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WHITE PAPER

Casting clean: today's solutions and opportunities

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VESUVIUS

CONTENT

EXECUTIVE SUMMARY

Improving as-cast quality has always been an important element in foundry processes. In today's market conditions, however, they have taken on an increased relevance. Solutions aimed at enabling cleaner casting have also proliferated – to an almost dizzying degree.

This article aims to cut through the noise and bring some clarity to the clean steel debate. We begin with an overview of common casting defects. The major part of the article will review the technologies on offer to reduce casting defects and improve casting quality, focusing on each step in the casting process in turn.

Ultimately, selection of the appropriate solutions will depend on the specific conditions within a foundry. Expert advice will assist in formulating process-specific strategies for optimal results.

INTRODUCTION

Clean Steel

The clean steel concept has been around for many decades. This opening paragraph appeared in an article published in the February 1988 issue of Modern Casting:

"Clean steel" is the latest buzzword in the steel foundry sector, with good reason [...] Like other segments of the foundry industry, steel castings producers are feeling the pinch of customer requirements for better properties and improved performance of their cast components.[1]

The article goes on to report conference proceedings that focused on clean steel technology and controlling steel casting defects. If that all feels very relevant today, it is because it is. Clean steel is still a top priority for steel foundries and those that supply them. As the authors of a paper published in 2021 noted:[2]

The destructive nature of variability on manufacturing systems and the resulting scrapped and reworked products, high amounts on work-in-process, long lead times, and ultimately, the overall cost to manufacture a product have all been well documented. [Therefore] projects that target as-cast quality variability and improved yield should be prioritized by steel foundry management.

The world of the late 1980s is very different from that of today. However, many of the challenges that existed then remain current. Customers continue to tighten quality specifications. Cost inflation continues to eat away at steel foundry margins. Delivery schedules continue to cause headaches.

There are new factors in the mix too. COVID-19 showed the limits and vulnerabilities of globalisation. There is a resulting trend to reshore and secure supply chains: an opportunity for local foundries to acquire new business – but only if they are able to meet quality standards and delivery schedules. Meanwhile the push for more sustainable steel casting adds an environmental impetus to efforts to reduce scrap and reworking.

THE BENEFITS OF CASTING CLEAN STEEL

It should be apparent that clean steel technologies offer significant advantages for steel foundries. Top of these are improved yield and reducing costs associated with scrap, reworking (defect removal and welding), inspection and re-heat treating. There are also competitive advantages that come with being able to offer higher degrees of surface finish, mechanical properties and machinability.

On the foundry management side, improved as-cast quality cuts the number of pieces that require post-cast cleaning, while shortening the wait and processing times for pieces that do enter the cleaning room. This speeds up the flow of castings through the foundry, reducing work-in-progress and lead times, and improving delivery times. Ultimately, this benefits the bottom line through improved cash flow, as well as creating capacity to take on more business.

There is a broad range of clean steel technologies on offer today from suppliers such as Foseco. The second part of this article will discuss these technologies and provide a complete picture of what clean steel means at each of stages in the foundry process. Before that, we will provide an overview of common casting defects and their causes.

COMMON CASTING DEFECTS

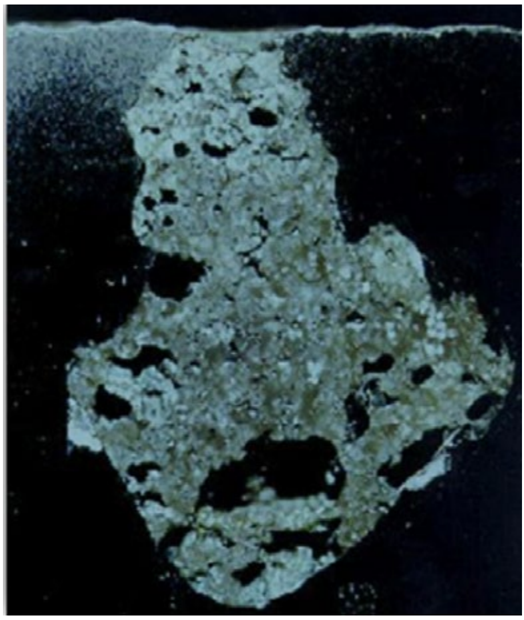
INCLUSION

Inclusions occur when non-metallic particles are entrained in the melt and form pockets in the casting. These defects negatively affect surface finish, mechanical properties and machinability. This may result in the casting failing to meet customer specifications, and requiring rework – with subsequent delay to dispatch. Larger inclusions may ultimately result in the scrapping of the casting.

