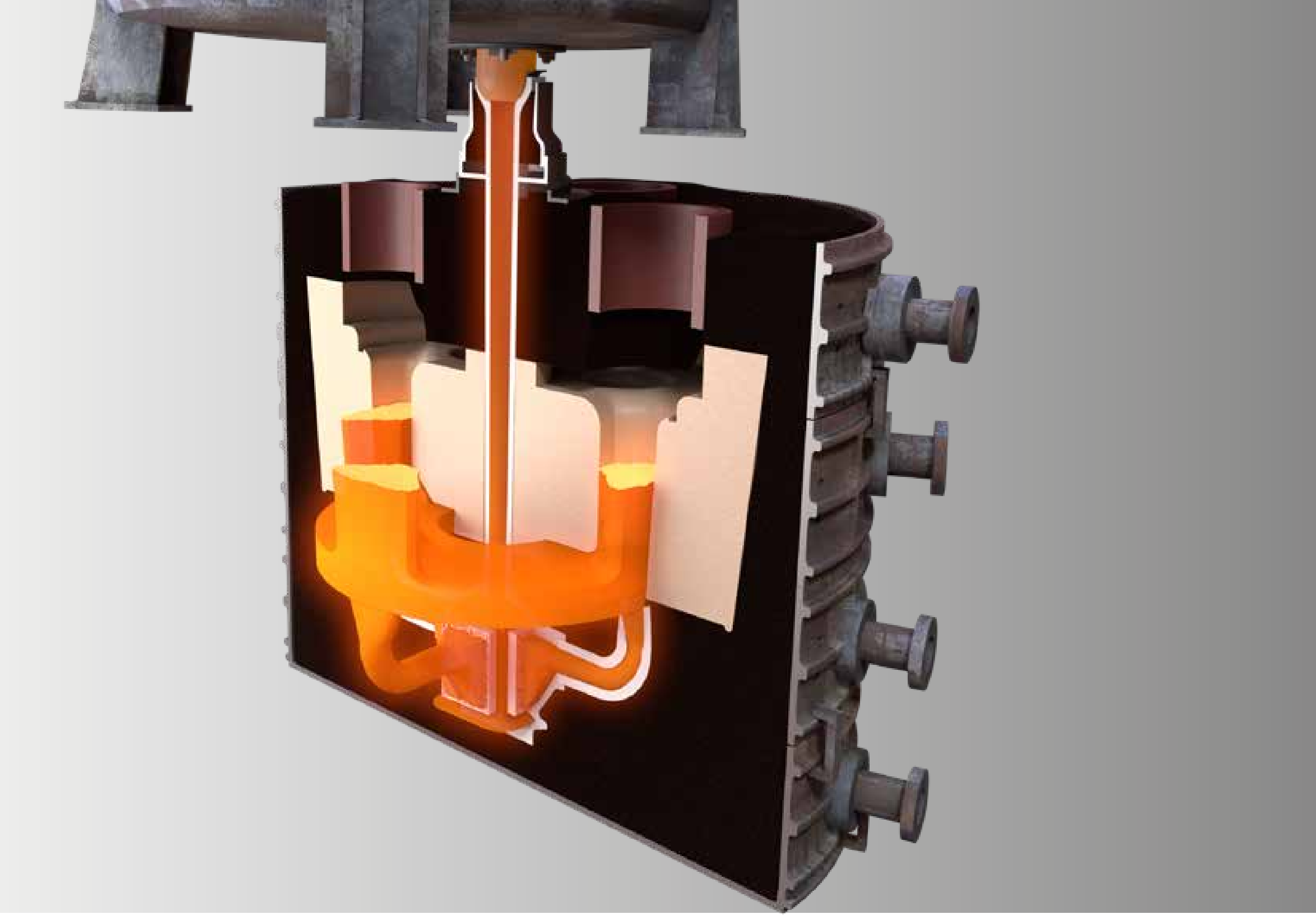

ADVANCES IN THE POURING OF STEEL CASTINGS WITH A SHROUDED METAL STREAM

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FOSECO

Thin oxide films rapidly form on a liquid metal surface when exposed to the atmosphere. These protect the melt from further oxidation or gas enrichment. However, these surface films become brittle, tear and are then entrained in the molten metal. The melting temperatures of most oxide films are far greater than the temperature of the melt, so once formed they remain solid. These films float through buoyancy forces, as they have a lower density than molten metal, but this process is slow due to their extremely small size (just several nanometres having almost no volume). Oxide bi-films generated within conventional molten metal casting process have no time to float. They unfurl and agglomerate during the casting process. These bi-films have high surface activity and grow into bigger non-metallic agglomerations as solidification advances. Foundries increase pouring temperature hoping gas bubbles and related impurities float, but an increased pouring temperature is not beneficial to castings quality and cast surface appearance.

