PUBLISHED DOCUMENT

PD ISO/TR 10809-1:2009

Cast irons

Part 1: Materials and properties for design

ICS 77.080.10

British Standards

National foreword

This Published Document is the UK implementation of ISO/TR 10809-1:2009.

The UK participation in its preparation was entrusted to Technical Committee ISE/35, Cast iron.

A list of organizations represented on this committee can be obtained on request to its secretary.

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This Published Document was published under the authority of the Standards Policy and Strategy Committee on 30 November 2009.

ISBN 978 0 580 62879 5

Amendments/corrigenda issued since publication

Date	Comments

TECHNICAL REPORT

ISO/TR 10809-1

First edition
2009-11-01

Cast irons —

Part 1: **Materials and properties for design**

Fontes —

Partie 1: Matériaux et propriétés pour la conception

Reference number
ISO/TR 10809-1:2009(E)

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Published in Switzerland

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Foreword

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 10809-1 was prepared by Technical Committee ISO/TC 25, *Cast irons and pig irons*.

ISO/TR 10809 consists of the following parts, under the general title *Cast irons*:

— *Part 1: Materials and properties for design*

— *Part 2: Welding*

Introduction

Worldwide cast iron production is in excess of 60 000 000 tonnes per annum. 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 technology of cast irons is not widely taught or understood around the globe. This part of ISO/TR 10809 is intended to provide information about cast iron materials so that users and designers are better able to understand cast iron as a design material in its own right and correctly specify cast iron for suitable applications.

Cast irons —

Part 1:
Materials and properties for design

1 Scope

The purpose of this part of ISO/TR 10809 is to assist the designer and engineer in understanding the family of cast iron materials and 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. This is because metallurgy is not one of the scientific disciplines taught to engineering students. Thus, such students often have a lack of knowledge regarding the fundamentals underpinning the material properties of cast irons. This part of ISO/TR 10809 suggests what can be achieved, what cannot be achieved and why, if and when cast irons are specified. It is not designed to be a textbook of metallurgy. It is intended to help people to choose the correct material for the right reasons and also to 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 Why use cast irons as an engineering material?

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?

The following sub-clauses give general information on the cast iron types currently standardized in International Standards.

2.1 Why use grey cast iron?

Grey cast iron provides the largest worldwide tonnage of all cast irons produced, mainly because of its wide range of uses within general engineering, its ease of machining, and its cost advantage. The material has the highest thermal conductivity among the range of cast irons, which is why it is used in applications where this property is important. Typical examples are automotive parts such as brake drums, discs, clutch plates, and cylinder blocks and heads. Grey cast iron lacks ductility, but for parts where requirements for ductility and impact strength 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 should be considered for a potential application unless there are ductility issues, or the design requires ultimate strengths in excess of 300 N/mm^2.

2.2 Why use spheroidal graphite cast iron?

Spheroidal graphite cast iron has the benefit of ductility as well as strength, which is why it is often considered to be a material superior to grey cast iron. Its main disadvantage in this respect is that it does not have the thermal conductivity provided by grey cast iron and is not normally used where this property is important. A large number of grades of spheroidal graphite cast iron 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 and, for this reason, spheroidal graphite cast iron is increasingly being used to produce cast parts to replace steel fabrications. Large tonnages of spheroidal graphite cast 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 cast iron are of advantage.

2.3 Why use compacted cast iron?

Compacted graphite cast irons have applications as components which require additional strength, stiffness, and ductility over and above that offered by grey cast 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 in conjunction with thermal conductivity properties similar to those found in grey cast irons.

2.4 Why use malleable cast iron?

There are two different types of malleable cast iron, blackheart and whiteheart. The blackheart grades have properties similar to the spheroidal graphite cast irons and the materials have traditionally been considered interchangeable in most general engineering applications. The main advantage of blackheart malleable iron, compared with spheroidal graphite cast iron, is that it is easier to machine, because of the different metal composition. The whiteheart malleable grades are still used to produce traditional thin section castings, particularly fittings such as hinges and locks. Now, however, their uses are more usually confined to the production of thin section castings where the heat treatment process involved can be adjusted to completely decarburize the material. This is of considerable advantage to designers; it allows malleable whiteheart castings to be welded to steels as part of a fabrication process, because the whiteheart material possesses properties that are not dissimilar to the steel to which it is welded.

2.5 Why use ausferritic cast iron?

The austempering heat treatment carried out on a normal spheroidal graphite cast iron enhances its properties to produce a range of grades with exceptionally high tensile strengths. The highest tensile strength grade also has a high hardness that allows it to be used in abrasion-resisting applications, the most common one being as digger teeth on earth-moving equipment. As with all spheroidal graphite cast 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, provided that their combination is applicable to the component design. Tensile strengths up to 1 400 N/mm^2, hardness greater than 400 HBW, and tensile elongation up to 10 % are possible (although not all three simultaneously in the same grade of material). These mechanical properties also generate a high fatigue strength that is useful in gears and other components for use in a rotating/bending application.

2.6 Why use abrasion-resistant cast iron?

The abrasion-resisting cast irons are a range of hard and tough materials that compete with other alloys such as manganese steel, mainly in the mining and extraction industries, in wear-resistant applications 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 should not 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 which it is in contact with and the circumstances under which it performs. 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. The 13 grades of abrasion-resisting irons specified in ISO 21988 offer a wide choice of alloys for matching the material against the intended application.

2.7 Why use austenitic cast iron?

The austenitic cast irons (sometimes called Ni-resists) are a range of materials that provide corrosion resistance, heat resistance or a combination of both. Austenitic cast irons are often compared with stainless steels when a design is being considered. One specific application for which the austenitic cast iron grades are considered is where the component to be produced needs to be non-magnetizable and other properties are of secondary importance. Both flake graphite and spheroidal graphite iron grades are produced: the spheroidal graphite iron grades exhibit superior tensile properties to those of the flake graphite grades. These materials vary widely in their metal composition in order to meet a broad range of applications; in general, the most arduous applications are met by those grades containing the highest nickel content. The 12 grades of austenitic cast iron cover the spectrum of applications where highly alloyed materials are required in order to meet arduous conditions in service.

3 Commentary

Cast irons have particular and peculiar metallurgical and other properties which are unique to the material and which give it specific valuable attributes that make it a useful material in certain applications.

3.1 Recent changes in standardization

ISO/TC 25 is the International Technical Committee responsible for the development of International Standards for cast irons. Since 1998, when it was reactivated after a dormancy of 14 years, ISO/TC 25 has been working through a programme of creation, revision, assessment and publication of cast iron material and related standards. 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 International Standards that have been reviewed, created, published or retained in their current form are shown in Table 1.

Table 1 — International Standards for cast iron materials and microstructure

Scope	Standard number
Grey cast irons	ISO 185
Spheroidal graphite cast irons	ISO 1083
Compacted (vermicular) graphite cast irons	ISO 16112
Malleable cast irons	ISO 5922
Ausferritic spheroidal graphite cast irons	ISO 17804
Abrasion-resistant cast irons	ISO 21988
Austenitic cast irons	ISO 2892
Designation of microstructure of cast irons – visual analysis	ISO 945-1

The seven International Standards for cast iron materials (see Table 1) encompass a huge international tonnage. In 1999, reported world production reached 49,3 million tonnes/annum, and this figure had increased to 61,6 million tonnes/annum by 2006 (the last available statistics). The trend is continuing for cast irons utilized in the manufacture of a wide range 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 which together specify 84 different grades. It is recommended that these standards and the associated annexes of supporting information be carefully consulted, in order to allow the most appropriate material to be chosen for the application. Table 2 provides a short résumé of properties that will 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 2 — General properties for the range of International Standards for cast iron

Property	ISO 185 Grey	ISO 1083 Spheroidal	ISO 16112 Compacted (vermicular)	ISO 5922 Malleable	ISO 17804 Ausferritic spheroidal	ISO 21988 Abrasion-resistant	ISO 2892 Austenitic
Tensile strength	√√	√√√√	√√√	√√√√	√√√√√	0	√√√
Proof strength	√	√√√√	√√	√√√	√√√√√	0	√√√
Elongation	√	√√√√√	√	√√√	√√√	0	√√√
Impact resistance	√	√√√	√	√√√	√√	√√√	√√√
Low-temperature properties	√√	√√√	√√	√√√	√√	√	√√√
Thermal conductivity	√√√√√	√√√	√√√√	√√√	√√√	√	√√√
Thermal expansion	√√	√√	√√	√√	√√	√	√√√√
Abrasion resistance	√√	√√	√√	√	√√√	√√√√√	√√
Corrosion resistance	√√	√√	√√	√√	√√	√√√√√	√√√√√
Heat resistance	√√√	√√	√√	√√	√√	√	√√√√
Machinability	√√√√√	√√√	√√√	√√√	√√	√	√√√
Weldability	√√	√√√	√√	√√√	√	0	√√

0 Not applicable
√ Low
√√ Average
√√√ High
√√√√ Very high
√√√√√ Highest

Ausferritic spheroidal graphite cast irons should only be welded prior to austempering.

NOTE ISO 5922 JMB grades = √√√, JMW grades = √√√√, JMW-S grade = √√√√√.

Table 3 provides data on typical applications (the list is not exhaustive). Table 3 should also help the designer and engineer to select the most appropriate International Standard, and ultimately the choice of the grade within it.

Table 3 — Typical mechanical property ranges and applications for cast irons

ISO 185 Grey	**Minimum tensile strength range 100 N/mm² to 350 N/mm², elongation < 1 %** Wide range of general engineering parts: pumps, valves, compressor bodies, machine tools, cylinder blocks, brake drums and discs, clutch plates, press tools, street furniture.
ISO 1083 Spheroidal	**Minimum tensile strength range 350 N/mm² to 900 N/mm², elongation range 2 % to 22 %** Wide range of general engineering parts requiring higher strength, elongation, and fatigue properties than grey cast iron: crankshafts, valves, pumps, steering knuckles, suspension components, axle boxes.
ISO 16112 Compacted (vermicular)	**Minimum tensile strength range 300 N/mm² to 500 N/mm², elongation range 0,5 % to 2 %** Components requiring good thermal conductivity in conjunction with higher strength than grey cast iron: ingot moulds, cylinder blocks, brake drums and discs, cylinder liners, hydraulic parts.
ISO 17804 Ausferritic	**Minimum tensile strength range 800 N/mm² to 1 400 N/mm², elongation range 2 % to 11 %** Castings requiring very high strengths with good elongation, fatigue, and abrasion resistance properties: gears and cams, crankshafts, differentials, digger teeth, wear shoes, track guides.
ISO 5922 Malleable	**Minimum tensile strength range 270 N/mm² to 800 N/mm², 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 2892 Austenitic	**Minimum tensile strength range 140 N/mm² to 440 N/mm², 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 cast irons, where, depending on the section thickness, the mechanical properties in the casting may be either lower or higher 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.

The cast irons have a complex metallurgy and a wide range of different material properties or specific property requirements can be obtained through the correct choice of material.

3.2 General metallurgy of the cast irons

The glossary of terms relating to International Standards for cast irons (see Annex A) explains the meaning of the metallurgical terms given below.

The 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. At 0 % carbon content, the material is soft pure iron, or ferrite. As the carbon content is increased, increasing amounts of pearlite are formed, which is harder and stronger, such that at about 0,9 % carbon content the structure is fully pearlitic. This range of carbon content is where the majority of plain carbon steels exist. Raising the carbon content results in the formation of iron carbide in increasing amounts (sometimes called cementite), which is hard and brittle. Above about 1,7 % carbon content, the material is called white cast iron and comprises a mixture of pearlite and iron carbide.

It is this structure (a mixture of pearlite and iron carbide) that forms the basis of the manufacture of the abrasion-resistant cast irons and malleable cast 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 the other cast irons require the majority of the carbon content to be present in the form of graphite, and this is achieved by the addition of silicon, which promotes the formation of graphite instead of carbide. Grey cast irons contain flake (lamellar) graphite, which is the normal graphite form that occurs during solidification. Spheroidal and compacted graphite cast irons are produced by deliberate modification of the solidification mechanism, usually by an addition of magnesium. In the case of the austenitic cast irons, high levels of other elements are also added to produce the required material properties. Ausferritic cast irons are both alloyed and subjected to heat treatment, in order to meet the requirements of the appropriate International Standard. Heat treatments are applied to all of these materials, either as part of the production route, or to enhance properties, or to obtain stress relief in complex components.

Summarizing, therefore, there are seven material types each broadly described as follows.

Grey cast iron — cast iron with a flake graphite form, usually in a pearlitic matrix except for the very lowest grades where ferrite is present. The material does not normally require heat treatment, unless stress relief is applied to ensure dimensional stability.

Spheroidal graphite cast iron — cast iron with the solidification mode modified to produce graphite in spheroids as opposed to flakes. The grades range from those containing fully ferritic to fully pearlitic matrices including a recently developed high silicon grade. Heat treatment is sometimes used to produce the ferritic grades, particularly those requiring high impact values at low temperature. The highest-strength grade can be produced by an oil quench and temper heat treatment. Stress relief can be applied if necessary.

Compacted (vermicular) graphite cast iron — cast iron with the solidification mode modified to produce stubby, or compacted graphite flakes, usually with a small percentage of spheroidal graphite present. The grades range from those containing mainly ferritic to fully pearlitic matrices. The material is not normally heat treated unless stress relief is required.

Malleable cast iron — two types of cast iron called separately 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 quenched and tempered to produce the highest grade.

Ausferritic cast iron — spheroidal graphite cast iron deliberately subjected to an austempering heat treatment that enhances material properties, producing an ausferritic matrix containing graphite spheroids. It sometimes requires special alloying to ensure structural uniformity of the matrix in thick sections. It rarely requires further heat treatment following production.

Abrasion-resistant cast iron — cast iron, usually with a martensitic matrix, resulting from heat treatment, that contains complex carbides to provide good abrasion resistance.

Austenitic cast iron — cast iron with an austenitic matrix that is stable down to sub-zero temperatures. It contains grades with either graphite flakes or spheroids, and is highly alloyed and used in special-purpose applications. It can be stress relieved and stabilized for high-temperature applications.

3.3 Section sensitivity and its effects 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 in both the castings and the test pieces poured with them. This is largely the case with steels and many other alloys, but is not the case with cast irons, for reasons related to the section sensitivity.

The expression “section sensitivity” is used to explain 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 speeds of solidification in varying casting sections.

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 also possibly in the matrix. These effects result in differing mechanical properties within the various casting sections. In ISO 185, for grey cast irons, where the effects of section sensitivity are most pronounced, 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 185:2005, Table 1, an extract from which is shown in Table 4.

Table 4 — Extract from Table 1 of ISO 185:2005 relating to section sensitivity

Material designation	**Tensile strength** (mandatory values in separately cast samples) N/mm^2 minimum	**Relevant wall thickness** mm over	up to and including	**Tensile strength** (anticipated values in castings) N/mm^2 minimum
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	—

Section sensitivity of whiteheart and weldable blackheart malleable cast irons is affected by the decarburization process (see 6.3 and 6.7).

