

These materials are available as hot-rolled sections.

5.4.5 Physical characteristics

A more complete definition of these materials may be based on the following characteristics:

- magnetic: maximum BH product, remanent flux density, coercivity;
- thermal: temperature coefficients of magnetic remanence and of coercivity, and Curie temperature;
- mechanical: density;
- metallurgical state: hot-rolled and quenched, tempered;
- dimensions: determined by application.

For hysteresis motors which are the main application of these materials, a tempering heat treatment in the range 300 °C to 550 °C is applied. This reduces the coercivity H_{cB} and improves the fullness of the curve.

This application requires material in the form of a thin walled cylinder, mechanically strong and magnetically homogeneous.

5.4.6 Main applications

In the tempered condition the materials are used for hysteresis motors.

Their use in other conditions is almost obsolete.

5.5 Class U – Bonded magnetically hard materials

5.5.1 General

These bonded magnets are composite materials. They consist of permanent magnet powders embedded in a plastic matrix. This binder phase determines to a large extent the mechanical properties of the composite, while the magnet powder determines its magnetic properties. The properties of the composite are determined not only by the type of magnet powder and the matrix material but also by the fill factor and for anisotropic material the degree of alignment. There is a wide variety of grades.

In spite of their lower magnetic values compared with sintered materials, bonded magnets offer economic and technical advantages in many applications because they are cost-effective to manufacture and allow a wide scope for shaping and good mechanical properties. Expensive and elaborate processing steps required in powder metallurgy are not needed.

5.5.2 Class U1 – Bonded aluminium-nickel-cobalt-iron-titanium (AlNiCo) magnets

5.5.2.1 Reference document

These materials are covered by IEC 60404-8-1.

5.5.2.2 Chemical composition and manufacturing method

These bonded magnets contain crushed alloys as given in class R1 together with a resin binder. This mixture is pressed at elevated temperature and cured.

5.5.2.3 Basis of subclassification

The recommended subclassification is based on the chemical composition, the degree of magnetic anisotropy and the manufacturing method.

5.5.2.4 Available form

The magnets are mainly produced in the form of small blocks.

5.5.2.5 Physical characteristics

The magnetic properties are determined by the alloy and the fill factor of the bonding material.

The thermal properties are determined by the alloy and the bonding material.

Ranges of specified values of magnetic properties and density for isotropic bonded AlNiCo magnets are given in the corresponding product specification.

5.5.2.6 Main applications

The materials are used for watt-hour meters and measuring devices.

5.5.3 Class U2 – Bonded rare earth-cobalt (RECo) magnets

5.5.3.1 Reference document

These materials are covered by IEC 60404-8-1.

5.5.3.2 Chemical composition and manufacturing method

These bonded magnets contain powdered alloys as given in class R5. The powder is mixed with a suitable binder and the compact is then formed to shape using either compression or injection moulding.

5.5.3.3 Basis of subclassification

The recommended subclassification is based on the chemical composition, the degree of magnetic anisotropy and the manufacturing method.

5.5.3.4 Available forms

The magnets are produced in simple shapes by compression moulding. More complicated shapes are produced by injection moulding.

5.5.3.5 Physical characteristics

The magnetic properties are determined by the alloy and the fill factor of the bonding material. The magnets may be isotropic or by the application of a magnetic field, anisotropic magnets may be produced.

The thermal properties are determined by the alloy and the bonding material.

Ranges of specified values of magnetic properties and density for isotropic and anisotropic bonded RECo magnets are given in the corresponding product specification.

5.5.3.6 Main applications

The materials are used in small motors, follower drives, HiFi equipment, sensors and watches.

5.5.4 Class U3 – Bonded neodymium-iron-boron (REFeB) magnets

5.5.4.1 Reference document

These materials are covered by IEC 60404-8-1.

5.5.4.2 Chemical composition and manufacturing method

These bonded magnets contain powdered alloys as given in class R7. ~~The powder is mixed with a suitable binder and the compact is then formed to shape using either compression or injection moulding.~~ There are 2 kinds of REFeB powders for isotropic and anisotropic bonded magnets. The isotropic powders have submicron grain size and are produced by the melt-spinning method and subsequent heat treatment. The anisotropic powders are produced by the Hydrogen Disproportionation Desorption Recombination (HDDR) process. The REFeB ingots are heated to absorb hydrogen and cause disproportionation in the hydrogen gas atmosphere (HD) and to desorb hydrogen and produce recombination in a vacuum (DR). The obtained anisotropic powders are around 100 µm in diameter of which alignment is along a certain direction and the grain size is submicron.

5.5.4.3 Basis of subclassification

The recommended subclassification is based on the chemical composition, the degree of magnetic anisotropy and the manufacturing method

5.5.4.4 Available forms

The magnets are produced in simple shapes by compression moulding. More complicated shapes are produced by injection moulding.

5.5.4.5 Physical characteristics

The magnetic properties are determined by the alloy and the fill factor of the bonding material. The magnets may be isotropic or, by the application of a magnetic field, anisotropic magnets may be produced.

The thermal properties are determined by the alloy and the bonding material.

Ranges of specified values of magnetic properties and density for isotropic bonded NdFeB magnets are given in the corresponding product specification.

5.5.4.6 Main applications

The materials are used in small motors, hand tools, follower drives, sensors and HiFi equipment.

5.5.5 Class U4 – Bonded hard ferrite magnets

5.5.5.1 Reference document

These materials are covered by IEC 60404-8-1.

5.5.5.2 Chemical composition and manufacturing method

These bonded magnets contain powdered ferrites as given in class S1. The powder is mixed with a suitable binder and the compact is then formed into shape. This can be by compression, injection moulding, extrusion or by rolling.

5.5.5.3 Basis of subclassification

The recommended subclassification is based on the chemical composition, the degree of magnetic anisotropy and the manufacturing method.

5.5.5.4 Available forms

The magnets are produced in simple shapes by compression moulding or extrusion. Sheets of magnet material can be produced by rolling. More complicated shapes are produced by injection moulding.

5.5.5.5 Physical characteristics

The magnetic properties are determined by the ferrite and the fill factor of the bonding material. The magnets may be isotropic. Anisotropic magnets may be produced by compression moulding or rolling or by the application on a magnetic field.

The thermal properties are determined by the alloy and the bonding material.

Ranges of specified values of magnetic properties and density for isotropic and anisotropic bonded hard ferrite magnets are given in the corresponding product specification.

5.5.5.6 Main applications

The materials are used in magnetic catches, holding magnets, magnetic displays, small motors and toys.

5.5.6 Class U5 – Bonded rare earth-iron-nitrogen magnets

5.5.6.1 Reference document

These materials are covered by IEC 60404-8-1.

5.5.6.2 Chemical composition and manufacturing method

~~These~~The anisotropic bonded magnets contain powdered $Sm_2Fe_{17}N_3$ intermetallic compound. These materials consist of 22 % to 27 % samarium, 3,0 % to 4,0 % nitrogen and the balance iron. The SmFeN powders are manufactured by the reduction diffusion process using Sm_2O_3 and Fe powders with calcium as a reductant followed by nitrogenation. When the size of the processed powders is coarse, a subsequent milling is required. ~~The powder is mixed with a suitable binder and the compact is then formed to shape using injection moulding in a magnetic field. Obtained bonded magnets are usually anisotropic.~~

The isotropic bonded magnets contain powdered $TbCu_7$ type intermetallic compound. These materials consist of 19 % to 25 % samarium, 2,5 % to 3,5 % nitrogen, 0 % to 5 % cobalt, 0 % to 2 % other elements such as zirconium, hafnium and niobium and the balance iron. The SmFeN powders are manufactured by melt spinning process followed by heat treatment and nitrogenation.

The $Sm_2Fe_{17}N_3$ type powder and the $TbCu_7$ type powder are mixed with a suitable binder and the compacts are then formed to shape using injection moulding or compression moulding in a magnetic field and no magnetic field.

5.5.6.3 Basis of subclassification

The recommended subclassification is based on the chemical composition.

5.5.6.4 Available forms

The magnets are produced in simple shape by injection moulding in a magnetic field.

5.5.6.5 Physical characteristics

The magnetic properties are determined by the alloy, the fill factor of the bonding material and the magnetic field strength for alignment.

The thermal properties are determined by the alloy and the bonding material.

Ranges of specified values of magnetic properties and density for anisotropic bonded REFeN magnets are given in the corresponding product specification.

5.5.6.6 Main applications

The materials are used in small motors such as stepping and spindle motors and sensors.

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

Magnetic materials -
Part 1: Classification

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) IEC draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). IEC takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, IEC had not received notice of (a) patent(s), which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at https://patents.iec.ch. IEC shall not be held responsible for identifying any or all such patent rights.

This consolidated version of the official IEC Standard and its amendment has been prepared for user convenience.

IEC 60404-1 edition 3.1 contains the third edition (2016-10) [documents 68/533/CDV and 68/555/RVC] and its amendment 1 (2025-07) [documents 68/780/CDV and 68/791A/RVC].

This Final version does not show where the technical content is modified by amendment 1. A separate Redline version with all changes highlighted is available in this publication.

International Standard IEC 60404-1 has been prepared by IEC technical committee 68: Magnetic alloys and steels.

This bilingual version (2017-12) corresponds to the monolingual English version, published in 2016-10.

This third edition cancels and replaces the second edition published in 2000 and constitutes a technical revision.

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

a) Removal of all tables and values describing typical properties of the material to be consistent with the aim of the document to be a classification and not a specification.
b) Enlargement of the Ni content for the classes E1 and E3.
c) Enlargement of the Co content for the classes F3.
d) Addition of a new class: U5 bonded rare earth-iron-nitrogen magnets.

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

CDV	Report on voting
68/533/CDV	68/555/RVC

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

The French version of this standard has not been voted upon.

This document 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 document and its amendment will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

1 Scope

This part of IEC 60404 is intended to classify commercially available magnetic materials.

The term "magnetic materials" denotes substances where the application requires the existence of ferromagnetic or ferrimagnetic properties.

In this document, the classification of magnetic materials is based upon the generally recognized existence of two main groups of products:

- soft magnetic materials (coercivity ≤1 000 A/m);
- hard magnetic materials (coercivity >1 000 A/m).

Within these main groups, the classification when appropriate recognizes the following characteristics:

- the main alloying element and the metallurgical state and physical properties of the material;
- when possible and convenient, the relationship between these characteristics is identified.

