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Review

Casting Defects in Sand-Mold Cast Irons—An Illustrated Review with Emphasis on Spheroidal Graphite Cast Irons

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Abstract: Cast irons are known to be easy to shape by sand casting due to their high eutectic fraction. Despite this fact, together with cost benefits, obtaining good quality castings is not an easy task, although it depends on the level of defects allowed in each case. Casting defects are here reviewed and classified into three classes according to their known main origin: (1) related to the sand mixtures used to make the molds; (2) associated with the mold design and the geometry of the castings; (3) related to the casting alloy itself. The present work is an illustrated description of these defects, with details of their origin when well established, and of known remedies. In addition, an attempt has been made to clarify the possible cross-effects of the above three origins.

Keywords: casting defects; sand molding; cast irons

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Citation: Sertucha, J.; Lacaze, J. Casting Defects in Sand-Mold Cast Irons—An Illustrated Review with Emphasis on Spheroidal Graphite Cast Irons. *Metals* **2022**, *12*, 504. https://doi.org/10.3390/met12030504

Academic Editors: Alexander McLean and Cristiano Fragassa

Received: 28 January 2022
Accepted: 5 March 2022
Published: 16 March 2022

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1. Introduction

Casting defects are any anomaly that compromises the mechanical strength, tightness or even the external appearance of the parts. Therefore, any alteration in the intended geometry or physical integrity of a part, the presence of which could potentially impair its performance, could be defined as a defect. The glossary of terms of the 1988 ASM handbook [1] defines a defect as "*a discontinuity whose size, shape, orientation, or location makes it detrimental to the useful service of the part in which it occurs*" (definitions from the 1988 ASM casting handbook will appear in italics all along this paper). With such a definition, all parts have defects and can be rejected or not based on pre-defined criteria. Typically, the criteria used to consider an "alteration" or "irregularity" to be a defect that invalidates the casting (i.e., significantly affects its functionality) are agreed upon between the caster and the customer.

As with the wide variety of existing casting processes and castings, a large number of different casting defects have been reported. In addition, a given type of defect may have different characteristics depending on the geometry of the casting, the timing of the casting process, or the foundry. Although such differences can lead to diagnostic errors, a correct description can help to understand the causes and formation mechanisms of each defect. This work is, therefore, an attempt to group and classify the most common defects found in sand castings in order to be a guide and with which foundrymen can orient their diagnoses based on visual defect recognition. Other classifications of casting defects are certainly possible and valid, and the authors have here prioritized these criteria based on their foundry practice.

A priori, it should be possible to find whether the origin of a casting defect is related to the mold or to the cast alloy. Because of the strong interactions between the melt and the mold during casting, this classification cannot be exact, and we hope that this will be clarified in this work. The defects described in this catalog have been classified according to their main origin in three successive sections dealing with the sand (Section 2), the mold (Section 3) and the cast alloy (Section 4). Although the emphasis in this work is

on spheroidal graphite cast irons (SGI), reference will be made here and there to lamellar graphite cast irons (LGI) when the defect is more pronounced there and allows its origin in SGI to be understood. It will be recognized, however, that it is sometimes more difficult to identify than to describe casting defects, and that confusion is possible because of the similar appearance of many defects whose origins differ.

This compilation is descriptive, meaning that no attempt has been made to consider modeling or simulation results. This work has benefited from classical casting handbooks [1,2], the cast iron technology monograph by Elliott [3] as well as the literature compilation offered by Hecht [4].

2. Sand-Related Defects

Sand casting defines a metal casting process in which molds and cores made from sand mixtures are used (Figure 1). These mixtures are first prepared by mixing sand grains with binders, and then they are squeezed against a pattern or shot into a pattern box to obtain the corresponding cavities in a compacted sand mold, or to create a core with the required shape. The terms green sand and chemically bound sand differentiate the nature of the binders used to provide strength to compacted sand mixtures. In the case of green sand, the binders are natural clays (bentonites) and water that are typically mixed in 2 to 5 ton batch mixers with recycled sand, new sand and coal and then pressed into drags and copes. The main advantage of green sand is the high reusability of the mixes (minimal costs), although the molds should be poured as soon as possible to avoid drying effects that result in reduced compactability (aptitude of sand mixtures to be compacted adopting a given shape defined by models) and elastic strength. In the case of chemically bonded sands, the binders are organic resins or inorganic compounds (usually silicates) that are usually mixed with new sand in 100–200 kg batch mixers or in continuous mixers when production rates are high. Curing is achieved by adding a catalyst or hardener to the mix that accelerates the polymerization of the organic resins or causes chemical changes in the inorganic compounds to strengthen the bonds between the sand grains.

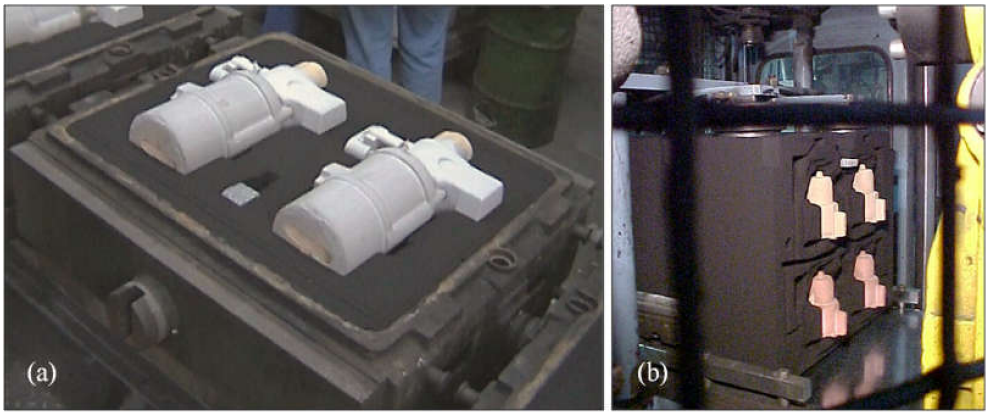

Figure 1. (**a**) Drag unit of a mold containing partially coated cores on a high-pressure horizontal molding line; (**b**) cores in a mold prepared using a high-pressure vertical molding line.

Sand selection, mixing procedures, mix and binder composition and compactness of sand mixtures are all important parameters for casting quality. The most important defects described in the following subsections as sand-related are shown in Figure 2. The possibility that a particular defect is enhanced by other mechanisms is indicated in blue when it is also due to the mold (Section 3) or in red when it is also due to the metal (Section 4). Similarly, the "inclusions" section describes defects other than those due to sand, e.g., slag, dross, graphite, inoculants and metallic inclusions.

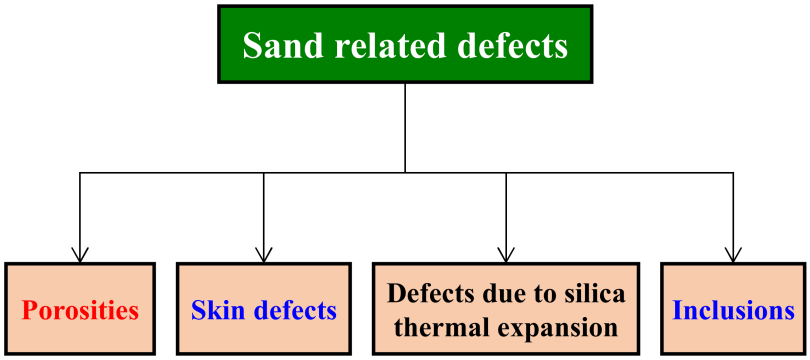

Figure 2. Casting defects related to sand.

2.1. Porosities

Porosity is "*a characteristic of being porous, with voids or pores resulting from trapped air or shrinkage in a casting*". Such a definition encompasses several mechanisms of void and porosity formation that can certainly influence each other. Thus, while shrinkage is a metal characteristic that will be discussed in Section 4, gas porosities are related to gas trapped or precipitated after being dissolved in the liquid metal. Figure 3 shows the different voids and porosities that can be observed in castings classified in two main categories according to the dendritic or smooth aspect of their inner surface. In Figure 3, the three types of defects which are caused by gas formation are highlighted in green and will be considered in this subsection, while the others will be detailed in the following sections.

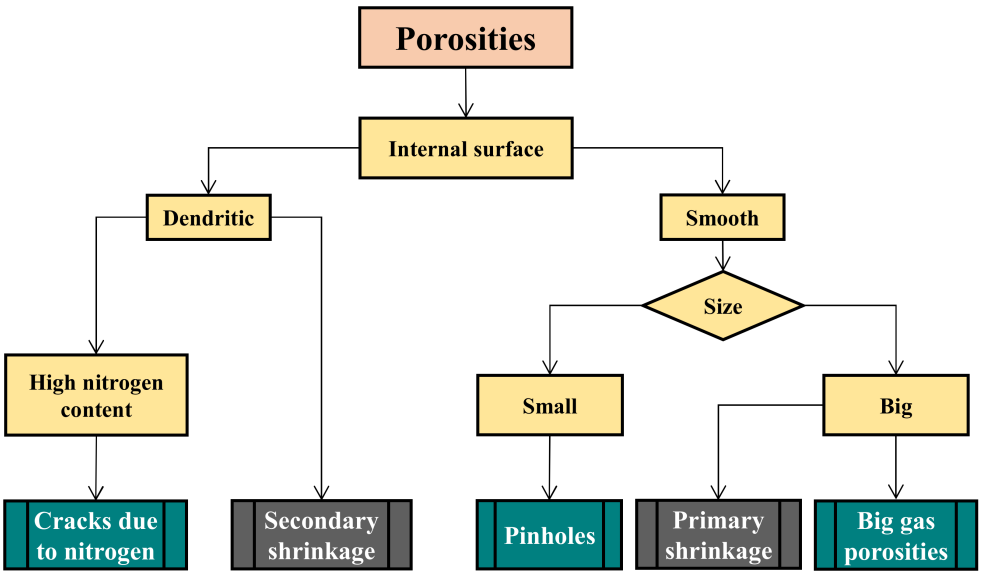

Figure 3. Classification of voids and porosities according to their internal surface characteristics.

The gases dissolved in the melt before casting and/or resulting from interaction between the melt and the sand are mainly nitrogen and hydrogen. In addition, the reaction between highly oxidizing slag (manganese sulfides, silicates, etc.) and the carbon in the metal gives rise to carbon monoxide (CO). During cooling, the gases dissolved in the liquid alloy can evolve in bubbles due to the progressive decrease of their solubility limit with temperature, i.e., the supersaturation of the melt can provide the excess energy needed to overcome surface tension. Gases resulting from the interaction between the melt and the sand can dissolve partly in the melt but also lead to voids in case of insufficient venting of the mold. The first subsection to follow deals with gases in cast iron melts, which is followed by subsections successively describing pinholes, blowholes and nitrogen cracks, and the section concludes with an attempt to provide common remedies for gas porosity.

2.1.1. Gases in Cast Iron Melts

In cupolas, one of the sources of nitrogen is the atmospheric air introduced with the metallic charges and the air introduced by the nozzles. Figure 4a shows the maximum solubility of nitrogen in pure liquid iron under ambient air (78 vol.% N_2) at 1600 °C and its significant decrease in solid phases. Alloying increases or decreases this maximum solubility as illustrated in Figure 4b for various added elements. However, elements such as V and Ti (not shown in Figure 4b) easily form nitrides and carbo-nitrides, which precipitate as small inclusions and reduce the amount of nitrogen dissolved in the alloy.

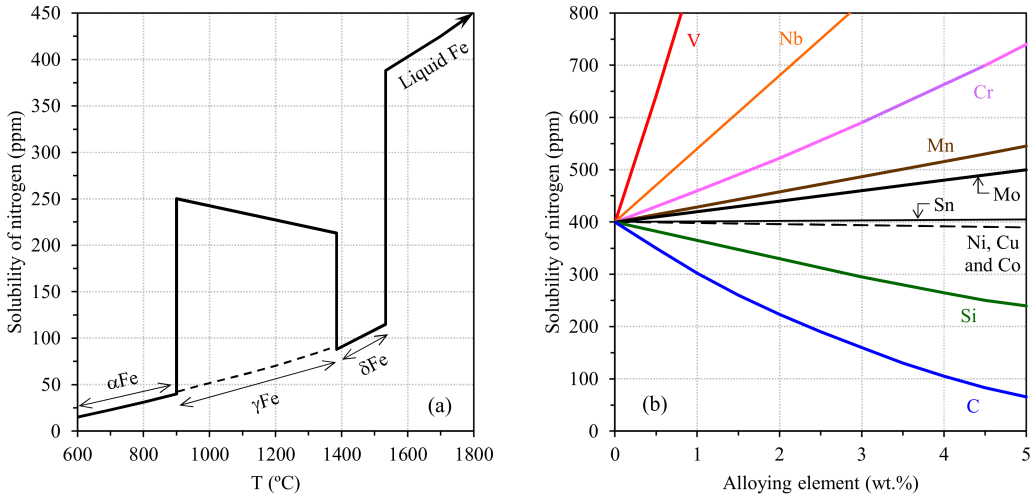

Figure 4. (**a**) Solubility of nitrogen in pure liquid iron at one atmosphere pressure (Adapted with permission from ref. [5]. Copyright 1979 American Foundry Society); (**b**) effect of various elements on nitrogen solubility in pure liquid iron at one atmosphere pressure and 1600 °C (Adapted with permission from ref. [6]. Copyright 1953 McGraw-Hill).

Probably the most interesting result in Figure 4b is that increasing Si and C contents reduces the solubility of nitrogen in pure liquid iron. Figure 5 shows the evolution of nitrogen solubility calculated as a function of carbon content and temperature for melts containing 2.0 wt.% silicon [7]. For a eutectic composition with 3.70 wt.% carbon, the nitrogen solubility is about 55 ppm according to Figure 5. Typical nitrogen contents in castings range from 50 ppm to 120 ppm, without generally generating gas porosity. This is probably due to the presence of some alloying elements (mainly Ti) and the effect of high cooling rates (see below).

The solubility of hydrogen in pure iron evolves similarly to that of nitrogen; see Figure 6a. Notice that the maximum solubility of hydrogen in the liquid and solid phases are about 10 times lower than those for nitrogen (Figure 4). Thus, porosities formed during solidification are mainly due to nitrogen, but the very high diffusion rate of hydrogen leads to a size increase of the porosities by solid state diffusion. Despite this, small bubbles with evidences of hydrogen gas precipitation as the main cause (see next section) are also found in castings. Figure 6b shows the effect of increasing carbon content on the maximum solubility of hydrogen in a Fe-C alloy at 1550 °C. This solubility drastically drops until reaching a minimum for carbon contents of about 4.0–4.5 wt.%. Above this value, graphite appears that can tight up hydrogen, leading to an increase of its total content in the alloy [8]. Though not much documented, it is also quite possible that alloying elements do change hydrogen solubility, as was the case of nitrogen.

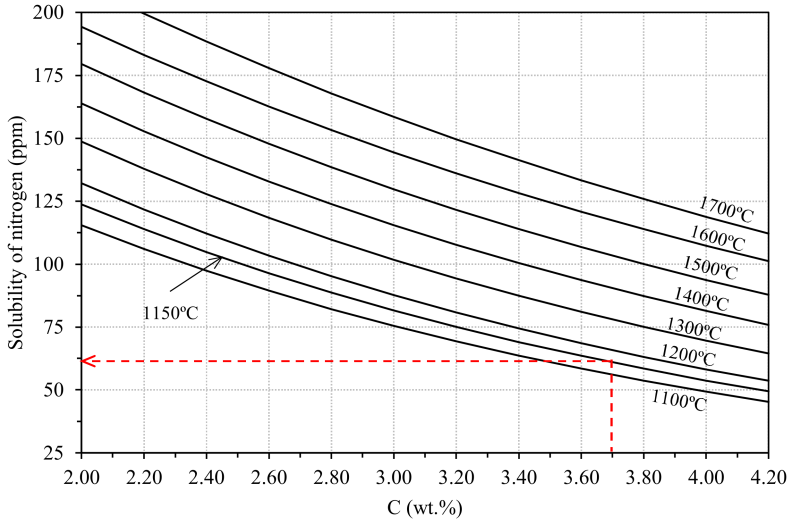

Figure 5. Evolution of the theoretical solubility of nitrogen with carbon content and temperature (Adapted with permission from ref. [7]. Copyright 1979 American Foundry Society).

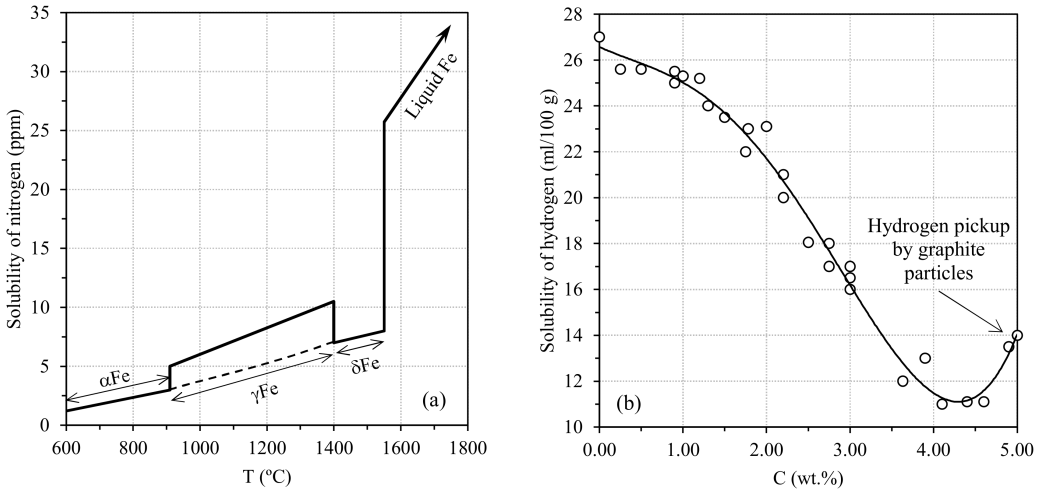

Figure 6. (**a**) Solubility of hydrogen in pure iron at one atmosphere pressure and (**b**) effect of carbon on hydrogen solubility at 1550 °C in liquid Fe-C alloys. (Both graphs have been adapted with permission from ref. [8]. Copyright 1983 Fonderie).

A possible source of hydrogen is the chemical binders used in the manufacture of cores and/or molds. Furthermore, ammonia contained in some binders can dissociate to form both hydrogen and nitrogen gases. When using green sand molds, hydrogen results from the reaction of moisture with metallic elements (Me) prone to be oxidized, such as Al, Ti, Zn, Mg, etc., according to the following equation:

$$xMe + yH_2O \rightarrow Me_xO_y + yH_2 \quad (1)$$

For the same reason, other sources of hydrogen can be the moisture of linings in the furnaces or ladles, condensation phenomena on cores, etc. Once hydrogen has dissolved in the melt, it can precipitate as small bubbles during the cooling step. However, if the conditions for bubble formation are not reached until the part has begun to solidify, the bubbles cannot float to the walls of the mold, where they could have been removed through the sand if it was not too compact.

2.1.2. Pinholes: Small Gas Porosities

Pinholes are comparatively small gas bubbles [9,10] originated by precipitation of dissolved gases or by chemical reactions (combustion) of slag into melts. In the ASM handbook [1], gas porosity is defined as "*Fine holes or pores within a metal that are caused by entrapped gas or by the evolution of dissolved gas during solidification*". If this kind of porosity extends to a large part of the casting, the ASM handbook suggests calling it pinhole porosity, which is "*Porosity consisting of numerous small gas holes distributed throughout the metal; found in weld metal, castings, and electrodeposited metal*". Nowadays, however, pinhole designates single as well as a group of spherical gas pores with a diameter often smaller than 3 mm. As illustrated in Figure 7, they appear either on the surface of a part or in the subsurface layer. In the latter case, visual inspection cannot detect them before machining and shot blasting does not modify their original shape (Figure 7d). On the contrary, those pinholes intersecting the casting surface are frequently deformed by shot blasting; see Figure 7c.

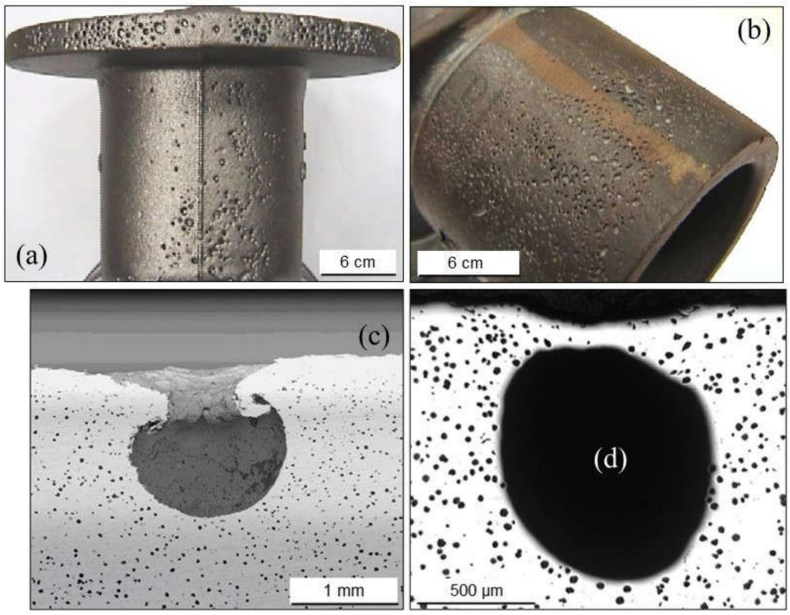

Figure 7. Pinholes found in the skin (**a**) and after machining (**b**). Deformed aspect of an open pinhole with irregular graphite and Mn-S layer in its internal surface after shot blasting (**c**). Internal pinhole close to the skin of the casting (**d**).

The most affected zones are usually those far from the metal ingates (last filling areas so they are the coldest ones) and narrow sections with high solidification rates. Pinholes preferentially appear in upper surfaces of the castings or distributed in all surfaces. They are often irregularly distributed, except in the case where they are caused by a mold–metal reaction when more uniform distributions are found. Although with limited detrimental effects, external pinholes are usually considered a cause of rejection for small and medium sized castings which are the riskiest ones due to comparative low cooling rate. When pinholes are present in any area of castings affected by the machining process, they can be properly eliminated.

Pinholes can be classified according to the type of gases which originates them. Thus, these defects are hydrogen and hydrogen-nitrogen pores or CO-related pores. Features observed in the internal surfaces of pinholes give valuable information to determine their possible origin. Irregular graphite layers usually appear on the inner surfaces of hydrogen and hydrogen-nitrogen pores found in both ductile and grey iron castings; see Figure 8a. Thus, at high temperatures and with the right pressure, the hydrogen gas and the carbon

dissolved into the melt react to give a hydrocarbon (methane) that, at a lower temperature, decomposes according to:

$$C_{dissolved} + 2H_2 \rightarrow CH_4 \rightarrow C_{graphite} + 2H_2 \quad (2)$$

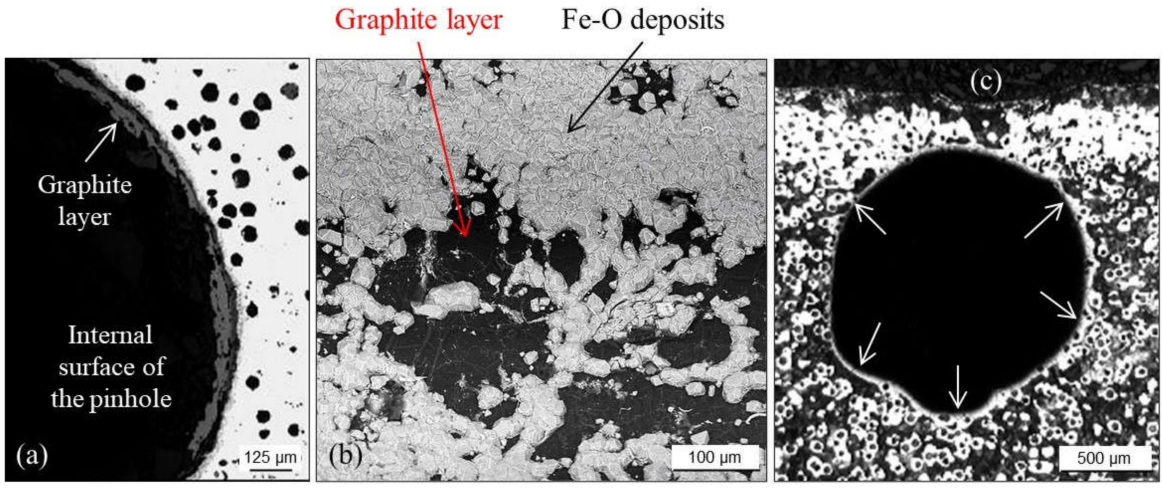

Figure 8. (**a**) Graphite layer on the internal surface of a pinhole found in a ductile iron casting; (**b**) iron oxides found on the graphite layer; (**c**) detail of the matrix close to the internal surface of a pinhole detected in a ductile iron casting.

This reaction leads to some decarburization of the material near to the inner surface of the pinhole that is evidenced by the fact that the graphite particles do not reach the surface of the hole in LGI and a ferrite layer is observed in SGI (Figure 8c). Additionally, dendrite tips can be observed in these inner surfaces due to shrinkage in case of hypoeutectic alloys. Additionally, an iron oxide layer as in Figure 8b can also appear on top of the graphite layer when important amounts of water vapor were present.

The CO-related pinholes are due to reactions between highly oxidizing slags (manganese sulfides, silicates, etc.) and the carbon dissolved into the melt to, thus, form carbon monoxide gas. In that case, spots of slag are found nearby the pinholes as illustrated with Figure 9. In a subsequent step, other gases dissolved into the melt, such as hydrogen and nitrogen, can diffuse into the voids generated by the CO gas and, thus, increase the volume of these porosities. [11].

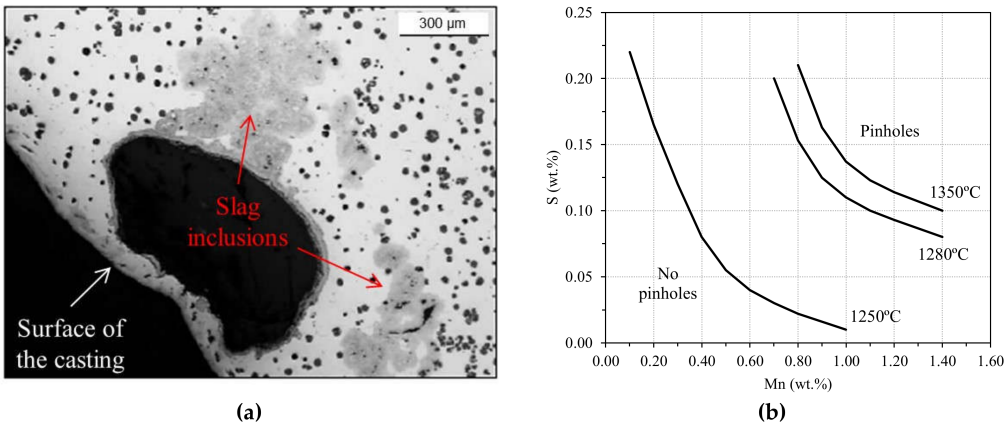

Figure 9. (**a**) Example of a carbon monoxide-related pinhole, which is deformed after shot blasting the surface of the casting; (**b**) evaluation of the pinholes' formation according to sulfur and manganese contents in the melt (grey cast irons) at different temperatures. (Adapted with permission from ref. [12]. Copyright 1994 IKO-Erbslöh).

Finally, in case of grey iron castings, uneven Mn-S bearing layers coexist on the internal surfaces of pinholes together with the graphite layers if the contents of these two elements in melts are high enough to promote the formation of slag inclusions and voids for a given temperature (Figure 9b).

2.1.3. Blowholes: Big Gas Porosities

Blow is "*A term that describes the trapping of gas in castings, causing voids in the metal*". The most known is blowhole: "*A void or large pore that may occur because of entrapped air, gas, or shrinkage; usually evident in heavy sections*". In contradistinction, Campbell [2] noticed it is better to keep the name "blowhole" for describing defects "blown" into the liquid metal, to avoid using it for pores due to precipitation of gas or to shrinkage. This advice will be followed here.

Blowholes are usually individual cavities, of rounded morphology, variable size and whose interior always has smooth surfaces. They can be close when they are present deep in the casting (close blowhole), or nearby and open to the outer casting surface (open blowholes). They are preferentially located in the upper areas of the casting where evacuation of gases is difficult, and/or where the melt arrives with low temperature (fast solidification rates). Blowholes can be found in any type of cast irons, though blowholes in grey iron castings frequently show a rounded protuberance in the internal surface of the void, which is commonly attributed to exudation of phosphorus-rich liquid (Figure 10a,b). One of the most peculiar variants of blowholes is the so-called blister (Figure 10c,d), which is described as "*A defect in metal, on or near the surface, resulting from the expansion of gas in a subsurface zone. It is characterized by a smooth bump on the surface of the casting and a hole inside the casting directly below the bump".* In some cases, the bump is marked enough to resemble a crack; hence, the wording egg-shell that is sometimes used for defect as in Figure 10c.

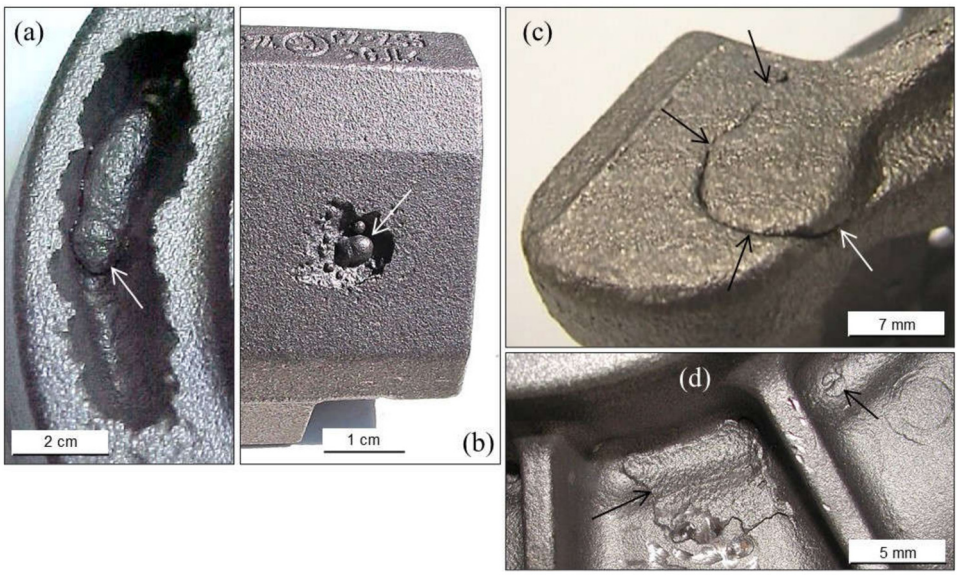

Figure 10. (**a**,**b**) open blowholes with rounded protuberances inside found in grey iron castings; (**c**,**d**) blister blowholes found in the upper area of a ductile iron caliper.

The direct cause of all types of blowholes is the formation of important amounts of gas when filling the sand molds. During this step, the high temperature of the liquid alloy originates water vapor (green sand molds) and the combustion of different constituents of cores (resins) and/or sand molds (coal). It is worth stressing here that all sand molds generate important amounts of gas during filling process, so that it is essential to guarantee their proper evacuation. In case of too high compaction of the sand (low permeability) or because of an excess of humidity, part of the produced gas could remain into the cavity until complete solidification of the casting with the risk of blowhole formation.

Accordingly, the risk of blowholes may be increased by low pouring temperature, lack of vents or gas outlets in the molds, excessive use of resins, coal or other combustible products in the core and mold making processes, turbulent filling of molds, the use of wet processing tools such as wet linings in ladles, etc.

2.1.4. Cracks or Fissures Due to Nitrogen

As illustrated in Figure 11a, these fissures are narrow and elongated voids, macroscopically similar to cracks (see Section 3.3). They can be usually found in groups of randomly oriented elongated voids, which are often located close to the skin of massive areas of grey iron castings. This defect is, thus, commonly detected after machining castings produced with this kind of cast iron (Figure 11a,c). Observation at slightly higher enlargement shows that the inner surface of these fissures is rounded (Figure 11b) and usually shows dendrites (Figure 11d,e). This demonstrates that these defects are related to gas and their occurrence has been clearly associated to high nitrogen alloys or mold materials. This kind of defect has, thus, been named nitrogen fissures.

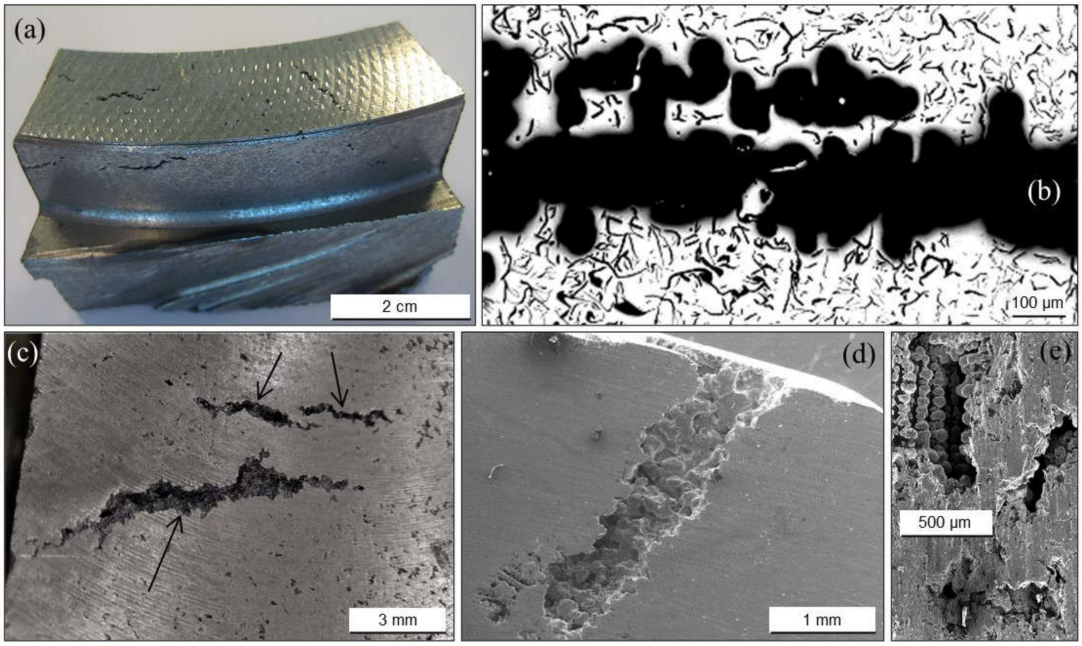

Figure 11. Fissures provoked by the precipitation of nitrogen gas during solidification: (**a**,**c**) fissures found after machining steps; (**b**) metallographic view of a defect present in a gray iron casting; (**d**,**e**) SEM views showing dendritic morphologies in the internal surfaces of the fissures.

If the defect is exposed to air or if the affected part is heat-treated after casting, some iron oxides can be detected on the internal surfaces. A smooth graphitic layer can also be detected (occasionally with oxides and MnS commonly found in grey iron castings) whose formation can be related to the presence of some hydrogen as described before. However, graphite particles present in the metallic matrix touch its inner surface (Figure 11b), meaning that decarburization as described for hydrogen and hydrogen-nitrogen pinholes is uncommon. This feature is considered important, as nitrogen fissures can take an aspect similar to hydrogen pinholes when small. In those grey cast iron alloys with high nitrogen contents (>100 ppm), the internal surfaces of voids can show smooth shapes instead of the dendritic morphologies described above. The highest risk of nitrogen fissures appearance is expected in low carbon equivalent and, thus, in non-Mg-treated cast irons.

The general shape of the fissures and the presence of dendrites demonstrate that the defect appears while solidification of the casting skin is already in an advanced stage. The main cause of the nitrogen fissures would, thus, be precipitation during solidification

of nitrogen dissolved in the melt. This can be due to originally high nitrogen contents in the liquid alloy or to nitrogen picked up by the melt from the mold materials before solidification starts. It is considered that nitrogen contents higher than 0.008% (80 ppm) are risky, though the formation of these fissures also depends on other processing parameters (pouring time and temperature, casting section or cooling rate, mold permeability, gas outlets, etc.). The use of large amounts of steel scrap during melting the metallic charges can lead to high nitrogen levels, but the most common reason is the use of high nitrogen coals in the green sand mixtures, resins or coatings when core making. A maximum content of 0.10–0.13 wt.% of nitrogen in the green sand mixtures is, thus, adopted as a useful criterion for avoiding the risk of nitrogen fissures.

2.1.5. Remedying against Gas Porosities

Regarding gas porosities, everything that would help limiting the amount of gases should be considered. On the melt preparation side, the concern goes mostly on the amount of nitrogen that is affected by titanium through the formation of nitrides and carbo-nitrides. Thus, the nitrogen threshold provoking gas precipitation can be increased by an adequate ratio between nitrogen and titanium contents in melts.

In addition, the amount of elements that can be easily oxidized must be kept below strict limits, namely aluminum below 0.009 wt.% and titanium, zinc and magnesium below 0.050 wt.%. This minimizes the reduction of water present in the green sand molds and the associated formation of hydrogen. Although foundry practice demonstrates the additive effect of these elements, aluminum is the most active and its total amount must be verified in typical sources, namely FeSi and FeSiMg alloys, automotive steel scrap and inoculants. In the manufacture of malleable parts, the addition of aluminum to minimize the oxidation of melts should be done early enough and not just before casting, as this increases the risk of hydrogen pinholes formation. Although the alloy composition is determined by other considerations, it is recommended that high carbon equivalents be used because the solubility of nitrogen and hydrogen decreases with increasing carbon content. However, care must be taken to ensure that the added carbon products have a limited nitrogen content. Finally, proper skimming of the melt prior to the casting stage will remove small slag inclusions that can react in the melt to form carbon monoxide gas porosities (pinholes).