NEW TRENDS IN CASTINGS DESIGN OPTIMIZATION & QUALITY REQUIREMENT

Designers use advanced software to simulate stress analysis and optimise casting weight and design. Their aim is to increase strength focusing on critical zones to achieve maximum casting performance. This trend has forced casting buyers to increase the quality demand, constantly pushing conventional technological limits to meet them. The Czech foundry, UNEX, produces "high value" castings for world-known leaders, in the mining and earth moving industry. Critical casting zones have always been inspected by Magnetic Particle Inspection (MPI), X-ray and ultrasonic methods. The latest quality requirements provide new challenges including X-ray level I for complex castings in carbon steel and high strength low alloy steel weighing up to several tons. "Hairline cracks" (**Figures 1a & 1b**) revealed through MPI are limited to 2 mm length on cast surfaces, detected after heat treatment and quenching. This can require extensive and repeated defect removal and welding with several cycles until all defects are repaired; as these are repaired other defects became apparent. This process is expensive and significantly reduces production capacity. Comprehensive metallographic and Scanning Electron Microscope (SEM) investigation of MPI detected linear defects called "hairline cracks". The origin of these defects was found to be bi-film related.

A further challenge is achieving X-ray level I. Customers require level I X-ray (Level II just for non-critical zones) on 5 castings following each other in production to be accepted without internal defect repair to achieve production approval.

PRINCIPLE OF BI-FILM FORMATION

The surface tension of molten low alloy and carbon steel is approximately 20-25 times greater than the surface tension of water at room temperature and is affected by many parameters including chemical composition, temperature etc. However, the viscosity of molten low alloy and carbon steel are nearly identical to water viscosity at room temperature.

Due to this similarity, water modelling is used worldwide to simulate the flow behaviour of molten metal. The principle of air entrainment into liquid metal and bi-film formation, is affected by the molten metal surface tension and velocity. The molten metal surface is covered by an oxide film including the metal in the pouring cup. The air from the meniscus of both oxide films gets entrained into the metal and bi-films are produced as shown in **Figure 2a**. Water modelling shows this process in detail (**Figure 2b**) [1].