Section sensitivity is less pronounced in the compacted graphite cast irons, even less pronounced in the range of cast irons containing graphite spheroids, and least pronounced in the grades of blackheart malleable cast irons and the abrasion-resistant cast irons. In the International Standards for compacted graphite cast irons, spheroidal graphite cast irons, and ausferritic spheroidal graphite cast irons, separately cast test pieces are also required, but with the option of utilizing a cast-on test piece. This arrangement more closely replicates the properties of the wall thickness to which it is attached, provided that the correct test piece is used. Tables in the various International Standards for cast iron dictate the required mechanical properties, depending upon the relevant wall thickness.

The terminology “relevant wall thickness” was deliberately chosen for inclusion in the International Standards concerned, so that the manufacturer and the producer can agree on the section of the casting where the cast-on sample, from which the test piece is taken, is placed. The relevant wall thickness would normally be construed to be the wall thickness that is the most important for the purposes of design; this is often the most highly stressed area. Where precision is required in the determination of material properties, the International Standards allow for the option of cutting samples from the casting at an agreed location. Obviously this destroys the casting and is invariably carried out according to agreed routine sampling plans, or as initial validation during first-off sampling.

3.4 Understanding hardness

National 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 for the materials that are required. ISO 185 contains special hardness-only grades which are normative and which do not require tensile strength validation. Therefore, it is now possible to specify castings according to a mandatory hardness grade, but they might also be produced according to a tensile strength grade where, in addition, the customer demands a hardness range to be met.

It is important to make clear that the section-sensitivity phenomenon affects hardness. For example, the graphite in graphitic materials is coarser in thick sections than in thin sections and the matrix may also be affected by the different cooling rates; thus thick sections will be softer than thin sections. An illustration is given in ISO 185:2005, 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 185:2005, 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 cast iron grades, 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 variable results and usually cause confusion.

When hardness is specified, the hardness range needs to be realistic to take into account normal variations in the material. 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 cast iron, the hardness variation will be between 10 HBW and 70 HBW depending upon the grade and matrix. For abrasion-resistant cast iron materials, the situation is somewhat different because the hardness minimum is specified. It must be appreciated, however, that there will still be a hardness variation between thin and thick sections, even though the minimum specified value is 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 should be agreed between the manufacturer and purchaser.

3.5 Heat treatment

Some of the materials specified in the International Standards for cast irons require special heat treatment operations as part of the production process; the manufacture of malleable and ausferritic irons require heat treatment according to 6.3 and 7.2, 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. Examples of common heat treatments are given in Table 5.

Table 5 — Examples of common heat treatments applied to cast irons

Process	Temperature °C	Time	Subsequent process
Annealing	900	1 h + 1 h per 25 mm of casting section[a]	Slow furnace cooling to below 200 °C
Normalizing	900	1 h + 1 h per 25 mm of casting section[a]	Air quench outside the furnace, sometimes using cooling fans for larger castings
Oil quench and temper	900	1 h + 1 h per 25 mm of casting section[a]	Quench in oil and then temper at the temperature for the desired hardness, usually ~300 °C
Stress relief	550	1 h + 1 h per 25 mm of casting section[a]	Slow furnace cool to below 200 °C

[a] Time at temperature depends on the size of the castings and their packing density. The times are for individual castings or small numbers in a batch. Where large numbers of small castings are packed together in a furnace, it is essential that the complete batch is raised to the desired temperature before process commences.

3.6 Welding

There is a common misconception that cast irons cannot be welded and, in many internal company specifications, or in requirements additional to those demanded in International Standards and other standards, it is specifically disallowed as a result of the belief that a weld will act as a stress-raiser, promoting failure of the part.

It has been accepted that some cast irons do not respond well to welding, whilst others need special considerations regarding acceptable techniques. With the exception of the weldable cast irons, manual arc welding using steel rods typically employed for steel welding purposes should never be used, as the weldment will have no long-term integrity and may cause catastrophic failure of the casting. Engineers and designers would be wrong, however, to dismiss a welding operation as out of hand without consideration of the reliable possibilities. These fall into two categories, namely: finishing welding to remove unwanted defects and joint welding of cast irons to other materials as part of a fabrication. As with all repair 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 irons are fully described in ISO/TR 10809-2.

4 ISO 185 Grey cast irons

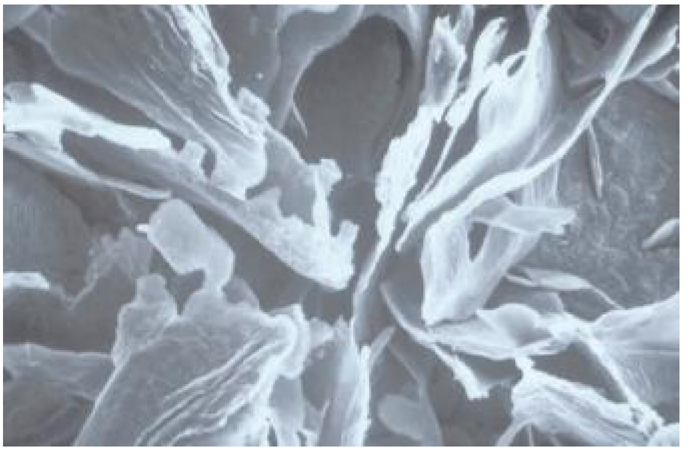
4.1 Overview

Grey cast irons are sometimes called flake graphite cast irons or lamellar graphite cast irons. Their properties are specified in ISO 185:2005, Tables 1 and 2. The structure of grey cast irons contains graphite flakes in a mainly pearlitic matrix as shown in Figure 1.

Magnification × 300

Figure 1 — Flake graphite in a pearlitic matrix

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

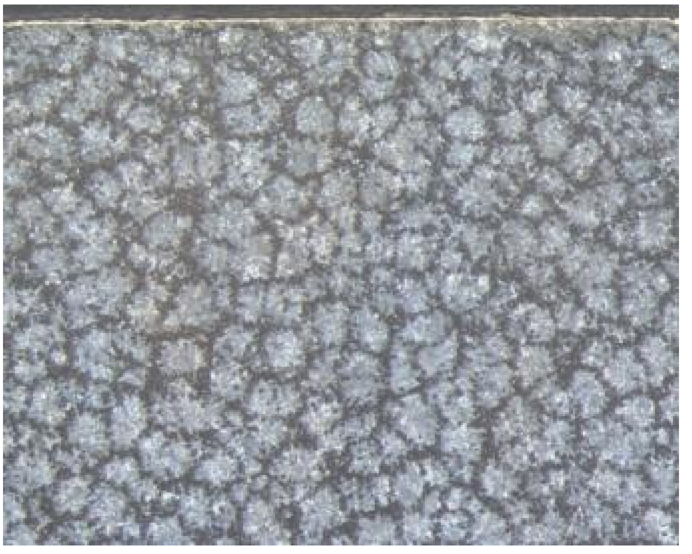


Magnification × 350

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. Figure 4 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.

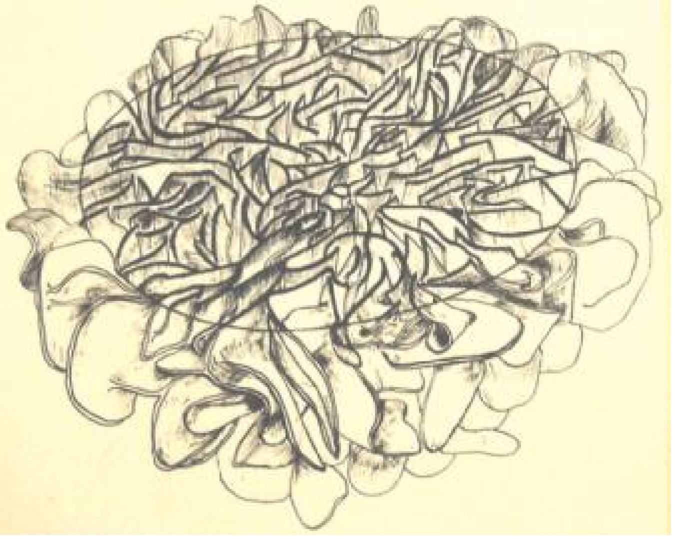


Figure 4 — Schematic of the cut top of a eutectic cell

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

4.2 Effect of structure on properties

When flake (lamellar) graphite is present, its amount and distribution have a major effect in determining the mechanical properties. Low-tensile-strength grey irons generally contain 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. These changes in the direction of higher strengths are obtained by lowering the carbon and silicon contents (ultimately the carbon equivalent), by using good inoculation techniques and, where appropriate, by alloying with pearlite-promoting elements.

NOTE The relationship between the structure and properties of grey cast irons is that the graphite, rather than the matrix, largely dictates the tensile properties.

4.3 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 liquidus (CEL) measurement using a thermal analysis technique. The CEL is calculated using Equation (1), where 4,25 is the CEL eutectic. All of the grades normally have hypoeutectic compositions. Reducing the carbon and silicon levels increases the tensile strength, as shown in Table 6.

$$\mathrm{CEL} = \left(\mathrm{C} + \frac{\mathrm{Si}}{4} + \frac{\mathrm{P}}{2} \right) \% \qquad (1)$$

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 CEL that is dependent upon the agreed thickness of the casting at the location of the test.

Table 6 — CEL ranges for ISO 185 grades

Material designation	Typical CEL 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	3,5 to 3,6

These ranges 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 CEL ranges will not necessarily give the same properties in the casting, however, due to section-sensitivity issues.

4.4 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 speed of solidification and the number of eutectic cells. The speed 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 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 higher 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 CEL 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.

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 should this be necessary. The most common specification for the graphite form and size of grey cast iron, which is sometimes appended to the grade requirement, is ISO 945-1 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.

4.5 Section sensitivity

Section sensitivity is so important for the understanding of cast iron metallurgy and performance that it is described in detail in 3.3 with a specific example relating to grey cast iron. The ISO 185 grey cast irons are 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

b

c

d

e

Figure 5 — Reference diagrams for graphite distribution

4.6 Effect of alloying elements

Alloying elements are sometimes added to grey cast irons in order to ensure a fully pearlitic matrix in the higher-strength grades. These alloying elements are normally copper and 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 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 a well-formed graphite form resulting from good inoculation, rather than by the introduction of unnecessary alloying elements.

4.7 Heat treatment

Heat treatment is generally applied to enhance material properties. Grey cast irons do not respond well to this form of treatment, because the graphite form principally dictates the properties, and any change in the matrix resulting from a heat-treatment operation provides little improvement.

Sometimes, particularly with grade JL/100, an annealing operation is requested, because the principal requirement is for high-speed machining, as opposed to mechanical properties. Remedial normalizing treatments are also employed to ensure a fully pearlitic matrix, in cases when thick section castings have cooled slowly, resulting in a ferritic matrix, or to remove hard, unwanted carbide. Typical heat treatment cycles are given in Table 7.

The most usual form of heat treatment operation utilized for grey cast iron is stress relieving. A very common problem in machine shops is that of dimensional change and distortion in castings, during or after the machining operation. This distortion is 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 series of stress-relieving operations as shown in Table 7 solves the problem. The thickest section of the casting determines the correct timescale for the holding time at a temperature for all heat treatments.

Table 7 — Typical heat treatment cycles for grey cast iron

Cycle	Anneal	Normalize	Stress relieve
1. Raise the temperature	100 °C to 200 °C per hour[a]	100 °C to 200 °C per hour[a]	100 °C to 200 °C per hour[a]
2. Holding temperature	900 °C to 950 °C	900 °C to 950 °C	550 °C to 600 °C
3. Holding time	1 h per 25 mm section + 1 h	1 h per 25 mm section + 1 h	1 h per 25 mm section + 1 h
4. Cooling	50 °C to 100 °C per hour to below 200 °C	Air cool outside the furnace[b]	Slow cool in the furnace (maximum 50 °C/h)

[a] For thin section and fragile castings, this should be 50 °C/h to 100 °C/h.

[b] For thick section castings, a fan may be necessary.

It is important to remember that machining operations can introduce internal stresses that result in distortion and dimensional change, particularly if machining cuts are excessive, if feeds and speeds are too high, or if clamping and jigging are insecure. The effects of these problems can be overcome by utilizing a stress-relieving heat treatment, provided that there is sufficient material left for the final cut.

4.8 Choosing the grade

The grades available in ISO 185 range from a 100 N/mm^2 material with a mainly ferritic matrix, increasing in strength to a 350 N/mm^2 material with a fully pearlitic matrix. All of the grades have a defined minimum tensile strength as indicated in ISO 185:2005, Table 1, but a requirement regarding the maximum strength is also defined in ISO 185:2005, 7.2.1, and is often missed. For each grade, the maximum tensile strength is no more than 100 N/mm^2 above the minimum; for example, grade 200 has a tensile strength between 200 N/mm^2 and 300 N/mm^2. 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 lower-tensile-strength grades JL/100 and JL/150 have high carbon and silicon contents and thus the highest thermal conductivity and damping capacity. These grades are useful therefore 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 important, such as bedplates and optical benches, where there is little or no stress. The high carbon content of these materials also imparts good lubricated bearing properties, provided that the environment does not include abrasive debris that can score and wear the soft matrix.

The intermediate-tensile-strength grades JL/200 to JL/275 have lower carbon and silicon contents with mainly or completely pearlitic matrices. The thermal conductivity and damping capacity remain good, and the higher-tensile strength and hardness values 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.

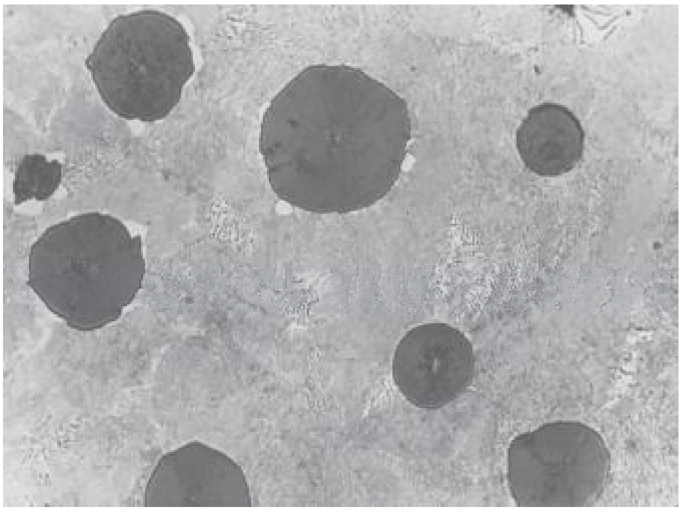
The higher-tensile-strength grades JL/300 and JL/350 provide a combination of high strength whilst still maintaining good thermal conductivity compared with other types of cast iron. These grades approach the maximum tensile strength attainable in grey cast iron. Applications therefore tend to be confined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

All the ISO 185 grades have elongation limited to a maximum of about 1,0 % and poor impact properties. This makes grey cast irons unsuitable for use where ductility properties are required.

