NON-METALLIC INCLUSIONS IN DUCTILE CAST IRON, STEEL, AND ALUMINIUM CASTINGS

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The term 'non-metallic inclusions' covers a range of casting defects with a range of causes. This article provides a short introduction to the topic in ductile cast iron, steel, and aluminium casting, covering types and causes, detection, and prevention.

WHAT ARE NON-METALLIC INCLUSIONS

Non-metallic inclusions are the most common cause of casting defects; the enemy of the quality-conscious foundryman. And an elusive enemy too. Although there are some common types of inclusions (e.g., slag, sand, and oxides), as Gallo has noted, in any specific foundry application, uncovering 'the root cause of inclusion defects may present great difficultly because of the wide range of interdependent molten metal and casting process contributing factors'.[1]

Any discussion of non-metallic inclusions must therefore be contextualised by metallurgy. This is the approach we take here to discuss the types and formation, detection, and prevention of non-metallic inclusions in some of the most-commonly cast metals and alloys. These are ductile (spheroidal graphite) cast iron, steel, and aluminium.

Before we move to these specifics, however, there is one general comment we may make regarding the categorization of non-metallic inclusions by cause. Broadly speaking, inclusions will either be exogenous or endogenous:

- Exogenous inclusions are caused by input from outside of the melt (e.g., furnace lining, mould sand or slag/oxides in the feed material) (Figure 1).
- Endogenous inclusions are caused by a reaction of the molten metal or alloy with dissolved gases within the melt (oxygen, sulphur, or nitrogen) (Figure 2).

Figure 1. Exogenous non-metallic inclusion in cast steel

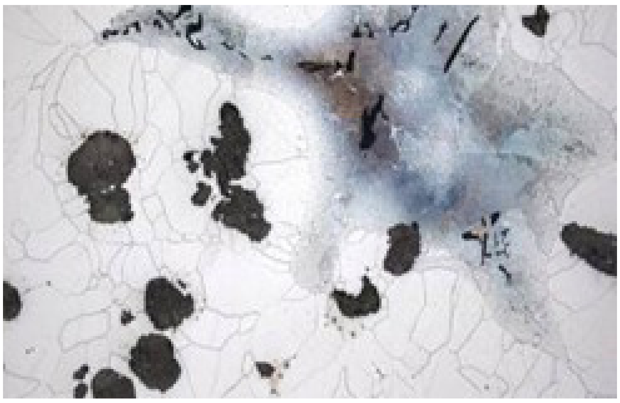

Figure 2. Endogenous MgO inclusion in ductile cast iron.

But even here, the reality is more complex, and the groups are not entirely distinct. Borderline cases include inclusions formed either by diffusion of unwanted elements from the mould sand wall into the melt or by reaction of the melt with atmospheric oxygen.

The following discussion is by necessity an incomplete guide to the topic of non-metallic inclusions in ductile cast iron, cast steel, and aluminium: a comprehensive account would require significantly more space than is available here. However, it is hoped that it will provide a useful introduction to and inspire further interest in some of the major types and causes of inclusions, as well as how to detect and prevent them.

DUCTILE CAST IRON INCLUSIONS - TYPES AND CAUSES

Cast iron components are most often produced using disposable sand moulds. These moulds offer a cost-effective and flexible solution for the mass production of cast iron pieces; however, they are also a common source of inclusion defects. According to one review of academic literature on this topic, sand inclusions account for between 30% and 40% of rejected castings.[2]

Sand inclusions are exogenous and are caused by 'loose sand, mould erosion, [and] mould and core wash particles.[3] Moulding sand may also act as a carrier of contaminant materials, e.g., core residues, slag, alloy from in-the-mould treatment, binder agglomerates, and slag coagulants. The quantity of such contaminants will depend on the quality of the sand preparation in the foundry. Despite the prevalence of sand inclusion defects, however, it is 'usually possible to identify where in the system they come from and so devise remedial action'.[3]

A second common non-metallic inclusion in the metal is slag, which can be found both in the form of small or larger inclusions, and in the form of skins (the so-called dross defect) (Figure 3). Dross is a particularly feared type of inclusion defect in ductile iron: due to its shape, it can greatly reduce the local mechanical properties of castings. It belongs to the above-mentioned borderline cases because slag (dross) is predominantly caused by contact between the melt surface and ambient air.

