NEW CLASSIFICATION OF DEFECTS AND IMPERFECTIONS FOR ALUMINUM ALLOY CASTINGS

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Introduction

The final properties and in-service behavior of castings are determined by the microstructure and defects, which are the result of process stages, alloy properties and die/mold design. For instance, in high-pressure diecasting, extreme conditions are prevailing: complex components lead to complicated dies, and the required high production rates (up to 120 castings/hour) require high filling velocities of the molten alloy up to 40 m/second (131 ft./second) with significant turbulence in the flow. Solidification takes place in a few seconds, and the die is first in contact with a molten alloy at a temperature higher than 700°C (1,292°F) and, after 30-40 seconds, sprayed with a die release agent at room temperature. For these reasons high-pressure diecasting, as well as other foundry processes for Al alloys, can be considered a "*defects generating process.*" Not only is an average of 5-10% scrap typically generated, but the type, size and severity of defects also vary. The analysis of defects could provide foundries with useful correlations between defects type/distribution and their origin, which can be used for process adjustments for improving product quality.

Three main approaches for defects classification in cast components are proposed in literature or currently adopted by foundries: Cocks' approach based on defect geometry/location,[1] Campbell's approach based on defect metallurgical origin/causes,[2,3] and North American Die Casting Association's (NADCA) approach based on defect morphology.[4]

The first approach, proposed by Cocks, discerns between surface and internal defects. Surface defects are visible by the naked eye and impact both the product aesthetics and functionality. On the other hand, internal defects influence only the in-service behavior of the component.[1] The second route, suggested by Campbell, classifies defects on the basis of their metallurgical origin/causes (casting geometry, alloy, die characteristics, lubrication, process parameters, etc.). The main advantage of this classification is the opportunity to design and adopt strategies for improving the product quality. Nevertheless, the origin/causes of defects are discovered concurrently to defect identification and the same defect can be due to several factors. Furthermore, this approach is less suitable for application in foundries with respect to the previous geometry/position-based techniques, in which specific inspections can be used to reveal different defect groups.[2,3]

The third approach has been proposed by NADCA and is based on defect morphology. NADCA suggests seven defects categories that are indicated by a letter. Each category is divided into groups that are in turn divided into different

subgroups.[4] In this paper, a new terminology is presented, together with a classification of defects and imperfections with the purpose of helping die casting facilities address defects-related issues with increased confidence and ability in order to assure quality and reliability of their products.

A Multi-Level and Hybrid Classification of Defects and Imperfections

The Standard EN 12258-1:2012[5] defines "defect" as a quality characteristic which does not allow the product to carry out the requested function. This European Standard (EN 12258-1:2012) defines general terms relating to products made from aluminum alloys such as processing, sampling, testing and overall characteristics. On the contrary, the presence of an imperfection does not necessarily mean the product is not suitable for use. An imperfection should be evaluated by means of a proper scale, based on the related specifications, to decide if the product has the necessary level of quality to make it suitable for use.

In this paper, the word "defect" is used mainly for simplicity. The new classification of defects and imperfections is based on three-level approach:[6]

I) morphology/location of defects (internal, external, geometrical);
II) metallurgical origin of defects (e.g. gaseous porosity, solidification shrinkage, etc.);
III) specific type of defects (the same metallurgical phenomenon may generate various defects).

Level I distinguishes defects on the basis of their location and investigation techniques suitable for their detection (visual inspections and controls including the bulk material). In this level, internal and external (i.e. surface) defects are included, while sub-surface defects (i.e. so close to the surface that they affect external aspect of casting) are accounted for as surface defects. Finally, geometrical defects imply non-compliance of a casting to the designed shape in terms of dimension and tolerances.[6]

Level II is focused on the metallurgical origin of defects. Defects are grouped into several categories, such as shrinkage defects, gas-related defects, filling-related defects, undesired phases, thermal contraction defects and metal-die interaction defects.

As previously mentioned, the knowledge of metallurgical origin supplies a starting point for corrective actions on the process.[6]

Level III identifies the specific type of defect. Usually, the term adopted to describe a particular type of defect allows a better explanation of the metallurgical origin mentioned in Level II.[6]

The present classification of defects and imperfections is hybrid and multi-level, as schematically shown in Tables 1, 2 and 3. This proposal refers to metallurgical defects arising in permanent mold cast products. In contrast, defects related to handling, finishing and machining operations following the ejection from the die are excluded from this classification, even if they could be possible causes for product rejection.

Internal/Surface Defects and Imperfections

Shrinkage Defects

Shrinkage defects are metal discontinuities resulting from volume contraction during solidification and occur in regions with insufficient or even absent feeding. Such regions are the last to solidify (*hot spots*) and are normally well inside the casting, but sometimes they are sufficiently close to the casting surface to give rise to surface defects.

Macro-shrinkage (A1.1 in Table 1) is a relatively large (with respect to casting thickness) cavity formed inside a hot spot due to volume contraction during solidification.