A classification by specific areas of application cannot be applied to all materials because different materials can very often be used for the same application depending on the characteristics required.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-121, *International Electrotechnical Vocabulary – Part 121: Electromagnetism*

IEC 60050-151, *International Electrotechnical Vocabulary – Part 151: Electrical and magnetic devices*

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

IEC 60401-3, *Terms and nomenclature for cores made of magnetically soft ferrites – Part 3: Guidelines on the format of data appearing in manufacturers catalogues of transformer and inductor cores*

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

IEC 60404-3, *Magnetic materials – Part 3: Methods of measurement of the magnetic properties of magnetic sheet and strip by means of a single sheet tester*

IEC 60404-4, *Magnetic materials – Part 4: Methods of measurement of d.c. magnetic properties of iron and steel*

IEC 60404-6, *Magnetic materials – Part 6: Methods of measurement of the magnetic properties of magnetically soft metallic and powder materials at frequencies in the range 20 Hz to 200 kHz by the use of ring specimens*

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

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

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

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

IEC 60404-8-5, *Magnetic materials – Part 8: Specifications for individual materials – Section Five: Specification for steel sheet and strip with specified mechanical properties and magnetic permeability*

IEC 60404-8-6, *Magnetic materials – Part 8-6: Specifications for individual materials – Soft magnetic metallic materials*

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

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

IEC 60404-8-9, *Magnetic materials – Part 8: Specifications for individual materials – Section 9: Standard specification for sintered soft magnetic materials*

IEC 60404-8-10, *Magnetic materials – Part 8-10: Specifications for individual materials – Magnetic materials (iron and steel) for use in relays*

IEC 60404-8-11, *Magnetic materials - Part 8-11: Specifications for individual materials - Fe-based amorphous strip delivered in the semi-processed state*

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

ISO 4948-1, *Steels – Classification – Part 1: Classification of steels into unalloyed and alloy steels based on chemical composition*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-121, IEC 60050-151, IEC 60050-221 and in the product standards of the IEC 60404-8 series apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

4 Magnetically soft materials (coercivity ≤1 kA/m)

4.1 Class A – Irons

4.1.1 Reference documents

These materials are covered by IEC 60404-8-6 and IEC 60404-8-10.

4.1.2 Chemical composition

The basic constituent of these materials is pure iron, and they are often referred to as "commercially pure" or "magnetically soft" irons. The material also contains unavoidable impurities that may affect magnetic properties. The amount of impurities that adversely affect the remanence, coercivity, saturation, magnetic polarization and stability of the magnetic properties are limited to produce the required magnetic properties for the proposed application. For information the most significant impurities when they are present in these materials are carbon (up to 0,03 %), silicon (up to 0,1 %), manganese (up to 0,2 %), phosphorus (up to 0,015 %), sulphur (up to 0,03 %), aluminium (up to 0,08 %), titanium (up to 0,1 %) and vanadium (up to 0,1 %).

NOTE For improved free machining capability, the amount of phosphorus and sulphur can be higher than indicated above.

4.1.3 Basis of subclassification

The recommended subclassification is based on coercivity values.

4.1.4 Available forms

These materials are available in a wide variety of forms. They may be supplied as slabs, billets, ingots or forgings; as hot-rolled bar in rectangular and square cross-sections; as hot-rolled wire rod in round, hexagonal and octagonal cross-sections; in cold-rolled and drawn forms as bar and wire; as hot- or cold-rolled sheet and strip.

4.1.5 Physical characteristics

In addition to the values of coercivity, a more complete definition of these materials can be based on the following characteristics:

- magnetic: saturation magnetic polarization, magnetic polarization at various values of magnetic field strength (from which permeability can be derived), stability of characteristics with time;
- mechanical: hardness, suitability for punching operations, free machining capability, deep drawing properties, tensile strength;
- metallurgical state: hot- or cold-worked, forged, deep drawn, fully processed state, i.e. final annealed.

NOTE For material not delivered in the fully processed state, subclassification is based on the coercivity measured after heat treatment according to the requirements of the product standard or the recommendations of the manufacturer.

Ranges of specified values for the above-mentioned magnetic characteristics in the fully processed state are given in the corresponding product specifications.

4.1.6 Main applications

The main applications are in DC relays, loudspeakers, electromagnets, magnetic clutches, brakes, parts for magnetic circuits in instruments and control apparatus, as well as for pole pieces and other DC parts for generators and motors.

4.2 Class B – Low carbon mild steels

4.2.1 Class B1 – Bulk material

4.2.1.1 Reference document

Some of these materials are covered by IEC 60404-8-10.

4.2.1.2 Chemical composition

The basic constituent of these materials is iron containing unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process. The amount of alloying elements is limited to that of a non-alloy steel as defined in ISO 4948-1, in particular silicon is less than 0,5 %.

4.2.1.3 Basis of subclassification

The recommended subclassification is based on the coercivity.

4.2.1.4 Available forms

These materials are normally supplied in the form of castings or forgings in a final heat-treated condition or partially machined to drawings supplied by the user or as bar, wire rod or wire in the hot-rolled, cold-rolled or cold-drawn condition.

4.2.1.5 Physical characteristics

In addition to the coercivity a more complete definition of these materials can be based on the following properties:

- magnetic: magnetic polarization at various values of magnetic field strength;
- mechanical: yield strength (or 0,2 % proof stress) elongation (L_o = 5 d_o), freedom from defects;
- metallurgical state: hot- or cold-worked, annealed to produce required magnetic characteristics.

Mechanical and non-destructive tests are made in accordance with the appropriate ISO standards. Coercivity shall be measured in accordance with IEC 60404-7, other magnetic properties in accordance with IEC 60404-4.

Ranges of typical values of magnetic and mechanical properties are given in the corresponding product specification.

4.2.1.6 Main applications

The materials are used for large DC magnets where no mechanical strength is required, for example, in deflection magnets in elementary particle physics and for relay applications.

4.2.2 Class B2 – Flat material

4.2.2.1 Reference documents

These materials are covered by IEC 60404-8-3, IEC 60404-8-4 and IEC 60404-8-10.

4.2.2.2 Chemical composition

The basic constituent of these materials is iron containing unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process. The amount of alloying elements is limited to that of non-alloy steel as defined in ISO 4948-1, in particular silicon is less than 0,5 %. These materials can have an annealing treatment after punching to enhance their magnetic properties.

4.2.2.3 Basis of subclassification

The recommended subclassification is based either on the specific total loss which is a function of thickness and is normally measured at a magnetic polarization value of 1,5 T and at normal industrial power frequencies or (for relay application) on the coercivity.

4.2.2.4 Available forms

These materials are supplied in the form of cold-rolled coils or sheets or (for relay application) in the form of hot-rolled strip, sheet or plate.

4.2.2.5 Physical characteristics

In addition to specific total loss, a more complete definition of these materials can be based on the following properties:

- magnetic: magnetic polarization at various values of magnetic field strength;
- mechanical: suitability for punching operations, surface condition, stacking factor;
- metallurgical state: hot-rolled; hard state – i.e. cold-rolled; semi-processed state – i.e. annealed and finally cold-rolled;

  fully processed state – i.e. final annealed.

NOTE For material delivered in the hard or semi-processed state, subclassification is based on the total specific loss or coercivity measured after heat treatment according to the requirements of the product standard or recommendations of the manufacturer.

- dimensions: thickness, width and (as required) length.

Recommended nominal thicknesses for the cold-rolled materials are given in the corresponding product specifications.

Magnetic measurements are made in accordance with IEC 60404-2, IEC 60404-3 or IEC 60404-7.

Ranges of specified values of maximum specific total loss, after annealing, for the commonly used thicknesses are also shown in the corresponding product specifications.

The specified maximum value of coercivity for relay material ranges from 40 A/m to 240 A/m.

4.2.2.6 Main applications

The materials are used in the manufacture of laminated cores for electrical apparatus and especially small machines and for relay applications.

4.3 Class C – Silicon steels

4.3.1 Class C1 – Bulk material

4.3.1.1 Reference documents

Some of these materials are covered by IEC 60404-8-6 and IEC 60404-8-10.

4.3.1.2 Chemical composition

The basic constituent of these materials is iron in which the main alloying element is silicon with a content of up to approximately 5 %.

4.3.1.3 Basis of subclassification

The recommended subclassification is based on coercivity values or on electrical resistivity which is a function of silicon content.

4.3.1.4 Available forms

These materials are available as hot-rolled and cold-drawn bar, wire, ground bar and forging billets and require heat treatment after mechanical working to achieve the required magnetic properties.

4.3.1.5 Physical characteristics

In addition to the coercivity and the electrical resistivity, a more complete definition of these materials can be based on the following characteristics:

- magnetic: saturation magnetic polarization, magnetic polarization at various values of magnetic field strength, remanent magnetic polarization;
- mechanical: machinability, ductility, hardness;
- metallurgical state: hot- or cold-worked, annealed to produce required magnetic characteristics.

4.3.1.6 Main applications

The main applications are for the magnetic circuits of relays, magnetic clutches, magnetic pole pieces, stepping motors and gyro housings.

4.3.2 Class C2 – Flat material

4.3.2.1 Class C21 – Isotropic[1] (non-oriented) steels for use at power frequencies

4.3.2.1.1 Reference documents

These materials are covered by IEC 60404-8-3, IEC 60404-8-4, IEC 60404-8-6 and IEC 60404-8-10.

4.3.2.1.2 Chemical composition

The basic constituent of these materials is iron. The main alloying element is silicon, whose content may be up to approximately 5 %. Other alloying elements, for example aluminium, may also be present. The material also contains unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.3.2.1.3 Basis of subclassification

The recommended subclassification is based on the specific total loss which is a function of thickness and normally measured at a magnetic polarization value of 1,5 T and at power frequencies.

When the application demands it (for example relays), it may be more appropriate for the subclassification to be based on coercivity or permeability.

1 This describes a material which is substantially isotropic and deliberately processed to be so.

4.3.2.1.4 Available forms

These materials are normally supplied in the form of cold-rolled coils or sheets.

4.3.2.1.5 Physical characteristics

In addition to the values of specific total loss, a more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, specific apparent power for different values of magnetic polarization anisotropy of loss;
- electrical: type of surface insulation and its resistance, resistivity;
- mechanical: suitability for punching operations, ductility, tensile strength, hardness, surface condition and finish, stacking factor, flatness, edge camber;
- metallurgical state: hard state, i.e. as cold rolled semi-processed state, i.e. annealed or annealed and temper rolled; fully-processed state, i.e. final annealed;

NOTE For material delivered in the hard or semi-processed state, the subclassification is based on the specific total losses measured after heat treatment according to the requirements of the product standard or the recommendations of the manufacturer.

