

Magnetic materials —

Part 1: Classification

ICS 29.030

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Summary of pages

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MAGNETIC MATERIALS –

Part 1: Classification



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Международная Электротехническая Комиссия

CONTENTS

	Page
FOREWORD.....	5
Clause	
1 General	6
1.1 Scope and object	6
1.2 Normative references.....	6
1.3 Definitions	7
2 Magnetically soft materials (coercivity ≤ 1 kA/m)	8
2.1 Class A – Irons	8
2.1.1 General.....	8
2.1.2 Physical characteristics	8
2.1.3 Main applications	9
2.2 Class B – Low carbon mild steels.....	9
2.2.1 Class B.1 – Bulk material	9
2.2.2 Class B.2 – Flat material	10
2.3 Class C – Silicon steels	12
2.3.1 Class C.1 – Bulk material	12
2.3.2 Class C.2 – Flat material	13
2.4 Class D – Other steels	19
2.4.1 Class D.1 – Bulk material	19
2.4.2 Class D.2 – Flat material	22
2.4.3 Class D.3 – Stainless steels	23
2.5 Class E – Nickel-iron alloys	25
2.5.1 Class E.1 – Nickel content 72 % to 83 %	25
2.5.2 Class E.2 – Nickel content 54 % to 68 %	27
2.5.3 Class E.3 – Nickel content 45 % to 50 %	28
2.5.4 Class E.4 – Nickel content 35 % to 40 %	30
2.5.5 Class E.5 – Nickel content 29 % to 33 %	31
2.6 Class F – Iron-cobalt alloys.....	32
2.6.1 Class F.1 – Cobalt content 47 % to 50 %	32
2.6.2 Class F.2 – Cobalt content 35 %	34
2.6.3 Class F.3 – Cobalt content 23 % to 27 %	35
2.7 Class G – Other alloys	36
2.7.1 Class G.1 – Aluminium-iron alloys	36
2.7.2 Class G.2 – Aluminium-silicon-iron alloys	37
2.8 Class H – Magnetically soft materials made by powder metallurgical techniques..	38
2.8.1 Class H.1 – Soft ferrites	38
2.8.2 Class H.2 – Magnetically soft sintered materials	40
2.8.3 Class H.3 – Powder composites	41
2.9 Class I – Amorphous soft magnetic materials	42
2.9.1 Class I.1 – Iron-based alloys	42
2.9.2 Class I.2 – Cobalt-based alloys	43
2.9.3 Class I.3 – Nickel-based alloys.....	45

Clause	Page
3 Magnetically hard materials (coercivity >1 kA/m).....	45
3.1 Class Q – Magnetostrictive alloys – Rare earth iron alloys (Class Q.1)	45
3.1.1 General.....	45
3.1.2 Physical characteristics.....	46
3.1.3 Main applications	47
3.2 Class R – Magnetically hard alloys.....	47
3.2.1 Class R.1 – Alloys of aluminium-nickel-cobalt-iron-titanium.....	47
3.2.2 Class R.3 – Iron-cobalt-vanadium-chromium alloys.....	48
3.2.3 Class R.5 – Rare earth cobalt (RE-Co) alloys	49
3.2.4 Class R.6 – Chromium-iron-cobalt alloys	50
3.2.5 Class R.7 – Rare earth iron boron alloys	51
3.3 Class S – Magnetically hard ceramics – Hard ferrites (Class S.1)	52
3.3.1 General.....	52
3.3.2 Physical characteristics.....	53
3.3.3 Main applications	53
3.4 Class T – Other magnetically hard materials – Martensitic steels (Class T.1)	53
3.4.1 General.....	53
3.4.2 Physical characteristics.....	54
3.4.3 Main applications	54
3.5 Class U – Bonded magnetically hard materials	54
3.5.1 Class U.1 – Bonded aluminium-nickel-cobalt-iron-titanium magnets	55
3.5.2 Class U.2 – Bonded rare earth cobalt magnets	55
3.5.3 Class U.3 – Bonded neodymium-iron-boron magnets	56
3.5.4 Class U.4 – Bonded hard ferrites.....	57
Table 1 – Ranges of chemical composition.....	8
Table 2 – Ranges of specified values for magnetic properties.....	9
Table 3 – Ranges of typical values of magnetic and mechanical properties.....	10
Table 4 – Ranges of specified values of maximum specific total loss	11
Table 5 – Ranges of specified values for magnetic and electric properties	12
Table 6 – Ranges of specified values of maximum specific total loss	14
Table 7 – Ranges of specified values of maximum specific total loss	15
Table 8 – Ranges of typical values of maximum specific loss.....	16
Table 9 – Specified values of maximum specific total loss	17
Table 10 – Typical values of mechanical and magnetic properties for the thickness of 0,50 mm	18
Table 11 – Typical values of magnetic properties	19
Table 12 – Typical ranges of magnetic and mechanical properties	20
Table 13 – Typical ranges of mechanical properties	21
Table 14 – Ranges of specified values of mechanical and magnetic characteristics of hot-rolled products	23
Table 15 – Ranges of specified values of mechanical and magnetic characteristics of cold-rolled products	23
Table 16 – Ranges of chemical composition.....	24

