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Cast irons —

Part 1: Materials and properties for design

Fontes —

Partie 1: Matériaux et propriétés pour la conception

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 25, *Cast irons and pig irons.*

This second edition cancels and replaces the first edition (ISO/TR 10809-1:2009), which has been technically revised.

The main changes are as follows:

— Clauses 4 to 10 have been reordered in line with microstructural similarities between cast iron types;

— the Bibliography has been updated.

A list of all parts in the ISO 10809 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Worldwide cast-iron production is in excess of 74 million metric tonnes per annum.[13] It is manufactured in a wide range of alloys and has applications in all sectors of world production and manufacture. Its use spans many industries, including automotive, oil, mining, etc.

The purpose of this document is to assist the designer and engineer in understanding the family of cast iron materials and to be able to utilize them with a more complete knowledge of their potential, among the wide range of other engineering materials and fabrication methods now available. A considerable amount of the data provided are metallurgical, but it is usually the metallurgical aspects of the cast irons that create misunderstandings when these materials are specified. Metallurgy is not one of the scientific disciplines commonly taught to engineering students, so the material properties of cast irons are not often well understood. Thus, such students often have a lack of knowledge regarding the fundamentals underpinning the material properties of cast irons.

Cast irons —

Part 1:
Materials and properties for design

1 Scope

This document provides information about cast iron materials so that users and designers are in a better position to understand cast iron as a design material in its own right and to correctly specify cast iron for suitable applications.

This document suggests what can be achieved, and what is not achievable when cast irons are specified as well as the reasons why. It is not designed to be a textbook of cast iron metallurgy. It is intended to help people to choose the correct material for the right reasons and to also help to obviate the specification or expectation of unrealistic additional requirements, which are unlikely to be met and which can be detrimental to the intended application.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
alloying
addition of elements such as copper, nickel and molybdenum to enhance hardenability

3.2
annealing
heat treatment (3.17) that breaks down *iron carbide* (3.21) and *pearlite* (3.26) to produce *ferrite* (3.12)

3.3
ausferrite
cast iron matrix microstructure, produced by a controlled thermal process, which consists of predominantly acicular *ferrite* (3.12) and high carbon *austenite* (3.5)

3.4
austempering
<of spheroidal graphite cast iron> *heat treatment* (3.17), consisting of heating the castings to a temperature at which *austenite* (3.5) starts to form during heating and holding a sufficient time for carbon diffusion into the austenite, followed by cooling at a rate sufficient to avoid the formation of *pearlite* (3.26), and transforming the matrix structure for a time and temperature (above the *martensite* (3.23) start temperature) sufficient to produce the desired properties

Note 1 to entry: This process produces a microstructure that consists predominantly of acicular *ferrite* (3.12) and high carbon austenite. This microstructure is called *ausferrite* (3.3). Examples of ausferritic microstructures are given in ISO/TR 945-3.

[SOURCE: ISO 17804:2020, 3.3]

3.5
austenite
cast iron matrix microstructure, formed in cast irons immediately upon solidification that at lower temperatures transforms into *ferrite* (3.12), *pearlite* (3.26), *ausferrite* (3.3) and/or *martensite* (3.23), unless the austenite is stabilized at lower temperatures by either sufficient *alloying* (3.1) with nickel in austenitic cast irons, or by carbon enrichment in the austenite phase during the *austempering* (3.4) of ausferritic cast irons containing sufficient silicon to prevent formation of *bainite* (3.6)

3.6
bainite
cast iron matrix microstructure that can form if a white iron with low silicon content is *austempered* (3.4)

Note 1 to entry: Ausferritic cast irons contain sufficient silicon to prevent the formation of bainite.

3.7
carbon equivalent
formula based on the carbon and silicon contents of molten cast iron by thermal analysis

3.8
compacted
stubby form of graphite flakes providing material properties in between those of the grey and spheroidal graphite irons

3.9
ductility
elongation measured on the tensile test piece following testing

Note 1 to entry: It is expressed as a percentage.

3.10
eutectic
point at which elements are present at a level where the lowest solidification temperature is reached

3.11
eutectic cell
solidification mechanism in grey cast iron where cells form, each with its individual internal graphite structure

Note 1 to entry: These ultimately coalesce to form a uniform material.

3.12
ferrite
cast iron matrix microstructure formed during slow cooling of *austenite* (3.5), provided that *pearlite* (3.26) is not rapidly forming to consume the austenite

Note 1 to entry: The formation of ferrite is promoted by both slower cooling and higher silicon content. The latter results in considerable substitutional solution strengthening of the ferrite. A new kind of ferrite, also interstitially solution strengthened by medium carbon contents, is formed during *austempering* (3.4) into ausferritic microstructures.