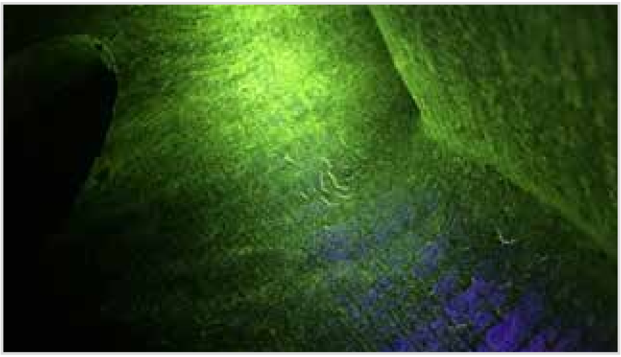


Fig. 1a: Hairline cracks on cast surface of low alloy steel

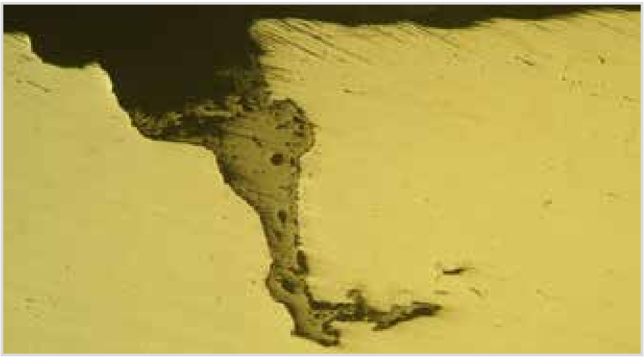


Fig. 1b: Vertical section of this hairline crack Mag.100x

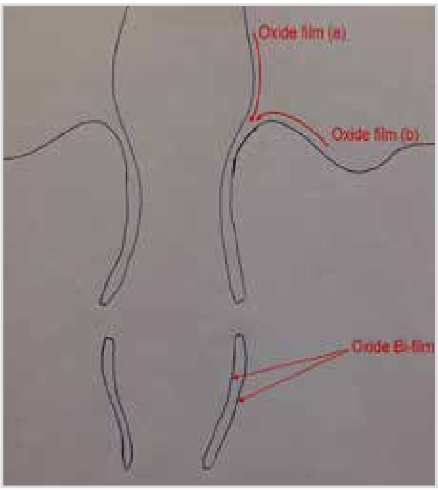


Fig. 2a: Air entrainment and bi-film formation principal

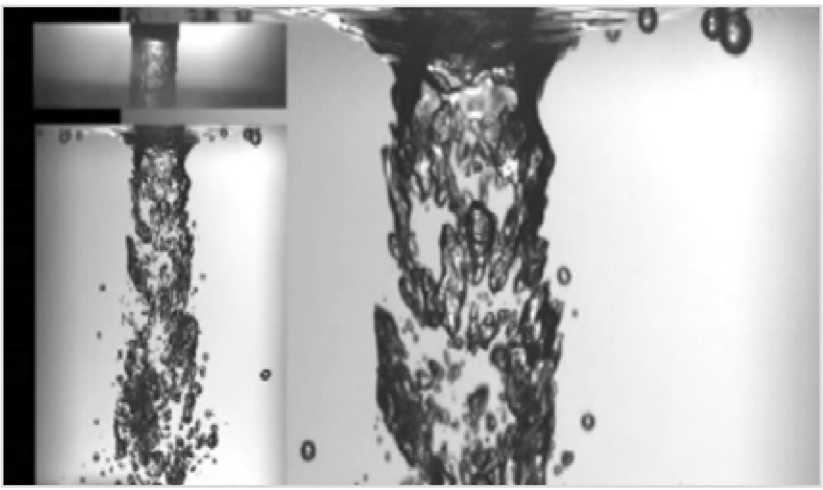


Fig. 2b: Air Entrainment Mechanism [1]

The same principle of air entrainment and bi-film formation within casting process is applicable for metal being tapped into the ladle from the melting furnace as well. **Figure 2c** shows metal tapping from an EAF and **Figure 2d** shows water modelling displaying high levels of air entrainment. Argon purging through a purge plug (PP) is installed at the ladle bottom for optimally more than 10 minutes provides some inclusions and bi-film removal. More efficient metal cleaning process at the ladle will be of advantage but this paper is focused to casting process only.

AIR ENTRAINMENT AND BI-FILM EFFECT TO CASTINGS QUALITY:

Entrained air is compressible and changes its volume through temperature and pressure variations inside the casting's cavity. Floating and expanding air bubbles leave oxide bi-film trails behind contaminating molten metal as described in detail by professor John Campbell [2] (**Figure 3a**). Oxide bi-film galaxies are found at dendrite boundaries, these disconnect primary metallic grains from each other limiting the castings mechanical properties significantly. Bi-films can initiate hot tearing during solidification and act as nucleation for non-metallic inclusions formation and segregation of elements precipitated at grain boundaries such as sulfur, carbon, and others. Metallic matrix discontinuities will allow hot tearing and the formation of "hairline cracks" during heat treatment and quenching. Bi-films also contain cavities with residual atmospheric gases which inflate during the final unpressurised solidification stage, they cannot be fed properly as mushy metal approaching solidification will limit feeding distances (**Figure 3b**). Ultrasonic waves do not pass through such affected sections although they are not visually apparent when the defects are repaired.

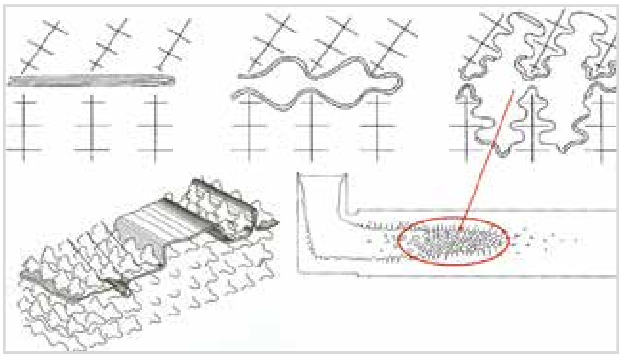
SHROUD METAL STREAM PROTECTION TO IMPROVE CASTINGS QUALITY

To protect molten steel from air entrainment and bi-film formation during the casting process, the HOLLOTEX Shroud, has been developed to meet the increasing casting quality standards and faster delivery requirements. The new shrouding process is applicable at foundries meeting the latest H&S standards and differentiates itself from ladle shrouds in steel plant applications which are operated using robotic manipulators. Foundries require the ability to cast several moulds from the pouring ladle. They also demand a safe, quick, and flexible way to operate a shroud system; having the shroud fixed to the ladle is not considered to be safe and practical for foundry use. The HOLLOTEX Shroud meets these requirements, it is positioned in the mould and lifted towards the ladle nozzle using a simple, efficient and reliable mechanical bayonet lifting system.