Inclusions have a range of causes. Particles of refractory lining, moulding sand or slag may become entrained in the melt. Inclusions may also be the result of deoxidation and reoxidation of the melt.

Deoxidation is standard practice in the steel casting process to remove excess oxygen from the melt. It may take place in both the furnace and the ladle; actual practice will depend on a range of factors, including the alloy, casting design, specification, and preferences of the foundry's metallurgist.

Typical deoxidants include silicon, aluminium, titanium, zirconium and calcium, all of which react with excess oxygen to form oxides and readily form slags. Deoxidants may also react with other elements in the melt, e.g., nitrogen and sulphur, to form compounds such as nitrides and sulphides. Unless appropriately removed, the products of deoxidation may coalesce with other non-metallic elements in the melt to form complex inclusions.



Inclusions from the moulding material

REOXIDATION: BIFOLDS, BUBBLES AND TURBULENCE

Reoxidation – as the name suggests – is the opposite of deoxidation and occurs when the melt reacts with oxygen. It occurs most commonly at points along the casting process where the melt is exposed to air (e.g., furnace tapping, pouring from the ladle into the mould, mould filling).

Reoxidation is particularly undesirable since it occurs late in the casting process. As a result, the products of reoxidation are the largest cause of inclusions in steel castings, accounting for some 83% of inclusion defects. As has been discussed in the work of John Campbell, however, the mechanism by which reoxidation of steel occurs has, until recently, been a relatively under-studied topic. In a 2016 paper, Campbell aims to correct this oversight. In it he explains that:

During the turmoil of pouring of a liquid metal, random collisions between droplets and waves cause the surface oxides on the liquid to impinge. An analogous action occurs during the folding over of the liquid surface. The two surfaces come together, dry oxide to dry oxide, thus forming an interface between the two stable oxide films, but with no bonding between them. The double film, known for convenience as a bifilm, is submerged, resembling a crack in suspension in the liquid.[3]

Severe turbulence may cause these bifolds to form bubbles, as air is also entrained in the melt; as Campbell notes, 'the only difference between a bifold and a bubble is the amount of air which each contains'. Whether bifold or bubble, it is the entrainment of the surface oxide layer that is the primary mechanism by which reoxidation defects in the melt occur.[4]

TEMPERATURE DEFECTS: HEAT LOSS, EXCESSIVE AND UNEVEN HEAT

Temperature of the melt is another key factor influencing casting quality. As with Goldilocks' experience with the Three Bears' porridge, the melt should be neither too hot or too cold, but just right.

A range of defects result when temperature of the melt is too low, for example:

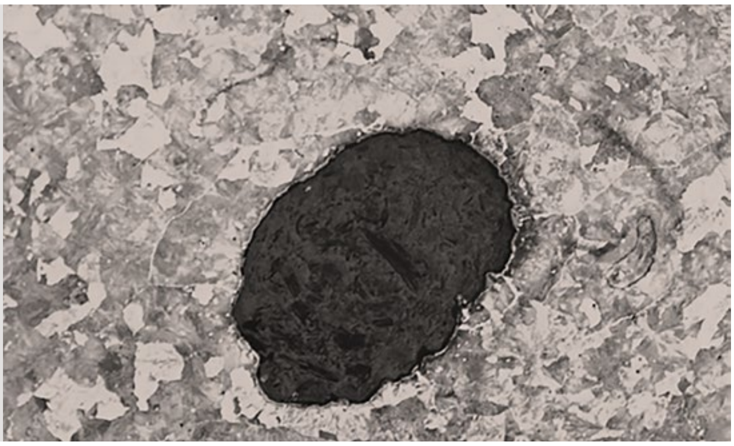
- Cold shot result when the melt splashes during the pour, creating small balls or drops that freeze faster than the rest of the melt, and then become embedded or attached to the casting.
- Cold shuts are caused when the melt enters the mould from two (or more) points, but lacks the heat at the point(s) where the pours meet to form a seamless casting, resulting in a crack-like defect.
- If a melt is cold enough, it will simply freeze before filling the entire mould. The result is incomplete castings, known as misruns.