A high pouring temperature (and/or a low pouring time) decreases solidification rates but increases the time available for gas removal. However, it also increases the solubility limit of gases, making it easier to take gases from the air or mold. Thus, a low pouring temperature is preferred, which also reduces any combustion reaction in the mold. Similarly, optimized filling systems would minimize turbulence and prolonged contact between the melt and the mold and cores, thus limiting the amount of gas transferred to the liquid alloy during filling.

On the mold side, the use of nitrogen bearing organic resins for the manufacture of cores, coatings, adhesives, etc. should be limited. Similarly, using coal products with high nitrogen contents for preparing the green sand mixtures that are then used to manufacture sand molds should be avoided. When preparing sand mixtures, sufficient new sand should be added to reduce the accumulation of nitrogen and other elements. The maximum recommended nitrogen content in the return sand to prevent nitrogen fissures is about 0.15 wt.% for small and medium section castings and about 0.10 wt.% for heavy-section castings.

To avoid hydrogen formation, the lining and ladles must be thoroughly dried, and the moisture content of the cores and sand molds must be kept as low as possible. Care should be taken to avoid free water in the final green sand mixtures, as well as water condensation on cores due to severe temperature differences.

A correct evacuation of gases formed during filling should be ensured by open vents, appropriate permeability of the compacted sand mixtures, correct shapes of the cores prints which should not be coated as they play an important role in evacuating gas from cores combustion, etc., in particular in relation with blowhole formation.

Finally, overheated areas in castings due to deficient lay-out designs should be avoided. As nitrogen and hydrogen solubility decreases with temperature, these elements that are still dissolved in the liquid alloy migrate to those areas of the casting with the lowest cooling rates. Thus, local contents of nitrogen and hydrogen can be higher than nominal contents and important precipitation of gas can occur in these last solidifying areas (pinholes and nitrogen fissures).

2.2. Skin Defects

Foundries must provide their customers with castings with a good-looking outer surface, which requires sufficiently low roughness. It is, therefore, recommended to agree on the desired finish of the castings before producing regular batches. Consequently, the type of shot blasting balls (size and shape) to be used should be defined in order to achieve the agreed surface quality. In addition, a continuous evaluation of the surfaces of the castings is mandatory during production to detect any irregularities affecting the metal finish expected after shot blasting. In this section, the most common skin defects observed on the surface of castings are described, classified into two groups (Figure 12):

- Minor defects such as wrinkles or high roughness are essentially aesthetic problems with no or little incidence on the casting soundness.
- Severe defects result from important thermal interactions between the cast melt and the compacted sand which forms the mold cavities (vitrification, burn-on and penetrations). These defects are associated with high roughness that can affect the coating quality and fatigue properties of finished parts.

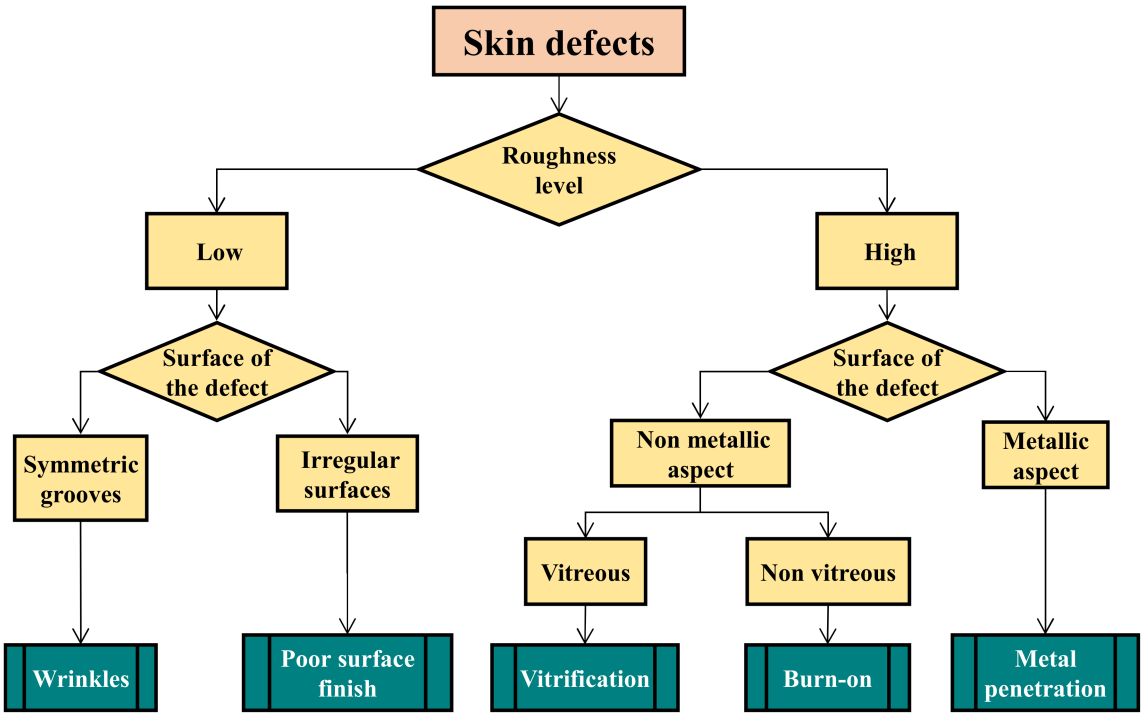

Figure 12. Classification of skin defects according to their characteristics.

2.2.1. Wrinkles

The term "wrinkles" [13] refers to grooves of reduced depth that are generally not perceptible when the surface is touched; see Figure 13a. They are visually highlighted by the fact that the middle of the grooves is darker than the rest of the surface. The defect appears preferably on horizontal or convex surfaces and at the surface of parts of reduced thickness having solidified at high cooling rates. In grey cast irons with high carbon contents, the defect can be formed in thick sections in which C-type graphite (hypoeutectic alloys) is

commonly present. Although wrinkles can be mistaken for rat tails or buckles, they differ from them as the grooves do not show steps in cross section and have their bottom close to the level of the casting skin (Figure 13b).

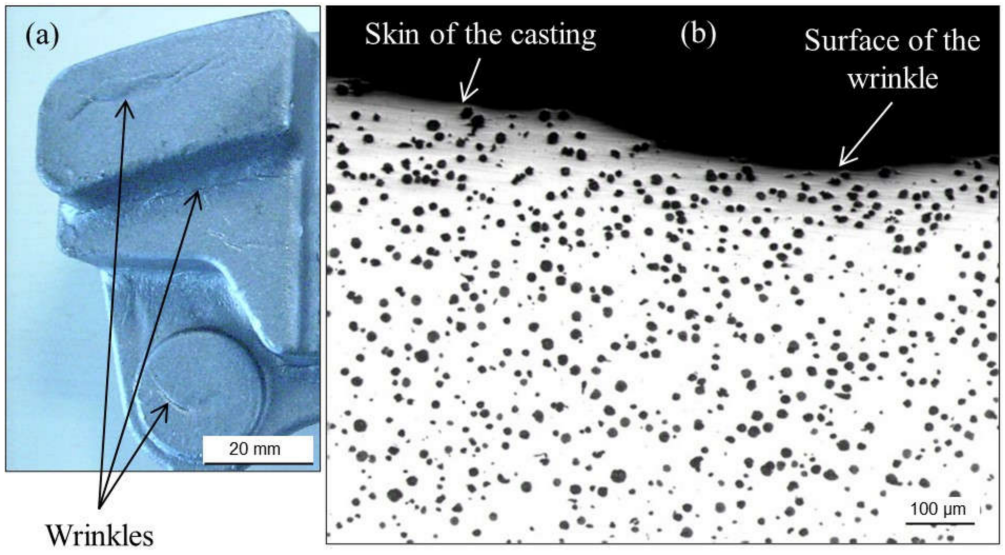

Figure 13. Macroscopic view of wrinkles at the surface of a ductile iron casting (**a**) and micrograph of a cross section showing the bottom of the wrinkle groove (**b**).

Wrinkles are flow marks due to turbulence during casting and are typical of alloys with a strong propensity to oxidation, such as aluminum alloys. Because of turbulence, some oxidation of the melt surface occurs, resulting in a slag film that sticks as a thin coat, evidencing the flow marks. In those alloys with high density, such as cast irons, metallostatic pressure and surface tension commonly avoid wrinkles, though the defect can appear in locations solidifying at high cooling rates.

In the case of cast irons, one of the main causes of melt oxidation is the use of steel scrap with a high oxygen and sulfur content, as well as the addition during the melting process of elements that oxidize easily. Another important cause of melt oxidation is an excessive amount of "free water" (unabsorbed water) in the greensand mixtures, for example due to too high compaction. The use of low-strength sand molds (bentonites with low thermal stability) can cause deformation and breakage that expose fractured wet surfaces to melt. This promotes water-melt contact and turbulence during filling. Another simple case is the introduction of cold cores, typically at 35–40 °C, into greensand molds, leading to significant water condensation on the cores. Finally, the use of low casting temperatures and low carbon equivalent contents decreases the flowability of the melts, thus promoting the formation of flow marks.

2.2.2. Poor Surface Finish

In all generality, the surface finish of a casting depends on: (i) the surface quality of the pattern; (ii) the size, shape and distribution of the sand grains used for preparing molds and cores; (iii) the compaction level of the sand; (iv) the cast alloy composition and the pouring temperature; (v) the cooling rate (casting section), the height of metal (metallostatic pressure) and the location of hot spots, ingates, etc.; (vi) the shot blasting conditions (size and shape of balls and shot blasting time).

A casting is said to have a "poor surface finish", such as the one in Figure 14, when the surface roughness is greater than that required by the customer specifications. Poor surface finish does not affect the functionality of the castings, but it can be detrimental to other expensive processes, such as machining, coating, etc. Uneven surfaces are usually located in hot areas, such as those near metal ingates and hot spots, and in areas where sand is loosely compacted and melt can penetrate due to metallostatic pressure. Because of

their lower position, the part of the castings located in drags are more susceptible to this defect. Poor surface condition is considered the stage before calcination (Section 2.2.4) and penetrations (Section 2.2.5).

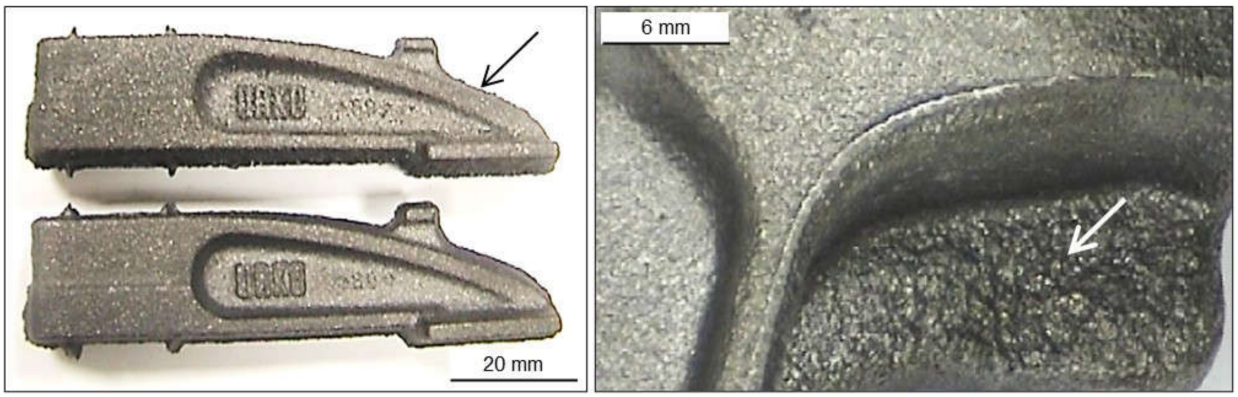

Figure 14. Examples of poor surface finish in iron castings.

A poor surface finish is, thus, a consequence of interaction between sand mold and melt. Sand-related poor surface finish may be due to:

- The use of return or/and new sand grains with low AFS index (coarse grains).
- High compactability and permeability of the sand mixtures (low fluidity of the sand mixtures during molding process).
- Low loss on ignition value (low content of coal in the green sand mixtures). Keep this parameter in the range 4.0–6.0 wt.%.
- Low contents of silica sand grains in the green sand mixtures.
- Deficient mixing process (low mixing time or operative problems when mixing) which originate heterogeneous mixtures (comparative wet and dry fractions or even presence of "free" water in the mixtures).
- Low fines (particles size lower than 20 μm) content in the sand mixtures that leads to an increase in mold permeability.
- Inadequate (low) compaction of sand mixtures during molding step leading to molds with excessive permeability.
- Low strength of the prepared green sand mixtures (damaged molds).
- The use of inappropriate or damaged resins for core making.
- Excess of demolding liquids on the surfaces of molds (these liquids are used to ease the separation of molds from the patterns after squeezing step).
- Melt related and other common causes of poor surface finish are:
- High pouring temperatures (increase of melt fluidity and time before solidification) and low pouring times.
- The use of layouts with areas where metallostatic and/or dynamic pressure of the melt is high.
- Overheating of any part of the molds or cores (layout design).
- Inadequate coating of cores and/or molds.
- Lack of proper venting (problems when evacuating gases formed when filling the molds), which originates overpressures and promotes the interaction between the melt and compacted sand grains. Coated prints in cores, closed vents due to sand wash and/or other tools on.
- Phosphorous content lower than 0.050 wt.% in grey cast irons increases the risk of metal penetration in castings.

2.2.3. Burned-In Sand: Calcination

Burned-in sand [13] is described as "*Sand in which the binder or bond has been removed or impaired by contact with molten metal*". This definition has been refined by differentiating

the wordings burned-in and burned-on sand. Burned-in sand is "*A defect consisting of a mixture of sand and metal cohering to the surface of a casting*", which is also called calcination. Burned-on sand is "*A misnomer usually indicating metal penetration into sand resulting in a mixture of sand and metal adhering to the surface of a casting. See also metal penetration*", which is dealt with in Section 2.2.4.

The calcination layer (or burned-in sand) consists of a mixture of sand grains and metal that remains stuck to the surface of the casting and is difficult to remove by shot blasting (Figure 15). This layer forms when the liquid alloy partially penetrates the compacted sand. Depending on the intensity of the calcination process, the defect may appear as a significant deterioration of the surface finish of the casting or as a layer that is clearly distinguishable from it. The defect appears more frequently in massive areas (low cooling rates), in areas close to the metal inlets (hot spots) or even in areas of the mold undergoing intense heating when pouring is carried out at high temperatures.

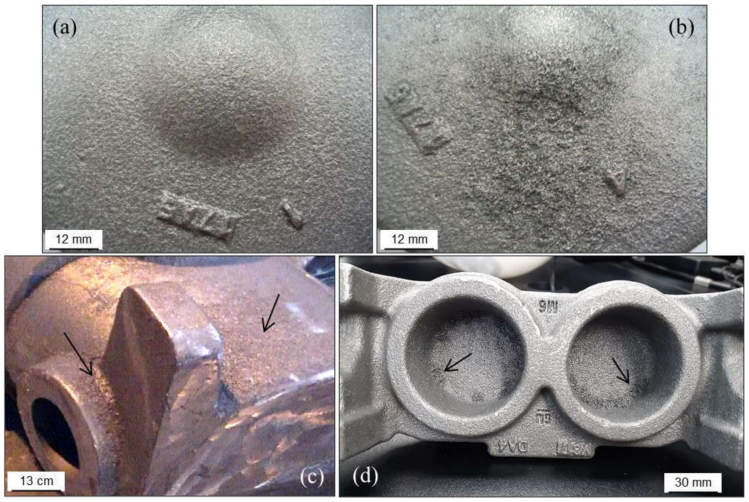

Figure 15. Burn-in or calcination defects: (**a**,**b**) comparison of same surface in ductile iron castings without and with a slight defect which can be confused with a poor surface finish; (**c**) burned-in sand on a plate surface and in internal angles of a heavy-section grey iron casting; (**d**) calcinations located in internal angles of the hydraulic areas (hot spots) of a ductile iron caliper.

Burned-in sand is often confused with metal penetration and only a detailed observation of these defects by optical microscopy shows differences in the amount of metal present in the corresponding layer. Thus, burned-in sand shows sand grains that are not completely embedded in the metal, as is the case in metal penetration, so that a removed layer would not be magnetized, whereas a metal penetration would. Despite this, the two defects are not commonly differentiated in foundry shops and the two terms are used interchangeably for both defects.

The most important remedies against calcination or burn-in are the ones already described for the poor surface finish in Section 2.2.2.

2.2.4. Metal Penetration

Metal penetration is defined as *"a surface condition in castings in which metal or metal oxides have filled voids between sand grains without displacing them"*. It occurs when the liquid metal penetrates the molds (Figure 16a,c) or the cores (Figure 16b) without any relevant deformation of the mold. Metal penetration happens when the combination of metallostatic pressure, dynamic pressure and capillarity of the melt exceeds the friction pressure between the mold and the metal and the expansion pressure of the gas between the grains [14]. The dynamic pressure of the metal is the pressure peak associated to the momentum effect when the liquid hits the mold wall; thus, it is directly related to the filling velocity.

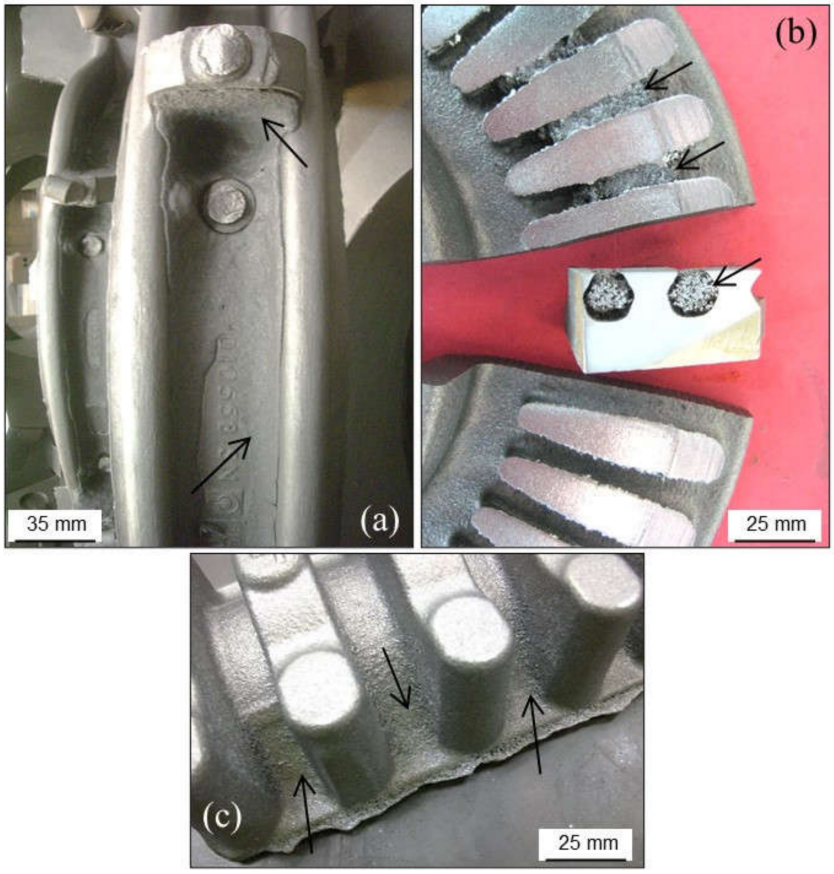

Figure 16. Metal penetrations found in (**a**) a ductile iron casting inner zone shaped with a chemically bonded mold with low compaction of sand; (**b**) a grey iron brake disc with compaction problems in some areas of the core; (**c**) overheated areas of a ductile iron casting produced with a green sand mold.

In general, the incidence of metal penetration into a mold is higher when it is poured with a grey iron alloy compared to a ductile iron alloy with similar carbon and silicon contents. This is probably due to the lower surface tension of the former than of the latter, leading to a lower critical pressure for the melt to penetrate between the compacted sand grains. In addition, this defect is more frequent in areas that are barely compacted during the molding process, which are mainly areas that are hidden from the projection of sand mixtures into the molding chamber and areas of the model plates with high reliefs.

One can define three variants of this defect, the common metal penetration due to the simple entry of the melt into areas occupied by compacted sand grains with higher porosity (penetration without chemical reaction), metal penetration with chemical reaction (caused by reactions between melts and some constituents of sand mixtures) and explosive penetration, especially common in those areas of molds with low permeability (high sand compaction) and without any gas venting. Unfortunately, a clear distinction among these three variants is not easy when inspecting the castings, but there are some different characteristics that are described in the subsections below. All three variants have the same causes, and they can be minimized by the remedies already described for poor surface finish.

Metal Penetration without Chemical Reaction

In this variety of metal penetration, layers can be easily identified (Figure 17a,b) and sand grains appear totally surrounded by the alloy (Figure 17c), leading to irregular layers deposited on the casting surfaces (Figure 17d). A clear limit between the penetration layer and the metallic surface is found and this layer is usually removed without difficulties by

using a hammer. A more detailed inspection of the cross section in the layer shows that the number of products formed after the interaction between the sand grains and the melt is low. However, iron oxide films and some small particles of degenerated graphite can be observed within the metal (black arrow in Figure 17d). These features indicate that some metal-sand reaction is always present, though at low levels in this variant [15,16].

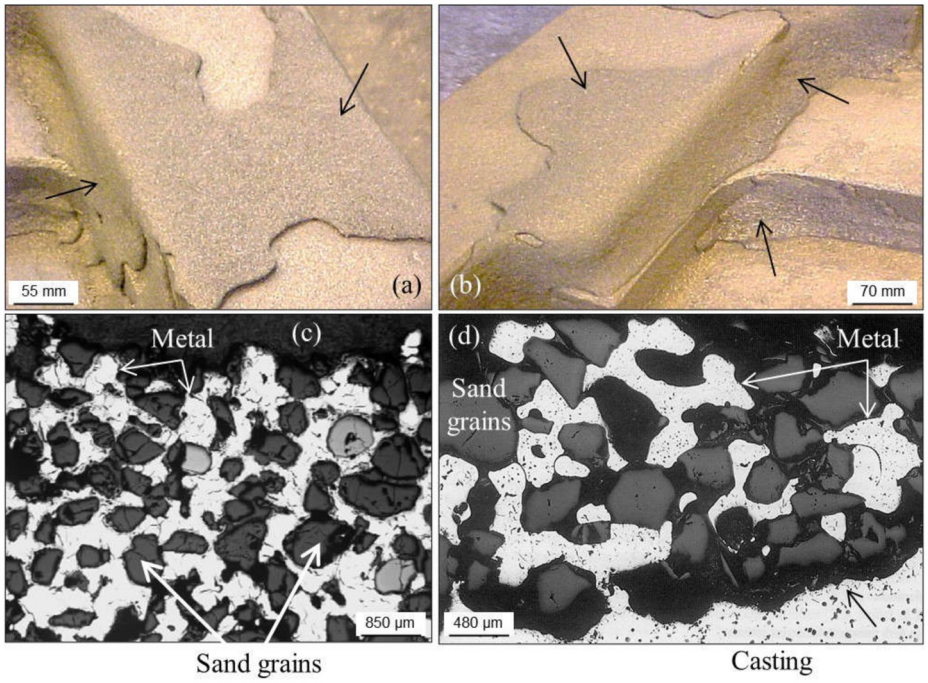

Figure 17. Conventional metal penetration (no marked chemical reaction) in a heavy-section casting manufactured in chemically bonded sand mold (**a**,**b**); microscopic view of the layer in two different locations (**c**,**d**).

Metal Penetration with Chemical Reaction

In this case, the penetration is accompanied by strong chemical reactions between the melt, the sand grains and bentonite, the residues surrounding them and the coal [13]. In the layer where metal and sand are mixed, reaction products can be detected as illustrated in Figure 18. These layers are mainly located in hot areas, and particularly hot spots, or in those locations of the molds where sand grains are not highly compacted.

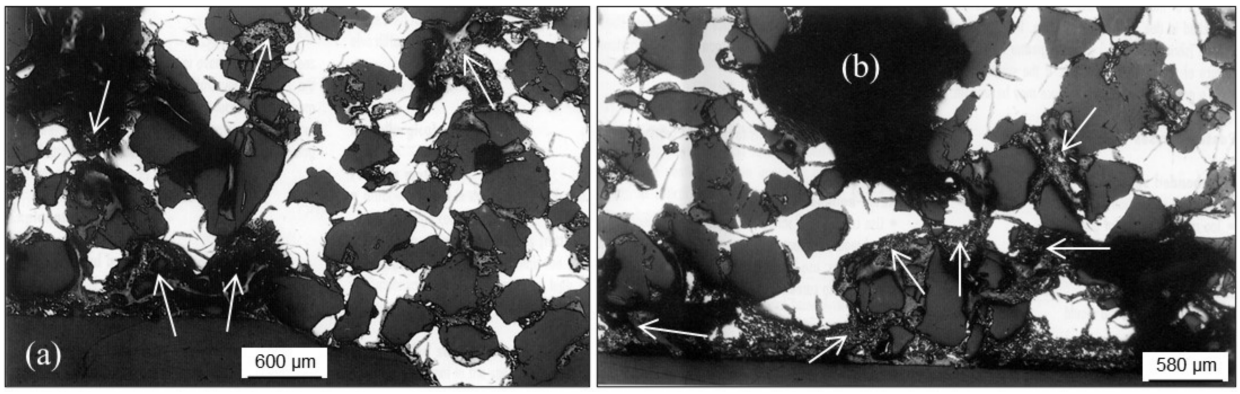

Figure 18. Microscopic views of the layer obtained in a metal penetration with chemical reaction: (**a**) external area and (**b**) internal area. Compounds formed due to chemical reactions are pointed with arrows.

In the case of penetration with chemical reaction, the surface tension of metal alloys is expected to be significantly reduced, so penetration occurs on a larger scale. In copper-zinc and copper-tin alloys, enrichment in lead favors the reactions between metal and green sand. In case of cast steels with high manganese contents, reactions with silica sand grains are also common and alternative sands are used to minimize these interactions (chromite or olivine sands). Oxidation of cast iron melts decreases their fluidity but increases their wettability on molds, thus increasing the risk of penetration.

Explosive Penetration

This type of penetration commonly occurs in castings with large and irregular sections (Figure 19) and it is related to fast pouring with rapid gas formation in the molds, which then evolves in important problems to be evacuated from the molds [15]. Sometimes, this leads to explosions that can be heard in the foundry. These phenomena indicate that an overpressure has occurred in the molds, and that the retained gases have pushed the liquid alloy toward the walls of the mold, thus promoting massive penetration. This often occurs in the lower parts of the castings that are the opposite side of the mold from where the gases are accumulating. As a consequence, layers are formed in these areas, consisting of metal, sand grains and possibly compounds related to chemical reactions. It can, therefore, be said that explosive penetrations are metal penetrations with chemical reactions caused by overpressure in the molds. The incidence of this defect has increased since the use of high-pressure molding lines that result in relatively low mold permeability and for which proper venting becomes essential.

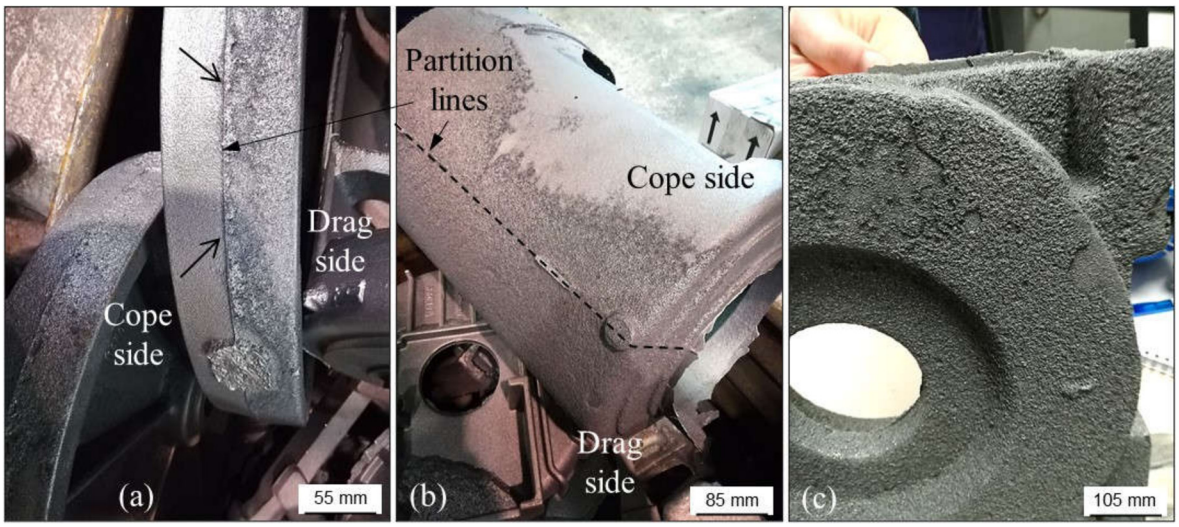

Figure 19. Explosive penetrations in grey iron castings. Notice that the defects appear more intense in the areas defined by drags in (**a**,**b**). In (**c**) the areas of the casting produced with drags correspond to the areas in the top of the picture.

An important feature that can facilitate correct diagnosis of this defect is the clear difference in surface finish that can be seen when comparing the areas of the casting in the drag and in the cope (Figure 19a,b). The overpressure generated in the molds can be eliminated on the cope side because the parting line can act as an effective gas vent. Thus, the quality of the surface above the parting line is much better than that observed in the drag zones. In any case, a proper venting system at the top of the molds should minimize this type of metal penetration.

All actions devoted to avoiding gas accumulations into the molds will help to minimize the risk (limitation of resins content in cores, of coal dust and water content in green sand mixtures). The most important remedies against metal penetration are the ones already described for poor surface finish in Section 2.2.2.

2.2.5. Vitrification

Vitrification relates to the presence of a film of molten sand firmly adhered to the casting surface, which is hardly separated when compared to the crust generated in case of burn-on and/or metal penetrations [17]. Many metal oxides (including iron oxides) can react with silica at relatively low temperatures to form semi-molten, glassy-looking layers with vitreous aspect (Figure 20). The reaction of silica with iron causes the formation of fayalite or iron (II) silicate (Fe_2SiO_4) with a low melting point, which remains strongly stuck to the skin of the casting. Thus, the defect shows a vitreous and irregular external appearance at room temperature, which cannot be removed by shot blasting. The incidence of this defect increases in the hot areas of the castings.

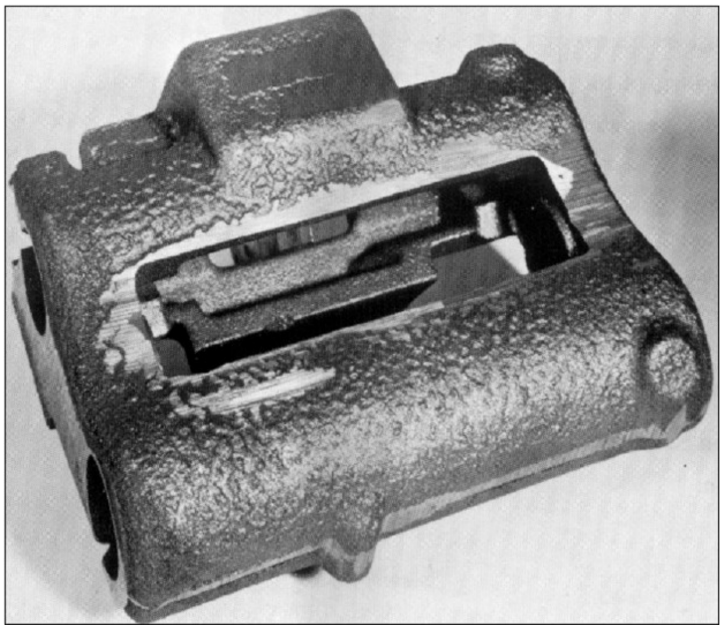

Figure 20. Vitrified surfaces in a malleable iron housing (Reprinted with permission from ref. [17]. Copyright 1999 American Foundry Society, page 202).

The main cause of vitrified surfaces in cast iron is the lack of thermal resistance of the sand mixtures. Silica grains are commonly a good enough refractory material, while the rest of the constituents of the mixture are not. Bentonites and coals originate residues after being heated, leading to ashes, cinder, oolitic compounds and other compounds which can react with silicon and iron from the melt, and with oxygen and/or sulfur to form vitreous compounds just at the metal–mold interface. In addition, this glassy layer can be thickened when other impurities (contaminants) in the sand mixtures are increased. This defect is, thus, related to poor regeneration of the sand mixtures due to low silica contents, low refractoriness of bentonites when containing high amounts of carbonates and/or iron oxides, low loss on ignition values (low coal contents) and also to high amounts of decomposition products from organic binders used for core making.

On the other hand, the use of layout which originates hot spots in the molds as well as high pouring temperatures should be avoided. Finally, fast demolding steps at a high temperature strongly reduces the deoxidizing role of coal on the casting surfaces, and this fact can favor the formation of vitreous compounds on them when low refractory sand mixtures are present.

2.3. Defects Due to Silica Thermal Expansion

Figure 21 compares the thermal expansion of various constituent phases of the molding sands. It is seen that the thermal expansion of silica is the most significant and is characterized upon heating by two successive solid transitions that transform, respectively,

quartz α to quartz β at 573 °C, and quartz β to tridymite at 867 °C. Abrupt linear changes (expansion) of about 0.45% and 5.50% are generated by these phase transformations [18]. Although silica has other crystallographic forms at high temperatures, the maximum values reached inside the molds are about 1300 °C for cast irons and about 1500 °C for cast steels, so it is not necessary to take them into account. Furthermore, it is also useful to know that the first change (α-quartz→β-quartz) is easily reversible, while the second one is not favored. Thus, an important permanent expansion is obtained in all the silica grains which reach more than 867 °C, that is, those close to the inner surfaces of the molds.

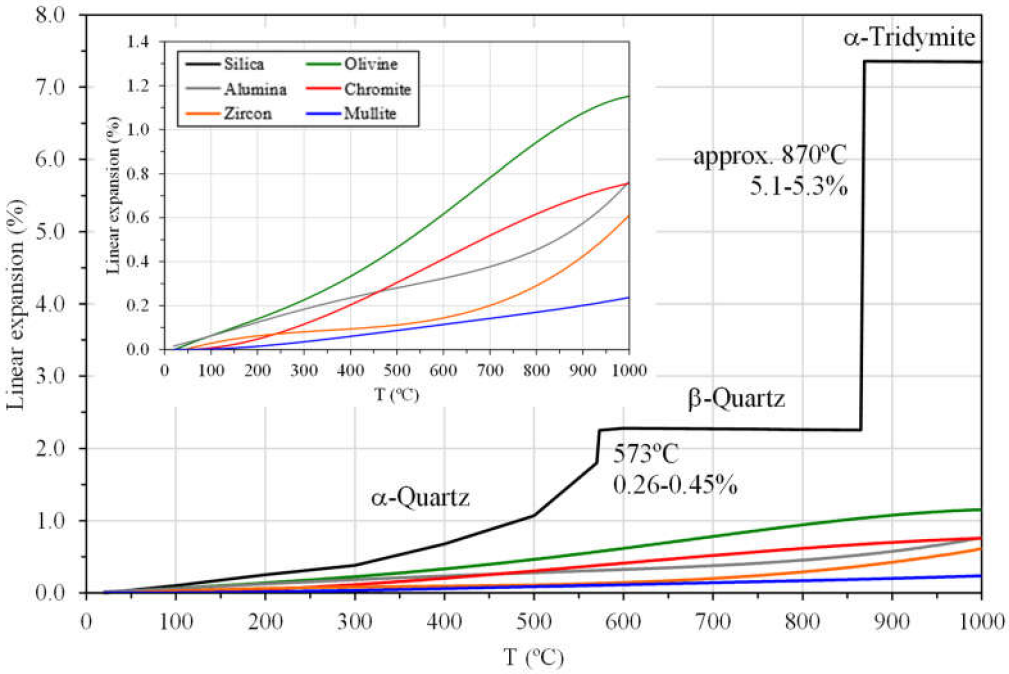

Figure 21. Schematic comparing the thermal expansion of different phases constitutive of molding sands [19–21].

The evolution of the thermal expansion of silica makes it essential to use well distributed sand grains for the manufacture of molds and cores. This means that the distribution of the grains must contain different sizes in order to avoid massive and simultaneous expansions in the concerned areas. This is because smaller grains raise their temperature more quickly than larger ones, resulting in a gradual expansion effect instead of a sudden phenomenon. In addition, rounded grains give higher levels of compaction than angular or irregular grains and are, therefore, likely to cause higher expansion effects in the molds.

Defects related to the thermal expansion of compacted silica grains are diverse, as illustrated in Figure 22. Such variations can confuse any diagnosis in foundry shops, so it is necessary to properly characterize all aspects of these defects to minimize this risk. The change in volume due to silica expansion generates stresses in the molds and cores that can lead to cracking and subsequent interaction with the liquid melt. The final appearance of each type of defect is a consequence of the different characteristics of the compacted sand and the interactions with the melt.

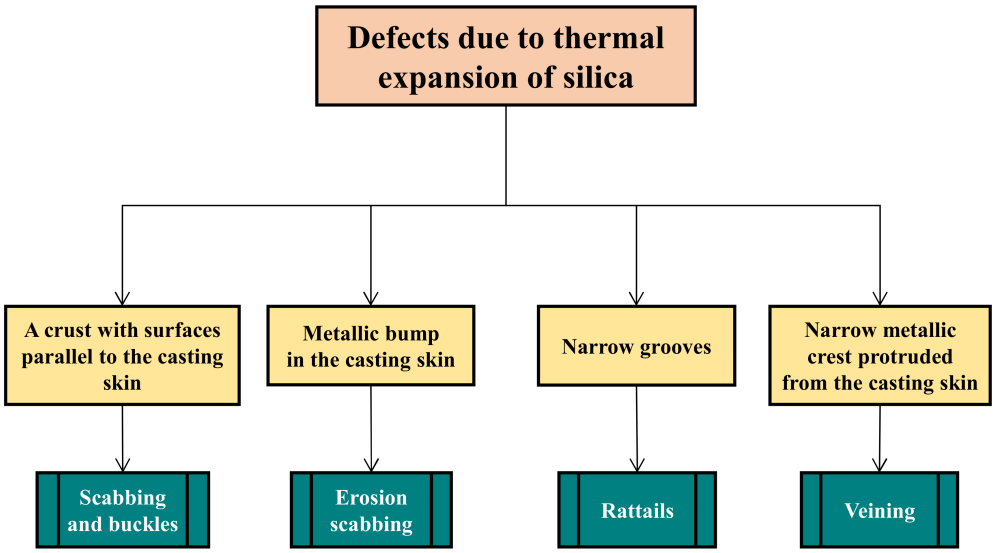

Figure 22. Classification of defects due to silica thermal expansion according to their characteristics under visual inspection.