- dimensions: thickness, width and (as required) length.

The values of nominal thickness are given in the corresponding product specifications.

Magnetic measurements are made in accordance with IEC 60404-2 or IEC 60404-3. The density values to be used for magnetic measurements should be as defined in the relevant product standard. In other cases, the density values should be the subject of agreement.

Ranges of specified values of specific total loss, after final annealing, for four commonly used thicknesses are shown in the corresponding product specifications.

4.3.2.1.6 Main application

These materials are used mainly in the magnetic circuits of electrical apparatus, particularly in the parts of rotating machines in which the flux is not unidirectional. They may also be used in electromagnetic relays, small transformers, chokes for fluorescent tubes, electrical meters, shielding and magnetic poles of electron and proton synchrotrons.

4.3.2.2 Class C22 – Anisotropic[2] (oriented) steels for use at power frequencies

4.3.2.2.1 Reference documents

These materials are covered by IEC 60404-8-6, IEC 60404-8-7 and IEC 60404-8-8.

4.3.2.2.2 Chemical composition

The basic constituent of these materials is iron and the main alloying element is silicon (approximately 3 %), together with unavoidable impurities and low levels of other elements which may arise from additions necessitated during the manufacturing process. This type of magnetic material possesses anisotropic properties (orientation) such that the direction parallel to the axis of rolling shows the lowest values of specific total losses and the highest permeability. These properties are sensitive to mechanical treatment, and stress relief annealing may be used to optimize the inherent properties.

[2] This describes a material which is substantially anisotropic and deliberately processed to be so.

4.3.2.2.3 Basis of subclassification

The recommended subclassification is based on the perfection of crystal orientation expressed by the magnetic polarization for a magnetic field strength of 800 A/m and on the specific total loss, which is a function of thickness and of the orientation, and is normally measured at magnetic polarization values of 1,5 T or 1,7 T and at power frequencies.

With the revision of IEC 60404-8-7 in 2020, an additional subclassification has been introduced in order to distinguish between high-permeability grades with and without magnetic domain refinement.

4.3.2.2.4 Available forms

These materials are normally supplied in the form of cold-rolled coils or sheets having an inorganic insulating coating.

4.3.2.2.5 Physical characteristics

In addition to the perfection of crystal orientation and to the values of specific total loss, a more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength;
- Domain Refined (DR) state: whether or not the material has been treated with a technology for magnetic domain refinement;
- electrical: type of surface insulation and its resistance, resistivity;
- mechanical: ductility, surface condition and finish, stacking factor, flatness, edge camber;
- metallurgical state: annealed and fully recrystallized;
- dimensions: thickness, width and (if required) length.

The values of nominal thickness normally used are given in the corresponding product specifications.

Magnetic measurements are made in accordance with IEC 60404-2 or IEC 60404-3. The density used for calculations is normally 7,65 kg/dm³ and test pieces are taken parallel to the axis of rolling and, before measurement, undergo stress relief annealing in accordance with the recommendations of the manufacturer.

Ranges of specified values of maximum specific total loss, after stress relief annealing, for the normally used thicknesses are also shown in the corresponding product specifications.

NOTE According to IEC 60404-8-7, the magnetic properties of non-heatproof magnetic domain refined high-permeability grades are determined according to IEC 60404-3 without applying a supplementary heat treatment, and in the case of heatproof magnetic domain refinement grades, these properties are determined in accordance with IEC 60404-2 after the required heat treatment.

In addition, materials which are not yet specified in IEC 60404-8-7 are available.

4.3.2.2.6 Main applications

These materials are used mainly for the manufacture of magnetic cores in which the magnetic flux paths are substantially parallel to the direction of cold-rolling, as for example in transformer cores.

4.3.2.3 Class C23 – Thin silicon steels

4.3.2.3.1 Reference document

These materials are covered by IEC 60404-8-8.

4.3.2.3.2 Chemical composition

The basic constituent of these materials is iron. The main alloying element is silicon, whose content may be between 2 % and 4 %. Other alloying elements, namely aluminium, may also be present. The material also contains unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.3.2.3.3 Basis of subclassification

The recommended subclassification is based on the magnetic anisotropy and the specific total loss which is a function of thickness, magnetic polarization value and test frequency.

4.3.2.3.4 Available forms

These materials are normally supplied in the form of cold-rolled coils or sheets.

4.3.2.3.5 Physical characteristics

In addition to the values of specific total loss, a more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength;
- electrical: type of surface insulation and its resistance, resistivity;
- mechanical: ductility, stacking factor, flatness, edge camber;
- metallurgical state: annealed and fully recrystallized;
- dimensions: thickness, width and (if required) length.

The specified values of maximum specific total loss for the commonly used thicknesses are shown in the corresponding product specification.

The magnetic properties are determined in accordance with IEC 60404-10 and the test specimens are prepared as described in the specification.

4.3.2.3.6 Main applications

These materials are mainly used in magnetic circuits of transformers and rotating machines operating at frequencies above 100 Hz.

4.3.2.4 Class C24 – Steels with specified mechanical properties and specific total loss

4.3.2.4.1 Reference document

These materials are not covered by an IEC publication.

4.3.2.4.2 Chemical composition

The basic constituent of these materials is iron. The main alloying element is silicon whose content may be between 2 % and 5 %. Other alloying elements, such as aluminium, manganese, may be added to increase strength and improve magnetic properties. The material also contains unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.3.2.4.3 Basis of subclassification

The recommended subclassification is based on the yield strength.

4.3.2.4.4 Available forms

These materials are normally supplied in the form of cold-rolled and final annealed coils or sheet.

4.3.2.4.5 Physical characteristics

In addition to the yield strength, a more complete definition of these materials can be based on the following characteristics:

- magnetic: specific total loss, magnetic polarization at various values of magnetic field strength;
- electrical: surface insulation and its resistance, resistivity;
- mechanical: tensile strength, elongation, hardness, stacking factor;
- metallurgical state: fully processed, i.e. final annealed;
- dimensions: thickness, width and (if required) length.

4.3.2.4.6 Main applications

These materials are generally used under conditions of alternating flux for the stressed parts of magnetic circuits such as rotors of high-speed rotating electric machines.

4.3.2.5 Class C25 – 6,5 % silicon steels

4.3.2.5.1 Reference document

These materials are not covered by an IEC publication.

4.3.2.5.2 Chemical composition

The basic constituent of these materials is iron. The main alloying element is silicon whose content may be between 6 % and 7 %. Other alloying elements may also be present. The material also contains unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.3.2.5.3 Basis of subclassification

The recommended subclassification is based on the specific total loss which is a function of thickness, magnetic polarization value and test frequency. Specific total loss is determined in accordance with IEC 60404-10, using sheared specimens consisting of half the strip taken parallel and half taken perpendicular to the axis of rolling.

4.3.2.5.4 Available forms

These materials are normally supplied in the form of cold-rolled coils or sheets.

4.3.2.5.5 Physical characteristics

In addition to the values of specific total loss, a more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength;
- electrical: type of surface insulation and its resistance, resistivity;
- mechanical: stacking factor, flatness, edge camber;
- metallurgical state: fully processed, i.e. final annealed;
- dimensions: thickness, width and (if required) length.

As an information, particular features of this material are:

- a nearby zero magnetostriction of almost 1 x 10^{-7} at 1 T and 400 Hz when measured with an optical fiber displacement meter.
- the losses measured according to IEC 60404-10 for a material of 0,10 mm thickness at 1 T and 400 Hz is around 6 W/kg and at 0,05 T and 20 kHz around 7 W/kg.

4.3.2.5.6 Main applications

These materials are generally used in magnetic circuits of the electrical apparatus operating at frequencies above 100 Hz, which require low noise output and low core loss at higher frequency, such as high-frequency transformers, reactors and the motors used in portable electrical apparatus.

4.4 Class D – Other steels

4.4.1 Class D1 – Bulk material

4.4.1.1 Class D11 – Cast solid steels

4.4.1.1.1 Reference document

These materials are not covered by an IEC publication.

4.4.1.1.2 Chemical composition

The basic constituent of these materials is iron containing unavoidable impurities. The main alloying elements are carbon, whose content is lower than 0,45 %, and other elements (namely chromium, nickel, manganese, molybdenum and silicon) which may be necessary to develop the required properties.

4.4.1.1.3 Basis of subclassification

The recommended subclassification is based on the yield strength or 0,2 % proof stress, which are a function of chemical composition and heat treatment.

4.4.1.1.4 Available forms

These materials are usually supplied in the form of castings in a final heat-treated condition or partially machined to drawings supplied by the user.

4.4.1.1.5 Physical characteristics

In addition to the values of yield strength, a more complete definition of the material may be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, coercivity;
- electrical: resistivity;
- mechanical: tensile strength, elongation, impact properties, freedom from defects;
- metallurgical state: either normalized and tempered or quenched and tempered.

Mechanical and non-destructive tests are made in accordance with the appropriate ISO standards. Coercivity is measured in accordance with IEC 60404-7, other magnetic properties in accordance with IEC 60404-4.

4.4.1.1.6 Main applications

The materials are used in the magnetic circuits of electrical apparatus, where a certain mechanical strength is required, particularly in parts of rotating machinery such as rotors, pole pieces, pressure plates and magnet frames.

4.4.1.2 Class D12 – Forged solid steel

4.4.1.2.1 Reference document

These materials are not covered by an IEC publication.

4.4.1.2.2 Chemical composition

The basic constituent of these materials is iron. The main alloying elements are carbon whose content may vary from 0,15 % to 0,5 % and other alloying elements such as nickel (up to 4 %), chromium (up to 1,8 %), molybdenum (up to 0,5 %), vanadium (up to 0,12 %) and manganese (up to 1,9 %), depending on the mechanical properties required and the size of the forgings. The material also contains unavoidable impurities together with a low content of other elements (Si, Al) which may arise from additions necessitated during the manufacturing process.

4.4.1.2.3 Basis of subclassification

The recommended subclassification is based on the yield strength or 0,2 % proof stress which are normally a function of chemical composition and heat treatment.

4.4.1.2.4 Available forms

The materials are usually supplied in the form of forgings in a finally heat-treated and partially machined condition to drawings supplied by the user.

