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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

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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 Compact-ed	ISO 2892 Auste-nitic	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 is hard and brittle, thus increasing strength and reducing elongation. Above 2,0 % carbon content, the material is called “white cast iron” and comprises a mixture of pearlite and carbides. It is this structure (a mixture of pearlite and iron carbide) that forms the basis of the manufacture of the abrasion-resistant irons and malleable irons; although, refinements to metal composition and the use of heat treatment are required to meet the specified requirements of their respective International Standards.

The International Standards for most cast irons require the majority of the carbon content to be present in the form of graphite. This is achieved by the addition of at least 1,7 % silicon, which promotes carbon in excess of the solubility in iron to form graphite in the stable Fe-C phase diagram, instead of iron carbide in the metastable Fe-C phase diagram, which is common for steels.

Grey irons contain flake (lamellar) graphite, which is the default graphite form that occurs during solidification. Spheroidal and compacted irons are produced by deliberate modification of the solidification mechanism, usually by an addition of magnesium. Rare earth elements are also used as the treatment agent, either alone or in combination with magnesium.

In the case of the austenitic irons and abrasion resistant irons, high levels of other alloying elements are also added to produce the required metallic matrix microstructures and resulting material properties. Ausferritic irons are both alloyed (for hardenability purposes only) and heat treated, in order to obtain an ausferritic matrix. These are standardized for spheroidal graphite irons but can also be applied for compacted graphite irons and grey irons.

Heat treatments can be applied to all cast iron materials, either as part of the production route, to enhance properties, or to stress relief in complex components.

In summary, there are seven cast iron types, each broadly described as follows:

— Grey iron: Cast iron with a flake (lamellar) graphite form, usually in a pearlitic matrix except for the lowest strength grades where ferrite is present. The material does not normally require heat treatment unless stress relief is applied to ensure dimensional stability. Austempering grey iron to produce an ausferritic matrix results in increasing strength, vibration and noise damping, and wear resistance.

— Spheroidal graphite iron: Cast iron with the solidification mode modified to produce graphite in spheroids as opposed to flakes. The grades range from fully ferritic to fully pearlitic matrices, including three recently developed solution strengthened ferritic grades. Heat treatment is sometimes used to produce the ferritic grades, particularly LT grades requiring high impact values at low temperature. Ferritic-pearlitic grades can be produced by avoiding pearlite-promoting elements in the composition as well as using the appropriate heat treatment. The highest-strength grades can be heat treated using processes similar to steel such as normalizing or quench and tempering. In a martempering process, spheroidal graphite iron can be quenched in a salt bath to avoid potential cracking associated with conventional quenching, followed by air cooling and tempering. Quenching in a salt bath can also be used to obtain a perferritic microstructure using an isothermal ductile iron (IDI) process. A stress relief can subsequently be applied, if necessary. Irons can also be quenched in a salt bath above the martensite start temperature to avoid martensite formation or a tempering requirement (IDI). As a result, cracks that can potentially form due to nonuniform transformation associated with conventional quench and tempering can be avoided. Stress relief can be applied if necessary.

— Ausferritic iron: Spheroidal graphite iron deliberately subjected to an austempering heat treatment that enhances material properties, producing an ausferritic matrix containing graphite spheroids. Alloy additions (copper, nickel, molybdenum) can be required for hardenability purposes to ensure the formation of ausferrite in thick sections.

— Malleable iron: There are two types of malleable cast irons, termed “blackheart” and “whiteheart”. They are deliberately produced with a low silicon level to produce iron carbide and are then heat treated to break down the carbide and form graphite, as ragged spheroids usually known as “temper carbon nodules”. The grades range from fully ferritic to fully pearlitic. The material can be oil quench and tempered to produce the highest strength grade.

— Compacted graphite iron: Cast iron with the solidification mode modified to produce worm-like or vermicular graphite, usually with a small percentage of spheroidal graphite present. The grades range from those containing mainly ferritic to fully pearlitic matrices. The same heat treatments as described above can be applied to compacted graphite iron. However, this material is not typically heat treated unless a stress relief is required.

— Austenitic iron: Cast iron with an austenitic matrix that is alloyed with nickel to be stable down to sub-zero temperatures. It contains grades with either graphite flakes or spheroids, used in special applications.

— Abrasion-resistant iron: Cast iron with a microstructure that consists essentially of carbides typically in a matrix of martensite; bainite or austenite can also be present. Heat treatment can be employed to achieve the desired matrix microstructure.

5.4 Section sensitivity and the effects of relevant wall thickness on material properties

Section sensitivity is one of the most important phenomena to be understood with regard to cast iron material properties. Most engineers expect that the same properties will be obtained over the entire casting independent of wall thickness, and in both the castings and the test pieces poured with them. This is largely the case with steel and many other alloys, but is not the case with cast iron, for reasons related to the section sensitivity.

The expression "section sensitivity" is used to explain wall thickness dependent properties of the casting and the relationship between the results from the separately cast test piece used to confirm the tensile properties of cast iron materials and the tensile properties in the casting. These properties usually differ. This is a very important aspect of design with cast iron materials and is related to the effects produced on material structure, resulting from different rates of solidification in varying casting sections.

For validation of properties in the relevant wall thickness of interest (e.g. where high design loads occur), one option is to cut a sample from the casting (except for single castings). Most material standards provide informative (typical) data for the casting itself. For spheroidal graphite irons and ausferritic spheroidal graphite irons, ISO 1083:2018, Annex D, and ISO 17804:2020, Annex E, give guidance values for mechanical properties in samples cut from the casting, divided in ranges of relevant wall thickness.

In thin section castings, the solidification will be rapid, whereas in thick sections solidification will be slow. Thus, depending on the section thickness, there will be differences in the graphite form and size, and possibly in the matrix structure. These effects result in differing mechanical properties within the various casting sections. The effects of section sensitivity in grey irons are dominated by the flake size and are less pronounced in compacted irons. In contrast, the tensile properties of cast irons containing graphite spheroids are mainly controlled by the matrix. Blackheart malleable irons and the abrasion-resistant irons are the least sensitive to section size. The effects of wall thickness of weldable whiteheart malleable irons are influenced by the decarburization process (see 9.2 and 9.7).

In the International Standards for compacted irons, spheroidal graphite irons and ausferritic irons, test pieces are required, machined from either separately cast, cast-on or side-by-side cast samples. This arrangement more closely replicates the properties of the wall thickness to which the sample is attached, provided that the correct size of test piece is used. Tables in the various International Standards for cast iron specify the required mechanical properties, depending upon the relevant wall thickness. In addition, guidance values for mechanical properties measured on test pieces machined from samples cut from the castings are provided in informative annexes.

5.5 Understanding hardness

Standards do not always specify hardness, although informative data are sometimes provided for the various grades. Customers, on the other hand, commonly specify hardness ranges required for their components. Hardness does not guarantee the final microstructure of a casting which, in turn, will determine the mechanical properties. However, hardness at a specified location on the casting is a useful tool to determine if a casting will meet mechanical requirements providing that the manufacturing process is capable and carefully controlled. The relationship between mechanical properties of the casting and hardness can be established in the first sample stages.

ISO 185 contains special hardness-only grades which are normative and do not require tensile strength validation. It is now possible to specify castings according to a mandatory hardness grade or to be produced according to a tensile strength grade where the customer mandates an additional hardness range to be met.

It is important to clarify how the section-sensitivity phenomenon affects hardness. For example, the flake (lamellar) graphite in grey irons is coarser in thick sections than in thin sections, which is determined by the cooling rate during the liquid to solid transformation. The matrix can also be affected by different cooling rates in the solid state; thus, thick sections will be softer than thin sections. An illustration is given in ISO 185:2020, Table 2, which takes this situation into account by specifying the hardness range of 40 mm to 80 mm sections and providing anticipated values in other, thinner sections. Additional information regarding the section sensitivity in relation to hardness is given in ISO 185:2020, Annex C.

An important point to note for all cast irons is that they are metallic materials with graphite, or in the case of the abrasion-resistant iron grades, with carbides, in a steel-like matrix. For this reason, it is inappropriate to use a hardness tester with an indenter smaller than 5 mm in diameter. The usually specified test apparatus is a Brinell hardness-testing machine fitted with a 10 mm ball and 3 000 kg load (10/3 000) as this provides the most accurate reading. For thinner sections, a 5 mm ball and 750 kg load (5/750) are applicable. Rockwell, Vickers and other hardness-testing apparatus with small indenters and light loads give inconsistent results and usually cause confusion.

When hardness is specified, the hardness range needs to be realistic in considering normal variations in the material and/or the process. Grey iron (typically pearlitic) and ferritic-pearlitic spheroidal graphite cast iron are sensitive to the casting wall thickness. In grey iron this is dominated by the flake size and the pearlite lamellae spacing. In ferritic-pearlitic spheroidal graphite iron, the hardness variation is primarily caused by the ferrite-pearlite ratio and the pearlite lamellae spacing. The process stability, which is influenced by the metal base quality, the inoculation practices and the shake-out time (the temperature of the casting when removed from the mould) also play a fundamental role.

Spheroidal graphite iron with a uniform wall thickness can be successfully produced with an optimum combination of strength and elongation when the process is managed within an appropriate Brinell hardness range. A typical hardness variation for a grey cast iron would be about 50 HBW. For example, a JL/250 grey cast iron material would typically have a hardness range of 187 HBW to 241 HBW. For a spheroidal graphite iron, the hardness variation will be between 10 HBW and 70 HBW depending upon the grade and matrix. The lowest hardness variation is obtained in fully ferritic matrices. For abrasion-resistant irons, the situation is somewhat different because the minimum hardness is specified. It must be noted there will still be hardness variations between thin and thick sections, even though the minimum specified value has been met.

The most important point of all is that if castings are specified to be hardness tested, then the hardness range and the locations of the hardness test on the castings are agreed between the manufacturer and purchaser.

5.6 Heat treatment

Some of the materials specified in the International Standards for cast irons require special heat treatment operations to be carried out on the components as part of the production process; the manufacture of ausferritic and malleable irons require heat treatment according to 8.2 and 9.3, respectively. Other cast iron types can require heat treatment processes for remedial reasons, as is allowed in the relevant International Standards, or to help achieve the requirements of the grade. Heat treatments applied to cast iron are listed in Table 3.

Table 3 — Heat treatments applied to cast irons

Process	Temperature[b]	Subsequent process
Annealing	$T > A_{c3}$	Slow furnace cooling to below 200 °C.
Austempering — conventional — intercritical	$T > A_{c3}$ $A_{c3} > T > A_{c1}$	Quenching to avoid pearlite transformation of the austenite to a temperature above the M_s, followed by isothermal transformation to ausferrite, without versus with proeutectoid ferrite.
Isotherming[a]	$A_{c3} > T > A_{c1}$	Quenching to transform the austenite and proeutectoid ferrite into perferrite (matrix structure composed by ferrite and pearlite formed at a high rate of eutectoid transformation) uniformly in thin and thick sections, while maintaining the casting at a temperature above the M_s.
Normalizing	$T > A_{c3}$	Air quench outside the furnace, sometimes using cooling fans for larger castings. A subsequent temper can be necessary to relieve residual stresses formed on cooling or to achieve the final hardness target.
Oil quench and temper	$T > A_{c3}$	Quench in oil and then temper at a temperature to achieve the desired hardness.
Stress relief	550 °C to 650 °C	Slow cooling to below 200 °C.

[a] The process IDI is patented in several countries. For more information, see Reference [23].

[b] A_{c1} is the temperature where austenite starts to form during heating. A_{c3} is the temperature where austenite formation is completed during heating.

5.7 Welding

Cast irons have superior castability when compared with other cast metals of similar strength, therefore finishing welding is not common. There is a common misconception that cast iron cannot be welded. In many internal company specifications, contract requirements or international standards, it is specifically disallowed in the belief that a weld will act as a stress raiser and contribute to failure of the part.

While some cast irons do not respond well to welding, others need special considerations regarding acceptable techniques. With the exception of the weldable malleable whiteheart iron, manual arc welding using steel rods (typically employed for steel welding purposes) can never be used, as the weldment will not have long-term integrity and can result in catastrophic failure of the casting.

Engineers and designers would be wrong, however, to dismiss a welding operation out of hand without consideration of the reliable possibilities. These fall into two categories, namely: finishing welding to remove unwanted imperfections and joint welding of cast iron to other materials as part of a fabrication. As with all repairs or finishing welding, the question arises as to whether welding is cost-effective or whether it is more sensible to produce a replacement casting. This is particularly the case in the manufacture of large numbers of small castings. The welding processes for cast iron are described in ISO/TR 10809-2[9].

6 ISO 185, Grey cast irons

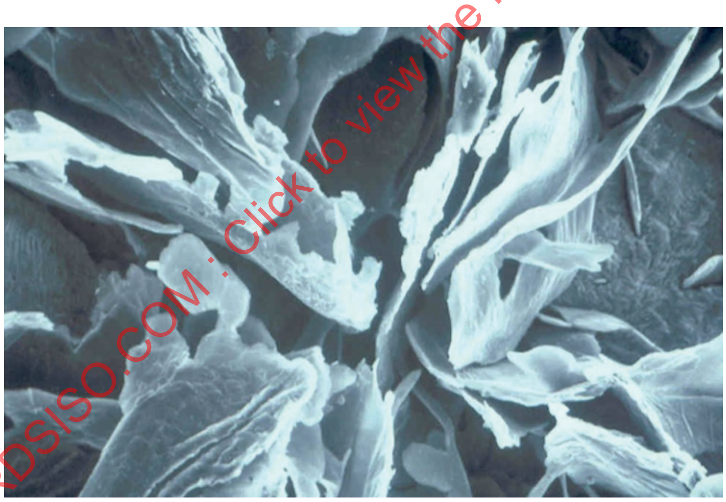
6.1 Overview

The properties of grey cast iron, also known as “flake (lamellar) graphite iron”, are specified in ISO 185:2020, Tables 1 and 2. The structure of grey iron contains graphite flakes in a predominantly pearlitic matrix is shown in Figure 1.

Magnification × 300

Figure 1 — Flake graphite in a pearlitic matrix

In reality, the solidification of grey iron involves the formation of eutectic cells; each cell contains its own continuous graphite skeleton. Figure 2 shows a stereo-photograph of the surface of a grey iron eutectic cell, after all of the metallic matrix has been etched away to leave the graphite structure.

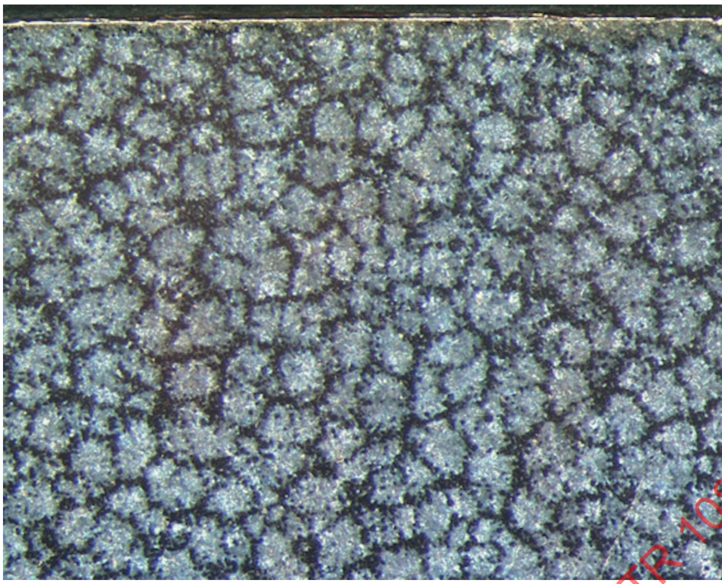


Magnification × 350

Figure 2 — Deep-etched structure of the graphite in a eutectic cell

The eutectic cell structure can often be seen on machined surfaces, particularly when the finish is fine; this is often misconstrued as being a discontinuous and defective structure. In reality, it is quite normal for the material. It is caused by the machining operation slicing off the top of the cells to expose a section through them, outlined by small amounts of trace elements, such as phosphorus, in the material.