While these defects may be caused by an insufficiently heated melt, cold defects may also be an issue even when the melt is heated appropriately, due to heat loss during transfer and pouring of the melt. Conversely, melts with too high a superheat also cause challenges. Increased superheat raises the potential for the melt to absorb gases and form oxides. It also increases the melt's ability to damage the mould. This may result in moulding sand inclusions and surface defects including:

- Surface roughness
- Mould erosion
- Rat tails, veins and buckles
- Fusion

GAS POROSITY DEFECTS

It is a basic physical concept that solids do not hold as much gas as liquids.



As the melt cools and freezes, gases – most often nitrogen, oxygen or hydrogen – are therefore released. If the mould is not sufficiently porous, these gases can become trapped, forming cavities or holes in the casting, also known as pinholes and blowholes (the difference is one of size, pinholes being smaller than blowholes).

PREVENTING CASTING DEFECTS

Having provided an overview of the various casting defects, the question for the remainder of this paper is this: how to we avoid these defects and ensure clean steel castings? To answer this, we will follow the casting process from melting through transfer of the molten metal, pouring, and filling of the mould. Finally, we will consider the role of mould coatings to minimise surface defects.

MELT CLEAN: FURNACE LININGS

Due to their versatility, efficiency and lower environmental footprint compared to other furnace types, induction furnaces continue dominate the steel foundry sector. Many factors contribute to optimal operation of these furnaces; however, the basis for success is the lining.[5] At the basic level, furnace linings should provide efficient melting of the steel, e.g., through good thermal insulation, linings can reduce the energy consumed per melt and shorten melt times.

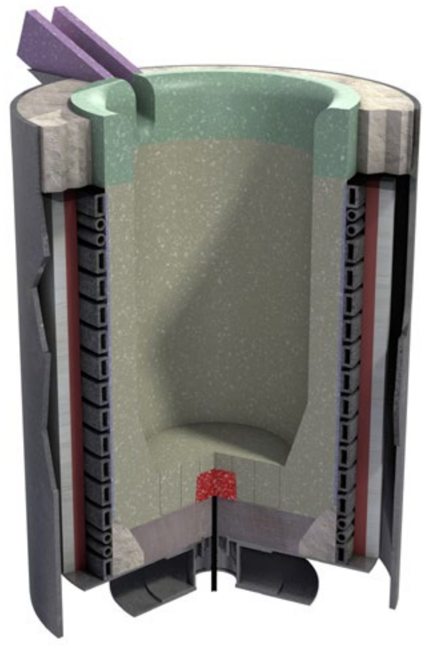
From a clean casting perspective, the lining system should offer good resistance to thermal and chemical attack, and to mechanical abrasion during charging. This will minimise the risk of lining materials wearing into and contaminating the melt (with the potential to form inclusions).

The working lining is the part of the lining system that is exposed to direct contact with the molten metal. Composition of the working lining should be engineered so that, when heated, it forms a dense hot face that can withstand the stresses of thermal cycling and attack by a variety of slag chemistries. Behind the hot face, however, the lining should maintain a loose structure to provide flexibility against cracking and ingress of molten material.

An optional lining component is a purging plug. These are installed below the hot face of the lining and allow injection of inert gases into the melt, resulting in the following benefits:

- Reduction in slag generation and slag line erosion of the refractory.
- Reduction in inclusion and gas defects.
- Improved melt homogeneity.

Foseco offers a complete range of induction furnace lining materials. For example, KELLUNDITE spinel-forming, high alumina dry-vibratable working linings are specifically designed to achieve high resistance to slag and thermal wear. KELLUNDITE is also available for top cap lining. We also offer purge plug systems for all furnace sizes and capacities and for use with our full range of linings, including KELLUNDITE.



TRANSFER CLEAN: LADLE LININGS

Ladle linings do a similar job to their furnace counterparts in terms of providing consistent melt temperature (by reducing heat loss) and melt cleanliness. A well-designed ladle lining system will therefore combine good insulating properties with good resistance to chemical and thermal erosion. Ideally, it will also be quick and easy to replace.