As shown in Figure 1, macro-shrinkage is characterized by rough and spongy surfaces due to the interrupted growth of emerging dendrites.[1-3,7-12]

Interdendritic shrinkage (A1.2 in Table 1) forms when liquid metal cannot adequately feed the interdendritic regions to counterbalance shrinkage during solidification (Figure 2). The resulting small discontinuities are interconnected and can affect pressure tightness.[1-3,7-23]

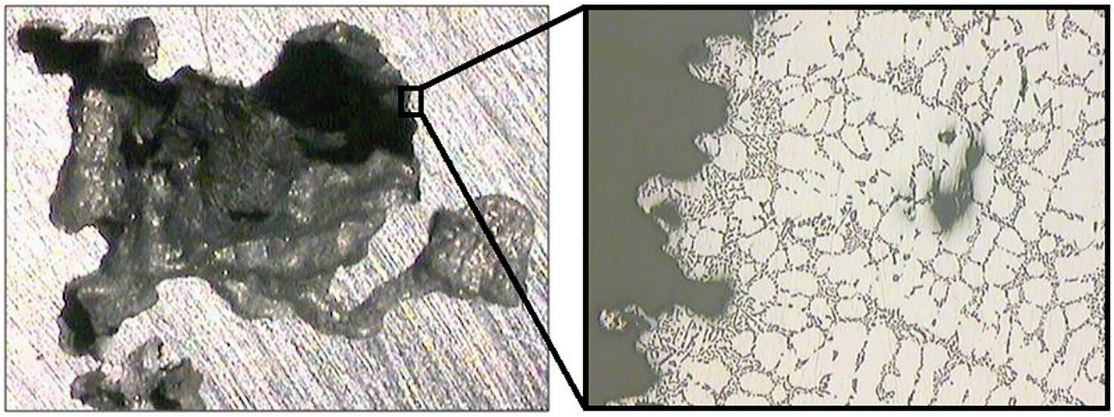


Figure 1. Macrograph of a macro-shrinkage (left) and corresponding micrograph (right).[12]

Table 1. Classification of Internal Defects and Imperfections

1st Level	2nd Level		3rd Level	
A **Internal Defects and Imperfections**	A1	Shrinkage defects and imperfections	A1.1	Macro-shrinkage
			A1.2	Interdendritic shrinkage
			A1.3	Layer porosity
	A2	Gas-related defects and imperfections	A2.1	Air entrapment porosity
			A2.2	Hydrogen porosity
			A2.3	Vapor entrapment porosity
			A2.4	Lubricant and/or die release agent entrapment porosity
	A3	Filling-related defects and imperfections	A3.1	Cold joint
			A3.2	Lamination
			A3.3	Cold shot
	A4	Undesired phases	A4.1	Inclusion
			A4.2	Undesired structure
	A5	Thermal contraction defects and imperfections	A5.1	Cold crack
			A5.2	Hot tear, hot crack

Table 2. Classification of Internal Defects and Imperfections

1st Level	2nd Level		3rd Level	
B **Surface Defects and Imperfections**	B1	Shrinkage defects and imperfections	B1.1	Sink
	B2	Gas-related defects and imperfections	B2.1	Blister
			B2.2	Pinhole
	B3	Filling-related defects and imperfections	B3.1	Cold joint, vortex
			B3.2	Lamination
			B3.3	Cold shot
	B4	Undesired phases	B4.1	Surface deposit
			B4.2	Contamination, inclusion
	B5	Thermal contraction defects and imperfections	B5.1	Cold crack
			B5.2	Hot tear, hot crack
	B6	Metal-die interaction defects and imperfections	B6.1	Erosion
			B6.2	Soldering
			B6.3	Thermal fatigue mark
			B6.4	Ejection mark
			B6.5	Corrosion of the die

Table 3. Classification of Geometrical Defects and Imperfections

1st Level	2nd Level		3rd Level	
C **Geometrical Defects and Imperfections**	C1	Lack of material	C1.1	Incompleteness
	C2	Excess material	C2.1	Flash
	C3	Out of tolerance	C3.1	Deformation

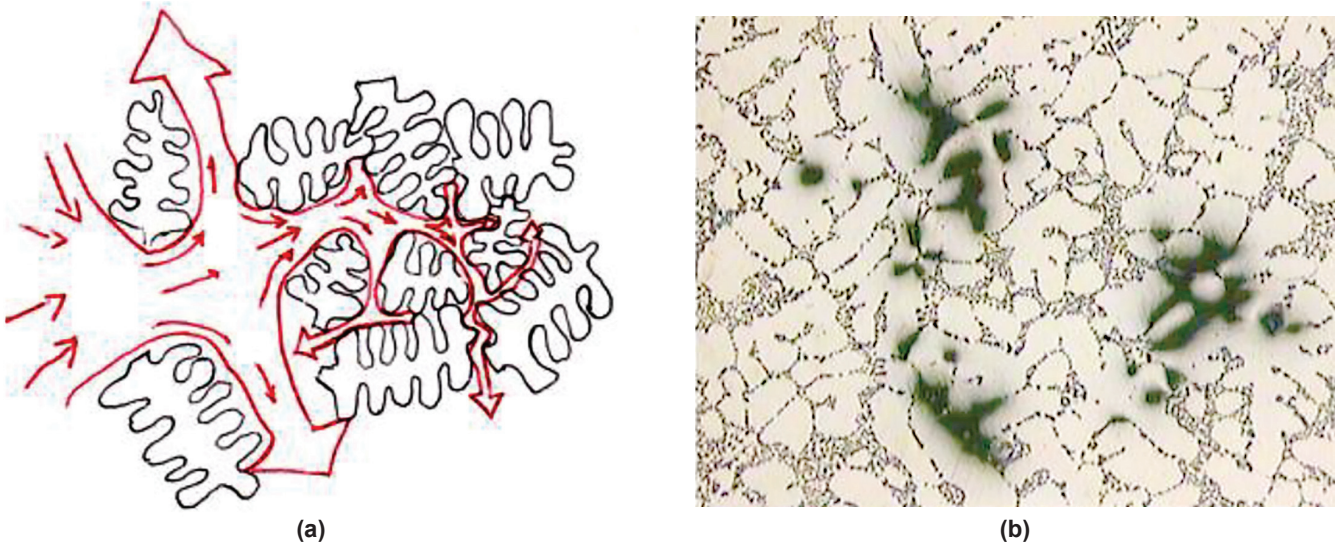


Figure 2. (a) Schematic view of metal flow around dendrites and (b) micrograph of a region with interdendritic porosity.[12]