5 ISO 1083 Spheroidal graphite cast irons

5.1 Overview

Spheroidal graphite cast irons are sometimes called ductile or nodular cast irons. Their properties are specified in ISO 1083:2004, Tables 1 to 4. The structure of spheroidal graphite cast irons contains graphite in spheroidal form as shown in Figure 6 (in this case in a mainly pearlitic matrix). ISO 1083 specifies grades ranging from fully ferritic materials with tensile strengths above 350 N/mm^2 and elongation in excess of 22 % to fully pearlitic materials with tensile strengths above 900 N/mm^2 and elongation as low as 2 %.



Magnification × 500

Figure 6 — Pearlitic spheroidal graphite cast iron

The normal production route for spheroidal graphite cast irons is to add a small percentage of magnesium to a molten alloy with low sulfur content. This procedure is followed by an addition of silicon 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; importantly, unlike grey cast irons, spheroidal graphite cast irons solidify without the formation of eutectic cells. In general terms, the graphite spheroids are about 0,5 % to 1,0 % as large as the eutectic cells normally seen in a well-inoculated grey cast iron.

5.2 Effect of structure on properties

The mechanism of solidification is entirely different from that of grey cast irons, which results in a wide range of grades with tensile properties that are substantially higher than grey cast iron can achieve. 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. By comparison, graphite spheroids approach the optimum in terms of surface area to volume ratio, and do not act as stress raisers. 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 matrix dictates the structure of spheriodal graphite cast irons and thus the tensile properties. This is the opposite situation to that which pertains with grey cast irons.

5.3 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 cast irons, the carbon equivalent does not need to be controlled in the same way as in grey cast irons. In principle, it is possible to meet the material demands of all the grades using a fairly narrow range of carbon and silicon contents. The phosphorus content of spheroidal graphite cast irons needs to be kept low, generally less than 0,04 %, and thus has little influence on the carbon equivalent liquidus value (CEL). The carbon content remains constant, and the silicon content is commonly maintained at about 2,0 % to 2,25 % in irons that are heat treated. In irons requiring high-impact properties at low temperatures, the silicon content is maintained between 1,9 % and 2,1 %. However, for the vast majority of the spheroidal graphite cast iron produced, in most of the grades, the base composition values are as given in ISO 1083:2004, Table A.3. In practice, most manufacturers operate as closely as possible to the eutectic value of 4,25 % CEL. The major exception is the case of the high-silicon grades with improved machinability (see ISO 1083:2004, Annex A).

Table 8 — Typical base composition of spheroidal graphite cast irons

Carbon content, %	3,40 to 3,90
Silicon content, %	2,40 to 2,70[a]
CEL, %	4,00 to 4,27

[a] Si content can be outside this range, depending on the section thickness.

5.4 Graphite form and size

Spheroidal graphite shape, often referred to as "percent nodularity", is often specified in company specifications in addition to the material grade. A common requirement is "nodularity to be greater than 90 %". This requirement is specified because non-spheroidal graphite can reduce mechanical properties. 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.

Most company specifications require a minimum of 80 % to 90 % nodularity, which means 80 % to 90 % 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 spheroidal graphite cast 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 could 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, might 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. The graphite size can be specified together with the form, if this is considered important. Prior to completely specifying the graphite form and size, however, the user should understand the issues related to the section sensitivity and its effect upon the graphite.

5.5 Section sensitivity in spheroidal graphite cast iron

As the wall thickness increases, the graphite spheroids become larger, the number of spheroids is reduced, and the graphite shape may deteriorate from Form VI to Form V or IV. Therefore, the mechanical 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 may be different from that in the sample.

Because the matrix defines the properties, these properties may not be seriously affected until a significant deterioration in graphite form occurs. This phenomenon is illustrated in Table 9, which shows the properties of three JS/600-3 materials, each of which has a similar amount of pearlite in the matrix.

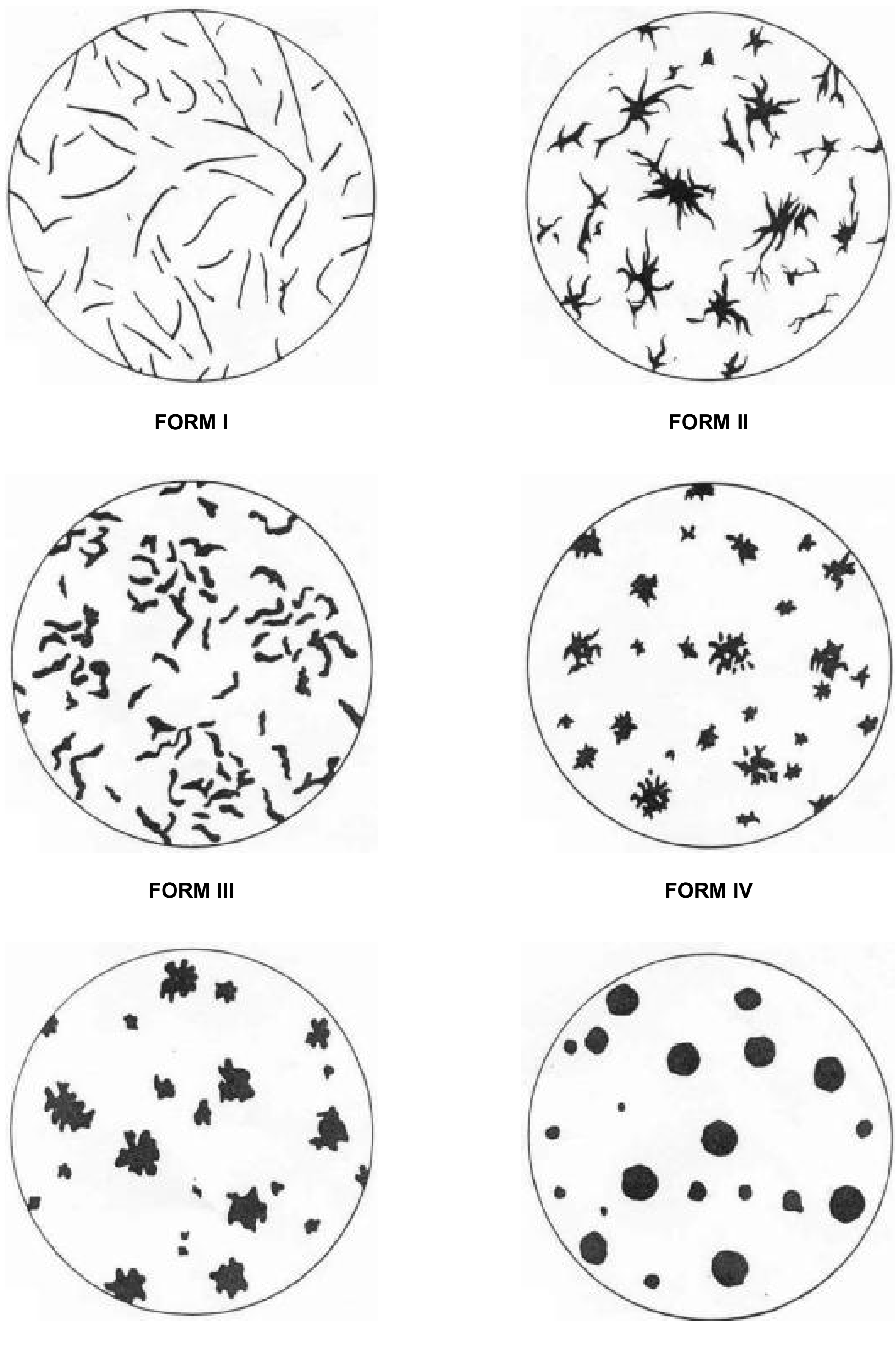


Figure 7 — Graphite forms in ISO 945-1

Table 9 — Typical tensile properties of spheroidal graphite cast irons at selected percentage nodularity and percentage pearlite

Nodularity %	Pearlite %	Tensile strength N/mm^2	0,2 % Proof strength N/mm^2	Elongation %
100	65	679	399	9,0
75	70	632	386	5,0
45	68	534	343	5,0

NOTE The degradation in properties due to lower nodularity is different for ferritic matrices. The section sensitivity increases as the hardness increases.

5.6 Effect of alloying elements

When the pearlitic grades are produced, there is a tendency to add alloying elements to obtain the required amount of pearlite. 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, however, because it increases the tensile strength and maintains a higher ductility than tin. 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. Users who specify alloy additions, supplementary to the designated mechanical properties, need to be aware of this problem. Users should confine their requirements to the mechanical properties of the standard grade and allow the manufacturer to identify the necessary alloying levels.

5.7 Matrix structure and resultant properties

Table 10 shows the properties of the 15 grades of spheroidal graphite cast iron specified in ISO 1083:2004. Users should note that, as the tensile strength increases, there is an accompanying reduction in elongation. 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.

All grades can be produced from lower-purity raw materials, followed by heat treatment. In this case, there is little or no difference in the mechanical properties compared with the as-cast route, although the lower-purity route is avoided because of increased cost associated with both the heat treatment operation and additional shot cleaning. The exceptions are grades JS/800-2, JS/900-2, and 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, whilst some of the impact-resistant grades are heat treated to ensure that the required Charpy “V” values are met.

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

Table 10 — Structure and properties of ISO 1083 cast iron grades; minimum values obtained from separately cast samples

Material designation	Tensile strength R_m N/mm^2 minimum	0,2 % Proof strength $R_{p0,2}$ N/mm^2 minimum	Elongation A_5 % minimum	Typical matrix structure
ISO 1083/JS/350-22LT/S[a]	350	220	22	Ferrite
ISO 1083/JS/350-22-RT/S[b]	350	220	22	Ferrite
ISO 1083/JS/350-22/S	350	220	22	Ferrite
ISO 1083/JS/400-18-LT/S[a]	400	240	18	Ferrite
ISO 1083/JS/400-18-RT/S[b]	400	250	18	Ferrite
ISO 1083/JS/400-18/S	400	250	18	Ferrite
ISO 1083/JS/400-15/S	400	250	15	Ferrite
ISO 1083/JS/450-10/S	450	310	10	Mainly ferrite
ISO 1083/JS/500-7/S	500	320	7	Ferrite with pearlite
ISO 1083/JS/500-10/S	500	320	10	Ferrite with pearlite
ISO 1083/JS/550-5/S	550	350	5	Ferrite with pearlite
ISO 1083/JS/600-3/S	600	370	3	Mainly pearlite
ISO 1083/JS/700-2/S	700	420	2	Pearlite
ISO 1083/JS/800-2/S	800	480	2	Pearlite or tempered martensite
ISO 1083/JS/900-2/S	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 Figures 1, 2 or 3.

NOTE 4 Elongation values are determined from $L_0 = 5_d$. For other gauge lengths, see ISO 1083:2004, 9.1 and Annex B.

NOTE 5 1 N/mm^2 = 1 Mpa.

a LT for low temperatures (–20 °C or –40 °C).

b RT for room temperature (23 °C).

5.8 Spheroidal graphite cast iron with high silicon content

One grade with high silicon content is specified in ISO 1083:2004, Annex A. The composition is not specified, but ISO 1083:2004, A.4.3 gives a typical value of about 3,7 % Si. The advantage of these materials is that they have improved machinability and more consistent hardness.

5.9 Special case of impact-resistant grades

Tables 2 and 4 of ISO 1083:2004 specify the minimum impact resistance values from separately cast samples. These materials are specifically designed for situations where impact conditions may occur at ambient temperature, −20 °C, and −40 °C. They do not meet the impact properties that can be obtained from some steels, but do find many applications, such as steering knuckles in vehicles that need to be operated successfully at widely differing temperatures. The properties are summarized in Table 11.

Table 11 — ISO 1083 impact values

Material designation	Minimum impact resistance 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/S[a]	—	—	—	—	12	9
ISO 1083/JS/350-22-RT/S[b]	17	14	—	—	—	—
ISO 1083/JS/400-18-LT/S[a]	—	—	12	9	—	—
ISO 1083/JS/400-18-RT/S[b]	14	11	—	—	—	—

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 may be suitable for some pressure vessel applications.

[a] LT for low temperature.

[b] RT for room temperature.

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. (Metal composition is not specified in ISO 1083.) Success depends upon a reduction in the normal silicon content to about 1,9 % to 2,0 % and an addition of about 0,8 % nickel. The lower silicon level raises the impact value and the nickel addition strengthens the matrix, to ensure achievement of the minimum proof-strength value. It is unlikely that the required impact values will be met in the –40 °C material, unless it is then annealed to ensure a fully ferritic matrix. Designers and engineers must understand that, to achieve fitness for purpose from these materials, these guidelines must be followed and the associated costs must be accepted.

5.10 Heat treatment

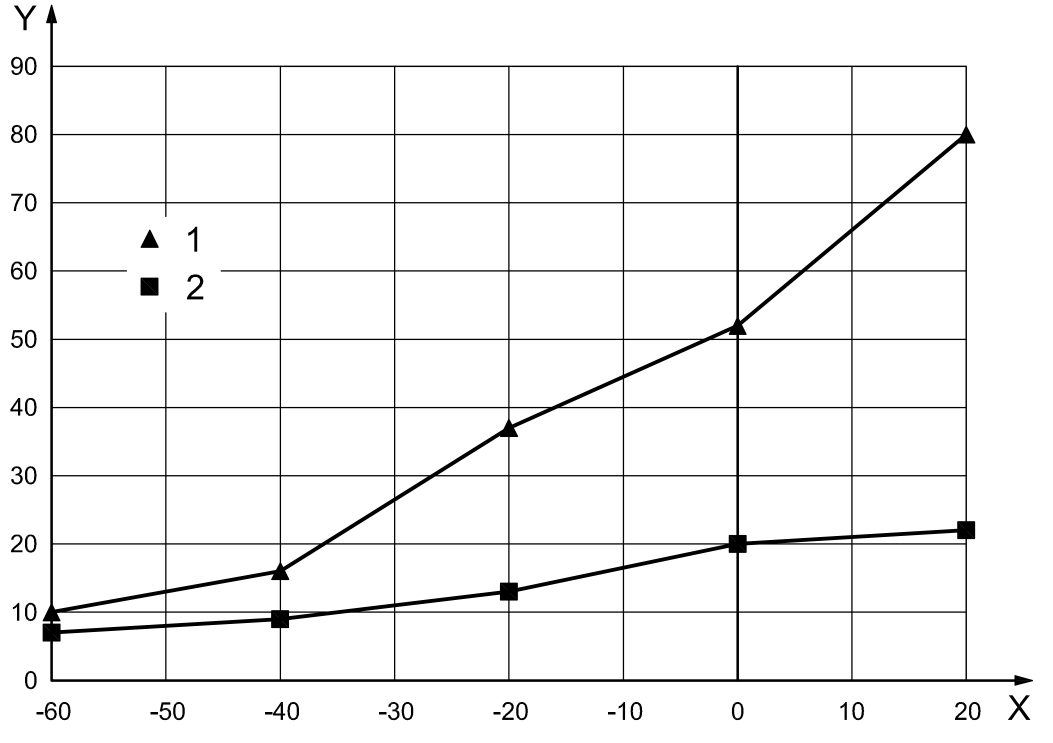
Because of the associated costs compared with the use of high-purity pig iron and good-quality steel scrap, it is not normal practice for the ferritic grades to be manufactured using an annealing treatment. However, this can be done by annealing at 900 °C and then slowly cooling to ambient temperature. The time interval at this temperature depends upon the size and packing density of the castings in the batch. Mechanical properties are normally the same as those found in as-cast ferritic castings, but because it is possible to use a lower silicon content when heat treating, impact values tend to be slightly higher and machinability is improved. Annealing, as described in 6.8, should be considered mandatory for those grades requiring high impact values at –40 °C.