The benefits of such a lining system include:

- Lower risk of cold melt defects.
- Enables a reduction in melt superheat with subsequent reduction in gas absorption/ melt oxidation (inclusions).
- Lower furnace tapping temperatures. Melt residency time in the furnace is thereby shortened, reducing the time the lining is exposed to thermal/chemical attack.
- Avoidance of cross contamination and slag inclusions.

KALTEK boards from Foseco are a simple-to-apply ladle lining technology have been proven to improve temperature control and casting cleanliness. For example, at Akdas Foundry,[6] one of the largest steel foundries in Turkey, temperature loss on tapping of just 30°C was achieved with KALTEK, compared to 70°C with a conventional ladle lining system. A 27% reduction in the consumption of welding rods was also recorded, a good indicator that post-cast rework was reduced following the installation of KALTEK.

A further benefit for the KALTEK lining system is that it can be used cold. This negates the need to preheat the ladle, reducing fuel (gas) consumption and energy costs, while also improving the carbon intensity of foundry operations.

SLAG COAGULANTS AND THE ROTOCLENE PROCESS

However clean the original melt, the process of tapping into the pouring ladle will introduction contamination. This is especially true when the tapping is not well controlled and the melt is exposed to the atmosphere. Melt treatment in the ladle is thus an integral part of achieving a clean casting. This traditionally takes the form of slag coagulants; however, a new rotary treatment process has proven to achieve a higher degree of melt cleanliness and to help deliver an improved pour into the mould.

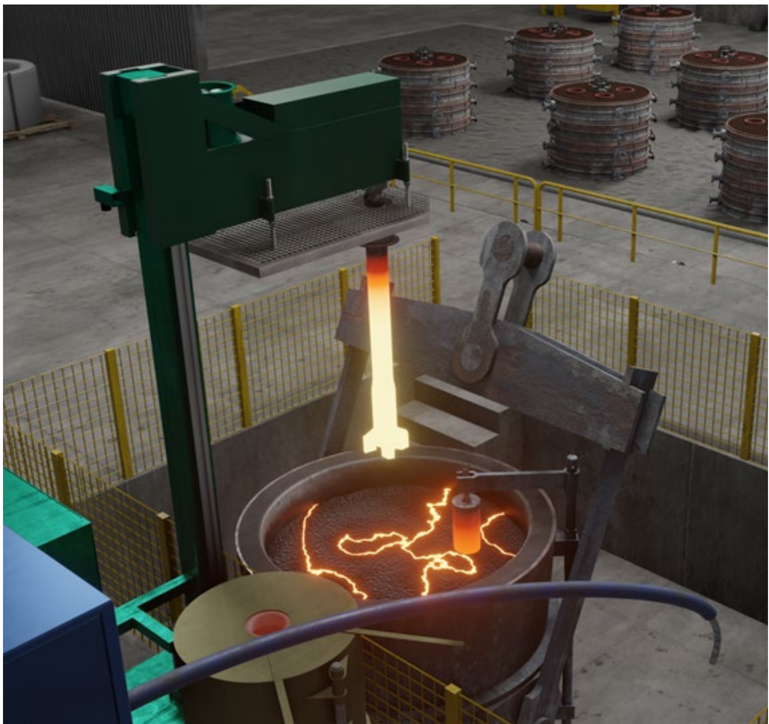
Coagulants are used in a range of industries to remove contaminants from liquids, whether that be for wastewater treatment or in the processing of mineral ore slurries. They do so by providing a nucleus around which contaminant particles aggregate and thereby become easier to remove.

In the foundry, coagulants, such as SLAX from Foseco, are added to the melt either in the furnace or in the ladle to attract slag and other non-metallic impurities trapped in the metal. As these materials have a lower specific gravity than the molten steel, they rise to the top of melt and react with the coagulant to form a viscous layer that can be easily and quickly removed by skimming or rolling. This leaves a purer melt, subject to fewer inclusions and, ultimately, casting defects.