Table 17 – Typical magnetic properties of materials in the fully processed state	25
Table 18 – Specified magnetic properties of material with a round hysteresis loop	26
Table 19 – Typical magnetic properties of material with a flat hysteresis loop	26
Table 20 – Typical magnetic properties of material with a rectangular hysteresis loop	27
Table 21 – Typical magnetic properties of material with a round hysteresis loop	28
Table 22 – Typical magnetic properties of material with a flat hysteresis loop	28
Table 23 – Specified magnetic properties of material with a round hysteresis loop	29
Table 24 – Typical magnetic properties of material with a flat hysteresis loop	30
Table 25 – Typical magnetic properties of material with a rectangular hysteresis loop	30
Table 26 – Specified magnetic properties of materials in the fully processed state	31
Table 27 – Typical magnetic properties	32
Table 28 – Ranges of specified magnetic properties of material with a round hysteresis loop	33
Table 29 – Typical magnetic properties of material with a rectangular hysteresis loop	34
Table 30 – Specified magnetic properties	35
Table 31 – Specified magnetic properties	36
Table 32 – Typical properties for Mn-Zn ferrites	39
Table 33 – Typical properties for Ni-Zn ferrites	39
Table 34 – Ranges of specified properties	40
Table 35 – Typical physical and magnetic properties	41
Table 36 – Typical physical and magnetic properties	42
Table 37 – Typical physical and magnetic properties	43
Table 38 – Typical physical properties	46
Table 39 – Ranges of specified magnetic properties	48
Table 40 – Specified values of magnetic properties	49
Table 41 – Ranges of specified magnetic properties and density of sintered material	50
Table 42 – Ranges of specified magnetic properties	51
Table 43 – Ranges of specified magnetic properties and density for anisotropic RE-FeB alloys	52
Table 44 – Ranges of specified values of magnetic properties	53
Table 45 – Typical magnetic properties	54
Table 46 – Specified values of magnetic properties	55
Table 47 – Specified values of magnetic properties	56
Table 48 – Ranges of typical physical and magnetic properties	57
Table 49 – Ranges of specified magnetic properties	58

INTERNATIONAL ELECTROTECHNICAL COMMISSION

MAGNETIC MATERIALS –

Part 1: Classification

FOREWORD

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

This second edition cancels and replaces the first edition published in 1979 and constitutes a technical revision.

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

FDIS	Report on voting
68/214/FDIS	68/216/RVD

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 3.

The committee has decided that the contents of this publication will remain unchanged until 2009. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

MAGNETIC MATERIALS –

Part 1: Classification

1 General

1.1 Scope and object

This standard 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 standard, 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.