2.3.1. Scabs and Buckles

A scab can be defined as "*a defect on the surface of a casting that appears as a rough, slightly raised surface blemish, crusted over a thin porous layer of metal, under which is a honeycomb or cavity that usually contains a layer of sand; defect common to thin-wall portions of a casting or around hot areas in the mold*". Although scabs were common in foundries a few decades ago, they are a minor phenomenon in parts manufactured in modern facilities. In spite of this, certain geometries of castings, generally of medium-high section, still present this defect on their surface, which causes their rejection.

Scabs are metallic protrusions that appear as rough and irregular layers of varying size, often several millimeters thick (Figure 23). These layers run parallel to the surface of the part, creating an irregular area with clear boundaries (Figure 23d). The scabs could be mistaken externally for "drops of metal pressed onto the surface of the part", but at least one of the inner areas of the scab is directly connected to the rest of the part. Thus, by removing the outer crust, it should be possible to confirm the internal morphology of the defect. However, the most important feature is the presence of sand beneath this crust (indicated by a white arrow in Figure 23d) which is a direct consequence of the typical scab formation mechanism.

This defect can form on any surface of the molded parts, although its preferred locations are large flat areas on the top and bottom faces of the molds. Most likely, scabs form in hot areas, where compacted sand grains are subjected to high temperatures for a long period of time. Different shapes and morphologies can, therefore, be obtained in relation to variations in the solidification time of the alloy during the scab formation process.

The three images in the column to the left of Figure 24 show the three stages of common scab formation in the roof of a sand mold during casting. At the beginning of cavity filling, the melt fills the lower part and heats the roof by radiation, which increases the temperature of the exposed compacted sand grains. Moisture initially present in this part of the mold migrates inwards to the upper areas of the mold, creating a "wet or condensation zone" in which the water content becomes higher than the nominal value of the sand mixture used to make the mold (Figure 24a). As a result, a dry exposed zone is present underneath an adjacent wet zone, the two having very different mechanical strengths due to their different water content. The sand grains present in the hot zone expand, causing a crack between the two zones due to the low strength of the over-wetted zone, leading to the formation of a "suspension bridge" (Figure 24b). Finally, when the liquid alloy has finished filling the cavity, it pushes the previously formed bridge and breaks it (Figure 24c). The images in

the column on the right of Figure 24 represent the formation of a floor crust, following a mechanism similar to that just described.

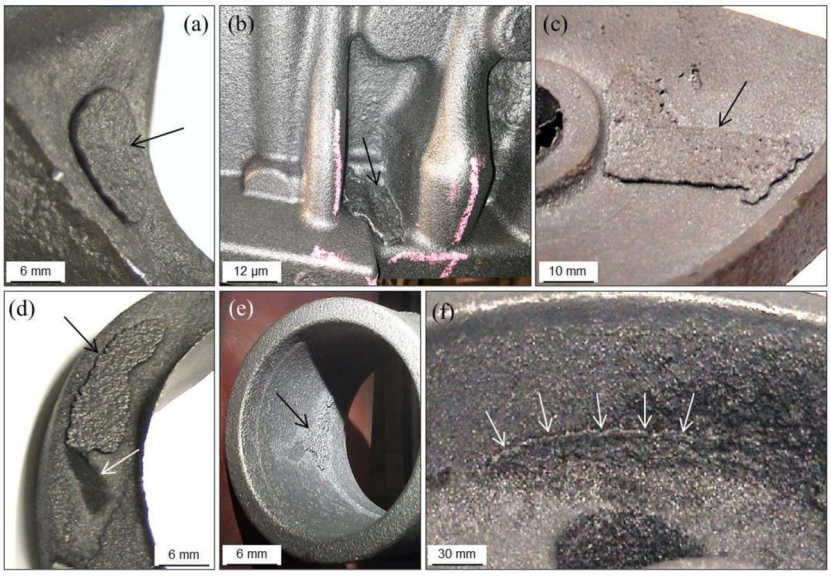

Figure 23. Examples of common scabbing with different appearances: (**a**) rounded scab; (**b**,**c**,**e**) scabs with irregular crusts; (**d**) partially broken scab showing sand remnants adhering to the inner surface and (**f**) one-side scabbing in a casting surface with relevant calcination.

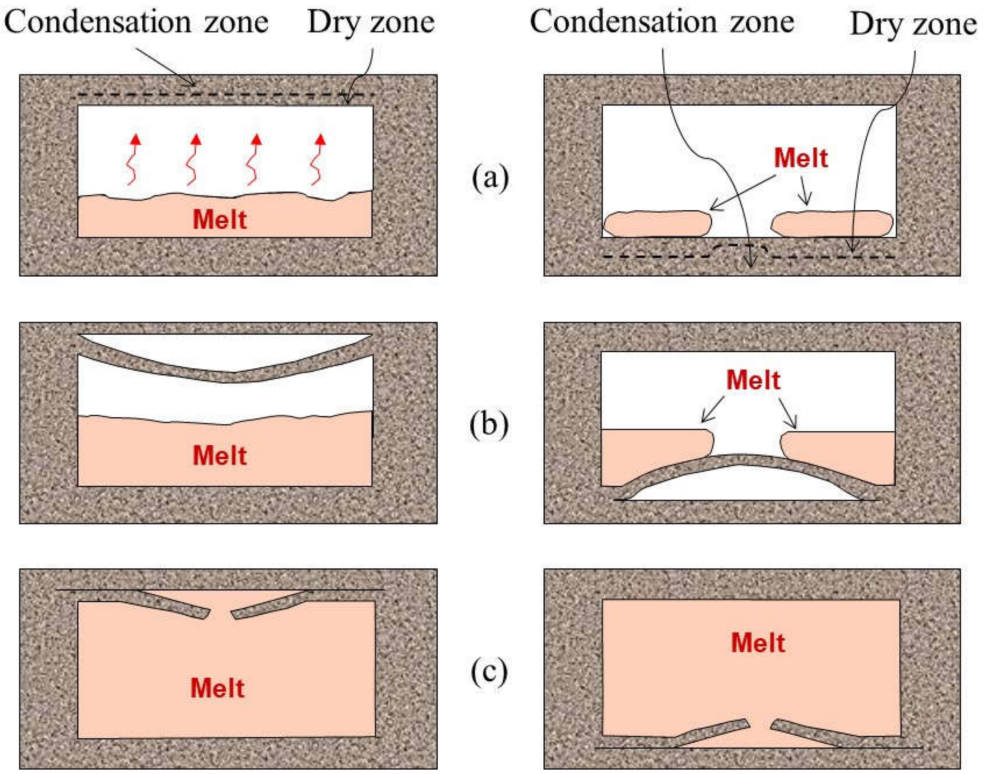

Figure 24. Different steps (**a**–**c**) in the formation mechanism of a common roof scab (**left** column) and a floor scab (**right** column).

In the case of a common scab, melts are able to fill the space between the wet zone and the broken bridge described above. However, various evolutions of the broken bridge can occur once the melt reaches this area, which can lead to a variety of morphologies that are discussed in the following sections. A variant also considered a common scab is obtained

when a suspended bridge cracks near one of its ends and the space is then filled with liquid metal. The resulting morphology is a "one-sided" scab, like that shown in Figure 23f.

Thus, common scabs can coexist with other variants also caused by the thermal expansion of sand grains and provoked by small changes in the mechanism, shown in Figure 24. This is the case of buckles (Figure 25), which are formed when the melt does not fill the free space above the bridge, and a lined groove with variable lengths and a small rib at the bottom is formed (Figure 25). In the ASM glossary, this corresponds to the second definition of a buckle: "*(2) An indentation in a casting, resulting from expansion of the sand, can be termed the start of an expansion defect*".

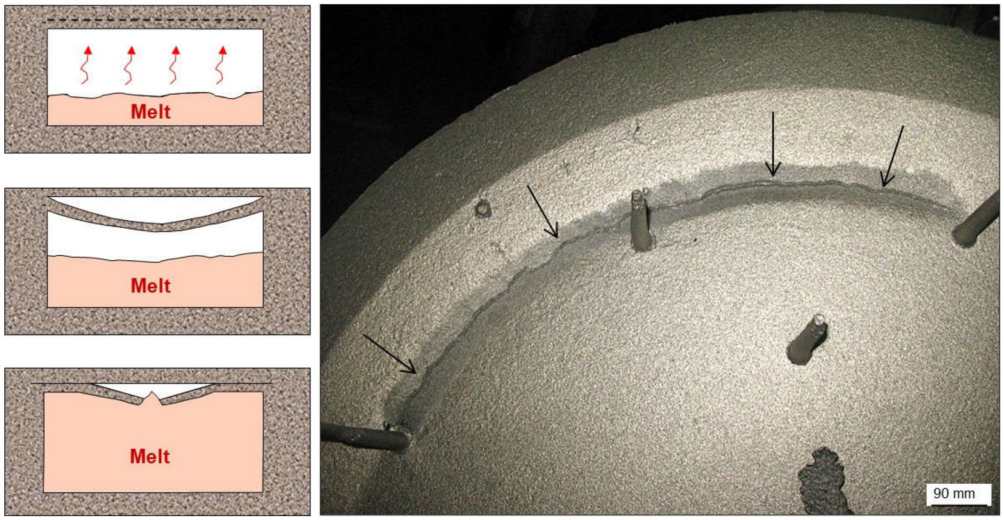

Figure 25. Schematic of a buckle formation (**left** column) and photography of a buckle formed all around a heavy-section ductile iron valve.

2.3.2. Erosion Scabs

Although the external appearance of erosion scabs differs from common scabs and/or buckles (black arrows in Figure 26), the causes and formation mechanism are the same. In the case of erosion scabbing, a final crust as shown in Figure 24c is damaged by turbulence or intense liquid flow, so that irregular pieces of compacted sand separate from the area where scabbing was forming. After shot blasting, metallic protrusions can be seen to appear with sand inclusions in surrounding areas (white arrows in Figure 26b). These sand inclusions are not always present, as they may have been transferred to other areas far from the erosion scab.

The morphology of erosion scabs is variable because it depends on the circumstances of their formation process (type of filling system, strength of sand mixtures and the characteristics of molding process). Erosion scabs are preferably located near liquid ingates, down sprues, etc., where metal flows are maximum and the heating effect becomes high.

As this variant of scabbing combines expansion and erosion, its causes are the combination of those which provoke these two phenomena. Thus, in addition to the remedies listed in Section 2.3.6, smooth filling of cavities and avoiding intense flows and/or sharp intersections are also helpful. Interrupted pouring that decreases homogeneity of filling process and that can produce damages to the molds (erosions) should be avoided. Regarding molding, a correct assembling of all parts, namely drag, cope and cores, must be guaranteed.

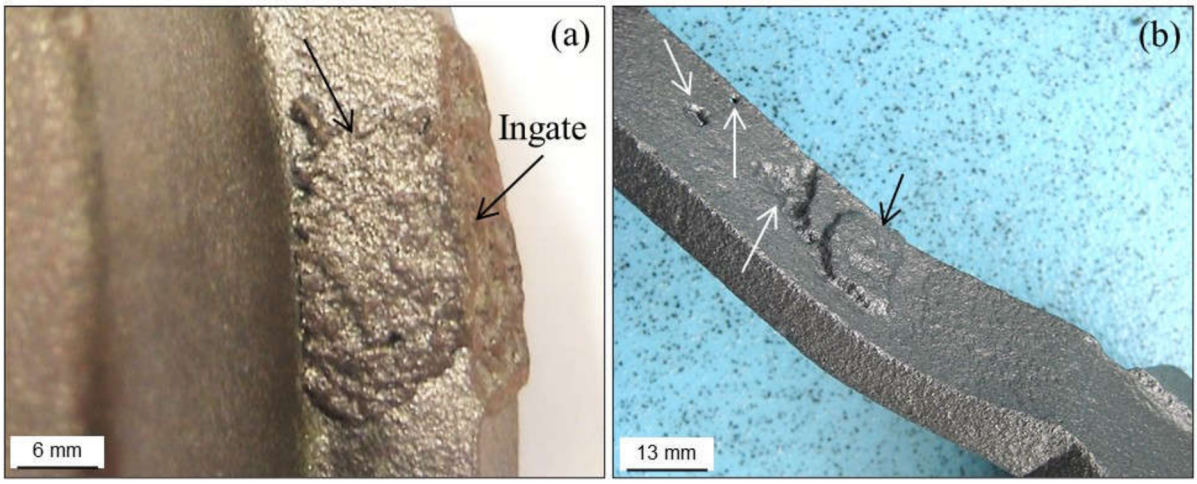

Figure 26. Erosion scabs found in (**a**) an area of a casting close to the ingate and (**b**) one runner of a filling bunch.

2.3.3. Rattail

Rattail is defined as "*A surface imperfection on a casting, occurring as one or more irregular lines, caused by the expansion of sand in the mold*". This defect appears as irregular grooves that run along the outer surface of the casting [22]. The name is due to the fact that ancient foundrymen saw a similarity to rat tails (Figure 27). Rattails result from the early cracking of the dry area as it expands, resulting in an additional volume of sand that creates a step rather than a bridge on the inner surface of the mold. It is interesting here to make a comparison between rattails and buckles because, in both cases, the liquid does not engulf the expanded sand. In buckles, there is usually a V-shaped depression with a central rib, while rattails are grooves with a steep step relative to the mold surface. In addition, rattails generally follow the flow of melt in molds and are especially common on flat surfaces at the bottom of casting parts. Hard (very compact) molds with smooth surfaces are considered very risky with respect to this type of defect.

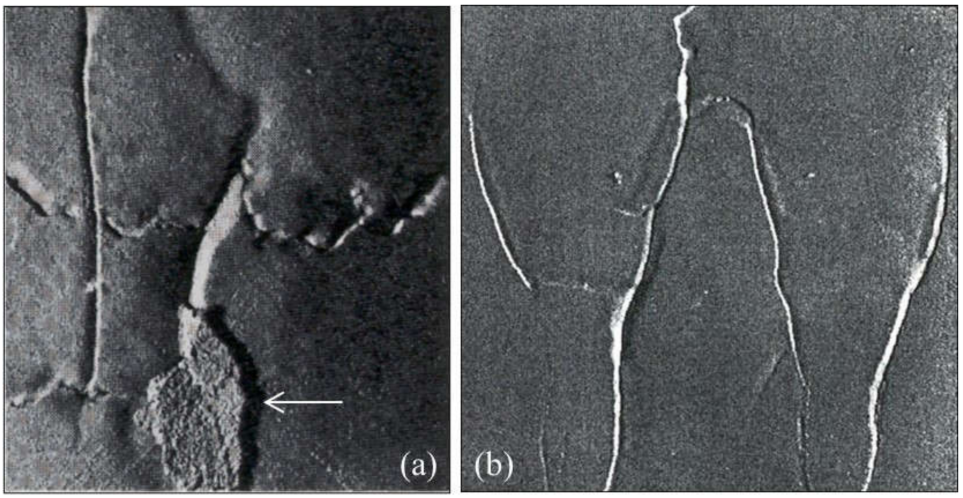

Figure 27. Rattails in flat surfaces of iron castings with high (**a**) and medium (**b**) incidence (Reprinted with permission from ref. [17]. Copyright 1999 American Foundry Society, page 186). In (**a**) a common scab (highlighted with a white arrow) is formed together with rattails.

Modern casting practices have minimized the appearance of rat tails in castings. However, a common mistake is to confuse "rat tails" with "veining", which is described in Section 2.3.5.

2.3.4. Solid Scabs

A particular type of scabbing is obtained when a suspended bridge on the surface of the cavity roof is broken before the cavity is filled by the melt. The sand pieces fall onto the surface of the melt and are eventually trapped by the melt as it fills. They then stick to the roof of the cavity, resulting in prints on the upper surfaces of the castings (Figure 28). A characteristic feature of these prints is that sand grains are observed in their inner corners.

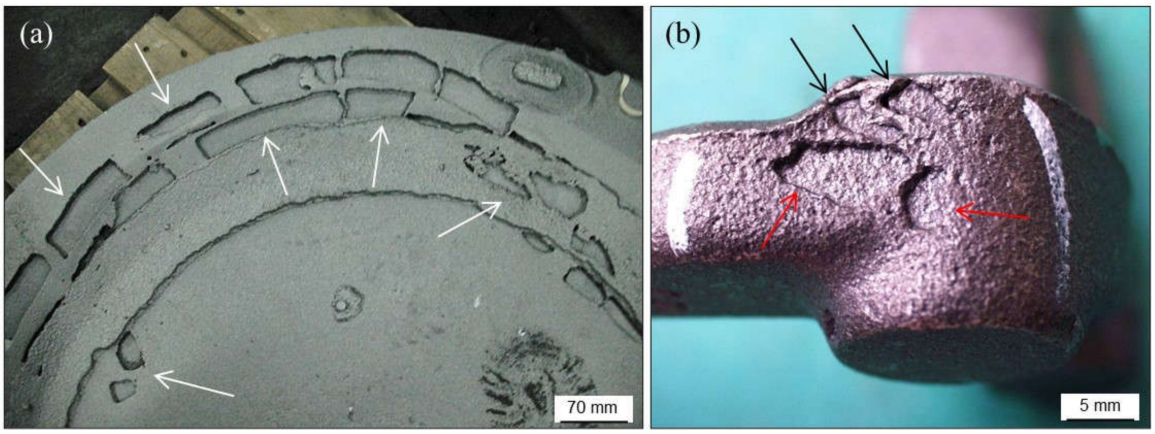

Figure 28. Solid scabs found in (**a**) a heavy-section ductile iron valve manufactured in a green sand mold with large flat surfaces; (**b**) a ductile iron caliper.

A "coating scab" is a variety of this defect caused by damage to the coating applied to molds and/or cores. This damage is primarily due to overheating in the affected area and/or the use of improper coatings. In all cases, these broken pieces lead to sand inclusions in other areas of the castings.

2.3.5. Veining

Veining shows up as irregular and thin metal sheets or crests [23], which raise from the surface of the casting, often following irregular lines (Figure 29). This is the only defect with a formation mechanism differing from the rest of defects described in this Section 2.3. Veining is the result of two steps: a crack is formed in rigid and highly compacted sand molds due to thermal expansion, and this crack is finally occupied by liquid metal. Veining should not be mistaken with mold cracking due to tensions, even though they are macroscopically quite similar. A detailed examination of the locations affected and of the thermal evolution in these zones could help to differentiate both defects.

This defect is mostly found in overheated areas of castings (hot spots), those locations with stress after solidification (abrupt section changes) and rigid areas of the mold. Chemically bonded sands commonly used for cores making are especially sensitive to this defect, as these compacted sand mixtures show high rigidity.

Though uncommon, veining can also be found in large castings made in green sand molds (see Figure 30) despite grains being widely surrounded by wet bentonite, coal and other burned compounds. Figure 30a,b show two views of a large gray iron engine block for which the filling was carried out in such a way that there was significant thermal radiation. In this case, overheated areas of compacted green sand led to the crests indicated with the white arrows in both images of Figure 30.

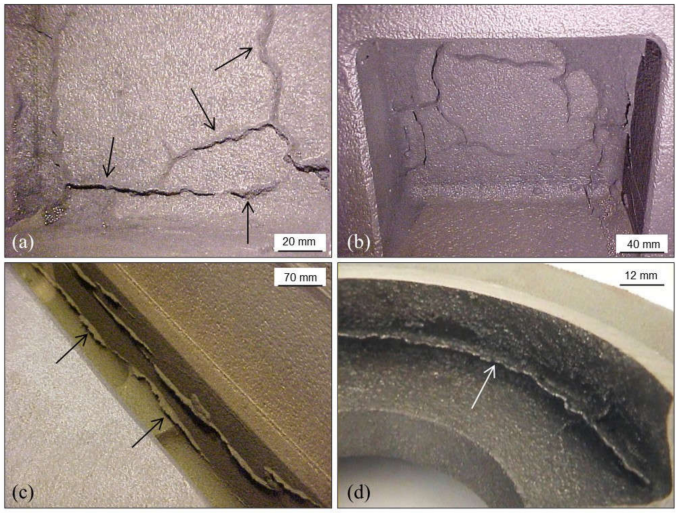

Figure 29. Veining in (**a**–**c**) ductile iron heavy-section castings produced with chemically bonded silica sand molds; (**d**) an internal area of a grey iron casting produced in a green sand mold with cores that led to the shown defect.

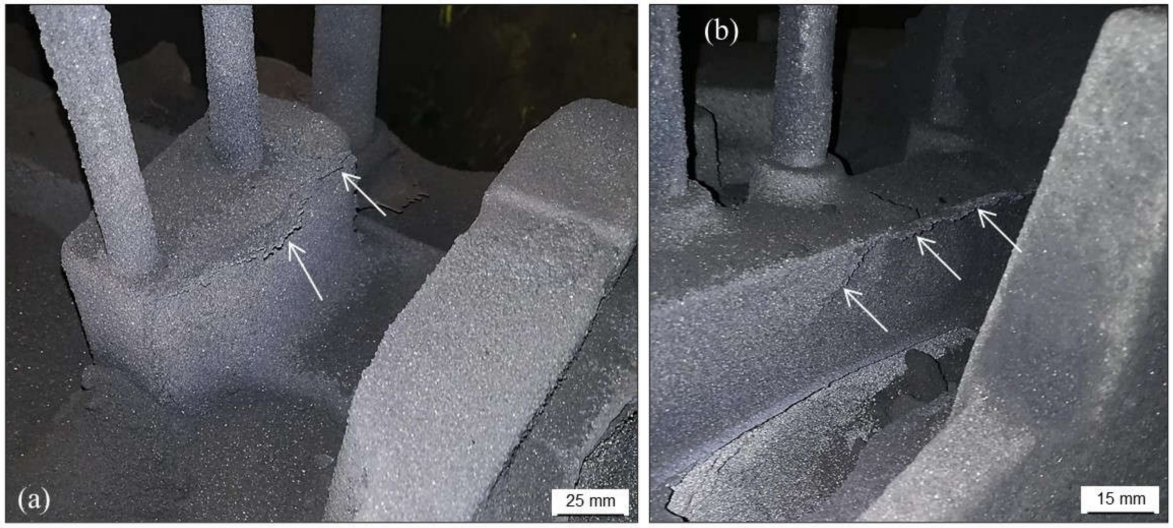

Figure 30. Veining in two different areas (**a**,**b**) of a grey iron engine block produced with green sand molds.

In addition to the general remedies listed in Section 2.3.6, veining can also be avoided by reducing the amount of binders during the manufacture of cores and molds to decrease their stiffness. A similar effect can be achieved by adding about 1–2 wt.% of iron oxides (Fe_2O_3 or Fe_3O_4) or coal to the resins so as to increase the flexibility of the bonded sand. The use of non-silica sands with low thermal expansion (chromite, zirconium and olivine) can also be a solution to avoid veining, although this is an expensive measure and difficult to use in foundries. A more common remedy is the use of suitable coatings.

2.3.6. Remedying Defects Due to Silica Expansion

Figure 31 shows a diagram summarizing the formation process of each of the defects described in this Section 2.3. The formation of these defects begins with prolonged thermal radiation to the mold walls, so the use of high casting temperature and low casting times increases the risk. The size and geometry of the mold are also important aspects, as these defects preferentially form in heavy sections and in geometries with extensive horizontal surfaces. The areas adjacent to the vents can also become overheated as superheated air begins to escape through the vent system.

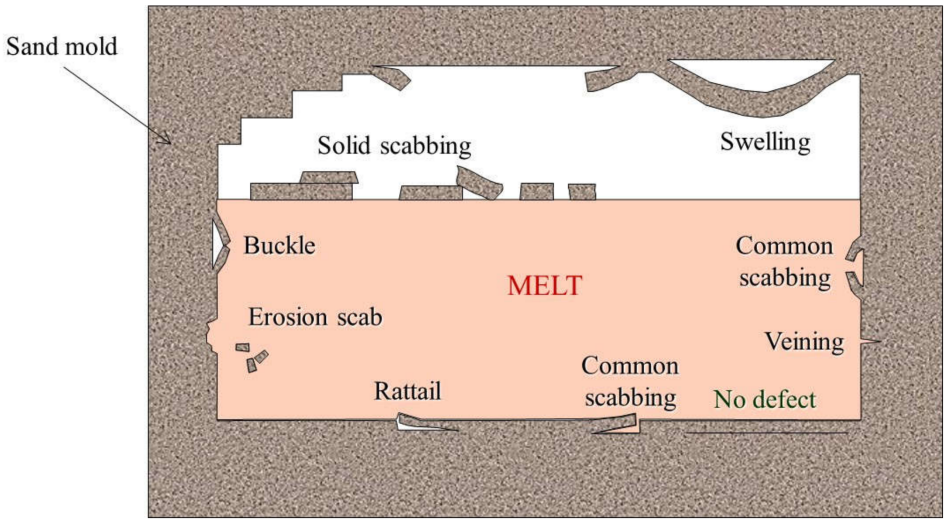

Figure 31. Schematic of defects related to silica expansion according to their formation process.

If the proper diagnostic of a given defect is scabbing, it is possible to list a group of measures to avoid this defect, following the aspects related to its formation:

- Effective control of silica grain sizes avoiding coarse and rounded ones.
- Use of sand distributions in which a minimum of three sieves must contain more than 10 wt.% of the total weight in a tested sand sample (compensated grain distributions to minimize cooperative expansion effects).
- Keep satisfactory contents of bentonite, coal (high enough loss on ignition values) and fines in the green sand mixtures to cover all grains with enough coating and to compensate for expansion efforts.
- Keep adequate strength values in the green sand with proper bentonite and water contents.
- Avoid the use of low-quality bentonites, contaminated water and/or ineffective mixing processes.
- Minimize pouring temperatures to limit possible overheating effects in any area of the cavities.
- In case of coated molds or cores, assure a proper adsorption of the product to guarantee that sand grains are correctly surrounded and also protected against intense radiation.
- The tendency of a given green sand mixture to scabbing is evaluated with the parameter "wet tensile strength" that should be kept higher than 0.20–0.25 N/cm^2.

2.4. Inclusions

Inclusions are "*Particles of foreign material in a metallic matrix. The particles are usually compounds (such as oxides, sulfides, or silicates), but may be any substance that is foreign to (and essentially insoluble in) the matrix*". As seen in Figure 32, the most common foreign compounds are slag and dross, sand, graphite and inoculant.

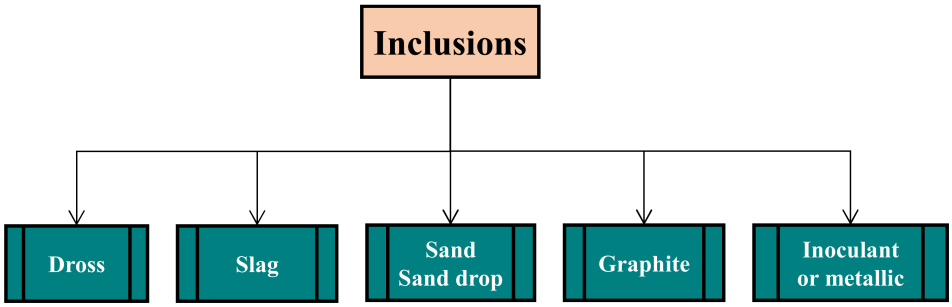

Figure 32. Classification of inclusions found in iron castings.

2.4.1. Slag Inclusions

Slag inclusions, i.e., "*slag or dross entrapped in metal*" are non-metallic inclusions of irregular shape and different sizes (Figure 33) with some tendency to appear in the top parts of castings [24]. Slag inclusions are sometimes found together with gas porosities because the compounds that make up the slag can be oxidizing and react with the dissolved carbon in the cast iron melts to give carbon monoxide (see Section 2.1.2). Although this defect can be mistaken by the naked eye for other types of inclusions (notably sand inclusions), a close inspection can distinguish them. Slag inclusions are highly irregular and porous and generally do not contain sand grains. If there is any doubt, metallographic and SEM characterizations should definitely help to correctly identify the inclusion under investigation. Castings with slag inclusions are not accepted by customers because these defects are discontinuities in the material that strongly affect mechanical properties and/or machinability.

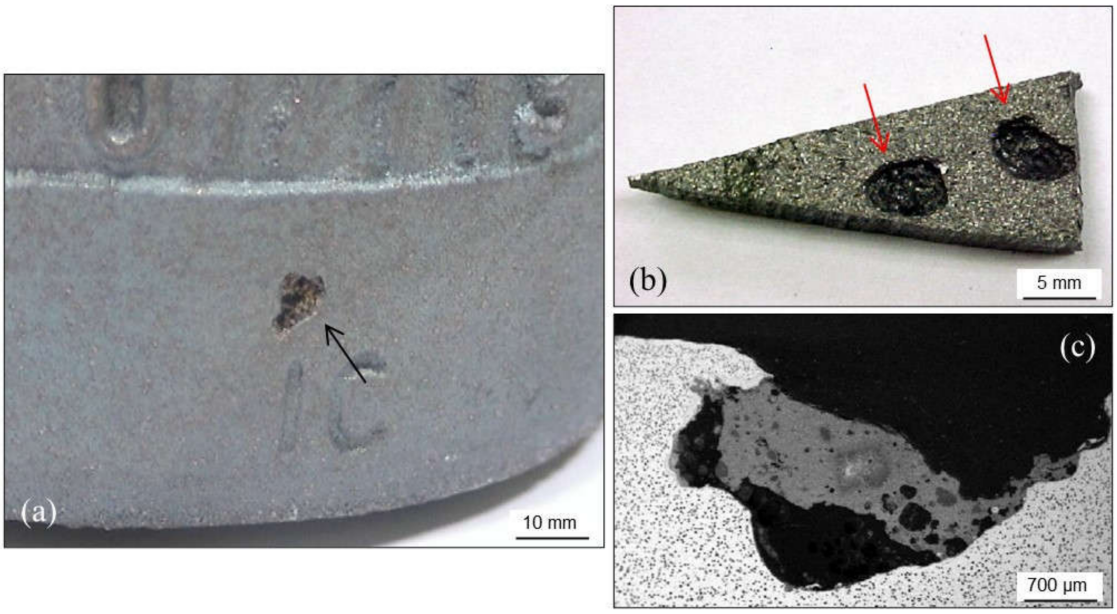

Figure 33. Slag inclusions found in the surface of iron castings (**a**,**b**). Internal characteristics of a slag inclusion in a ductile iron casting (**c**).

A first possible origin of the slag inclusions is that they formed before filling and were carried away during the filling of the mold cavity. Depending on the density of the slag, inclusions may remain inside the casting if the density is high or appear on the upper surfaces by floating if the density is low. These two types of inclusions behave differently during casting. In the first case, the slag is in the form of semi-solid aggregates of a slightly darker color than that of the melt, and of sufficient flowability to have a tendency to stick to the refractories lining the ladles, pouring basins, etc. In the second case, solid slag aggregates are clearly identifiable because they float and remain on top of the melt, so proper deslagging allows for easy removal. With proper casting practice, this second type of slag generally does not go into the molds, while semi-solid slag can certainly be introduced into the mold cavities.

The slag inclusions discussed below correspond to defects that form in the mold as a result of interactions between the constituents of the cast iron, the oxygen present in the cavities and in the walls of the mold and the compacted sand mixtures. The composition of the slag inclusions is very variable because it depends on the additions made during casting (nodularization step in ductile cast iron, inoculation, etc.), on the composition of the cast alloys, on the nature and state of the refractories, on the casting time and temperature, on the layout used in the molds, etc. However, it is possible to define a characteristic composition of the slag formed in ductile and gray cast iron. For the former,

SEM microanalyses generally provide a peak of Si, O and Mg as well as other minor elements (Ce, La, Ca, etc.). For gray cast iron, the slag is mainly formed of Mn and S, as well as a variety of other low-level elements. In all cases, the metal matrix surrounding the slag inclusions typically has significant amounts of iron oxide films and degenerate graphite particles as in ductile iron castings (Figure 34).

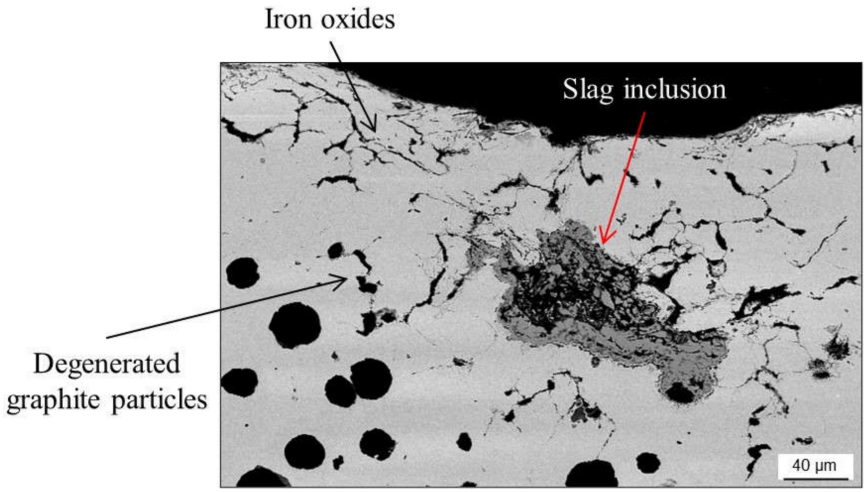

Figure 34. Metallographic cross section of a slag inclusion in a ductile iron casting.

Both slag inclusions already formed before pouring the melt into molds and those formed in-mold can change their composition when interacting with compacted sand grains. Thus, remedies for minimizing slag inclusions can be applied to melts and to molds and sand mixtures as listed in the following [25,26]:

- Reduce the amount of oxides present in the metallic charges used for preparing base melts.
- Increase the pouring temperature (slag inclusions can be easily trapped in the alloy when increasing cooling rate). Temperature-controlled pouring systems show lower risk than manual pouring ladles. Note that it is the pouring temperature of the last molds that you should pay attention to.
- Avoid long time periods between melt preparation and the pouring step.
- Keep proper S vs. Mn ratio in the melts. For grey irons, the optimal ratio is given by Mn (wt.%) = 1.7·S (wt.%) + 0.2.
- Assure satisfactory deslagging of melt batches before pouring.
- Use refractory materials in casting tools with low reactivity at high temperature.
- Pouring practice must guarantee that cup and down sprue are totally full and that the filling is not interrupted.
- Slag inclusions formed into molds are quite related to turbulence. Check if improvements could be made to the layout to smooth filling, that the section changes in runners and ingates are appropriate, if filters or slag trapping shapes can be added, etc.
- Avoid contaminations and excessive contents of not refractory constituents in the green sand mixtures. This means that a proper regeneration level is needed, adding new silica sand.
- Assure a correct compaction of sand grains during molding processes for minimizing interactions with the melts.
- Keep high enough loss on ignition values in the green sand mixtures (reduction of reactive oxygen level in molds).

2.4.2. Dross

The term "dross" is defined as "*the scum that forms on the surface of molten metal largely because of oxidation but sometimes because of the rising of impurities at the surface*", and it refers to an especial case of slag inclusions mainly found in heavy-section ductile iron

castings [27,28]. This defect is composed of nonmetallic precipitates (sulfides and oxides of silicon, manganese, aluminum, and primarily magnesium) from reactions between the liquid alloy and the oxidizing elements in the sand molds and the gases present in the cavities (oxygen and water vapor). Although it is not common to find dross inclusions in the skin of castings, they can sometimes be detected as dark areas of irregular appearance (Figure 35a–c). After machining, the areas affected by this defect become more obvious, showing a dark shadow with a low metallic sheen. Metallographic inspection of the affected areas shows a network of interconnected curved lines (Figure 35d).

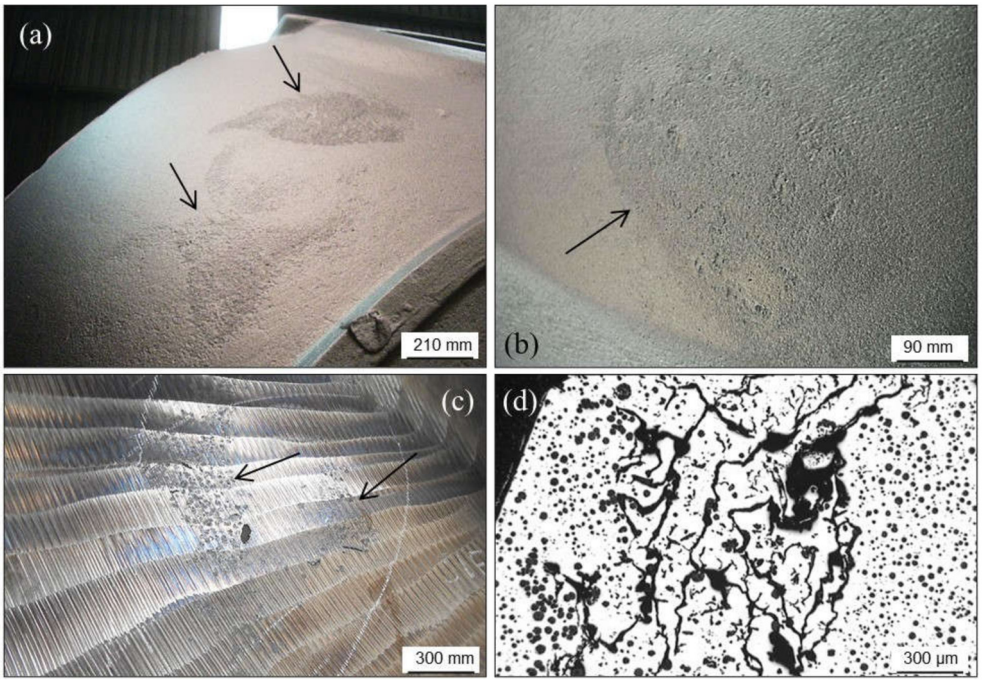

Figure 35. Dross inclusions in heavy-section ductile iron castings (**a**–**c**); metallographic view of a dross inclusion in the same castings (**d**).