The ROTOCLENE process has been developed by Foseco to improve treatment of molten metal in the ladle for application requiring high quality casting. It brings together a number of products and processes to produce high-quality and inclusion-free steel. During the treatment, a hollow ceramic rotor stirs the melt as argon is purged through and dispersed to form curtains of very fine bubbles. As these bubbles float slowly through the melt, they adhere to slag particle inclusions and oxide bifilms, which are brought to the top slag layer.

Stirring of the melt also homogenises metal temperature and eliminates any cold spots that may have formed, particularly at the bottom of the ladle where there can be a risk of premature solidification. This allows foundries to eliminate superheating and reduce the pouring temperature by 30°C or more. The resulting pour is less prone to shrinkage; it also cools faster in the mould, which reduces dendrite formation and achieves a finer-grained casting, with benefits for the mechanical properties of the metal.

It is worth noting here, that – once treated – the melt should be protected to prevent reoxidation and air entrainment during pouring. The HOLLOTEX shroud has been developed specifically for this job: see below discussion on preventing in-stream reoxidation.



Synthetic slag can also be injected into the melt during ROTOCLENE treatment to dissolve non-metallic inclusions and desulfurize the melt, as can pure calcium-cored wire to modify the shape of remaining inclusions and reduce their negative impact on the properties of the steel. The latter point is a particular benefit, as pure calcium reacts violently with steel unless injected into a moving stream of material, such as that generated by the ROTOCLENE process. Pure calcium is however a more effective modifier than the traditional calcium silicide (SiCa), and does not contribute to premature clogging of the filters.

POUR CLEAN (1): BOTTOM POUR LADLES, STOPPERS AND NOZZLES

Bottom pour ladles have important benefits over other ladle types, such as lip pour and t-pot ladles, when it comes to clean casting. These ladles are widely used in the steel industry for ladle sizes of 500kg to 40 tonnes.

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The use of bottom pour ladles for casting steel is already a common practice in modern foundries, but there is still significant scope for growth, especially in situations where slag is a problem. Bottom pour ladles can have the benefits of requiring less maintenance than teapot ladles, and allow the steel to be poured with minimal ingress of slag into the stream.[7]

When using bottom pour ladles, however, adequate control is important in order to mitigate turbulence in the steam, which can cause reoxidation of the melt, as well as erosion of and inclusions from the nozzles. Turbulent streams are also a health and safety concern due to the potential for splashing.

Appropriate stoppers and nozzles for bottom pour ladles help produce a smooth, concentrated pouring stream. A foundry may employ various stopper configurations, depending on their casting process. Two general types of stopper are available: monolithic (available for ladle heights up to 2150mm) and assembled.

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Nozzles have traditionally been one-shot products; however, the use of multiple usage nozzles is now established with a range of products available on the market.

- Foseco VISO monolithic stoppers and nozzles are a range of isostatically-pressed shapes, based on carbon-bonded alumina graphite, and offer reliable thermal shock and oxidation resistance.
- Foseco VAPEX stoppers and nozzles are extruded shapes made from a combination graphite and alumina. They maintain high mechanical strength over long periods, and is therefore well suited to automated pouring processes. VAPEX nozzles are available in a range of designs, including as cross bore nozzles, which offer maximum control of the pouring flow over other more conventional designs.

The VAPEX nozzle range has also recently been enhanced with the VAPEX FOSFLOW system, which is designed to enable nozzle diameter to be changed – even when the ladle it full. Launched in 2021, the VAPEX FOSFLOW system comprises a base nozzle, which remains in the refractory bottom of the ladle, and an interchangeable pouring nozzle, which comes in a variety of inner diameters. Pouring nozzles can be easily swapped, depending on the casting requirements, even within ladle cycles, to ensure the appropriate nozzle is always in place for optimum flow control for each casting.

POUR CLEAN (2): FILTERS

Filters offer two major benefits: they help clean the melt of inclusions and they help reduce turbulence in the pour.[8] The result is a reduction in upgradetime (thus also reducing the value of work in process), reduced welding material consumption, and an overall improvement in surface finish and casting machinability.[9]

Ceramic foam filters have been used in the steel casting industry since the late 1980s with current systems including the STELEX ZR, STELEX PrO, and STELEX OptiFlow3D product lines.