Fig. 2c: Tapping causes air entrainment and bi-films

Fig. 2d: Water modelling of tapping process

Fig. 3a: Air bubbles and bi-film trails behind



3b: Bi-film among grain boundaries and micro porosity formation [1]

SHROUD INSTALLATION AND OPERATION PRINCIPAL

The HOLLOTEX Shroud (**Figure 4a & b**) consists of a nozzle with a hemispherical outlet, a seamless sealing gasket and a pouring shroud inserted through an already assembled mould into the filter box, which is installed in the mould at the base of the casting. The installation process begins with the filter box and the running system assembly being moulded in the drag (**Figure 5a**). The cope is moulded to incorporate a hole for the shroud and a groove in the top of the mould to locate the metallic lifting system. The lifting system is installed into this pre-moulded groove just before the cope moulding box is ready for assembly (**Figure 5b**). The cope and drag boxes are clamped together and the shroud is inserted through the mould cavity into the filter box at the base of the casting (**Figure 6a**). A sealing gasket is applied to the hemispherical shroud's inlet just before the pouring ladle is positioned. The bayonet lifting system is operated manually by metallic handles rotating it round a vertical axis lifting the shroud inside it towards the nozzle installed in the ladle (a cam system). This lifting system is self-locking, so once twisted and sealed, the ladle operator can start pouring without physically holding it within the casting process (**Figure 6b**). The hemispherical nozzle is self-centring so even if the ladle position is not perfectly aligned over the HOLLOTEX Shroud a seal can be achieved. The Pouring shroud delivers the molten metal into the filter box without air entrainment and metal oxidation (**Figure 7a**). The filter box is designed to eliminate metal splashing at the beginning of pouring and then distributes molten metal through STELEX ZR ULTRA filters into the ceramic hollowware which forms the gating system (**Figure 7b**). The shroud is tapered to ensure it fills with metal and keeps the sprue system pressurised. During development, the Shroud was first evaluated in the FOSECO global Research and Development centre based at Enschede in the Netherlands to prove functionality of the concept and to ensure all related health and safety aspects were addressed before progressing to production trials at UNEX foundry.

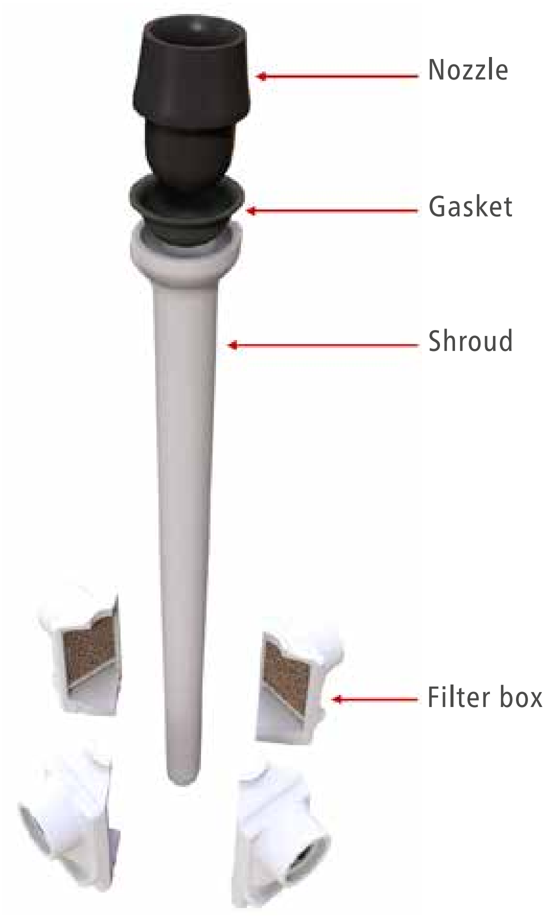


Fig. 4a: HOLLOTEX Shroud set assembly

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Fig. 5a: Filter box and running system installation in drag