1.2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of IEC 60404. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of IEC 60404 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60050(121):1998, *International Electrotechnical Vocabulary (IEV) – Part 121: Electromagnetism*

IEC 60050(151):1978, *International Electrotechnical Vocabulary (IEV) – Chapter 151: Electrical and magnetic devices*

IEC 60050(221):1990, *International Electrotechnical Vocabulary (IEV) – Chapter 221: Magnetic materials and components*

IEC 60401:1993, *Ferrite materials – Guide on the format of data appearing in manufacturers' catalogues of transformer and inductor cores*

IEC 60404 (all parts), *Magnetic materials*

IEC 60404-2:1996, *Magnetic materials – Part 2: Methods of measurement of the magnetic properties of electrical steel sheet and strip by means of an Epstein frame*

IEC 60404-3:1992, *Magnetic materials – Part 3: Methods of measurement of the magnetic properties of magnetic sheet and strip by means of a single sheet tester*

IEC 60404-4:1995, *Magnetic materials – Part 4: Methods of measurement of d.c. magnetic properties of iron and steel*

IEC 60404-6:1986, *Magnetic materials – Part 6: Methods of measurement of the magnetic properties of isotropic nickel-iron soft magnetic alloys, types E1, E3 and E4*

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

IEC 60404-8-1:1986, *Magnetic materials – Part 8: Specifications for individual materials – Section one: Standard specifications for magnetically hard materials*

IEC 60404-8-2:1998, *Magnetic materials – Part 8-2: Specifications for individual materials – Cold-rolled electrical alloyed steel sheet and strip delivered in the semi-processed state*

IEC 60404-8-3:1998, *Magnetic materials – Part 8-3: Specifications for individual materials – Cold-rolled electrical non-alloyed steel sheet and strip delivered in the semi-processed state*

IEC 60404-8-4:1998, *Magnetic materials – Part 8-4: Specifications for individual materials – Cold-rolled non-oriented electrical steel sheet and strip delivered in the fully processed state*

IEC 60404-8-5:1989, *Magnetic materials – Part 8: Specifications for individual materials – Section five: Specification for steel sheet and strip with specified mechanical properties and magnetic permeability*

IEC 60404-8-6:1999, *Magnetic materials – Part 8-6: Specifications for individual materials – Soft magnetic metallic materials*

IEC 60404-8-7:1998, *Magnetic materials – Part 8-7: Specifications for individual materials – Cold-rolled grain-oriented electrical steel sheet and strip delivered in the fully processed state*

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

IEC 60404-8-9:1994, *Magnetic materials – Part 8: Specifications for individual materials – Section 9: Standard specifications for sintered soft magnetic materials*

IEC 60404-8-10:1994, *Magnetic materials – Part 8: Specifications for individual materials – Section 10: Specification for magnetic materials (iron and steel) for use in relays*

IEC 60404-10:1988, *Magnetic materials – Part 10: Methods of measurement of magnetic properties of magnetic steel sheet and strip at medium frequencies*

ISO 4948-1:1982, *Steels – Classification – Classification of steels into unalloyed and alloy steels based on chemical composition*

1.3 Definitions

The definitions relating to the various terms used in this part of IEC 60404 are defined in IEC 60050(121), IEC 60050(151), IEC 60050(221) and in the product standards of the IEC 60404-8 series.

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

2.1 Class A – Irons

2.1.1 General

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

2.1.1.1 Chemical composition

The basic constituent of these materials is iron, and they are often referred to as "commercially pure" or "magnetically soft" irons. Elements that adversely affect the remanence, coercivity, saturation, magnetic polarization and stability of the magnetic properties are controlled to produce the required magnetic properties for the proposed application. The amounts of the most significant elements, other than iron, when they are present in these materials are characteristically within the ranges of table 1.

Table 1 – Ranges of chemical composition

C %	Si %	Mn %	P %	S %	Al %	Ti %	Va %
Up to 0,03	Up to 0,1	0,03 to 0,2	Up to 0,015*	Up to 0,03*	Up to 0,08	Up to 0,1	Up to 0,1
* For improved free machining capability, the upper limits for P and S may be higher than indicated in the table.							