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 1083:2004, 10.4, allows for this 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 time. The castings are then air cooled; thicker castings can benefit from the use of forced air from a fan. Where many small castings are normalized in a batch, they need to be separated, in order to allow a satisfactory cooling speed.

5.11 Relationship between ferritic spheroidal graphite cast iron and ferritic steel

Ferritic steels are generally considered to have superior properties to spheroidal graphite cast irons, and this is generally true when the materials are compared at room temperature or above.

This is not the case at sub-zero temperatures, however, where the impact properties and fracture toughness in particular begin to converge. This is illustrated in Figures 8 and 9, which show the pattern of change as temperatures are reduced. The curves with triangular markers relate to a fully ferritic low-carbon steel, whilst the curves with the square markers relate to a fully ferritic spheroidal graphite cast iron. At these low temperatures, the two materials could be considered as interchangeable in service. More details regarding this subject are given in ISO 1083:2004, Annex C.



Key

X temperature °C

Y impact energy value J

1 low-carbon steel

2 ferritic spheroidal graphite cast iron

Figure 8 — Comparison of impact values at various temperatures between ferritic ductile cast irons and low-carbon steels

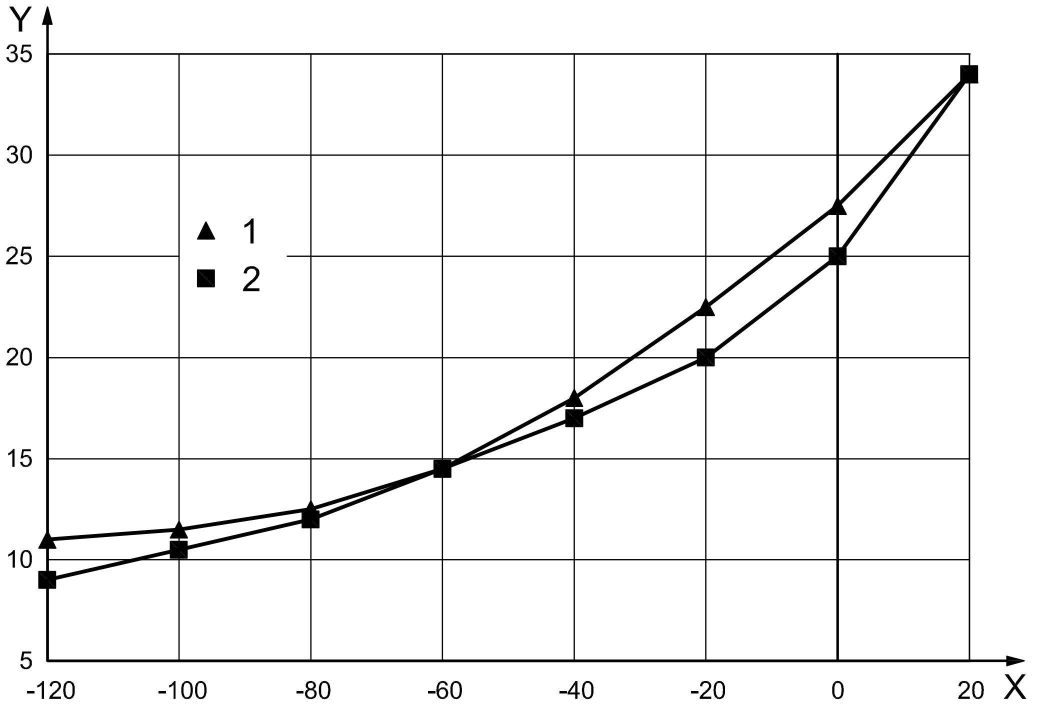


Figure 9 — Comparison of fracture toughness at various temperatures between ferritic ductile cast irons and low-carbon steels

All ferritic grades of spheroidal graphite cast iron have a tensile strength exceeding that of the highest-tensile-strength 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, proof strength, and elongation specifications between those of the ferritic and the pearlitic grades. The fully pearlitic grades have high tensile strengths whilst still exhibiting some ductility. Therefore, there is a wide range of property combinations from which to choose. Other properties, typical of the materials, are summarized in ISO 1083:2004, Table G.1.

Grades JS/350-22-LT and JS/400-18-LT are specifically designed to provide good impact properties at low temperature. These impact-resistant grades are commonly used for automotive and other parts such as pumps and valves that are likely to operate in sub-zero temperatures; for example, in refrigeration applications or in winter conditions in countries with cold climates. The other JS/350 and JS/400 grades can be utilized in similar applications where tensile strength is less important than their impact and elongation properties.

Grades JS/450-10, JS/500-7, JS/500-10 and JS/550-5 have good combinations of tensile strength and elongation, although the impact properties are reduced by the pearlite present, and, in the case of the JS/500 10S grade, the higher silicon content. 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 fatigue. 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 have high tensile strengths with low elongation and low impact resistance. 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.

One important point about the whole range of spheroidal graphite cast iron grades is that their thermal conductivity is less than that of grey cast iron, as shown in ISO 1083:2004, Table G.1. If a grey cast iron has insufficient tensile properties for an application, then before a spheroidal graphite cast iron is chosen, care should be taken to ensure that any heat transfer issues have been carefully assessed. Compacted graphite cast iron fills the gap between these two materials in terms of thermal conductivity (see Clause 6).

6 ISO 16112 Compacted (vermicular) graphite cast irons

6.1 Overview

Compacted graphite cast irons are sometimes called vermicular graphite cast irons. Their properties are specified in ISO 16112:2006, Tables 1 and 2.

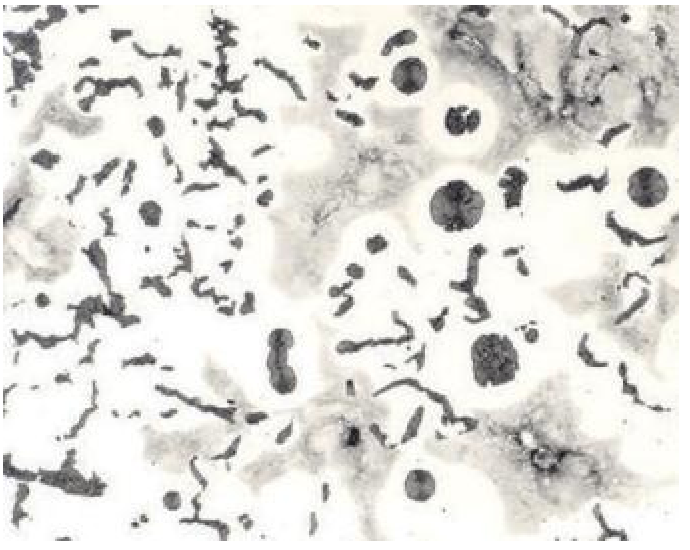
The ideal structure contains graphite as shown in Figure 10. The benefit of using this material is related to its strength, which is higher than most grey cast iron grades, but with a thermal conductivity approaching that of grey cast iron.

Magnification × 300

Figure 10 — Pearlitic compacted graphite cast iron

This graphite form, which is unlike the normal smooth-sided and sharp-pointed Type A flake graphite found in grey cast irons, is stubby and compacted; hence the name. Such graphite can result accidentally, particularly in heavy sections, from the presence of high levels of nitrogen in the iron. In terms of ISO 16112, it results from treating with magnesium in a concentration insufficient to produce spheroidal graphite. Whereas spheroidal graphite cast irons typically contain about 0,04 % to 0,06 % magnesium, compacted graphite iron contains about 0,015 % to 0,025 %.

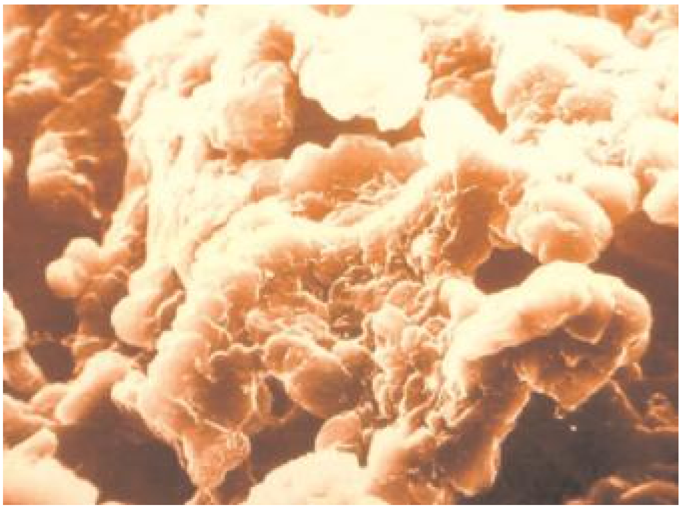
For reasons related to the section sensitivity, it is common to see some spheroids in a compacted graphite iron, as illustrated in Figure 11.



Magnification × 200

Figure 11 — Graphite spheroids in a compacted graphite cast iron

Deep etching shows the compacted nature of the graphite in the eutectic cell in Figure 12.



Magnification × 350

Figure 12 — Deep-etched compacted graphite cast iron

6.2 Why use compacted graphite cast iron?

Compacted graphite cast irons have been found to have properties that are generally about midway between the grey and spheroidal graphite cast irons, with the exception of their thermal conductivity, which tends to be closer to that of grey cast iron. These properties are of benefit in circumstances where thermal conductivity is important, but where grey cast iron does not have tensile or other properties that are suitable for the application. Because the graphite flakes are stubby as a result of the treatment process, the tensile properties are raised, such that the lowest grades of compacted graphite iron are comparable with the highest grades of the grey cast irons. Thus, there is increased strength in combination with good thermal properties, which can be utilized where heat transfer is important. This property is of particular benefit in the automotive industry for the manufacture of cylinder blocks, although many other applications have also been found. Typical thermal conductivity properties of grey, spheroidal graphite and compacted graphite irons are given in Table 12, for comparison purposes.

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

Comparison of thermal conductivity W (m · K) — by Grade									
Material/Grade	**Temp. °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	**Temp. °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	**Temp. °C**						**JS/400-18**	**JS/500-7**	**Blank**
Spheroidal	100						36	35	Blank
	400						36	35	Blank

6.3 Effect of structure on properties

Deep etching of the material shows that the compacted graphite remains largely within eutectic cells, as is the case for grey cast irons, but the spheroids remain outside. Also, because the production route mirrors that of spheroidal graphite cast iron, the matrix structure can be modified by alloying or sometimes by heat treatment, to produce a range of mechanical properties. Therefore, most of the properties of compacted graphite cast irons are between those of grey and spheroidal graphite cast irons. With compacted graphite cast irons, both the matrix and the amount of spheroids present in the structure influence the properties of the material.

6.4 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 as shown in Table 13. The phosphorus content of the compacted graphite cast irons needs to be kept low, generally less than 0,04 %, and thus has little influence on the CEL value. In practice, most producers operate as close as possible to the eutectic value of 4,25 % CEL.

Table 13 — Normal base composition of compacted graphite cast irons

Carbon content, %	3,40 to 3,90
Silicon content, %	2,40 to 2,70[a]
CEL, %	4,00 to 4,27
[a] The Si content can be outside this range, depending on the section thickness.	

6.5 Graphite form and size

ISO 16112 describes a compacted graphite cast iron as a material that contains a minimum of 80 % of the graphite in the compacted form, defined as Form III in ISO 945-1. The remaining graphite should be defined as Forms V or VI. The six graphite forms are shown in Figure 7.

In ISO 16112, typical nodularity is between 5 % and 20 %. This is illustrated in ISO 16112:2006, Annex B, which also gives guidance on graphite particle size and roundness. The nodularity microstructures can be used as comparators against which test samples can be evaluated at × 100 magnifications.

In ISO 945-1, 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 cast irons. However, opposing meanings can apply, depending whether the reference is to compacted or spheroidal graphite cast iron. For compacted graphite cast iron, percent nodularity means the maximum amount of spheroids that are acceptable in the material, whereas in spheroidal graphite cast iron it means the minimum acceptable amount of spheroids.

ISO 16112:2006, 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 graphite. The graphite size can be specified together with the form, if this is considered important.

6.6 Section sensitivity in compacted graphite cast iron

As with all of the cast irons, designers and engineers need to understand the metallurgical issues related to the structure and section sensitivity in compacted graphite cast iron, in order to obtain maximum advantages from the material.

The manufacture of compacted graphite cast iron is similar to the production of spheroidal graphite cast iron; however, compacted graphite cast iron with a structure similar to that shown in Figure 7 has a section sensitivity closer to grey cast irons. This section-sensitivity similarity is because of the formation of eutectic cells with a compacted geometry. 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 16112:2006, 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 the numbers of nodules that 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 its thermal conductivity. It should be remembered that the principal reason for the increased use of compacted graphite cast iron is because it has similar thermal conductivity to that of grey cast iron, together with higher mechanical properties.

In compacted graphite iron castings, an increase in the nodule number lowers the thermal conductivity, which may influence fitness for the purpose. 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, should this matter, 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 structure throughout the casting. This problem needs to be understood, and this is the reason why the test location needs to be agreed between the manufacturer and purchaser.

6.7 Matrix structure and the resultant properties

ISO 16112:2006, Table 1, shows five grades of compacted graphite cast iron. As the tensile strength increases from grade to grade, the elongation decreases. The lowest-tensile-strength grade (JV/300) has a mainly 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, because this provides a greater measure of control than other methods, such as the selection of suitable steel scrap in the manufacturing process. The alloying additions are usually the same as those used for spheroidal graphite cast irons. Copper is normally added, with tin as an alternative.

6.8 Heat treatment

Heat treatment is not required specifically 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 may produce dimensional change during machining.

6.9 Choosing the grade

All of the compacted graphite cast 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. Thus, it is ideal in circumstances where strength is not the main criterion in design. (It should be kept in mind that the tensile strength of JV/300 is higher than that of most of the grey cast iron grades.) Examples of uses of 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, but 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 whilst providing good thermal conductivity and are used in a wide range of applications, such as bedplates, brake drums and discs, pump housings, cylinder blocks and hydraulic components.

7 ISO 5922 Malleable cast irons

7.1 Overview

ISO 5922 specifies the requirements for two types of malleable cast 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 cast irons differ. Blackheart malleable cast irons are annealed in a neutral, non-decarburizing atmosphere, whereas whiteheart malleable cast irons are annealed in an oxidizing, decarburizing atmosphere. A variant of the whiteheart malleable heat treatment process involving intensive decarburation provides an important third type of malleable cast iron known as whiteheart weldable malleable iron.

The original reason for these definitions of malleable cast irons is the colour and appearance of the fractured section of the material. Blackheart, as a fully ferritic material, has a dark-to-black fracture appearance, whereas whiteheart and also the pearlitic blackheart grades usually exhibit a bright crystalline, white fracture, which is associated with the presence of pearlite in the matrix. Even in wall thicknesses where the whiteheart and weldable grades are fully decarburized, that is, where no pearlite exists, their fractures are a fine crystalline velvety grey.