Figure 35d suggests turbulent flow of the melt into the mold and as the alloy begins to solidify. It is possible that reactive elements such as Mg contribute to the increase in aggregate size during solidification. Although the location of dross inclusions is variable and dependent on filling and turbulence, the most critical areas are hot spots, turbulent areas and the upper portions of the castings. It has also been reported that high carbon equivalent favors the formation of dross-type slag.

Although other elements also contribute (O, S, Si, C, Al, etc.) to the formation of dross, the main cause is the reaction of elemental magnesium dissolved in the liquid alloy. It should, therefore, be considered that the risk of dross formation is permanent in Mg-treated cast irons, even after successive cleaning. Thus, the use of oxidized wet linings in ladles and casting facilities, poor quality steel scrap and low loss on ignition values in the greensand mixtures used to prepare the molds can trigger this type of defect. These aspects apply to the common slag inclusions described in Section 2.4.1. Since heavy-section castings are susceptible to dross inclusions and these large castings are typically made in molds produced with chemically bonded sand mixtures, it is essential to ensure a minimum moisture content in these mixtures.

It is considered that a pouring temperature below 1400 °C is conducive to the formation of slag inclusions, including dross. Such a limit depends on the size of the part, the characteristics of the layout, the composition of the alloy, the condition of the casting tooling, etc. Heavy section castings are commonly produced with casting temperatures below 1350–1370 °C and they are, therefore, subject to dross formation. Therefore, a correct mold layout, without turbulence and allowing gas evacuation, is essential.

2.4.3. Sand Inclusions (Sand Drops, Sand Cuts and Sand Washes)

Many foundries still prefer the use of green sand mixtures because they are comparatively cheap and recyclable. Specifically, casting in green sand molds is still appropriate because their strength is usually high enough. However, compacted green sand is susceptible to erosion, which is probably the main reason for sand inclusions in castings produced with these molds. This is the most common defect in castings made with sand molds.

The low severity version of this defect is the presence of a small number of sand grains on or near the surface of the part which can be termed "sand drop", that is: "*A casting imperfection due to a portion of the sand dropping from the cope or other overhanging section of the mold*". This definition is a bit too restrictive, as sand inclusions have various origins, which will be detailed in this section. If the defect is more extensive and even affects the original geometry of the casting, it may be termed a "sand cut" (Figure 36a). According to the third definition in the ASM glossary a cut is a "*Defect in a casting resulting from erosion of the sand by metal flowing over the mold or cored surface*". Finally, when a very serious defect is found in a casting, it is usually referred to as a "sand wash" (Figure 36b). In this last case, the molds have been severely damaged and sand inclusions appear with metallic protrusions in nearby areas or in other sections. It should be emphasized here that all defects involving cracks in the mold surfaces (silica expansion defects, erosions, etc.) are potential sources of sand inclusions.

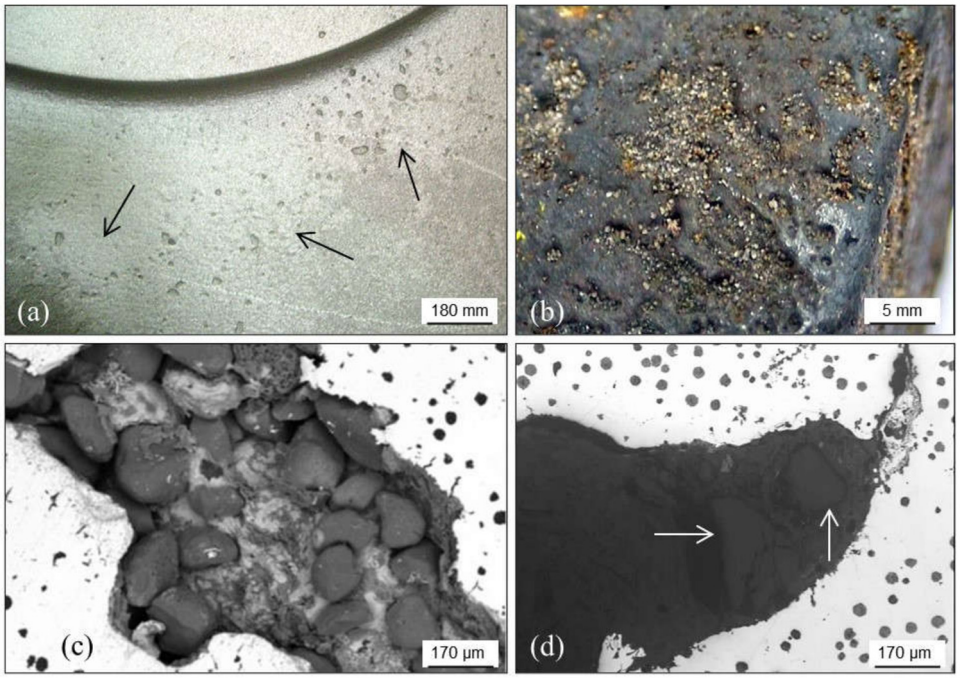

Figure 36. Sand inclusions found (**a**) in a heavy-section ductile iron casting and (**b**) in a grey iron casting produced in a dry green sand mold. Images (**c**,**d**) show micrographs of sand inclusions in ductile iron castings.

As mentioned previously, sand inclusions can be easily mistaken with slag inclusions when observed with the naked eye; compare Figures 33b and 36a. The presence of small pale-colored grains adhering to the internal surfaces of the defects would be helpful for identifying sand inclusions. Such grains can be seen deteriorated or fractured due to shot blasting and the diagnosis should be confirmed via metallographic inspection, where the sand grains can be analyzed in detail (Figure 36c,d).

The two most severe versions of sand inclusions, cuts and washes, appear as rough areas on the surface of the castings along with severe damage to the original forms or even irregular holes due to a lack of cavity filling (Figure 37). The cavities left by mold erosion result in protrusions on the surface of the casting while sand is displaced to other

areas of the casting to form extensive sand inclusions (Figure 37c). It is interesting to note the similarity in the shape of the erosion scabs and the sand cuts and washes; compare Figure 26 with Figure 37e,f. However, they have opposite causes, with the sand cuts and washes being due to poor mold compaction, whereas the erosional crusts are related to highly compacted molds.

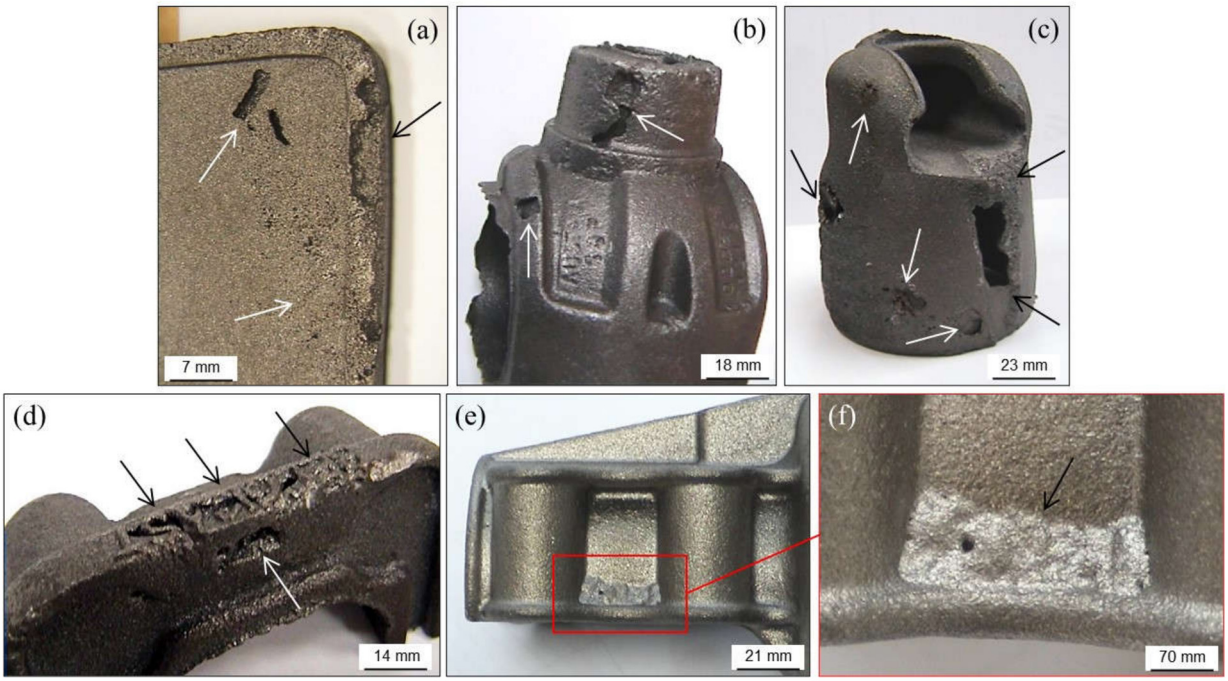

Figure 37. Sand cuts and washes in different locations of ductile iron castings (**a**,**b**,**d**–**f**). Severe sand wash in a malleable iron casting (**c**).

Although the distribution of small sand inclusions or sand drops in the casting surfaces may be irregular, it is common to find a reason for the defect, such as improper filling, damage to the cores during the assembly steps, compaction problems during molding, etc. One possibility is to check a few cast bunches with all cavities remaining attached to the runners to define the most affected areas and determine the origin of the sand inclusions. However, it is certainly difficult to handle molds and cores without any erosion, damage or deviation during assembly. Therefore, some level of "loose sand grains" is always present and can cause sand inclusions in the castings. An effective method of removing these loose grains is to blow out entire drags and copes before closing the molds. It should be noted also that limited damages to the molds should appear quite randomly and could not be a regular cause of sand cuts or washes.

Effective control of sand mixture properties should prevent low strength, low plasticity and friability in all areas of the molds. In green sand molds that cannot be cast soon after manufacture, one possible way to delay significant property losses is to reduce the temperature of the sand mixtures and/or use moisture-retaining compounds, such as carbon or dextrin. While these remedies may help, they are not considered appropriate measures in casting processes. The most common problems related to sand inclusions are as follows [29]:

- The use of green sand mixtures with low moisture or compactability. Water makes bentonite play its necessary role of bonding the sand grains so as to maintain effective compaction. Low water content, thus, originates high erosion risk in molds both before pouring and when filling the molds (friability).
- Poor mixing, which leads to irregular absorption of water by bentonite and other constituents of the mixtures, leading to fractions with low humidity and high friability.

- Low bentonite content in the sand mixtures (bentonite originates strength in the compacted molds).
- The use of sand mixtures with high contents of coarse grains (low AFS index values) and of silica grains (highly regenerated mixtures).
- High carbon content, capable of absorbing most of the water intended for mixing with bentonite.
- Poor compaction of sand mixtures during the molding step (free grains or groups of grains).
- Pouring molds produced long time ago (drying effect is always present).
- Turbulent and/or aggressive filling of molds which increase the risk of erosion.
- Damages produced on any part of molds and cores as a result of bad practice during molding step (not correct closing of drag and cope, inefficient core prints which allow some core shaking and erosion in the touching areas, molds and cores damaged during handling or being transported, etc.).

2.4.4. Lustrous Carbon Inclusions

The use of coals as a constituent of green sand mixtures is necessary to minimize oxidation reactions between liquid alloys and molds. The carbon in the coals reacts with oxygen to form CO/CO_2 gas and create a reducing environment at the metal–mold interface. When the oxygen has been consumed, lustrous carbon films precipitate around the sand grains on the inner surface of the mold. The defect is seen when portions of these films are removed from the interfaces and are engulfed in the liquid alloy [30]. After solidification is complete, the lustrous carbon films remain trapped as inclusions. This type of inclusion is not commonly found in cast iron parts.

However, the defect usually appears as flow marks, thin metallic layers (Figure 38a,b) or, occasionally, smooth inclusions on the upper casting skin. In some way, this defect can show an aspect similar to gas blowholes close to castings surface (see Figure 10c,d). However, the inspection of the surface below the external thin layer shows important amounts of precipitated graphite (Figure 38c,d). Sand grains can be also observed in these inclusions, as they are present in the metal–mold interfaces (see the black arrows in Figure 38c).

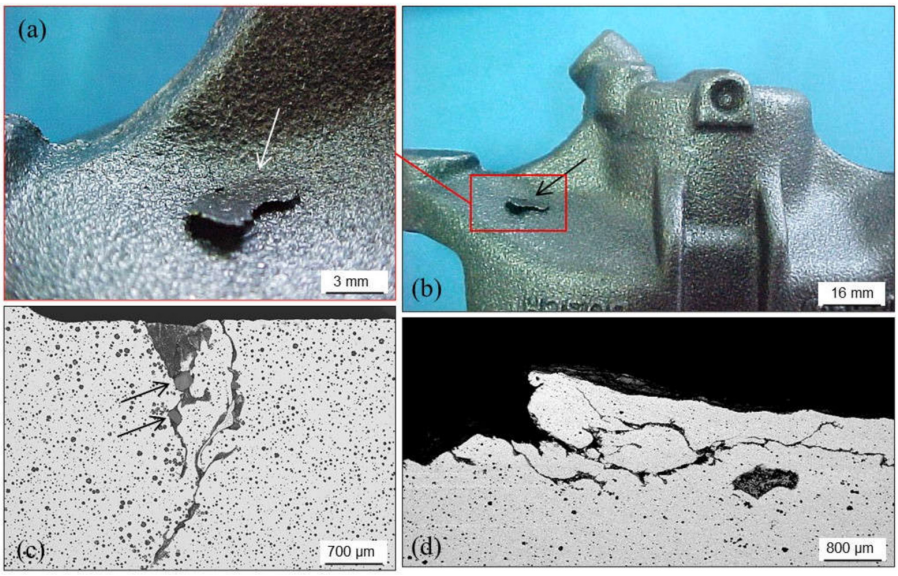

Figure 38. Lustrous carbon inclusions in ductile iron castings: (**a**,**b**) automotive caliper, and (**c**,**d**) metallographic cross section view of this defect.

The two main reasons for this defect are, first, high loss on ignition values due to excessive carbon content in sand mixtures and, second, turbulent filling during pouring that separates the lustrous carbon films from the mold interface. Once solidified, the alloy

retains the carbon inclusions with most of their layered characteristics. Further reasons can be also considered [31–33]:

- The use of low pouring temperatures and high pouring times and/or of long runners, which promotes relevant temperature losses in melts.
- If blue shades are detected close to the defect, the most probable cause is the high content of coal in the green sand mixtures used to produce the molds.
- Organic resins used for hardening cores are also burned when pouring the molds, increasing the lustrous carbon deposited.

2.4.5. Inoculant and Metallic Inclusions

The final composition of cast irons is obtained after the addition of certain metallic or semi-metallic ferroalloys to the liquid alloy at various stages of the manufacturing process. These products are expected to dissolve fairly quickly in the melt before pouring. However, some ferroalloys, such as FeMo, FeCr or FeNb, can cause inclusions in castings because they dissolve relatively slowly and some fragments of the additive can become embedded in the matrix [34,35]. A particularly important case of rapid dissolution is the post-inoculation of castings just before mold filling. Thus, grain sizes of about 0.2–0.8 mm and efficient addition tools are used to ensure proper dissolution of the inoculant (FeSi alloy with minor amounts of active elements, such as Ca, Al, rare earths, etc.). Despite all these controls, sporadic errors may occur, and metallic inclusions are observed in the castings.

If the metallic inclusions are small or if a single inclusion is found, they may resemble other common inclusions (sand or slag). However, severe variants of this defect present in the skin of the castings result in irregular surfaces sometimes with a porous appearance, as shown in Figure 39. In this case, the inoculant had been added to the pouring cup a few seconds before pouring began. The inoculant grains had begun to aggregate and the subsequent metal flow carried them into the mold. Because some of these inoculant aggregates were not completely dissolved, they eventually settled in some areas of the castings (arrows in Figure 39b). Metallographic analysis of the affected area shows that the inoculant grains are partially dissolved in the alloy (Figure 39c).

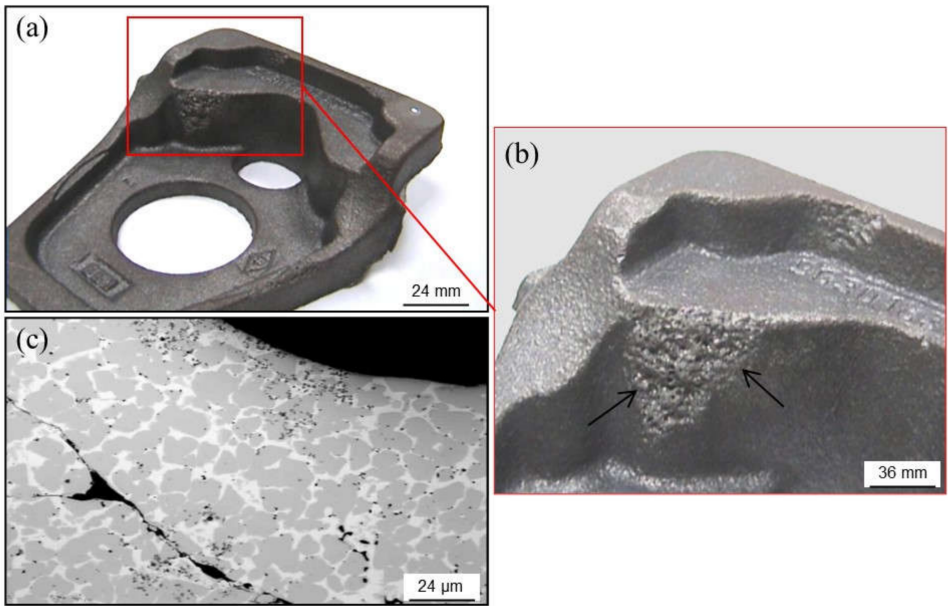

Figure 39. Macroscopic view of a metallic inclusion in a ductile iron casting produced in a vertical molding line with post inoculation (**a**,**b**). Metallographic view of an inoculant inclusion (**c**).

If the defect is located below the casting skin, it is commonly found after machining as areas with different shade than the matrix. Once the affected surfaces have been polished,

the defects can be easily detected (Figure 40a), and their limits are even better defined after etching with Nital reactant (Figure 40b).

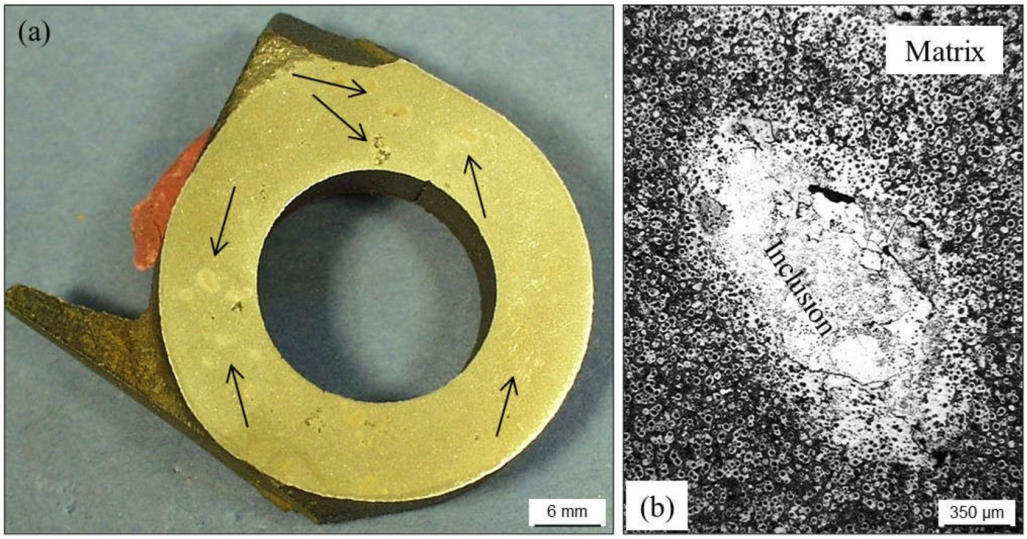

Figure 40. A group of metallic inclusions found in a polished cross section of a ductile iron casting (**a**). Optical micrograph of one of these defects after etching with Nital for 10–15 s (**b**).

As well as too early additions of inoculant into cups and down sprues present in molds, other processing aspects such as the use of low pouring temperatures, too coarse inoculant grains for post inoculation, wrong position of the inoculation pipe, etc. also promote the formation of this kind of inclusions. For other products, such as FeCr, FeMo, etc., low temperature in melts when adding these ferroalloys can originate metallic inclusions, also promoting the formation of high hardness areas and negatively affecting machining. A proper control of each of these aspects should eliminate any metallic inclusion in castings.

3. Mold-Related Defects

This section gathers three different sources of defects, those due to molding practice, those resulting from interaction between the melt and the molds and, finally, cracks appearing in the casting during solidification or post-solidification cooling (Figure 41).

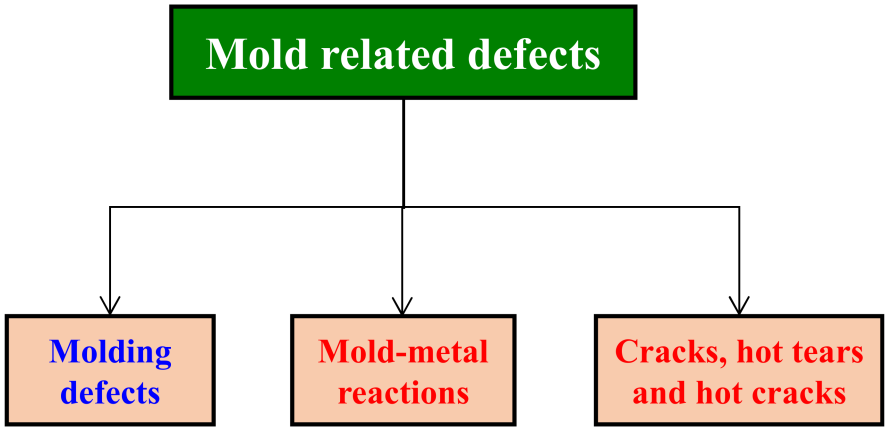

Figure 41. Different types of casting defects related to molds.

3.1. Molding Defects

Horizontal sand molds are primarily composed of three components: drag, cope and cores. In the case of vertical molding lines, the molds are produced by closing successive units of compacted sand, which are then stacked to form a chain of molds without frames

(cores are introduced just before closing step). Drags and copes and cores are made by compacting mixtures of green or chemically bonded sand against patterns, which are usually made in metal or solid resins. On the other hand, cores are manufactured with chemically bonded sand mixtures which are first shot into metallic boxes and then hardened. These tasks are preferably carried out in automatic high-pressure molding lines, except for small series or large-section parts for which "artisanal" compacting with wooden models is commonly used. On the other hand, metal or wooden boxes containing the required shapes are used for the manufacture of sand cores, which are then cold or bake-hardened.

Once all the components are available, the molding stage begins with the installation of the cores into the corresponding cavities of the drag. The cope is then put in place and the drag and cope are mechanically locked together. Additional components, such as filters, sieves, brackets, etc., can also be placed in the drag. Before closing the assembly, proper blowing of all components should be performed to minimize free sand. This section describes six different common problems listed in Figure 42 that are associated with mold preparation errors.

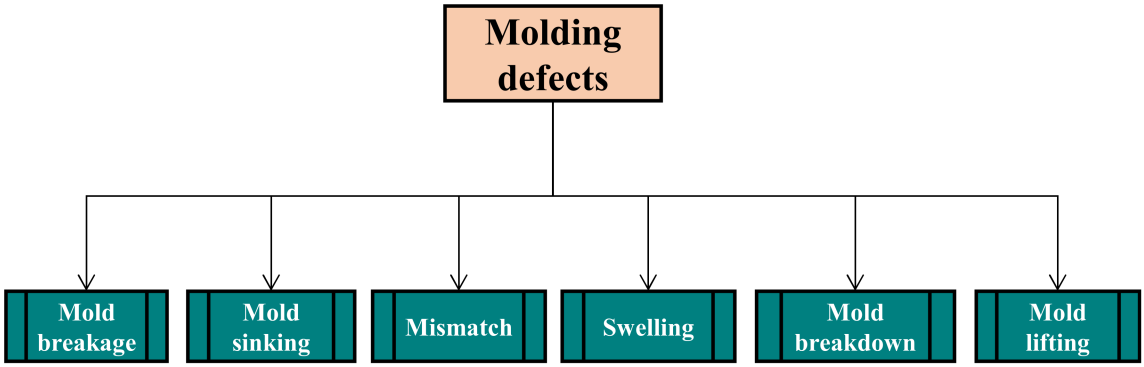

Figure 42. Classification of the different molding defects considered in this section.

3.1.1. Mold Breakage

Mold breakage leads to defective castings such as those illustrated in Figure 43. The defects can appear as metallic, irregular and rough protrusions at the surface of the casting (Figure 43a,b), as significant changes in the original shape of the casting (Figure 43c) or as lack of matter (Figure 43d). Although it is difficult to relate such breakages to any special location in molds, those areas with high prints and/or with complex shapes are considered as risky areas [36].

The examples in Figure 43 were selected to illustrate the most common defects. When a crack has appeared in a mold, e.g., because of high deformation of the compacted sand, the liquid penetrates in the space open by the crack either during or after filling the mold (Figure 43a,b). Other variants of mold breakage can also originate severe erosions and irregular oversized surfaces in castings (white arrows in Figure 43c and deformed areas in the casting as shown in Figure 43d). Compacted sand fragments originated during breakage can lead to sand inclusions and voids or lack of matter where the fragments deposited. Breakage can also occur in cores and important changes of geometry are produced in the affected areas (see the white arrows indicating protrusions and the black arrow pointing a relevant burr in the casting shown in Figure 43c). Figure 43d illustrates a case of lack of matter due to the lack of a core (the white arrow indicates the zone for one of the core prints). The mold broke during the filling step because of the increased amount of liquid alloy poured.

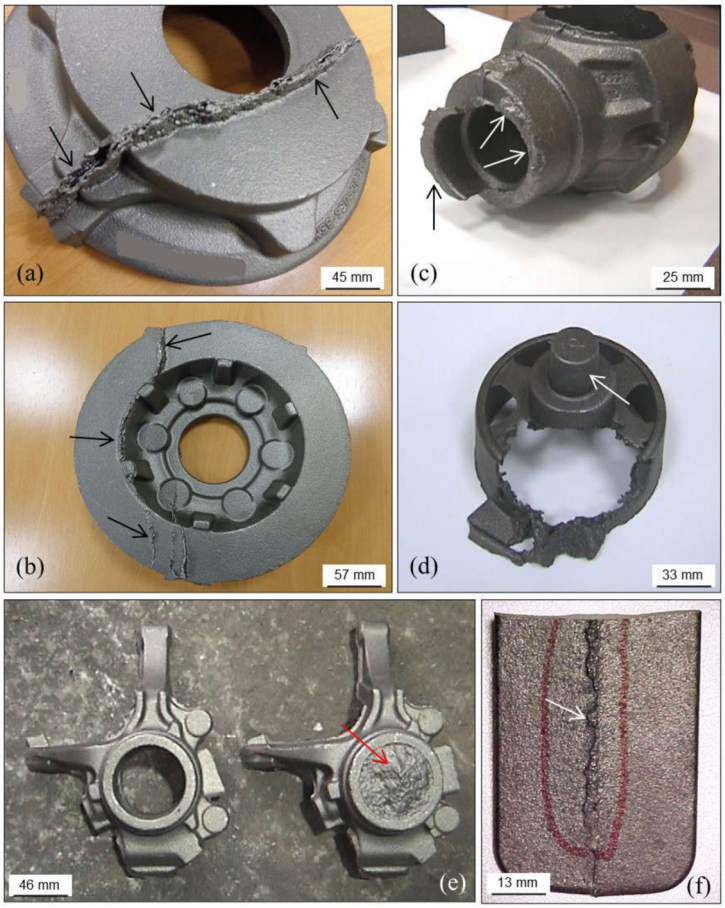

Figure 43. Images (**a**,**b**) show a metallic wall in a compacted iron casting due to mold cracking. Image (**c**) shows an irregular internal void in a ductile iron differential housing due to a core breakage (white arrows), which also originated a coarse burr (black arrow). (**d**) Effects of massive mold breakage in a grey iron casting due to a lack of setting a core before pouring. (**e**) In the steering knuckle on the right, the internal void was not obtained as the corresponding sand boss broke during molding step. (**f**) Mold breakage in the partition line of a casting due to local stress when closing the mold.

During mold preparation, if sand mixtures show high compactability or high strength, or if complex models with high prints are used, mold fragments can be broken when separating drags and copes from pattern plates. The produced mold is, thus, damaged and the castings will reproduce the originated broken surfaces (red arrow in Figure 43e). In case the sand fragment remains stuck to the model in the pattern plate, all successively produced molds will reproduce the defect until cleaning the model. A final possible cause of defect is when the mold is closed and that stresses are generated when drag, cope and cores enter into contact. In that case, a mold can break, as illustrated in Figure 43f.

As these examples show, mold failure can be caused by a wide variety of reasons, most of which are related to both the properties of the sand mixture and the practice of molding, as the following list of possible causes indicates [36,37]:

- Too high moisture and/or compactability of green sand mixtures, often leading to low strength and high deformability of the molds.
- Too low moisture and/or compactability of green sand mixtures, which makes the compacted sand dry-rigid and friable with high risk of mold cracking. This can be related to the use of hot sand mixtures that get quickly dry and friable.
- Low homogeneity of sand mixtures due to low mixing time, malfunction of mixers, irregular additions of essential constituents, etc.
- Low temperature of pattern plates, which originates local condensation of water in those areas of sand mixtures in contact with the model. These areas remain stuck to

the model when separating drag or cope from the patterns. Good venting of pattern plates and an effective control of separation speed can prevent this problem.
- Insufficient demolding angles in models that make difficult separations of drags and copes from pattern plates.
- Low or irregular compaction of molds due to errors in the molding facilities, lack of demolding liquid, use of pattern plates without previous warming, wrong molding practices, etc.
- Closing molds carelessly and with impacts between drags and copes.

3.1.2. Mold Sinking

This defect does not relate to a characteristic shape, as it depends on the layout of the castings. In general, sinking appears as irregular depressions located below the expected surface of the casting and with a surface finish similar to the normal one after shot blasting (Figure 44). Most often, the contours of the sinking defect have the characteristics of a failure zone, for example with a section jump or step on the casting. This can be used to detect sinking areas, especially when these contours are partially deformed and evolve into cracks, so that mold failure can coexist with mold sinking, as shown in Figure 44a. However, sinking can also result in a slow and steady surface change that makes it difficult to detect the defect during inspection of the castings. In these cases, mold sinking can be confused with wall shrinkage (Section 4.1.1), although the ribs already mentioned are commonly present in the defect studied here. When sinking is severe, sand fragments can be released and sand inclusions are found in the castings.

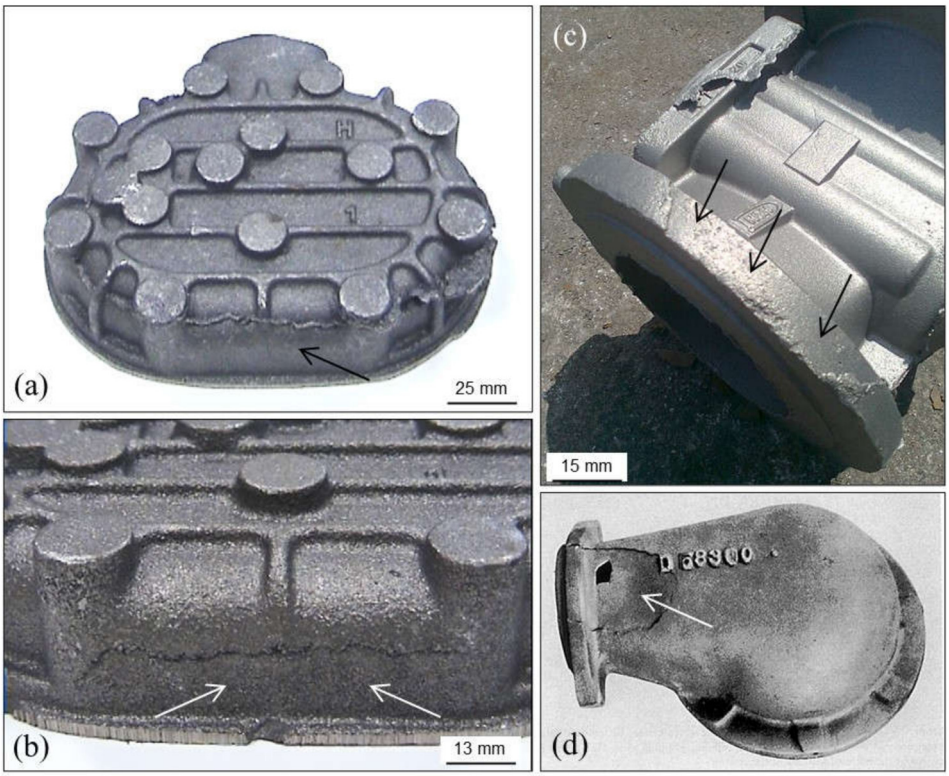

Figure 44. Iron castings with areas affected by mold sinking: (**a**,**b**) ductile iron covers with sunken areas close to the partition line; (**c**) a ductile iron valve with the defect affecting one of the flanges; (**d**) a cast iron part showing the defect (Reprinted with permission from ref. [17]. Copyright 1999 American Foundry Society, page 199).

Mold sinking is related to external or internal stresses and pushes made on molds during their manufacture, transport and/or pouring. External pressures can be due to heavy cores setting, molds piling and setting on irregular floors, knocking, use of excessive

weights on molds to avoid lifting effects during and after pouring, use of deformed metallic molding tools as flasks, lockers, etc. Additionally, low mold strength because of low compaction of sand mixtures or too high moisture, as well as too high rigidity due to the use of hot and/or dry sand mixtures, should be avoided.

3.1.3. Mold Failure or Collapse

Mold failure mainly occurs on green sand molds and occurs when the dynamic or metallostatic pressures are greater than the strength of the compacted sand. These pressures both increase with the height of the liquid poured into the molds, which is why the areas most affected are those at the bottom of the drags. Mold breakdown results in irregular projections of varying thickness and high roughness (Figure 45). This defect occurs during or immediately after the casting of the mold and, in the most severe cases, metal leakage can occur and the castings then exhibit misrun-type defects in the upper areas.

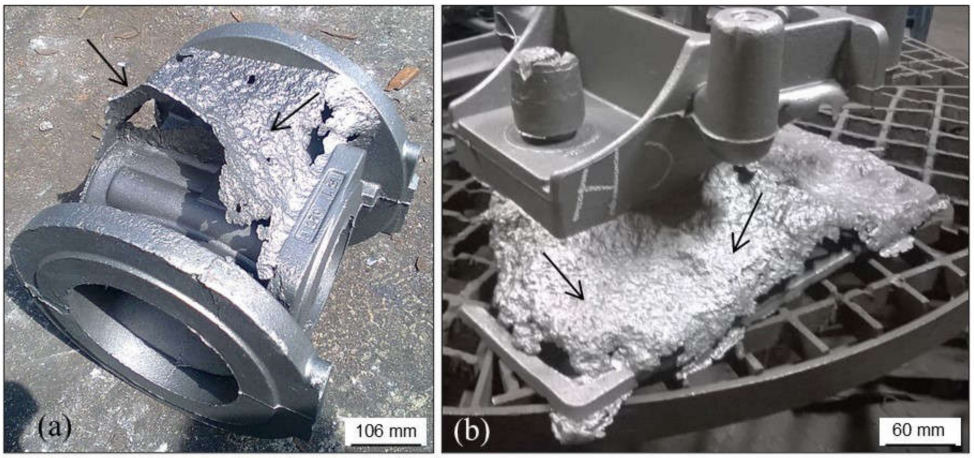

Figure 45. (**a**) Ductile iron casting with severe damages in the drag zone due to green sand mold breakdown. (**b**) Steel casting affected by green sand mold breakdown.

The effective strength of the mold depends mainly on three parameters: (i) the green compressive strength of the sand mixture, which is ensured by sufficient bentonite and moisture contents and appropriate mixing; (ii) the level of compaction, which depends on the molding and demolding methods; and (iii) the thickness of the mold, in particular the distance between the bottom of the cavities and the outer surface of the molds. Thus, careful attention to these three aspects, in addition to following the good practices indicated in Sections 3.1.1 and 3.1.2, should minimize defects caused by mold failures.

3.1.4. Swelling

The defect manifests itself as a thickening of the internal and/or external surfaces of a casting, and the affected areas have a poor surface finish [37,38]. Geometrically, it can be considered as the opposite of mold sinking. In fact, swelling occurs due to an increase in cavity volume caused by the development of pressure against the compacted sand. Such pressure may firstly be due to dynamic effects during the pouring of the liquid, but it appears to be most often caused once the cavities have been filled, and thus, is associated with metallostatic pressure, graphite expansion during solidification and stresses from thermal expansion of the sand grains. The deformation of the mold surfaces generates an oversize of the castings (Figure 46). When mold deformation occurs while the alloy is solidifying, voids may appear due to the lack of material to compensate for the increase in volume caused by swelling. The voids thus obtained are called "false shrinkage" and will be discussed in Section 4.1.3.