3.13
graphite flake
two-dimensional appearance of the *graphite form* (3.14) in grey cast iron, when looking at the material structure through a microscope

3.14
graphite form
descriptor of graphite shape, which can define material properties

Note 1 to entry: It is shown in ISO 945-1.

3.15
graphite size
size of the free graphite, whether in the form of flakes, nodules, temper nodules or vermicular graphite

Note 1 to entry: It can be quantified using the relevant cast iron type standard, and will have an effect on the mechanical properties of the final product.

Note 2 to entry: It is classified in accordance with ISO 945-1.

Note 3 to entry: Fine graphite normally provides better properties than coarse graphite.

3.16
hardening
heat treatment (3.17) that generally produces *martensite* (3.23) in the *matrix* (3.24)

3.17
heat treatment
thermal process that removes internal stress or enhances properties

3.18
hypoeutectic
composition below the *eutectic* (3.10)

3.19
hypereutectic
composition above the *eutectic* (3.10)

3.20
inoculation
technique of adding inoculant to molten iron to enhance the graphite growth

3.21
iron carbide
iron and carbon in a combined form

EXAMPLE Fe3C.

3.22
iron-chromium carbide
complex carbide principally found in abrasion-resisting irons

3.23
martensite
cast iron matrix microstructure formed from cooling any *austenite* (3.5) not previously transformed at higher temperatures into *ferrite* (3.12), *pearlite* (3.26), *bainite* (3.6) and/or *ausferrite* (3.3)

Note 1 to entry: In contrast to these transformations relying on the diffusion of carbon and thus depending on both temperature and time, the formation of martensite is diffusionless and is dependent only on temperature.

3.24
matrix
structural phases surrounding the graphite in graphitic cast irons and carbide in abrasion-resisting irons

EXAMPLE *Ferrite* (3.12), *pearlite* (3.26), *ausferrite* (3.3), *austenite* (3.5) and *martensite* (3.23).

3.25
nodularity
assessment of the proportion of spheroidal graphite particles in a cast iron sample

Note 1 to entry: Nodularity is generally expressed as a percentage.

[SOURCE: ISO 945-4:2019, 3.5]

3.26
pearlite
cast iron two-phased lamellar matrix microstructure composed of alternating layers of *ferrite* (3.12) and cementite (Fe3C), formed by a eutectoid reaction during slow cooling of *austenite* (3.5) not previously transformed into ferrite

Note 1 to entry: The formation of pearlite is promoted by both faster cooling and lower silicon content.

3.27
quenching
rapid cooling of previously austenitized castings to prevent formation of *ferrite* (3.12) and *pearlite* (3.26), cooled either in a salt bath for subsequent *austempering* (3.4) into *ausferrite* (3.3) or in oil to form *martensite* (3.23)

3.28
relevant wall thickness
section thickness of the casting, agreed between the manufacturer and the purchaser, to which the determined mechanical properties apply

[SOURCE: ISO 185:2020, 3.2, modified — "thickness" added before "section".]

3.29
section sensitivity
change in material properties that occurs due to variations in the solidification and cooling rates of cast iron poured into different wall section thicknesses

3.30
spheroidal graphite
graphite in spheroidal graphite iron that is present as spheroids as opposed to flakes

3.31
stress relieving
low-temperature *heat treatment* (3.17) that removes stress without affecting structure

3.32
tempering
heat treatment (3.17) that enhances properties or relieves stress after *hardening* (3.16)

3.33
temper carbon
graphite form (3.14) found in malleable iron with the appearance of "ragged" spheroids, also known as "temper carbon nodules"

3.34
trace elements
elements that are present in small amounts

EXAMPLE Copper, nickel, molybdenum, vanadium, titanium.

Note 1 to entry: Such elements can also be added for *alloying* (3.1) purposes.

4 Why use cast irons as an engineering material?

4.1 General

The first questions that the designer and engineer will probably ask are:

— Can I use a cast iron?

— Should I use a cast iron?

— Which type and grade are applicable?

— What are the advantages?

General information on the cast iron types currently standardized in International Standards is given in 4.2 to 4.8.