In previous malleable specifications, three types of malleable cast irons were standardized: blackheart, whiteheart and pearlitic. However, in ISO 5922:2005, 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 (Clause 3 of ISO 5922:2005) malleable cast irons are now subdivided as follows.

a) whiteheart malleable cast iron;

b) blackheart malleable cast iron:

    1) blackheart ferritic malleable cast iron;

    2) blackheart pearlitic malleable cast 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 may, for example still be demanded on old drawings and company specifications.

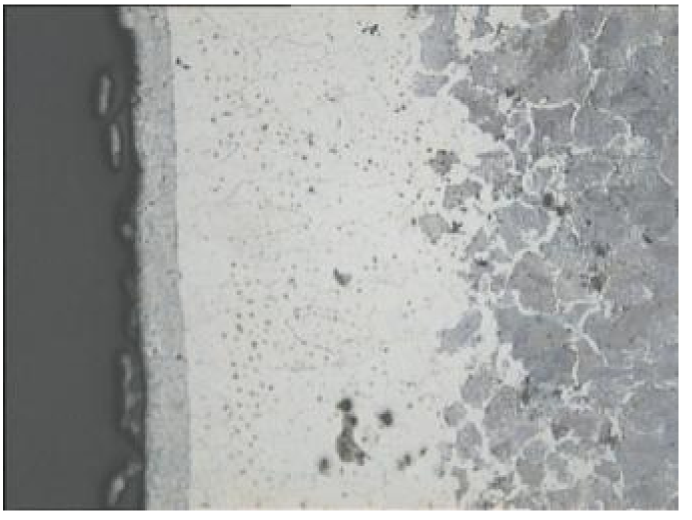
Properties of the malleable cast irons are specified in ISO 5922:2005, Tables 1 and 2. Ten grades of blackheart malleable cast iron are specified with tensile strengths ranging from 275 N/mm^2 to 800 N/mm^2, with corresponding elongations between 10 % and 1 %. Five grades of whiteheart malleable cast irons are specified with tensile strengths between 350 N/mm^2 and 550 N/mm^2 and with elongations between 12 % and 3 %. The malleable cast irons also have useful impact properties; these impact 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 cast irons.

Due to its higher silicon content, the temper carbon nodules in blackheart malleable cast irons are normally smaller and more numerous than those in whiteheart malleable cast irons.

In whiteheart malleable cast 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. They do not contain any graphite or pearlite, whereas wall thicknesses of less than about 6 mm contain a ferritic rim, followed by a transition zone containing increasing percentages of pearlite and temper carbon. Finally, in wall thicknesses greater than 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 cast 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.

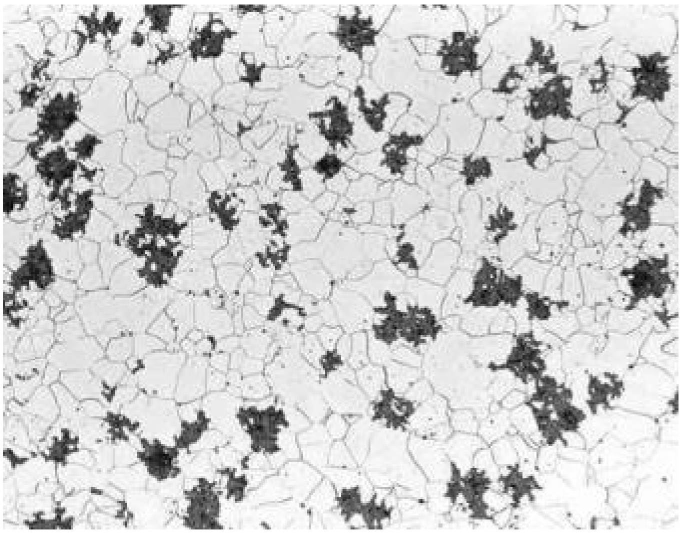


Magnification × 200

Figure 13 — Whiteheart malleable cast iron (left to right: temper zone, ferritic rim, transition zone, core structure)

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

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



Magnification × 200

Figure 14 — Ferritic blackheart malleable cast iron

Magnification × 200

Figure 15 — Pearlitic blackheart malleable cast iron

7.2 Metal composition and carbon equivalent

Metal composition is not specified in ISO 5922. However, blackheart and whiteheart malleable cast 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 cast irons can be optimized for the welding process and to avoid the generation of temper carbon.

Whiteheart malleable cast iron grades have always contained typically about 3,0 % to 3,4 % carbon with 0,4 % to 0,6 % silicon. The composition of the blackheart malleable cast iron grades, however, have changed over the years. Originally, blackheart malleable cast irons contained about 2,0 % to 2,5 % carbon and 0,8 % to 1,0 % silicon and required long heat treatment times to produce the required ferritic matrix. Nowadays the silicon content is 1,25 % to 1,50 %, because the increased silicon level substantially reduces heat treatment times and thus the cost.

Bismuth is added to some grades of blackheart malleable cast irons to ensure a stucture completely free of carbide, particularly in thicker sections and to ensure increased resistance to hot-tearing.

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

The simplified carbon equivalent formula [Equation (1)] is valid for malleable cast irons too and, in the past, CEL 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 analysis. However, the CEL technique has not become superfluous.

7.3 Heat treatment

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

7.3.1 Blackheart malleable cast irons

To avoid excessive scaling, blackheart malleable cast 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 cast irons.

For ferritic blackheart malleable cast 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 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 graphite segregating out of the austenite and accumulating on existing temper carbon nodules. At approximately 720 °C, the castings are removed from the furnace and are quickly cooled to room temperature by blowers. 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 may need 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, there is fast cooling 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 and quenched and tempered blackheart malleable cast irons.

The second annealing stage for the pearlitic grades is operated 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 hours and 5 hours. This 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 may 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 cast iron involves alloying with manganese, which is a pearlite stabilizer. The second-stage annealing cycles must then be modified accordingly. By annealing blackheart malleable cast iron in a neutral atmosphere, the structure is almost uniform throughout all casting sections, unlike whiteheart malleable cast iron, which is annealed in an oxidizing/decarburizing atmosphere.

7.3.2 Whiteheart malleable cast irons

Whiteheart malleable cast irons are produced by annealing the castings in an oxidizing/decarburizing atmosphere using either iron ore or 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 thus created and 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 cast irons are primarily affected by the degree of decarburization, and thinner wall thicknesses generally decarburize faster than thicker ones. Thus, the structures and the mechanical properties are dependent upon the wall thickness. ISO 5922 accommodates this fact by standardizing 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 but 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 with that for blackheart malleable irons. Because of the 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 an air quench, prior to spheroidizing the pearlite. The spheroidizing temperatures for whiteheart malleable cast irons are between 700 °C and 760°C, according to the material grade to be targeted. By lengthening the annealing time, weldable malleable cast irons can be decarburized to a maximum residual carbon content of 0,3 % in wall thicknesses of ⩽ 8 mm, to guarantee unrestricted weldability. Therefore, compared with normal whiteheart malleable cast iron, grade JMW/400-5, the mechanical properties of the weldable malleable grade JMW/380-12S show slightly lower tensile strength, but the elongation and toughness properties are enhanced. By adjusting the malleablizing process to the required intensity of decarburization for weldability, the mechanical properties can be achieved with the chemical composition of a blackheart malleable cast iron (JMW/400-12S). The higher silicon content retards decarburization, but the ferrite strengthening effect thus obtained increases tensile strength and yield strength.

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.

7.4 Graphite form and size

The graphite in malleable cast 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 upon the chemical composition of the as-cast malleable iron and, secondly, the ledeburitic carbide, which is determined by the solidification rate in relation to wall thickness. Graphitization controls the process time of blackheart malleable cast iron castings and this can also be reduced by boron additions, as opposed to whiteheart malleable cast iron castings, which are only controlled by decarburization. The addition of boron decreases the processing time in state-of-the-art production. Thus, blackheart malleable cast iron castings normally show smaller but more numerous temper carbon nodules, mainly influenced by the silicon.

7.5 Mechanical property requirements and the influence of structure

Malleable cast irons have some similarities to spheroidal graphite cast 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 cast 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 % proof stress, 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 should be chosen to validate the castings. The influence of pearlite in the whiteheart malleable cast 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 ten grades of blackheart malleable cast 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 and this process produces oil residues that need to 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 proof 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, free of primary graphite, in the structure of pearlite and carbide, 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 cast irons, for the reasons described in 7.3 and 7.5.

7.6 Impact properties

ISO 5922:2005 does not specify impact properties, although informative data are provided in Annex A of that International Standard. These properties relate to both notched and unnotched test specimens in both whiteheart and blackheart malleable cast irons. Some users demand impact properties in addition to the specified tensile properties, to ensure 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, and the minimum impact properties that must be achieved.

7.7 Section sensitivity

Malleable cast iron castings are manufactured in a range of wall thicknesses from 3 mm to approximately 60 mm.

Because the graphite in malleable cast irons (temper carbon) is formed firstly during annealing, blackheart and also completely decarburized whiteheart malleable cast iron show the lowest section sensitivity of all graphitic Fe-C materials (see 5.3). For whiteheart malleable cast iron, the drastic decarburization is limited to wall thicknesses in the range between 3 mm and 4 mm, that is, 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, that is, with increasing wall thickness, the fraction of the pearlitic core zone increases, as do 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.

7.8 Choosing the grade

The range of appllications for whiteheart malleable cast 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 % proof strength, impact strength, if required), or with other special properties (for example, weldability), allow the correct choice to be made among the five grades of whiteheart malleable cast irons.

Blackheart malleable cast irons are used in a wide range of components. Pipe fittings, which in Europe are still often manufactured in whiteheart malleable cast iron, are traditionally produced in the United States and Japan using ferritic blackheart malleable cast iron. An extra-wide range of applications is delivered to the automotive industry: for example, front-axle suspensions, suspension arms, gearboxes, rear-axle housings, pump cases, cam shafts, 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. Generally, it should be noted that the mechanical properties of blackheart malleable and spheroidal graphite cast irons are very similar. Therefore, the application examples are also very similar.

The ferritic grades JMB/275-5 to JMB/350-10 have the lowest tensile properties, but also have good combinations of strength with ductility because of the low silicon content. This low silicon content also assists in 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 fatigue. 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 cast irons. All have high tensile strengths with little 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 little 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.

8 ISO 17804 Ausferrite spheroidal cast irons

8.1 Overview

Ausferritic spheroidal graphite cast irons are sometimes called austempered ductile irons (ADIs). Their properties are specified in ISO 17804:2005, Tables 1, 2 and A.1.

Table 14 shows the properties of the six grades of ausferritic spheroidal graphite cast irons specified in ISO 17804:2005.

Table 14 — Properties of ISO 17804 cast iron grades

Material designation	**Relevant wall thickness** mm	**Tensile strength** R_m N/mm² minimum	**0,2 % Proof strength** $R_{p0,2}$ N/mm² minimum	**Elongation** A_5 % minimum	**Brinell hardness** HBW guidance values
ISO17804/JS/800-10 ISO17804/JS/800-10RT	$t \leqslant 30$	800	500	10	250 to 310
	$30 < t \leqslant 60$	750		6	
	$60 < t \leqslant 100$	720		5	
ISO17804/JS/900-8	$t \leqslant 30$	900	600	8	280 to 340
	$30 < t \leqslant 60$	850		5	
	$60 < t \leqslant 100$	820		4	
ISO17804/JS/1050-6	$t \leqslant 30$	1 050	700	6	320 to 380
	$30 < t \leqslant 60$	1 000		4	
	$60 < t \leqslant 100$	970		3	
ISO17804/JS/1200-3	$t \leqslant 30$	1 200	850	3	340 to 420
	$30 < t \leqslant 60$	1 170		2	
	$60 < t \leqslant 100$	1 140		1	
ISO17804/JS/1400-1	$t \leqslant 30$	1 400	1 100	1	380 to 480
	$30 < t \leqslant 60$	1 170	To be agreed between the manufacturer and the purchaser		
	$60 < t \leqslant 100$	1 140			

The specified impact properties of ISO17804/JS/800-10RT are shown in Table 15.

Table 15 — Impact properties of ISO17804/JS/800-10RT

Material designation	Relevant wall thickness of the casting t mm	Minimum impact resistance value at room temperature (23 °C ± 5 °C) Mean value of three tests J	 Individual value J
ISO17804/JS/800-10RT	$t \leqslant 30$	10	9
	$30 < t \leqslant 60$	9	8
	$60 < t \leqslant 100$	8	7

The properties of ISO 17804 abrasion-resistant grades are shown in Table 16.

Table 16 — Properties of ISO 17804 abrasion-resistant grades

Material designation	Brinell hardness HBW minimum	Other properties (for information only) R_m N/mm²	 $R_{p0,2}$ N/mm²	 A_5 %
ISO17804/JS/HBW400	400	1 400	1 100	1
ISO17804/JS/HBW450	450	1 600	1 300	—

Interest in these materials started in the 1940s, but serious development work began in America in the 1970s for the production of gears. During the initial development stages, the resultant matrix following austempering was described as bainite, and this definition is still sometimes used. However, the terminology "ausferrite" now predominates because the resulting microstructure is a mixture of ferrite and high-carbon ausferrite.

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

The structure of ausferritic spheroidal graphite cast iron under the microscope is shown in Figure 16 and comprises graphite spheroids in an ausferritic matrix. This is a fairly typical microstructure; differences in the fineness of the microstructural scale are observed in cast irons that are austempered at different temperatures.