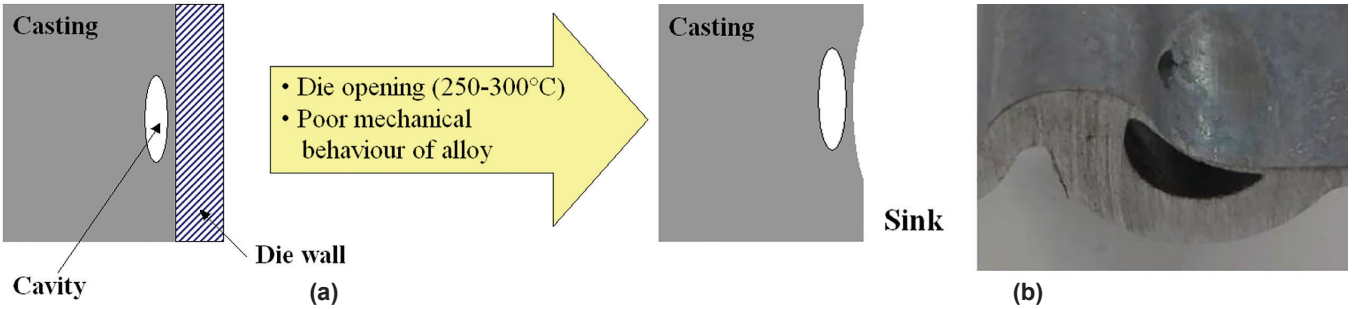


Figure 3. (a) Draft of sink formation and (b) sink appearance on the external surface of casting.[12]

Formation of both macro- and interdendritic shrinkage depends on mold-filling conditions, alloy physical properties (e.g. solidification range- and shrinkage), geometry of the casting and process parameters.

Layer porosity (A1.3 in Table 1) consists of a set of shrinkage defects typically aligned along the neutral thermal axis/surface of the casting. The neutral thermal axis/surface is located in sections of the castings where the thermal gradient is lower than adjacent points.[2,3,11,13]

Sink (B1.1 in Table 2) is a surface depression related to the presence of a sub-surface shrinkage porosity. This kind of defect occurs during the casting solidification, when a hot spot is localized close to the metal/die interface. The skin layer, formed as a consequence of melt contact with the die, is not able to sustain the atmospheric pressure and plastically deforms (Figure 3). Sinks are typically found in components with relatively wide plane surfaces or sharp cross section changes.[1,12]

Gas-Related Defects

Gas-related defects are small cavities due to entrapment of air, or gas mixture, inside the die cavity.

Air entrapment porosity (A2.1 in Table 1) forms as a consequence of air entrapment in the liquid metal. As shown in Figure 4a, air porosity appears as spherical or ellipsoidal cavities characterized by relatively smooth surfaces on which a thin oxide layer, due to the interaction between air and liquid metal at high temperature, can be found. Air porosity is the most frequent gas-related defect in high-pressure diecasting: air bubbles can form in the turbulent metal vein in the shot sleeve, in the runners and gates or inside the die cavity.[1-4,12,19,20,22,24-36]

Hydrogen porosity (A2.2 in Table 1) consists of spherical or elongated cavities characterized by a smooth and non-oxidized surface (Figure 4b). Such cavities are small and distributed almost homogeneously within the casting. Humidity in the die cavity or air causes the presence of monoatomic hydrogen in the liquid metal at high temperature. Due to the abrupt reduction of hydrogen solubility in the solid phase, the solidifying metal rejects the hydrogen, which forms bubbles near the liquid/solid interface. In high-pressure diecasting, hydrogen porosity is far less frequent than air entrapment porosity. This is due to the high pressure on solidifying melt increasing the solubility of nascent hydrogen in the remaining melt, drastically reducing the size of forming molecular gas pores.[2,3,12,13,16,35,37-41]

Vapor entrapment porosity (A2.3 in Table 1) is due to residual humidity on the die surface, which becomes vapor when it comes into contact with the molten metal. The presence of humidity on the die surface could result from an excess of water-based lubricant and/or die release agent.

Lubricant and/or die release agent entrapment porosity (A2.4 in Table 1) forms when gases resulting from decomposition of shot sleeve lubricant and/or die release agent remain trapped as bubbles in the liquid metal. The surface of these bubbles appears darker than the other gas-related defects due to the presence of combustion products.

Superficial gas-related defects are commonly known as blisters and pinholes.