4.4.1.2.5 Physical characteristics

In addition to the values of yield strength, a more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength;
- electrical: resistivity;
- mechanical: tensile strength, elongation, impact properties, bend test, freedom from defects;
- metallurgical state: either normalized and tempered or quenched and tempered;
- dimensions: according to drawings supplied by the user.

Mechanical and non-destructive tests are made in accordance with the appropriate ISO standards. Magnetic properties are measured in accordance with IEC 60404-4.

4.4.1.2.6 Main applications

These materials are used in magnetic circuits of electrical apparatus, particularly in the stressed parts of rotating machines such as shafts for rotating machines, pole shoes, pole bodies and pole endplates.

4.4.2 Class D2 – Flat material

4.4.2.1 Class D21 – High strength steels – Steel with specified mechanical properties and permeability

4.4.2.1.1 Reference document

These materials are covered by IEC 60404-8-5.

4.4.2.1.2 Chemical composition

The basic constituent of these materials is iron. Alloying elements may be carbon or others, for example silicon. The material also contains unavoidable impurities and a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.4.2.1.3 Basis of subclassification

The recommended subclassification is based on the 0,2 % proof stress value.

4.4.2.1.4 Available forms

The materials are normally supplied in the form of coils or sheet.

4.4.2.1.5 Physical characteristics

In addition to the proof stress values, a more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, from which the relative permeability can be derived;
- electrical: resistivity;
- mechanical: tensile strength, elongation, surface condition, suitability for punching operations, flatness, edge camber;
- metallurgical state: hot-rolled, hot-rolled and temper-rolled, cold-rolled and final annealed, cold-rolled, annealed and temper-rolled;
- dimensions: thickness, width and (if required) length.

The values of nominal thickness normally recommended lie in the range from 0,5 mm to 4,5 mm.

Ranges of specified values of mechanical and magnetic properties are shown in the corresponding product specification.

4.4.2.1.6 Main applications

These materials are generally used under conditions of DC magnetization for the stressed parts of the magnetic circuits of rotating electrical machines, particularly spiders, rims and poles.

4.4.3 Class D3 – Stainless steels

4.4.3.1 Reference document

These materials are presently not covered by an IEC publication.

4.4.3.2 Chemical composition

The basic constituent of these materials is iron. The main alloying element is chromium in the range of 11 % to about 20 %. Other alloying elements, for example silicon and manganese, may also be present. The material also contains unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process, to improve machinability for example sulphur, selenium or lead or to enhance corrosion resistance for example molybdenum, titanium or niobium. As compared to conventional stainless steels, grades developed for magnetic applications have more stringent chemical and processing limits to yield more consistent magnetic performance.

4.4.3.3 Basis of subclassification

The recommended subclassification is based on chromium content and fabrication characteristics. Grades D31-01, D31-03 and D31-05 are intended for applications requiring good cold forming characteristics and weldability. Grades D31-02, D31-04 and D31-06 are intended for applications requiring improved machinability. Grades D31-01 and D31-02 have reduced chromium contents for reduced alloy cost and higher saturation polarization. They are, however, only suitable for moderately corrosive environments. Grades D31-03 and D31-04 are intended for use in more corrosive environments, while grades D31-05 and D31-06 are intended for use in the most corrosive environments though with some reduction in magnetic performance.

4.4.3.4 Available forms

The materials are normally supplied as billet, bar, rod, wire, sheet or strip.

4.4.3.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: saturation magnetic polarization, maximum permeability, remanent magnetic polarization, coercivity;
- electrical: resistivity;
- mechanical: machinability, cold formability, weldability, hardness;
- chemical: corrosion resistance.

Although the chromium content influences the magnetic polarization and electrical resistivity, it does not have a pronounced effect on maximum permeability and coercivity.

4.4.3.6 Main applications

These materials are used in magnetic cores and other parts requiring a high-permeability stainless steel having low coercive force and low residual magnetism: magnetic solenoid valves and automotive electromechanical devices such as fuel injectors and anti-lock braking systems.

4.5 Class E – Nickel-iron alloys

4.5.1 Class E1 – Nickel content 70 % to 85 %

4.5.1.1 Reference document

These materials are covered by IEC 60404-8-6.

4.5.1.2 Chemical composition

The basic constituents of these materials are iron and nickel whose content is in the range of 70 % to 85 %. Alloying elements such as molybdenum, copper, manganese, chromium or silicon may be added to increase resistivity and improve magnetic properties. The materials also contain unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.5.1.3 Basis of subclassification

The recommended subclassification is based on the coercivity or the amplitude permeability at a magnetic field strength of 0,4 A/m and the shape of the hysteresis loop: round, flat or rectangular.

4.5.1.4 Available forms

The materials are available as hot-rolled sections and strip, forgings, cold-drawn wire and cold-rolled sheets, strip. They are commonly supplied in the semi-processed state, but a number of materials, particularly those with flat or rectangular hysteresis loop, are available in the final heat-treated state for example as toroidal strip wound cores.

4.5.1.5 Physical characteristics

A more complete definition of the material can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, saturation magnetic polarization, coercivity, maximum amplitude.

Magnetic measurements are made in accordance with either IEC 60404-4 or IEC 60404-6 according to product form.

4.5.1.6 Main applications

The materials are used where high permeability at low magnetic field strength in combination with high remanent or saturation magnetic polarization is required.

- Round hysteresis loop: measuring instruments, current transformers, low-power transformers, relay parts, transducers, protective ground-fault circuit breakers, rotor and stator laminations, magnetic shielding;
- Flat hysteresis loop: pulse transformers, thyristor protective chokes, protective ground-fault circuit-breakers;
- Rectangular hysteresis loop: magnetic amplifiers, AC/DC converters, saturable inductors, pulse transformer cores.

4.5.2 Class E2 – Nickel content 54 % to 68 %

4.5.2.1 Reference document

These materials are covered by IEC 60404-8-6.

4.5.2.2 Chemical composition

The basic constituents of these materials are iron and nickel whose content is in the range of 54 % to 68 %. In some instances, part of the nickel may be replaced by cobalt. Additionally, molybdenum, copper, manganese, chromium or silicon may be present to increase resistivity and improve magnetic properties. The materials also contain unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.5.2.3 Basis of subclassification

A possible basis is the shape of the hysteresis loop: round or flat (magnetic field annealed).

4.5.2.4 Available forms

The materials are available as semi-processed cold-rolled strip or fully processed strip-wound cores.

4.5.2.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: maximum amplitude permeability, saturation magnetic polarization, remanent magnetic polarization, coercivity;
- electrical: resistivity;
- mechanical: suitability for winding operations;
- metallurgical state: semi-processed state, i.e. cold-rolled or fully processed state, i.e. final annealed (with or without magnetic field).

Typical values for magnetic properties in the fully processed state are given in the corresponding product specification.

Magnetic measurements are made in accordance with IEC 60404-6.

4.5.2.6 Main applications

The materials are used where high permeability at low magnetic field strength is required.

- Round hysteresis loop: protective ground-fault circuit-breakers, transducers, measuring transformers;
- Flat hysteresis loop: protective ground-fault circuit-breakers, pulse transformers, thyristor protective choke.

4.5.3 Class E3 – Nickel content 40 % to 51 %

4.5.3.1 Reference document

These materials are covered by IEC 60404-8-6.

4.5.3.2 Chemical composition

The basic constituents of these materials are iron and nickel whose content is in the range of 40 % to 51 %. Alloying elements such as molybdenum, manganese, copper, chromium or silicon may be added to increase resistivity and improve magnetic properties. The materials also contain unavoidable impurities, together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.5.3.3 Basis of subclassification

The recommended subclassification is based on the amplitude permeability at a magnetic field strength of 0,4 A/m or the shape of the hysteresis loop: round (isotropic), flat (magnetic field annealed) or rectangular (anisotropic).

4.5.3.4 Available forms

The isotropic materials are available as hot-rolled sections and strip, forgings, cold drawn wire and cold-rolled sheet and strip.

The materials with flat hysteresis loop are available as strip-wound core.

The anisotropic materials are available as cold-rolled strip or tape.

4.5.3.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, saturation magnetic polarization, coercivity, remanence ratio;
- electrical: resistivity;
- mechanical: suitability for punching or deep drawing operation;
- metallurgical state: the materials require a heat treatment to develop their full magnetic properties.

Values for magnetic properties in the fully processed state are given in the corresponding product specification.

Magnetic measurements are made in accordance with either IEC 60404-4 or IEC 60404-6, according to product form.

4.5.3.6 Main applications

The materials are used where high permeability at low magnetic field strength in combination with high remanent or saturation magnetic polarization is required.

- Round hysteresis loop: measuring instruments, current transformers, low-power transformers, relay parts, transducers, protective ground-fault circuit-breakers, rotor and stator laminations, magnetic shielding, sensors;
- Flat hysteresis loop: pulse transformers, thyristor protective chokes, protective ground fault circuit breakers;
- Rectangular hysteresis loop: magnetic amplifiers, AC/DC converters, saturable inductors, pulse transformer cores.

4.5.4 Class E4 – Nickel content 35 % to 40 %

4.5.4.1 Reference document

These materials are covered by IEC 60404-8-6.

4.5.4.2 Chemical composition

The basic constituents of these materials are iron and nickel whose content is in the range of 35 % to 40 %. Alloying elements such as molybdenum, manganese, copper, chromium or silicon may be added to increase resistivity and improve magnetic properties. The materials also contain unavoidable impurities, together with a level of other elements which may arise from additions necessitated during the manufacturing process.

4.5.4.3 Basis of subclassification

The recommended subclassification is based on the coercivity or the amplitude permeability at a magnetic field strength of 1,6 A/m.

4.5.4.4 Available forms

The materials are available as hot-rolled sections and strips, forgings, cold-drawn wire and cold-rolled sheet and strip. It is commonly supplied in the semi-processed state, but a number of materials are available in the fully processed state.

4.5.4.5 Physical characteristics

A more complete definition of the material can be based on the following characteristics:

- magnetic: coercivity, magnetic polarization at various values of magnetic field strength;

- electrical: resistivity;
- mechanical: suitability for punching and deep drawing operations;
- metallurgical state: the materials require a heat treatment to develop their full magnetic properties.

Specified values for magnetic properties of materials in the fully processed state are given in the corresponding product specification.

Magnetic measurements are made in accordance with either IEC 60404-4 or IEC 60404-6, according to product form.

4.5.4.6 Main applications

The materials are used for high-frequency and pulse applications, telecommunication translators, high-frequency filters or transformers, blocking transformers, pulse transformers, magnetic shields.