Fig. 5b: Bayonet lifting system on the top of mould

Fig. 6a: HOLLOTEX Shroud insertion into assembled mould

Fig. 6b: Metal casting through HOLLOTEX Shroud

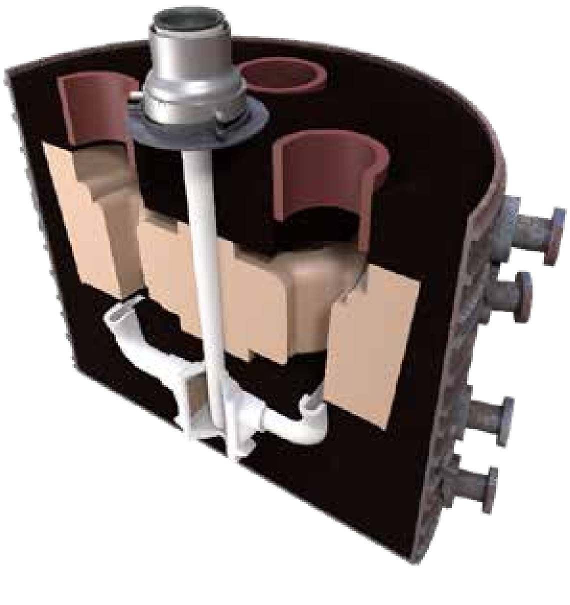

Fig. 7a: HOLLOTEX Shroud system applied in the mould

Fig. 7b: HOLLOTEX Shroud system during pouring

The HOLLOTEX Shroud system is also applicable for inclined moulds being cast uphill or simply placed on uneven foundry is safely connectible to the ladle nozzle despite not always being installed perfectly upright. It can also be used even if the ladle is not perfectly aligned above the Shroud (**Figure 8a & b)**.

CASE STUDY: SMALL PLANET CARRIER

A planet carrier made from low alloy high strength steel (G 42CrMo4 QT), poured weight 750 kg, was selected for the first HOLLOTEX Shroud trial for commercial castings. The upper part of the lower flange (thickness 16 mm) suffered from linear "hairline crack" defect accumulations in an area with limited access for welding. Melting was undertaken using a medium frequency 4 t capacity induction furnace. Five castings were poured from a stopper operated bottom-pour ladle, with a capacity of 5 t. The pouring time was between 20-24 s. The nozzle and shroud outlet diameter were 80 and 35 mm respectively. This HOLLOTEX Shroud technology enables the use of a universal nozzle diameter for any casting size; the metal flow rate is determined by the shroud outlet diameter and is not dependent on the nozzle diameter (**Figure 9a & b)**. This means that small and heavy castings can be poured from the same ladle.

Defects found on MPI were almost eliminated when comparing the shrouded casting to the conventional method (Figure 10a &10b). The shrouded castings successfully passed the X-ray Level I and ultrasonic inspection. A specimen from a conventionally cast carrier was taken for SEM investigation at Saarbrücken University, Germany. Complex formations of secondary slag wrapped in thin oxide films were detected (**Figure 10c & d**). Some were attached to the casting surface, but others were found hidden several millimetres under the surface making them difficult to detect, even with DC-MPI. These defects are usually found following welding of previously detected defects. They are near the crystalline grain boundaries but disconnected due to entrained bi-films. This leads to repeated MPI inspection and welding cycles.

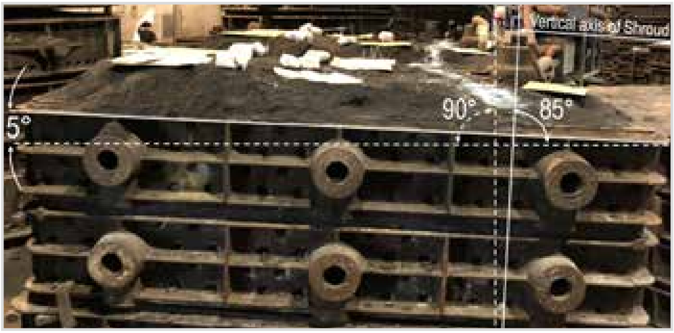

Fig. 8a: The HOLLOTEX Shroud allows to cast moulds uphill as well

Fig. 8b: Ladle in position. Ready to twist bayonet by steel bars and connect shroud to the nozzle