Figure 3 illustrates a typical grey iron eutectic cell structure as revealed by a specific etching.



Magnification × 25

Figure 3 — Eutectic cell outline on a fine surface

A complete eutectic cell is illustrated in the schematic diagram shown in Figure 4. It not only illustrates a three-dimensional image of the geometry of the graphite within a cell, but also how a slice taken across it during machining or metallographic preparation in the laboratory exposes an apparent flake graphite form.

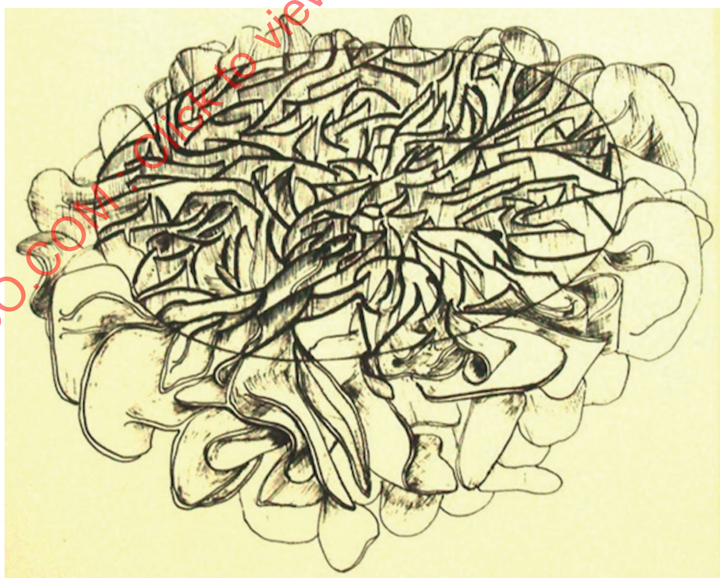


Figure 4 — Schematic of the cut top of a eutectic cell

The volume of the graphite present is primarily dependent upon the carbon content, while the eutectic cell size and number of cells determines the size of the graphite flakes. These factors largely determine the mechanical properties of the material.

6.2 Effect of structure on properties

When flake (lamellar) graphite is present, the amount and distribution have a major effect in determining the mechanical properties. Low-tensile-strength grey iron generally contains relatively large quantities of coarse graphite flakes, often in association with ferrite in the matrix. Tensile properties increase as the quantity of graphite decreases, as the graphite becomes finer, and as the amount of ferrite in the matrix is reduced, although the last factor has the least influence. Higher strengths are obtained by lowering the carbon and silicon contents (the carbon equivalent, see 6.3), by using good inoculation techniques and, where appropriate, by alloying with pearlite-promoting elements.

NOTE In grey iron it is the graphite, rather than the continuous metal matrix, that largely dictates the tensile properties.

6.3 Metal composition and carbon equivalent

ISO 185 does not specify metal composition requirements. Metal composition is left to the discretion of the manufacturer, who will adjust the composition in order to meet the specified tensile requirements. Pearlite-promoting elements can be used to increase the amount of pearlite in the matrix, but the major control factors are the carbon and silicon contents. These contents are often evaluated in terms of carbon-equivalent stable eutectic (CEE) measurement using a thermal analysis technique. The CEE, in per cent, is calculated using Formula (1):

$$\mathrm{CEE} = 100 \times \left(\mathrm{C} + \frac{\mathrm{Si}}{3,2} + \frac{\mathrm{P}}{3} \right) \quad (1)$$

Except for JL/100 and JL/150, all other grades have hypoeutectic compositions. Reducing the carbon and silicon levels increases the tensile strength, as shown in Table 4.

In most foundries today, the phosphorus content is low and consistent, such that the level can be inserted into thermal analysis apparatus. A precise carbon content can be obtained, and the silicon content can be derived to within ±0,15 % by automatic calculation. Those grades specified only on the basis of hardness (allowed in ISO 185) will require a CEE that is dependent upon the agreed thickness of the casting at the location of the test.

Table 4 — CEE ranges for ISO 185 grades

Material designation	Typical CEE range
ISO 185/JL/100	4,0 to 4,2
ISO 185/JL/150	4,0 to 4,2
ISO 185/JL/200	3,8 to 4,0
ISO 185/JL/225	3,7 to 4,0
ISO 185/JL/250	3,6 to 3,8
ISO 185/JL/275	3,5 to 3,7
ISO 185/JL/300	3,4 to 3,6
ISO 185/JL/350	3,4 to 3,6

The ranges in Table 4 assume good inoculation to provide a high level of nucleation and a satisfactory graphite form. The ranges will enable the minimum tensile strength requirement of each grade to be achieved in separately cast samples of diameter 30 mm. These CEE ranges will not necessarily give the same properties in the casting, however, due to section-sensitivity issues.

6.4 Graphite form, distribution and size

The graphite precipitates in different forms, distributions, and sizes depending on the solidification rate and the efficiency of inoculation.

The graphite form and size (as opposed to volume) are principally determined by the rate of solidification and the number of eutectic cells. The rate of solidification is basically a function of the section size. Heavier sections solidify more slowly than thin sections and therefore contain fewer, larger eutectic cells and coarser graphite. Generally, the number of eutectic cells increases, and the graphite distribution becomes finer when an inoculating addition of silicon and other elements is made just prior to pouring the molten iron into the moulds. If inoculation practice is poor, less desirable graphite distributions result, but if inoculation is good, the graphite distribution is optimized, and better tensile properties are obtained. ISO 945-1 characterizes the graphite into five distributions, as shown in Figure 5.

The five distributions of graphite are as follows:

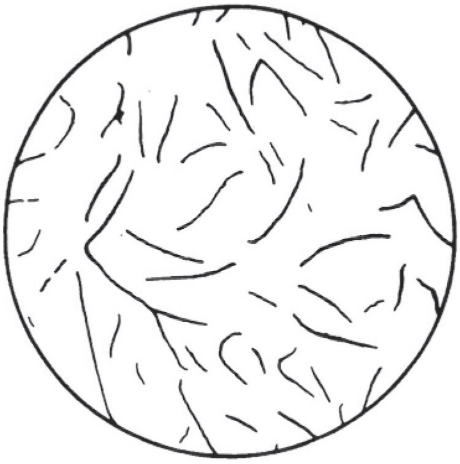
— Type A graphite: Uniform distribution and an apparent random orientation. Normal in well-produced and inoculated materials.

— Type B graphite: Rosette graphite. Typical of a moderate rate of cooling and not uncommon in more rapidly cooling surface areas of the casting. Can be indicative of less than perfect inoculation.

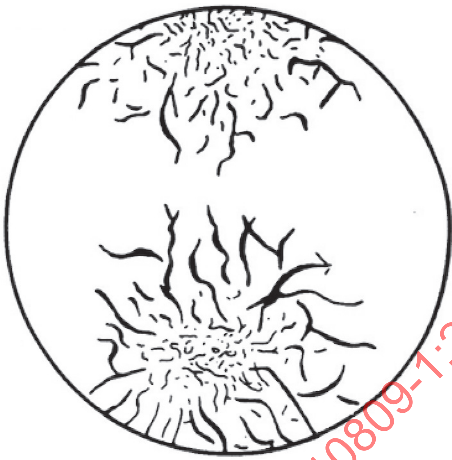
— Type C graphite: Primary graphite. Occurs in hypereutectic irons, that is, those with CEE values greater than 4,25. Present in heavy sections as coarse plates and in light sections as clusters and star-like shapes.

— Type D graphite: Undercooled graphite. Normally associated with rapid rates of cooling and most common in thin sections, particularly if the inoculation practice is less than perfect.

— Type E graphite: Interdendritic graphite with preferential orientation. Normally occurs in strongly hypoeutectic irons, that is, those with low carbon equivalents and solidified with a low or moderate undercooling, generally with higher cooling rates.



a) Type A



b) Type B

c) Type C

d) Type D

e) Type E

Figure 5 — Reference diagrams for graphite distribution

ISO 945-1 also divides graphite into eight sizes, with size 1 being very coarse and size 8 being very fine. Thus, the graphite form and size can be specified if necessary. The most common specification for the graphite form and size of grey iron, which is sometimes appended to the grade requirement, is ISO 945-1:2019, Type A, size 4 to 6. However, because of section-sensitivity issues in castings of varying section thickness, it is necessary to agree on the location and depth at which the test is made.

6.5 Section sensitivity

The ISO 185 grey iron is the most section-sensitive of all the cast iron materials, and it is essential that this be taken into account during the design calculations that predict actual performance in service. A separately cast test piece of uniform dimensions is used to determine the precise mechanical properties of the material and the properties in the casting can be obtained empirically to ratify design strengths. Much research has been conducted to derive data on the properties in different sections and this research has resulted in the collection of data such as that detailed in ISO 185:2020, Table 1, an extract from which is shown in Table 5.

Table 5 — Extract from ISO 185:2020, Table 1, relating to section sensitivity (relevant wall thickness)

Material designation	**Tensile strength** (mandatory values in separately cast samples) MPa minimum	**Relevant wall thickness** mm		**Tensile strength** (anticipated values in castings) MPa minimum
		over	up to and including	
ISO 185/JL/150	150	2,5	5	180
		5	10	155
		10	20	130
		20	40	110
		40	80	95
		80	150	80
		150	300	—
ISO 185/JL/250	250	5	10	250
		10	20	225
		20	40	195
		40	80	170
		80	150	155
		150	300	—
ISO 185/JL/350	350	10	20	315
		20	40	280
		40	80	250
		80	150	225
		150	300	—

6.6 Effect of alloying elements

Alloying elements are sometimes added to grey iron in order to ensure a fully pearlitic matrix in the higher-strength grades. These alloying elements are normally copper or tin, both of which promote the formation of pearlite. Chromium is sometimes added; although it does assist in the formation of pearlite, it is a powerful promoter of eutectic carbide and thus needs to be used with caution. Users sometimes ask for the addition of such elements over and above the normal requirements of the standard, in the mistaken belief that further improvement in properties will result. It must be understood that when the matrix is fully pearlitic, further additions of pearlite-promoting elements generally have an adverse effect on properties. For example, tin promotes embrittlement, and in a fully pearlitic matrix, chromium can only promote carbide. Nickel, an element commonly demanded in low amounts (up to about 2 %) in the belief that properties will be enhanced, has a zero effect upon properties in grey irons until the level present approaches the point where an austenitic matrix is formed. In general terms, the higher-strength grades are achieved with a fully pearlitic matrix and, most importantly, with well-formed graphite flakes resulting from good inoculation, rather than by the introduction of unnecessary alloying elements.

6.7 Heat treatment

The heat treatments used for grey cast iron are stress relieving, annealing, normalizing and austempering.

The most common heat treatment applied is stress relieving. A problem that can be encountered is dimensional change and/or distortion during or after the machining operation. These changes are usually caused by the presence of internal stresses in the casting created by differing rates of solidification and cooling in thick and thin sections, the presence of cores to produce the internal casting geometry, excessive shot cleaning, etc. Machining operations can change the distribution of these stresses and cause distortion of the casting. Undertaking a stress-relieving operation can solve the problem, provided that there is sufficient material left for the final cut.

Annealing can be requested to improve machinability rather than to increase mechanical properties. Normalizing treatments are used to ensure a fully pearlitic matrix, in thick section castings where slow cooling has resulted in a ferritic matrix, or to remove hard, unwanted carbide.

The thickest section of the casting determines the holding time at a temperature for all heat treatments.

In addition to the grades listed in ISO 185, grey iron can be austempered to increase tensile strength up to 400 MPa (depending on graphite structure) with a corresponding improvement in wear resistance. The microstructural refinement from the austemper heat treat process further improves the damping capacity of grey iron.

6.8 Choosing the grade

The grades available in ISO 185 range from a 100 MPa tensile strength material with a mainly ferritic matrix, increasing in up to a 350 MPa tensile strength material with a fully pearlitic matrix. All of the grades have a defined minimum tensile strength as indicated in ISO 185:2020, Table 1, but a requirement regarding the maximum strength is also defined in ISO 185:2020, 7.2.1, and is often missed. For each grade, the maximum tensile strength is no more than 100 MPa above the minimum, e.g. grade JL/200 has a tensile strength between 200 MPa and 300 MPa. This is to prevent a situation in which a grade is supplied that has a tensile strength substantially higher than the minimum, but with adverse effects on most of the other properties.

The lowest-tensile-strength grades JL/100 and JL/150 have the highest carbon content and thus the highest thermal conductivity and damping capacity. These grades are useful in situations where tensile strength and hardness are not the crucial properties in service. Castings produced in these grades are likely to be used in conditions where thermal conductivity and damping capacity are more important than mechanical strength. The high content of graphite in these materials also imparts good lubricated bearing properties, provided that the environment does not include abrasive debris, e.g. sand particles, that can score and wear the soft matrix.

The intermediate-tensile-strength grades JL/200 to JL/275 have lower carbon content resulting in mainly or completely pearlitic matrices. The thermal conductivity and damping capacity remain good, and the higher-tensile strength and hardness values, within this range of grades, provide superior wear properties. These grades, therefore, find a large number of applications in general engineering castings, such as pumps and valves, machine tool beds, and particularly automotive parts such as cylinder heads and blocks, brake drums and discs, and clutch plates.

The highest-tensile-strength grades JL/300 and JL/350 provide a combination of high strength while still maintaining good thermal conductivity compared with other types of cast iron. These grades approach the maximum tensile strength attainable in grey iron. Applications, therefore, tend to be confined to those where thermal conductivity requirements in service preclude the use of one of the other higher-strength materials such as spheroidal graphite irons, which have inferior thermal conductivity.

All the ISO 185 grades have elongation limited to a maximum of about 1,0 % and poor impact properties. This makes grey iron unsuitable for use where ductility is required. Compression strengths are, however, much higher than tensile strengths, see ISO 185:2020, Table A.1.

7 ISO 1083, Spheroidal graphite cast irons

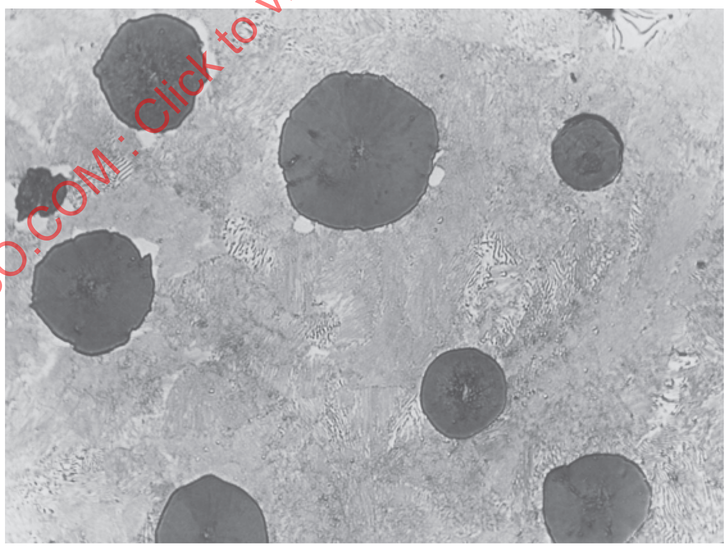
7.1 Overview

The properties of spheroidal graphite irons (sometimes called “ductile” or “nodular cast irons”) are specified in ISO 1083. The structure of spheroidal graphite irons contains graphite in spheroidal form as shown in Figure 6 (in this case in a predominantly pearlitic matrix). The properties are dominated by the matrix, as long as the graphite particles are isolated and approximately spherical.