4.5.5 Class E5 – Nickel content 29 % to 33 %

4.5.5.1 Reference document

These materials are not covered by an IEC publication.

4.5.5.2 Chemical composition

The basic constituents of these materials are iron and nickel. The Curie temperature is strongly dependent on the nickel content. Alloying elements such as copper may be added to improve magnetic performance. The materials also contain unavoidable impurities together with a low level of other elements which may arise from additions necessitated during the manufacturing process.

4.5.5.3 Basis of subclassification

A possible basis of subclassification is the maximum service temperature.

4.5.5.4 Available forms

The materials are supplied as cold-rolled strip or cold-drawn wire usually in the fully processed condition.

4.5.5.5 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: change of magnetic polarization with temperature for a given magnetic field strength and a given range of temperature;
- electrical: resistivity;
- metallurgical state: semi-processed, i.e. cold-rolled or cold-drawn;
  fully processed, i.e. final annealed.

4.5.5.6 Main applications

Temperature compensators (magnetic shunts) for permanent magnet measuring devices especially for electric current (watt-hour) meters and automotive voltage regulators.

4.6 Class F – Iron-cobalt alloys

4.6.1 Class F1 – Cobalt content 47 % to 50 %

4.6.1.1 Reference document

These materials are covered by IEC 60404-8-6.

4.6.1.2 Chemical composition

The basic constituents of these materials are iron and cobalt whose content is in the range of 47 % to 50 %. Alloying elements such as vanadium, chromium, zirconium, niobium or tantalum may be added to improve ductility.

4.6.1.3 Basis of subclassification

The recommended subclassification is based on the coercivity.

4.6.1.4 Available forms

The materials are supplied as hot-rolled rectangular and round bars, cold-drawn wire, strip and sheet, forgings and cold-rolled strip.

4.6.1.5 Physical characteristics

A more complete definition of the material can be based on the following characteristics:

- magnetic: maximum relative permeability, saturation magnetic polarization, magnetic polarization for various values of magnetic field strength, remanence, coercivity, specific total loss;
- mechanical: suitability for punching operations in the cold-worked state, machinability in the hot-worked or heat-treated state, yield strength;
- metallurgical state: the materials require a heat treatment to develop their full magnetic properties.

Magnetic measurements are made in accordance with either IEC 60404-4 or IEC 60404-6, according to product form.

Values for magnetic properties of final annealed material are given in the corresponding product specification.

4.6.1.6 Main applications

The materials are used in applications involving extremely high magnetic polarizations in low or medium magnetic fields such as motors and generators with highest power density, actuators, transformers, relays, electromagnetic and electro-mechanical devices for aeronautical or aerospace equipment, pole pieces for electromagnets, magnetic lenses and magnetic bearings.

4.6.2 Class F2 – Cobalt content 35 %

4.6.2.1 Reference document

These materials are covered by IEC 60404-8-6.

4.6.2.2 Chemical composition

The basic constituents of these materials are iron and cobalt the content of which is approximately 35 %. Alloying elements such as vanadium or chromium may be added to improve ductility.

4.6.2.3 Basis of subclassification

The recommended subclassification is based on the coercivity.

4.6.2.4 Available forms

The materials are available as hot-rolled strip and sheet, forgings and castings.

4.6.2.5 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, saturation magnetic polarization;
- mechanical: machinability in the hot-worked or heat-treated state;
- metallurgical state: semi-processed state, i.e. hot-rolled or hot-worked; the material requires a heat treatment to develop its full magnetic properties.

Magnetic measurements are made in accordance with either IEC 60404-4 or IEC 60404-6, according to product form.

Specified values for magnetic properties of the final annealed materials are given in the corresponding product specification.

4.6.2.6 Main applications

The materials are mainly used for applications involving either extremely high magnetic polarizations or unusually high temperatures and as pole pieces for electromagnets.

4.6.3 Class F3 – Cobalt content 23 % to 30 %

4.6.3.1 Reference document

These materials are covered by IEC 60404-8-6.

4.6.3.2 Chemical composition

The basic constituents of these materials are iron and cobalt of which the content is in the range of 23 % to 30 %. Alloying elements such as vanadium, niobium, molybdenium or chromium may be added to improve ductility.

4.6.3.3 Basis of subclassification

The recommended subclassification is based on the coercivity.

4.6.3.4 Available forms

The materials are available as hot-rolled round bars, hot-rolled sheet and strip, forgings, cold-drawn wire and cold-rolled strip and tape.

4.6.3.5 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, saturation magnetic polarization;
- mechanical: ductility; suitability for punching operations in the cold-worked state and machinability in the hot-worked or heat-treated state;
- metallurgical state: semi-processed state, i.e. hot-rolled, cold-rolled, forged, cast or cold-drawn. The material requires a heat treatment to develop its full magnetic properties.

Magnetic measurements are made in accordance with either IEC 60404-4 or IEC 60404-6, according to product form.

Specified values for the magnetic properties of final annealed material are given in the corresponding product specification.

4.6.3.6 Main applications

These materials are mainly used for applications involving either extremely high magnetic polarizations or particularly high temperatures, such as for electromagnetic and electro-mechanical devices for aeronautical or aerospace equipment, especially when subjected to mechanical load in service such as liquid metal pumps and magnetic bearings. They are also used for pole pieces for electromagnets.

4.7 Class G – Other alloys

4.7.1 Class G1 – Aluminium-iron alloys

4.7.1.1 Reference document

These materials are not covered by an IEC publication.

4.7.1.2 Chemical composition

The basic constituents of these materials are iron and aluminium whose content may be between 12 % and 16 %, together with unavoidable impurities. These materials may contain additions of chromium and rhenium to improve the magnetic properties of the alloy.

4.7.1.3 Basis of subclassification

The recommended subclassification is based on the aluminium content.

4.7.1.4 Available forms

The materials are normally supplied in the form of hot-rolled bars, strips and sheets or cast or sintered structural parts.

4.7.1.5 Physical characteristics

In addition to aluminium content, a more complete definition can be based on the following properties:

- magnetic: initial and maximum permeability, coercivity, saturation magnetic polarization, magnetostriction;
- mechanical: hardness, suitability for punching operations, surface condition;
- metallurgical state: hot-rolled, cast, sintered;
- dimensions: thickness, width (as required), diameter.

4.7.1.6 Main applications

The materials are used in the manufacture of laminated cores for magnetic heads and ultrasonic transducers or as structural parts of magnetic circuits.

4.7.2 Class G2 – Aluminium-silicon-iron alloys

4.7.2.1 Reference document

These materials are not covered by an IEC publication.

4.7.2.2 Chemical composition

The basic constituents of these materials are iron, aluminium, the content of which may be between 5 % to 6,5 %, and silicon, the content of which may be between 7 % and 9,5 %, together with unavoidable impurities. These alloys may contain additions of titanium, cerium, niobium and vanadium to improve magnetic and mechanical properties.

4.7.2.3 Basis of subclassification

The recommended subclassification is based on the initial permeability.

4.7.2.4 Available forms

The materials are normally supplied in the form of castings or of semi-processed products, for example, powder.

4.7.2.5 Physical characteristics

In addition to the initial permeability, a more complete definition can be based on the following characteristics:

- magnetic: saturation magnetic polarization, coercivity, initial permeability, maximum permeability;
- electrical: resistivity;
- mechanical: hardness;
- metallurgical state: as cast;
- dimensions: determined by application.

4.7.2.6 Main applications

The materials are used for the parts of magnetic circuits, magnetic heads and as semi-processed products, for example, powder.

4.8 Class H – Magnetically soft materials made by powder metallurgical techniques

4.8.1 Class H1 – Soft ferrites

4.8.1.1 Reference document

These materials are covered by IEC 60401-3.

4.8.1.2 Chemical composition

The majority of commercially available soft ferrites are polycrystalline ceramics having a cubic crystal structure and a typical formula MFe_2O_4 where M usually represents one or more of the divalent transition metals. In the most common materials, M is either a combination of manganese and zinc, or of nickel and zinc.

4.8.1.3 Basis of subclassification

The recommended subclassification is based on the initial permeability.

4.8.1.4 Available forms

Magnetically soft ceramics are generally supplied in the form of magnetic components, for which the raw materials are made into powder, formed to the required shape, sintered and mechanically finished. Only a very small proportion is supplied as a material in the form of a (fully sintered) magnetic powder.

Calcined powders for component production cannot be considered as ferrite material for the purpose of this classification.

4.8.1.5 Physical characteristics

A more complete definition of these materials may be based on the following characteristics:

- magnetic: initial permeability, saturation magnetic flux density, remanent flux density, coercivity, relative loss factor at low flux density, hysteresis material constant, relative temperature factor, disaccommodation factor, total harmonic distortion factor, power loss (volume) density, amplitude permeability;
- mechanical: density;
- thermal: Curie temperature;
- electrical: resistivity, normalized impedance;
- shapes: rods, tubes, screw and drum cores, balun cores, multi-hole bead, ring cores, EP, E, EFD, PQ, pot, PM, RM and U cores.

Where material values are quoted, these are normally measured on ring cores of stated dimensions and identical characteristics cannot always be realized on a component of differing geometry.

Typical ranges of properties for the Mn-Zn- and the Ni-Zn-ferrites are given in the corresponding product specification.

The properties depend strongly on the exact composition, i.e. the metal ions and their proportion. The heat treatment including atmosphere and cooling rate are critical factors in developing the properties.

Variation of one property normally influences the value of various other properties. This situation gives rise to the existence of many separate materials, each intended for a relatively small group of applications.

4.8.1.6 Main applications

Among the most important applications are the following:

- cores for inductors and transformers operating at frequencies in the range from audio frequency to several hundred MHz;
- cores for pulse transformers up to several hundred MHz;
- aerial rods;
- cores for power transformers operating at frequencies in the range from about 5 kHz to about 30 MHz;
- ring cores and multiaperture cores for data storage devices;
- cores for recording heads;
- cores for deflection coils on cathode-ray tubes;
- cores for reciprocal and non-reciprocal microwave devices;
- beads for RF decoupling and attenuation of unwanted signals.

4.8.2 Class H2 – Magnetically soft sintered materials

4.8.2.1 Reference document

These materials are covered by IEC 60404-8-9.

4.8.2.2 Chemical composition and manufacturing method

Magnetically soft sintered materials are produced by the powder metallurgical (PM) technique. This manufacturing technology allows the economical manufacture of structural parts. An additional heat treatment is necessary if the structural parts have to be machined to keep the prescribed tolerances or to complete the final shape.