4.2 Why use grey cast iron?

Grey cast iron is sometimes called "flake graphite cast iron" or "lamellar graphite cast iron". It provides the largest worldwide tonnage of all cast irons produced, mainly because of its wide range of uses within general engineering, its ease of casting and machining, and its cost advantage. The material has the highest thermal conductivity and vibration damping capacity among the range of cast irons, which is why it is used in applications where these properties are important. Typical examples are automotive parts such as brake drums, discs, clutch plates, and cylinder blocks and heads. Grey iron lacks ductility, but for parts where requirements for ductility and impact resistance are low or unimportant, a huge range of applications can be found. These include, for example, the manufacture of machine tools such as lathe beds, where slideways can easily be surface hardened and the self-lubricating properties of the material are advantageous. This highly versatile material can be considered for a potential application unless there are ductility requirements, or the design requires ultimate strengths in excess of 350 MPa.

4.3 Why use spheroidal graphite cast iron?

Spheroidal graphite cast iron, also known as "ductile iron" or "nodular graphite iron", has the benefit of ductility as well as strength, which is why it is often considered to be a material superior to grey iron. Its main disadvantage in this respect is that it does not have as high thermal conductivity as grey iron and is not normally used where this property is important. A large number of spheroidal graphite iron grades are available to the designer, based on the fact that as tensile strength increases, ductility decreases. Thus, the designer has the opportunity to utilize different combinations of tensile/ductility properties, depending upon the application. The lower-strength grades with high ductility also have good impact properties at low temperatures and, for this reason, spheroidal graphite iron is increasingly being used to produce cast parts to replace steel fabrications. Large tonnages of spheroidal graphite iron are used to produce centrifugally cast pipe for water and sometimes gas transportation, but the majority is used in general engineering applications where its considerably higher tensile properties, compared with grey iron, are of advantage.

4.4 Why use ausferritic spheroidal graphite cast iron (austempered ductile iron, ADI)?

The austempering heat treatment carried out on a conventional spheroidal graphite cast iron enhances its properties to produce a range of grades with exceptionally high tensile strengths. The highest tensile strength grade, with a high hardness, allows it to be used in abrasion-resisting applications. As with all spheroidal graphite iron materials, increases in tensile strength and hardness are accompanied by decreases in ductility. This allows for a wide range of properties that can be exploited. Tensile strengths up to 1 600 MPa, hardnesses greater than 400 HBW, and tensile elongations up to 10 % are possible (although not all three simultaneously in the same grade of material). These mechanical properties also result in a high fatigue strength that is useful in gears and other components for use in rotating/bending applications. Certain ausferritic grades exhibit good toughness and impact properties, even at sub-zero temperatures and/or high strain rates.

Additional variations of ausferritic spheroidal graphite iron include carbidic austempered ductile iron (CADI), interrupted quench ausferritic spheroidal graphite iron and intercritical ausferritic spheroidal graphite iron (also known as “intercritical austempered ductile iron (IADI)” or referred to as “dual phase ausferritic spheroidal graphite iron”). Both CADI and interrupted quench variations are produced to further improve the abrasion resistance of standard grades of ausferritic spheroidal graphite iron by either austempering spheroidal graphite iron with a controlled volume of carbides or using a shortened quench time, respectively. Applications include agricultural components such as plough points and tillage tine where abrasion resistance combined with some toughness is needed. Intercritical ausferritic spheroidal graphite iron is produced by modifying the austempering process to produce a final microstructure that contains a controlled volume of proeutectoid ferrite. This is done to improve post-heat-treatment machinability.

Although International Standards exist only for ausferritic spheroidal graphite iron, grey iron and compacted graphite iron can both be austempered. This is done to improve tensile strength and wear properties, as well as vibration and noise damping properties of as-cast grades.

4.5 Why use malleable cast iron?

There are two different types of malleable cast iron, blackheart and whiteheart (see 9.1). The blackheart grades have properties similar to the ferritic spheroidal graphite irons and the materials have traditionally been considered interchangeable in most general engineering applications. The whiteheart malleable grades are still used to produce traditional thin section castings, particularly fittings such as hinges and locks. Its usage is more typically confined to the production of thin section castings where the heat treatment process can be adjusted to completely decarburize the material, allowing for welding to steels.

4.6 Why use compacted (vermicular) graphite cast iron?

Compacted graphite cast iron, also known as “vermicular graphite iron”, has applications for components which require additional strength, stiffness and ductility over and above that offered by grey iron. Typical applications include cylinder blocks and heads, brake drums and brake discs, pump housings, hydraulic components, and cylinder liners. The benefits of the material are that it provides higher tensile strengths and some ductility compared to grey iron. The thermal conductivity and vibration damping properties are between those of grey iron and spheroidal graphite iron. These are also influenced by the compacted graphite morphology and the metal matrix microstructure.