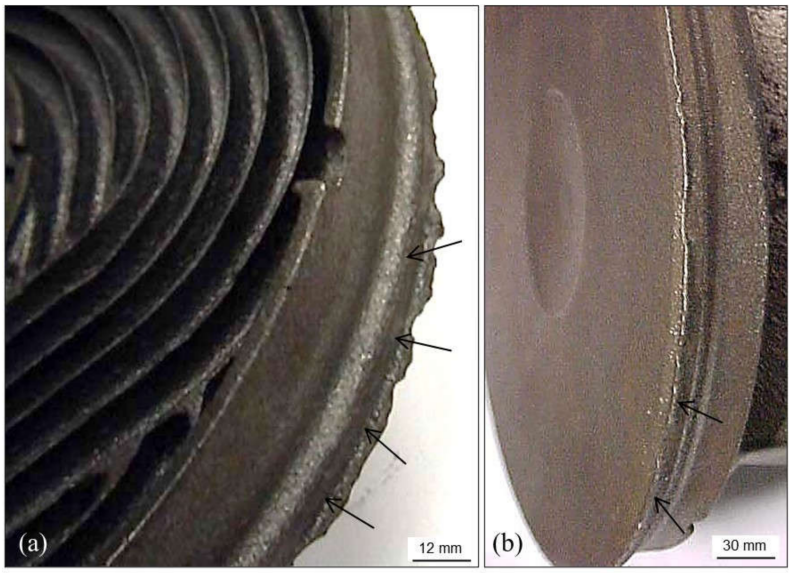

Figure 46. (**a**,**b**) swelling defect in a grey iron cook plate.

Severe levels of swelling can also cause cracks that should appear as burrs in the castings, while lighter levels of this defect are barely detected by normal visual inspection, so accurate dimensional checks of the castings are needed to reveal them. Another method of evaluating swelling phenomena in castings is to weight all the parts made in a given mold and compare the resulting values.

The main areas of swelling are the drag zones (lower parts of the molds) and those where the sand grains are loosely packed. With the exception of very stiff molds (dies and almost all those made with chemically bonded sand grains), all molds and especially those produced with green sand mixtures undergo some level of swelling after filling. Clear evidence of this is the increased calcination and metal penetration in castings produced in the lower mold cavities compared to those produced in the upper cavities. As discussed in Sections 2.2.4 and 2.2.5, such a difference in surface quality is due to the metallostatic pressure that increases with the height of the liquid alloy in the molds. The usual practice to compensate for the greater swelling in the lower part of the molds is to reduce the dimensions of the patterns used for molding the bottom cavities.

The main causes of swelling are the same as those listed for the defects presented in Sections 3.1.1 and 3.1.2. Specific causes are the use of alloys with high graphite expansion in the solidification stage, low strength of metal flasks in horizontal molding lines or low sand wall thickness in molds, high mold height (high metallostatic pressure on molds), intense pouring flows (high dynamic pressure on molds), etc.

3.1.5. Mismatch

Most molds used in industry are made by joining two parts or half-molds, called drag and cope. This joining is usually referred to as "closing" a mold and involves correctly matching the cavities of the two half-molds. The mismatch comes from errors in this matching of drags and copes and generates a displacement of one half-mold relative to the other [39]. In the case where the defect is due to errors during the placement of the cores in the molds, it appears at the junctions between the drags or copes and the cores. Figure 47 shows some examples of jumps and steps found in the parting lines.

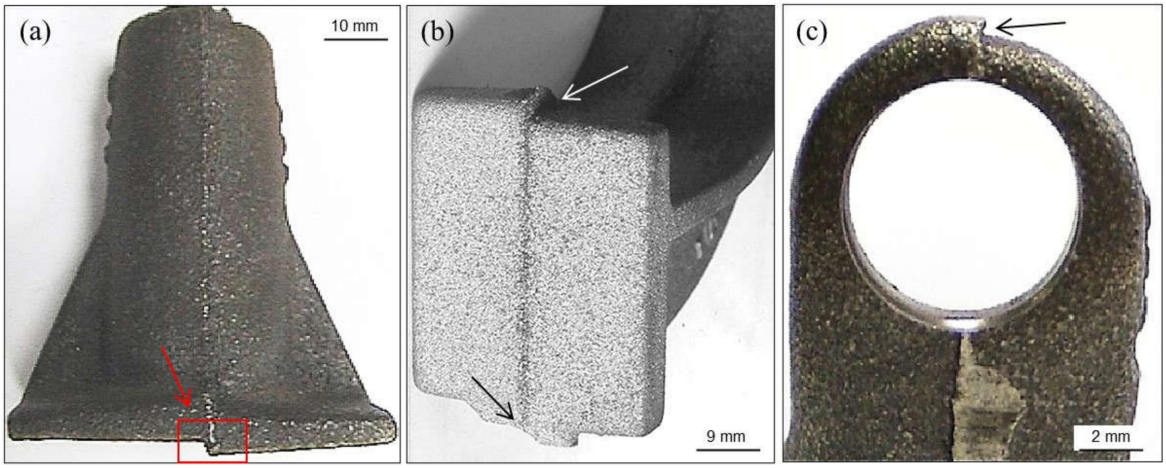

Figure 47. Mismatch defect in ductile iron castings: (**a**,**b**) steps found in the ends of the partition lines and (**c**) change of the casting section after machining a hole in the casting.

As mentioned above, the main causes of mismatching in castings are related to movements of drags, copes and cores. The most important detailed reasons for this defect are the following:

- Any external action which provokes deviations of matching between drags and copes.
- In horizontal molding lines, too much clearance of the lugs and pins, which does not guarantee a correct match of drags and copes.
- Malfunction of molding operations and/or of molds transport systems in automatic vertical molding lines.
- Too high dynamic and metallostatic pressure in the molds, which can push cores out from their correct locations.
- Too high dimensional tolerance of core prints.
- Inadequate locking of horizontal partitioned molds (low and/or unbalanced clamping of closed molds). Incorrect location of counterweights on molds.

3.1.6. Mold Lifting or Mold Separation

Although severe cases of this defect are quite unusual in modern high-pressure molding machines, mild forms can still be observed. The defect manifests itself as a thickening in the parting line (Figure 48), associated with the fact that the liquid alloy has filled the space between the drag and the cope (horizontal molds) or between the mold units (vertical mold stacks). This leads to the presence of metal plates, commonly referred to as burrs (Figure 48b,c), which correspond to excess metal in any mold junction, including those defined by cores [34].

Although causes already listed in previous subsections also apply to these kinds of defects, some are more important:

- The use of copes with large heights with respect to drags heights, leading to high pressure on the areas close to the partition line.
- Insufficient counterweighting on horizontal molds or inefficient clamping.
- Accumulation of gas into molds (lack of venting), which can separate the two half-molds.
- Long distances between pouring cups and nozzles (long melt streams which originate high dynamic pressure of melts) and long down sprues can also lead to this effect.

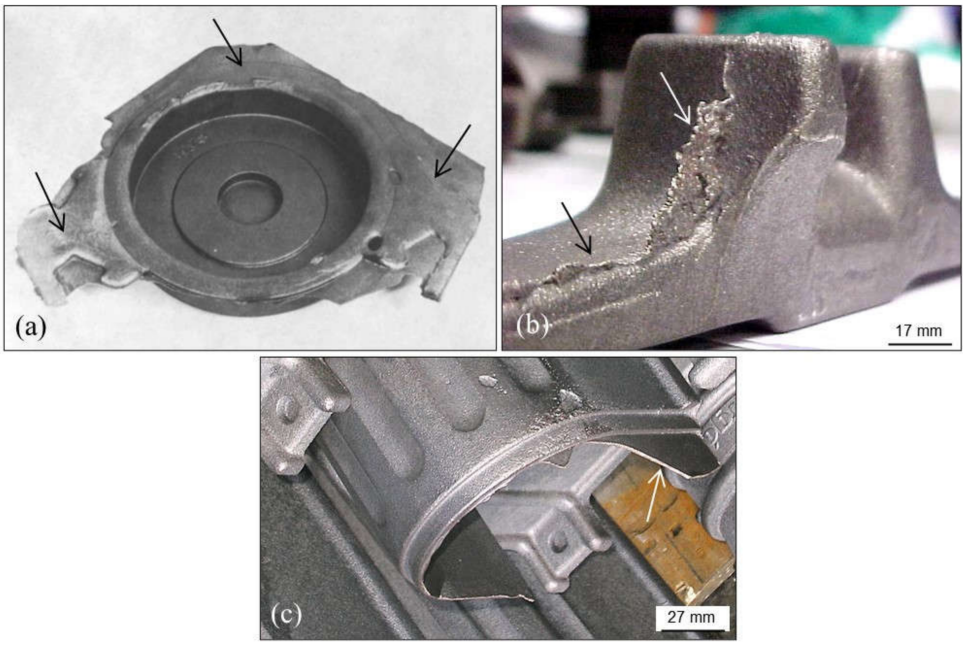

Figure 48. (**a**) Mold lifting in a brake drum of malleable iron (Reprinted with permission from ref. [17]. Copyright 1999 American Foundry Society, page 55). Burrs originated in ductile iron casting (**b**) and in grey iron casting (**c**) due to mold separation (vertical molding lines).

3.2. Mold–Metal Reactions

This section completes Sections 2.2 and 2.4, which presented the defects due to the reaction between the cast metal and the sand in the molds, the emphasis here being on the metal side instead of the sand side. Figure 49 shows the different types of defects that will be described, separated into a first group that concerns all cast alloys (steels, cast irons, aluminum alloys, bronzes, etc.) and a second group that is limited to cast irons.

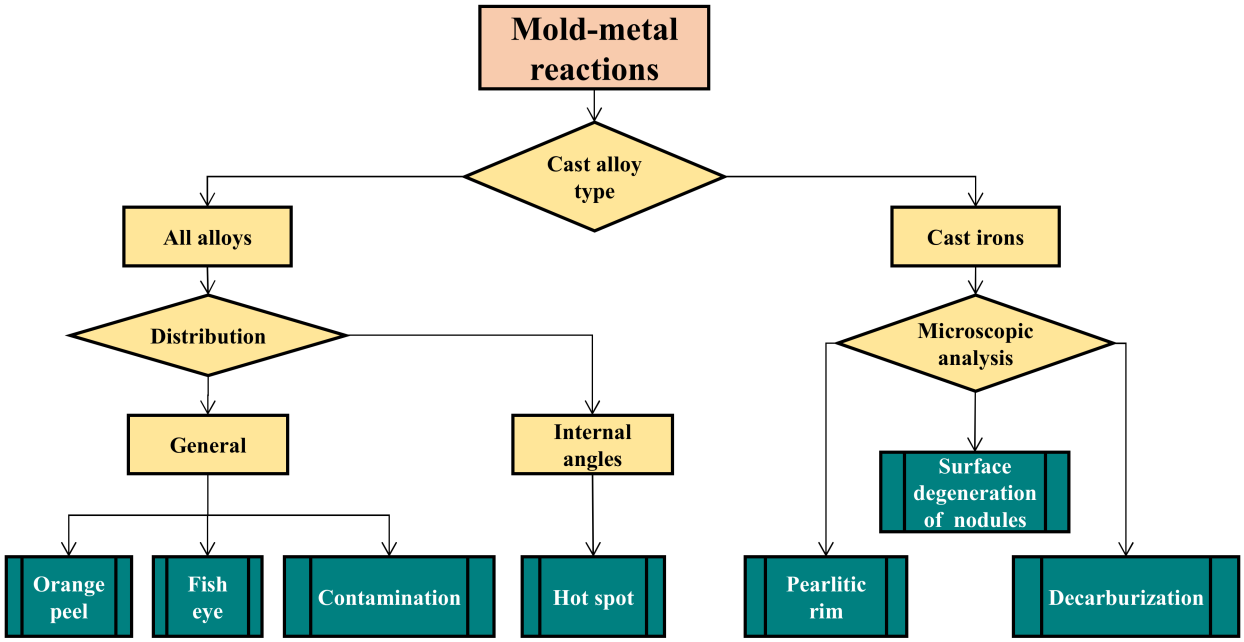

Figure 49. Classification of mold–metal reaction defects.

3.2.1. Pitting or "Orange Peel"

This surface defect is known as "pitting", "dross pitting" or "slag pitting" in connection with its different appearances (Figure 50). In all cases, the affected surface appears covered with small holes of varying size depending on the severity, forming very irregular surfaces similar to an orange peel [40]. The holes are shallow cavities that are sometimes detected after shot peening and are larger in heavy-section castings. The defect appears mainly in heavy areas at the top of the parts, where the temperature remains high after casting (internal corners of the castings, riser necks, areas near down sprues, etc.). However, the most important cause is the use of poor-quality sand mixtures with low silica content, high combustion products and/or low coal content (low loss on ignition). Closer inspection of the affected surfaces shows the presence of a white compound (silica or silicates) in the pits that can be removed by shot peening leaving a rough final finish. Two morphologies can be finally observed: on the one hand, the defect shows a large amount of holes that seem to be the result of material removal (Figure 50a,b), probably during the shot blasting step; on the other hand, the appearance of the surfaces is similar to that of the vitrified compounds, with an irregular finish (Figure 50c). This second case can be associated with the most severe variants due to the large amount of reaction products that cannot be removed for the usual shot blasting times.

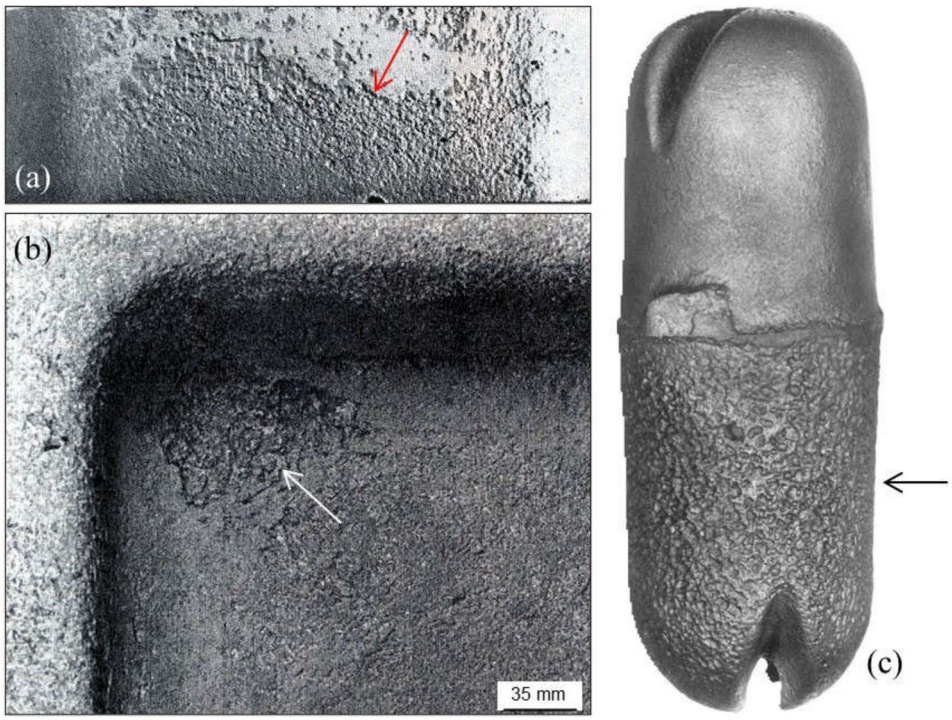

Figure 50. (**a**) Pitting or orange peel defect in heavy-section ductile iron bar with 3.5 wt.% Si; (**b**) defect located in an internal corner (hot spot) and (**c**) variant with vitrified aspect found in a test grey iron casting with cumulative contamination of core waste products and insufficient regeneration in the low half (Reprinted with permission from ref. [17]. Copyright 1999 American Foundry Society, page 191).

Pitting is, thus, clearly related to metal–mold reactions that are mainly caused by long exposure times at high temperatures and by the low refractoriness of sand mixtures. The first cause explains the higher risk for heavy-section castings and for hot spots in molds. The second cause is associated with reactions between liquid alloys with non-heat resistant constituents present in excessive amounts in cores or molds produced with chemically bonded sand grains (organic resins, sulfonic acid, ashes, oolitic materials and other contaminants, such as oils, dextrin, iron oxide dust, etc.). Iron silicates, iron oxides

and other compounds are formed and remain in the skin of the castings, partially embedded in the solid matrix. Shot blasting removes most of these deposits leaving holes that retain remnants of the compounds formed by the reaction between the liquid alloys and the sand mixtures.

Chemically bound sands are usually recovered using mechanical and/or thermal procedures for reuse in foundry shops. Appropriate additions of new sand must be made to ensure a minimum level of refractoriness in the recovered mixtures. Thermal treatments of used sand are expensive methods and the treatment of the grains can affect the hardening effect of the resins when reused. On the other hand, mechanical reclamation is not able to remove all the residues surrounding the sand grains, resulting in a cumulative effect of successive reclamations that leads to a decrease in the refractoriness of the mixtures (Figure 51). Note also that chemically bonded sand casting is an expensive method, used especially to produce heavy-section castings that are subjected to prolonged high-temperature exposure to the liquid alloy.

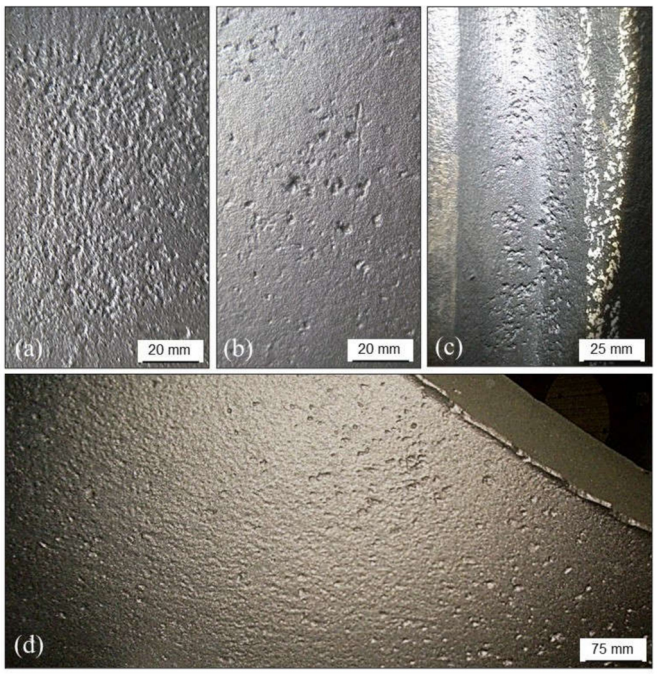

Figure 51. Different levels of pitting found in heavy-section ductile iron castings: detailed views (**a**,**b**) and general view (**d**) of the defect. Notice that defects only appear in the concave surface in (**c**), as it is the hottest area.

In the case of green sand molds, the risk is comparatively low, although heavy contamination caused by the use of reclaimed sand and insufficient additions of new sand for core preparation can also lead to the formation of this defect with a low incidence. It has also been observed that pitting defects contain deposits of silicon oxide dust in those areas where melt is in contact with the mold walls.

A summary of the most relevant causes of pitting or orange peel defects present in castings is given in the following:

- High silicon, magnesium and aluminum contents in the cast alloys.
- High or even intermediate contents of any compound with low refractory in chemically bonded sand mixtures used for mold making (resins, ashes, additives, catalysts, etc.).
- Low pouring temperatures (slag formation is promoted and these compounds promote reactions between melts and sand molds).
- High pouring temperatures which promote oxidations in the mold–metal interface.
- Low quality of silica sands (low refractoriness).
- Low additions of new sand to prepare green sand mixtures.

- Low loss on ignition values in green sand mixtures.
- The use of complex layouts with high number of hot spots in castings.
- Insufficient protective coating or low quality of the coating products used.

3.2.2. Fish-Eye Defect

This mold–metal reaction defect appears only on the surfaces of ductile iron castings made with green sand molds in the form of a single hole with a small protrusion in its center (Figure 52). It has been suggested that this defect is localized in areas of the molds that experience high temperatures (hot spots, Figure 53) when high fluorine contents were present in the green sand mixture. The usual origin of such contamination is the use of poor-quality high fluorine bentonites and an excess of high fluorine exothermic sleeves in cryolites [41].

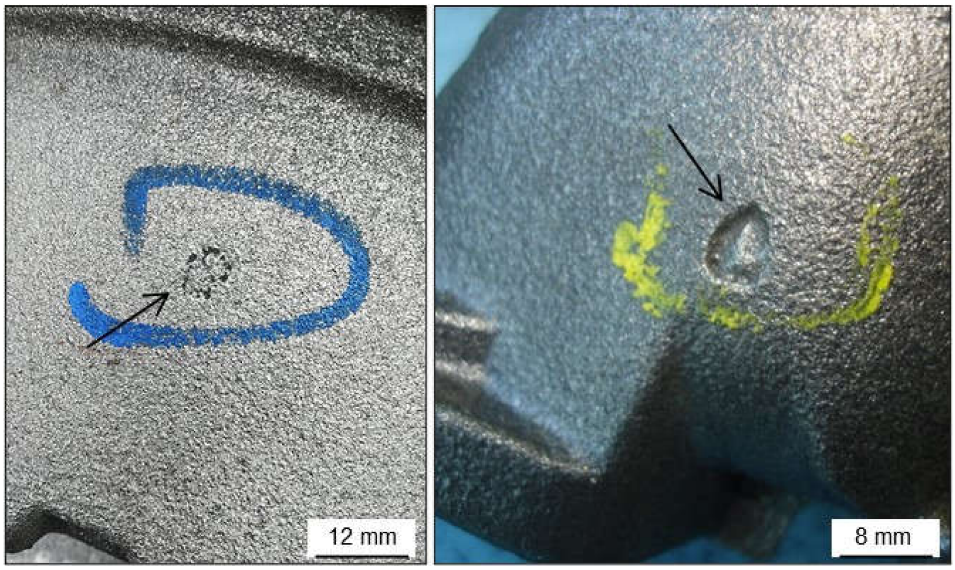

Figure 52. Fish-eye defects present in iron castings surfaces.



Figure 53. Areas of castings showing fish-eye defects.

The mechanism for the formation of the fish-eye defect involves hot water vapor and oxidized magnesium, which then react with fluorine to create the holes in the material surface. Evidence of these interactions is the fact that gray iron castings (and thus, without magnesium) and areas of ductile iron castings in contact with compacted sand at low moisture do not exhibit this defect. It has also been suggested that silicon contents above 2.5 wt.% in cast alloys and the presence of aluminum in the exothermic compounds of the

sleeves also favor this defect. The most important preventive actions to avoid the formation of fish-eye defects are:

- Use of proper bentonites for preparing the green sand mixtures.
- Avoid the use of any exothermic sleeve with a fluorine content greater than 0.10 wt.%.
- Ensure proper regeneration levels in green sand mixtures (regular additions of new silica sand). This defect also occurs when using other types of sand than silica (chromite, olivine, zirconium, etc.), as fluorine reacts with magnesium containing oxides.
- Avoid hot spot areas in castings and high casting temperatures.
- Maintain appropriate loss on ignition levels to minimize oxidation reactions.
- Optimize the sand mixing stage to reduce the moisture content required to achieve sufficient compactability of the prepared mixtures.
- Reduce fluorine contamination of sand blends when the fluorine content is greater than 0.030 wt.%.

3.2.3. Surface Defect Due to Massive Contamination of the Sand

Massive contamination of sand mixtures can be caused by a large number of different substances (oily products, small particles of slag or metal, inoculant remnants, organic wastes, etc.), giving rise to gas holes, inclusions, poor surface finish and other irregularities. In this subsection, we describe a particular case that involves massive metal–mold reaction affecting large areas of castings. This example shows the consequences of accidental contamination of the return sand with a product used to skim liquid metal that was gradually added in a belt. That belt was used for transferring the reused sand from the demolding area to the cooler device. This led to widespread metal–mold reactions and castings affected on all surfaces (Figure 54).

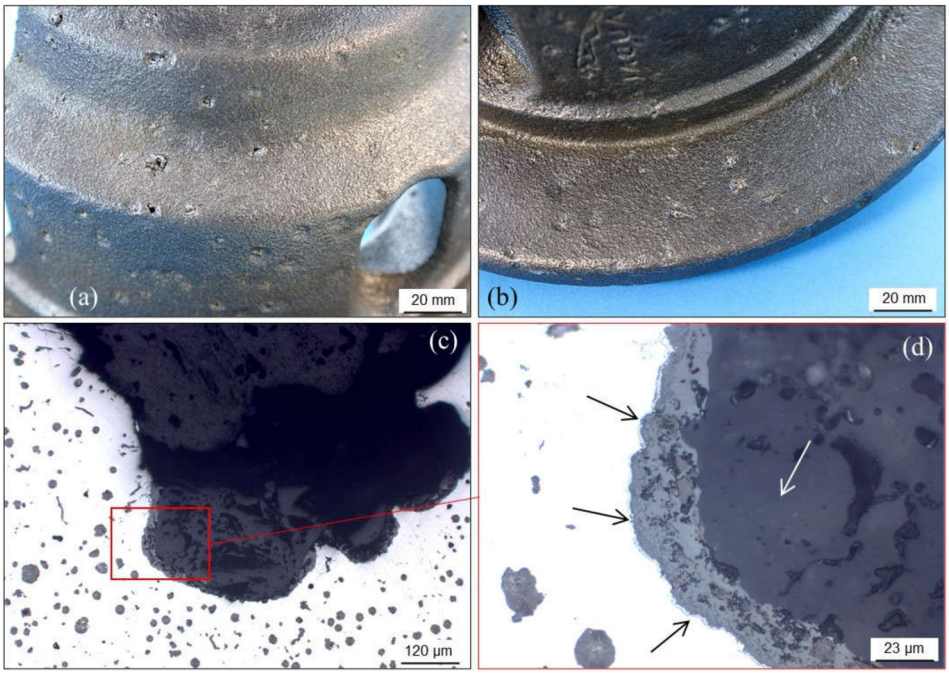

Figure 54. Surface defects found in a ductile iron casting manufactured with highly contaminated green sand mixtures. Macroscopic views of these defects in different areas of the casting (**a**,**b**) and metallographic views (**c**,**d**).

The differential case shown in Figure 54 has multiple irregular holes in the skin (Figure 54a,b) that contained two different products (Figure 54c and the zoom in Figure 54d). SEM characterization of these two products showed that the one accumulated on the inner surface of the holes (black arrows in Figure 54d) is composed of iron oxides, while peaks of Si, O, Al, Na and K were found in the precipitate marked by a white arrow in Figure 54d.

Subsequent analysis of the commercial product used to remove slag from melts led to similar EDS microanalyses.

Although the example described in this subsection shows an uncommon problem in foundries, it demonstrates how important it is to keep return sands clean and free of contaminants. Such measures will prevent a large number of defects and will ensure the correct surface aspect of the castings.

3.2.4. Hot Spot

Hot spot defects appear on the skin of castings as small sags, isolated or aligned (Figure 55a) or as small holes with different levels of incidence similar in appearance to gas pinholes (Figure 55b,d). The location of the hot spot holes in the casting usually distinguishes them from pinholes. As can be seen from the photographs in Figure 55, the hot spot defects are mainly found in the overheated areas of the castings. In Figure 55a, the defects are present at the corner defined by an ingate and the casting skin, while in Figure 55b–d they have formed in internal corners where the liquid alloy has surrounded sand bosses. An effective method of distinguishing these defects from gas pinholes is by metallographic inspection as shown in Figure 55e. In contrast to gas pinholes, hot spot holes contain significant amounts of compounds rich in Si, O, Fe and other minor elements. Beneath these compounds, on the surface of the metal, there is a film of iron oxides and below some degenerate graphite (ductile iron). These results indicate that hot spot holes are formed by oxidation of the alloy in contact with the substances present in the green sand mixtures. Furthermore, these reactions are favored by insufficient levels of coal (low values of loss on ignition).

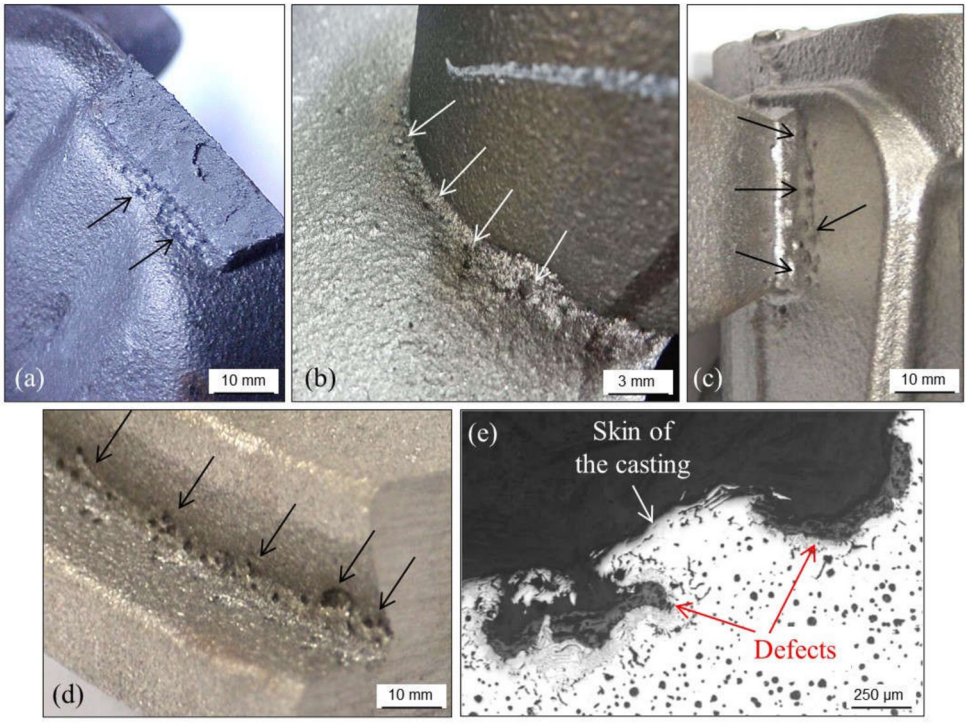

Figure 55. Hot spot defects in different ductile iron castings (**a**–**d**); metallographic cross section of two hot spot holes (**e**).

The causes of hot spot defects are those listed in Section 3.2.1 for orange peel or pitting defects, with the most common reason being the low loss on ignition values in greensand mixtures (high oxidation environment in the mold–metal contact area). Thus, hot spot holes can be considered as the preliminary step to the formation of pitting or orange peel defects.

3.2.5. Pearlitic Rim

This defect appears as a pearlitic layer on the surface of fully or predominantly ferritic castings (Figure 56). Abnormally high hardness values measured on the skin of the part and metallographic observations on cross sections are the two most common methods of detecting this irregularity. The usual reason for the formation of these pearlitic layers or rims is a high sulfur content in green sand mixtures, as this element promotes pearlite. Sulfur contamination of the sand may be due to high sulfur content in the coal materials used as an additive and/or high resin content in the cores. It is considered that the sulfur content of sand mixtures should be less than 0.10 wt.%, but this threshold should be lowered when increasing the casting section size. On the other hand, the thickness and irregularity of the pearlitic rim increases with the sulfur content of the molds.

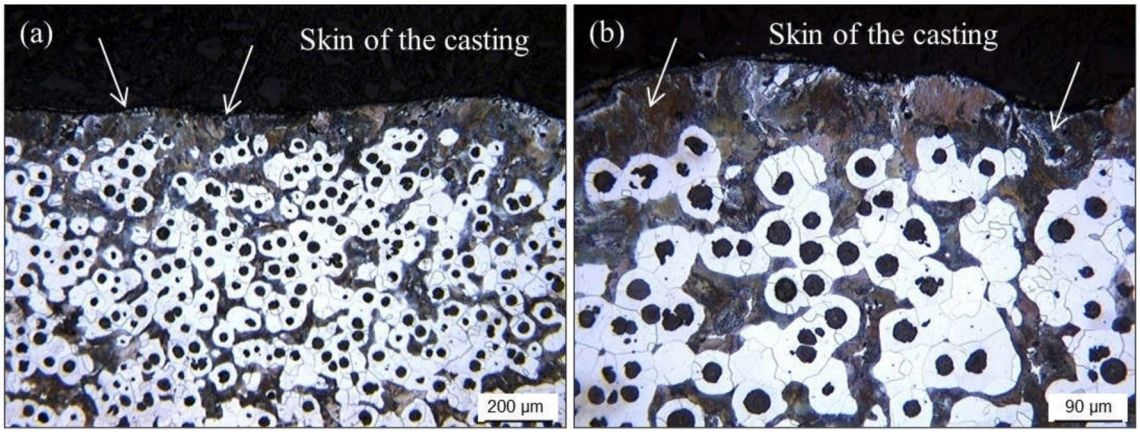

Figure 56. Metallographic cross sections of a ductile iron casting with a continuous pearlitic rim and a mainly ferritic matrix (**a**). A detailed view is shown in (**b**).

3.2.6. Decarburization

Decarburization of the outer surface of the metal can occur during casting or during heat treatment. This leads to a layer devoid of graphite particles (Figure 57a,b) or, in the case of pearlitic castings, to a ferritic layer (Figure 57c–e). This latter case is the most serious in practice. The thickness of these layers is variable because it depends on the intensity of the decarburization process, but an average range is 0.05–0.30 mm. It should be noted that this defect cannot be detected by routine visual inspections.

Decarburization proceeds due to diffusion of carbon from the casting to adjacent zones (molds or atmospheres) where carbon levels are low. This diffusion process depends on temperature and time of exposure, giving different layer morphologies. Malleable iron castings are originally manufactured as white iron and a heat-treatment is then applied during which a decarburized layer devoid of graphite particles develops (Figure 57a,b) if the oven atmosphere is not controlled. Note, however, that although treated here as a casting defect to be avoided, decarburized layers are required for certain applications, for example to ensure the deposition of a continuous layer of zinc on castings.

Figure 57c,d show an interesting example of a decarburized layer in a ductile iron caliper produced in a die without any graphite coating. After etching the metallographic section prepared for inspection, three different zones were observed in the decarburized layer. The inner zone remained fully pearlitic, while the narrowest outer zone was fully ferritic due to complete diffusion of carbon to the mold. The middle zone showed a mixed pearlitic and ferritic microstructure, with both constituents varying progressively from side to side.

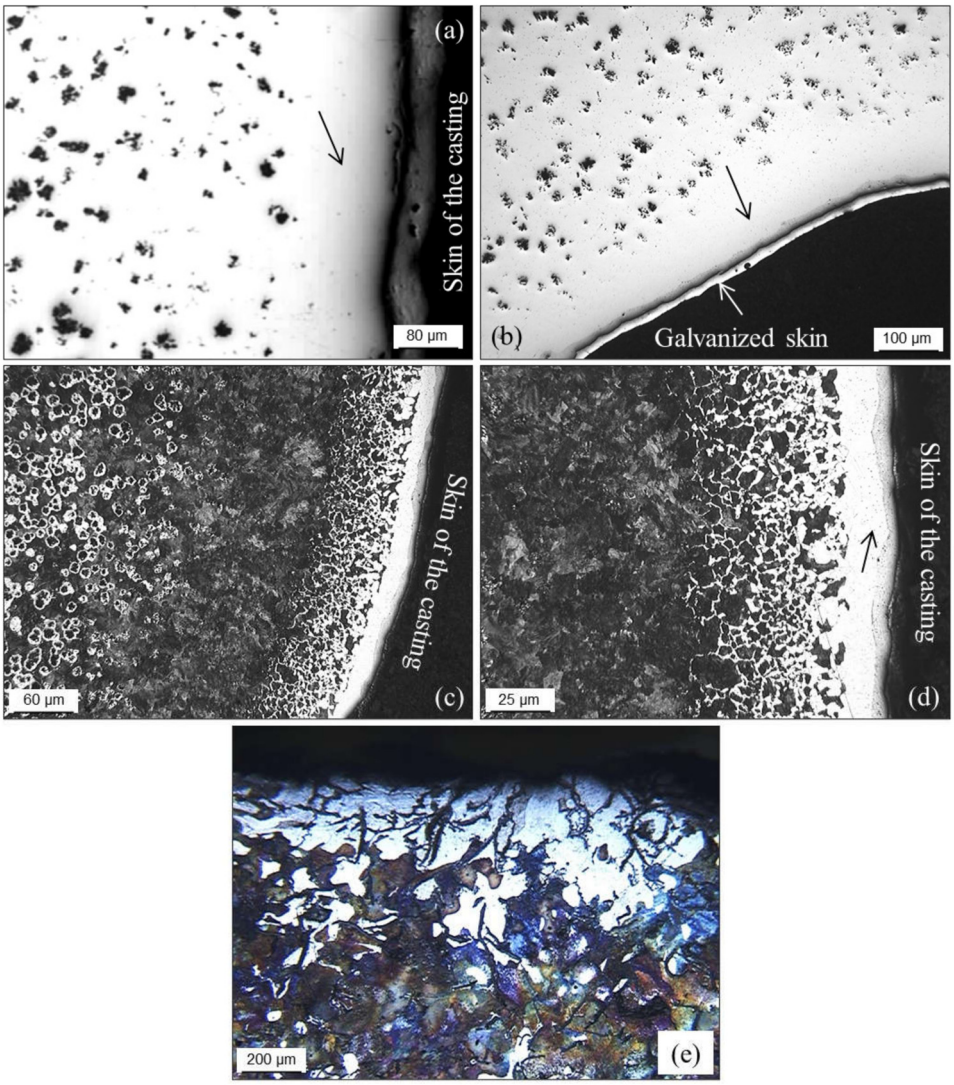

Figure 57. (**a**,**b**) examples of decarburized layers without graphite particles in malleable iron castings. (**c**,**d**) etched surfaces of a ductile iron casting produced in a die with a decarburized layer composed of three different zones: the inner segment is fully pearlitic, the intermediate one contains pearlite and ferrite and the outer one is fully ferritic. (**e**) Ferritic decarburization layer in a grey iron casting.

The fully ferritic decarburized layer shown in Figure 57e in the case of a grey iron casting resulted from a heat-treatment intended to give a fully pearlitic structure so as to improve tensile strength.

In green sand molds, decarburization of the metal in contact with the mold is due to insufficient loss on ignition contents that cause the carbon in the alloy to be oxidized by the moisture in the molds. Although this defect can be present in any casting, it appears preferentially in heavy sections because the exposure times to high temperature are critical. In addition, high casting temperatures promote decarburization.