ISO 1083:2018, Tables 1 and 2, specify ferritic to pearlitic matrix grades, ranging from fully ferritic materials with tensile strengths above 350 MPa and elongation in excess of 22 % to fully pearlitic materials with tensile strengths above 900 MPa and elongation as low as 2 %.

A second way to increase strength is to increase the solid solution strengthening of a ferritic matrix by increasing its silicon content to achieve tensile strengths of 450, 500 or 600 MPa. When compared to ferritic-pearlitic grades of the same tensile strength, higher yield strengths of 350 MPa, 400 MPa or 470 MPa concurrently with higher elongations of 18 %, 14 % and 10 % are realized as shown in ISO 1083:2018, Table 3.

All of these grades are compiled in Table 6 in 7.7.



Magnification × 500

Figure 6 — Pearlitic spheroidal graphite iron

The normal production route for spheroidal graphite irons is to add a small percentage of magnesium (or a mixture of magnesium and rare earth elements) to a molten alloy with low sulfur content. This procedure is followed by an addition of a silicon-based inoculant to counteract the carbide-promoting effects of the magnesium. The result of this treatment is a material that contains graphite spheroids, as opposed to graphite flakes.

7.2 Effect of structure on properties

The mechanism of solidification is entirely different from that of grey irons, which results in a wide range of grades with tensile properties that are substantially better than what grey iron can provide. This difference in properties results from differences in graphite form. Graphite flakes have a large ratio of surface area to volume, and because they are sharp edged, they act as stress raisers in the matrix. By comparison, graphite spheroids approach the minimum in terms of surface area to volume ratio, and do not act as stress raisers, although they restrict the plastic zone size around stress concentrations. The opportunity also exists to utilize a variety of different matrix structures ranging from fully ferritic to fully pearlitic by the controlled choice of raw materials, alloying, and heat treatment. For this reason, the possible microstructures of the matrix described in ISO/TR 945-3 dictates the structure of spheroidal graphite irons and, thus, their tensile properties. This is the opposite situation to that which pertains with grey irons where the size and the shape of the graphite flake (lamellae) dictate the final properties.

7.3 Metal composition and carbon equivalent

ISO 1083 does not specify metal composition requirements; metal composition is left to the discretion of the manufacturer. The mechanical property requirements of the various grades in the specification are met by chemical composition and/or heat treatment. Because the matrix principally dictates the properties of the spheroidal graphite irons, the carbon equivalent does not need to be controlled in the same way as in grey irons. These grades normally have hypoeutectic compositions to prevent graphite flotation. The range of silicon is from 1,9 % in order to meet low temperature impact energy requirements, up to 4,2 % in the strongest solution strengthened ferritic grade, with a corresponding decrease of carbon, resulting in slightly less amounts of graphite. The most common silicon composition range is between 2,4 % to 2,7 %.

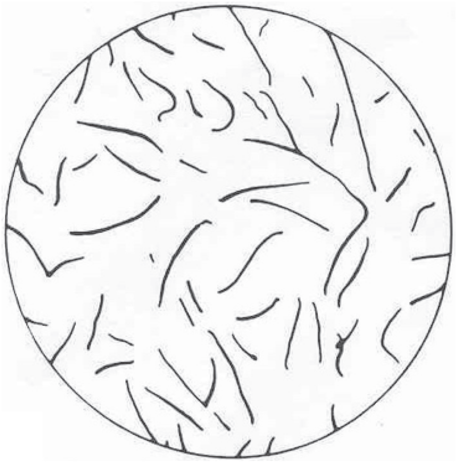
7.4 Graphite form and size

Spheroidal graphite shape, referred to as “nodularity” expressed as a percentage, is often required in company specifications in addition to the material grade. Nodularity is specified because non-spheroidal graphite can reduce mechanical properties, in particular the elongation at fracture. The presence of less than perfect graphite spheroids is not unusual, which is why ISO 1083 refers to the material as having the carbon present mainly in the form of graphite spheroids.

ISO 945-1 designates six forms of graphite defined as Forms I to VI. These are shown in Figure 7. ISO 945-4 specifies a test method for evaluating nodularity in spheroidal graphite cast irons by comparative visual analysis and image analysis techniques. This document provides figures for different levels of nodularity and graphite particle count of spheroidal graphite cast irons for visual analysis. Most company specifications require a minimum of 80 % nodularity or higher of graphite in Form V and Form VI. However, it is inappropriate to specify percent nodularity unless the remaining percentage of graphite is also specified. A level of nodularity of 80 % to 85 % or more generally ensures the minimum tensile properties (more than enough for $R_{p0,2}$) specified in ISO 1083. Most of the 15 % to 20 % of graphite not in Form VI or V is typically in Form IV, possibly in Form III.

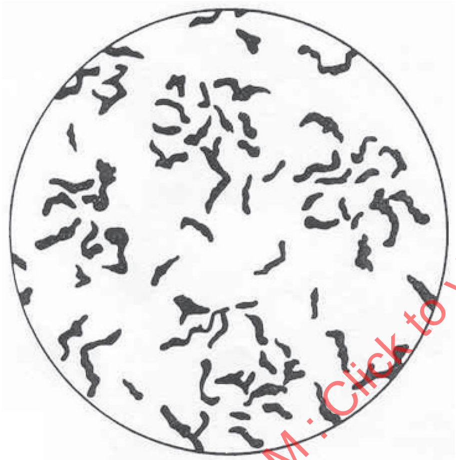
A spheroidal graphite iron containing 91 % of Form VI and 9 % of Form I, for example, would meet the nodularity requirement of 90 %, but not the mechanical properties required by ISO 1083. Although it can be argued that the requirements of ISO 1083 would filter out the unsatisfactory material, it is far better to be specific by designating the full requirement for the graphite form with reference to ISO 945-1. This designation, for example, can be “more than 80 % Form VI, more than 95 % of Form VI and Form V, with the remainder of Form III”. ISO 945-1 also designates eight sizes of graphite.

Because of the interaction between the liquid metal and the mould surface, a degenerate surface layer containing flake graphite and the possible formation of inclusions is often unavoidable. When this is not acceptable, the surface layer can be removed by machining and/or shot blasting. The maximum depth of this degenerate surface layer can be agreed upon between the manufacturer and purchaser, if necessary. Some applications of spheroidal graphite iron (e.g. those requiring low temperature toughness) can require graphite particle count (graphite particles/mm^2) and/or graphite particle size to be specified. Section thickness and casting geometry will affect the selection of these criteria. As a result, graphite particle count or particle size parameters are typically established by agreement between the purchaser and manufacturer at a specific location in a casting or other designated sample. ISO 945-1 provides information on nodule size 3 to 8.



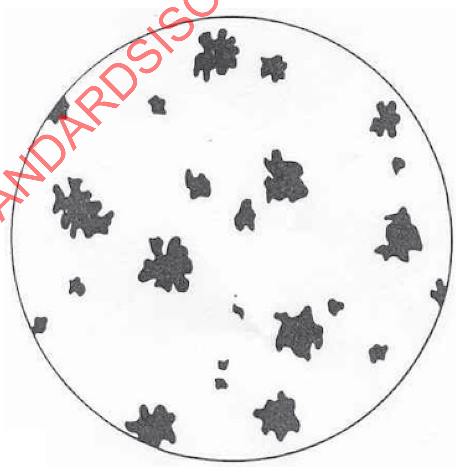
a) Form I

b) Form II

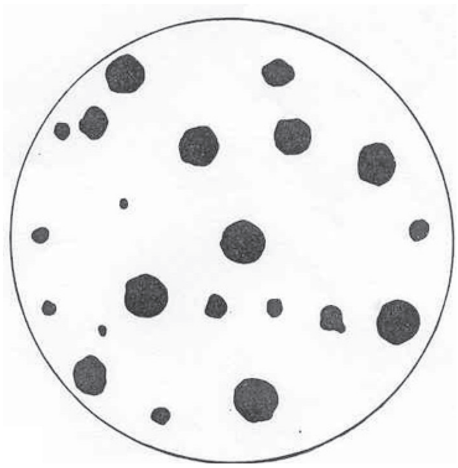


c) Form III

d) Form IV



e) Form V



f) Form VI

Figure 7 — Graphite forms in ISO 945-1

7.5 Relevant wall thickness in spheroidal graphite iron

As the wall thickness increases and solidification rate is reduced, the graphite spheroids become larger so the number of spheroids is reduced, which can cause the graphite shape to deviate from Form VI to Form V or lower. Therefore, the tensile properties in the heavier sections will be lower than those in the thin sections. Thus, when graphite form and size are specified in the casting, it is imperative that the test location be agreed between the manufacturer and the user to avoid conformance disagreements. If the form and size are specified within a separately cast sample, often cast to validate the material as part of routine control procedures, it is important to note that the form and size of the graphite in the casting can be different from that in the sample.

Because the matrix primarily defines the static tensile properties, they are not seriously affected until a significant deviation in graphite form occurs.

7.6 Effect of alloying elements

When the ferritic-pearlitic and pearlitic grades are produced, there is a tendency to add alloying elements to obtain the required amount of pearlite. In addition to alloying, increased cooling rate in the solidified casting promotes pearlite over ferrite. Therefore, thinner parts of a ferritic-pearlitic grade casting usually have higher pearlite contents than thicker parts. In contrast to this, the higher silicon content in the solution strengthened ferritic grades also prevents pearlite in thinner parts.

The most common pearlite-promoting elements are copper and tin. Tin promotes pearlite about 10 times more powerfully than an equal percentage of copper. Copper is normally used in preference to tin because it increases the tensile strength and maintains a higher ductility. The important aspect of alloying to produce pearlite is that once the structure is fully pearlitic, further additions of pearlite-promoting elements increase embrittlement, with possible adverse effects on service performance. To address this, users can confine their requirements to the mechanical properties of the standard grade and allow the manufacturer to identify the necessary alloying levels.

7.7 Matrix structure and resultant properties

Table 6 shows the properties of the 17 grades of spheroidal graphite iron specified in ISO 1083, for castings with a relevant thickness up to 30 mm. As the tensile strength increases, there is an accompanying reduction in elongation at fracture, especially for grades with low ferrite contents. Elements such as copper or tin are added to produce the higher-strength, lower-ductility grades, as these metals are pearlite-promoting elements that raise the tensile strength but lower the elongation.

Table 6 — Structure and properties of ISO 1083 cast iron grades; minimum values obtained from cast samples corresponding to castings with a relevant wall thickness up to 30 mm

Material designation	Tensile strength R_m MPa minimum	0,2 % Yield strength $R_{p0,2}$ MPa minimum	Elongation A_5 % minimum	Typical matrix structure
ISO 1083/JS/350-22LT[a]	350	220	22	Ferrite
ISO 1083/JS/350-22-RT[b]	350	220	22	Ferrite
ISO 1083/JS/350-22	350	220	22	Ferrite
ISO 1083/JS/400-18-LT[a]	400	240	18	Ferrite
ISO 1083/JS/400-18-RT[b]	400	250	18	Ferrite
ISO 1083/JS/400-18	400	250	18	Ferrite
ISO 1083/JS/400-15	400	250	15	Ferrite
ISO 1083/JS/450-10	450	310	10	Mainly ferrite
ISO 1083/JS/450-18	450	350	18	Ferrite
ISO 1083/JS/500-7	500	320	7	Ferrite with pearlite
ISO 1083/JS/500-14	500	400	14	Ferrite
ISO 1083/JS/550-5	550	350	5	Ferrite with pearlite
ISO 1083/JS/600-3	600	370	3	Pearlite with ferrite
ISO 1083/JS/600-10	600	470	10	Ferrite
ISO 1083/JS/700-2	700	420	2	Mainly pearlite
ISO 1083/JS/800-2	800	480	2	Pearlite or tempered martensite
ISO 1083/JS/900-2	900	600	2	Bainite or tempered martensite

NOTE 1 The values for these materials apply to castings that are cast in sand moulds of comparable thermal behaviour. Subject to amendments to be agreed upon in the order, these values can apply to castings obtained by alternative methods.

NOTE 2 Whatever the method used for obtaining the castings, the grades are based on the mechanical properties measured on test pieces machined from samples separately cast in a sand mould or a mould of comparable thermal behaviour.

NOTE 3 The mechanical properties of the materials refer to separately cast samples produced in accordance with ISO 1083:2018, Figures 1, 2 or 3.

NOTE 4 Elongation values are determined from $L_0 = 5_d$. For other gauge lengths, see ISO 1083:2018, 9.1 and Annex B.

a LT for impact testing at low temperatures (−20 °C or −40 °C).

b RT for impact testing at room temperature (23 °C).

All grades can be produced from lower-purity raw materials if followed by heat treatment, although the lower-purity route is usually avoided because of increased cost associated with both the heat treatment operation and additional shot blasting. The exceptions regularly adopting heat treatments are grades JS/800-2, JS/900-2, as well as some of the impact-resistant grades. The JS/800-2 and JS/900-2 grades are heat treated because of the difficulties of meeting the high tensile strength requirements in the as-cast condition, while some of the impact-resistant grades are heat treated to ensure a fully ferritic matrix combined with lower silicon content in order to absorb the required impact energy in Charpy V testing.

It is important to note that grades JS/450-10, JS/450-18, JS/500-7, JS/500-14 and JS/550-5 have a balanced combination of yield strength and elongation. This point is often missed.

Some ferritic-pearlitic grades appear to be brittle materials because of low minimum elongation specified (600-3, 700-2, 800-2). The international material standards do not provide an understanding whether the low elongation figures specified are consequences of wide hardness range and/or sensitivity to imperfections. Commercial grades have traditionally been specified based on control of hardness range resulting in significantly higher minimum elongation requirements. Designers can be put off using the aforementioned grades due to a misconception that minimum strength and minimum elongation occur simultaneously in the same material. For a possible solution to this problem, see Reference [14].

7.8 Influence from strain rate and temperature on properties for ferritic, ferritic-pearlitic and pearlitic grades

7.8.1 General

The three-solution strengthened ferritic grades specified in ISO 1083 have raised great interest due to their beneficial combinations of concurrently high yield strength and high elongation, as well as small hardness variation and good machinability. However, if the yield strength is exceeded at combinations of high strain rate $\dot{\varepsilon}$ and low temperature T, the ductile behaviour can transition into brittle behaviour.

Japanese research[15] pioneered in describing this behaviour for solution strengthened ferritic grades with 3,0 % mass fraction to 4,0 % mass fraction Si to depend on the effect of ln $\dot{\varepsilon}$ and $1/T$ on yield phenomena in steels and body centred cubic (BCC) metals using Bennett and Sinclair's theory, resulting in a combined strain rate and temperature parameter R, where $R = T\ln(10^8\ \text{s}^{-1} / \dot{\varepsilon})$ [K].

In later research[16], they investigated the properties of four different spheroidal graphite irons in high-speed tensile tests, using both smooth and notched round specimens with a blunt notch R = 0,2 mm (similar to Charpy V impact energy bending samples) and with the same waist diameter (Ø4 mm) as the diameter of the smooth round specimens.