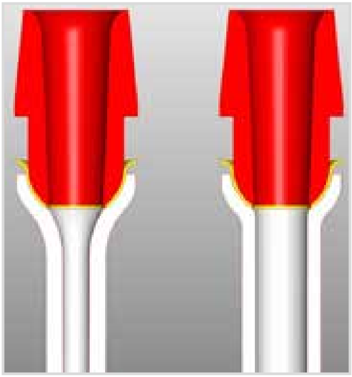

Fig. 9a: The universal nozzle for any Shroud size

Fig. 9b: Nozzle installed at the ladle ready to use

Fig. 10a: Shrouded casting

Fig. 10b: Conventionally cast

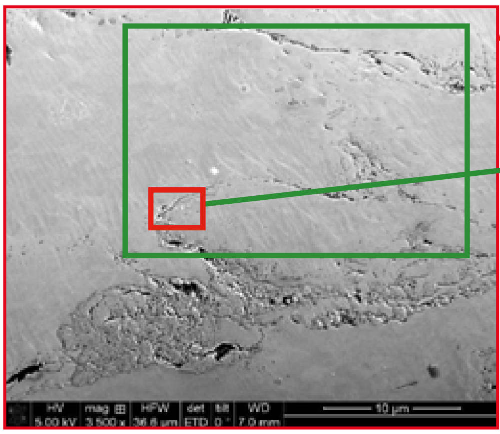

Fig. 10c: SEM of hairline crack from Saarbrücken Univ.

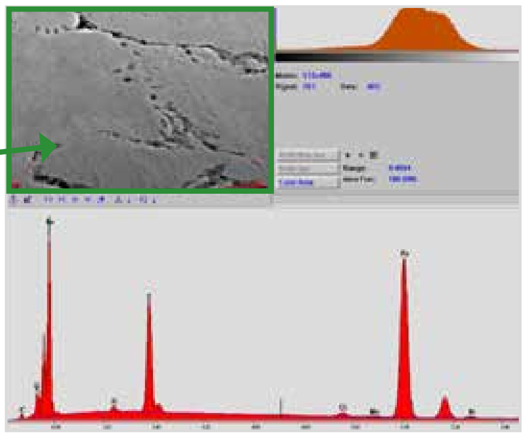

Fig. 10d: EDX analysis showed O, Fe, Ni, Si, S, Cr, Mn presence

CASE STUDY: HEAVY PLANET CARRIER

Following these encouraging results, a heavier planet carrier, poured weight 2500 kg produced in the same low alloy high strength steel, was used for further trials. These castings were much thicker having an exponentially longer solidification time which allows bi-films and inclusions to float, unfurl, and accumulate beneath the surface (5-12 mm deep). Quenching as the final heat treatment operation initialises stress and disconnects grain boundaries through bi-film residuals cause them to fail on MPI. The welded parts must be tempered which decreases the final mechanical properties. Melting was undertaken in an Electric Arc Furnace (EAF); the molten metal was transferred to an 8.5 t capacity bottom-pour ladle.

The conventional practice uses argon purging through a purge plug (PP) fitted in the base of the ladle. The metal temperature is not measured during the pouring process but is measured during argon purging. This process continues until the metal reaches the required temperature and the ladle is transferred to the pouring area, the mould pouring process starts within 5-6 minutes from argon disconnection. The temperature requirement at argon disconnection for conventional cast planet carriers, through ceramic foam filters, was 1575-1580 °C.

The first shrouded castings (70 mm diameter shroud outlet) were poured at this same temperature. The pouring time was in the range of 20-24 s, this is significantly faster than conventional production (40-60 s cast from a nozzle diameter 90 mm). The most probable reason for this slow conventional pouring is ladle operators throttling the stopper during pouring to avoid metal overflow and metal splashing injuries. The first shroud test of these heavier planet carriers demonstrated a Health and Safety improvement and consistency in pouring time due to the stopper being fully opened during the casting process. Unexpectedly MPI did not show significant reduction of hairline cracks formation (**Figure 11a**). Rapid pouring speed causing turbulent mould filling was suspected to be the cause.

To eliminate metal re-oxidation associated with turbulent pouring, the mould cavity was filled with argon just before the next shroud test. The results, however, were not improved despite the oxygen level within the mould being reduced from 20.9 % to 0.3 % according to the Greisinger GOX 100 oxygen detector measured just before the stopper opening. Argon disappeared from the mould quickly once pouring commenced. The detector showed an oxygen level of 15.8 % within the first 2 s of pouring. This test was repeated with the same results on more moulds which did not provide measurable MPI defects reduction.