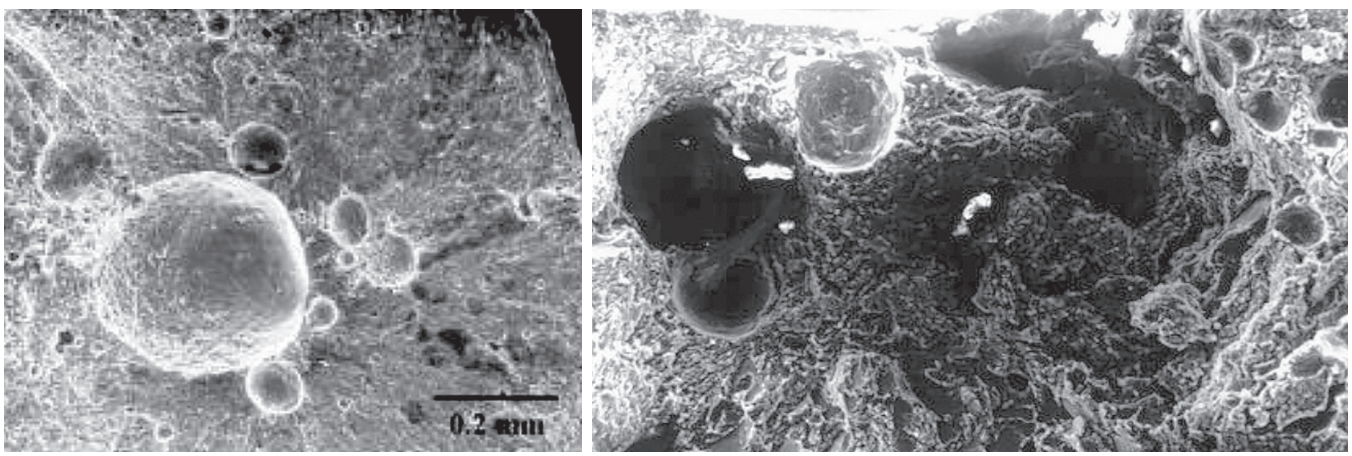
Blisters (B2.1 in Table 2) consist of small surface areas that protrude from the surface when the internal pressure of subsurface gas-related porosity plastically deforms the skin of the casting (Figure 5a). The layer deformation usually happens at relatively high temperatures, when castings are ejected from the die or during subsequent heat treatments.[1,12]

Pinhole (B2.2 in Table 2) is a smooth-walled cavity approximately spherical and located in sub-surface regions, as shown in Figure 5b. Pinholes are caused by gas entrapment in the metal during solidification. Such gases arise from moisture, binders and additives (containing hydrocarbons, blacking and washes) from sand cores.[36]

Filling-Related Defects

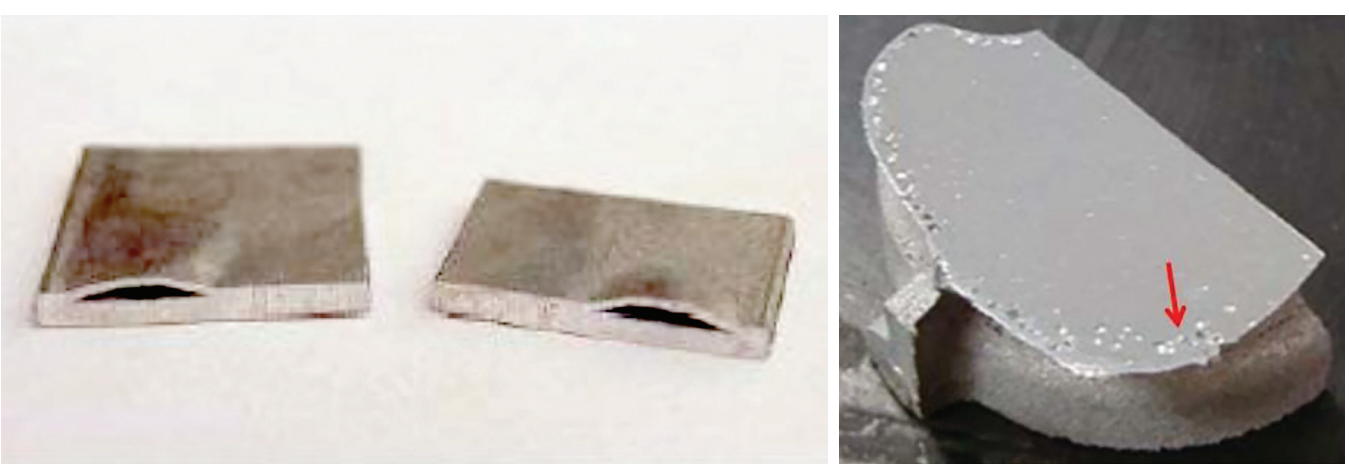
Filling-related defects are caused by anomalous melt flow. During the die cavity filling, liquid and solidified metal veins at different temperatures and sometimes covered by oxide films can accidentally meet, causing a metallurgical inhomogeneity.

Cold joint (A3.1 in Table 1 and B3.1 in Table 2) forms when a relatively cold metal flow, partially solidified and in some cases covered by an oxide film, meets another warmer metal vein that can flow around it (Figure 6a). A particular cold joint defect is the *vortex* (B3.1 in Table 2) which occurs on a casting surface and shows a characteristic spiral distribution of oxide films and microstructures. Cold joint and vortex usually cause fracture at relatively low stresses.[1,3,12,22,24,26,27- 29,31-33,35,42-48]



(a) (b)

Figure 4. SEM image of (a) air porosity and (b) hydrogen porosity.[12,26]



(a) (b)

Figure 5. Examples of (a) blisters and (b) pinholes.[12,36]

Lamination (A3.2 in Table 1 and B3.2 in Table 2) is a typical surface defect (Figure 6b), but can sometimes also be considered as internal defect. This is a type of thin metallic layer/skin with different microstructure from the surrounding material and partly separated by an oxide film. Lamination forms when metal comes into contact with the die surface and solidifies with a higher rate.[1,3,12,22,26-29,31-33,35,42-46,48]