Three spheroidal graphite ductile irons (SGIs) with a low Si content of 2,1 % mass fraction and varying Cu contents to produce pearlitic matrix contents of 52 %, 84 % and 100 % (balance ferrite) corresponding to static tensile strengths of 500 MPa, 700 MPa and 900 MPa, respectively, were investigated. The fourth iron tested was a fully ferritic, solid solution strengthened spheroidal graphite iron with a high silicon content of 3,9 % mass fraction and a static tensile strength of 500 MPa. The notch strength curves were obtained for strain rates in the range $\dot{\varepsilon} = 2 \times 10^{-3} - 2 \times 10^{1}\ \text{s}^{-1}$ and temperatures in the range of −130 °C to +25 °C.[16]

7.8.2 Influence from pearlite content at constant silicon level

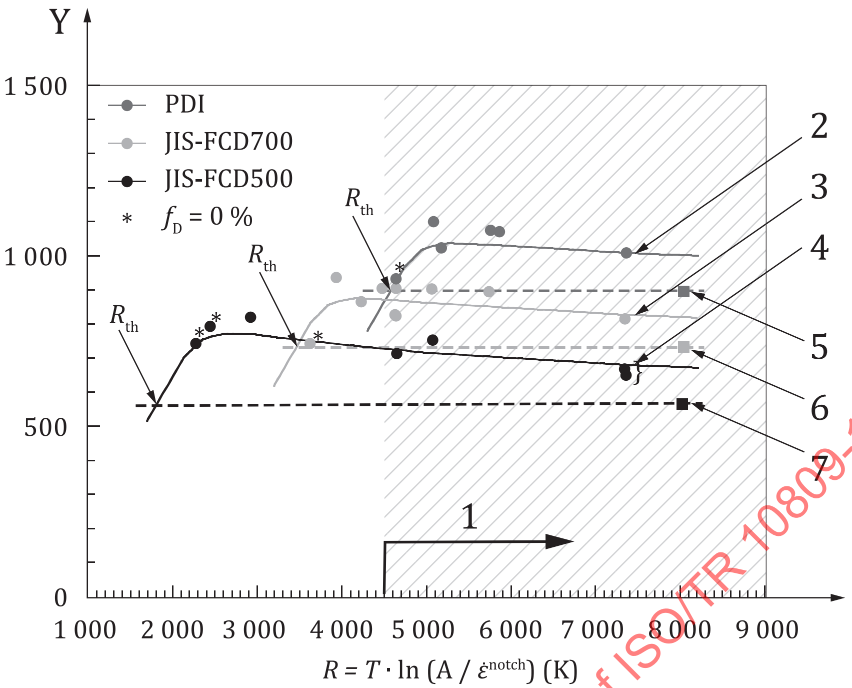
Figure 8 shows the influence of notch strength dependence on the R parameter for the three low-silicon (2,1 % mass fraction) irons with three different pearlite contents:

— 52 % (JIS-FCD500 JIS-FCD500-7 in JIS G 5502:2022[24], similar to ISO 1083/JS/500-7);

— 84% (JIS-FCD700 JIS-FCD700-2 in JIS G 5502:2022[24], similar to ISO 1083/JS/700-2);

— 100 % (pearlitic ductile iron (PDI), similar to ISO 1083/JS/800-2).

It also compares the notch strengths with the static (defined as $\dot{\varepsilon} = 2{,}1 \times 10^{-4}\ \text{s}^{-1}$) strengths at 25 °C of smooth (unnotched) specimens (shown as horizontal broken lines).



Key

Y notch strength σ_B^{notch} (MPa)

1 R parameter required for architectural structure

2 $\sigma_{B,RT\,PDI}^{notch}$ (static, 25 °C)

3 $\sigma_{B,RT\,FCD700}^{notch}$ (static, 25 °C)

4 $\sigma_{B,RT\,FCD500}^{notch}$ (static, 25 °C)

5 $\sigma_{B,RT\,PDI}^{smooth}$ (static, 25 °C)

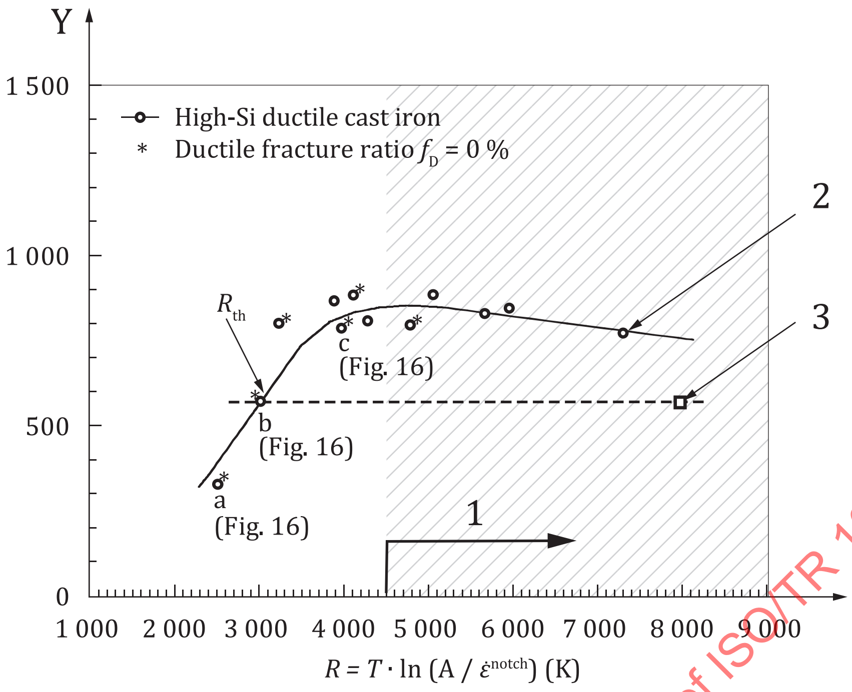
6 $\sigma_{B,RT\,FCD700}^{smooth}$ (static, 25 °C)

7 $\sigma_{B,RT\,FCD500}^{smooth}$ (static, 25 °C)

Figure 8 — Notch strength of low silicon (2,1 %) ferritic-pearlitic irons in terms of parameter *R*[16]

7.8.3 Influence from silicon content in fully ferritic matrix

Figure 9 shows the influence of notch strength dependence on the *R* parameter for a fully ferritic solution strengthened iron with high silicon content (3,9 % mass fraction) compared with the static strength at 25 °C of a smooth specimen (horizontal broken line).



Key

Y notch strength σ_B^{notch} (MPa)

1 *R* parameter required for architectural structure

2 $\sigma_{B,RT\,High\text{-}Si}^{notch}$ (static, 25 °C)

3 $\sigma_{B,RT\,High\text{-}Si}^{smooth}$ (static, 25 °C)

Figure 9 — Notch strength of high silicon (3,9 %) fully ferritic iron in terms of parameter *R*[16]

The notch strengths are generally higher than the tensile strengths of smooth specimens at room temperature and quasi-static condition because of the notch-strengthening effect combined with strain rate and temperature, except for regions of low *R* value to the left (corresponding to high strain rates, low temperatures, or both).

The notch-strengthening threshold R_{th} is defined as the intersection between the notch strength curve and the horizontal broken line corresponding to static tensile strength at room temperature of smooth specimens. This threshold R_{th} gives the combinations of highest strain rates and lowest temperatures that can be safely applied to structural spheroidal graphite iron components, designed with reference to a net section yielding criterion at room temperature and quasi-static conditions.

In Figure 8, as the pearlitic matrix increases, the notched strength curves move to the right, and the same applies if silicon contents are increased from low to medium (2,4 % mass fraction to 2,7 % mass fraction). Likewise, the notched strength curve in Figure 9 moves to the left if the degree of solid solution strengthening of the ferritic matrix is reduced by decreasing its silicon content.

For these reasons, it is strongly discouraged to combine very high silicon contents that stabilize ferrite with additions of pearlite stabilizers such as copper, because pearlite is intrinsically brittle when its ferrite phase is strongly solution strengthened.

One important conclusion in the aforementioned Japanese research is the following: Instantaneous fracture is prevented at high strain rates and/or low temperatures as long as the parameter $R \geq R_{th}$ during loading, when the mechanical design of spheroidal graphite iron components is conventionally based on static tensile strength at room temperature with reference to a net section yielding criterion applied to the experienced geometry.

Intermediate Swedish research[17] on the solution strengthened ferritic grade JS/500-14 has shown that for three-point bending tests on V-notched specimens at room temperature, predominantly ductile fracture is observed for strain rates in the range $\dot{\varepsilon} = 1 \times 10^{-4} - 4 \times 10^{-2}\ \mathrm{s}^{-1}$ (corresponding to R = 8 770 – 6 340 K). By increasing the strain rate to $\dot{\varepsilon} = 1\ \mathrm{s}^{-1}$ (R = 5 400 K), a more significant change in ductile to brittle fracture is seen. At the estimated strain rate of $\dot{\varepsilon} = 300\ \mathrm{s}^{-1}$ (R = 3 730 K), completely brittle fracture occurred. When the temperature was decreased to −15 °C, predominantly brittle fracture was observed for the strain rates investigated in the range $\dot{\varepsilon} = 3{,}6 \times 10^{-2} - 2{,}3\ \mathrm{s}^{-1}$ (R = 5 610 – 4 540 K).

Therefore, another important conclusion is that the use of solution strengthened ferritic grades is only restricted by this phenomenon if the component can be rapidly loaded in service above $R_{p0,2}$ under a combination of high strain rate and low temperature that results in $R < R_{th}$.

7.9 Special case of impact-resistant grades

The relevance of the use of absorbed impact energy as a measure of resistance to brittle fracture in castings, subjected to application loads, is being reassessed. The Charpy V test was initially developed for welded steel and was never intended for different materials such as spheroidal graphite irons (being invented later). Spheroidal graphite irons have considerably lower absorbed impact energy than steels of comparable strength because the size of the plastic zone formed in the stress field under the blunt (R = 0,2 mm) V-notch is severely restricted by the short distance between graphite nodules. During a Charpy V-notch test, most of the absorbed energy is consumed by the plastic zone formation rather than by the crack propagation. If the blunt V-notch is replaced by a sharp crack, the graphite nodules will favourably blunt the propagating crack, giving an advantage over steel. ISO 1083:2018, Annex C, gives information about a fracture mechanics approach to spheroidal graphite irons to select a material that better corresponds with the specific loading situation in a casting.

ISO 1083:2018, Table 2, specifies the minimum impact energy values from separately cast samples corresponding to castings with a relevant wall thickness up to 30 mm. These materials are specifically designed for situations where impact conditions can occur at ambient temperature, −20 °C and −40 °C. They do not meet the impact energy values that can be obtained from some steels, but do find many applications, such as steering knuckles in vehicles that must operated successfully at widely differing temperatures. The properties are summarized in Table 7.

Table 7 — ISO 1083 V-notch impact energy values corresponding to castings with a relevant wall thickness up to 30 mm

Material designation	Minimum impact energy values J					
	Room temperature (25 ± 5) °C		Low temperature (−20 ± 2) °C		Low temperature (−40 ± 2) °C	
	Mean of 3 tests	Single value	Mean of 3 tests	Single value	Mean of 3 tests	Single value
ISO 1083/JS/350-22-LT	—	—	—	—	12	9
ISO 1083/JS/350-22-RT	17	14	—	—	—	—
ISO 1083/JS/400-18-LT	—	—	12	9	—	—
ISO 1083/JS/400-18-RT	14	11	—	—	—	—

Key

LT: low temperature

RT: room temperature

NOTE 1 The values for these materials apply to castings that are cast in sand moulds of comparable thermal behaviour. Subject to amendments to be agreed upon in the order, these values can apply to castings obtained by alternative methods.

NOTE 2 Whatever the method used for obtaining the castings, the grades are based on the mechanical properties measured on test pieces machined from samples separately cast in a sand mould or a mould of comparable thermal behaviour.

NOTE 3 These material grades can be suitable for some pressure vessel applications.

Production of the ambient temperature grades is not particularly difficult, providing that the material has a fully ferritic matrix. However, the low-temperature grades, particularly the grade with specified impact properties at −40 °C, can be difficult to make unless the normal metal composition is modified. Success depends upon a reduction in the normal silicon content to about 1,9 % mass fraction to 2,0 % mass fraction and an addition of about 0,8 % mass fraction nickel. The lower silicon level and added nickel shifts the ductile-to-brittle transition temperature (DBTT) to lower temperatures, thereby raising the impact energy value. Simultaneously, the nickel addition compensates for the reduced silicon on solution strengthening of the ferritic matrix to ensure achievement of the minimum yield strength value. It is unlikely that the required impact values will be met in the −40 °C material, unless it is annealed to ensure a fully ferritic matrix. Designers and engineers recognize that to achieve fitness for purpose from these materials, these guidelines must be followed, and the associated costs must be accepted.

7.10 Heat treatment

Spheroidal graphite irons can be obtained in the as-cast state or by heat treatment. Annealing applies to some ferritic grades; normalizing applies to ferritic-pearlitic grades with lower or no alloying content.

Because of the associated costs of an additional heat treatment compared with sound foundry melt practice, it is not common to require heat treatment to produce most of the grades of spheroidal graphite iron. Examples of when heat treatment is used include:

a) grades of iron described in 5.10 that require high impact values at −40 °C can be annealed;

b) thin sections where fast cooling rates impede the formation of ferrite are annealed;

c) thick sections where slow cooling rates favour the formation of ferrite rather than pearlite are normalized.

The selection of an annealing process is dependent upon the starting microstructure. If the ferrite-pearlite ratio needs to be modified to increase the ferrite content, then a subcritical anneal is employed. If eutectic carbides must be eliminated and a ferritic matrix produced, a full anneal is required. It is important to specify which type of annealing process is necessary as a full anneal requires a higher soak temperature which will be reflected in the cost of the heat treatment.

Subcritical annealing consists of heating to 705 °C to 720 °C and soaking for 1 h per 25 mm section thickness followed by slow cooling in the furnace to convert pearlite to ferrite.

A full anneal consists of heating to 900 °C and soaking for 1 h per 25 mm section thickness followed by slow cooling in the furnace to promote the formation of ferrite. In order to break down eutectic carbides, temperatures up to 925 °C or longer soak times can be necessary.

Normalizing is sometimes undertaken to achieve the properties in the pearlitic grades, usually to raise properties when as-cast tensile strength values are low. ISO 1083:2018, 10.4, allows for a normalizing treatment. A typical normalizing process involves raising the temperature of the castings and holding at 900 °C for 1 h, plus one additional hour for each 25 mm of section thickness; the thickest section is the criterion for determining the normalizing time. The castings are then air cooled; thicker castings can benefit from the use of forced air from a fan. It can be necessary to temper components with complex shapes to relieve residual stresses created by accelerated cooling using fans. Tempering can also be used to lower the hardness of pearlite, if needed. When many small castings are normalized in a batch, they must be separated in order to allow for a satisfactory cooling rate.

Isotherming heat treatment is similar to normalizing regarding the target matrix to be obtained and similar to an intercritical austempering process. (The process definition is described in Table 3). With this process, it is possible to optimize strength and ductility in casting wall thicknesses up to 75 mm by heat treating an unalloyed as-cast ferritic matrix, resulting in a special ferritic-pearlitic structure called “perferrite”. It is possible to achieve minimum tensile properties of 800 MPa tensile strength, 480 MPa yield strength and 6 % elongation in all section sizes and with a more controlled hardness range than possible with normalizing[14].

7.11 Choosing the grade

All ferritic grades of spheroidal graphite iron have a tensile strength exceeding that of the highest tensile-strength (pearlitic) grade of grey cast iron, together with much higher elongation and impact resistance. The intermediate tensile-strength grades have a balanced combination of mechanical properties, with tensile strength, yield strength and elongation specifications between 400 MPa ferritic and 700 MPa pearlitic grades. The fully pearlitic grades have high tensile strengths while still exhibiting some ductility. Therefore, there is a wide range of property combinations from which to choose. Other properties, typical of these materials, are summarized in ISO 1083:2018, Table G.1.