To eliminate the mould filling turbulence, the shroud was redesigned to give an outlet diameter of 45 mm. The aim was to reduce the metal flow rate and keep the whole system pressurised during the whole casting process and provide laminar flow especially at the beginning of mould filling. The metal temperature at the end of the argon purging in the ladle was reduced to 1550 °C, the subsequent pouring time was in the range of 40-45 s. There were no problems with foam filters priming in the filter box, and after shake-out the castings still had thin metal flash at the parting line indicating further pouring temperature reduction would be possible. MPI found linear defects in critical zones being mostly in the accepted length of 2 mm (**Figure 11b)** and X-ray and ultrasonic inspection found those castings acceptable according to Level I. The shroud trial was extended to a bigger serial production to confirm results, metal temperature after argon purging was further reduced to 1530 °C. A minimal pouring temperature was targeted to reduce hot tearing defects caused by linear contraction within the solidification process. Such a low pouring temperature is not applicable to a conventional pouring process due to cold shut and misrun parts but using the HOLLOTEX Shroud this is possible. There were no metal freezing issues within the casting process when the nozzle was connected to the HOLLOTEX Shroud, however, pouring of the separate test blocks was problematic due to metal freezing at the nozzle outlet. Subsequently test blocks have been integrated with the castings so they are poured through the shroud at the same time. Based on these results, the shroud was implemented into regular serial production of those castings and more than 100 pieces have already been cast successfully providing very constant in terms of MPI, and X-ray results. The HOLLOTEX Shroud has now been implemented into production of even heavier planet carriers (3500 kg poured weight) successfully.

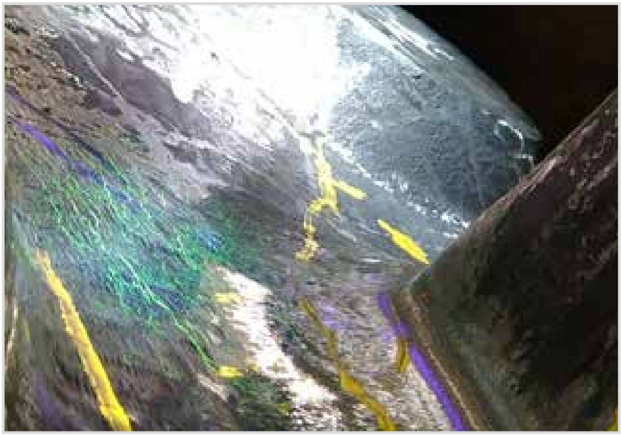

Fig. 11a: Hairline cracks from turbulent mould filling

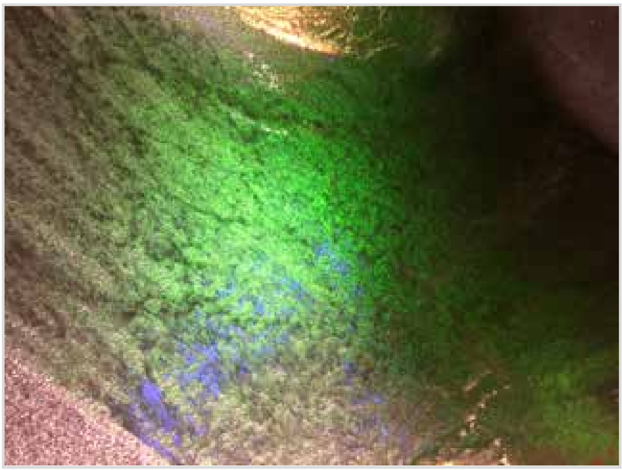

Fig. 11b: The same surface with choked conical shroud

CASE STUDY: MINING TRUCK WHEEL HUB

The Material used was GS-22 NiMoCr 56. Poured weight is 1200 kg. Melting undertaken in an EAF. Argon purging through PP was performed in the ladle for 5-6 minutes. A shroud outlet diameter of 35 mm was used. At a pouring temperature 1560-1570 °C a pouring time of 35-40 s was achieved. Six castings were poured from one ladle proving shroud technology can be used on a series of castings (**Figure 12a & b**). The castings passed ultrasonic inspection successfully with almost no MPI detected defects and passed through production process with no delay and additional rework expenses (**Figure 12c & d**).

Fig. 12a: Wheel hub with HOLLOTEX Shroud

Fig. 12b: Upper casting surface after shot blasting

Fig. 12c: MPI after quenching

Fig. 12d: Upper surface after ultrasonic and MPI inspection

CASE STUDY: HEAVY MINING TRUCK WHEEL HUB

The material used was GS-22 NiMoCr 56, poured weight 3000 kg. Conventionally produced castings suffered from large defects revealed by MPI on the upper and internal surface under the core. These defects required extensive welding and repeated inspection, the most critical were small defects revealed during final machining which led to external castings reject (**Figure 13a & b**). A HOLLOTEX Shroud with outer diameter of 45 mm was implemented on 5 castings (**Figure 13c**). Melting was carried out in an EAF and subsequent argon purging through PP in the ladle for 10 minutes. The pouring temperature was 1550-1560 °C and pouring time was in the range of 45-50 s. Sand inclusions, bubbles and MPI indications were almost eliminated (**Figure 13d**).