Besides plain iron FeP-alloys containing 0,3 % to 0,8 % P, FeNi-alloys containing 30 % to 85 % Ni, FeCo-alloys containing 40 % to 55 % Co and FeSi-alloys containing 0,3 % to 3,5 % Si are usual.

4.8.2.3 Basis of subclassification

For each alloy the recommended subclassification is based on the coercivity.

4.8.2.4 Available forms

Magnetically soft sintered materials are generally supplied as structural parts.

4.8.2.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: magnetic polarization at various values of magnetic field strength, saturation magnetic polarization, maximum permeability;
- mechanical: density, porosity, hardness;
- electrical: resistivity.

Physical and magnetic properties are given in the corresponding product specification.

4.8.2.6 Main application

The materials are used as structural parts in magnetic circuits.

4.8.3 Class H3 – Powder composites

4.8.3.1 Reference document

These materials are not covered by an IEC publication.

4.8.3.2 Chemical composition and manufacturing method

Powder composite materials consist of a basic magnetic powder and inorganic or organic electrically insulating additives and binders.

Pure iron (Fe), iron-silicon (FeSi, FeSiAl) and nickel-iron (FeNi, FeNiMo) powder composites are in use. Powder metallurgical techniques such as cold-isostatic pressing, die pressing or injection moulding are used for manufacturing.

4.8.3.3 Basis of subclassification

For each material the recommended subclassification is based on the initial permeability. A possible basis of subclassification is the composition of the alloying elements.

4.8.3.4 Available forms

Powder composite materials are supplied as structural parts (powder cores) or cold isostatic pressed blanks. In the case of organic bound composites, shaping by machining is possible.

4.8.3.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: initial permeability, saturation magnetic polarization, total loss density;
- mechanical: density;
- electrical: resistivity.

4.8.3.6 Main application

The materials are used as ring-shaped powder cores for inductive components (storage chokes) and as structural parts in motor applications.

4.9 Class I – Amorphous soft magnetic materials

4.9.1 General

Amorphous alloys are non-crystalline materials which are produced via rapid solidification by casting as thin sheets, wires and powders. Due to the lack of long-range atomic order, they have no magneto-crystalline anisotropy. Interesting soft magnetic properties are found in Fe-based alloys with relatively high saturation magnetic polarization and in Co-based alloys with near-zero magnetostriction.

4.9.2 Class I1 – Iron-based amorphous alloys

4.9.2.1 Reference document

These materials are covered by IEC 60404-8-11.

4.9.2.2 Chemical composition

The basic constituents of these materials are iron and metalloids (mainly silicon and boron) the content of which is commonly in the range of 16 % by atoms to 30 % by atoms. These alloys may further contain additions of titanium, vanadium, chromium, zirconium, niobium, manganese, carbon or molybdenum to improve magnetic and mechanical properties. Part of the iron may be substituted by nickel or cobalt.

4.9.2.3 Basis of subclassification

The recommended subclassification is based on the saturation magnetic polarization and the shape of the hysteresis loop.

4.9.2.4 Available forms

The materials are normally supplied in the form of rapidly solidified thin ribbons of typical thickness 20 μm to 50 μm and in the form of tape wound cores.

4.9.2.5 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: specific total loss as a function of magnetic polarization and frequency, specific apparent power, saturation magnetic polarization, magnetostriction, coercivity, initial permeability, reversible permeability at various values of magnetic field strength, squareness of the B-H loop, remanence;
- electrical: resistivity;
- thermal: Curie temperature, crystallization temperature;
- dimensions: thickness, width;
- mechanical: ductility, stacking factor;
- metallurgical state: semi-processed state, i.e. as cast. The magnetic properties are developed by the heat treatment in a magnetic field.

The properties depend strongly on the exact composition of the material and on the heat treatment.

4.9.2.6 Main applications

Variation of one property normally influences the value of various other properties. This situation gives rise to the existence of many different materials, each intended for a relatively small group of applications.

The most important ones are:

- core material for distribution transformers at power frequency,
- cores for inductors and transformers operating at frequencies up to several hundred kHz, and
- theft detection tags.

4.9.3 Class I2 – Cobalt-based amorphous alloys

4.9.3.1 Reference document

These materials are not covered by an IEC publication.

4.9.3.2 Chemical composition

The basic constituents of these materials are cobalt and iron or manganese whose content is commonly in the range of 2 % by atoms to 10 % by atoms and metalloids (silicon and boron mainly) whose content is in the range of 18 % by atoms to 30 % by atoms. Cobalt may be partly substituted by nickel. These alloys may contain additions of titanium, vanadium, chromium, zirconium, niobium, molybdenum, ruthenium, hafnium, tantalum and tungsten to improve magnetic and mechanical properties.

4.9.3.3 Basis of subclassification

The recommended subclassification is based on the saturation magnetic polarization and the shape of the hysteresis loop.

4.9.3.4 Available forms

The materials are normally supplied in the form of rapidly solidified thin strips with a typical thickness of 10 μm to 50 μm and in the form of tape wound cores.

4.9.3.5 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: magnetostriction, initial permeability, reversible permeability at various values of magnetic field strength, specific total loss as a function of frequency, squareness of the B-H loop, coercivity;
- electrical: resistivity;
- thermal: Curie temperature, crystallization temperature;
- dimensions: thickness, width;
- metallurgical state: semi-processed state, i.e. as cast.

The properties depend strongly on the exact composition of the material and on the heat treatment. Some magnetic properties can be developed by further heat treatment with or without a magnetic field.

4.9.3.6 Main applications

Variation of one property normally influences the value of various other properties. This situation gives rise to the existence of many different materials, each intended for a relatively small group of applications.

The most important ones are

- cores for inductors and transformers operating at frequencies in the range from 50 Hz to several MHz,
- cores for pulse transformers,
- cores for recording heads, and
- flexible magnetic shielding.

4.9.4 Class I3 – Nickel-based amorphous alloys

4.9.4.1 Reference document

These materials are not covered by an IEC publication.

4.9.4.2 Chemical composition

The basic metallic constituents of these materials are nickel and iron in approximately equal amounts by weight and which form about 90 % of the alloy by weight. In some alloys molybdenum can be present. The principal metalloid is boron although phosphorus and silicon can also be present.

4.9.4.3 Basis of subclassification

The recommended subclassification is based on the shape of the hysteresis loop.

4.9.4.4 Available forms

The materials are normally supplied in the form of rapidly solidified thin strips with a typical thickness of 15 µm to 50 µm.

4.9.4.5 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: magnetostriction, initial permeability, reversible permeability at various values of magnetic field strength, specific total loss as a function of frequency, squareness of the *B-H* loop, coercivity, shielding attenuation ratio;
- electrical: resistivity;
- thermal: Curie temperature, crystallization temperature;
- dimensions: thickness, width;
- metallurgical state: semi-processed state, i.e. as cast.

The properties depend strongly on the exact composition of the material and on the heat treatment. Some magnetic properties can be developed by further heat treatment with or without a magnetic field.

4.9.4.6 Main applications

The main applications are for article surveillance sensors and magnetic EMI shielding.

4.10 Class J – Nano-crystalline soft magnetic materials

4.10.1 Reference document

These materials are not covered by an IEC publication.

4.10.2 Production process

Iron-based nano-crystalline alloys are produced via rapid solidification by casting as thin sheets, wires or powders. After this casting process the material is in the amorphous state. The desirable nano-crystalline state is achieved by annealing at temperature between 500 °C and 600 °C. Nano-crystalline alloys exhibit a high saturation magnetic polarization and an almost zero magnetostriction due to their nano-crystalline microstructure.

4.10.3 Chemical composition

The basic constituents of these materials are iron, copper typically around 1 % by atoms, niobium around 3 % by atoms and metalloids (mainly silicon and boron) typically in the range of 16 % by atoms to 28 % by atoms. These alloys may further contain additions of zirconium, molybdenum, tantalum, titanium, vanadium, phosphorus, chromium, manganese and carbon to improve the magnetic and mechanical properties.

4.10.4 Basis of subclassification

The recommended subclassification is based on the saturation magnetic polarization and the shape of the hysteresis loop.

4.10.5 Available forms

The materials can be supplied in the amorphous state in the form of rapidly solidified thin ribbons of typical thickness 12 μm to 30 μm and in the nanocrystalline state in the form of tape wound cores.

4.10.6 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: specific total loss as a function of magnetic polarization and frequency, specific apparent power, saturation magnetic polarization, magnetostriction, coercivity, initial permeability, reversible permeability at various values of magnetic field strength, squareness of the B-H loop, remanence;
- electrical: resistivity;
- thermal: Curie temperature, crystallization temperature of the nanocrystalline grains, crystallization temperature of the amorphous matrix;
- dimensions: thickness, width;
- mechanical: ductility, stacking factor;
- metallurgical state: semi-processed state, i.e. as cast. The magnetic properties are developed by the heat treatment above the crystallisation temperature. Magnetic fields can be used to support the formation of induced anisotropies.

The properties depend strongly on the exact composition of the material and on the heat treatment.

4.10.7 Main applications

Variation of one property normally influences the value of various other properties. This situation gives rise to the existence of many different materials, each intended for a relatively small group of applications.

The most important ones are

- magnetic cores,
- inductive components like current transformers and yokes,
- shielding foils.

5 Magnetically hard materials (coercivity > 1 kA/m)

5.1 Class Q – Magnetostrictive alloys – Rare earth iron alloys (Class Q1)

5.1.1 Reference document

These materials are not covered by an IEC publication.

5.1.2 Chemical composition

The basic constituents of these materials are iron, terbium and dysprosium. In $Tb_xDy_{(1-x)}Fe_y$ compounds, the value of x determines the Tb/Dy ratio and y is the Fe/(Tb + Dy) ratio. The optimum values of x are close to 0,3, where high magnetostriction is obtained without excessive hysteresis losses. The stoichiometric value for y = 2,0 produces optimum magnetostrictive properties but the resulting materials are very brittle. As y is decreased from 2, the material becomes less brittle and the value of y = 1,95 provides a good compromise.

5.1.3 Basis of subclassification

There is no recognized subclassification.

5.1.4 Available forms

Grain-oriented, round bars of different sizes are available manufactured by free stand zone melting or modified Bridgeman solidification processes. The cylinder axis is the easy direction of magnetization.