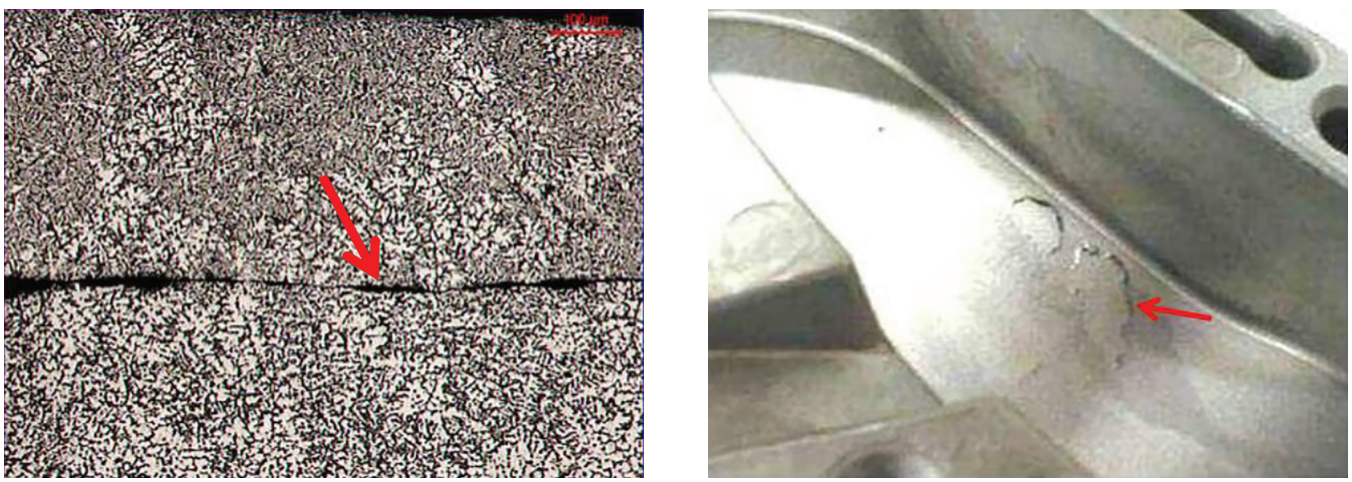
Cold shot (A3.3 in Table 1 and B3.3 in Table 2) is a small amount of metal characterized by finer microstructure than surrounding regions and separated by a thin oxide layer, as shown in Figure 7b. It forms when the melt flows turbulently with a front characterized by the presence of droplets (*spray effect*) and comes into contact with the surface of the die (Figure 7a). Under such conditions, the molten metal solidifies rapidly.[1,3,12,22,26-29,31-33,35,42-46,48]

Undesired Phases

Some phases are undesired for their high hardness, stiffness, brittleness and because they create microstructural discontinuities resulting in crack nucleation and propagation sites. Intermetallics sometimes can be identified as undesired phases.

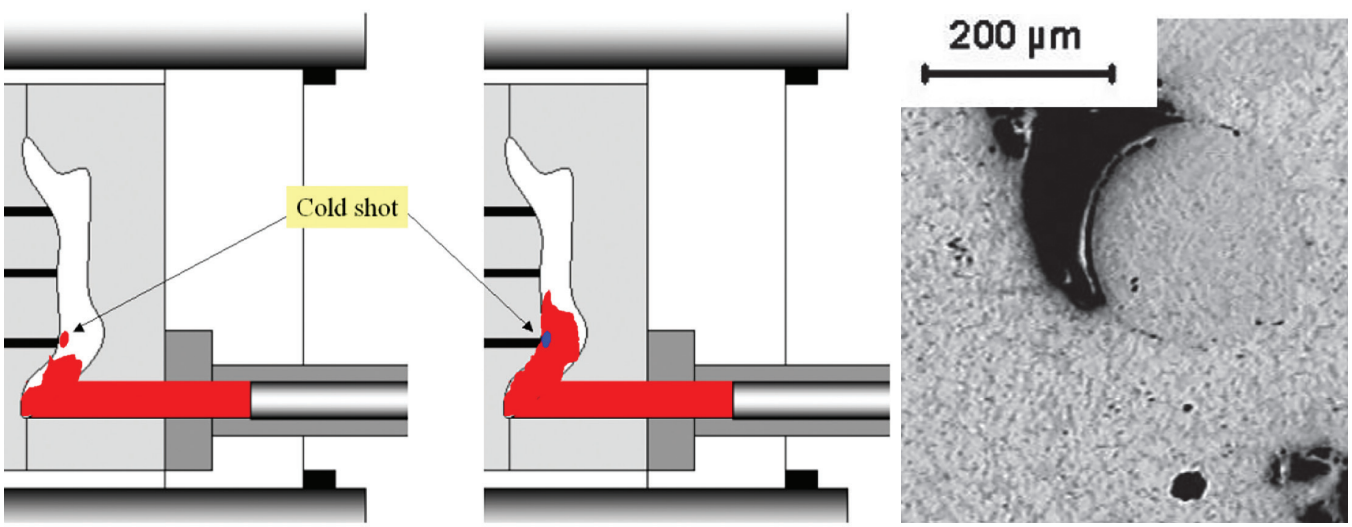
Inclusions (A4.1 in Table 1 and B4.2 in Table 2) are typically non-metallic phases and include oxides (Figure 8a), pieces of refractories (often silicon carbide) and dross. In Al alloys, the most frequent type of inclusion is aluminum oxide, Al_2O_3.[1,3,12,22,26,32,33,35,41-46,49-51]

Undesired structure (A4.2 in Table 1) consists of local unsuitable structure characterized by low strength or higher values of dendrite arm spacing than surrounding microstruc-



(a) (b)

Figure 6. Examples of (a) cold joint and (b) surface lamination.



(a) (b)

Figure 7. (a) Scheme of cold shot formation and (b) micrograph showing a cold shot associated with air entrapped porosity.

ture (Figure 8b).[1,3,51-53] Undesired phases also can be located on the surface of castings, such as surface deposits and contamination defects.

Surface deposit (B4.1 in Table 2) is a layer of varying chemical composition, thickness, distribution and adhesion, which deposits on the surface of casting (Figure 9a). The formation of surface deposit can be caused by lubricant and/or die release agent excess.