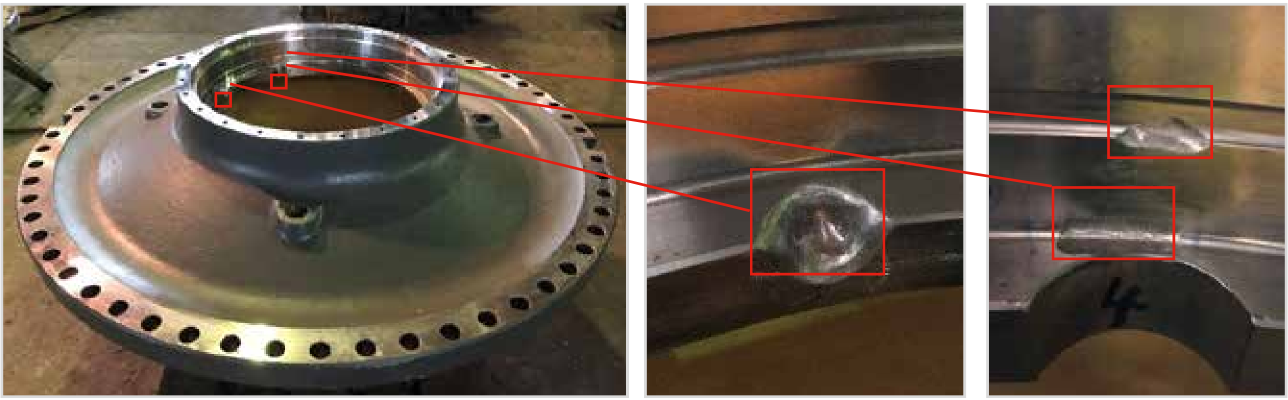

Fig. 13a: Defects after final machining

Fig. 13b: Defect removal and welding

Fig. 13c: Casting with HOLLOTEX Shroud

Fig.13d: Casting after MPI inspection

CASE STUDY: EXCAVATOR ARM BOOM

The material used was modified GS-24 Mn 6, poured weight 5000 kg. These complex shape castings have a large surface area and a combination of thin and thick sections being sensitive to sand inclusion galaxies, slag presence and deep gas bubbles on the upper part (**Figure 14a & b)**. There was extensive testing of various methoding solutions to reduce rework, but no satisfactory progress was achieved on these castings. A Shroud with an outlet of 45 mm was implemented in the casting of several arm booms.

Melting was carried out in an EAF and argon purging through PP in the ladle for 5-6 minutes. The pouring temperature was about 1550 °C and the pouring time between 72-90 s. The running system was connected to the bottom of the casting by thin oval ingates to reduce hot spots (**Figure 15a & b**). Sand and slag defects were not detected on the surface and castings were free from gas bubbles (**Figure 16a & b**). Significant fettling reduction was achieved which lead to increased production capacity as welding was one of the main limiting factors for the output of these castings.

Fig. 14a: Typical gas hole defects on top surface

Fig. 14b: Sand inclusions galaxies on upper part

Fig. 15a: Gating system with HOLLOTEX Shroud filter box installed

Fig. 15b: Casting with HOLLOTEX Shroud - shot blasted

Fig. 16a: Upper surface with HOLLOTEX Shroud

Fig. 16b: No sand inclusions or gas bubbles present

SUMMARY

The HOLLOTEX Shroud is an innovative technology for metal stream protection enabling foundries to meet and exceed latest casting quality expectations and significantly increase the mechanical properties. Defect free castings flow through the fettling process much faster and final delivery dates are predictable. This can give the foundry a competitive advantage being recognised as a reliable supplier, or preferably partner, winning more contracts.

References

[1] Kiger, K.T., & Duncan, J.H. (2012). Air Entrainment Mechanism in Plunging Jets and Breaking Waves. Annual Review of Fluid Mechanics, Vol. 44, pp. 563-596.

[2] Campbell, J. (2015). Complete Casting Handbook: Metal Casting Processes, Metallurgy, Techniques and Design (2nd ed.). Oxford, UK: Elsevier

Major benefits of the HOLLOTEX Shroud include:

- No air entrainment
- Reduced unacceptable X-ray and MPI defects
- Reduced repair requirements
- Process repeatability (consistent casting quality)
- Faster delivery of castings
- Pouring temperature reduction
- Improvement in mechanical properties
- Health and safety through reduced exposure to molten metal during the casting process
- Environmental improvements

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