5.1.5 Physical characteristics

A more complete definition can be based on the following characteristics:

- magnetic: magnetostrictive strain at saturation, Curie temperature, magneto-elastic coupling factor k_{33}, d-constant ($\mathrm{d}\lambda/\mathrm{d}H$), relative permeability, magnetic specific acoustic impedance, energy density;
- mechanical: density, modulus of elasticity, sound speed, tensile strength, compressive strength;
- thermal: thermal expansion coefficient;
- electrical: resistivity;
- metallurgical state: grain-oriented and heat-treated

The machinability is limited due to their brittleness. The materials can be ground or cut by means of a spark cutter or a diamond wheel.

5.1.6 Main applications

The materials are of prime interest for applications involving large forces and fast, high-precision motion at high power levels. Such applications are in high-power sound projectors in sonars and defence systems, for oil field logging and oceanography studies.

Other applications being developed are as active elements in electromechanical applications.

5.2 Class R – Magnetically hard alloys

5.2.1 Class R1 – Aluminium-nickel-cobalt-iron-titanium (AlNiCo) alloys

5.2.1.1 Reference document

These materials are covered by IEC 60404-8-1.

5.2.1.2 Chemical composition and manufacturing method

These alloys consist of 8 % to 13 % aluminium, 13 % to 28 % nickel, 5 % to 42 % cobalt, 0 % to 9 % titanium, 2 % to 6 % copper, 0 % to 3 % niobium, 0 % to 0,8 % silicon and the balance iron. They may contain other additions.

They are made by casting or a powder metallurgical process. The magnetic performance of alloys with a cobalt content higher than 20 % can be increased in a preferred direction by applying a magnetic field during heat treatment producing magnetic anisotropy. The best performances of cast magnets are achieved with alloys of columnar or single crystal structure, the magnetic field being applied parallel to the columnar axis.

5.2.1.3 Basis of subclassification

The subclassification is based on the magnetic degree of anisotropy and the manufacturing method.

5.2.1.4 Available forms

The magnets are mainly produced in the form of rings, prisms, cubes, cylinders or arc segments. Cast magnets with columnar or single crystal structure are subject to limitations of form and dimensions.

5.2.1.5 Physical characteristics

In addition to the degree of anisotropy and the manufacturing method, a more complete definition can be based on the following characteristics:

- magnetic: maximum BH product, remanent flux density, coercivity, recoil permeability;
- thermal: temperature coefficients of remanent flux density and of coercivity, and Curie temperature;
- mechanical: density, machinability;
- metallurgical state: cast or sintered and heat-treated;
- dimensions: determined by application.

Ranges of specified values of magnetic properties and density for isotropic and anisotropic AlNiCo alloys are given in the corresponding product specification.

5.2.1.6 Main applications

These materials are used in measuring devices and loudspeakers.

5.2.2 Class R3 – Iron-cobalt-vanadium-chromium (FeCoVCr) alloys

5.2.2.1 Reference document

These materials are covered by IEC 60404-8-1.

5.2.2.2 Chemical composition and manufacturing method

These materials consist of 49 % to 54 % cobalt, 4 % to 13 % vanadium plus chromium and the balance being iron.

The FeCoVCr alloys are manufactured by casting and subsequent hot and cold rolling or drawing to produce strips or wires, respectively.

5.2.2.3 Basis of subclassification

The recommended subclassification is based on the coercivity H_{cJ}.

5.2.2.4 Available forms

The material is generally available in the form of wires and bars with diameter < 20 mm or strips with a thickness < 6 mm.

5.2.2.5 Physical characteristics

A more complete definition of these magnetically anisotropic materials can be based on the following characteristics:

- magnetic: maximum BH product, remanent flux density, coercivity;
- thermal: temperature coefficients of remanent flux density and of coercivity, and Curie temperature;
- mechanical: machinability before hardening;
- metallurgical state: hot- and cold-rolled, heat-treated to develop magnetic properties;
- dimensions: determined by application.

Specified values of magnetic properties and density for final annealed anisotropic FeCoVCr alloys are given in the corresponding product specification.

5.2.2.6 Main applications

These materials are used for compass needles, hysteresis motors, speedometers and sensors, and actuators for electromechanical displays.

5.2.3 Class R5 – Rare earth cobalt (RECo) alloys

5.2.3.1 Reference document

These materials are covered by IEC 60404-8-1.

5.2.3.2 Chemical composition and manufacturing method

Two main types of RECo magnet material are available; they are based on the compounds $SmCo_5$ and Sm_2Co_{17}. The $SmCo_5$ alloys consist of 33 % to 36 % samarium and the balance cobalt. The Sm_2Co_{17} alloys consist of 24 % to 26 % samarium, 10 % to 20 % iron, 4,5 % to 12 % copper, other elements (e.g. zirconium, hafnium or titanium) and the balance cobalt.

Magnets may be formed by compacting the powder in a magnetic field and sintering the compacted body followed by heat treatments.

5.2.3.3 Basis of subclassification

The recommended subclassification is based on chemical composition and manufacturing method.

5.2.3.4 Available forms

The materials are typically available in the form of blocks, cylinders, rings and arc segments.

5.2.3.5 Physical characteristics

All RECo magnetic materials are normally magnetically anisotropic.

A more complete definition can be based on the following characteristics:

- magnetic: maximum BH product, remanent flux density, coercivity, recoil permeability, uniformity field strength;
- thermal: temperature coefficients of remanent flux density and of coercivity, and Curie temperature;
- mechanical: density, machinability;
- metallurgical state: sintered;
- dimensions: determined by application.

Sintered materials are brittle but machinable by grinding.

Ranges of specified values of magnetic properties and density for anisotropic sintered RECo alloys are given in the corresponding product specification. In addition, materials with improved magnetic properties, especially H_{cJ}, are available.

5.2.3.6 Main applications

These materials are mainly used in rotating machines and many other motor applications, transducers, separators, magnetic clutches and for medical applications. They find particular application where miniaturization is a requirement.

5.2.4 Class R6 – Chromium-iron-cobalt (CrFeCo) alloys

5.2.4.1 Reference document

These materials are covered by IEC 60404-8-1.

5.2.4.2 Chemical composition and manufacturing method

The materials consist of 25 % to 35 % chromium, 7 % to 25 % cobalt, 0,1 % to 3 % other elements (e. g. silicon, titanium, molybdenum, aluminium and vanadium) and the balance iron.

The CrFeCo alloys can be manufactured by casting, followed by hot and cold rolling and drawing to produce strips and wires. The magnets can also be formed by a powder metallurgical process. The magnetic performance of the cast as well as sintered material can be increased in a preferred direction by applying a magnetic field during heat treatment.

5.2.4.3 Basis of subclassification

The recommended subclassification is based on the degree of magnetic anisotropy and the manufacturing method (cast or sintered).

5.2.4.4 Available forms

The materials are generally available in the form of wire, strip and rod. They are also available in the form of cast shapes.

5.2.4.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: maximum BH product, remanent flux density, coercivity, recoil permeability;
- thermal: temperature coefficients of remanent flux density and of coercivity, and Curie temperature;
- mechanical: machinability and workability;
- metallurgical state: cold-rolled or drawn, cast, sintered;
- dimensions: determined by application.

Ranges of specified values of magnetic properties and density for final annealed isotropic and anisotropic CrFeCo alloys are given in the corresponding product specification.

5.2.4.6 Main applications

These materials are used for measuring devices, loudspeakers, rotating machines (including hysteresis motors), speedometers and theft detection labels and tags.

5.2.5 Class R7 – Rare earth-iron-boron (REFeB) sintered magnets

5.2.5.1 Void

5.2.5.2 Chemical composition and manufacturing method

The sintered magnets are based on the compound $RE_2Fe_{14}B$. RE is mainly neodymium, which may be partially substituted by dysprosium, praseodymium or other rare earths. Iron may be partially substituted by cobalt. The alloys consist of 28 % to 35 % total rare earth, 0 % to 15 % cobalt, 0,85 % to 1,2 % boron, 0 % to 11 % dysprosium and terbium, 0 % to 15 % praseodymium, cerium (Ce), etc., 0 % to 1 % vanadium, niobium, aluminium, gallium and copper and the balance iron.

The sintered magnets are prepared by compacting milled alloy powder in a magnetic field and sintering the compacted body for densification followed by a heat treatment, resulting in a magnet with anisotropic magnetic properties.

A metallic or resinous layer on the surface of the magnet may be applied to resist corrosive attacks.

5.2.5.3 Basis of subclassification

The recommended subclassification is based on the degree of magnetic anisotropy of the material and the manufacturing method.

5.2.5.4 Available forms

The materials are typically available in the form of blocks, cylinders, rings and arc segments.

5.2.5.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: maximum BH product, remanent flux density, coercivity, recoil permeability, demagnetization field strength;
- thermal: temperature coefficients of remanent flux density and of coercivity, and Curie temperature;
- mechanical: density, machinability;
- dimensions: determined by application.

Sintered or hotpressed materials are brittle, but machinable by grinding.

Ranges of specified values of magnetic properties and density for anisotropic sintered REFeB alloys are given in the corresponding product specification.

5.2.5.6 Main applications

The materials are mainly used for traction motors for hybrid electric vehicles (HEV) and electric vehicles (EV), direct drive type generators for wind turbines, voice coil motors and many other electrical motors, electroacoustical applications, separators, magnetic resonance imaging (MRI).

5.2.6 Class R8 - Rare earth-iron-boron (REFeB) hot deformed magnets

5.2.6.1 Reference document

These materials are covered by IEC 60404-8-1.

5.2.6.2 Chemical composition and manufacturing method

The hot deformed magnets are based on the compound $RE_2Fe_{14}B$. The composition of the magnets are the same as the REFeB sintered magnets (Class R7).

The hot deformed magnets use rapidly solidified flakes prepared by the melt-spinning process. After obtaining isotropic pressed bodies, the pressed bodies are consolidated and subsequently hot deformed at elevated temperatures. Alignment of grains is obtained along compression stress during die-upsetting or extrusion.

5.2.6.3 Basis of subclassification

The recommended subclassification is based on the degree of magnetic anisotropy and chemical compositions of the material.

5.2.6.4 Available forms

The materials are typically available in the form of rings and plates.

5.2.6.5 Physical characteristics

The physical characteristics of REFeB hot deformed magnets are the same as REFeB sintered magnets (Class R7).

5.2.6.6 Main applications

The main applications of REFeB hot deformed magnets are the same as REFeB sintered magnets (Class R7).