Grades JS/450-10, JS/450-18, JS/500-7, JS/500-14, JS/550-5 and JS/600-10 have good combinations of tensile strength and elongation, although the impact properties are reduced by the pearlite present and, in the case of the solution strengthened ferritic grades, by their higher silicon contents. These grades have applications where higher strength in combination with good ductility are required. As the fatigue properties increase in proportion to the tensile strength, these materials can be useful where service conditions involve some dynamic loading. Pump impellers, suspension units and reciprocating parts fall into this category.

Grades JS/600-3, JS/700-2, JS/800-2, and JS/900-2 are specified at high minimum tensile strengths and low minimum elongation. They are valuable either directly because of their high tensile strength, or indirectly because this property imparts good fatigue properties. The best example of this is the automotive crankshaft: a huge percentage of the world's total production uses JS/700-2 or JS/800-2 to avoid fatigue failure in service, with the tensile strength actually being immaterial to the service conditions. In order to achieve satisfactory service performance, the actual choice of a material in the range JS/600-3 to JS/900-2 depends on the design requirements in terms of tensile strength and other properties. Relatively low elongation values can be improved through effective Brinell hardness control, resulting in better combinations of strength and ductility for these iron grades.

When higher combinations of strength and ductility are required, the designer can consider ausferritic spheroidal graphite irons (ADI) which are described in Clause 8.

The thermal conductivity for all spheroidal graphite iron grades is less than that of grey cast irons where the graphite lamellas provide better thermal conductivity as shown in ISO 1083:2018, Table G.1. In spheroidal graphite irons, ferritic grades have higher thermal conductivity than pearlitic grades. If a grey cast iron has insufficient tensile properties for an application, spheroidal graphite iron can be substituted providing any potential heat transfer issues have been carefully assessed and determined not to be an issue. Compacted iron fills the gap between these two materials in terms of thermal conductivity and mechanical properties (see Clause 10).

8 ISO 17804, Ausferritic spheroidal graphite cast irons (ADI)

8.1 Overview

Ausferritic spheroidal graphite iron, typically referred to as "austempered ductile iron (ADI)", is specified in ISO 17804. Table 8 shows the properties of the six grades of ausferritic spheroidal graphite irons for three ranges of relevant wall thickness.

Table 8 — Properties of ISO 17804 ausferritic spheroidal graphite iron grades

Material designation	Relevant wall thickness mm	Tensile strength R_m MPa minimum	0,2 % yield strength $R_{p0,2}$ MPa minimum	Elongation A_5 % minimum	Brinell hardness HBW guidance values
ISO 17804/JS/800-10 ISO 17804/JS/800-10RT	$t \leq 30$	800	500	10	250 to 310
	$30 < t \leq 60$	750		6	
	$60 < t \leq 100$	720		5	
ISO 17804/JS/900-8	$t \leq 30$	900	600	8	280 to 340
	$30 < t \leq 60$	850		5	
	$60 < t \leq 100$	820		4	
ISO 17804/JS/1050-6	$t \leq 30$	1 050	700	6	320 to 380
	$30 < t \leq 60$	1 000		4	
	$60 < t \leq 100$	970		3	
ISO 17804/JS/1200-3	$t \leq 30$	1 200	850	3	340 to 420
	$30 < t \leq 60$	1 170		2	
	$60 < t \leq 100$	1 140		1	
ISO 17804/JS/1400-1	$t \leq 30$	1 400	1 100	1	380 to 480
	$30 < t \leq 60$	1 170	To be agreed between the manufacturer and the purchaser		
	$60 < t \leq 100$	1 140			

Castings with an ausferritic matrix can be produced by higher alloying without the need for heat treatment. However, these materials fall outside the scope of ISO 17804.

The specified V-notch impact energy properties of grade ISO 17804/JS/800-10RT are shown in Table 9.

Table 9 — Impact energy properties of ISO 17804/JS/800-10RT

Material designation	Relevant wall thickness of the casting t mm	Minimum impact energy value at room temperature (23 °C ± 5 °C) Mean value of three tests J	 Individual value J
ISO 17804/JS/800-10RT	$t \leq 30$	10	9
	$30 < t \leq 60$	9	8
	$60 < t \leq 100$	8	7

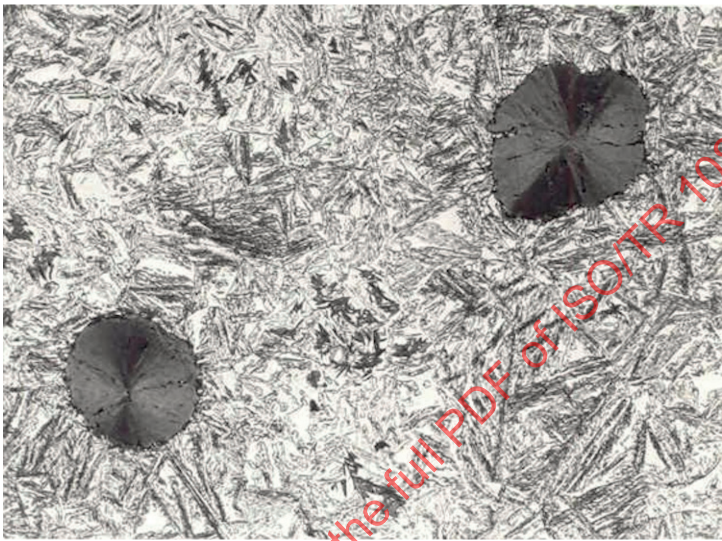
The properties of ISO 17804 abrasion-resistant grades designated based on minimum Brinell hardness are shown in Table 10.

Table 10 — Properties of ISO 17804 abrasion-resistant grades

Material designation	Brinell hardness HBW minimum	Other properties (for information only) R_m MPa	 $R_{p0,2}$ MPa	 A_5 %
ISO 17804/JS/HBW400	400	1 400	1 100	1
ISO 17804/JS/HBW450	450	1 600	1 300	—

During the initial development stages, the resultant matrix following austempering was described as bainite, and this definition is still sometimes used due to the similarities with the heat treatment used for bainite in low-silicon steels. However, the terminology “ausferrite” now predominates because the resulting microstructure is a mixture of ferrite and high carbon stabilized austenite due to the prevention of bainitic carbide formation by substitutional silicon in the iron matrix.

The microstructure after etching with Nital is shown in Figure 10 and comprises graphite spheroids in an ausferritic matrix. This is a fairly typical microstructure of grade 900-8; differences in the fineness of the microstructural scale and proportions of austenite and ferrite in the ausferritic matrix are observed in cast irons that are austempered at different temperatures.



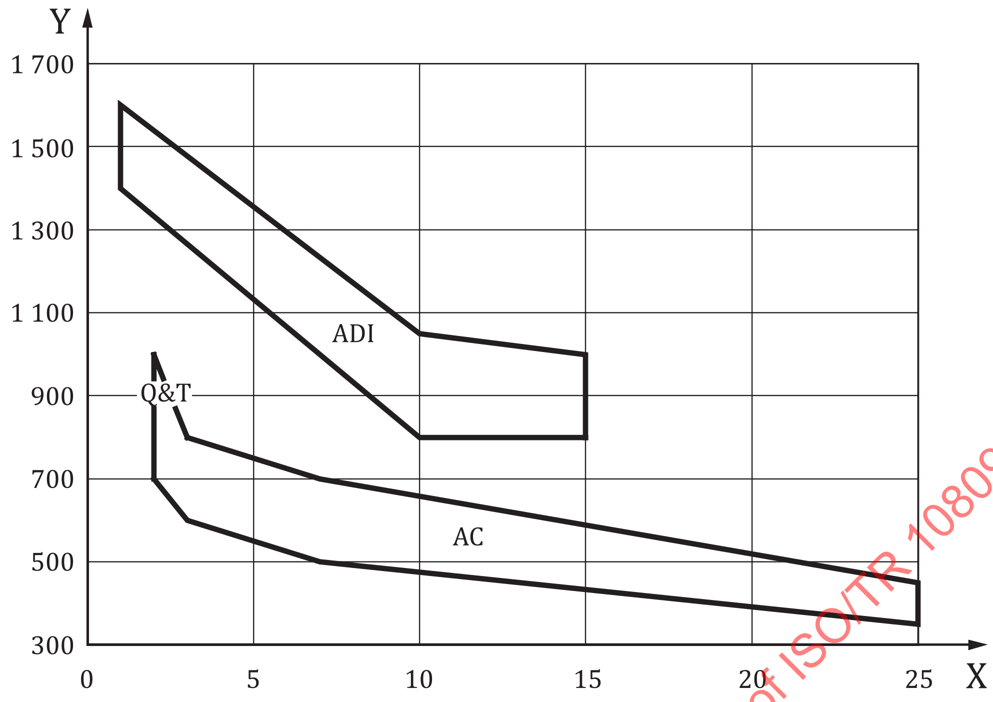
Magnification × 200

Figure 10 — Ausferritic spheroidal graphite iron (Grade JS/900-8)

ISO 17804 has five grades of ausferritic spheroidal graphite iron with minimum tensile strengths ranging from 800 MPa to 1 400 MPa and minimum elongation between 10 % and 1 %. As can be seen in Table 8 or ISO 17804:2020, all but the highest tensile strength grades have a range of property requirements that depend upon the relevant wall thickness and sample size, as defined in ISO 17804:2020, Table 3.

Two grades that require only hardness validation are specified in Table 10 or ISO 17804:2020, Annex A.

The outcomes of the austempering heat treatment process (described in 6.2) are unique combinations of high strength, toughness and wear resistance that cannot be attained from typical normalizing or quench and temper treatments. This is shown in Figure 11, which illustrates the ranges of tensile strengths and elongations at fracture obtained in various grades of spheroical graphite cast iron materials in the as-cast condition, through normalizing as well as quench and tempering; compared with the range of properties typically expected from the ausferritic (ADI) grades.



Key

X elongation, %

Y tensile strength, MPa (higher line) and yield strength, MPa (lower line)

ADI ausferritic spheroidal graphite iron

Q&T quenched and tempered spheroidal graphite iron

N normalized

AC as-cast spheroidal graphite iron

Figure 11 — Comparisons between ranges of typical tensile strength and elongation at fracture properties of ausferritic and other matrix microstructures in spheroidal graphite irons

8.2 Heat treatment process

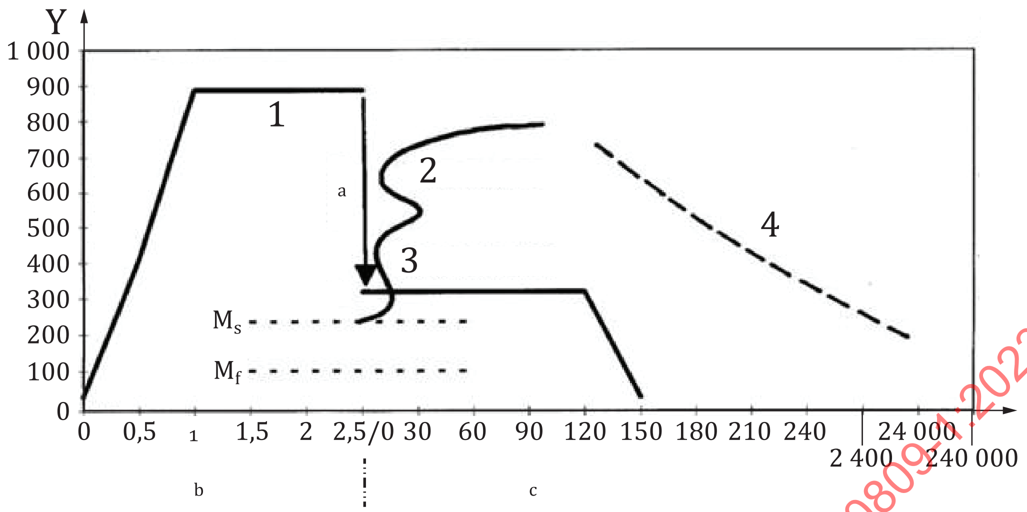
The austempering process is crucial to the manufacture of ausferritic spheroidal graphite iron. Austempering is more complex than other heat treatments. It consists of three major steps:

a) austenitizing;

b) rapidly cooling to a selected temperature above the martensite start temperature M_s;

c) isothermal holding at the selected temperature to form an ausferrite matrix.

Figure 12 shows the austempering heat treatment process. The material is heated to the austenitizing temperature of usually 840 °C to 920 °C and held to produce austenite with a uniform carbon content surrounding the graphite structure. It is then rapidly quenched into a molten salt bath at a temperature determined by the final properties to be produced. The temperature of the salt bath is normally set in a range of 250 °C to 400 °C. The material is held at this selected temperature until the transformation from undercooled austenite into ausferrite microstructure is finished. In the range of 250 °C to 325 °C, the higher-strength, lower-ductility materials are produced. Above 325 °C, the lower-strength, higher-ductility materials result.



Key

1 austenite
2 pearlite
3 ausferrite
4 bainite

Y temperature
a Quench.
b Austenitizing (hours).
c Austempering (minutes).

NOTE Actual temperatures and times differ in production for each grade of ausferritic iron.

Figure 12 — Schematic diagram describing the austempering heat treatment process

8.3 Effects of alloying elements

Ausferrite is easily obtained in thin sections, but as the section thickness increases in unalloyed materials there is an increased likelihood of pearlite formation. This can particularly be the case at the junction of wall sections where there is a localized increase in thickness. Pearlite forms because of an insufficient hardenability, resulting in hitting the pearlite nose on the isothermal transformation diagram (see Figure 12) during cooling from the austenitizing temperature to the isothermal transformation temperature.

The presence of small amounts of pearlite in the centre of sections is unlikely to have an adverse effect on fitness for this purpose but is best avoided. Reduction of pearlite in the centre of sections can be achieved by the addition of alloying elements that help to ensure the formation of ausferrite. Common additions are combinations of copper, nickel and molybdenum. Manganese content must be kept low to prevent segregated areas where the transformation into ausferrite will be incomplete, resulting in inferior mechanical properties.

Alloy additions are recommended only if needed, as excessive levels add to the cost of the base iron and will often increase the cost of the heat treatment because transformation times to make ausferritic iron will be longer. As a result, the heat treater will recommend the proper alloy content for the section thickness to be austempered. Chemical composition recommendations are unique to the heat treat equipment used. Consequently, if a different heat treat supplier is employed, the initial recommended alloy composition will be re-evaluated by the new supplier.

8.4 Graphite form and size

The solidification mechanism for spheroidal graphite and ausferritic spheroidal graphite irons is identical; therefore, issues relating to the graphite form and size of the ausferritic materials are as described in 7.5. The supplier of heat treatment services can recommend a higher minimum nodularity as well as a minimum spheroidal graphite particle count (nodule count).

8.5 Matrix structure and the resultant properties

The properties of ausferritic spheroidal graphite irons are dictated by their matrix structure. The matrix is predominantly ausferrite. The microstructural scale of the ausferrite becomes finer as the isothermal transformation temperature is reduced. Likewise, the relative amounts of high carbon austenite and ferrite within the ausferrite change with austenite volume decreasing as the isothermal transformation temperature decreases.

Proeutectoid ferrite is present in larger amounts in ISO 17804/JS/800 if intercritical austenitizing is used to meet the minimum properties and, in some instances, in minute amounts in the remaining grades that do not greatly influence overall mechanical properties. Small levels of martensite can be found within the higher strength grades of ADI, the presence of which does not affect overall mechanical performance.

It is important to note that no useful purpose is served to specify the microstructure in extreme detail beyond "predominantly ausferrite" in addition to meeting minimum mechanical property requirements because of the likely difficulties in agreeing on the interpretation of what microstructural features are present.