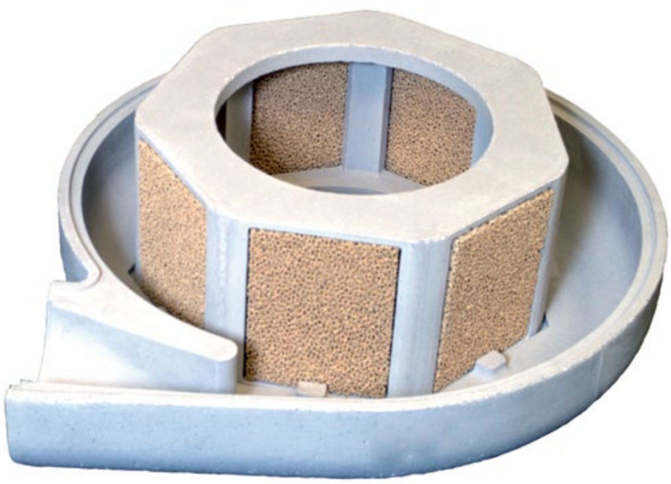
Based on a zirconia ceramic foam, STELEX ZR filters were developed to allow casting of ferrous alloys up to 1680°C. The latest generation STELEX ZR *ULTRA* filters feature an improved zirconia ceramic formulation and framing technology to deliver lower filter mass and a more consistently open structure. This allows:

- More consistent capacity and flow rates.
- Improved filtration efficiency and improved potential for turbulence control.
- Reduced chance that metal might bypass the filter.
- Very low friability, reducing the potential incidence of filter-related defects in the casting.

Meanwhile, STELEX PrO lightweight carbon-bonded filters expand filtration to low-carbon steel and steel alloy applications. Superior priming properties mean that these filters can be placed at the ingate, rather than at the base of the downsprue. This is particularly advantageous when casting steel alloys, which are at particular risk of reoxidation during the pour, as the ingate position ensures removal of any inclusions generated in the running system.

Most recently, Foseco launched its STELEX Optiflow3D range of additive manufactured filters. No longer bound by the constraints imposed by traditional manufacturing techniques, STELEX OptiFlow3D filters are available in an increasing number of structures, porosities, and shapes. This enables the production of filters with far higher capacities, thus reducing the number of filters required per casting and opening up the potential to filter even very large castings.

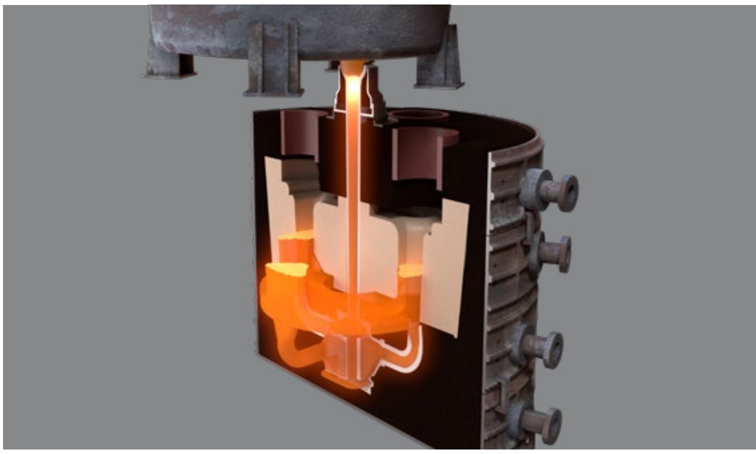
Staying with filters, both KALPUR feeding sleeves and HOLLOTEX centrifugal filter units (CFU) incorporate integral STELEX filters. The first of these replaces an existing top or slide feeder sleeve to receive the melt, absorbing the impact through the filter, eliminating turbulence, and removing inclusions. The unit also functions as a feeder system for "enhanced directional solidification within the filled casting [and] reduced shrinkage problems". The second system is used in the production of large ferrous castings and comprises a HOLLOTEX refractory centrifuge system to separate large inclusions, followed by integral STELEX ZR filters to remove remaining contaminants and reduce turbulence.



POUR CLEAN (3): PREVENTING IN-STREAM (RE) OXIDATION

As noted previously, reoxidation is the major cause of casting defects, but can be avoided by protecting the melt from exposure to air. The HOLLOTEX shroud was developed to do just this as melt is poured into the mould.