Magnification × 200

Figure 16 — Ausferritic spheroidal graphite cast iron

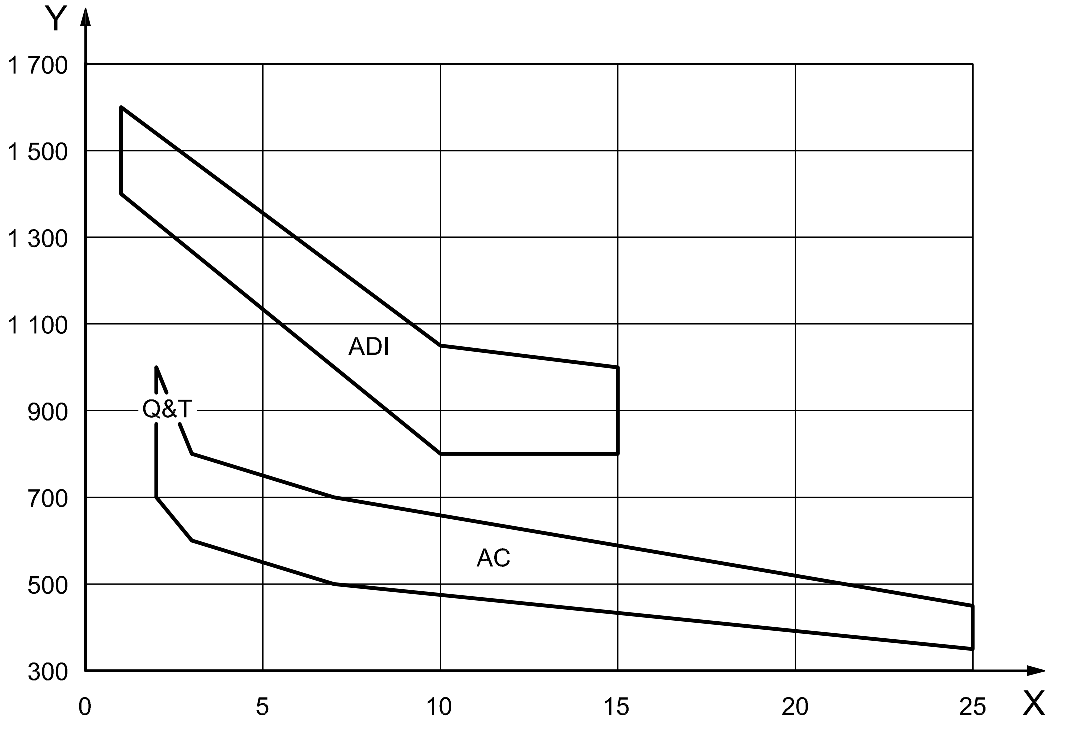
ISO 17804 has five grades of ausferritic spheroidal graphite cast iron with tensile strengths ranging from 800 N/mm^2 to greater than 1 400 N/mm^2 and elongation between 10 % and 1 %. As can be seen in ISO 17804:2005, Table 1, all but the highest-tensile-strength grade have a range of property requirements that depend upon the relevant wall thickness and sample size, as defined in ISO 17804:2005, Table 3. Two grades that require only hardness validation are specified in ISO 17804:2005, Annex A.

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 is essentially a quench and temper process carried out above the martensite start temperature and one that provides a range of properties higher than those obtained from the usual normalizing or quench and temper treatments. This is shown in Figure 17, which illustrates the range of tensile strengths obtained in various grades of spheroidal graphite cast iron materials in the as-cast condition, through the normalizing process and then to a quench and temper treatment. These conditions are compared with the range of properties usually expected from the ausferritic grades.

When quench and temper treatments are carried out, the process involves heating to about 900 °C where the matrix is austenitic, then rapidly quenching the material to below about 200 °C. The latter temperature is called the martensite start temperature (Ms), and defines the point where hard martensite is formed, which can subsequently be tempered between about 250 °C and 450 °C, depending on the final properties required. Figure 18 shows a simplified time-temperature-transformation (TTT) diagram with the abcissa being time and the ordinate being temperature, for a typical quench and temper heat treatment process.

Figure 18 also shows the austempering heat treatment process. The material is heated to the austenitizing temperature of 840 °C to 920 °C and is then rapidly quenched. But instead of quenching to below the temperature t_{Ms} where martensite would be formed, the material is quenched and held, usually in a salt bath, at a temperature above t_{Ms}. During the time that the material is held at the austempering temperature, isothermal transformation to ausferrite occurs. The salt bath temperature has to be varied according to the required material properties, but is normally within the range 250 °C to 425 °C. In the range 250 °C to 325 °C, the higher-strength, lower-ductility materials are produced; above 325 °C, the lower-strength, higher-ductility materials result.



Key

X elongation, %

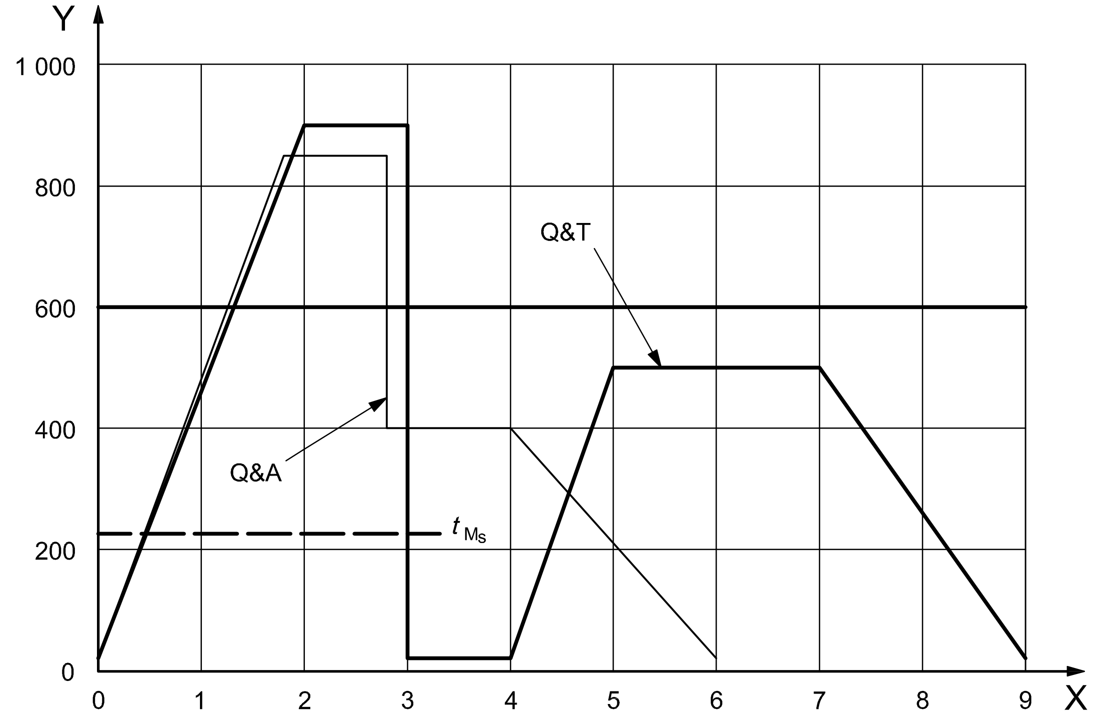
Y tensile strength, MPa

ADI ausferritic spheroidal graphite cast iron

Q&T quenched and tempered spheroidal graphite cast iron

AC as-cast spheroidal graphite cast iron

Figure 17 — Comparisons between typical tensile strength properties of ausferritic and spheroidal graphite cast irons



Key

X time, h

Y temperature, °C

Q&T quench and tempering

Q&A quench and austempering

t_{Ms} martensite start temperature

Figure 18 — Diagram describing the austempering and quench and tempering heat treatment processes

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.

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 copper, manganese, molybdenum and nickel.

8.4 Graphite form and size

The solidification mechanism for spheroidal graphite and ausferritic spheroidal graphite cast irons is identical; therefore, issues relating to the graphite form and size of the ausferritic materials are as described in 5.4.

8.5 Matrix structure and the resultant properties

The properties of ausferritic spheroidal graphite cast irons are dictated by their matrix structure. The matrix structure typically contains ausferrite along with some martensite and ferrite. Martensite is only likely to be present when the material is austempered at a very low temperature. It is the heat treatment that determines the phases present and their fineness; these in turn dictate the material properties. It is important to note that no useful purpose is served to separately specify the material structure in detail, in addition to the material properties and the description of a predominantly ausferritic microstructure, because of the likely difficulties in agreeing on the interpretation of what is present.

8.6 Section sensitivity

Section-sensitivity issues relating to the ausferritic materials are similar to those described in ISO 17804:2005, Clause 3. However, the properties in different sections can be influenced by the heat treatment operation and any alloys that are added to ensure a uniform ausferritic matrix. If alloying is insufficient or heat treatment is not correctly controlled, then there is the possibility of reduced material properties due to pearlite in the core of thick sections.

8.7 Special case of the impact grade

Grade JS/800-10RT has specified impact properties according to ISO 17804:2005, Table 2, with additional informative data given in Annex F of that International Standard. The specified impact properties of this grade are shown in Table 15. It should be noted that the required impact properties relate to a different relevant wall thickness, with impact properties reducing as the section thickness increases due to the section sensitivity. The impact grade has the same tensile properties as grade JS/800-10 in ISO 17804:2005, Table 1, because they are identical materials. RT simply designates that the grade requires impact values to be met; JS/800-RT is specified where service conditions require some impact resistance.

8.8 Special case of the abrasion-resistant grades

Normative requirements for two abrasion-resistant grades of ausferritic spheroidal graphite iron are specified in ISO 17804:2005, Annex A. These grades have useful abrasion resistance but fall outside the range of materials specified in ISO 21988, where alloying has a significant influence on performance for most grades.

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 proof strengths with little 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.

The specified hardness values of these grades are shown in Table 16 along with informative data on tensile strength, proof stress, and elongation.

8.9 Machinability

When machining is required, there has been considerable debate about whether the casting should be machined prior to or after heat treatment, because machinability is impaired when the austempering temperature is low and hardness is high. The debate arises because, when the matrix transformation occurs during the heat treatment operation, there is generally a volume expansion and therefore a dimensional change in the casting. The major concern is the possibility that the dimensions will not remain within tolerance. In castings with complex geometries, the change may not be uniform; variation has been observed from a slight contraction to 0,4 % growth, with growth being the expected norm. This problem needs to be considered when an ausferritic grade is chosen, particularly when dimensional tolerances are small. The problem can be eliminated if the casting is machined after heat treatment, but the machining operation is more difficult and costly. Information on the machinability of the ausferritic grades is given in ISO 17804:2005, Annex I.

8.10 Choosing the grade

The original development work on ausferritic spheroidal graphite cast irons concentrated on improvements to gear technology, but a wide range of components are now produced in the ausferritic materials. The essential feature of the ausferritic grades is the advantageous combination of properties that can be obtained in spheroidal graphite cast iron materials. For example, the lowest-tensile-strength grade in ISO 17804 is JS/800-10 whereas the highest-tensile-strength grade in ISO 1083:2004 is JS/900-2. ISO 17804 includes grades that provide tensile strengths of 1 000 N/mm^2 or more with appreciable elongation.

These higher-tensile-strength ausferritic spheroidal graphite cast iron grades are ideal when very high strengths are required for the application. They find applications where steels have been used historically, because there are cost savings to be made in both casting and machining costs. These cast irons are also lighter and quieter in service, because of the higher damping capacity. Typical applications are gears and drive pinions, crankshafts and differential spiders, axle boxes and spring components. The choice of grade depends upon the service requirements and design stresses. Tensile properties ranging from greater than 800 N/mm^2 to greater than 1 400 N/mm^2 in the engineering grades, in sections up to 30 mm, are available.

The special-purpose abrasion-resistant grades of ausferritic spheroidal graphite cast 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, but generally these grades have been successfully used for digger teeth on earthmoving equipment, rock guards, and wear shoes where considerable savings have been possible in comparison with steels.

9 ISO 21988 Abrasion-resistant cast irons

9.1 Overview

The properties of abrasion-resistant cast irons are specified in ISO 21988:2006, Tables 1, 2 and 3. Abrasion-resistant cast irons comprise a range of materials with properties that enable resistance to wear. Typical applications are castings utilized in earthmoving, rock crushing, mineral extraction and processing. They are also used in other abrasive environments, such as shot-cleaning plants, and in the transportation of abrasive liquids (e.g. the pumping of seawater carrying debris such as sand, or abrasive slurries).

ISO 21988:2006 divides the materials into three categories:

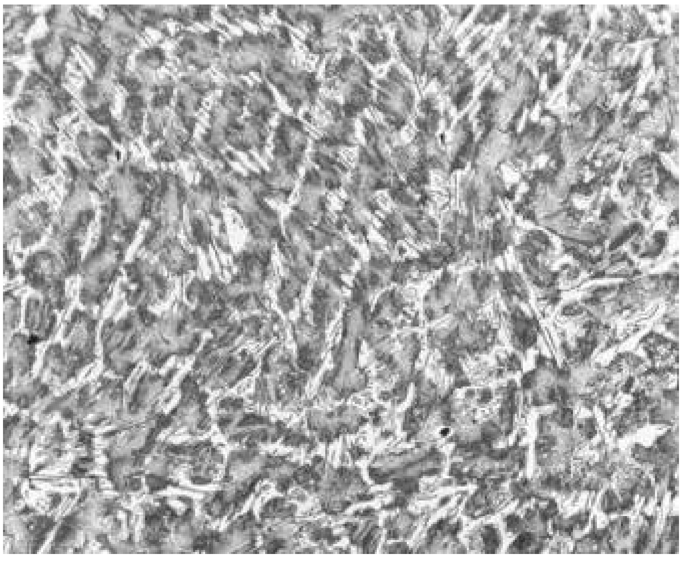
- unalloyed or low-alloy abrasion-resistant cast iron;
- nickel-chromium abrasion-resistant cast iron (commonly known as Ni-hard);
- high-chromium abrasion-resistant cast iron.

Unlike the other cast irons, abrasion-resistant cast irons are graphite-free; some of the carbon is dissolved in the matrix with the majority present as carbide. All of the grades contain chromium, with the lowest hardness grade specifying a maximum of 2 % Cr (but normally containing more than 0,5 % Cr in practice) and the highest hardness grade specifying a maximum of 40 % Cr. Complex iron-chromium carbides are therefore present; the complexity of the carbides inceases as the chromium content is raised.

The matrix in which the carbides are held varies with the grade. In the lowest hardness grade, categorized as unalloyed or low-alloy grades, the matrix is pearlitic. Those nickel-chromium and high-chromium grades of abrasion-resistant cast irons contain a martensitic matrix, perhaps also with small amounts of other transformation products and retained austenite. The martensitic matrix of the nickel-chromium grades is obtained from the nickel content, whilst the martensitic matrix in the high-chromium grades is obtained from both the nickel and molybdenum contents of the alloy.

The unalloyed and low-alloy grades are normally supplied as-cast, but the properties and performance of the nickel-chromium and high-chromium grades are enhanced by heat treatment. Costs also increase as higher levels of alloying elements are added and heat treatment is applied, so it is necessary to examine the cost/benefit relationship when choosing a particular grade.

Typical structures of the three categories of material are illustrated in Figures 19 to 21.