Parts with decarburized surfaces may have altered mechanical characteristics in the skin areas, different surface hardness, reduced wear resistance, increased risk of cracking, etc. Most parts produced in foundry shops show some decarburization in the skin areas. Therefore, the rejection criteria for these parts must be agreed upon between foundries and customers, with clear limits defined for each case. A correlation between the cross-sectional area of the part (up to 300 mm), the coal content in the green sand mixtures and the different levels of decarburized layer incidence is shown in Figure 58. In this graph, the coal contents should be considered as loss on ignition values, although this was not reported as such.

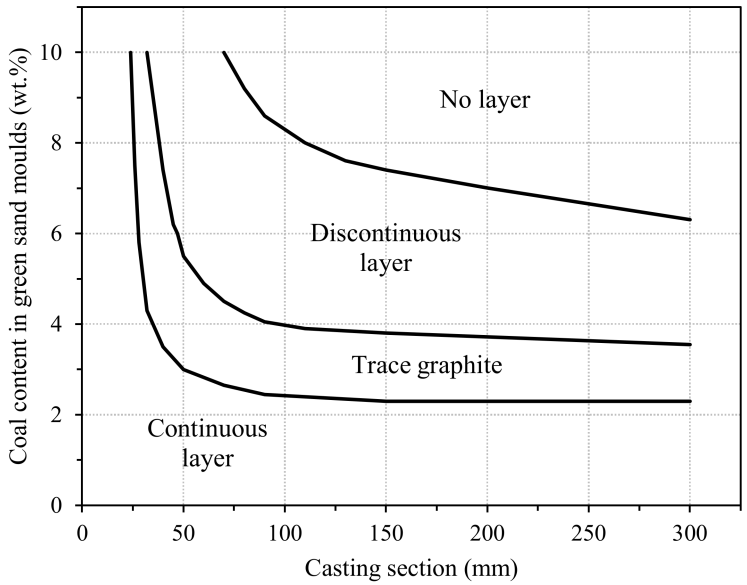

Figure 58. Effect of casting section and of coal content present in green sand molds on the characteristics of the decarburized layer [42].

3.2.7. Surface Degeneration of Spheroidal Graphite

Surface layers up to 1 mm thick with either degenerated or lamellar graphite particles [43,44] can be observed in ductile iron castings (Figure 59). Such changes in graphite shape are due to reaction of magnesium and cerium dissolved in the melt with high oxygen and/or sulfur in sand mold. In the former case, low loss on ignition values can be the main cause, while high sulfur content in coals (>0.80 wt.%) and/or in core making resins is the usual reason for the latter case. The following maximum sulfur contents in sand mixtures have been advised [45]: 0.15 wt.% for casting sections lower than 25 mm and 0.07 wt.% for casting sections higher than 75 mm.

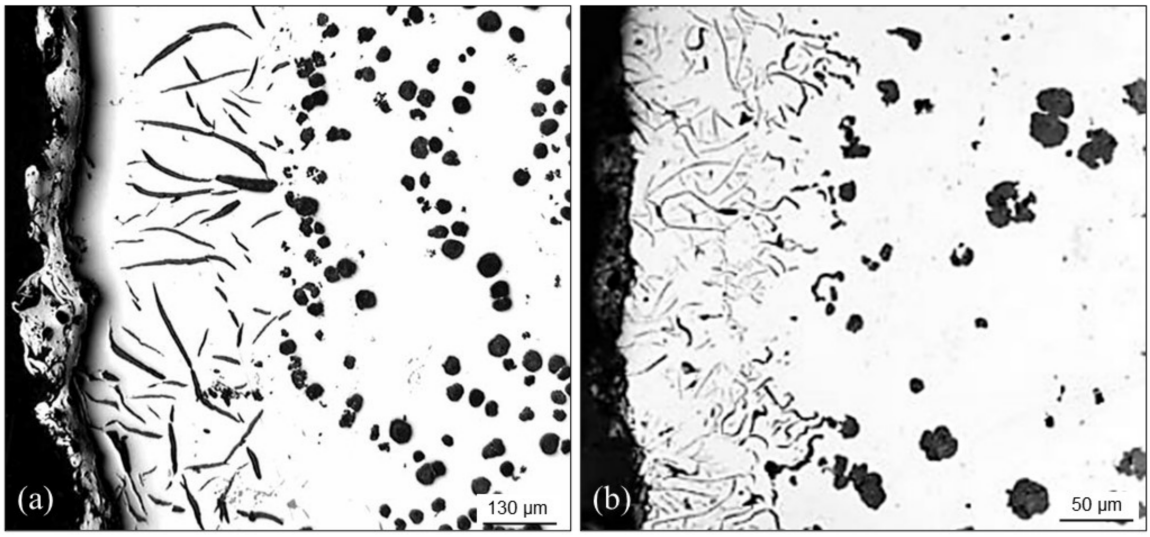

Figure 59. Graphite degeneration in the outer areas of (**a**) a heavy-section ductile iron casting in contact with a core produced using sand mixtures bonded with furanic resins and sulfonic acid; (**b**) a ductile iron casting (the latter is reprinted with permission from ref. [45]. Copyright 1994 IKO-Erbslöh).

Oxygen and sulfur contents can increase in poorly reclaimed sands due to accumulation effects, which is especially true for mixtures of sands bound with furan resins and

sulfonic acid as catalysts. Turbulent flow during filling also has negative effects on graphite nodule formation because slag inclusions typically contain magnesium-bearing compounds. It has also been suggested that silica can react with residual magnesium present in melts to also form slag inclusions [46].

The formation of layers with degenerated graphite particles, evolving from nodules to flakes, alters the mechanical characteristics of castings, and this can lead to their failure in service. Sometimes, this defect can be eliminated by subsequent machining, but it can be significant in large section castings and cause them to be rejected. Common remedies for this defect include minimizing oxidizing conditions in the molds (avoiding high moisture contents and maintaining sufficiently high loss on ignition values), adding controlled amounts of new sand to the mixtures (regeneration) and using refractory coatings on the affected mold and core surfaces.

3.3. Cracks, Hot Tears and Cold Tears (Hot Cracks)

During casting, solidification and cooling of alloys, stresses are created due to density changes, especially from liquid to solid state, and due to temperature gradients, which develop in complex geometries. The hindrance of metal shrinkage by the mold and by the cores also contributes to stress formation. Generally, these stresses are minimized with time and/or heat treatment, but they can cause cracks during the casting process itself. Cracks in a casting can occur either during solidification, which are referred to as "hot tears", or during solid state cooling (once solidification is complete), which are referred to as "cold tears" or "hot cracks". The latter formulation is confusing and will be avoided in what follows. Generally, the origin of a crack is given by whether its surface is (hot tear) or not (cold tear) oxidized. This simple information was used for the diagram in Figure 60.

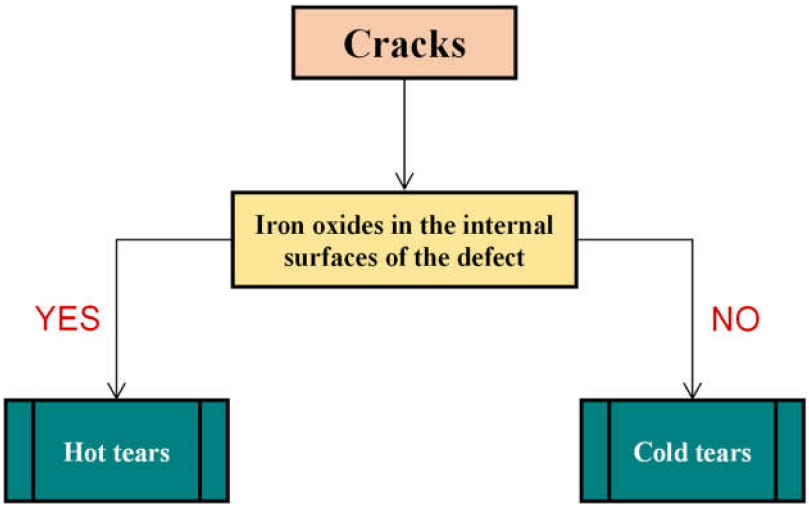

Figure 60. Classification of tearing in castings according to the characteristics of internal surfaces in cracks.

3.3.1. Hot Tears

Hot tear is "*A fracture formed in a metal during solidification because of hindered contraction. Compare with hot crack*". This manifests as intergranular cracks of irregular shape and varying depth. These cracks have a fine dendritic structure with an oxidized inner surface and are often located in the last solidification zones of castings that are highly stressed in tension during their solidification. These stresses are due to the different contraction effects of neighboring zones of different geometries and sizes.

Figure 61a shows an example of a hot tear found in a gray iron casting after machining the outer surfaces. After separating the two sides of the crack, iron oxide deposits were found adhering to the inner surfaces, as shown in the metallographic section in Figure 61b. Note that a decarburized zone with a ferritic microstructure was also present beneath

the iron oxide layer. SEM examination of one of the separated surfaces shows a smooth appearance (upper surface in Figure 61c) that corresponds to the original crack surface. The lower fractured area seen in Figure 61c was created during the crack opening stage. Figure 61d shows a detailed view of the crack surface covered with iron oxides and where intergranular facies appear.

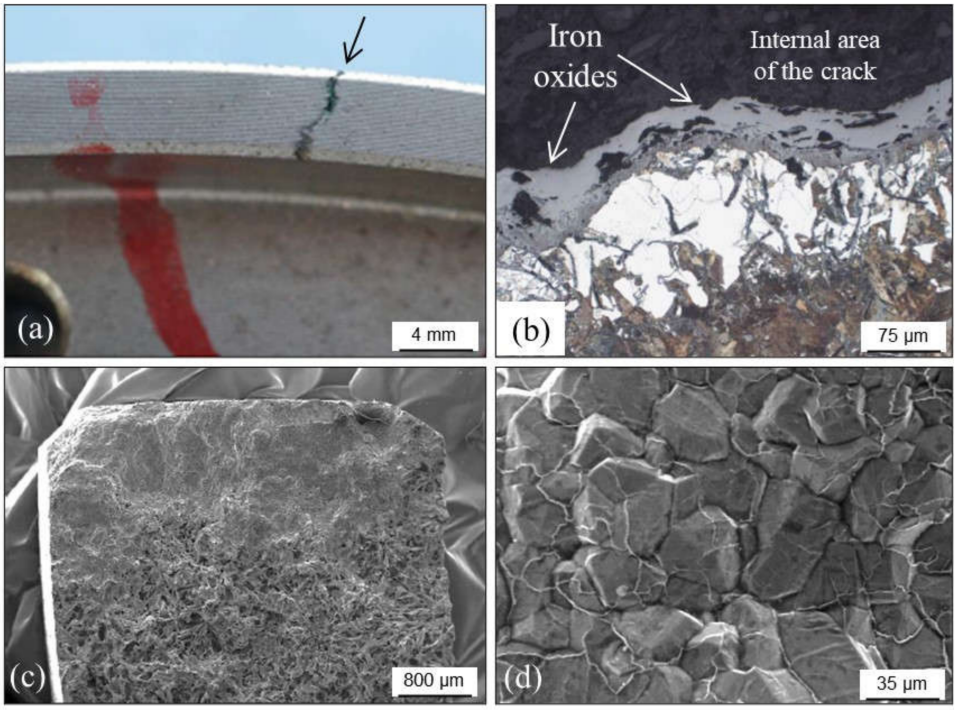

Figure 61. Hot tear found in a grey iron casting (**a**). Metallographic view of the internal surface of a crack (**b**). SEM view of the internal surface of a hot tear (**c**,**d**).

The geometric characteristics of the castings play an important role, as hot tears are favored by large thickness variations with large angles, large sections joining small sections, filling steps causing high temperature gradients in the layouts, sharp angles and corners (insufficient radius) and the formation of burrs that can alter cooling rates in nearby sections and make the usual shrinkage of the alloy during solidification difficult. All these elements increase the stresses during solidification and, thus, the risk of hot tearing.

With respect to molds, the high stiffness of drags, copes and cores, as well as of assemblies made during molding, poses problems when accommodating the dimensional changes produced by alloy solidification. For example, high bentonite contents (high green and dry compression strength) in sand mixtures and their excessive compaction must be avoided to minimize hot tearing in castings. Other effects, such as the formation of vitrified sand layers, should also be avoided, as they increase the stiffness of the mold–metal interfaces. High sulfur and/or phosphorus contents in greensand mixtures promote the formation of pearlitic and rigid layers near the skin of the castings, which also increases the risk of hot tearing.

Figure 62a shows a hot tear found in a gray cast iron engine block that was caused by high core stiffness used to create the concave surface shown in Figure 62b. On this concave side, an expansion defect already described in Section 2.3.4 and called veining was also created. Figure 62c,d show detailed views of the two defects, where the expected iron oxide layer has developed on the hot tear surface, while sand grains remain adhered to the vein protrusion. In Figure 62e, an X-ray tomography locates the two defects in the analyzed casting area.

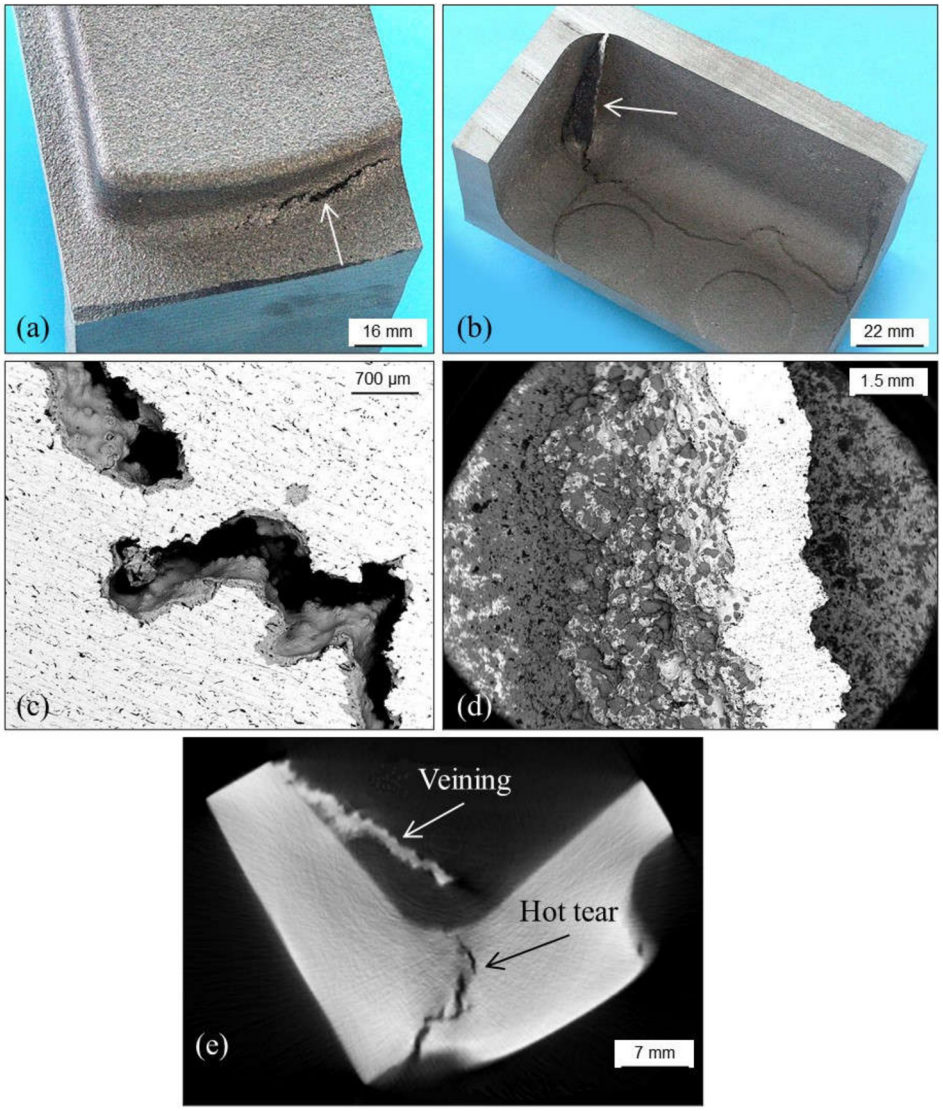

Figure 62. Concomitant hot tearing (**a**,**c**), and veining (**b**,**d**) defects found in a grey iron engine block. (**e**) X-ray tomography view of both defects.

Finally, hot tearing in castings depends on the shrinkage of the cast alloy during cooling, i.e., shrinkage of the liquid just after filling the mold, of the solid during final cooling, as well as solidification shrinkage. Shrinkage is, therefore, dependent on both the composition of the alloy and the casting temperature which determines the thermal gradients developing in the mold.

An interesting example that involves both the alloy composition and the geometric characteristics of the castings is the production of large gray iron castings with small sections used for the manufacture of ornamental stoves (Figure 63). These castings contain large surfaces with angles, ribs, changes in surface extension, bridges, etc., all of which make them very vulnerable to hot tearing effects.



Figure 63. Different locations of hot tears found in some large extended grey iron castings (**a**–**d**).

Some alloying elements are known to reduce mechanical properties and/or increase hot-temperature brittleness of cast irons, which are:

→ Sulfur and phosphorus that delay solidification. Sulfur can be counteracted with manganese additions.
→ Chromium, when higher than 0.1 wt.%, leading to carbides in thin casting sections.
→ Lead, when higher than 4 ppm, coming from non-ferrous scrap and coatings used in steel components.
→ Tin, when higher than 0.1 wt.%.
→ Antimony and boron together with lead that come from enameled scrap.

3.3.2. Cold Tears

A cold tear is defined as "*a crack formed in a cast metal because of internal stresses developed upon cooling following solidification. A hot crack is less open than a hot tear and usually exhibits less oxidation and decarburization along the fracture surface*". Cold tears form during the cooling of solid castings, either in the molds or after they have been shaken out, especially during machining. Cold tears are approximately constant in width with sharp edges and can sometimes affect the entire cross section of castings (Figure 64). The cracks may have metallic inner surfaces, sometimes oxidized to a limited extent depending on the temperature at which they occurred. Another interesting feature is that cold tears do not show intergranular or dendritic morphologies, but fracture surfaces with ductile and/or faceted patterns (Figure 65). As with hot tears, the risk of cold tears also depends on the mechanical properties of the alloys (gray irons are more risky than ductile irons), they are preferentially located in highly stressed areas and the casting geometry plays an important role.

As mentioned above, the stresses that developed in the castings after solidification evolve due to thermal gradients. Once room temperature is reached, they are called residual stresses [47,48]. Cracks can originate at any point in a part where the stresses exceed the strength of the material at a given temperature. If the tensile strength of the alloy at a given temperature is not able to compensate for these stresses by creeping, or if external stresses are applied, failure occurs. The presence of other defects in the material, such as inclusions, shrinkage porosities, etc., can promote the formation of cold tears because they are discontinuities in the metal matrix.

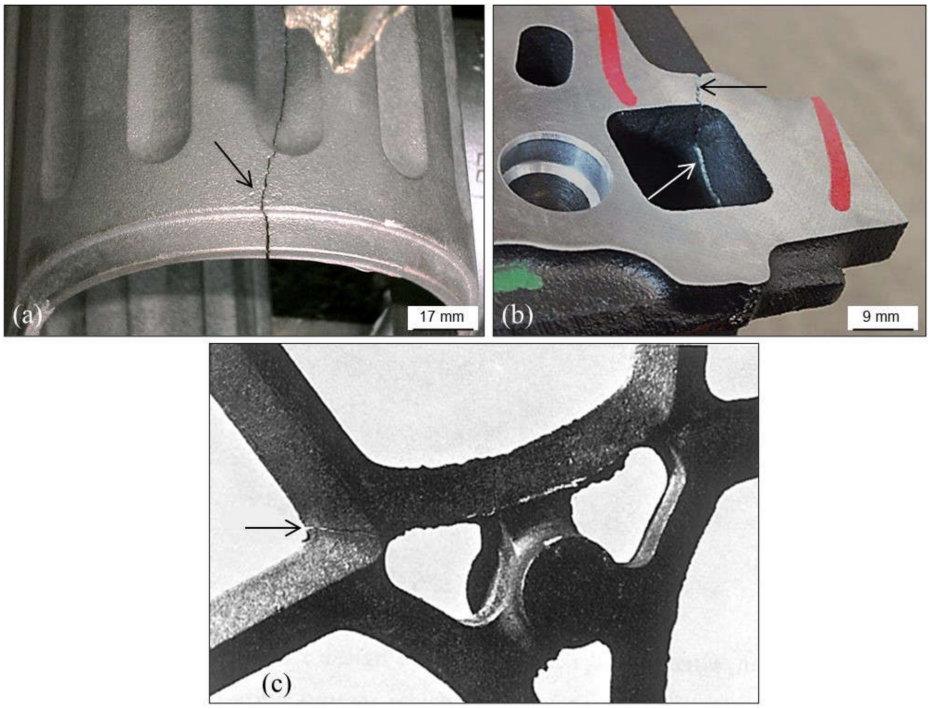

Figure 64. Cold tears found in (**a**) a grey iron casting with small sections, (**b**) a grey iron engine block and (**c**) a grey iron sewing machine wheel (Reprinted with permission from ref. [17]. Copyright 1999 American Foundry Society, page 140). All three castings were produced in green sand molds.

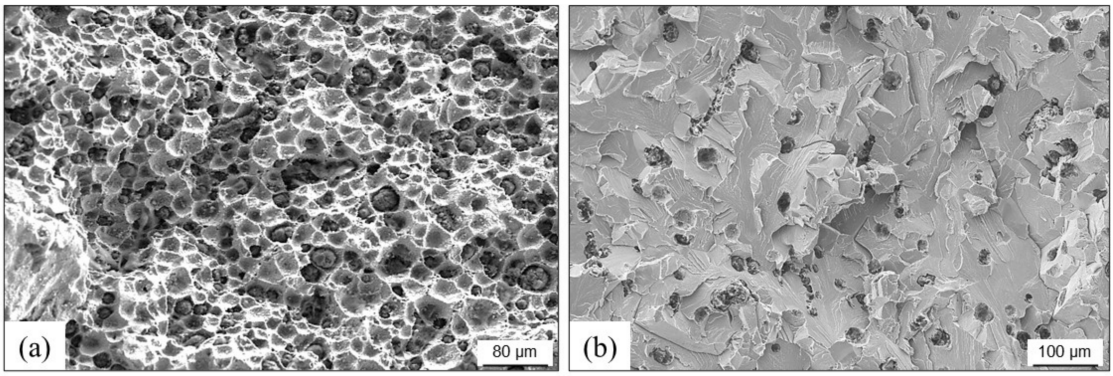

Figure 65. Typical fracture morphologies in ductile cast irons: ductile (**a**) and facetted (**b**) fractures.

Following a description similar to that used for hot tearing, casting geometries and/or layout designs with areas of widely differing thicknesses generate stresses, and thus, increase the risk of cold tearing. Additionally, excessive rigidity of sand molds and/or cores hinders solid shrinkage and cracks can occur. Furthermore, it is important to handle the castings properly to minimize external stresses that can increase the existing stresses in the materials.

Figures 61, 63 and 64 show tears that are easily detected by visual inspection of the castings. However, there may also be fine hot and cold tears that cannot be detected by simple visual inspection of the castings. Although these fine, short cracks are not usual in ductile cast irons, they sometimes appear in gray cast irons because of their comparatively low tensile strength and become common in white cast irons and cast steels because of their high solidification shrinkage. Two non-destructive techniques are commonly used in foundries to detect these fine cracks, namely magnetic particle inspection and penetrant inspection. This second technique is also called "liquid penetrant inspection" or "penetrating liquid". Figure 63d shows a crack revealed by this second technique,

while the image of a steel casting with small hot tears during inspection by the magnetic particle technique is shown in Figure 66a. The intergranular progression of these small cracks and details of their internal dendritic surfaces covered with iron oxides are shown in Figure 66b,c.

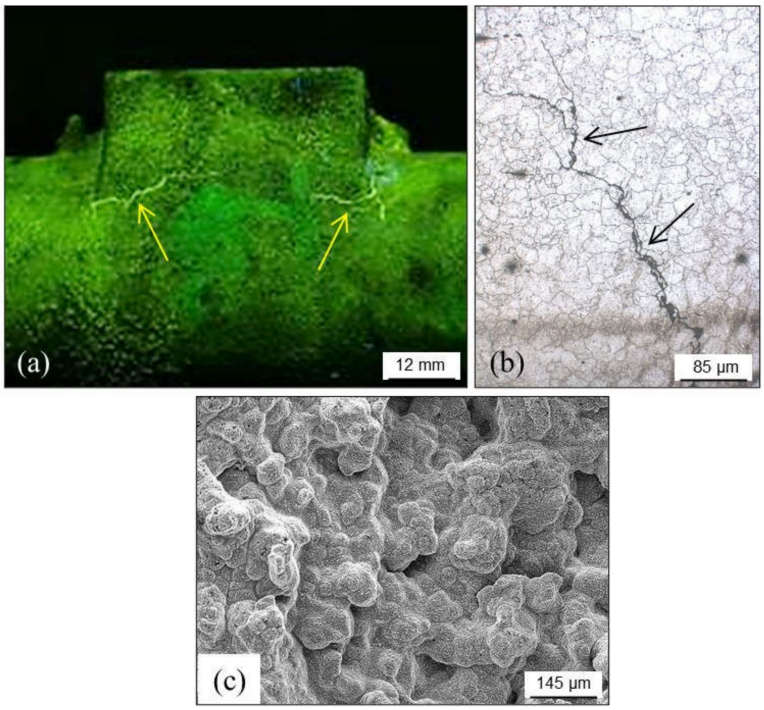

Figure 66. (**a**) Fine hot tears detected in a steel casting by using the magnetic particle inspection, (**b**) metallographic cross section of one tear showing intergranular progression and (**c**) SEM view of the internal dendritic surface of one tear showing iron oxides set on it.

4. Metal-Related Defects

The casting defects analyzed in this last section are mostly related to the characteristics of the cast alloys. The different groups considered in the present classification are shown in Figure 67, where the possibility that a particular defect is enhanced by the mold is indicated in blue or in red when it is almost exclusively due to the metal. As can be seen in Figure 67, most of these defects are also affected by sand molds.

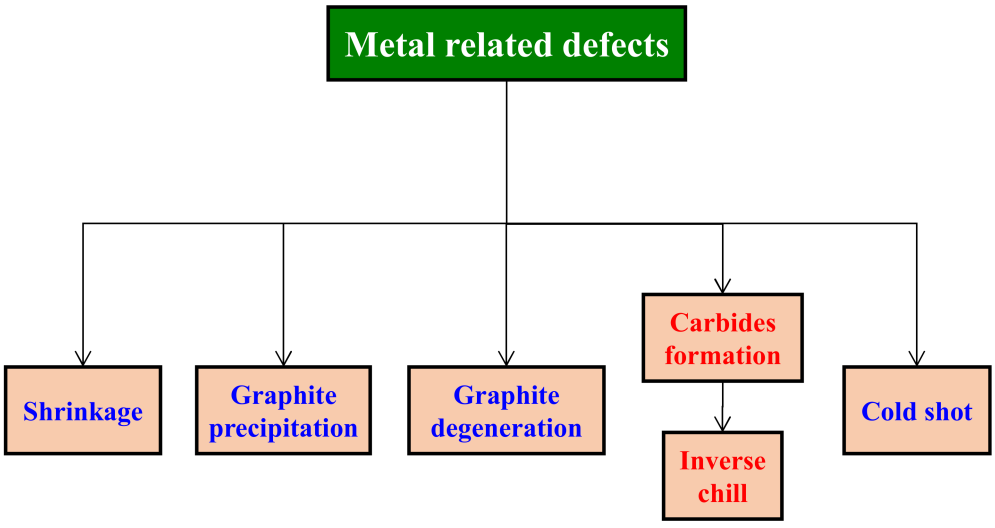

Figure 67. Classification of defects mostly related to cast alloys.

4.1. Shrinkage Porosities

The word "shrinkage" appears in the definition of a great number of casting characteristics and defects. Casting shrinkage is "*The amount of dimensional change per unit length of the casting as it solidifies in the mold or die and cools to room temperature after removal from the mold or die. There are three distinct types of casting shrinkage. Liquid shrinkage refers to the reduction in volume of liquid metal as it cools to the liquidus. Solidification shrinkage is the reduction in volume of metal from the beginning to the end of solidification. Solid shrinkage involves the reduction in volume of metal from the solidus to room temperature*". This is the sense in which the word was used in the previous sections, whereas what is addressed in this section is the fact that actual dimensional changes in a casting can be associated with the formation of defects such as internal shrinkage, which is "*A void or network of voids within a casting caused by inadequate feeding of that section during solidification*".

In practice, it is usual to classify such defects as either primary (macroshrinkage) or secondary (microshrinkage). One also defines macroshrinkage as "*Isolated, clustered, or interconnected voids in a casting that are detectable macroscopically. Such voids are usually associated with abrupt changes in section size and are caused by feeding that is insufficient to compensate for solidification shrinkage*". On the other hand, secondary shrinkage has characteristic dimensions related to those of the microstructure. Thus, although their origin is the same, the macro- and microshrinkage show clear differences in morphology related to the solidification stage in which they were formed (Figure 68). Primary shrinkage occurs in the early stages of solidification with a low solid fraction in the different areas of the casting and is normally compensated for by easy feeding by the feeders. On the contrary, secondary shrinkage occurs during the last stage of solidification, when most of the liquid flow is already interrupted and only graphite expansion can compensate for it.

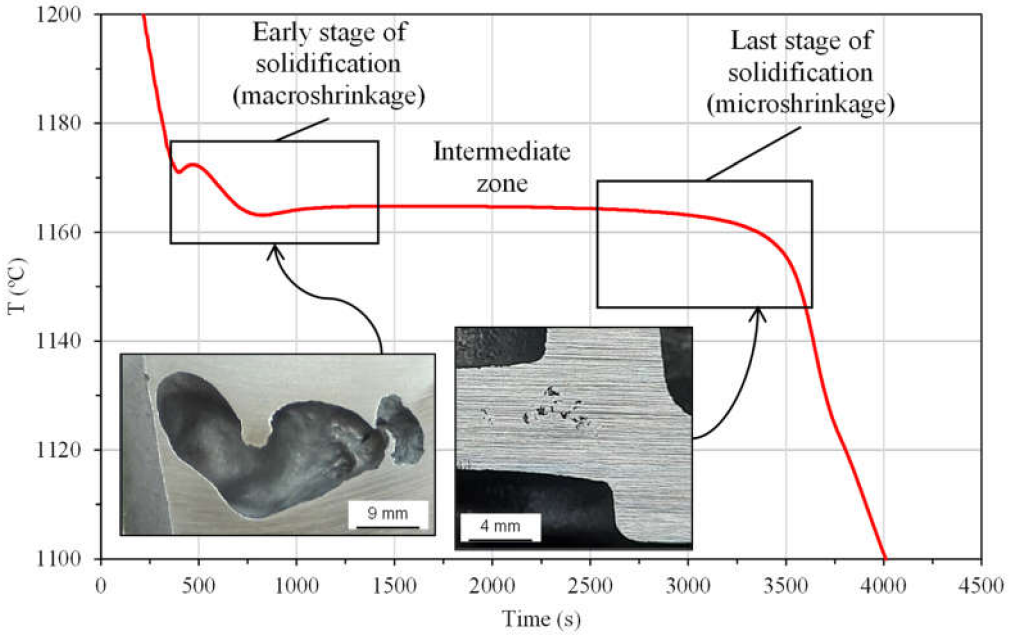

Figure 68. Example of a cooling curve obtained on the center of a ductile iron cylindrical test casting with a thermal modulus of about 4 cm. Solidification areas for primary and secondary shrinkage defects are indicated.

Related to the different stage of solidification during which they occur, primary shrinkage generally leads to large, smooth voids, while secondary shrinkage exhibits dendritic morphologies. This difference is exacerbated in areas where shrinkage acts for a long time. Figure 69 shows a ductile iron casting with a huge shrinkage void due to an error in the layout design. Thus, the casting acted as a feeder and the adjacent riser was free of any shrinkage void (right side of Figure 69). Notice that the inner surface of the

voids evolves from a smooth appearance (black arrows in the upper part of Figure 69) to an irregular surface in the intermediate area, and finally, the void's surface becomes dendritic (white arrows in the lower part of Figure 69).

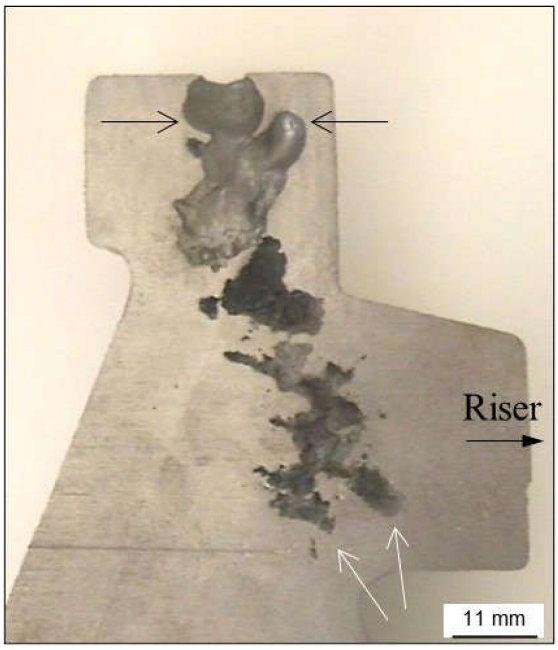

Figure 69. Shrinkage found in a small section ductile iron casting.

4.1.1. Primary Shrinkage or Macroshrinkage

The defect appears in the form of cavities or voids most often open to air (pipe or open shrinkage) generally present in the risers (Figure 70a) or in the castings (Figure 70b). In the case where it remains limited to internal areas (macroporosities, internal shrinkage or blind shrinkage), visual inspection can hardly detect it. The two most characteristic features of primary shrinkage are: (i) the voids are mainly located in the hottest areas of the castings and (ii) their internal surfaces are smooth although dendrites may also be present depending on the solidification characteristics of the cast alloy. Because of these morphological characteristics, primary shrinkage appears similar to gas blowholes (Section 2.1.2) so that a proper study of the locations where the defect is present can help to distinguish them.

The primary shrinkage defect may also be in the form of a depression in the casting skin, also called "wall shrinkage" or "caved surfaces", which may contain a nearly spherical-shaped phosphide or metal drop (Figure 70c,d) or lack one. Wall shrinkage commonly forms in gray iron castings produced with hypoeutectic alloys. Since they are shrinkage defects, these skin depressions preferably appear in surfaces near the superheated areas where solidification ends (internal corners, surfaces in contact with superheated cores, those near the sprues, etc.).

The severity of this defect depends on the liquid shrinkage of the cast alloy during cooling. On the metallurgical point of view, the cause of macroshrinkage is the overall change of volume due to liquid cooling and early solidification that has to be compensated for. When the designed rising is not enough, massive feeding is interrupted as the solid fraction increases at the scale of the casting. A negative pressure develops that put the liquid in tension and eventually breaks it.

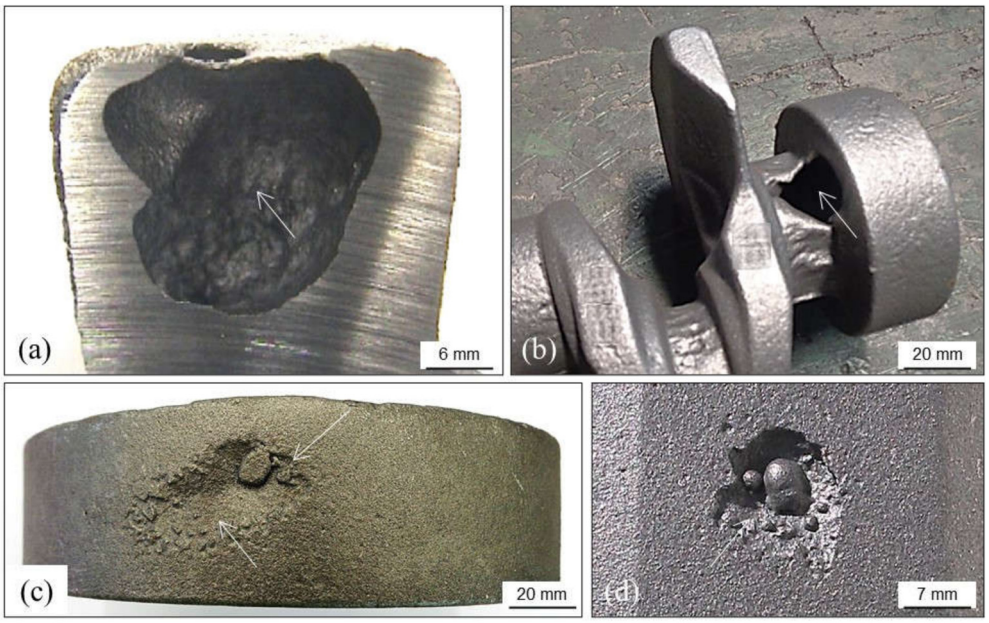

Figure 70. Primary shrinkage defects found in (**a**) grey iron riser; (**b**) a ductile iron crankshaft manufactured without any inoculant addition (low graphite expansion); (**c**,**d**) two grey iron castings with wall shrinkage as depressions containing phosphide drop.