4.7 Why use austenitic cast iron?

The austenitic cast iron, also known as “Ni-hard” or “Ni-resist”, is a family of materials that provide corrosion resistance, heat resistance or a combination of both. Austenitic irons are often compared with stainless steels when a design is being considered. One specific application for which the austenitic iron grades are considered is where the component to be produced needs to be non-magnetizable and other properties are of secondary importance. Both grey and spheroidal graphite iron grades are produced; the spheroidal graphite iron grades exhibit superior tensile properties to the grey iron grades. These materials vary widely in their metal composition to meet a broad range of applications; in general, the most arduous applications are met by those grades containing the highest nickel content.

4.8 Why use abrasion-resistant cast iron?

The abrasion-resisting cast irons are a range of hard materials that compete with other alloys such as manganese steel, mainly in wear-resistant applications including in mining and extraction industries, such as slurry pumps, and in more generalized applications such as in the operation of shot-cleaning plants. Thus, they are rightly considered to be a consumable item where the rate of wear or operational life is important in the decision-making process regarding the choice of material. Generally speaking, they tend to be less expensive and easier to manufacture than the abrasion-resisting steels with which they are usually compared. They perform well in a variety of applications and cannot be casually dismissed as the material of choice in any application that requires abrasion resistance. The effectiveness of any abrasion-resisting material is highly dependent upon the materials it is in contact with and the circumstances under which it is required to perform. For example, slight changes in the composition of an ore in an extraction application, and even its water content, can significantly influence the wear rate.

5 Overview

5.1 General

Cast irons have specific properties that make them useful materials in many applications.

5.2 Recent changes in standardization

ISO/TC 25 is the International Technical Committee responsible for the development of the following International Standards for cast irons:

— ISO 185:2020[1];

— ISO 945-1:2019[2];

— ISO/TR 945-2:2011[3];

— ISO/TR 945-3:2016[4];

— ISO 945-4:2019[5].

— ISO 1083:2018[6];

— ISO 2892:2007[7];

— ISO 5922:2005[8];

— ISO 16112:2017[10];

— ISO 17804:2020[11];

— ISO 21988:2006[12];

A majority of these standards have been revised or created since the first edition of this document in 2009. These International Standards include annexes of additional information about material properties, which are not requirements of the standards, but which provide helpful technical and application information to designers and engineers.

The seven International Standards for cast iron materials encompass a huge international tonnage. In 1999, reported world production reached 49,3 million tonnes/annum, and this figure had increased to 74 million tonnes/annum in 2020[13]. The trend is continuing for cast irons utilized in the manufacture of a wide variety of different components ranging in mass from a few grams to more than 100 tonnes.

The International Standards for cast irons detail the properties of seven individual types of cast iron material in order to enable selection of the most appropriate material for the application. Table 1 provides an approximate ranking of properties to lead the user to the relevant International Standard. It also compares one cast iron material type with another but does not compare the cast irons with other materials. For example, if a cast iron with high strength and ductility were required, then an examination of ISO 1083 or ISO 17804 would be beneficial. The individual grades within these two International Standards can then be consulted to find the most appropriate one and to determine whether the other, unspecified properties in the annexes are beneficial or detrimental to the application.

Table 1 — General property rankings for cast irons

Property	ISO 185 Grey	ISO 1083 Spheroidal	ISO 17804 Ausferritic	ISO 5922 Malleable	ISO 16112 Compacted	ISO 2892 Austenitic	ISO 21988 Abrasion-resistant
Tensile strength	√√	√√√√	√√√√√	√√√√	√√√	√√√	N/A
Yield strength	√	√√√√	√√√√√	√√√	√√	√√√	N/A
Elongation	√	√√√√√	√√√√	√√√	√√	√√√√	N/A
Impact resistance	√	√√√	√√√√√	√√√	√	√√√	√√
Low temperature mechanical properties < 0 °C	√√	√√√√	√√√√√	√√√	√√	√√√	√
High temperature mechanical properties > 450 °C	√	√√√	N/A	N/A	√√	√√√√√	N/A
High strain rate	N/A	√√√	√√√√√	N/A	N/A	N/A	N/A
Thermal conductivity	√√√√√	√√√	√√√	√√√	√√√√	√√√	√
Thermal expansion	√√	√√	√√	√√	√√	√√√√√	√
Abrasion resistance	√√	√√	√√√√	√	√√	√√	√√√√√
Corrosion resistance	√	√√	√√	√√	√√	√√√√√	√√√√√
Castability	√√√√√	√√√√	√√√√	√√	√√√√	√√	√√
Machinability	√√√√√	√√√	√√	√√√	√√√√	√√	√
Weldability	√	√√	√	√√√	√√	√√	N/A

Key

√ Low

√√ Average

√√√ High

√√√√ Very high

√√√√√ Highest

N/A Not applicable

NOTE 1 Rankings are based on choosing the grade with optimum properties within each standard, see Clauses 6 to 12.