Magnification × 100

Figure 19 — Low-alloy abrasion-resistant cast irons

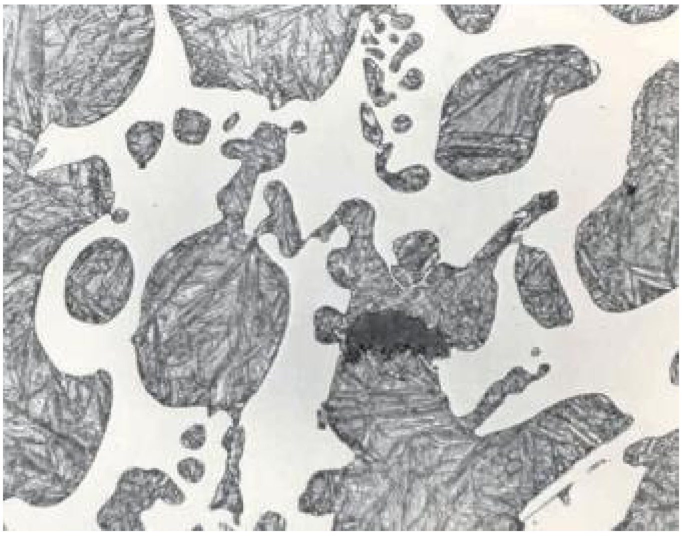


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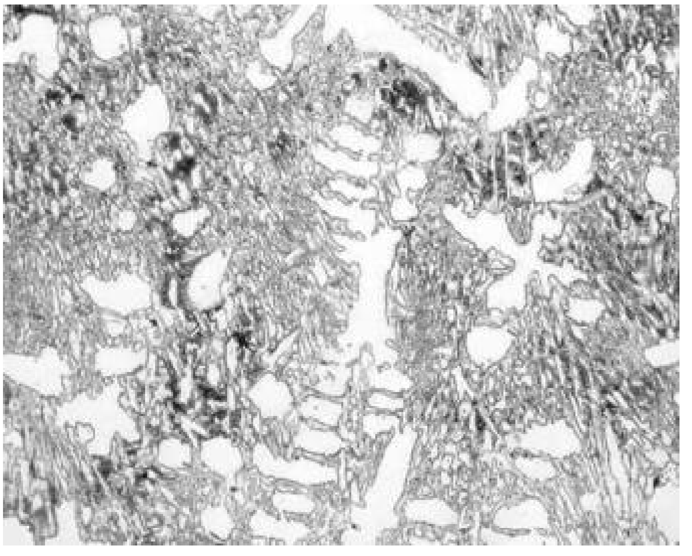
Figure 20 — Nickel-chromium abrasion-resistant cast irons (Ni-hard)



Magnification × 200

Figure 21 — High-chromium (28 %) abrasion-resistant cast irons

9.2 Effects of structure on properties

For abrasion-resistant cast irons in ISO 21988, the only specified mechanical property is hardness, which is normally measured as Brinell hardness. This measurement is undertaken using a 10 mm diameter tungsten carbide ball at a 3 000 kg load. The hardness requirements range from a minimum of 340 HBW for the unalloyed and low-alloy grades to a minimum of 630 HBW for the nickel-chromium grades. It should be understood that the measured Brinell hardness is a composite hardness of the material phases (comprising the carbide, the amount present and the matrix surrounding it) under the ball during test. The individual phases each have a different hardness, as shown in Table 17.

Table 17 — Typical hardness of constituents in abrasion-resistant cast irons

Typical hardness constituents[a]	
Carbides	**HV 30**
Fe_3C (iron carbide)	840 to 1 100
$(FeCr)_3C$ (iron-chromium carbide)	1 060 to 1 240
$(FeCr)_7C_3$ (iron-chromium carbide)	1 500 to 1 800
Matrix	**HV 30**
Ferrite	70 to 200
Pearlite	240 to 460
Austenite (high chromium)	350 to 600
Martensite	500 to 1 000

[a] Vickers HV is more commonly used for individual phases, particularly those with a high hardness.
Brinell HBW is normally confined to cast irons having composite structures.

It can be seen from Table 17 that, as the carbide-based compound form changes, the material increases in hardness, as does the matrix, and it is necessary to understand the following fundamentals.

— The unalloyed and low-alloy grades contain mainly Fe_3C with some $(FeCr_3)C$ in a pearlitic matrix.

— The nickel-chromium alloy grades with chromium levels up to about 5 % contain mainly $(FeCr_3)C$, with some $(FeCr_7)C_3$ in a martensitic matrix.

— The nickel-chromium alloy grades with chromium levels above 5 % contain mainly $(FeCr_7)C_3$, with some $(FeCr_3)C$ in a martensitic matrix.

— The high-chromium alloy grades predominantly contain $(FeCr_7)C_3$ in a martensitic matrix.

Thus, as the chromium content increases and the matrix changes from pearlite to martensite, the hardness and wear resistance are increased. The matrix is much softer than the carbides; the function of the matrix is essentially to assist in the overall toughness and wear resistance of the material by holding the carbide *in situ* through the working life of the material.

9.3 Chemical composition

ISO 21988 is one of two International Standards for cast iron that specify chemical composition (the other is ISO 2892 for austenitic cast iron) that specify chemical composition. In the case of all the others, chemical composition is at the discretion of the producer.

The chemical compositions required for each grade are specified in ISO 21988. ISO 21988:2006, 7.1 contains a note that other elements may be present, provided that they do not adversely affect performance.

9.4 Unalloyed and low-alloy cast irons

Unalloyed and low-alloy cast irons are uncomplicated materials with a low silicon content to produce eutectic carbide. Their properties can be enhanced by the presence of chromium up to a maximum of 2 %. As the casting section thickness increases, less silicon and more chromium are required to maintain a eutectic carbide structure that contains no free graphite. Both grades have the same composition range, which is specified in ISO 21988:2006, Table 1.

9.5 Nickel-chromium cast iron

The nickel-chromium cast irons essentially comprise two grades of material, which nominally contain 4 % nickel with 2 % chromium, and 5 % nickel with 9 % chromium. The latter grade (commonly called eutectic Ni-hard) has a more discontinuous carbide structure and is thus tougher. Each of these grades has a range of carbon contents, the choice of which depends upon the requirements for hardness, toughness, and impact resistance. A low carbon content provides toughness and resistance to repeated impact, whereas a high carbon content provides higher hardness in a material that is more brittle and less impact-resistant. The composition ranges are specified in ISO 21988:2006, Table 2.

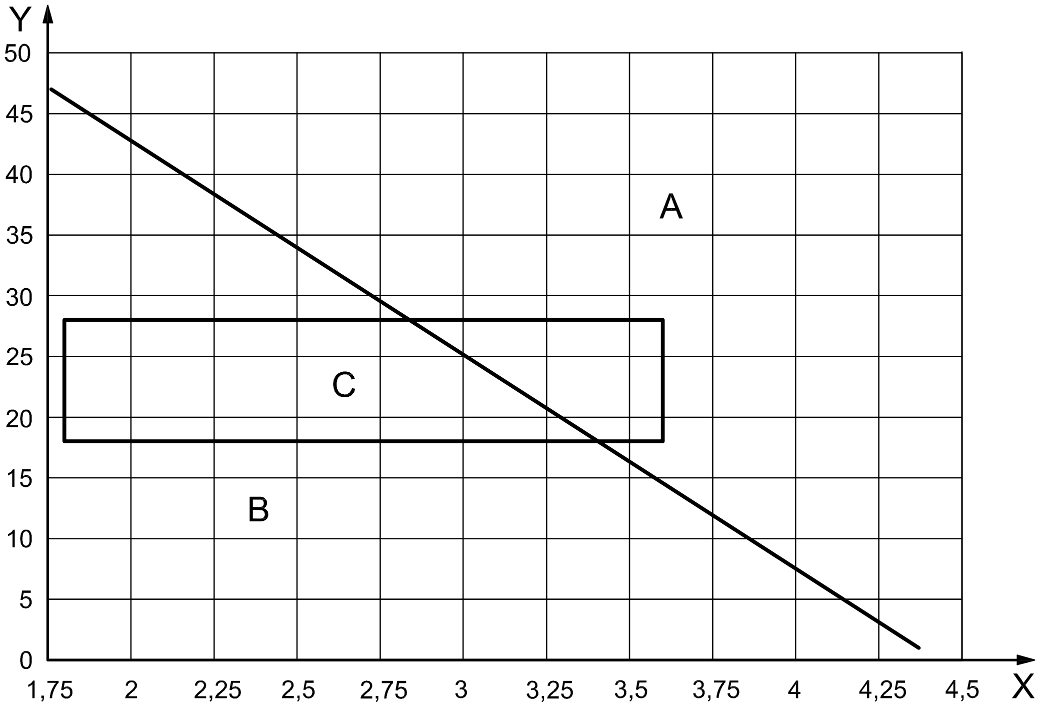
9.6 High-chromium cast iron

The high-chromium cast irons comprise five grades of material with increasing chromium content. The first four grades have three different carbon ranges, for the same reasons given for the nickel-chromium grades. The fifth grade, containing 30 % to 40 % chromium, is specified with only one carbon range. For all of these grades, an increasing carbon content can be expected to raise hardness at the expense of toughness and brittleness. The composition ranges are specified in ISO 21988:2006, Table 3.

9.7 Influence of chemical composition on properties and performance

The influence of carbon and chromium is not particularly great in the unalloyed and low-alloy grades. The main effect of these elements is to ensure a structure comprising carbides and pearlite without free graphite. However, carbon and chromium provide the major influence on properties and performance of the nickel-chromium and high-chromium grades. Additions of nickel and molybdenum also assist in the formation of hard martensite in the matrix.

The carbon-chromium cast irons with a low carbon content are tough. As the carbon increases, greater amounts of carbide are formed. Thus, the material becomes harder and more brittle until a continuous carbide network is present. A further increase in the carbon content has less effect on toughness until eventually massive carbides are formed which significantly increase brittleness. This begins to occur at the eutectic point, approximately defined by C % + (0,056 Cr %) = 4,4. Irons that are greater than 4,4 are hypereutectic, and those that are less than 4,4 are hypoeutectic. The majority of the irons are hypoeutectic; only those with both a high carbon and high chromium level are hypereutectic. It is important to understand that this latter range of materials, because of their brittleness, is unlikely to perform well in circumstances that involve significant impact in service (see Figure 22).



Key

X carbon content, %

Y chromium content, %

A hypereutectic

B hypoeutectic

C normal range of high-chromium cast irons

Figure 22 — Position of the eutectic point in relation to different carbon and chromium levels, the hypereutectic materials being on the right-hand side of the line

9.8 Section sensitivity

Abrasion-resistant cast irons are not section sensitive in the same way as some of the graphitic cast irons because there is no graphite present, but there are still material and property changes associated with the varying solidification and cooling rates in different section thicknesses. In thicker, more slowly cooling sections, the carbide and the matrix constituents both tend to be coarser, which lowers hardness. This may necessitate adjustments to the carbon and chromium levels, in conjunction with increases in the amounts of nickel and molybdenum, to maintain the required matrix hardness and thus the composite Brinell hardness.

Designers should avoid large section changes in the castings and ensure that section interchanges incorporate large radii.

9.9 Heat treatment

The unalloyed and low-alloy cast irons are not normally heat treated, but rather are used in the as-cast condition, because a heat treatment operation rarely improves their performance in service. Conversely, the nickel-chromium and the high-chromium cast irons are frequently heat treated because a significant improvement in service performance can be obtained. There are exceptions: for example, high-chromium cast irons with austenite in the matrix are sometimes used in the as-cast condition, on the basis that the austenite work-hardens to martensite, although field trials have indicated that service performance is not as good as that obtained from martensite generated by heat treatment. Another important point about the austenite in the as-cast matrix of both nickel-chromium and high-chromium cast irons is that, as it work hardens, there is a volume expansion. This creates internal pressure and stress close to the working surface of the component and, particularly if there is an impact application, the surface can break away. Heat treatment transforms much of the austenite to martensite before the component is put into service and the chances of this problem occurring are much reduced.

There are disadvantages to heat treatment, because the abrasion-resistant cast irons are intrinsically brittle and careless heating or cooling in the heat treatment cycle can result in cracking. Thus, with the development of cubic boron nitride cutting tools, some users have carried out cost-benefit trials, looking at the complete casting life cycle, to see if as-cast and machined components are cost effective. Generally, however, heat treatment is the normal route.

In the as-cast condition, the structures of both the nickel-chromium and high-chromium cast irons comprise complex carbides and martensite with retained austenite. The reason for heat treating the nickel-chromium cast irons is either to stress relieve the material at relatively low temperatures or to improve the impact resistance, in which case, a higher temperature operation is carried out, followed by the stress-relieving operation.

The high-chromium cast irons are more complex, because in the as-cast condition the matrix in thin sections can be austenitic, can contain some martensite in medium sections, and can be pearlitic in heavy sections. The objective is to heat treat in order to produce a predominantly martensitic matrix; this objective is achieved by treatment at around 1 000 °C for a time appropriate to the section thickness. A subsequent tempering operation can also be carried out to transform some of the remaining retained austenite, but the main effect of tempering is to provide stress relief.

If the castings are to be used without machining, producers of castings usually heat treat their own products, either by annealing for machining or by hardening and tempering. Manufacturers are thus familiar with the dangers of rapid heating and cooling with regard to cracking. When the casting is to be delivered in the annealed condition for machining, ISO 21988 places the responsibility for subsequent hardening and tempering upon the purchaser. It is crucial that the purchaser, or the purchaser's subcontractor, is fully aware of the fact that cracking will occur if the heating and cooling cycles are too rapid.

Typical heat treatment cycles are given in Table 18. It must be emphasized, however, that heating cycles, times at one temperature, and cooling cycles depend on the casting thickness and the complexity of the component’s geometry.

Table 18 — Typical heat treatments for abrasion-resisting cast irons

Material grade	Reason for heat treatment	Primary operation	Secondary operation
Unalloyed and low-alloy grades — heat treatment is not normally applied			
Nickel-chromium grades			
4 % Ni 2 % Cr	Stress relief	8 h to 16 h at 250 °C to 300 °C	~
	Improved impact resistance	4 h to 6 h at 425 °C to 475 °C	8 h to 16 h at 250 °C to 300 °C
5 % Ni 9 % Cr	Improved toughness	6 h to 12 h at 800 °C to 850 °C	~
	Improved impact resistance	8 h to 16 h at 800 °C to 850 °C	8 h to 16 h at 250 °C to 300 °C
High-chromium grades			
All	Soft annealing	1 h/25 mm of section thickness at 920 °C to 975 °C	Slowly cool[a] to 810 °C and then to 600 °C at > 55 °C/h, then to room temperature
All	Hardening	4 h to 12 h at 900 °C to 1 050 °C	Cool to room temperature in still or blown air
All	Tempering	4 h to 6 h at 425 °C to 475 °C	Cool to room temperature in still air

[a] In all cases with abrasion-resisting irons, heating and cooling must be carefully controlled to avoid cracking.

9.10 Choosing the material grade

The selection of the appropriate chromium and carbon grade can be difficult and dependent upon the application. Aspects such as wear resistance, impact resistance (therefore brittleness), and corrosion all need to be considered.

The unalloyed and low-alloy cast iron grades can be considered a low-cost abrasion-resistant material that provides moderate wear resistance in circumstances where the service conditions involve no significant impact or corrosion. This is mainly because the weak pearlitic matrix cannot support the brittle carbides and because corrosion resistance is low; applications are therefore limited. An example of effective use would be the material operating statically in lubricated conditions of sliding wear against a material softer than itself, with no contamination with hard, abrasive substances.

The nickel-chromium and high-chromium cast irons are used in applications that are significantly more arduous. It is not always easy to determine the best material under such conditions, particularly if such conditions are changeable: for example, the crushing and grinding of minerals where particle hardness and size may be variable. With these grades, it is preferable (if possible) to conduct a wear rate/replacement evaluation that takes into account some of the hidden costs, such as downtime, in continuous operations. It may be more economical to use a less wear-resistant, and thus less costly, material and to replace it more frequently.