In her work, Regordosa [49] investigated the formation of macro- and microshrinkage in SGI using a dedicated test casting with a thin section connected to a heavy section that worked as a feeder after filling the molds (bridge). The effects of carbon equivalent and of 0.20 wt.% inoculant addition on shrinkage voids was conducted, leading to the characteristics summarized in Table 1. This shows that high carbon equivalent suppresses the formation of pipe shrinkage and minimizes wall shrinkage (Figure 71a,c), while these two defects clearly appear in castings produced with hypoeutectic composition (Figure 71e,g). Furthermore, inoculation does not show a relevant effect on primary shrinkage defects apart from smoothing their internal surface, though only for hypereutectic compositions. Note that the macroporosity shown in Figure 71b also contains a rounded protuberance similar to those in Figure 70c,d or to those described for blowholes in Section 2.1.3. Interestingly, the ends of the dendrites found in all macroporosities were rounded, indicating that these voids began to develop before the final stage of solidification. In all cases, the voids due to piping effect showed smooth internal surfaces and are located in the section change between the massive area and the bridge (Figure 71e,g). Additionally, graphite layers deposited on austenite dendrites were found in the macroporosities of all four cases, which were continuous for the two hypereutectic alloys (white arrows in Figure 71b and yellow arrows in Figure 71d) but fragmented (black arrows in Figure 71f and red arrows in Figure 71h) or showing some graphite nodules set on internal surfaces (white arrows in Figure 71h) in the case of hypoeutectic alloys. Notice that microwrinkles (yellow arrows in Figure 71h) were only found in those dendrites formed in the not-inoculated hypoeutectic alloys, likely due to a high shrinking effect.

The root cause of all shrinkage defects is the volume change which all metallic alloys undergo when solidifying. Cast irons with graphite precipitation are able to compensate for such shrinking due to the graphite expansion effect. Thus, these alloys comparatively show low shrinkage risk when compared to white cast irons without graphite precipitation during solidification, cast steels, bronzes, etc. Among cast irons with graphite particles, those containing nodules (ductile irons) are known to present a higher shrinkage risk than grey irons, which is somehow further increased in case of low inoculation. Another relevant cause for shrinkage formation is the use of cast irons with either low carbon equivalent contents (hypoeutectic compositions) or high values of this parameter (see Section 4.1.3). A minimum in shrinkage occurs at near-eutectic compositions.

Although shrinkage defects are primarily metallurgical in origin, molds can also have a significant effect on the formation of these porosities. Primary shrinkage can be promoted by deformations of the mold cavities that increase their internal volume during solidification of the castings. This effect can be observed in heavy-section castings made in large chemically bonded sand molds where the liquid pressure becomes high enough to deform some internal areas. In these cases, oversizing of the parts is detected and all efforts to optimize melt feeding may be useless, while effective reinforcement of the metallic covers of the molds yields positive results. It seems obvious that such massive mold deformations are closely related to both high dynamic and metallostatic pressure of the melt in the molds and insufficient strength of the sand mixtures (low compaction of the sand grains and/or overheating of the compacted areas). Similarly, undersized or improperly shaped risers, small cross sections of the riser necks, complex geometries in the castings and/or feeding problems to areas of the castings remote from the risers are all possible reasons for macroshrinkage.

A high casting temperature can also promote shrinkage defects because it decreases solidification rates and mold damage is more likely, but conversely, a casting temperature that is too low can severely limit feeding from the risers via the necks that connect them to the castings.

Table 1. Characteristics of different shrinkage defects found in four ductile iron alloys with different carbon equivalent contents and inoculation levels [49].

Composition	Inoculation	Pipe	Wall	Macroporosity	Microshrinkage
Hypereutectic	Yes	No defect	No defect	Continuous graphite layers on smooth surfaces	No defect
	No	No defect	Yes	Continuous graphite layers on rounded dendrites	Continuous graphite layer on sharp dendrites
Hypoeutectic	Yes	Smooth surfaces	Yes	Continuous graphite layers on rounded dendrites Graphite nodules together with rounded dendrites	No defect
	No	Smooth surfaces	Yes	Discontinuous graphite layers on rounded dendrites	Discontinuous graphite layers on rounded dendrites Shrunk surfaces on dendrites

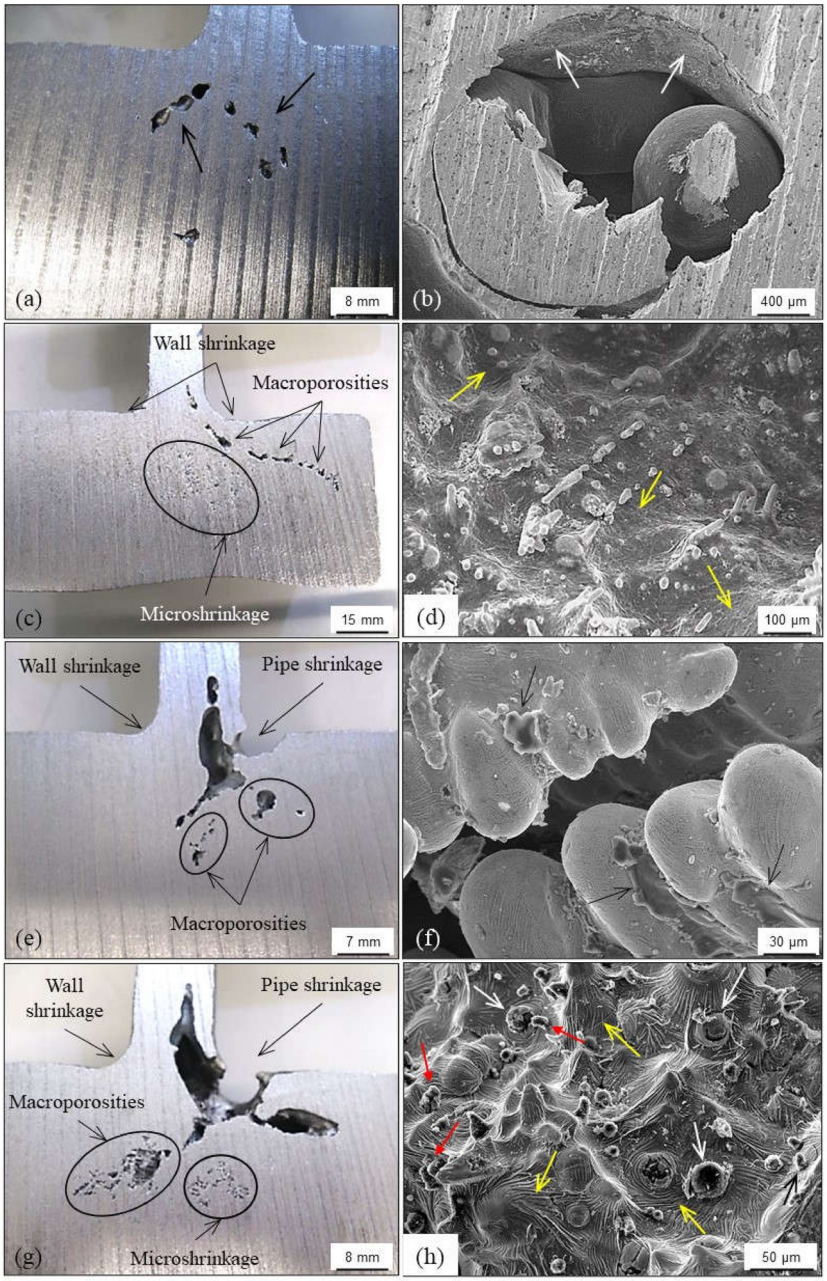

Figure 71. Different shrinkage defects found in ductile iron test castings manufactured with (**a**,**b**) an inoculated hypereutectic alloy; (**c**,**d**) a not-inoculated hypereutectic alloy; (**e**,**f**) an inoculated hypoeutectic alloy; (**g**,**h**) a not-inoculated hypoeutectic alloy (Reprinted with permission from ref. [49]. Copyright 2017 Universitat de Barcelona).

4.1.2. Secondary Shrinkage or Microshrinkage

Secondary shrinkage consists of voids clearly linked to the microstructure, often showing a dendritic morphology on their internal surfaces (Figure 72a,b). It is, hence, a lack of material in the last solidification zones at the microstructure scale, thus related to the difficulty for the liquid to circulate to compensate for the solidification shrinkage. Although the defect may be favored in hot spot areas of castings that are not properly supplied with liquid (Figure 72c,f), secondary shrinkage can result in microshrinkage in all the last solidification areas everywhere in a casting, in a manner very similar to microporosity (and thus, observable only with an optical microscope).

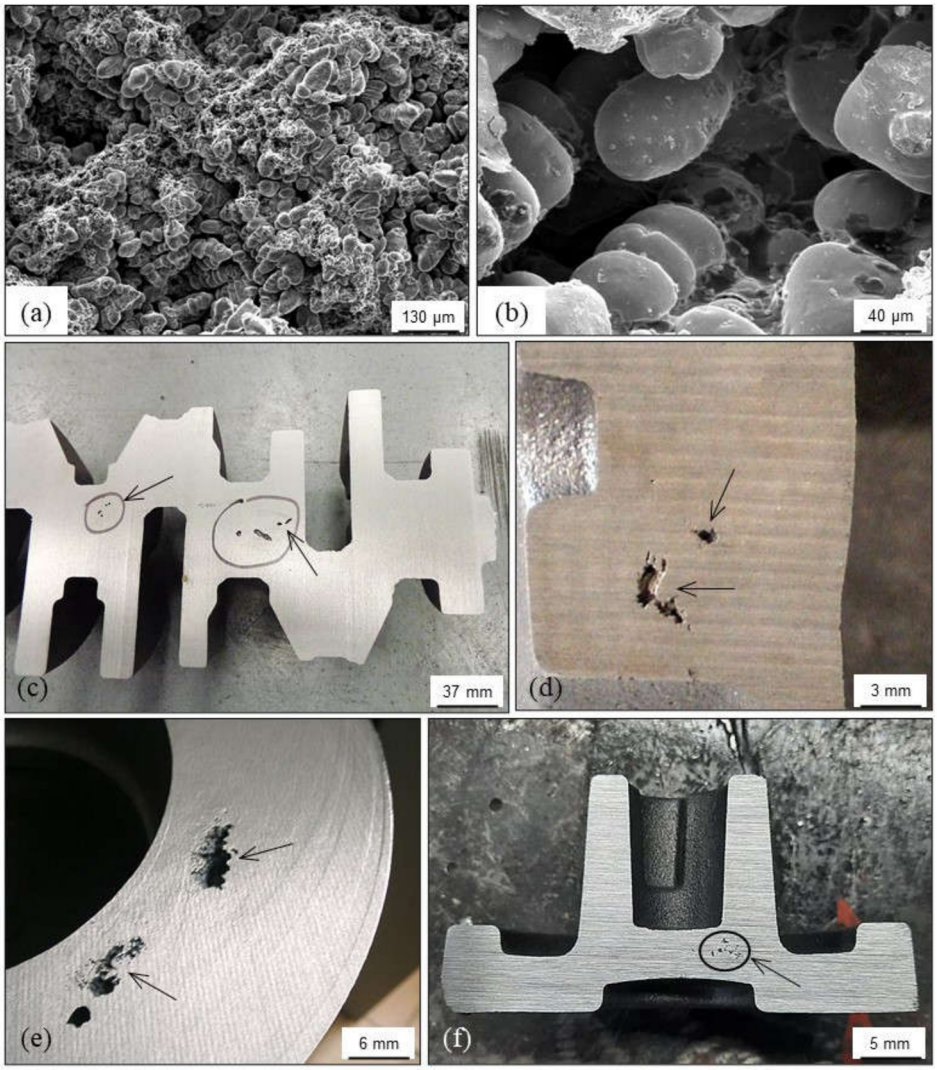

Figure 72. (**a**,**b**) SEM images of internal surfaces in a secondary shrinkage defect found in a ductile iron casting; (**c**–**f**) defects located in last solidification areas.

When the voids are of millimeter size, the defect is detected as a group of small voids, which commonly form a spongy area with different sizes (Figure 71c,h,f) or some voids together with an irregular shape (Figure 72c,e). These two different morphologies of defect are likely due to the solidification step at which shrinkage started to form.

During the last step of solidification of cast irons, profuse precipitation of graphite should compensate for the lack of liquid feeding. Accordingly, Regordosa [49] observed microshrinkage porosities only in the not-inoculated test castings. Contrary to what might be expected, she also reported that the carbon equivalent had virtually no effect on such shrinkage. While microshrinkage always showed dendritic voids, Regordosa found that the extension of the graphite layer on the internal surfaces and the sharpness of the dendrite tips increase with carbon equivalent content (Figure 73).

The different features described comparatively in Sections 4.1.1 and 4.1.2 for the four different shrinkage variants (pipe shrinkage, wall shrinkage, macroporosities and microshrinkage) should be effective tools for performing successful diagnostics in foundry plants. However, it should be considered that the characteristics of the defects listed in Table 1 and illustrated with Figures 71 and 72 may change depending on casting features and manufacturing practice.

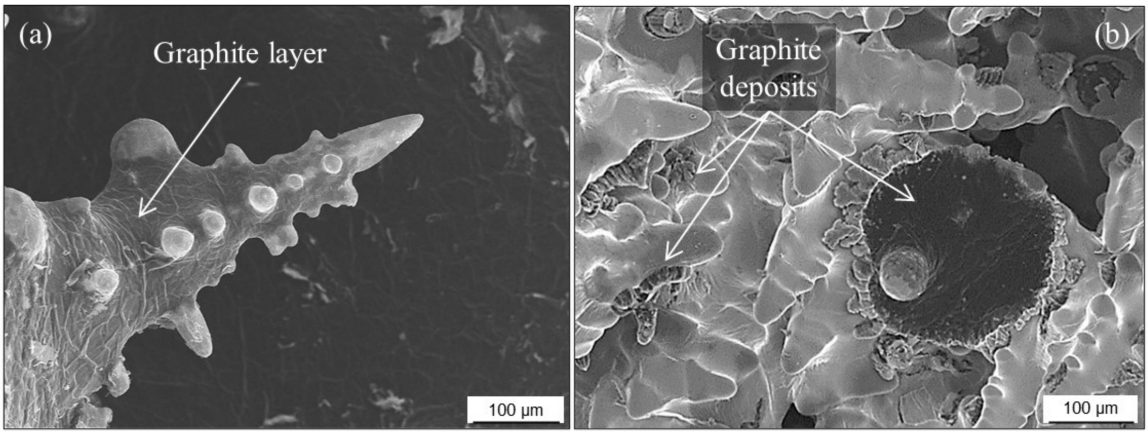

Figure 73. Characteristics in the internal surfaces of microshrinkage porosities found in the not-inoculated test castings (**a**) hypereutectic (Reprinted with permission from ref. [49]. Copyright 2017 Universitat de Barcelona) and (**b**) hypoeutectic composition.

4.1.3. False Shrinkage

This is a particular variant of shrinkage that can affect heavy-section castings produced in green sand or chemically bonded sand molds. Basically, the voids are mainly due to the progressive deformation of the molds that increases the volume of the already-cast cavities. The risk of this variant is the highest when mold deformation occurs and the fraction of solid in contact with the mold is already high. The resulting voids may have typical macro- and/or microshrinkage defect characteristics.

Mold deformation can be produced mainly for two reasons: first, high graphite expansion (high carbon equivalent content or excessive addition of inoculant) and second, high metal pressure. It is, therefore, necessary to ensure sufficient mold strength to minimize these deformations, which is particularly important when manufacturing heavy-section castings. Measures such as avoiding high compactibility values, adding sufficient amounts of bentonite (green sand molds) and optimizing the compaction of the sand grains will help to maintain sufficient mold strength. In addition, proper molding practice (closing, clamping, counterweights, etc.) and the use of a low pouring temperature will also contribute to strong molds [50,51].

4.2. Graphite Precipitation (White Cast Irons)

This defect consists in graphite precipitation in cast steels as well as in cast irons intended to be fully white. Such precipitation is not allowed in these alloys because it negatively affects the required physical properties (hardness, mechanical properties, fatigue, wear resistance, etc.). In case of white iron castings, graphite precipitates at the casting skin (inverse greyness) and as cells which remain isolated unless the incidence of this precipitates becomes severe (see the fractured surface in Figure 74a). Graphite particles formed in this defect are fine lamellas in areas between austenite dendrites (Figure 74b). In the case of cast steels, the main site of graphite precipitation is the casting skin in contact with molds made of high carbon sand mixtures, with some of this carbon being transferred to the melt. Notice that Figure 74a also shows veining defects (white arrows).

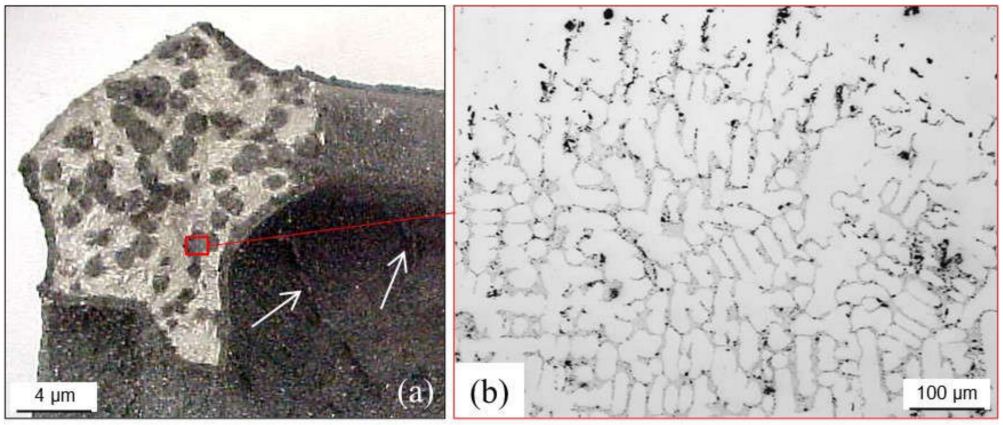

Figure 74. (**a**) Macroscopic view of fields with graphite precipitates in the heaviest section of a white iron casting. (**b**) Metallographic view of graphite particles found in one of these fields.

Graphite precipitation in white iron castings is triggered by too high carbon contents in melts (≥3 wt.%), low contents of those alloying elements used to promote white solidification (Cr, Mo, Bi, etc.) and low cooling rates which promote stable solidification. Figure 75 shows the influence of carbon and silicon contents on white or graphitic solidification in the preparation of malleable cast irons [52].

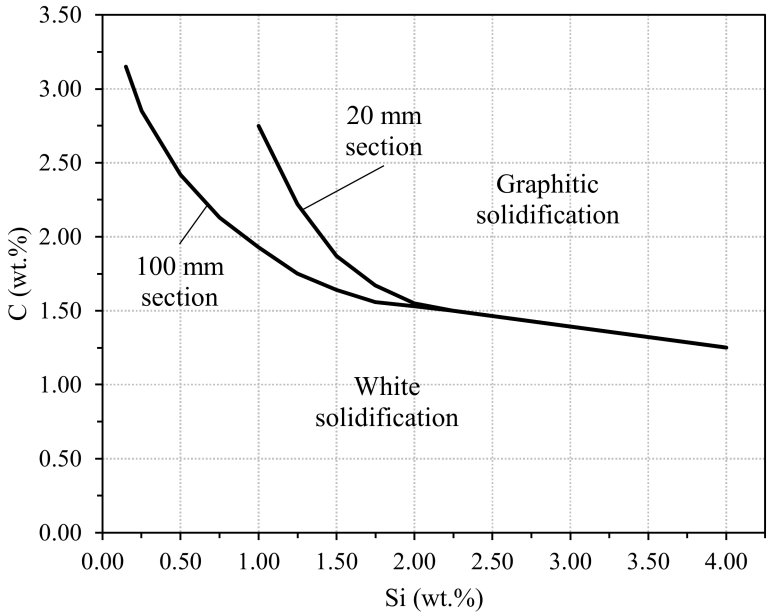

Figure 75. Effect of carbon and silicon contents on solidification of cast iron alloys prepared to manufacture malleable iron castings [52].

4.3. Graphite Degeneration

Graphite degeneration is most commonly found in ductile cast irons, although it is also present in grey cast irons, as studied for example by Reynaud [53], who related the different forms of degeneration to the presence of specific trace elements. The present subsection is limited to the degenerate forms occurring in ductile cast irons, as shown in Figure 76.

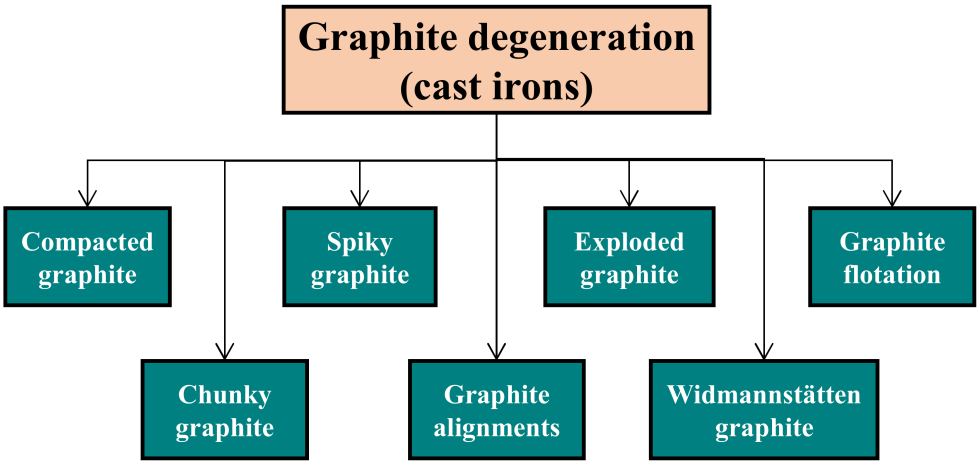

Figure 76. Various forms of degenerate graphite in ductile iron castings.

4.3.1. Compacted Graphite

Compacted graphite iron (CGI) is now well recognized as being a family of silicon cast irons, with graphite distributed as a low percentage of spheroids and the remaining as thick, rounded and interconnected plates looking like worms in 2D (see Figure 77a). Accordingly, CGI has better mechanical properties than LGI as well as a better thermal conductibility and lower propensity to porosity than SGI, which makes it an appropriate choice for thin-wall castings. Table 2 shows a comparison of the usual ranges of hardness, ultimate tensile strength (UTS), yield strength (YS), elongation at rupture (A) and thermal conductivity (TC) values found in SGI, LGI and CGI alloys with pearlitic and ferritic microstructures.

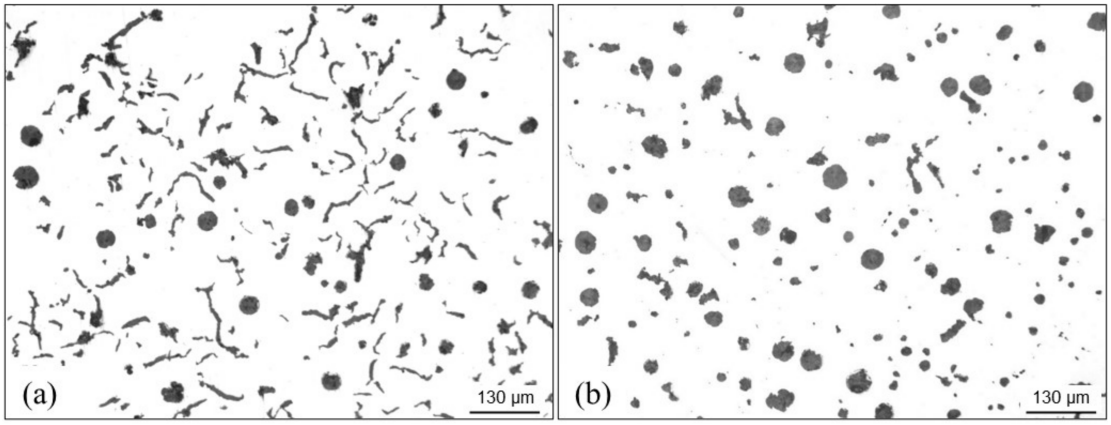

Figure 77. (**a**) Microstructure of compacted graphite iron; (**b**) microstructure of a spheroidal graphite iron with worms at about 15% in the area.

Table 2. Comparison of hardness, tensile properties and thermal conductivity ranges in grey irons, compacted irons and ductile irons with both pearlitic and ferritic structures.

Alloy	Matrix	HBW	UTS (MPa)	YS (MPa)	A (%)	TC * ($W \cdot K^{-1} \cdot m^{-1}$)
LGI	pearlitic	175–230	230–300	115–210	0–1	44–52
CGI	ferritic	130–190	330–410	240–350	5–10	40–50
	pearlitic	215–250	400–580	345–415	2–5	31–42
SGI	ferritic	140–200	400–600	285–315	15–25	32–38
	pearlitic	240–300	600–800	375–480	3–15	23–32

* TC: thermal conductivity measured at 300 °C.

However, the appearance of worms in the SGI, as illustrated in Figure 77b, is a defect leading to rejection of the casting when it reaches a critical level because it degrades the mechanical properties of the material (strength, toughness and elongation) without, however, affecting the machinability and/or the hardness of the cast alloy. This critical level of CGI in SGI castings is not easily defined by customers and casters, although it is common to find important rejection problems when a low number of compacted graphite particles are present. The distribution of these degenerate graphite in the metal matrix is most often generalized, without any preferential area being observed.

Once a proper level of inoculation is assured, the main cause of this graphite degeneration is the use of cast iron alloys with low free (active) magnesium content. On the contrary, compacted graphite particles can form in high Mg cast irons in the absence of inoculation. The critical threshold of active magnesium to ensure correct nodularity values in ductile iron castings depends mainly on the cooling rate (casting section) and the sulfur contents [43,54].

4.3.2. Exploded Graphite

The defect manifests as large spheroidal graphite particles with irregular adjacent sectors appearing at least partially disconnected from each other (Figure 78). This graphite degeneration is most likely to occur in massive areas of ductile iron castings produced with hypereutectic alloys and frequently occurs with graphite flotation (Section 4.3.3).

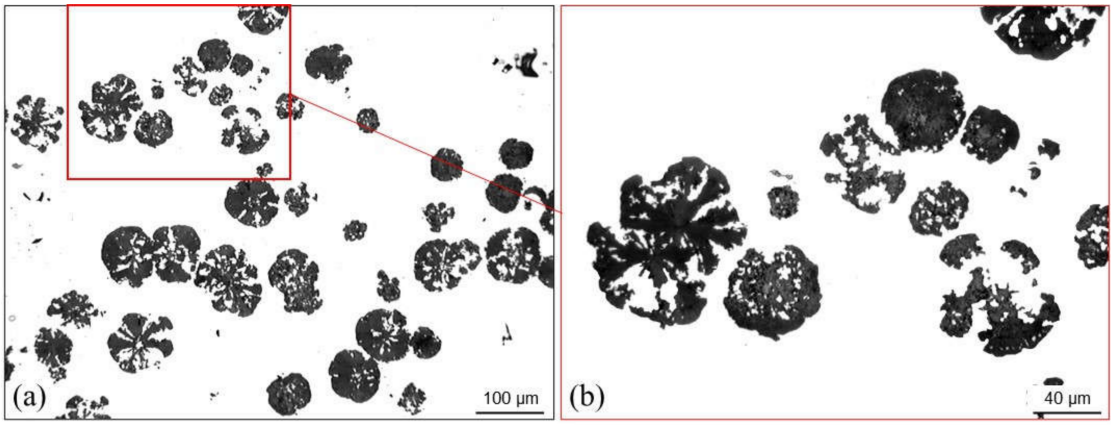

Figure 78. Optical micrographs showing exploded graphite particles in the top area of a massive ductile iron casting: general view (**a**) and detailed view (**b**).

The mechanical properties of ductile iron alloys containing exploded graphite can be severely diminished depending on the number of affected areas and the intensity of this defect, especially when associated with graphite flotation. In this case, the machined surfaces show dark shadows that allow the defect to be detected. On the contrary, if the distribution of the exploded graphite particles is uniform and at a low percentage compared to the nodules, detection is not easy even when checking the mechanical properties of the cast alloy. Generally, customers do not accept castings with this defect, except for a small amount of isolated exploded particles.

The main cause of exploded graphite in castings is the use of hypereutectic or even mildly hypereutectic compositions in areas with slow solidification rates (heavy sections). The use of some FeSiMg alloys with high rare earth contents can also promote this defect.

4.3.3. Graphite Flotation

This is a typical defect in castings with intermediate and/or heavy sections, which usually appears as a high concentration of large graphite nodules (Figure 79a,b) and is also associated with the presence of exploded graphite (Section 4.3.2). This defect negatively affects the hardness and mechanical properties of the produced alloy, since the fraction

of mechanically strong metal matrix is seriously decreased. This defect is often detected during machining and appears as dark-colored stains clearly distinguished from the rest by defined contours (Figure 79c). Similarly to the case of exploded graphite, flotation of graphite nodules often occurs in the top areas of castings or even in areas below cores. This defect is strongly promoted by an effective combination of low solidification rates, high pouring temperature and hypereutectic compositions [54,55].

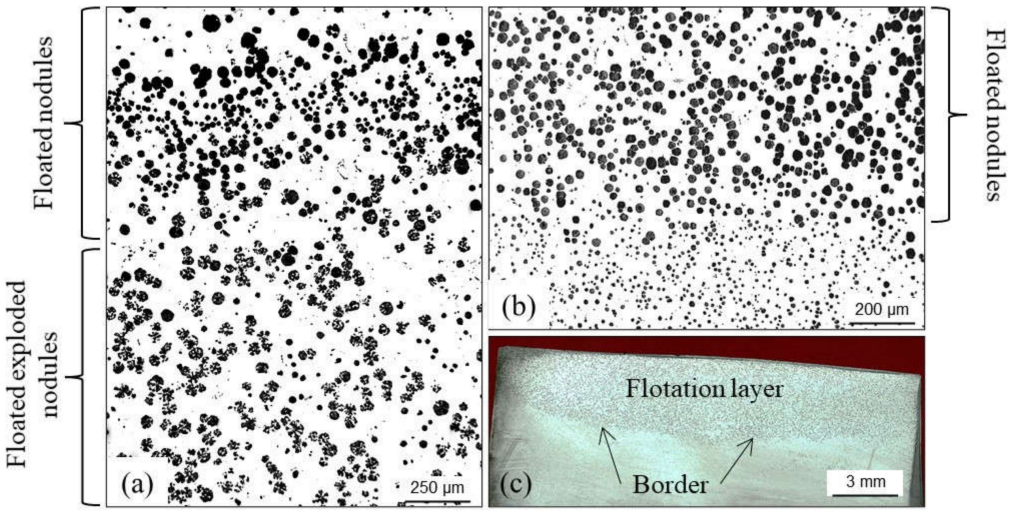

Figure 79. (**a**) Flotation layer containing primary graphite nodules over exploded ones. (**b**) Flotation layer composed of large primary nodules over a normal distribution of nodules. (**c**) Macroscopic view of a flotation layer and transition border.

Table 3 shows the relationship between graphite nodule characteristics and tensile properties for two areas of a fully ferritic ductile iron part, one with large nodules accumulated due to flotation and the other without graphite flotation (Figure 80). The material affected by primary nodule flotation shows a significant decrease in all tensile properties.

Table 3. Graphite nodules characteristics and tensile properties in one area with floated large spheroids and another one without any defect (see Figure 80). All tested sections were fully ferritic.

Area	Nodularity (%)	Average Diameter of Nodules (µm)	Nodule Count (mm^{-2})	UTS (MPa)	YS (MPa)	A (%)
No defect	>90	45.0	90	390	230	15.0
Flotation	>90	101.0	45–50	232	191	5.8

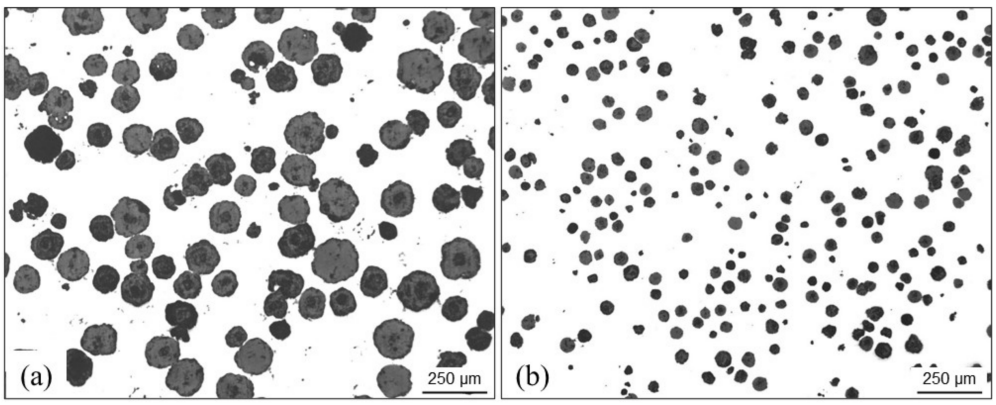

Figure 80. Distribution of graphite nodules present in (**a**) the area with graphite flotation and (**b**) the area without defects.

Causes and the recommended corrective actions to prevent graphite flotation are the ones described in Section 4.3.2 for exploded graphite.

4.3.4. Spiky Graphite

This name is used to describe graphite malformations that coexist with properly formed graphite nodules. Spiky graphite appears as irregular clusters of small, elongated, randomly oriented graphite particles (Figure 81a,b) generally limited to small and dispersed areas when observed in a metallographic section. In ductile ferritic iron castings, spiky graphite is mainly observed in areas that contain pearlite and probably correspond to the last zones of solidification (Figure 81c,d). This defect is typically found in heavy-section castings with a slow cooling rate that are produced using cast alloys with low rare earth contents (cerium and lanthanum, commonly added via FeSiMg and inoculant additions) but with the presence of trace elements, such as antimony, tin, bismuth, etc. These trace elements may be present in the alloy due to low contamination of the metallic charges used in the preparation of the melt or to minor additions made to avoid other degenerate forms of graphite. Indeed, antimony and tin can be used to limit the formation of chunky graphite (see Section 4.3.5). On the other hand, microsegregation also favors the formation of this defect in the last solidification zones by preventing any spheroidal graphite growth. The use of cerium-containing nodulizing alloys helps to minimize the formation of spiky graphite.

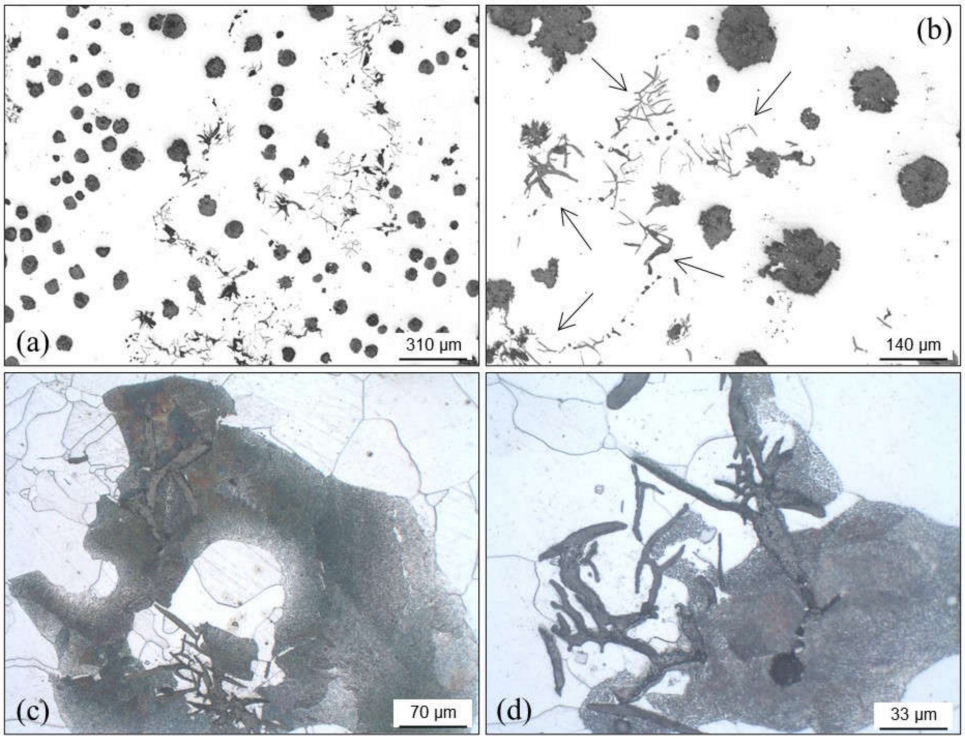

Figure 81. Spiky graphite found in a ductile iron casting solidified in about 60 min: views at different magnification in unetched samples (**a**,**b**) and in etched ones (**c**,**d**).

Even small amounts of spiky graphite in ductile iron castings have a negative effect on tensile properties and impact strength, while barely changing the hardness. A comparison of the effect of chunky graphite and spiky graphite was performed by Sertucha et al. [56]. In this work, several alloys were used to obtain both spiky and chunky graphite for eutectic and hypereutectic compositions (CE = 4.32–4.57 wt.%) and with a solidification time of about 60 min. The specific effect of spiky graphite was quantified in the case of a high silicon ductile iron, free of spiky graphite by adding antimony (3.27 wt.% C, 4.20 wt.% Si, 0.0043 wt.% Sb). Table 4 lists results on different samples, numbered 2 to 6, of this

alloy, which illustrate the effect of increasing the amount of spiky graphite (measured on metallographic sections by its relative surface fraction f_{Spiky_A}) on tensile test data. Spiky graphite was, thus, found to be detrimental and its avoidance is considered critical. This is made even more obvious by comparing these mechanical properties to those of the reference sample without chunky and spiky graphite (C = 3.13 wt.%, Si = 3.94 wt.% and Sb = 0.0038 wt.%) [57] given at the bottom of Table 4.

Table 4. Effect of different spiky graphite contents on tensile properties of a high silicon ductile iron alloy [56].

Sample	f_{Spiky_A}	UTS (MPa)	YS (MPa)	A (%)
2	0.24	444	441	1.0
3	0.28	451	444	0.5
4	0.27	459	425	1.5
5	0.12	487	430	3.5
6	0.18	486	430	3.0
Reference	0.00	565	456	16.7

4.3.5. Chunky Graphite

Chunky graphite [54,58] is primarily detected as dark, irregular spots on the surface of large-section ductile iron castings after machining (Figure 82). On a metallographic section, these dark spots appear as areas filled with small graphite particles typically distributed as shown in Figure 83a–d. The case shown with these micrographs corresponds to severe formation of this defect. In intermediate-section castings, chunky graphite may appear with a different distribution, often similar to that observed for compacted graphite particles; see Figure 83e,f. While chunky graphite generally appears in heavy-section castings, cast irons with high silicon content and/or containing high levels of cerium are also subject to this defect in small section castings.