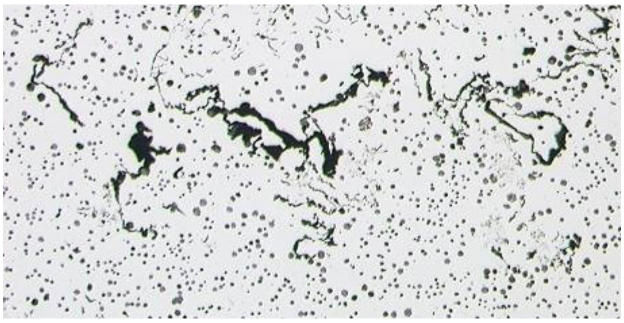

Figure 3. Dross defect in ductile cast iron.

The formation of a slag layer on top of the melt is an inevitable result of the nodularization treatment with magnesium and can be managed through adequate slag separation from the treatment vessel, the metal processing and pouring systems. Several factors may however result in slag skins being entrained in the pour and causing dross defects in the final piece:

- Inadequate slag separation practices.
- Excessive slag formation (e.g., from the use of returns and steel scrap as charge materials).[4]
- The need for high magnesium and/or aluminium additions.
- Slag formation late in the process (e.g., reoxidation of the melt due to turbulence during mould filling).

It must be accepted by the foundry and end-customer that dross defects cannot be prevented completely in each area of the casting.

In addition, magnesium oxide (MgO) may continue to form during solidification because of continuous enrichment of magnesium in the residual melt, and its reaction with dissolved oxygen. This reaction creates MgO particles, which can be identified as distinct endogenous inclusions. Larger proportions of MgO in the structure can adversely affect the cyclic and dynamic properties of the casting.

DETECTION AND PREVENTION

Dross inclusion defects are most often found in the upper half of the casting and under cores, as the lighter-weight dross particles naturally migrate up through the melt. The presence and thickness of both sand and dross inclusions layer may be determined by ultrasonic testing; however, ultrasound testing requires a flat surface on the casting and any other geometrical conditions to work effectively. A radius is much more difficult to scan. Dross inclusions with a connection to the surface (e.g., after mechanical processing) can also be detected using magnetic particle testing (MT) or penetration testing (PT).

It is not possible to determine the presence of the above-described MgO inclusions (Figure 2) non-destructively because of their small size. They may only be detected destructively, by preparing a metallographic sample for corresponding light-microscopical investigation.

Sand inclusions are best avoided through proper manufacture and preparation of the moulds – from the use of appropriate quality sand, and properly-constructed, undamaged patterns, to the correct application of mould coatings, blowing-out or vacuuming the mould before pouring, and the precise placement of cores and other inserts. Gating should be designed to minimise turbulence and direct impingement on the surface of the mould.[5]

Because dross formation is an inevitable part of the ductile iron casting process, it is not possible to eliminate dross development completely. The aim is thus to minimise the presence of dross and slag in the final casting via the following good practices:

- Start with the lowest possible sulphur and oxygen in the base iron:
- As sulphur is largely determined by the charge material, sulphur levels are controlled by the choice of raw materials (e.g. pig iron).
- Oxygen content is also influenced by the condition of the charge material. Oxidised (rusty) raw materials will naturally raise the concentration of oxygen.
- Keep final magnesium content as low as possible, i.e., below 0.05%.
- Slag conditioning and removal (e.g., with Foseco SLAX slag binder).
- Reduce turbulence during mould filling to avoid reoxidation of the melt.
- Filter the melt during pouring to remove inclusions and minimise turbulence (e.g., with Foseco SEDEX* filters).
- Maintain as high as possible a pouring temperature (being aware that higher temperatures come with their own challenges, e.g., shrinkage defects).
- Carry out preconditioning of the melt before treatment, e.g., with a barium-containing ferrosilicon alloy (e.g., with Foseco INOCULIN* 390).

CAST STEEL - TYPES AND CAUSES

Inclusions in cast steel are usually small (<0.1mm); however, they may aggregate into larger clusters (Figure 4). It is the quantity of these inclusions that determines the metallurgical purity grade of the steel. The increasing proportion of non-metallic inclusions reduces the static and dynamic toughness of cast steel, especially in heat-treated steels with high strength.