The system consists of a VAPEX nozzle with hemispherical outlet, seamless sealing gasket, and a VISO pouring shroud. Unlike traditional ladle shrouds, it is positioned in the mould and lifted towards the ladle nozzle using a simple and reliable mechanical bayonet lifting system; it then locks into place to create a seal between the nozzle and shroud. The bottom of the shroud protrudes into a filter box with STELEX ZR *ULTRA* filter, located at the base of the mould.



FILLING THE MOULD: RUNNERS

Runners take the molten metal from the base of the sprue and guide it into the mould cavity or cavities. They make sure the flow of material is smooth and uninterrupted – thus minimising turbulence-related defects – while keeping temperature loss to a minimum and avoiding shrinkage.

In conventional casting, when not incorporated into the mould, running systems were constructed using ceramic components. Foseco introduced the HOLLOTEX EG Runner for iron casting in 2009, which replaced ceramic with a lightweight construction of cellulose, mineral components, and carbon fibres. The HOLLOTEX EG Runner ST for steel casting followed in due course, featuring an additional internal refractory coating to allow the running system to withstand the higher temperatures involved when casting steel.

HOLLOTEX EG Runner ST casting systems are simple to prepare and construct, thanks to their lower weight, easy to cut formulation, and easy push-fit assembly, while also reducing the risk that ceramic residual fragments contaminating either the melt or the moulding sand. The shape of HOLLOTEX EG Runner ST components has also been optimised to introduce a less acute bend in the L-pieces for reduced turbulence and more even flow distribution.

MINIMISING SURFACE DEFECTS: COATINGS

Coatings applied to sand moulds and cores function as a protective barrier between the molten metal and mould or core substrate. Although coatings will vary with casting type and size, this relatively thin layer of material can have a significant impact on casting quality and output.

Coatings help to ensure the surface integrity of the cast and eliminate surface defects such as:

- Metal penetration
- Poor casting strip
- Mould erosion
- Gas defects
- Metal/mould reactions
- Sand expansion defects
- Scabbing

To achieve optimum protection, coatings should be deposited in a consistent layer, free of runs, drips and other discontinuities, and thick enough to supply the required protection. Due to the high temperatures associated with steel casting, coatings should be carefully selected to ensure performance in the extreme conditions it will be exposed to.

For example, the SEMCO and TENO range of coatings from Foseco utilise high-purity refractory minerals to meet the high demands placed on steel casting coatings. Specialist coatings are also available to cover specific alloy and casting applications, such as manganese steel, highly-alloyed stainless steels, or metal penetration due to hot spots or high metallostatic pressures.

When it comes to applying coatings, Foseco offers the Intelligent Coating Unit (ICU) and Flow Coating Unit:

- An Industry 4.0-ready solution, the ICU offers automatic coating preparation from its supplied state to the density that will deliver the most consistent thickness. Continuous monitoring, control and adjustment ensures optimized coating performance.
- The Flow Coating Unit ensures consistent coating distribution, irrespective of the operator and regardless of the mould surface, including on vertical walls and deep pockets. It also eliminates brush or swab marks and enhances finer detailing, such as numbering or lettering, as well as reducing the risk of mould abrasion.

THE

CONCLUSION

The range of solutions now available to enhance as-cast quality offers foundries significant opportunities to reduce costs, increase yield and improve their competitive offering. In doing so, these solutions also positively impact the environmental performance of the casting process, as less energy and materials are consumed for reworking and/or recasting defective products. Ultimately, today's clean casting solutions represent an opportunity that you cannot afford to ignore.

The sheer number of solutions not only acknowledges the increasing importance of casting clean, but also the range of unique conditions each individual foundry works under. What is appropriate at one foundry, will not necessarily be applicable to another. When assessing what measures to implement, foundries are advised to seek expert advice in order to select the most appropriate systems for their process.

With a history dating back to 1932, Foseco is a world leader in the supply of foundry consumables and solutions. Throughout its history, it has been at the forefront of innovation in the steel foundry industry, and remains so to this day. Wherever you are in the world, our technical specialists are available to advise you on the technologies and solutions available to improve your as-cast quality and help you to cast more cleanly, efficiently and safely.

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