Contamination defects (B4.2 in Table 2) are the result of interaction between metal and environment. When a contaminant defect occurs, part of the casting surface has a different color than other regions, as shown in Figure 9b.

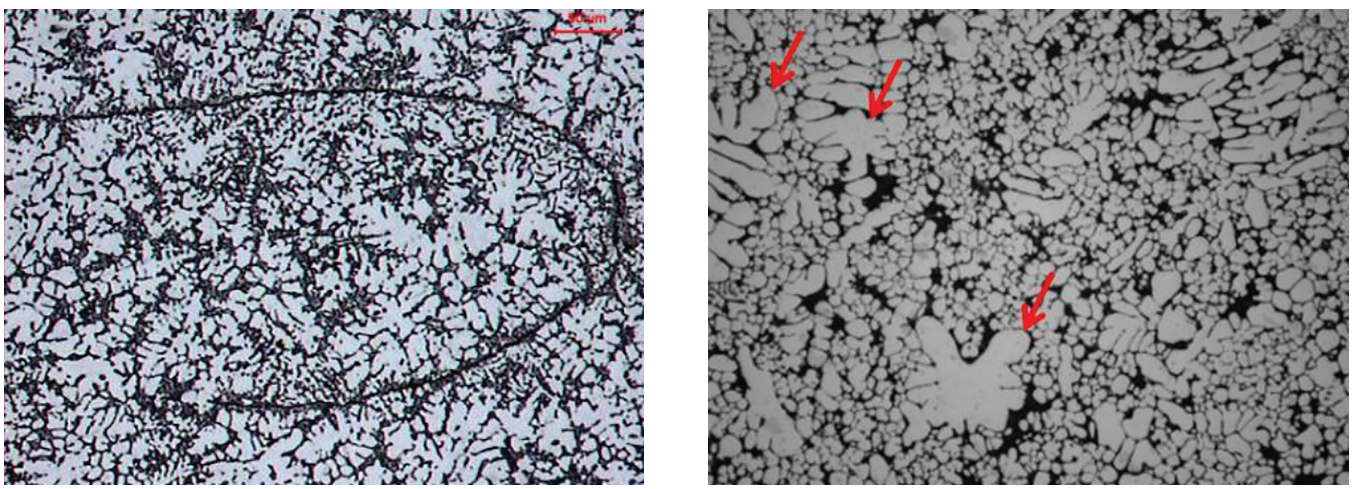
Thermal Contraction Defects

Thermal contraction defects consist of cracks formed during solidification or cooling to room temperature, when tensile stresses, arising from material contraction, exceed the ultimate tensile strength at local metal temperature.

Cold crack (A5.1 in Table 1 and B5.1 in Table 2) is a geometrical discontinuity characterized by one dimension far smaller than the two others, as shown in Figure 10a. The surfaces of a cold crack often show transcrystalline failure mode. In high-pressure diecasting such defects occur at relatively low temperatures, far below the solidification range. At these temperatures thermal contraction of casting is prevented by the die.[1,3]

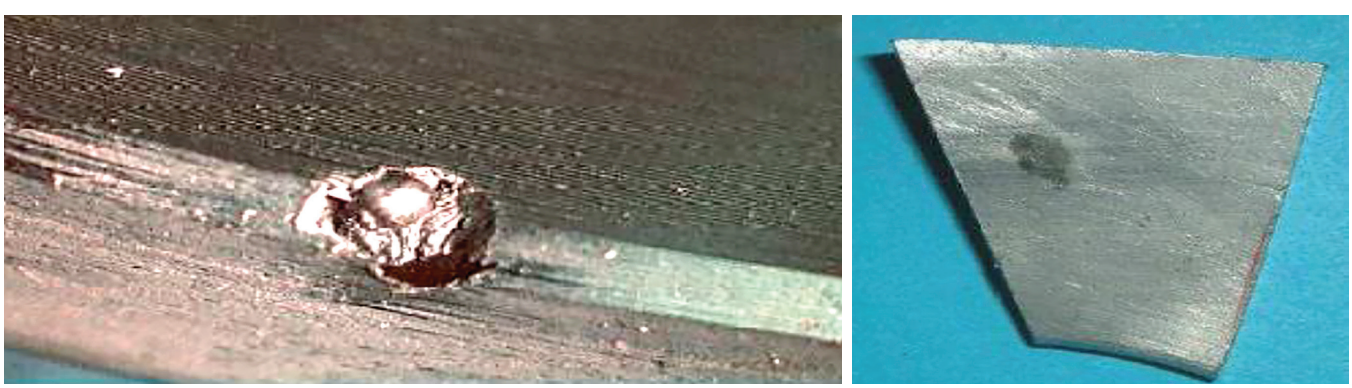
Hot tear or *hot crack* (A5.2 in Table 1 and B5.2 in Table 2) is a crack formed in liquid portions of the mushy zone during the final stages of solidification. The surface of a hot tear displays a dendritic morphology (Figure 10b), heavily oxidized since it formed at high temperature. This defect usually occurs in alloys characterized by a wide solidification range and in hot spot areas at stresses far below the tensile stress of the alloy.[1-3,12,54-56]

Both cold cracks and hot tears often occur in regions of stress, either due to macroscopic geometrical reasons or to the presence of microstructural defects, such as gas-related



(a) (b)

Figure 8. Micrograph of (a) an oxide bi-film and (b) a region with large dendrites surrounded by fine dendrites.[12,52]



(a) (b)

Figure 9. (a) Macrograph of a deposit and (b) example of contamination.

or interdendritic porosity. Since the thermal contraction defects can extend throughout the casting, they are accounted for both as internal and surface defects.