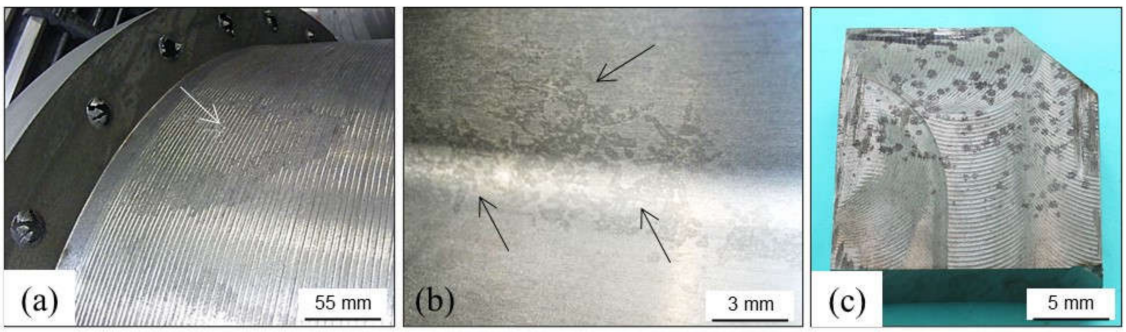

Figure 82. Dark shadows found in two heavy-section ductile iron castings after machining their surfaces (**a**,**b**). One affected sample showing a distribution of dispersed stains (**c**).

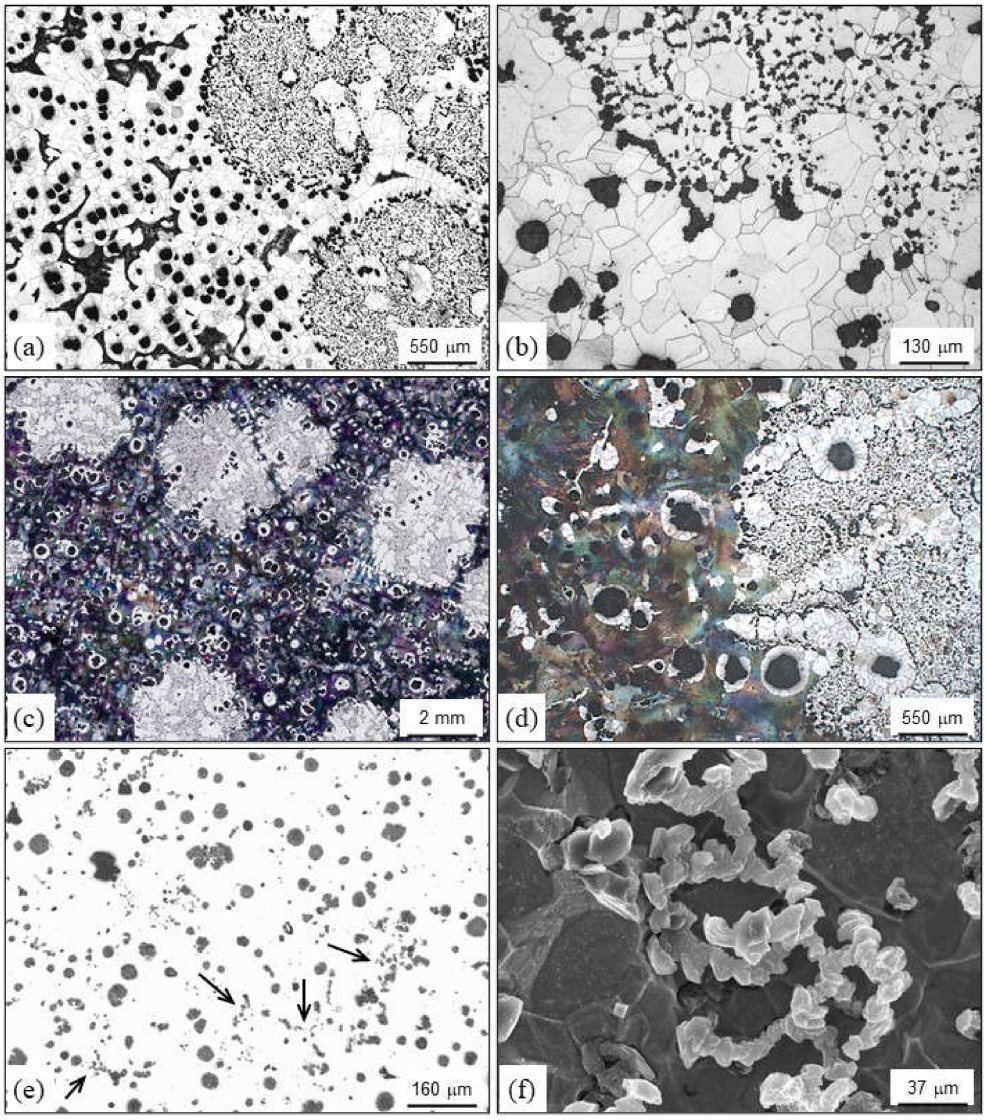

Figure 83. Conventional chunky graphite distribution in ferritic ductile iron castings (**a**,**b**). Chunky graphite cells in pearlitic ductile iron castings (**c**,**d**). Appearance of this defect in a Y2-wedge manufactured with a high silicon ductile iron alloy (**e**) and SEM view after deep etching this sample (**f**).

While chunky graphite certainly has a negative effect on the mechanical properties of ductile iron alloys, it is less detrimental than spiky graphite. On the other hand, it has been reported that this negative effect of chunky graphite on static tensile properties and on impact strength becomes smaller for high silicon ductile irons than for low silicon ones (see Table 5). In general, it is reported that if less than 20% of graphite is chunky, the decrease in the static material properties is not severe.

Although the original causes of chunky graphite formation are still controversial, it can be said that there is an increased risk of formation when the alloys contain high contents of rare earth elements (typically a cerium content higher than about 0.04 wt.%). On the other hand, this defect has been also detected in quite pure melts with cerium or lanthanum contents lower than 0.0005 wt.% [56]. Other relevant promoters of this graphite degeneration are silicon (contents higher than about 3.0 wt.%) and nickel (usual contents found in Ni-resist or Ni-hard cast alloys). It has also been suggested that the risk of chunky graphite increases with the undercooling of the melt, a situation that might be favored by a high-carbon equivalent.

Table 5. Effect of chunky graphite content on the tensile properties of a low silicon (2.46 wt.%) alloy with about 25% of pearlite and of a fully ferritic high silicon (4.17 w.%) ductile iron alloy, both free of spiky graphite [56].

Low Si Alloy	f_{Chunky_A}	UTS (MPa)	YS (MPa)	A (%)	High Si Alloy	f_{Chunky_A}	UTS (MPa)	YS (MPa)	A (%)
1	0.78	315	285	1.0	1	0.98	530	470	5.0
2	0.00	372	286	5.5	2	0.59	533	474	3.0
3	0.22	335	274	3.0	3	0.69	529	470	2.5
4 *	0.17	420	283	11.0	4	0.69	545	466	5.0
5	0.00	402	284	6.0	5	0.97	529	468	4.5

* Pearlite content in this sample was in the range 1–5%.

Only a few remedies are known to avoid chunky graphite formation: (i) increasing cooling rates and (ii) addition of well-controlled amounts of antimony, which forms compounds with cerium at high temperature (before or during solidification of the iron). The addition of tin probably has a similar effect to that of antimony, but the additions of antimony and tin must be properly balanced with the amount of RE present in the melt to avoid spiky graphite.

Although chunky graphite is one of the most common defects in fully ferritic heavy-section castings, it can also be found in pearlitic alloys, showing well-distinguished fully ferritic cells, owing to the fineness of their graphite distribution (Figure 83c,d). Because antimony is used as a pearlite promoter element and also to counteract chunky graphite formation, the incidence of this defect is comparatively lower in pearlitic castings than in ferritic ones. Finally, it is worthy to note that non-destructive inspection techniques (e.g., ultrasounds) are not usually able to detect the presence of chunky graphite in the material.

4.3.6. Graphite Alignments

This defect appears in spheroidal graphite castings and is usually seen by metallographic analysis as an alignment of graphite nodules with other graphite particles usually of a more or less rounded shape (Figure 84). It is a defect that can easily go unnoticed during low-magnification observations. However, in matrices containing ferrite and pearlite, these alignments can be easily detected after etching because the graphite particles are close to each other in "lanes" that are mainly ferritic (Figure 84b,c). In the case where several alignments are present in close areas, they generally appear along parallel lines.

In the most severe versions of this defect, the graphite nodules may have irregular morphologies and small inclusions may be present near the nodules (Figure 84c,d). SEM microanalysis of these inclusions revealed that they contain significant amounts of magnesium, silicon, aluminum, nitrogen and sulfur.

Graphite alignments create paths with abnormally small metal cross sections, whose strength may even be diminished due to the inclusions described above. This defect, therefore, creates low-strength paths in the material, which increases the risk of failure in stressed castings (Figure 85). The alignment of graphite nodules is associated with nucleation and flotation of the nodules, while a network of austenite dendrites had already developed from the surface of the casting. This defect is, thus, favored by:

- High solidification rates in thin section castings in which the eutectic undercooling is increased.
- Delayed effects of inoculation, giving more time to austenite dendrites to develop.

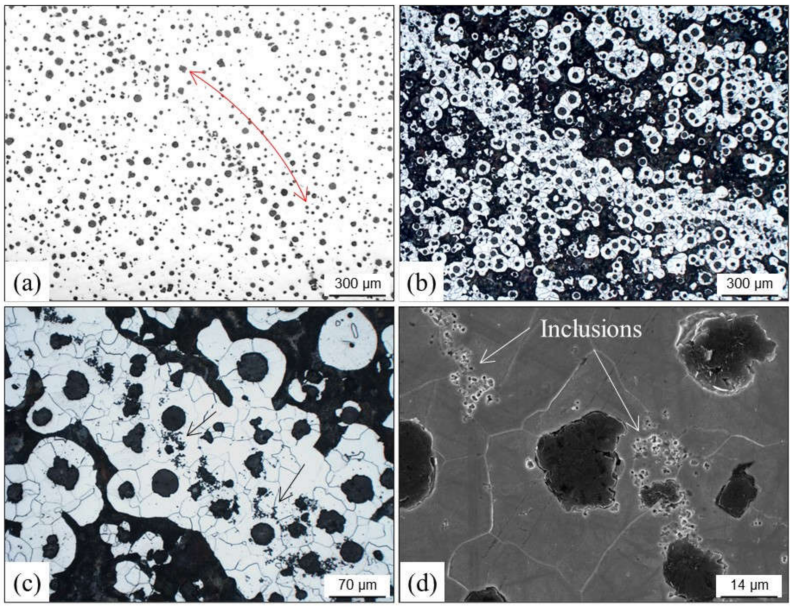

Figure 84. Examples of graphite nodules alignments in (**a**) an unetched sample and (**b**) a sample etched with Nital reactant. Optical (**c**) and SEM (**d**) images of small inclusions found in the area of graphite alignment.

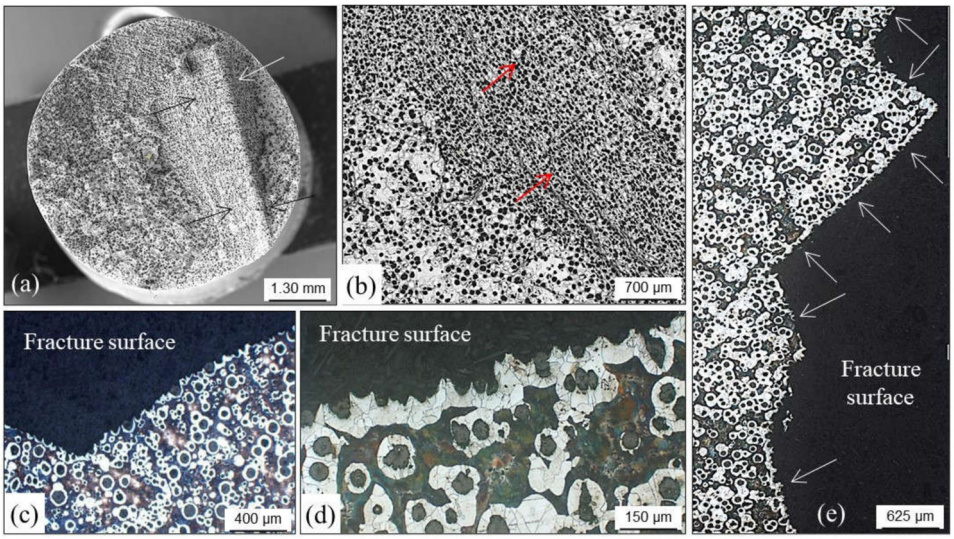

Figure 85. SEM views of a fracture surface with alignments of graphite nodules (**a**,**b**). Cross sections of the fractured surfaces showing the plates originated by alignments (**c**–**e**).

4.3.7. Widmanstätten Graphite

This defect mainly concerns LGI but can be also observed in SGI, showing some graphite degeneracy [58–60]. The defect consists in small graphite branches distributed at definite angles with respect to the surface of the main lamella (see Figure 86a,b). Usually, these branches are very thin and can go unnoticed in a routine metallographic inspection performed at 100× or 200×. It is also possible to detect irregular graphitic formations, in which the lamellae get interconnected and form "aggregates" (Figure 86c,d). It has been demonstrated that Widmanstätten graphite precipitates in the solid state, i.e., after solidification completion.

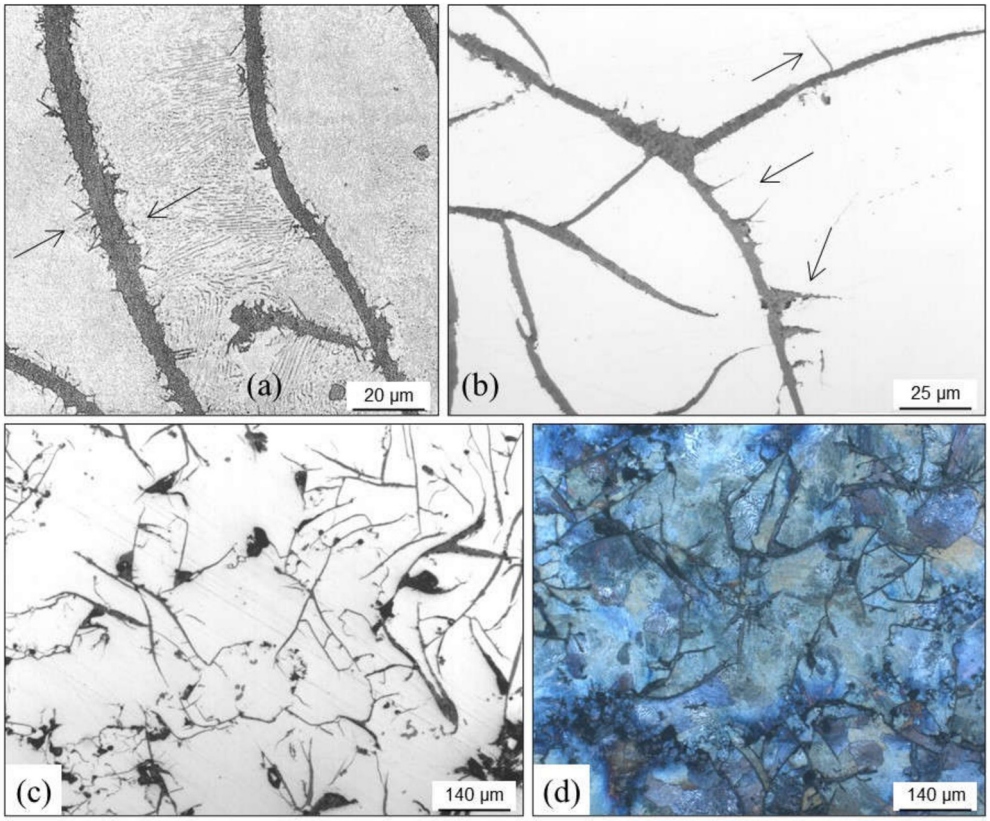

Figure 86. Examples of Widmanstätten graphite in fully pearlitic grey iron castings with graphite branches (**a**,**b**) and graphite aggregates (**c**,**d**).

Widmanstätten graphite in lamellar casting is related to low lead contamination in the alloy (>0.0005 wt.% or >5 ppm), but the defect is also observed with bismuth and has also been suggested when traces of tellurium are present. It has been reported that this defect is particularly accentuated if the metal absorbs hydrogen from the wet refractories used in the ladles and/or from mold moisture. Although it is not usual for lead to be present in ingots, any material used in the manufacturing process that contains lead (enameled machine scrap, painted steel scrap, especially in shipbuilding plants, bronzes, poor quality copper, etc.) can be a source of lead. After the defect is detected and the lead source is shut down, the problem may persist for some time because this element is usually transferred to the furnaces and/or ladle linings.

Although Widmanstätten graphite does not affect the Brinell hardness of the materials, a significant reduction in other mechanical properties is observed, particularly with respect to the ultimate tensile strength of gray irons (Figure 87). This means that very low lead contents in gray iron alloys are sufficient to cause failures in large castings.

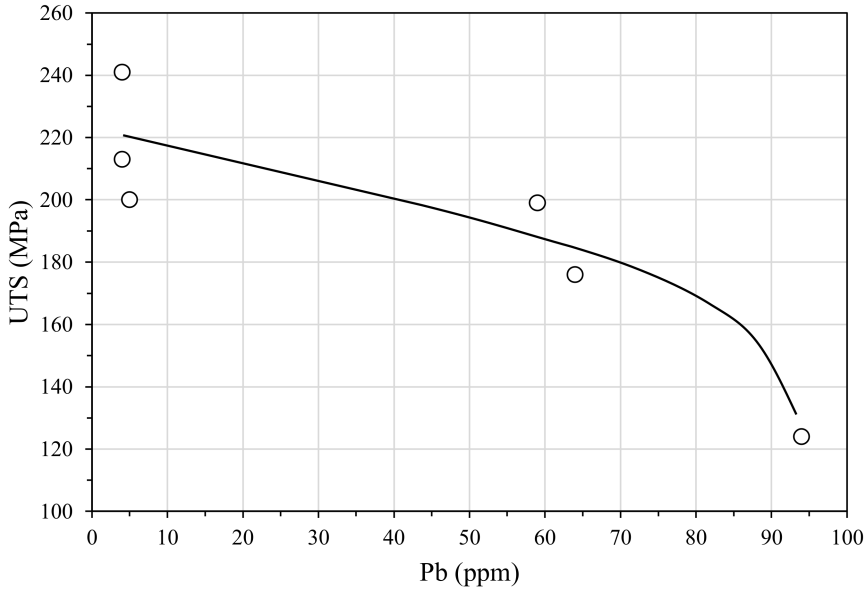

Figure 87. Evolution of ultimate tensile strength with lead content in grey cast irons [54].

4.4. Carbides and Inverse Chill

The formation of iron carbides in cast irons intended to be fully graphitic is an important defect. The term "chilling" is used in foundry plants to refer to the transition from graphitic solidification to white (carbides) solidification, and this is described in the subsection to follow, while the inverse chill that occurs in the center of castings is considered in the second subsection.

4.4.1. Carbide Precipitation: Chilling

Chill is defined as: *(1) A metal or graphite insert embedded in the surface of a sand mold or core or placed in a mold cavity to increase the cooling rate at that point. (2) White iron occurring on a gray or ductile iron casting, such as the chill in the wedge test*. It is this second definition that is of concerns in the present case.

Carbides [61] are very hard and brittle metallic-looking compounds that consist of carbon and various metallic elements (iron, chromium, vanadium, molybdenum, etc.). Specifically, iron carbide (Fe_3C) is the most common compound in cast irons and is also called "cementite". Elements such as Cr, Mo and V can substitute to Fe in cementite, but also lead to various other carbides if present in sufficient quantities in the alloy. Although detection of carbides is not easy by metallographic inspection of unetched surfaces, simple etching with Nital reagent will reveal them by showing bright precipitates with variable and often faceted shapes (Figure 88) that are difficult to confuse with ferrite grains. Another interesting hard phase commonly found in gray irons with a sufficiently high phosphorus content is steadite (Fe_3P), which shows characteristics similar to carbides (Figure 88d).

There are, however, cases where carbides are sought on the surface of castings that should have a gray core. This can be achieved by surface treatment after casting, but a special casting process has been designed for the production of grey cast iron camshafts using greensand molds. According to the customer's requirements, this part is to be manufactured with fine graphite flakes in a fully pearlitic matrix for the inner areas, but with a layer of iron carbides on the outer areas and the skin. This layer provides wear resistance and should be thick enough to cover the life of the camshaft (see Figure 89). Metallographic checks are regularly performed during production to verify the width of the carbide layers.

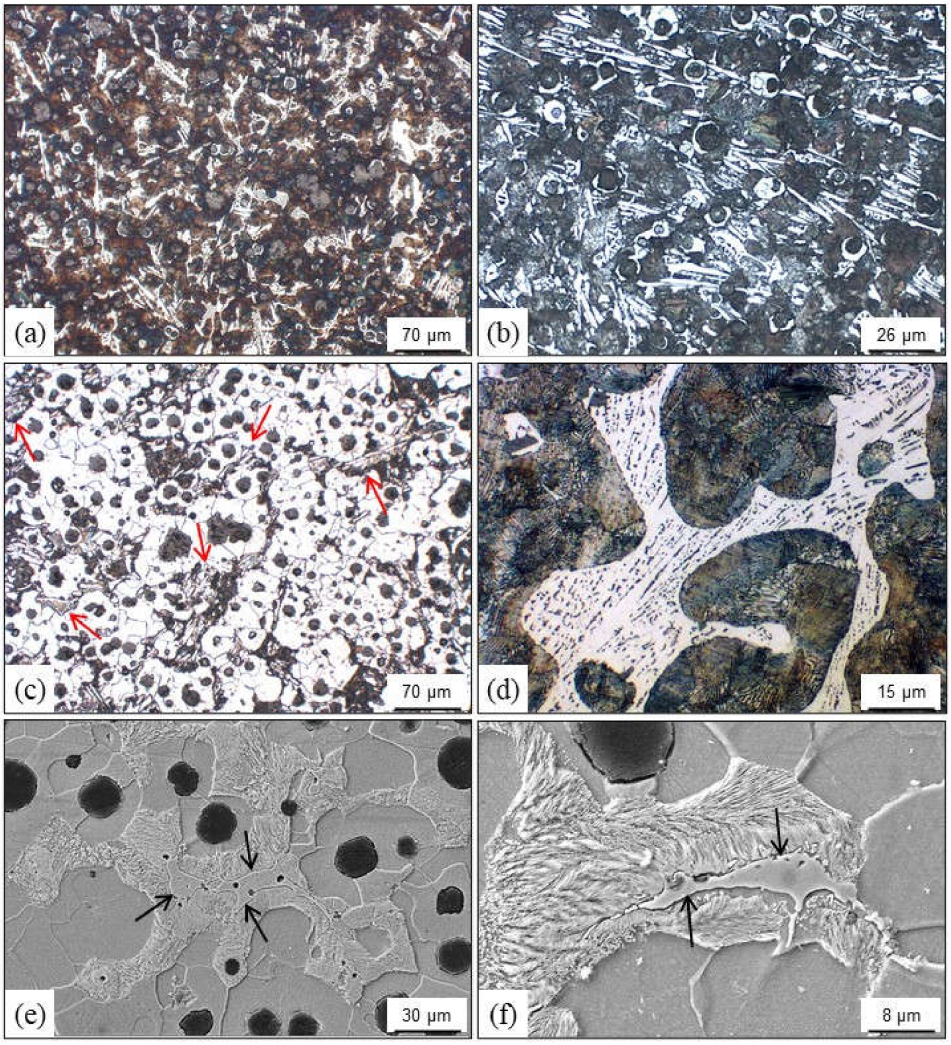

Figure 88. Iron carbides found in ductile iron pearlitic (**a**,**b**) and mostly ferritic (**c**) castings. Steadite (Fe_3P) found in a grey iron casting (**d**). SEM images which show carbides embedded in the last solidification areas together with pearlite (**e**,**f**).

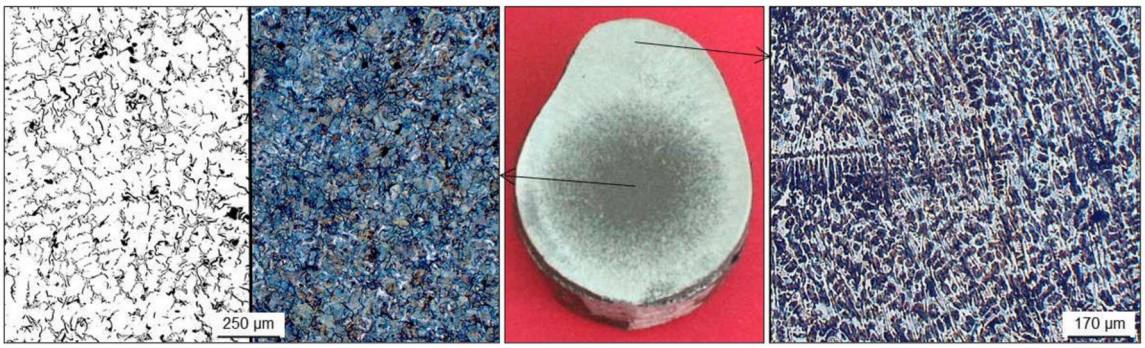

Figure 89. Cross section of a grey iron camshaft showing different microstructures.

From the macroscopic point of view, even low amounts of carbides present in castings can be easily detected by hardness measurements and/or simple tests to evaluate wear and/or cutting resistance. Other available techniques for evaluating the capacity of a melt to form carbides when solidifying (chilling tendency) are the use of chilling wedges or of cooling curves. Thermal analysis is now a modern methodology for monitoring pouring

melts before manufacturing castings as cooling curves recorded from graphitic samples and from white ones show relevant differences.

Carbides increase hardness, greatly reduce toughness and make machining operations on castings difficult. They can also cause cracks and breaks in castings during their service life. Although iron carbides (cementite) can be removed by heat treatment, this step is costly and should be avoided by applying other remedies. Carbides other than cementite are generally very stable in castings and heat treatments do little to break them down.

The formation of carbides in cast irons is caused by difficulties for graphite nucleation and growth for solidification to proceed in the stable system before the metastable one is reached. The most relevant reasons are, thus:

- High solidification rates (small casting sections, use of chills and/or die molds), casting sections located close to important burrs, etc.
- High contents of those alloying elements considered as carbide formers (chromium and vanadium) or carbide promoters because of limiting graphite growth (tellurium, magnesium, bismuth and rare earth elements).
- Melts of low graphite nucleation potential because of the use of highly oxidized metallic charges, long holding times in ladles and/or in melting furnaces, intense magnesium treatments and insufficient post-inoculation or a lack of it.
- Low carbon equivalent hypoeutectic alloys for which the silicon content plays an important role for graphite nucleation.

4.4.2. Inverse Chill

Inverse chill [62] is "*The condition in a casting section in which the interior is mottled or white, while the other sections are gray iron. Also known as reverse chill, internal chill, and inverted chill*". In other words, the solidification of a casting showing this defect starts as expected with the stable eutectic, but completes with the metastable one. As illustrated with the casting sections shown in Figure 90, the volume that is last to solidify decreases with time, eventually leading to an increase in the local cooling rate because the amount of latent heat to evacuate decreases for established temperature gradients. Above a critical cooling rate that depends on the composition of the alloy and on inoculation, solidification can shift from stable to metastable and carbides appear. It should be stressed that attempts to find macrosegregation for explaining this shift have always been unsuccessful, so that the causes of inverse chill are the same as those described for carbides precipitation in Section 4.4.1.

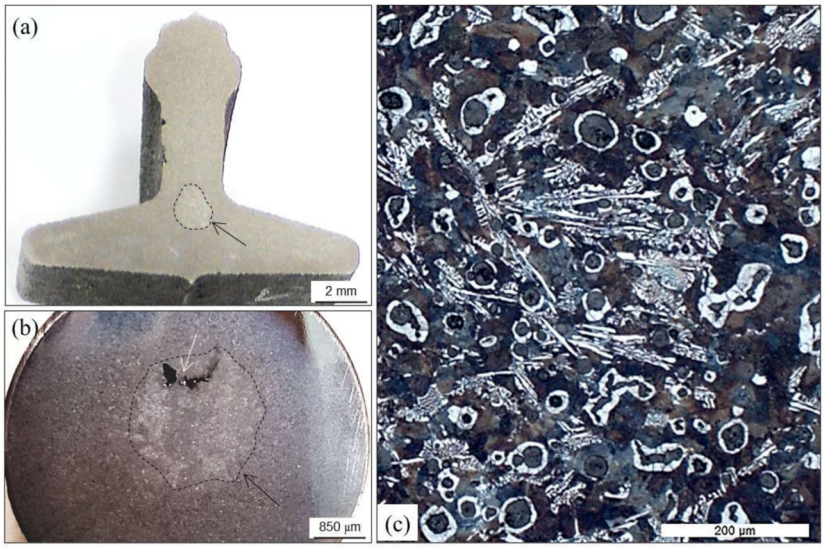

Figure 90. Inverse chill defects found in two different small section ductile iron castings (**a**,**b**). Microstructure found in the inverse chill areas (**c**).

The location of inverse chill makes its detection difficult, apart from random cuts and some operations such as machining. Once detected, simple etching with Nital reactant will clearly reveal this metallurgical anomaly. In the event that a hot spot is present in a casting due to an overheated portion of the mold or core, inverse chill may also be found near this area.

Although inverse chill can appear in parts of various sizes, it is more frequent in the last to solidify zone of narrow sections. Due to the carbide solidification mode, there is no expansion due to graphite growth and the areas affected by inverse chill also often contain microshrinkage porosities.

4.5. Cold Shut, Cold Lap

Cold shut can be defined as: *"(1) A discontinuity that appears on the surface of cast metal as a result of two streams of liquid meeting and failing to unite. (2) A lap on the surface of a forging or billet that was closed without fusion during deformation. (3) Freezing of the top surface of an ingot before the mold is full"*. Only the first and last definitions apply to cast iron castings, the first being due to poor design of the gating systems, while the last can be remedied by increasing the pouring temperature. A low impact version of the defect is the cold lap, which is defined as "*Wrinkled markings on the surface of an ingot or casting from incipient freezing of the surface and too low a casting temperature*".

The most evident version of cold shut defect is shown as a rounded groove or discontinuity that runs along the surface of the part in the coldest casting areas (Figure 91a–c). This variant can easily appear together with misrun defects in some location of the part (Figure 91d), usually the top of the mold or some region away from metal ingates. The ends which define these grooves show characteristic rounded edges, folds, wrinkles or two-part castings. Another important feature of these areas is their smooth finish, leading to an excellent surface quality due to the low temperature of the metal that reached these areas. Unlike other defects caused by massive misrun, castings containing cold shuts are produced with correctly filled runners, down sprues, risers, ingates, etc.

Cold shuts are frequent in small section castings and especially in those ones having extended surfaces. These shapes commonly show no discontinuity, but smooth areas are found that result from low temperature liquid alloy (see Figure 91e).

As mentioned above, cold shuts are directly related to low temperatures and/or low fluidity of melts when entering in molds. They can be due to the following reasons:

- Low pouring temperature, very low or very high carbon equivalent contents (see Figure 92) and high viscosity of melts due to the effect of alloying elements such as aluminum, phosphorus, etc., i.e., all those aspects which limit melt castability.
- High pouring time (too small sections in runners and ingates).
- The use of casting designs with small and large sections, which remove heat quickly from melts.
- Interrupted pouring steps (long pouring times and different parts of liquid metal entering in mold cavities).
- Low height difference between the top level of melts in the pouring cups when filling the molds and the top area of filling cavities (low dynamic and static pressure to correctly fill the entire cavities).
- Filling problems due to internal gas, which cannot be evacuated quickly to open air.
- In case of die molds, low temperature in any part of them.

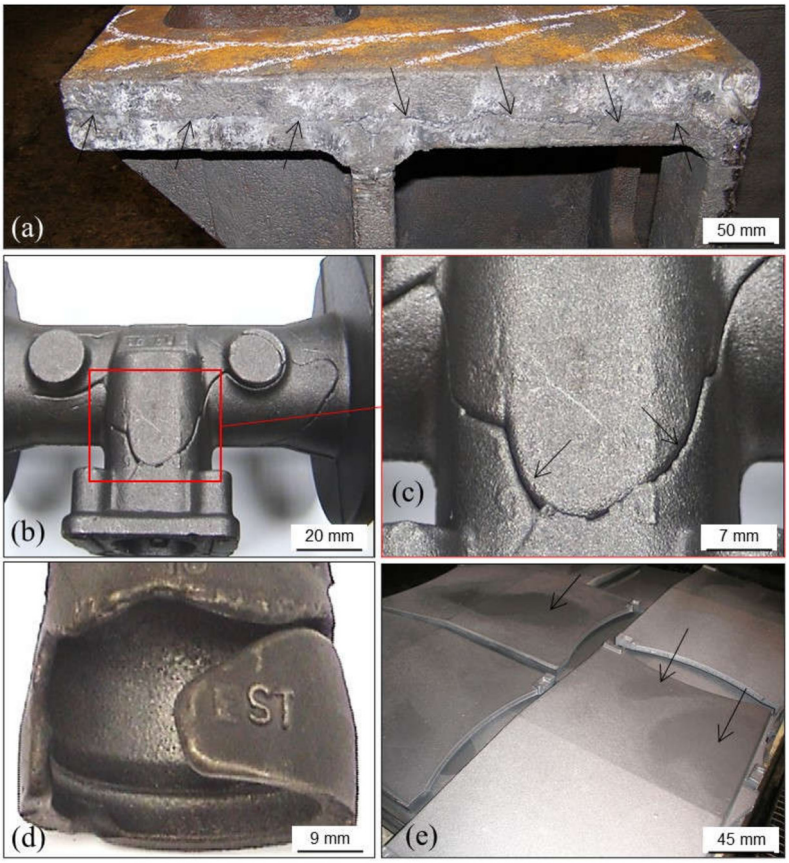

Figure 91. Severe cold shuts found in (**a**) the top area of a heavy-section casting and in a ductile iron valve (**b**,**c**). Cold shut together with misrun present in a ductile iron casting used for electrical insulators (**d**). Defect variant without discontinuities in grey iron castings used to manufacture ornamental cookers (**e**).

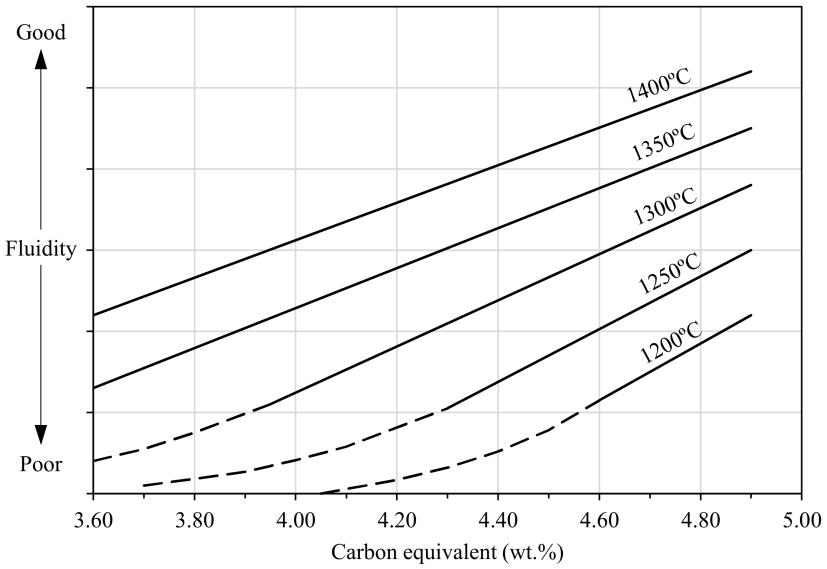

Figure 92. Evolution of fluidity in cast iron alloys with temperature [63]. The type of cast iron was not indicated. CE calculated as CE = C + Si/3 + P/2.

5. Conclusions

Casting metals is definitely the easiest way for shaping them, and cast irons are known as easy to shape, owing to their large eutectic fraction. However, getting good cast parts is not that easy, as illustrated in the present work, and it is more and more difficult as higher requirements are put on service properties. It has, thus, been seen that defective castings may be due to several reasons, related to the design of the mold and gating system, to alloy composition and melt preparation or else to sand mold manufacturing. The description of the examples detailed in this work are expected to help identifying the origin of the many illustrated defects.

Once the defects have been identified, the practical actions considered as remedies are highly dependent on each particular case, i.e., the characteristics of the foundry shop and facilities, the characteristics of the castings, the requirements from customers, etc. However, it was possible to list a number of general remedies that can help improve castings made with common foundry processes. It is interesting to note that a given remedy can generate counter-effects, i.e., lead to unexpected negative effects. Thus, foundry workers must evaluate the weight of each effect and then choose the most appropriate remedy to apply in a given case.

Author Contributions: Conceptualization, J.S. and J.L.; methodology, J.S. and J.L.; validation, J.S. and J.L.; formal analysis, J.S. and J.L.; data curation, J.S. and J.L.; writing—original draft preparation, J.S. and J.L.; writing—review and editing, J.S. and J.L.; supervision J.S. and J.L.; project administration, J.S. and J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research did not receive any external funding.

Acknowledgments: This work is dedicated to the memory of Miguel Munguira-Cañas, who started the thorough study of casting defects in Azterlan some years ago. The authors would also like to acknowledge the significant help of Marcelino Fernández-Larrakoetxea in the field of greensand and associated casting defects. The American Foundry Society (AFS) is also to be thanked for the provision of valuable books, such as "International atlas of casting defects" and "Analysis of Casting Defects". Finally, we would like to thank all the foundries that allowed the recording of original photos of various casting defects that they have unintentionally produced from time to time.

Conflicts of Interest: The authors declare no conflict of interest.

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