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- SINCE 1932 -

BINDERS

Innovative sand cores with water-soluble binder systems for the non-ferrous sector

NF METAL TREATMENT

A comparison of different sampling techniques for aluminium metal cleanliness investigations

CASTING DEFECTS

Non-metallic inclusions in ductile cast iron, steel, and aluminium castings

EDITORIAL

FOUNDRY PRACTICE 271

Dear Readers,

The customer comes first. It might be a familiar adage, but we take it very seriously here at Foseco. Customer support is at the centre of everything we do – whether it's correct product selection and application, or more general issues, such as problem solving and defect analysis.

This ethos also drives our approach to R&D. By listening to our customers and working with them to understand their specific needs and problems, we are able to develop solutions that directly address these issues. In this way, we help deliver enhanced competitiveness in a dynamic and rapidly-changing market.

A good example is presented in the first technical article of this issue. We start with the challenge: in this case, the electrification and lightweighting of vehicles. This is having a massive impact on the foundry industry, as ICE powertrains are replaced with electric motors. As a result, a dramatic increase in aluminium foundry output – and especially high-pressure diecasting – is needed.

But growth in this sector has been limited by difficulties in manufacturing cored castings. To address this issue, we developed a novel water-soluble binder system that enables high-pressure foundries to produce cored aluminium castings economically, efficiently, and sustainably. Vincent Haanappel and Mark Stapleton introduce this potentially game-changing innovation on pp. 5-8.

The theme of customer support continues through the rest of the issue. In the second technical paper, Mert Kurttepeli details a recent study comparing the reliability of sampling techniques for aluminium cleanliness investigations – a critical issue when it comes to delivering the high-quality castings needed by the auto industry.

And in the final paper, I'll take you through the types and causes, detection, and (most importantly!) the prevention of non-metallic inclusions in ductile cast iron, steel, and aluminium castings.

We hope you enjoy the issue!

Dr. Wolfram Stets
International Technology Manager
Metal Treatment

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INNOVATIVE SAND CORES WITH WATER-SOLUBLE BINDER SYSTEMS FOR THE NON-FERROUS SECTOR

Authors:
Vincent Haanappel (NL), Foseco
Mark Stapleton (UK), Foseco

A key limit on the high pressure die casting process (HPDC) is the inability to produce complex, hollow castings at high volume and in a cost-effective and sustainable way, due to the difficulty in producing suitable cores. Standard sand cores made with common organic or inorganic binders cannot be used for HPDC, as they are difficult to remove after casting and do not provide adequate surface finish. Salt cores are more suitable, but can be expensive to produce, whilst presenting other operational limitations. In response to this challenge, the Foseco Foundry R&D Centre in Enschede, the Netherlands, has developed a new type of sand core, using an innovative Water-Soluble Binder (WASCO*) and coating, which offers competitive strength and manufacturability, whilst enabling easy removal after casting.

INTRODUCTION

HPDC offers a range of advantages, such as higher production rates and good surface finish; as a result, is the process of choice for many of the new, lightweight parts needed by the growing e-mobility and 5G markets. However, it is also not without its challenges. One significant limitation is the ability to produce complex internal cavity shapes. In order to overcome that obstacle, it is necessary to develop disposable cores that must be able to tolerate the high pressures, temperatures and speeds involved in the HPDC process.

A new type of sand core, developed by the Foseco Foundry R&D Centre, provides a solution to these challenges. These cores are made with the innovative WASCO binder and coating using standard sand core production equipment. They therefore offer a more cost-effective and sustainable option for HPDC of complex, hollow shapes at high volume and are equally suitable for use in liquid HPDC or also in semi-solid (Rheocasting) process.

MANUFACTURING SAND CORES

All sand cores are produced using a standard core shooter equipped with a hot box system. For the new HPDC-suitable cores, the sand mixture is prepared using the liquid binder and the additive (powder). It is then automatically injected at high speed into a specially designed core box using compressed air, and cured using hot air. Several types of cores were produced (see examples in Figure 1).

For high-pressure casting processes, a coating may also be necessary to avoid penetration of the liquid metal into the pores of the sand, which results in unacceptable roughness (encapsulation of the sand grains) of the casting surface. Different techniques can be used to apply a sealant, such as dipping or spraying.

MECHANICAL STRENGTH

Figure 2 shows the mechanical strength and sample weight of sand cores made from H33-type quartz sand, as a function of the amount of the additive. The liquid binder was set at 6.0wt% of the sand. Depending on the casting process and the related requirements, the exact strength values can be selected.

As can be concluded from Figure 2, the strength values of samples without the additive were relatively low (low compaction (low sample weight)); the average value was about 100N/cm^2. However, the addition of only a small amount of the additive, in this case 2.0wt%, resulted in a significant improvement in the mechanical properties: strength values were around 700N/cm^2. A further increase of the concentration resulted in strength values higher than 1200N/cm^2 (high compaction (high sample weight)).

Figure 1: Sand cores manufactured with WASCO* systems and treated with a coating.