5.3 Class S – Magnetically hard ceramics – Hard ferrites (Class S1)

5.3.1 Reference document

These materials are covered by IEC 60404-8-1.

5.3.2 Chemical composition and manufacturing method

The composition of the hard ferrites can be described by the formula MO·n $Fe_2 0_3$ (where M is barium, strontium and calcium). The value of n can vary from 4,5 to 6,5. The magnetic properties may be improved by special substitutions. This is particularly so with substitutions of lanthanum for strontium or calcium and of cobalt for iron. The hard ferrites have a hexagonal crystal structure with magnetic anisotropy.

Compacting of the powder is carried out with or without a magnetic field, thus obtaining anisotropic or isotropic magnets. The pressed bodies are sintered.

5.3.3 Basis of subclassification

The recommended subclassification is based on the degree of magnetic anisotropy and the manufacturing method.

5.3.4 Available forms

Magnetic isotropic and anisotropic sintered hard ferrites are mainly produced as rings, prismatic blocks, cylinders and arc segments.

5.3.5 Physical characteristics

A more complete definition of these materials can be based on the following characteristics:

- magnetic: maximum BH product, remanent flux density, coercivity, recoil permeability;
- thermal: temperature coefficients of remanent flux density and of coercivity, and Curie temperature;
- mechanical: density, machinability, mechanical strength;
- dimensions: determined by application.

Sintered materials are brittle, but machinable by grinding. Sintered magnets have usually large transverse dimensions compared with their length.

Ranges of specified values of magnetic properties and density for isotropic and anisotropic hard ferrites are given in the corresponding product specification.

5.3.6 Main applications

The materials are mainly used in rotating machines, loudspeakers, holding devices and toys.

5.4 Class T – Other magnetically hard materials – Martensitic steels (Class T1)

5.4.1 Reference document

These materials are not covered by an IEC publication.

5.4.2 Composition

These materials have a tetragonal structure which is achieved by water quenching from the austenitic phase. This structure combines mechanical with magnetic hardness. In addition to carbon, alloying elements such as cobalt or chromium are present.

5.4.3 Basis of subclassification

The recommended subclassification is based on the cobalt content.

5.4.4 Available forms

These materials are available as hot-rolled sections.

5.4.5 Physical characteristics

A more complete definition of these materials may be based on the following characteristics:

- magnetic: maximum BH product, remanent flux density, coercivity;
- thermal: temperature coefficients of magnetic remanence and of coercivity, and Curie temperature;
- mechanical: density;
- metallurgical state: hot-rolled and quenched, tempered;
- dimensions: determined by application.

For hysteresis motors which are the main application of these materials, a tempering heat treatment in the range 300 °C to 550 °C is applied. This reduces the coercivity H_{cB} and improves the fullness of the curve.

This application requires material in the form of a thin walled cylinder, mechanically strong and magnetically homogeneous.

5.4.6 Main applications

In the tempered condition the materials are used for hysteresis motors.

Their use in other conditions is almost obsolete.

5.5 Class U – Bonded magnetically hard materials

5.5.1 General

These bonded magnets are composite materials. They consist of permanent magnet powders embedded in a plastic matrix. This binder phase determines to a large extent the mechanical properties of the composite, while the magnet powder determines its magnetic properties. The properties of the composite are determined not only by the type of magnet powder and the matrix material but also by the fill factor and for anisotropic material the degree of alignment. There is a wide variety of grades.

In spite of their lower magnetic values compared with sintered materials, bonded magnets offer economic and technical advantages in many applications because they are cost-effective to manufacture and allow a wide scope for shaping and good mechanical properties. Expensive and elaborate processing steps required in powder metallurgy are not needed.

5.5.2 Class U1 – Bonded aluminium-nickel-cobalt-iron-titanium (AlNiCo) magnets

5.5.2.1 Reference document

These materials are covered by IEC 60404-8-1.

5.5.2.2 Chemical composition and manufacturing method

These bonded magnets contain crushed alloys as given in class R1 together with a resin binder. This mixture is pressed at elevated temperature and cured.

5.5.2.3 Basis of subclassification

The recommended subclassification is based on the chemical composition, the degree of magnetic anisotropy and the manufacturing method.

5.5.2.4 Available form

The magnets are mainly produced in the form of small blocks.

5.5.2.5 Physical characteristics

The magnetic properties are determined by the alloy and the fill factor of the bonding material.

The thermal properties are determined by the alloy and the bonding material.

Ranges of specified values of magnetic properties and density for isotropic bonded AlNiCo magnets are given in the corresponding product specification.

5.5.2.6 Main applications

The materials are used for watt-hour meters and measuring devices.

5.5.3 Class U2 – Bonded rare earth-cobalt (RECo) magnets

5.5.3.1 Reference document

These materials are covered by IEC 60404-8-1.

5.5.3.2 Chemical composition and manufacturing method

These bonded magnets contain powdered alloys as given in class R5. The powder is mixed with a suitable binder and the compact is then formed to shape using either compression or injection moulding.

5.5.3.3 Basis of subclassification

The recommended subclassification is based on the chemical composition, the degree of magnetic anisotropy and the manufacturing method.

5.5.3.4 Available forms

The magnets are produced in simple shapes by compression moulding. More complicated shapes are produced by injection moulding.

5.5.3.5 Physical characteristics

The magnetic properties are determined by the alloy and the fill factor of the bonding material. The magnets may be isotropic or by the application of a magnetic field, anisotropic magnets may be produced.

The thermal properties are determined by the alloy and the bonding material.

Ranges of specified values of magnetic properties and density for isotropic and anisotropic bonded RECo magnets are given in the corresponding product specification.

5.5.3.6 Main applications

The materials are used in small motors, follower drives, HiFi equipment, sensors and watches.

5.5.4 Class U3 – Bonded neodymium-iron-boron (REFeB) magnets

5.5.4.1 Reference document

These materials are covered by IEC 60404-8-1.

5.5.4.2 Chemical composition and manufacturing method

These bonded magnets contain powdered alloys as given in class R7. There are 2 kinds of REFeB powders for isotropic and anisotropic bonded magnets. The isotropic powders have submicron grain size and are produced by the melt-spinning method and subsequent heat treatment. The anisotropic powders are produced by the Hydrogen Disproportionation Desorption Recombination (HDDR) process. The REFeB ingots are heated to absorb hydrogen and cause disproportionation in the hydrogen gas atmosphere (HD) and to desorb hydrogen and produce recombination in a vacuum (DR). The obtained anisotropic powders are around 100 µm in diameter of which alignment is along a certain direction and the grain size is submicron.

5.5.4.3 Basis of subclassification

The recommended subclassification is based on the chemical composition, the degree of magnetic anisotropy and the manufacturing method

5.5.4.4 Available forms

The magnets are produced in simple shapes by compression moulding. More complicated shapes are produced by injection moulding.

5.5.4.5 Physical characteristics

The magnetic properties are determined by the alloy and the fill factor of the bonding material. The magnets may be isotropic or, by the application of a magnetic field, anisotropic magnets may be produced.

The thermal properties are determined by the alloy and the bonding material.

Ranges of specified values of magnetic properties and density for isotropic bonded NdFeB magnets are given in the corresponding product specification.

5.5.4.6 Main applications

The materials are used in small motors, hand tools, follower drives, sensors and HiFi equipment.

5.5.5 Class U4 – Bonded hard ferrite magnets

5.5.5.1 Reference document

These materials are covered by IEC 60404-8-1.

5.5.5.2 Chemical composition and manufacturing method

These bonded magnets contain powdered ferrites as given in class S1. The powder is mixed with a suitable binder and the compact is then formed into shape. This can be by compression, injection moulding, extrusion or by rolling.

5.5.5.3 Basis of subclassification

The recommended subclassification is based on the chemical composition, the degree of magnetic anisotropy and the manufacturing method.

5.5.5.4 Available forms

The magnets are produced in simple shapes by compression moulding or extrusion. Sheets of magnet material can be produced by rolling. More complicated shapes are produced by injection moulding.

5.5.5.5 Physical characteristics

The magnetic properties are determined by the ferrite and the fill factor of the bonding material. The magnets may be isotropic. Anisotropic magnets may be produced by compression moulding or rolling or by the application on a magnetic field.

The thermal properties are determined by the alloy and the bonding material.

Ranges of specified values of magnetic properties and density for isotropic and anisotropic bonded hard ferrite magnets are given in the corresponding product specification.

5.5.5.6 Main applications

The materials are used in magnetic catches, holding magnets, magnetic displays, small motors and toys.

5.5.6 Class U5 – Bonded rare earth-iron-nitrogen magnets

5.5.6.1 Reference document

These materials are covered by IEC 60404-8-1.

5.5.6.2 Chemical composition and manufacturing method

The anisotropic bonded magnets contain powdered $Sm_2Fe_{17}N_3$ intermetallic compound. These materials consist of 22 % to 27 % samarium, 3,0 % to 4,0 % nitrogen and the balance iron. The SmFeN powders are manufactured by the reduction diffusion process using Sm_2O_3 and Fe powders with calcium as a reductant followed by nitrogenation. When the size of the processed powders is coarse, a subsequent milling is required.

The isotropic bonded magnets contain powdered $TbCu_7$ type intermetallic compound. These materials consist of 19 % to 25 % samarium, 2,5 % to 3,5 % nitrogen, 0 % to 5 % cobalt, 0 % to 2 % other elements such as zirconium, hafnium and niobium and the balance iron. The SmFeN powders are manufactured by melt spinning process followed by heat treatment and nitrogenation.

The $Sm_2Fe_{17}N_3$ type powder and the $TbCu_7$ type powder are mixed with a suitable binder and the compacts are then formed to shape using injection moulding or compression moulding in a magnetic field and no magnetic field.

5.5.6.3 Basis of subclassification

The recommended subclassification is based on the chemical composition.

5.5.6.4 Available forms

The magnets are produced in simple shape by injection moulding in a magnetic field.

5.5.6.5 Physical characteristics

The magnetic properties are determined by the alloy, the fill factor of the bonding material and the magnetic field strength for alignment.

The thermal properties are determined by the alloy and the bonding material.

Ranges of specified values of magnetic properties and density for anisotropic bonded REFeN magnets are given in the corresponding product specification.

5.5.6.6 Main applications

The materials are used in small motors such as stepping and spindle motors and sensors.

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

3, rue de Varembé
PO Box 131
CH-1211 Geneva 20
Switzerland

Tel: + 41 22 919 02 11
info@iec.ch
www.iec.ch