Surface Defects and Imperfections

Metal-Die Interaction Defects

Metal-die interaction defects are surface defects and result from unsuitable surface conditions caused by the interaction between metal and die. Since most of these defects are consequences of geometry modifications of the die surface, they are named according to the degradation phenomenon occurring in the die itself, i.e. erosion, soldering, thermal fatigue, ejection marks and corrosion. These defects are often located in regions of the die that are exposed to melt at relatively high temperature and flow rate. For this reason, they can be found frequently in high-pressure diecasting.

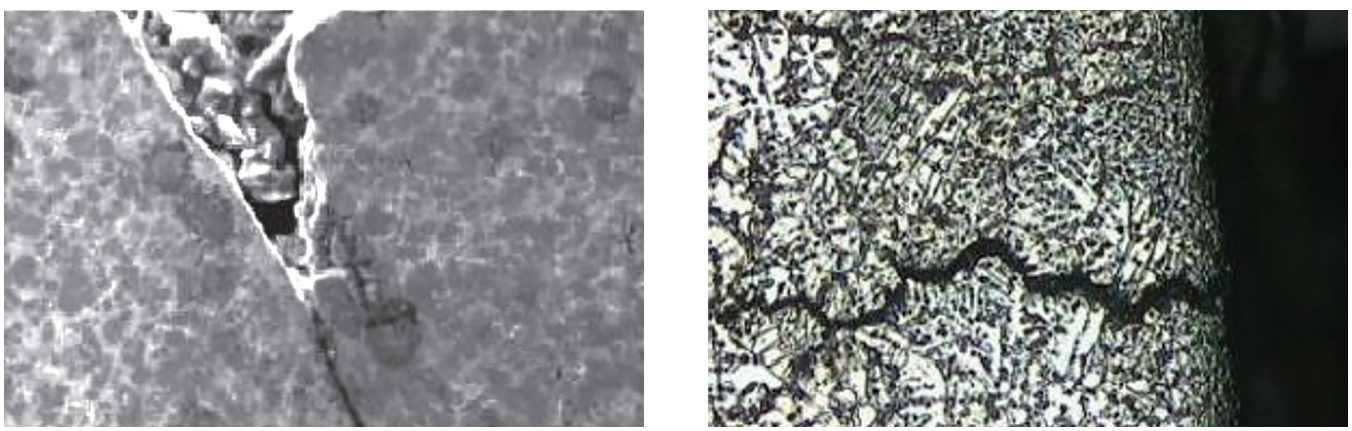
Erosion (B6.1 in Table 2) consists of excess material on the casting due to steel removal from the die for erosive wear. Erosion depends on the inclination angle between the melt flow and die surface and on the presence of particles, or bubbles in cavitation, in the liquid metal.[1,12,54,58-60]

Soldering (B6.2 in Table 2) appears as roughness or localized lack of material on the casting. The metallurgical origin of soldering is the formation of intermetallic phases on the die surface (Figure 11) and following adhesion of Al alloy onto these phases. Soldering can take place easily in zones of the die where thermal fatigue or erosion phenomena have previously occurred.[1,12,54,57-70]

Thermal fatigue marks (B6.3 in Table 2) result in a set of narrow reliefs on the surface of the casting, sometimes called "crocodile skin" (Figure 12). As the service time of the die increases, small cracks can form on its edges and surface, due to the thermal stress cycles. Subsequently the melt fills these cracks and gives rise to the relieves on the surface of casting.[1,6,12,54,58-61,65,66,71]

Ejection mark (B6.4 in Table 2) appears as a plastic deformation of the casting that extends along the direction of the die ejection, as shown in Figure 13a. This defect is related to the presence of an undercut in the die, which could be a result of die-geometry modifications due to one of the previously described phenomena.

Corrosion of the die (B6.5 in Table 2) results in surface roughness of the casting due to a corresponding surface roughness of the die caused by corrosion (Figure 13b).



(a) (b)

Figure 10. Micrographs of (a) cold crack and (b) hot crack.[12]

(a) (b)

Figure 11. (a) Example of a die affected by soldering and (b) die damage after soldering.[12]