Figure 4. Non-metallic inclusions in cast steel may aggregate into larger clusters.

As with ductile iron casting, sand moulds are commonly used to cast steel – sand of various types being one of the few materials to withstand the high temperatures involved in casting steel. Sand inclusion defects (as exogenous inclusions) thus present a similar challenge (and with similar solutions) for steel foundries as for iron foundries.

Cast steel can also contain exogenous slag inclusions (Figure 1), which can require considerable repair efforts in cast steel (grinding, welding, and heat treatment). These arise from the reaction of elements in the melt with an affinity for oxygen (e.g., Al, Ti, Ca, etc.) with oxygen in the air during melting and mould filling. Particles of refractory material or products of the reaction between refractories and metallurgical slag are possible as well.

DETECTION AND PREVENTION

It is generally not possible to identify and quantify endogenous inclusions in steel using non-destructive methods. Assessment requires the taking of a metallographic sample, either for on-site analysis via comparison to a reference sample or images, or via EDX analysis at a specialist laboratory, such as the Vesuvius facilities in the Netherlands (Enschede) or USA (Pittsburgh). This specific kind of analysis is known as Vmet.

Due to their size, exogenous non-metallic inclusions are easier to detect under certain conditions (e.g., ratio of particle and casting size) using non-destructive testing.

Again, complete avoidance is not possible; the target is to minimise inclusions. This can be achieved with the following best practices:

- Use of cleanest possible input materials.
- Correct temperature control and covering the crucible during melting to reduce nitrogen and oxygen uptake.
- Desulphurisation and removal of inclusions (e.g., by using Foseco rotary treatment technology).
- Secondary metallurgy with a converter.
- Addition of deoxidant tailored to the specific oxygen content of the melt.
- Use of low sulphur and nitrogen binders for moulds.
- Slag conditioning and removal (e.g. with Foseco SLAX slag binder).
- Filtering the melt during mould filling (e.g. with Foseco STELEX* filters).
- Minimising contact between the melt and air to avoid reoxidation (e.g., by use of Foseco shroud technology).

ALUMINIUM ALLOYS - TYPES AND CAUSES

The main non-metallic inclusions in aluminium alloy castings are oxidic compounds, including aluminium oxide, magnesium oxide, and spinel (dialuminium magnesium tetraoxide). These may be present as films, fragments, particles or clusters. Oxide films and particles may be introduced or generated during charging and melting, melt treatment, and melt handling operations (Figure 5).[7] The latter includes accrued aluminium oxide on the ladle or rotors, which may enter the melt if not adequately cleaned between applications. Oxidic inclusions may be either endogenous or exogeneous, and sometimes the above-mentioned borderline cases.

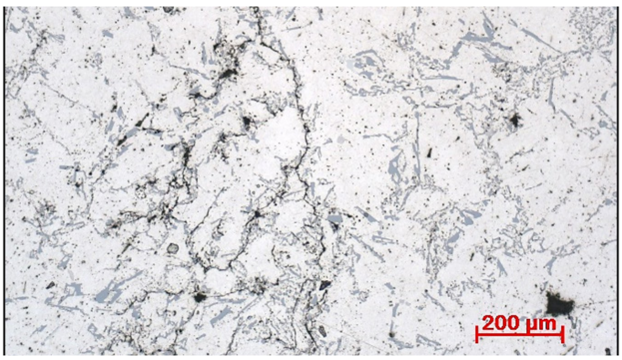

Figure 5. Oxide skin in an aluminium casting.

In addition, oxide content may vary markedly according to both the specific aluminium alloy being melted and the aluminium ingots being used, even when similar charging practices are used. Meanwhile, the same alloys from different heats will also exhibit different oxide contents. Thus, after meltdown, any molten aluminium alloy will have a large variety of finely divided small quantities of particles suspended in the body of the melt, and a layer of wet dross on the surface.[8]

Other common endogenous inclusions include borides, carbides, nitrides, and intermetallic compounds.[9] Intermetallic compounds (e.g., based on the iron content of the melt) are not distinct non-metallic inclusions, but are still undesirable because of their negative influence on the toughness of the material. Sources of exogenous inclusions range from degradation of the refractory (e.g., in the furnace walls, transfer ladles, launders, riser tubes, and filling funnels) or the mould, to impurities present in the charging materials. Finally, salt residuals and sludges can also be counted as exogenous inclusions.