Silica, in one form or another, is the most common material requiring the use of abrasion-resistant materials for processing. Typically, silica is not hard enough to scratch $(FeCr_7)C_3$ carbides, but it can scratch $(FeCr_3)C$ carbides and will scratch martensite. Thus, with silica and other feedstock of similar or greater hardness, the application would almost certainly favour the higher-chromium-containing grades of the nickel-chromium materials, or the high-chromium materials. Of these two, the high-chromium nickel-chromium materials are often preferable. This is because the high-chromium materials can contain up to 15 % of retained austenite, whereas it is usually lower in the nickel-chromium cast irons. Austenite work-hardens to martensite in service, and the volume expansion may result in surface spalling. The high-chromium cast irons are commonly used where there is a combination of wear and corrosion in service. Wear and corrosion in combination often occur in situations where wet abrasion is present: for example, the processing of slurries such as those containing acidic compounds. Here the material surface is constantly exposed to the opportunity for corrosion, through wear. Generally, the high-chromium materials have the best combination of hardness and toughness, but care needs to be taken to ensure that the application is not sufficiently severe for breakage to occur, because the material is brittle, particularly at high carbon levels.

10 ISO 2892 Austenitic cast irons

10.1 Overview

The property requirements of austenitic cast irons are specified in ISO 2892:2007, Tables 1 to 4. The austenitic cast irons are principally designed to provide good heat and corrosion resistance. Some of the grades also 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 % nickel means that all grades are commonly known as Ni-resists.

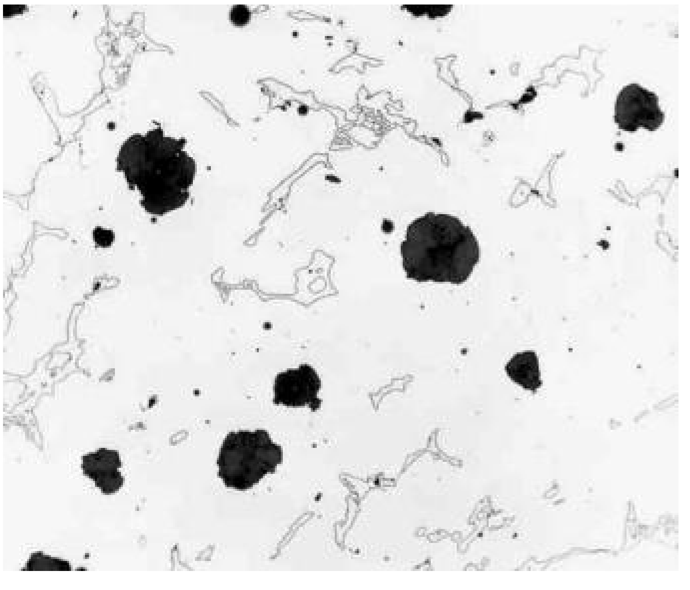
The high level of nickel and other elements in the material stabilizes the austenite, such that instead of transforming to pearlite and/or ferrite when the material solidifies and cools, austenite is retained down to very low temperatures. The grades therefore have an austenitic matrix, which can also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

The austenitic cast irons are graphitic irons and, depending upon the grade, can contain either flake or spheroidal graphite. The original research on the austenitic cast iron materials involved manufacture of grades with flake graphite forms, because it preceded the development of spheroidal graphite irons in the 1940s. Spheroidal graphite containing austenitic cast 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 in service.

Typical structures are shown in Figures 23 and 24. The magnifications are slightly different, but the matrix structures are the same. The particular grades shown in Figures 23 and 24 comprise austenite and chromium rich carbides; the carbides would be absent in the low-chromium grades.

Magnification × 200

Figure 23 — Flake graphite austenitic cast iron



Magnification × 300

Figure 24 — Spheroidal graphite austenitic cast iron

10.2 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 390 N/mm^2. The maximum value in practice rarely exceeds 420 N/mm^2. Furthermore, the flake graphite grades are specified to have minimum tensile strengths of 140 N/mm^2 and 170 N/mm^2; the maximum value in practice rarely exceeds 200 N/mm^2. 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.

10.3 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 may 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 %, 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 cast irons if the material is strongly hypereutectic and to minimize casting defects in the material. The simplified carbon equivalent formula [Equation (1)] ignores other elements such as nickel, because at trace levels their influence on CEL values is insignificant. All elements influence CEL to some extent, but nickel has the greatest influence. With nickel at levels between 12 % and 36 % across the range of grades and with a high carbon content, the material can be strongly hypereutectic. Thus, the carbon content is controlled to avoid a hypereutectic structure.

The silicon content ranges in each grade are deliberately wide to ensure the avoidance of excessive carbides 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 % and 6 % silicon to improve high-temperature growth and scaling properties.

Nickel is essential to produce the stable austenitic matrix. In pure iron-nickel irons, 30 % 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 a strong austenitizing element. However, copper can be added only when nickel is present, because copper increases the solubility of nickel. Also, the solubility of copper is lower in the spheroidal graphite grades than in the flake graphite grades. Thus, attempts to reduce costs by replacing nickel with copper are limited. As a general rule, 1 % nickel increases the solubility of copper by 0,4 % in flake graphite irons. JLA/XNi15Cu6Cr2, the flake graphite grade in the engineering grades, illustrates this and explains why the level of copper in all of the other grades is limited to 0,5 %.

Manganese is an austenite stabilizer with good solubility. Manganese is therefore 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, however, before unacceptable amounts of carbide are produced and mechanical properties decline. Only about 0,5 % 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 % 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 % and 0,20 % niobium.

10.4 Effect of composition on carbon equivalent

The carbon equivalent formula shown in 4.3 is a shortened version of the complete equation. This is because, in unalloyed irons, the effects of elements other than carbon, silicon, and phosphorus are too small to be significant. For the ISO 2892 austenitic cast irons, however, the much higher levels of elements such as nickel and manganese have pronounced effects upon carbon equivalent values. For this purpose, the full formula in Equation (2) should be adopted.

$$\mathrm{CEL} = \mathrm{C} + \frac{\mathrm{Si}}{4} + \frac{\mathrm{P}}{2} + \frac{\mathrm{Mn}}{6} + \left(\frac{\mathrm{Cr+Mo+V}}{5}\right) + \left(\frac{\mathrm{Ni+Cu}}{15}\right) \tag{2}$$

With normal carbon contents, such as those used in the production of the ISO 1083 spheroidal graphite iron castings, the carbon equivalent of the ISO 2892 austenitic materials would be strongly hypereutectic (greater than CEL 4,25). This could result in a number of undesirable defects, which is the reason why the carbon contents of the ISO 2892 materials are at the low levels specified in the standard.

10.5 Graphite form, distribution and size

As with other graphitic cast irons, the graphite form and size of austenitic cast irons can be specified according to the reference diagrams shown in ISO 945-1. Good inoculation practice will ensure an optimal graphite form, whilst at the same time controlling the amount of carbide present, as a function of the chromium level.

It is important to note that the production of spheroidal cast iron graphite austenitic grades results in graphite nodules that are normally less spherical and more ragged than would be seen in an unalloyed ISO 1083 spheroidal graphite cast iron. This anomaly is more severe in thick sections where solidification is slower.

Purchasers who specify the nodule shape in terms of certain minimum percentages of Forms VI and V for unalloyed irons, and then need to develop internal specifications for austenitic cast iron castings, will probably need to modify their requirements, depending on the section thicknesses involved. Graphite size is not likely to differ in austenitic cast irons compared to in unalloyed materials, but nodule numbers will differ. Where purchasers' specifications define nodules/mm^2 in a certain agreed location of the castings, it must be appreciated that the nodule number present will be substantially lower in a spheroidal graphite austenitic cast iron having a carbon content of less than 3 % than would be observed in an unalloyed spheroidal graphite cast iron typically containing 3,5 % carbon.

Section sensitivity occurs in the austenitic cast irons, but there are differences between the flake graphite and spheroidal graphite grades. The flake graphite austenitic grades follow the section-sensitivity situation of the grey cast iron grades of ISO 185, although to a lesser degree because of the lower carbon content and thus smaller graphite volume of the austenitic material. In the same way, the spheroidal graphite austenitic grades follow the section sensitivity of spheroidal graphite grades of ISO 1083, but again to a lesser extent because of the lower carbon content. The situation with the spheroidal graphite austenitic grades is also compounded by the fact that the graphite nodules become less rounded and more ragged in the slow-to-solidify heavy sections, as mentioned above.

Engineers and designers who wish to specify particular mechanical properties and structures in varying section thicknesses should take this into account and agree upon the requirements at a defined location in the casting.

10.6 Heat treatment

ISO 2892:2007, 7.3, specifies the requirements for heat treatment; it must be understood, however, that these requirements are limited, because the stable austenitic matrix precludes the opportunity to enhance mechanical properties. Thus, the applicable heat treatments are confined to providing stress relief and high-temperature stabilization. Stress relief is applied to remove those stresses introduced during the cooling of castings with complex geometry, whereas stabilization is used where castings are required to maintain close tolerances when operating at temperatures of 500 °C or above. Typical cycles are given in ISO 2892:2007, Annex B.

10.7 Choosing the material grade

The choice of material grade for an application is usually more dependent upon the heat and corrosion resistance, magnetic properties, ductility, and impact resistance, rather than the tensile properties, even though tensile properties are specified. It is important to understand that no individual grade can possess all of these properties to advantage. As an example, it is not possible to obtain good heat and corrosion properties and at the same time good impact properties at low temperatures, because one requirement needs the presence of chromium in the material, whilst the other does not.

Table 19 gives the important properties of each grade. This information helps in choosing an appropriate grade for the specific application under consideration.

Table 19 — Properties of the austenitic cast irons

No.	Material designation	Properties
1	ISO 2892/JLA/XNi15Cu6Cr2	Low-strength flake graphite grade with considerably better heat and corrosion properties than **8**. Good in saline, alkaline and dilute acidic environments. Non-magnetizable.
2	ISO 2892/JSA/XNi20Cr2	The most common grade produced, providing heat and corrosion resistance up to 750 °C. Non-magnetizable at low-chromium levels.
3	ISO 2892/JSA/XNi23Mn4	High ductility and impact resistance to sub-zero temperatures. Inappropriate where good heat, corrosion and erosion properties are required. Non-magnetizable.
4	ISO 2892/JSA/XNi20Cr2Nb	Identical to **2** but with the addition of niobium to improve weldability.
5	ISO 2892/JSA/XNi22	Low-chromium grade with good impact resistance to sub-zero temperatures. Heat and corrosion resistance less than for **2**. Non-magnetizable.
6	ISO 2892/JSA/XNi35	High-nickel material with the lowest thermal expansion of all the grades. Good shock resistance.
7	ISO 2892/JSA/XNi35Si5Cr2	Higher nickel and chromium with a high silicon level for superior growth and scaling properties up to 850 °C. Good thermal shock resistance and low expansion.
8	ISO 2892/JLA/XNi13Mn7	Least expensive low-strength flake graphite material with high manganese content. Not suitable in conditions requiring heat, corrosion and erosion resistance. Mainly used as a non-magnetizable material.
9	ISO 2892/JSA/XNi13Mn7	The same as **8** but with higher-strength spheroidal graphite providing superior mechanical properties. Mainly used as a non-magnetizable material.
10	ISO 2892/JSA/XNi30Cr3	Higher chromium level providing heat, corrosion and erosion resistance to 800 °C. High temperatures enhanced by a molybdenum addition.
11	ISO 2892/JSA/XNi30Si5Cr5	Heat resistance, corrosion and erosion properties superior to **2** and **10**. Can be superior to **7** in applications where erosion is a particular problem.
12	ISO 2892/JSA/XNi35Cr3	Similar to **6** but with superior thermal properties due to the chromium addition. High-temperature properties enhanced by a molybdenum addition.

Annex A
(informative)

Glossary of terms related to cast iron International Standards

Table A.1 — Glossary of terms

Alloying	Addition of elements such as copper, nickel and molybdenum to enhance properties.
Annealing	Heat treatment process that breaks down iron carbide and pearlite to produce ferrite.
Ausferrite	A mixture of austenite and ferrite obtained by an austempering heat treatment, with a higher carbon content than that contained in ferrite.
Austenite	A matrix phase that occurs in cast irons immediately upon solidification, but which then transforms to pearlite and/or ferrite on subsequent cooling. It can be retained down to very low temperatures if appropriate elements are added to stabilize its presence.
Bainite	A transformation product intermediate between pearlite and martensite.
Carbon equivalent	Formula indicating the carbon and silicon contents of molten cast iron by thermal analysis.
Compacted graphite	Stubby form of graphite flakes providing material properties in between those of the grey and spheroidal graphite cast irons.
Ductility	Percentage elongation measured on the tensile test piece following testing.
Eutectic	The point at which elements are present at a level where the lowest solidification temperature is reached.
Eutectic cell	Solidification mechanism in grey cast iron where cells form, each with its individual internal graphite structure. These ultimately coalesce to form a uniform material.
Ferrite	Phase in the matrix of ferrous materials. In cast irons, almost pure iron containing some silicon but very little carbon.
Graphite flakes	Two-dimensional appearance of the graphite form in grey cast iron, looking at the material structure through a microscope.
Graphite form	Descriptor of graphite shape, which can define material properties. Shown in ISO 945-1.
Graphite size	Size of the graphite as defined in ISO 945-1. Fine graphite normally provides better properties than coarse graphite.
Hardening	Heat treatment process that generally produces martensite in the matrix.
Heat treatment	Thermal processes that remove internal stress or enhance properties.
Hypoeutectic	Below the eutectic.
Hypereutectic	Above the eutectic.
Inoculation	Technique of adding silicon to molten iron to enhance the material properties.
Iron carbide	Iron and carbon in a combined form, e.g. Fe_3C.
Iron chromium carbide	A complex carbide principally found in abrasion-resisting irons.
Martensite	Hard needle-like phase in a matrix resulting from alloying or heat treatment.
Matrix	Structural phases surrounding the graphite in graphitic cast irons and carbide in abrasion-resisting irons. Examples are ferrite, pearlite, ausferrite, austenite and martensite.
Nodularity	Percentage of graphite spheroids determined in a spheroidal graphite cast iron structure.
Pearlite	Phase in the matrix of ferrous materials, comprising laths of ferrite and iron carbide.
Quenching	Rapidly cooling castings, normally in oil, to produce martensite.

Table A.1 (*continued*)

Relevant wall thickness	Wall thickness in a casting that the purchaser considers most important with regard to performance and properties.
Section sensitivity	Change in material properties that occurs due to variations in the solidification and cooling speeds of cast iron poured into different wall section thicknesses.
Softening	Heat treatment process confined to abrasion-resistant irons to soften the as-cast matrix to allow machining.
Spheroidal graphite	Graphite in spheroidal graphite iron that is present as spheroids as opposed to flakes.
Stress relieving	Low-temperature heat treatment process removing stress without affecting structure.
Tempering	Heat treatment process that enhances properties or relieves stress after hardening.
Temper carbon	Graphite form found in malleable iron with the appearance of “ragged” spheroids, also known as temper carbon nodules.
Trace elements	Elements such as copper, nickel, molybdenum, vanadium and titanium that are present in small amounts. Such elements may also be added for alloying purposes.

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1) Some of References [11] to [27] are quite old. This is because the technology to which they relate was researched many years ago, although it is not necessarily appreciated by those that use cast iron materials as opposed to those that produce them. The fundamentals have not changed and are relevant to the information provided in this Technical Report.

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