8.6 Influence from relevant wall thickness on mechanical properties

As the wall thickness increases, the graphite spheroids become larger so the number of spheroids is reduced, which can cause the graphite shape to deviate from Form VI to Form V or lower. Therefore, the tensile properties in the heavier sections will be inferior to those in the thin sections. Thus, when graphite form and size are specified in the casting, it is imperative that the test location be agreed between the manufacturer and the user to avoid conformance disagreements. If the form and size are specified within a separately cast sample, often cast to validate the material as part of routine control procedures, it is important to note that the form and size of the graphite in the casting can be different from that in the sample.

The properties in different sections are influenced by the heat treatment operation and any alloys that are added to ensure a uniform ausferritic matrix. If alloying is insufficient and/or the quench severity is insufficient and/or the heat treat process is not capable and controlled, then the resulting material properties will be reduced due to the presence of pearlite and/or insufficiently stable austenite.

8.7 V-notch impact energy grade

Grade JS/800-10RT has specified impact properties according to ISO 17804:2020, Table 2. The specified impact resistance properties of this grade are shown in Table 9. The required impact properties are dependent upon the relevant wall thickness, with impact properties reducing as the section thickness increases. The impact grade has the same tensile properties as grade JS/800-10 in ISO 17804:2020, Table 1, with an additional requirement for room temperature impact energy values, indicated by the suffix RT.

8.8 Abrasion-resistant grades

Normative requirements for two abrasion-resistant grades of ausferritic spheroidal graphite iron are specified in ISO 17804. These grades have useful abrasion resistance but are not alloyed to the extent of materials specified in ISO 21988 and Clause 12, where alloying has a significant influence on performance. Alloy addition for abrasion-resistant ausferritic grades is made primarily for hardenability purposes.

The abrasion resistance of the two ausferritic grades is mainly influenced by heat treatment as opposed to alloying, and Brinell hardness is the only property specified. These materials are austempered at low temperatures approaching the martensite start temperature. This heat treatment provides high tensile and yield strengths with low elongation, but because the material does not contain a high level of martensite, as is the case of some ISO 21988 grades, it tends to have better impact resistance. Its abrasion properties are not necessarily as good as the ISO 21988 grades because of the absence of alloy carbides. As with all abrasion-resistant materials, a cost-benefit analysis will determine its suitability in the varying environments in which the materials are expected to perform.

CADI refers to a family of spheroidal graphite cast irons produced with carbides (either chemically, thermally or mechanically introduced) that are subsequently austempered to exhibit adequate toughness and excellent wear resistance. CADI consists of an ausferritic microstructure that contains a controlled volume fraction of carbides; typically, in a range of 10 % to 40 % by volume. The heat treatment parameters for making CADI can be controlled in order to produce ausferrite with different ferrite/austenite ratios and microstructural fineness. Combining the austempering process with the controlled inclusion of carbides gives engineers the opportunity to design components with wear properties that are improved over the standard grades of ausferritic irons. CADI can compete favourably with expensive abrasion resistant irons. To date, the greatest interest in this material has been in agricultural applications; namely, ground engaging components.

8.9 Machinability

The casting can be machined before and/or after heat treatment; the latter is typically convenient for lower strength ausferritic grades, provided that the high carbon stabilized austenite in the ausferrite is sufficiently stable, the fixtures and machine tools are robust and that appropriate cutting tools are used. Due to varying cutting forces and heat generated, low cutting speeds and high feed rates are usually recommended.

8.10 Choosing the grade

The original development work on ausferritic spheroidal graphite cast irons concentrated on improvements to gear technology. However, a wide range of components (see Table 11) are now produced in the ausferritic condition. The essential feature of the ausferritic grades is the advantageous combination of mechanical properties that can be obtained in comparison with spheroidal graphite iron materials comprising other matrices. For example, the lowest tensile-strength grade in ISO 17804 is JS/800-10 whereas the highest tensile-strength grade in ISO 1083 is JS/900-2. ISO 17804 includes grades that provide tensile strengths of 1 400 MPa or more with appreciable elongation.

These higher-tensile-strength ausferritic spheroidal graphite iron grades are ideal when very high strengths are required for an application. They find applications where steels have been historically used, because there are cost savings to be made in both the casting and machining processes. Ausferritic irons are lighter and quieter in service due to the graphite structure which lowers the density and increases the damping coefficient.

The selection of grade of ausferritic irons depends upon the service requirements and design stresses. Tensile properties ranging from greater than 800 MPa to greater than 1 400 MPa in the engineering grades, in sections up to 30 mm, are available. They are increasingly used in applications involving high strain rates and/or low temperatures, where their properties are also superior to quench and tempered steels. Compression strengths are even higher, see ISO 17804:2020, Table G.1.

Ausferritic irons have a higher strength-to-weight ratio than aluminium, offering opportunities for light-weighting. Grades JS/900-8 and JS/1050-6 have a higher coefficient of thermal expansion than other ferrous materials; although closer to that of aluminium. This is advantageous for system design consideration.

The special purpose abrasion-resistant grades of ausferritic spheroidal graphite iron have high hardness. One grade is slightly less hard than the other and, thus, has better impact resistance. As always with abrasion-resistant materials, the environment determines the most appropriate material. In general, these grades have been successfully applied where considerable savings have been possible in comparison to steels.

Table 11 — Grades of ausferritic spheroidal graphite iron with common applications

Grade of ausferritic spheroidal graphite iron	General property combination	Applications
ISO 17804/JS/800-10 ISO 17804/JS/900-8 ISO 17804/JS/1 050-6	High fatigue and impact resistance combinations for dynamic components, best low temperature properties and machinable after heat treatment.	Suspension components such as control arms or steering knuckles, housings, brackets, subframes for off-highway applications, light vehicle recovery/tow hooks, all-wheel drive transmission differentials, splined pulleys and shafts, planet carriers, pump components, driven crankshafts, cylinder clevis, pistons and rod ends.
ISO 17804/JS/1 200-3	Best compromise between wear and dynamic properties with good fatigue strength and impact resistance along with increased wear resistance.	Low to medium speed gears, excavator bucket teeth, agriculture seeding points, agriculture hitches and railroad motion control components.
ISO 17804/JS/1 400-1	Fair fatigue strength in combination with good wear resistance and higher allowable contact stress.	High speed gears-transmissions, agriculture tillage, harvesting wear components, aggregate crushing, pump impellers, pump cases, pump wear pads, rock guards, wear shoes, wear guards (agriculture and construction/mining) and rollers for conveyors.

9 ISO 5922, Malleable cast irons

9.1 Overview

ISO 5922 specifies the requirements for two types of malleable iron: blackheart and whiteheart. These materials are produced with a low silicon content, such that solidification in the mould results in castings with a structure comprising a combination of pearlite and carbide. At this stage, they are commonly referred to as being in the “hard” state.

To produce the required structure comprising graphite in a ferritic, pearlitic, mixed ferritic/pearlitic or quenched and tempered matrix, all malleable castings are subjected to heat treatment and here the processing of blackheart and whiteheart malleable irons differ. Blackheart malleable irons are annealed in a neutral, non-decarburizing atmosphere, whereas whiteheart malleable irons are annealed in an oxidizing, decarburizing atmosphere. A variant of the whiteheart malleable heat treatment process involving intensive decarburization provides an important third type of malleable iron known as “whiteheart weldable malleable iron”.

The original reason for these definitions of malleable irons was the colour and appearance of the fractured section of the material. Blackheart, as a fully ferritic material with temper carbon, has a dark-to-black fracture appearance, whereas whiteheart and also the pearlitic blackheart grades usually exhibit a bright crystalline, white fracture, which is, in the latter case, associated with the presence of pearlite in the matrix, in contrast to abrasive resistant white irons, where the white fracture surface indicates iron carbides instead of graphite. Even in wall thicknesses where the whiteheart and weldable grades are fully decarburized and no pearlite exists, their fractures are a fine crystalline, velvety grey.

In previous malleable specifications, three types of malleable irons were standardized: blackheart, whiteheart and pearlitic. However, in ISO 5922, the pearlitic grades are incorporated into the blackheart section, because the chemical composition is the same as that of the ferritic grades and the annealing processes are very similar. Thus, in the terms and definitions of ISO 5922:2005, Clause 3, malleable irons are subdivided as follows:

a) whiteheart malleable iron;

b) blackheart malleable iron:

1) blackheart ferritic malleable iron;

2) blackheart pearlitic malleable iron.

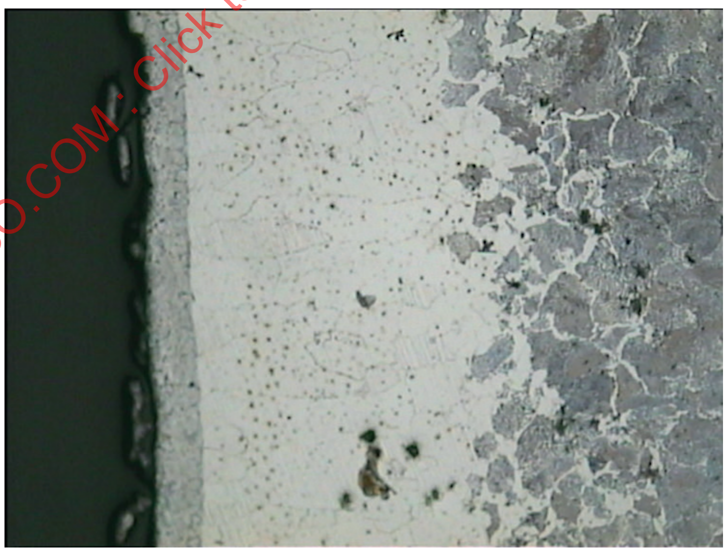
These revised definitions, which are now used in other International Standards, have been highlighted to avoid any confusion related to requirements specifically for pearlitic malleable iron which can still be specified on old drawings and in company specifications.

Properties of the malleable irons are specified in ISO 5922:2005, Tables 1 and 2. Ten grades of blackheart malleable iron are specified with tensile strengths ranging from 275 MPa to 800 MPa, with corresponding elongations between 10 % and 1 %. Five grades of whiteheart malleable irons are specified with tensile strengths between 350 MPa and 550 MPa and with elongations between 12 % and 3 %. The malleable irons also have useful impact resistance properties; their impact energy values are not specified, but typical values are given in ISO 5922:2005, Annex A.

When viewed under a microscope, temper carbon nodules are observed in a range of matrices depending upon the grade, and they tend to be more ragged in appearance than the spheroids found in spheroidal graphite irons. Due to its higher silicon content in blackheart malleable irons, their temper carbon nodules are normally smaller and more numerous than those in whiteheart malleable irons.

In whiteheart malleable irons, the number of temper carbon nodules depends upon the degree of decarburization, which is related to wall thickness and solidification rate. Wall thicknesses of 3 mm or less are completely decarburized and do not contain any graphite or pearlite. A ferritic rim, followed by a transition zone containing increasing percentages of pearlite and temper carbon is observed in section thicknesses exceeding 3 mm up to 6 mm. When the wall thicknesses exceed 6 mm, there is a core zone of 100 % pearlite and temper carbon nodules behind the ferritic rim and the transition zone.

Figure 13 shows the different structures of a whiteheart malleable iron material. In the case of a fully decarburized weldable whiteheart material, the carbon is removed, pearlite and temper carbon nodules are absent, and the structure is fully ferritic.



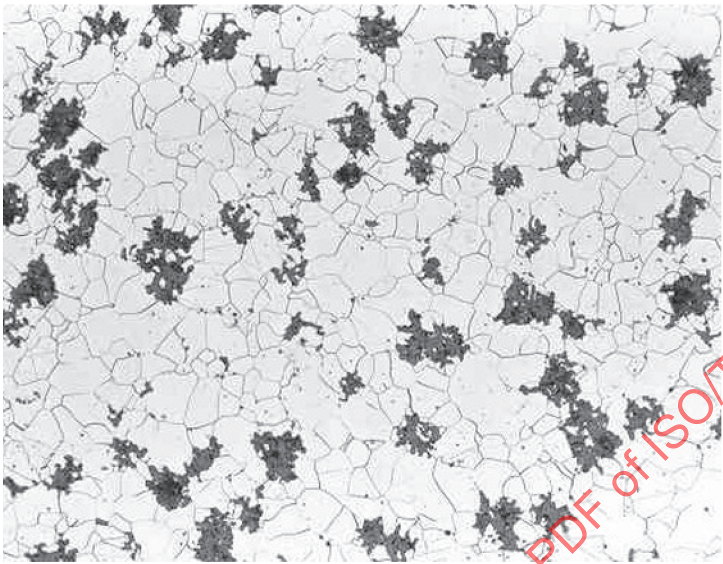
Magnification × 200

NOTE Left to right: temper zone, ferritic rim, transition zone, core structure.

Figure 13 — Whiteheart malleable iron

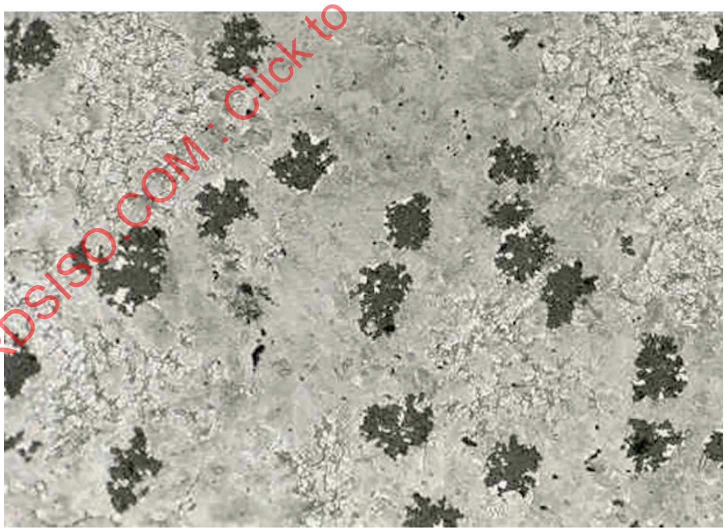
If the carbon content is 0,3 % mass fraction or less, whiteheart malleable irons can be welded without utilizing additional processing methods and/or special welding techniques. Further information on the welding of malleable irons is given in ISO/TR 10809-2.

Figure 14 shows a typical ferritic blackheart malleable iron material. Figure 15 shows a typical pearlitic blackheart malleable iron material.



Magnification × 200

Figure 14 — Ferritic blackheart malleable iron



Magnification × 200

Figure 15 — Pearlitic blackheart malleable iron

9.2 Metal composition and carbon equivalent

Metal composition is not specified in ISO 5922. However, blackheart and whiteheart malleable iron materials have different compositions, which are related to the differing time and temperature parameters of heat treatment described below. The chemical composition of weldable malleable irons can be optimized for the welding process and to avoid the generation of temper carbon.

Whiteheart malleable iron grades typically contain 3,0 % mass fraction to 3,4 % mass fraction carbon with 0,4 % mass fraction to 0,6 % mass fraction silicon. However, the composition of the blackheart malleable iron grades has changed over the years. Originally, blackheart malleable irons contained approximately 2,0 % mass fraction to 2,5 % mass fraction carbon and 0,8 % mass fraction to 1,0 % mass fraction silicon resulting in requiring long heat treatment times to produce a ferritic matrix. Nowadays, the silicon content is 1,25 % mass fraction to 1,50 % mass fraction, because the increased silicon level promotes graphite formation and substantially reduces heat treatment time and cost.