It is well known that inclusions in Al melts may reduce the mechanical properties drastically (depending on their amount and size): Figure 6 shows a prematurely broken tensile sample of an aluminium casting sample with a large oxide skin. Furthermore, their presence can negatively influence the melt flow in the mould and the feeding behaviour during solidification. Exogenous inclusions may deteriorate the machinability of the corresponding castings.

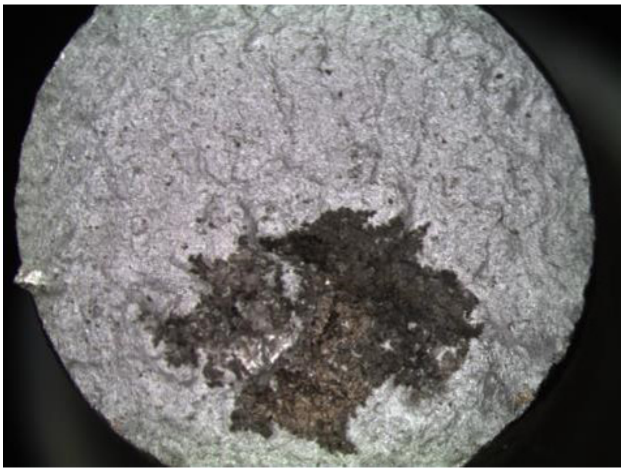

Figure 6. Large oxide skin in the fracture surface of an aluminium casting

DETECTION AND PREVENTION

There are several options available to detect inclusions within aluminium alloy melts based on ultrasonic and filtration methods (e.g., MetalVison®, PreFil®, and PoDFA®). Quantitative analysis based on a microstructural examination of (solidified) polished aluminium sections is also possible. This method (Vmet analysis) uses a scanning electron microscope with an automated stage and EDX detector to scan defects and measure size, morphology, distribution, and composition with a specific software.[10] Foseco offers this method to customers to evaluate the efficiency of their metal cleaning technology.

Because molten aluminium alloys are particularly prone to oxidation, when casting molten aluminium, it is important to establish proper procedures to maintain as clean a melt as possible. This is particularly important given the increasing demand for quality from consumers of aluminium castings. Systems to consider include:

- Ensuring a clean melt with a clean feedstock and regular cleaning of equipment.
- Melt purification with salts/degassing treatment (e.g., Foseco FDU degassers and COVERAL* fluxes).
- Processes to reduce turbulence during metal transfer and pouring.
- Avoiding melt turbulence during mould filling.
- Melt filtration by use of filters (e.g., Foseco SIVEX* filters).

CONCLUSION

Clean casting brings a range of benefits to the foundry and their customers. These include:

- Topline business advantages, such as improved yield, lower costs, and reduced lead times.
- Competitive advantages gained by foundries that offer tighter control of surface finish, mechanical properties, and machinability than competitors.
- Reduced environmental impact from greater energy and materials efficiency.

To take advantage of these benefits, however, foundries are in a constant battle against non-metallic inclusions. As this brief treatment of the topic has shown, it is a multifaceted challenge that requires a keen insight not only into the complete foundry process – from initial charging of the furnace to solidification in the mould – but the unique conditions of the casting application in question. Interested readers are therefore encouraged to contact the author to discuss their specific processes and available solutions.

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6. For a more detailed look at clean steel casting, see: 'Casting Clean: Today's Solutions and Opportunities' (Vesuvius; July 2022).
7. See, e.g., Gallo, R., p. 5.
8. Gallo, R., p.5
9. Gallo, R., p.4.
10. Shi, W., 'Vmet Analysis of Cast Aluminium Alloys, Fundamental, Application, and Statistical Analysis, Foundry Practice, no. 265 (2018), pp. 31-36 (p. 36). Vmet may also be used to analyse steel castings, although this application remain relatively rare.

ABOUT THE AUTHOR

Wolfram has worked for Foseco since 2016 and is currently International Technology Management, Metal Treatment. In this role, he is responsible for the Ferrous Metal Treatment (FMT) Group at our Global R&D Center, where he enjoys leading and participating in all FMT projects, collaborating with colleagues around the world. He also supports customers in identifying and preventing casting defects. In his free time, Wolfram enjoys running, cycling, dancing, and riding his motor bike.

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