NOTE 2 Weldabilty of grades in ISO 5922: JMB grade: = √√√, JMW grade: = √√√√, JMW-S grade: = √√√√√.

Table 2 provides data on typical applications (the list is not exhaustive). Table 2 can also help the designer and engineer to select the most appropriate International Standard, and ultimately the choice of the grade within it.

Table 2 — Typical mechanical property ranges and example applications for cast irons

Standard	Description
ISO 185 Grey	Minimum tensile strength range 100 MPa to 350 MPa, elongation < 1 %. Wide range of general engineering parts: pumps, valves, compressor bodies, machine tools, cylinder heads, cylinder blocks, cylinder liners, brake drums and discs, clutch plates, press tools, street furniture.
ISO 1083 Spheroidal	Minimum tensile strength range 350 MPa to 900 MPa, elongation range 2 % to 22 %. Wide range of general engineering parts requiring higher strength, elongation and fatigue properties than grey iron: crankshafts, hydraulic parts and valves, pumps, steering knuckles, suspension components, axle boxes, exhaust manifolds, turbo charger housings, wind turbine components.
ISO 17804 Ausferritic	Minimum tensile strength range 800 MPa to 1 600 MPa, elongation range 1 % to 10 %. Castings requiring very high strengths with good elongation, toughness including high strain rates and low temperatures, fatigue and abrasion resistance properties: suspension components, gears and cams, crankshafts, differential and planetary housings, pneumatic and hydraulic parts.
ISO 5922 Malleable	Minimum tensile strength range 270 MPa to 800 MPa, elongation range 1 % to 16 %. Wide range of general engineering parts requiring higher strength, elongation and fatigue resistance with some grades weldable: pipe fittings, suspension components, gear cases, universal joints.
ISO 16112 Compacted	Minimum tensile strength range 300 MPa to 500 MPa, elongation range 0,5 % to 2 % Components requiring good thermal conductivity in conjunction with higher strength than grey iron: ingot moulds, cylinder heads, cylinder blocks, cylinder liners, brake drums and discs, hydraulic parts.
ISO 2892 Austenitic	Minimum tensile strength range 140 MPa to 440 MPa, elongation range 1 % to 25 %. Parts requiring corrosion and heat resistance, some grades being non-magnetizable: pumps, manifolds, gas turbine housings, turbochargers, refrigeration components, compressors.
ISO 21988 Abrasion-resistant	Minimum hardness range 340 HBW to 630 HBW Castings requiring high abrasion and impact resistance: rock crushers, grinding balls, digger teeth, shot-cleaning wear-plates, pumps and valves carrying abrasive liquids.

There is often a communication difficulty between casting producers and the engineers and designers employed by their customers over the understanding of the cast iron material properties beyond those of the normative requirements of the specific International Standard. This can lead to confusion, a good example of which is the phenomenon of section sensitivity in grey irons, where, depending on the section thickness, the mechanical properties in the casting can be either worse or better than those in separately cast test pieces. Even experienced engineers are sometimes unfamiliar with the properties of the cast irons, leading to either an underestimation of the true potential of the material or unrealistic expectations of it.

Cast irons are among the best materials for production of structural parts with complex shapes, enabling designers to substitute assembled forgings and welded fabrications with a near-net shape component, thus reducing the total cost, mass and supply chain complexity.

5.3 General microstructure of cast iron

Generally, iron-carbon compositions with up to 2,0 % carbon are called “steel”. When carbon content exceeds 2,0 %, it is called “cast iron”.

Plain carbon steels are iron-carbon alloys where the carbon content dictates the main properties and other elements are generally at too low a level to be of major significance. Up to 0,02 % carbon content, the material is soft ferrite. As the carbon content is increased, increasing amounts of pearlite are formed, which is harder and stronger, such that at about 0,8 % carbon content the structure is fully pearlitic. Raising the carbon content results in increasing amounts of iron carbide, e.g. cementite, which