2.1.1.2 Basis of subclassification

The recommended subclassification is based on coercivity values.

2.1.1.3 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.

2.1.2 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 for various field strengths (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. finally 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 as shown in table 2.

Table 2 – Ranges of specified values for magnetic properties

Maximum coercivity	Minimum magnetic polarization for $H =$			Minimum saturation magnetic polarization*
	300 A/m	500 A/m	4 000 A/m	
A/m	T	T	T	T
12 to 240	1,30 to 1,15	1,40 to 1,30	1,60	2,10 to 2,16
* Value not specified but typical.				

2.1.3 Main applications

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

2.2 Class B – Low carbon mild steels

2.2.1 Class B.1 – Bulk material

2.2.1.1 General

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

2.2.1.1.1 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 %.

2.2.1.1.2 Basis of subclassification

The recommended subclassification is based on the coercivity.

2.2.1.1.3 Available forms

These materials are normally supplied in the form of castings or forgings in a finally 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.

2.2.1.2 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 ($L_0 = 5 d_0$), 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 table 3.

Table 3 – Ranges of typical values of magnetic and mechanical properties

Yield strength	Elongation ($L_0 = 5 d_0$)	Coercivity	Magnetic polarization at $H =$		
			2 500 A/m	5 000 A/m	10 000 A/m
N/mm ²	%	A/m	T		
100 to 180	25 to 45	40 to 400	1,65 to 1,55	1,75 to 1,65	1,85 to 1,75

2.2.1.3 Main applications

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

2.2.2 Class B.2 – Flat material

2.2.2.1 General

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

2.2.2.1.1 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.

2.2.2.1.2 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.

2.2.2.1.3 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.

2.2.2.2 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 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. finally 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 0,47 mm, 0,50 mm, 0,65 mm and 1,0 mm.

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

Ranges of specified specific total loss, after annealing, for the commonly used thicknesses are as shown in table 4.

Table 4 – Ranges of specified values of maximum specific total loss

Nominal thickness	Frequency	Ranges of specific total loss at $J = 1,5 \text{ T}$
mm	Hz	W/kg
0,50	50	6,6 to 10,5
0,65	50	8,0 to 12,0
0,50	60	8,4 to 13,4
0,65	60	10,2 to 15,3

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

2.2.2.3 Main applications

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

2.3 Class C – Silicon steels

2.3.1 Class C.1 – Bulk material

2.3.1.1 General

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

2.3.1.1.1 Chemical composition

The basic constituent of these materials is iron in which the main alloying element is silicon in the range of 0,5 % to 5 %.

2.3.1.1.2 Basis of subclassification

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

2.3.1.1.3 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.

2.3.1.2 Physical characteristics

In addition to the coercivity and the electrical resistivity for which ranges are given in table 5, a more complete definition of these materials can be based on the following characteristics:

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

Table 5 – Ranges of specified values for magnetic and electric properties

Silicon content*	Resistivity*	Coercivity	Minimum magnetic polarization $H =$			
			100 A/m	300 A/m	500 A/m	4 000 A/m
%	$\mu\Omega\text{m}$	A/m	T			
2 to 4,5	0,35 to 0,60	48 to 12	0,6 to 1,2	1,1 to 1,3	1,2 to 1,35	1,5
* Value not specified but typical.						

2.3.1.3 Main applications

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

2.3.2 Class C.2 – Flat material

2.3.2.1 Class C.21 – Isotropic* (non-oriented) steels for use at power frequencies

2.3.2.1.1 General

These materials are covered by IEC 60404-8-2, IEC 60404-8-4, IEC 60404-8-6 and IEC 60404-8-10.

2.3.2.1.1.1 Chemical composition

The basic constituent of these materials is iron. The main alloying element is silicon, whose content may be between 0,5 % and 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.

2.3.2.1.1.2 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.