Bismuth is added to blackheart malleable to ensure that primary graphitization (mottle) does not form. Mottle is more prevalent at higher carbon and silicon levels. Mottle is also more commonly found in thicker section sizes.

Manganese is used to neutralize the carbide-stabilizing effect of sulfur in malleable irons. The other elements of major importance are chromium and phosphorus. They ideally need to be maintained below 0,05 % mass fraction Cr and 0,1 % mass fraction P, because higher percentages have adverse effects on structure and properties.

The simplified carbon equivalent formula [see Formula (1)] is also valid for malleable irons and, in the past, CEE determination was used as a measure of control. The compositional ranges are so narrow that the procedure has partly been replaced by the rapid spectrographic (optical emission spectroscopy, OES) analysis.

9.3 Heat treatment

9.3.1 General

Heat treatment is a fundamental requirement for the production of malleable irons because it converts a virtually unusable iron-carbide-containing material into the range of useful engineering grades described in ISO 5922.

9.3.2 Blackheart malleable irons

To avoid excessive scaling, blackheart malleable iron castings are heat treated in a controlled non-decarburizing atmosphere, i.e. under a neutral protective gas with a predefined dew point at a graphitizing temperature of about 930 °C to 960 °C, during which the iron carbides decompose to form temper carbon in an austenitic matrix. The rate of decomposition of the eutectic carbide regulates the length of the holding time. This so-called “first annealing stage” is identical for all ferritic, pearlitic and quenched and tempered blackheart malleable irons.

For ferritic blackheart malleable irons, the first stage of annealing is followed by fast cooling in the same furnace to 800 °C. The temperature range between 800 °C and 720 °C is passed through very slowly at a cooling rate that continuously decreases from an initial 10 °C/h to a final 1,5 °C/h to 2,0 °C/h. During this annealing phase, the austenite is gradually converted to ferrite plus graphite, with the carbon segregating out of the austenite and accumulating on existing temper carbon nodules. At approximately 720 °C, the castings are removed from the furnace. This heat treatment process generates a structure of temper carbon nodules in a ferritic matrix. The temperature ranges of the three stages described above is highly dependent upon the silicon content of the material and the annealing cycle sometimes needs to be adjusted accordingly.

In the case of blackheart pearlitic cast irons and the quenched and tempered grades, at the end of the first annealing stage of around 930 °C to 960 °C, fast cooling occurs down to a temperature of 900 °C to 905 °C. The castings are then ejected from the furnace and intensively cooled by blowers. This provides a basis for the second annealing stage, which produces the different grades of pearlitic or quenched and tempered blackheart malleable irons.

The second annealing stage for the pearlitic grades is completed in low-temperature annealing furnaces. The holding temperature and time define the grade, and, thus, the mechanical properties. Annealing temperatures range from 720 °C to 680 °C with holding times between 2 h and 5 h. The holding temperature and time depend on the elements C, Si, Mn, P and S, together with trace elements such as Cr, Ni, Sn and Ti which can affect the annealing cycle. The second annealing stage results in a transformation from lamellar to granular (or spheroidized) pearlite with noticeably improved elongation and toughness properties. Another production option for blackheart pearlitic malleable iron involves alloying with manganese, which is a pearlite stabilizer. The second-stage annealing cycles must then be modified accordingly. By annealing blackheart malleable iron in a neutral atmosphere, the structure is almost uniform throughout all casting sections, unlike whiteheart malleable iron, which is annealed in an oxidizing/decarburizing atmosphere.

9.3.3 Whiteheart malleable irons

Whiteheart malleable irons are produced by annealing the castings in an oxidizing/decarburizing atmosphere using a controlled gas atmosphere.

Modern gas malleablizing is carried out in annealing pots without iron ore in a controlled gas atmosphere including the injection of water vapour into the annealing furnace. The K_c value (CO_2/CO ratio) adjusts the oxidizing potential of the atmosphere. The annealing temperatures can be elevated to between 1 050 °C and 1 060 °C, which significantly shortens the graphitization and decarburization processes during the annealing process.

The mechanical properties of whiteheart malleable irons are primarily affected by the degree of decarburization as thinner wall thicknesses generally decarburize faster than thicker ones. Thus, the structures and the mechanical properties are dependent upon the wall thickness. ISO 5922 addresses this by standardising four test pieces with 6 mm, 9 mm, 12 mm and 15 mm diameters. In the rupture test, the 6 mm test pieces show the lowest tensile strength with the highest elongation, whereas the 15 mm test pieces possess the highest tensile strength and the lowest elongation.

The second stage of annealing is comparable to that for blackheart malleable irons. Because of very slow cooling in the temper pot, castings annealed in iron ore must undergo a normalizing treatment at 860 °C to 870 °C followed by air cooling prior to spheroidizing the pearlite. The spheroidizing temperatures for whiteheart malleable irons are between 700 °C and 760 °C, according to the material grade to be targeted. By lengthening the annealing time, weldable malleable irons can be decarburized to a maximum residual carbon content of 0,3 % in wall thicknesses of ≤ 8 mm, to guarantee unrestricted weldability.

A common practice for high-volume production is to use a short-cycling heat treatment technique in continuous furnaces where the complete cycle is controlled.

9.4 Graphite form and size

The graphite in malleable irons is dictated by the decomposition of the eutectic carbides to produce temper carbon nodules (see Figures 13 to 15). The number and size of the temper carbon nodules are dependent first upon the chemical composition of the as-cast malleable iron, and second upon the ledeburitic carbide, which is determined by the solidification rate in relation to wall thickness. Graphitization controls the process time of blackheart malleable iron castings which can also be reduced by boron additions, as opposed to whiteheart malleable iron castings where the process time is controlled only by decarburization. The addition of boron decreases the processing time in state-of-the-art production. Thus, blackheart malleable iron castings normally show smaller but more numerous temper carbon nodules, mainly influenced by the silicon content.

9.5 Mechanical property requirements and the influence of structure

Malleable irons have some similarities to spheroidal graphite irons. These similarities include the fact that the matrix, as opposed to the graphite, principally dictates the mechanical properties. Thus, when adjustments to metal composition and heat treatment are required to meet specified properties, they are confined only to those that influence the matrix structure.

Mechanical properties of whiteheart malleable irons are standardized in ISO 5922:2005, Table 1, for five grades at four possible test piece diameters (6 mm, 9 mm, 12 mm, 15 mm). The basis for the designation of each material grade is the specified minimum value of the mechanical properties in the 12 mm test bar. As a consequence of the decarburization, the values for tensile strength, 0,2 % yield strength, and Brinell hardness increase with increasing test bar diameter, whereas the elongation decreases. This influence of the test bar diameter can be explained by the growth of the core, which is affected by decarburization, thereby increasing pearlite, which is responsible for strength. For example, the properties in a 15 mm test piece are unlikely to reflect the properties in a 6 mm casting section, and a suitably sized bar will need to be chosen to validate the castings. The influence of pearlite in the whiteheart malleable iron structure is far more profound than the effects of alloy additions that strengthen ferrite. For the production of fully decarburized ferritic grades, ferrite-strengthening alloy additions can also be used to increase material properties, as described for blackheart materials.

The 10 grades of blackheart malleable iron in ISO 5922:2005, Table 2, range from fully ferritic to fully pearlitic materials. It would be expected that the grades from JMB/275-5 to JMB/350-10 were fully ferritic; increasing amounts of pearlite are expected in the microstructure of higher-strength grades. The pearlite can be produced by a variety of methods; these include either alloying or modifications to the normal blackheart second-stage annealing cycle. The grades JMB/700-2 and JMB/800-1 are oil quenched after the normal graphitizing anneal. This process produces oil residues that must be removed by washing prior to the second-stage tempering process that involves tempering the martensitic structure. Changes in the metal composition are required in order to achieve the different combinations of tensile properties in grades with a fully ferritic matrix. All of these adjustments involve additions that strengthen the ferrite, including a modification of the manganese content, which affects tensile strength, and of the phosphorus content, which affects yield strength. The most powerful element that strengthens ferrite is silicon, but when silicon is raised, higher additions of bismuth are required in order to ensure an initial matrix structure of pearlite and carbide, free of primary graphite prior to heat treatment, which is unusual for cast irons. Unmachined test pieces are used to take into account any influences of surface structure that result from the heat treatment operation. This influence applies particularly to whiteheart malleable irons, for the reasons described in 7.3 and 7.5.

9.6 Impact properties

ISO 5922 does not specify impact properties, although informative data are provided in ISO 5922:2005, Annex A. These properties relate to both notched and unnotched test specimens in both whiteheart and blackheart malleable irons. Some users demand impact properties in addition to the specified tensile properties to indicate that the castings are suitable for the intended application. ISO 5922:2005, 7.4, specifies the phosphorus level and the procedure to be adopted under such circumstances, but it is up to the manufacturer and purchaser to agree on the type of test, notched or unnotched, as well as the minimum impact properties that must be achieved.

9.7 Section sensitivity

Malleable iron castings are manufactured in a range of wall thicknesses from 3 mm to approximately 60 mm. Because the graphite in malleable irons (temper carbon) is not formed until annealing, blackheart and completely decarburized whiteheart malleable iron exhibit the lowest section sensitivity of all graphitic Fe-C materials. For whiteheart malleable iron, the drastic decarburization is limited to wall thicknesses in the range between 3 mm and 4 mm, i.e. to extremely thin-walled castings. Whiteheart malleable castings above this wall thickness range are not completely decarburized. With increasing wall thicknesses, they exhibit increasing fractions of pearlite. Thus, this material exhibits a reverse section sensitivity, meaning that with increasing wall thickness, the fraction of the pearlitic core zone increases along with hardness and strength. The influence of wall thickness can be shown by comparing the specific values in ISO 5922 of the four test pieces with 6 mm, 9 mm, 12 mm and 15 mm diameters.

9.8 Choosing the grade

The range of applications for whiteheart malleable irons is extremely wide, and the spectrum of mechanical requirements ranges from low to extreme service conditions. A useful property of malleable castings is their ability to be easily galvanized, e.g. pipe and fence fittings and kitchen equipment. The grade of material to be used depends simply upon the stresses applied in service. Comparison of the requirements and service conditions with the specified mechanical properties in ISO 5922 (tensile strength, 0,2 % yield strength or impact resistance, if required) or with other special properties (e.g. weldability) allow the correct choice to be made among the five grades of whiteheart malleable irons.

Blackheart malleable irons are used in a wide range of components. Pipe fittings, which are still manufactured in whiteheart malleable iron in Europe, are traditionally produced in the United States and Japan using ferritic blackheart malleable iron. An extra-wide range of applications is utilized by the automotive industry, including front-axle suspensions, suspension arms, gearboxes, rear-axle housings, pump cases, camshafts, brake drums, wheel trunks, rocker arms and bell cranks. This volume comprises parts with a mass from a few grams to more than 20 kg. In general, the mechanical properties of blackheart malleable and spheroidal graphite irons are very similar. Therefore, the application examples are also very similar. In applications where stiffness (Young's modulus) is important and component shape cannot be modified, designers will generally recommend whiteheart malleable iron.

The ferritic grades JMB/275-5 to JMB/350-10 have the lowest tensile properties but high ductility providing good machinability, which makes the grades ideal for components that require high-volume repetitive machining. A good example is pipe fittings, which are produced in high volumes and are subsequently machined and threaded.

The intermediate grades JMB/450-6 to JMB/550-4 find applications where higher strength is required in combination with good ductility. Because the fatigue properties increase in proportion to the tensile strength, these materials can be useful where service conditions involve some dynamic loading. Pumps, suspension units and reciprocating parts fall into this category.

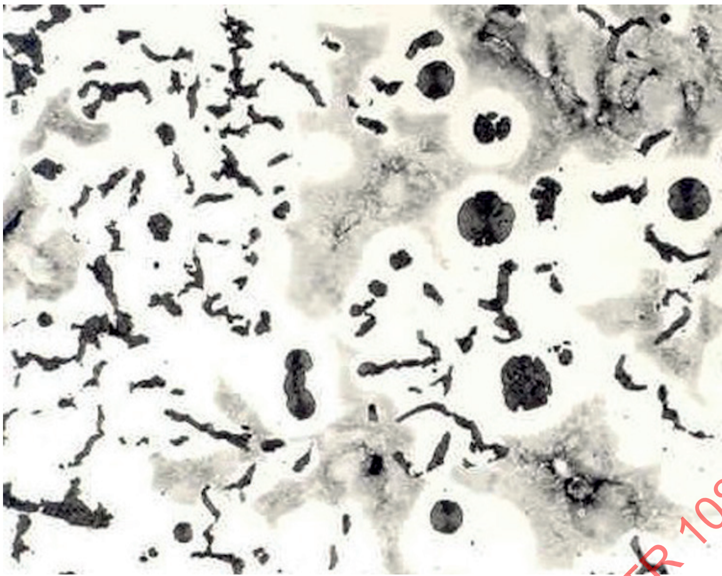
The higher grades JMB/600-3 to JMB/800-1 are very similar to the higher grades of spheroidal graphite irons. All have high tensile strengths with low elongation or impact resistance and are valuable either directly because of their high tensile strength or because this imparts good fatigue properties. High-pressure hydraulic valves and other parts that require high tensile strength and fatigue properties, but low ductility and impact resistance, fall into this category. In order to achieve satisfactory service performance, the actual choice of these materials depends on the design requirements.

10 ISO 16112, Compacted (vermicular) graphite cast irons

10.1 Overview

Compacted graphite cast irons are sometimes called "vermicular irons". Their properties are specified in ISO 16112:2017, Tables 1 and 2. The benefit of using this material is related to its strength, which is higher than most grey iron grades, but with a thermal conductivity better than that of spheroidal iron.

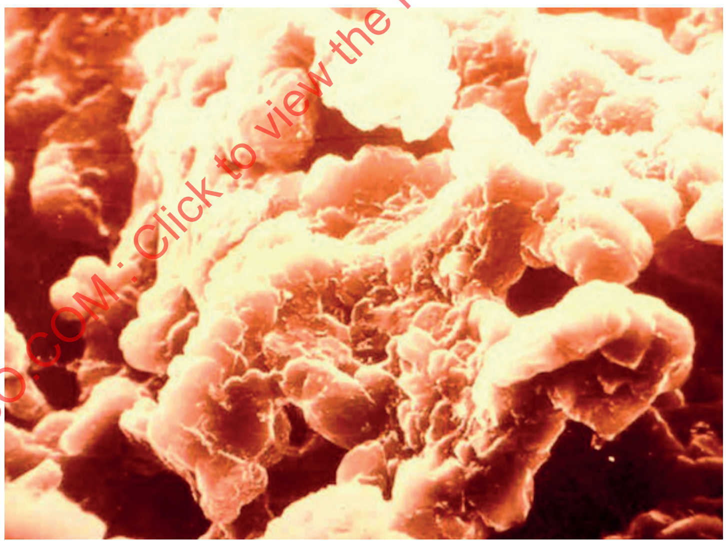
The graphite form, unlike the normal smooth-sided and sharp-pointed Type A flake graphite found in grey cast irons, is wormlike and compacted, hence the names. It results from treating with magnesium in a concentration insufficient to produce spheroidal graphite. Whereas spheroidal graphite irons typically contain about 0,03 % to 0,06 % magnesium, compacted iron contains about 0,015 % to 0,020 %. It is common to see some spheroids in a compacted iron, as illustrated in Figure 16, due to differences in cooling rates with changing section thicknesses.



Magnification × 200

Figure 16 — Graphite spheroids in compacted graphite iron

Deep etching shows the compacted nature of the graphite in the eutectic cell in Figure 17.