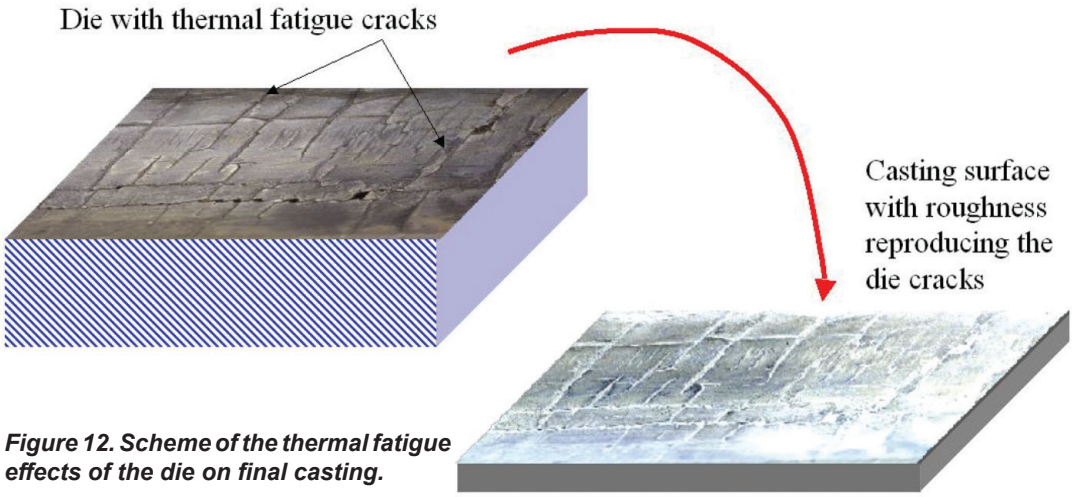
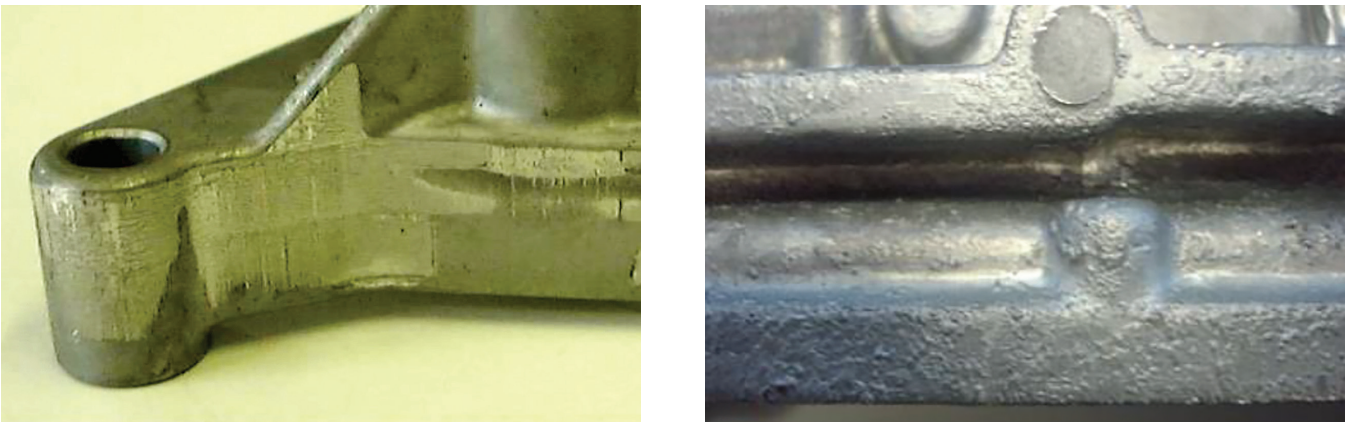


Figure 12. Scheme of the thermal fatigue effects of the die on final casting.



(a) (b)

Figure 13. Macrographs of (a) ejection marks and (b) casting produced using a corroded die.

Geometrical Defects and Imperfections

Geometrical defects cause non-compliance to designed shape in terms of lack or excess of material and out of tolerances. This class of defects includes incompleteness, flash and deformation.

Incompleteness (C1.1 in Table 3) shows a lack of material in the casting with respect to the designed geometry. The incomplete filling of the die cavity is related to an excessively high viscosity of the melt.[29]

Flash (C2.1 in Table 3) is an excess of material on the casting corresponding to melt infiltration into the thin gap between die parts (Figure 14). This defect is caused by an insufficient clamping force of the machine, which cannot counterbalance alloy pressure.[36]

Deformation (C3.1 in Table 3) consists of a geometrical non-conformity of the casting to its foreseen geometry due to thermal contraction during cooling. This defect is more evident in castings ejected from the die at high temperature or having high thickness variability.

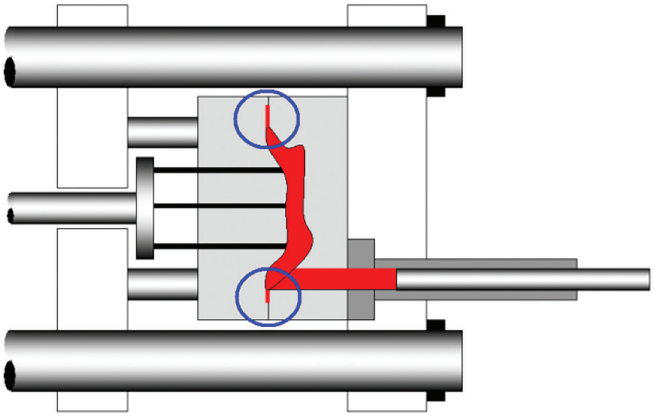


Figure 14. Image showing flashes' formation.

Conclusions

In the present paper, a new classification of defects and imperfections for Al alloy castings has been presented. Five categories of internal and surface defects in castings have been identified: shrinkage defects, gas-related defects, filling-related defects, undesired phases and thermal contraction defects. Briefly, shrinkage defects are macro- or interdendritic

cavities due to the volume contraction during solidification, while gas-related defects are spherical or elongated cavities characterized by smooth surface and caused by entrapment of air, hydrogen, vapor or lubricant/die release agent. Filling-related defects result from the interaction between melt flows at different temperature, while undesired phases are non-metallic phases, such as oxides, pieces of refractory and dross, which come from the interaction between melt and environment. Finally, thermal contraction defects are cracks due to the casting contraction constrained by the die or already solidified material.

Another class of defects is the metal-die interaction defects, which are only surface defects and appear as unsuitable surface conditions of the castings caused by the interaction between metal and die (e.g. soldering or thermal fatigue). Lastly, geometrical defects result in excess/lack of material or geometrical non-conformity of the casting to its designed shape.

Since defects are always present in foundry products and knowledge of them (in terms of morphology, size, causes, etc.) represents the first step for understanding their admissibility, the proposal of this new classification of defects and imperfections is of significant importance. The classification will allow all the actors of the design and manufacturing chain to adopt a common "technical language," which is fundamental for a correct approach to quality control and improvement. This new classification also will offer the opportunity to better understand the factors affecting product quality, providing the opportunity to perform corrective actions in order to reduce/eliminate defects.

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This paper presents the main key-issues of the CEN Technical Report, which has been elaborated on defects and imperfections classification of Al alloys approved by CEN Technical Committee 132 (Aluminum and its alloy).

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