2.3.2.1.1.3 Available forms

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

2.3.2.1.2 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 for 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. finally 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 normally recommended are 0,35 mm, 0,47 mm, 0,50 mm, 0,65 mm and 1,00 mm.

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

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 table 6.

Table 6 – Ranges of specified values of maximum specific total loss

Nominal thickness	Frequency	Ranges of specific total loss at $\hat{J} = 1,5 \text{ T}$
mm	Hz	W/kg
0,35	50	2,3 to 3,6
0,50	50	2,5 to 10
0,65	50	3,1 to 10
1,00	50	6,0 to 13
0,35	60	2,9 to 4,6
0,47	60	3,2 to 11,9
0,65	60	4,1 to 12,8
1,00	60	8,1 to 17,3

2.3.2.1.3 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.

2.3.2.2 Class C.22 – Anisotropic* (oriented) steels for use at power frequencies

2.3.2.2.1 General

These materials are covered by IEC 60404-8-7.

2.3.2.2.1.1 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.

* This describes a material which is substantially anisotropic and deliberately processed to be so.

2.3.2.2.1.2 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.

2.3.2.2.1.3 Available forms

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

2.3.2.2.2 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:

- 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: 0,23 mm, 0,27 mm, 0,30 mm and 0,35 mm. If other thicknesses are required, the values 0,18 mm and 0,50 mm are recommended.

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 shown in table 7.

Table 7 – Ranges of specified values of maximum specific total loss

Nominal thickness	Regular material		Material with high permeability	
	Maximum specific total loss at			
	50 Hz	60 Hz	50 Hz	60 Hz
	$\hat{J} = 1,7 \text{ T}$		$\hat{J} = 1,7 \text{ T}$	
mm	W/kg	W/kg	W/kg	W/kg
0,23	1,20 to 1,27	1,57 to 1,65	0,90 to 1,00	1,21 to 1,32
0,27	1,30 to 1,40	1,68 to 1,85	1,03 to 1,10	1,35 to 1,45
0,30	1,40 to 1,50	1,83 to 1,98	1,05 to 1,17	1,38 to 1,54
0,35	1,50 to 1,65	1,98 to 2,18	1,25 to 1,35	1,64 to 1,77

In addition, materials which are not yet specified in IEC 60404-8-7 are available, with the properties given in table 8.

Table 8 – Ranges of typical values of maximum specific loss

Nominal thickness	Domain-refined material	
	Maximum specific total loss at $\hat{J} = 1,7 \text{ T}$	
	50 Hz	60 Hz
mm	W/kg	
0,23	0,80 to 0,90	1,06 to 1,21
0,27	0,85 to 0,95	1,12 to 1,25

2.3.2.2.3 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.

2.3.2.3 Class C.23 – Thin silicon steels

2.3.2.3.1 General

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

2.3.2.3.1.1 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.

2.3.2.3.1.2 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.

2.3.2.3.1.3 Available forms

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

2.3.2.3.2 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 for different values of the 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 table 9.

Table 9 – Specified values of maximum specific total loss

Type	Nominal thickness	Maximum specific total loss at $\hat{J} =$		Frequency
		1 T	1,5 T	
	mm	W/kg		Hz
Grain-oriented	0,05	24	–	1 000
	0,1	–	15	400
	0,15	–	16	400
Non-oriented	0,05	45	–	1 000
	0,1	13	–	400
	0,15	14	–	400
	0,2	15	–	400

The magnetic properties are determined in accordance with IEC 60404-10 and, except for the non-oriented material of 0,2 mm thickness, on test specimens which have been annealed in accordance with the recommendations of the manufacturer.

2.3.2.3.3 Main applications

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

2.3.2.4 Class C.24 – Steels with specified mechanical properties and specific total loss

2.3.2.4.1 General

These materials are not covered by an IEC publication.

2.3.2.4.1.1 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.

2.3.2.4.1.2 Basis of subclassification

The recommended subclassification is based on the yield strength.

2.3.2.4.1.3 Available forms

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