Magnification × 350

Figure 17 — Deep-etched compacted graphite iron

10.2 Compacted graphite iron — intermediate properties

Compacted graphite irons have properties that are approximately midway between grey and spheroidal graphite irons, with the exception of thermal conductivity which tends to be closer to that of grey iron. These properties are beneficial in applications where thermal conductivity is important, but where grey cast iron does not have sufficient tensile strength.

The compacted graphite shape results in increased tensile properties, such that the lowest grades of compacted iron are comparable with the highest grades of grey iron. This increased strength in combination with good thermal properties can be utilized where heat transfer is important. This property combination is of particular benefit in the automotive industry for the manufacture of cylinder heads and blocks. Typical thermal conductivity properties of grey, compacted graphite and spheroidal graphite irons are given in Table 12.

Table 12 — Thermal conductivity of grey, compacted graphite and spheroidal graphite irons

Comparison of thermal conductivity W/(m × K) — by grade									
Material/grade	**Temperature °C**	**JL/150**	**JL/200**	**JL/250**	**JL/300**	**JL/350**			
Grey	100	66	53	51	48	45			
	400	47	44	42	41	40			
Material/grade	**Temperature °C**				**JV/300**	**JV/350**	**JV/400**	**JV/450**	**JV/500**
Compacted	100				45	42	39	37	35
	400				42	40	38	36	34
Material/grade	**Temperature °C**						**JS/400-18**	**Blank**	**JS/500-7**
Spheroidal	100						36	Blank	35
	400						36	Blank	35

10.3 Effect of structure on properties

Because the production route mirrors that of spheroidal graphite iron, the matrix structure can be modified by alloying, or sometimes by heat treatment, to produce a range of mechanical properties. With compacted graphite irons, both the matrix and the amount of spheroids present in the structure influence the properties of the material.

10.4 Metal composition and carbon equivalent

ISO 16112 does not specify metal composition requirements; metal composition is left to the discretion of the manufacturer. The mechanical property requirements of the various grades in the specification are usually met by alloying. As with spheroidal graphite irons, the carbon equivalent does not need to be controlled in the same way as in grey cast iron. In principle, it is possible to meet the material demands of all the grades utilizing a fairly narrow range of carbon and silicon contents, with the process window for compacted graphite iron being narrower than that for spheroidal graphite iron.

10.5 Graphite form and size

ISO 16112 describes compacted graphite iron as a material that contains a minimum of 80 % graphite in the compacted form, defined as ISO 945-1:2019, Form III. The remaining graphite is typically Forms V or VI. The six graphite forms are shown in Figure 7. Deviations from the percentage of compacted graphite forms are sometimes agreed upon between the manufacturer and the purchaser.

In ISO 16112, typical nodularity is between 5 % and 20 %. This is illustrated in ISO 16112:2017, Annex B, which also gives guidance on graphite particle size and roundness. The nodularity microstructures can be used for comparison to evaluate test samples at × 100 magnification.

In ISO 945-1:2019, form designations III, IV, V and VI give rise to the common expression “percent nodularity” when describing the graphite structure of both compacted and spheroidal graphite irons. However, opposing meanings can apply, depending on whether the reference is to compacted or spheroidal graphite iron. For compacted graphite iron, percent nodularity means the maximum number of spheroids that are acceptable in the material, whereas in spheroidal graphite iron it means the minimum acceptable amount of spheroids.

ISO 16112:2017, Clause B.10, requires the location of the nodularity test to be agreed between the manufacturer and the purchaser. This requirement is to ensure consistency of testing within the constraints of the section sensitivity. ISO 945-1 also designates eight sizes of compacted graphite. The graphite size can be specified together with the form, if this is considered important.

Because of the interaction between the liquid metal and the mould surface, a degenerate surface layer containing flake graphite and the possible formation of inclusions is often unavoidable. When this is not acceptable, the surface layer can be removed by machining and/or shot blasting. The maximum depth of this degenerate surface layer can be agreed upon between the manufacturer and purchaser, if necessary.

10.6 Section sensitivity in compacted graphite iron

The manufacture of compacted graphite iron is similar to the production of spheroidal graphite iron. However, compacted graphite iron with a structure similar to that shown in Figure 6 has a section sensitivity closer to grey irons. As the wall thickness increases and the solidification rate decreases, there is a lesser tendency for graphite spheroids to form. Thus, thick-walled sections will contain fewer nodules than thin sections and the properties will differ. This is illustrated by the mechanical property requirements shown in ISO 16112:2017, Table 2, for samples machined from cast-on samples. As the relevant wall thickness increases, the property requirements are reduced, because of the influence of solidification time and, thus, reduced numbers of nodules are likely to be present.

Increasing numbers of nodules will increase both the tensile strength and elongation. However, increasing the number of nodules in the material will reduce thermal conductivity. The principal reason for the increased use of compacted graphite iron is because it has similar thermal conductivity to that of grey iron, together with better mechanical properties.

In compacted graphite iron castings, an increase in the nodule number lowers the thermal conductivity. Thus, the designer and engineer will need to determine the critical wall thickness area of the casting in terms of both mechanical and thermal properties and, if needed, specify this area as the location for the test. ISO 16112 specifies a maximum of 20 % of Form V and Form VI graphite, which would then apply in this location. The manufacturer can adjust the treatment process to meet the specified requirement in the appropriate section, but, if there is a wide variation in the wall section thickness, cannot adjust the process to provide a uniform graphite shape throughout the casting. This is the reason why the test location needs to be agreed between the manufacturer and purchaser.

10.7 Matrix structure and the resultant properties

ISO 16112:2017, Table 1, shows five grades of compacted graphite iron. As the tensile strength increases the elongation decreases. The lowest tensile-strength grade (JV/300) has a predominantly ferritic matrix; the highest tensile-strength grade (JV/500) is fully pearlitic. The intermediate tensile-strength grades contain mixtures of ferrite and pearlite. Alloying additions are normally introduced into the melt to produce the various grades. The alloying additions are usually the same as those used for spheroidal graphite irons. Copper is normally added, with tin as an alternative.

10.8 Heat treatment

Heat treatment is not specifically required as part of the manufacturing process, although remedial action can be taken if test pieces fail to meet specified properties. Such remedial action would involve either annealing or normalizing. Stress relief is a further option in the case of complex parts that can produce dimensional change during machining.

In special cases, compacted graphite iron can be austempered to increase tensile strength up to 700 MPa with a corresponding improvement in wear resistance. Isotherming heat treatment can also be applied with the purpose to enhance the mechanical properties, while maintaining the thermal conductivity up to higher temperatures compared to austempered compacted graphite iron.

10.9 Choosing the grade

All of the compacted graphite iron grades are primarily used in applications where heat dissipation is an important design property.

Grade JV/300 has the lowest tensile strength together with the highest elongation and thermal conductivity. This grade is ideal in circumstances where strength is not the main criterion for design, although the tensile strength of JV/300 is higher than that of most of the grey iron grades. Examples of applications for JV/300 are in the manufacture of some exhaust manifolds and cylinder heads for large marine applications.

Grade JV/500 has the highest strength and still retains good thermal properties and improved wear resistance, even though its ductility is negligible. This grade is commonly used in the manufacture of automotive cylinder blocks and other components that are highly stressed in service, because the fatigue properties are also improved, due to the higher tensile strength. The intermediate grades from JV/350 to JV/450 show progressive increases in tensile strength, wear resistance and fatigue properties while providing good thermal conductivity and are used in a wide range of applications, such as bedplates, cylinder heads, pump housings, cylinder blocks and hydraulic components.

11 ISO 2892, Austenitic cast irons

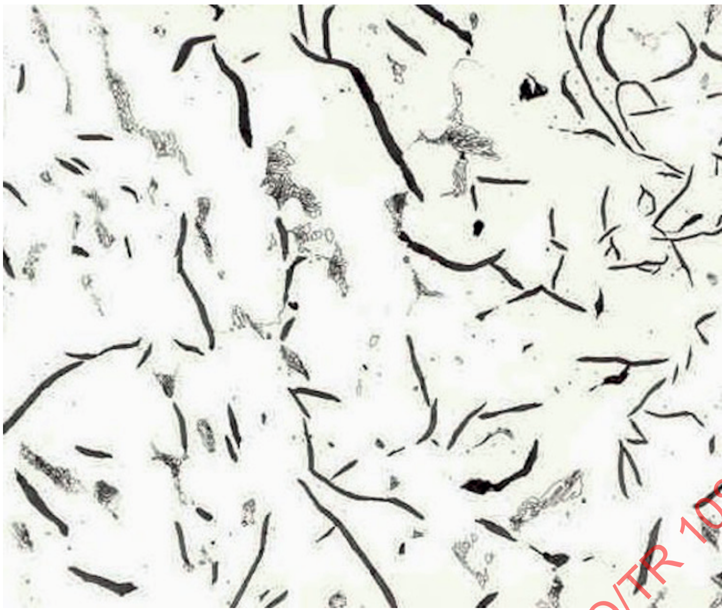
11.1 Overview

The property requirements of austenitic irons are specified in ISO 2892:2007, Tables 3 and 4. The austenitic irons are principally designed to provide good heat and corrosion resistance. Some of the grades have other valuable properties, such as good impact resistance at very low temperatures, oxidation resistance, low thermal expansion and the advantage of being non-magnetic. The material grades are divided into two distinct types: engineering grades and special-purpose grades. The minimum content of 12 % mass fraction nickel means that all grades are commonly known as “Ni-resist”.

The high level of nickel and other elements in the material stabilizes the austenite, such that instead of transforming to pearlite and/or ferrite when the material solidifies and cools, austenite is retained down to very low temperatures. Therefore, the grades have an austenitic matrix, which can also contain chromium-rich carbides if the chromium level is sufficiently high.

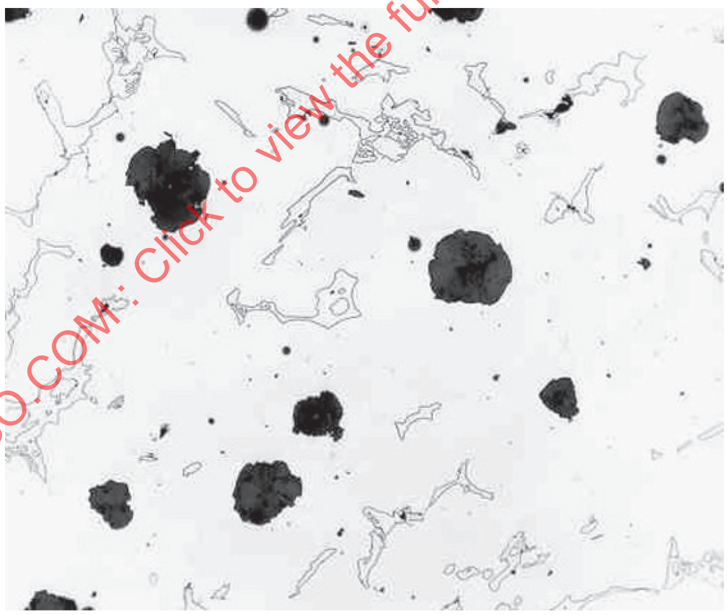
The austenitic irons are graphitic irons and, depending upon the grade, can contain either flake or spheroidal graphite. The original research on the austenitic iron materials involved the manufacture of grades with flake graphite forms, because it preceded the development of spheroidal graphite irons in the 1940s. Spheroidal graphite containing austenitic irons were subsequently produced to overcome the disadvantage of low tensile properties obtained from cast irons with a flake graphite form. The austenitic grades have a matrix that cannot transform to other constituents. Therefore, no significant improvement in mechanical properties and performance is possible by a heat treatment process. Any heat treatment applied is confined to stress relieving and stabilizing treatments in order to maintain dimensional tolerances when castings are machined and/or in service.

Typical structures are shown in Figures 18 and 19. The particular grades shown contain austenite and chromium rich carbides; the carbides are absent in the low-chromium grades.



Magnification × 200

Figure 18 — Flake graphite austenitic iron



Magnification × 300

Figure 19 — Spheroidal graphite austenitic iron

11.2 Effect of structure on properties

Cast irons with an austenitic matrix do not have particularly high tensile strengths; the highest-strength grade containing spheroidal graphite has a minimum tensile strength of 440 MPa. The maximum value in practice rarely exceeds 420 MPa. Furthermore, the flake graphite grades are specified to have minimum tensile strengths of 140 MPa (for the special purpose grades) and 170 MPa (for the engineering grades) with the maximum value in practice rarely exceeding 200 MPa. Thus, the materials are not used for very high-strength applications, although there is a clear advantage in utilizing the spheroidal grades where tensile strength is a consideration.

11.3 Chemical composition and its effect

ISO 2892 is one of two cast iron International Standards that specify chemical composition. The other is ISO 21988 for abrasion-resistant irons. In the case of all the other cast iron types, the chemical composition is at the discretion of the manufacturer.

The range of chemical composition required for each grade is specified in ISO 2892:2007, Tables 1 and 2, with the understanding that other elements can be present, provided that they do not adversely affect structure and properties. Elements are specified within the material composition to produce specific properties and performance.

The maximum carbon content is specified as 3 % mass fraction, although some grades with very high nickel contents have 2,4 % or 2,6 % maximum carbon content. This lower maximum carbon content is specified to meet the required mechanical properties of austenitic irons if the material is strongly hypereutectic and to minimize casting defects in the material. The simplified carbon equivalent formula [see Formula (1)] ignores other elements such as nickel, because at trace levels their influence on CEE values is insignificant. All elements influence CEE to some extent, but nickel has the greatest influence. With nickel at levels between 12 % mass fraction and 36 % mass fraction across the range of grades and with a high carbon content, the material can be strongly hypereutectic. Thus, the carbon content is lowered and carefully controlled to avoid a hypereutectic structure.

The silicon content ranges in each grade are sufficiently wide to ensure the avoidance of excessive carbide formation in varying section thicknesses. Silicon contents tend to be higher in thin sections compared with thick sections. The exceptions are the grades nominally containing between 4 % mass fraction and 6 % mass fraction silicon to improve high-temperature growth and scaling properties.

Nickel is essential to produce the stable austenitic matrix. In pure iron-nickel irons, 30 % mass fraction nickel is required to achieve this matrix, but the presence of carbon, copper, manganese and chromium all help to reduce the amount of nickel required in the specified grades.

Copper is added in a range of 5,5 % mass fraction to 7,5 % mass fraction to enhance the corrosion resistance of the flake graphite grade JLA/XNi15Cu6Cr2, while the level of copper in all of the remaining austenitic grades is limited to 0,5 %.

Manganese is an austenite stabilizer with good solubility. It is used in the flake graphite-containing grade JSA/XNi13Mn7 and in the spheroidal graphite-containing grade JSA/XNi13Mn7 to reduce the amount of nickel required to obtain completely non-magnetizable materials.

Chromium improves heat, corrosion and erosion resistance, and resistance increases in proportion to the amount of chromium present. There is a limit to the amount of chromium that can be introduced before unacceptable amounts of carbide are produced and mechanical properties decline. Only about 0,5 % mass fraction chromium is dissolved in the austenitic matrix; the remainder is present in the carbide phase. The disadvantage of chromium is that it reduces notch sensitivity, which is why low chromium grades with good ductility and impact resistance form part of ISO 2892.

Molybdenum is not specified within ISO 2892, but footnotes refer to its addition to improve high-temperature properties, particularly heat resistance and creep. A typical addition would be 1 % mass fraction molybdenum.

Niobium is added to only one grade, JSA/XNi20Cr2Nb, to improve weldability by preventing microcracks in the weldment and heat affected zone. A footnote indicating the formula that provides the desired level is given in ISO 2892:2007, Table 1. In practice, the residual niobium level in the casting is between 0,12 % mass fraction and 0,20 % mass fraction niobium.