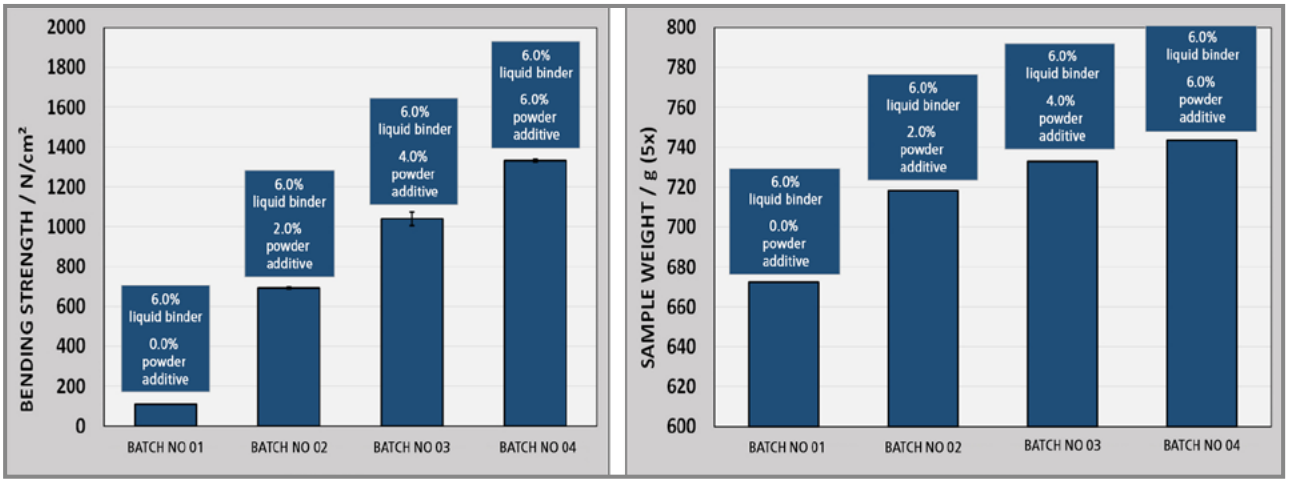
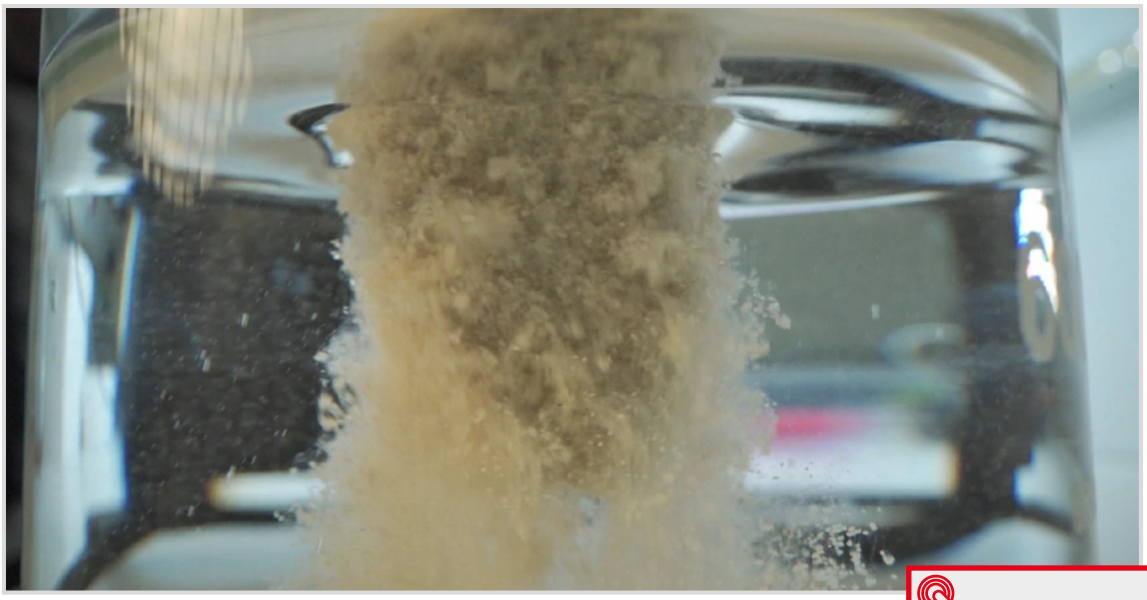


Figure 2: Bending (flexural) strength (left) and sample weight (right) as a function of the concentration of the additive. The concentration of the liquid binder was set at 6.0 wt% of the sand.



WATCH VIDEO

Figure 3: The core solubility shows the clear benefits against conventional core.

WATER-SOLUBILITY OF THE BINDER

Irrespective of the mechanical strength of the sand cores, the water solubility of the binder was excellent with full dissolution feasible in less than 5 seconds (Figure 3). It is interesting to note that the new WASCO binders showed excellent solubility after the casting trials in multiple processes from liquid HPDC, Rheocasting, Gravity and LPDC processes, indicating that the application temperature of such a type of binder is at least 750°C. This makes these cores very promising candidates for slow and fast solidifying casting processes. An example of a Rheocast part is shown in Figure 4.

Figure 4: Water tap manufactured in Rheocasting by Comptech AB

SURFACE ROUGHNESS

Surface roughness is one of the most important characteristics of the casting pieces after removal of core residue from the hollow part. In HPDC, use of a coating is indispensable, as an uncoated core will result in a casting with unacceptable surface roughness. This is caused by the penetration of liquid metal into the pores of the cores and consequent encapsulation of the sand grains into the surface of the casting. Figure 5 (left) shows the inner surface of a HPDC casting from an unsealed sand core; the use of an incorrect coating type can also result in similar surface appearance (Figure 5 – centre). Casting with an optimised coating, however, achieves a smooth and sand-free inner surface (Figure 5 – right).

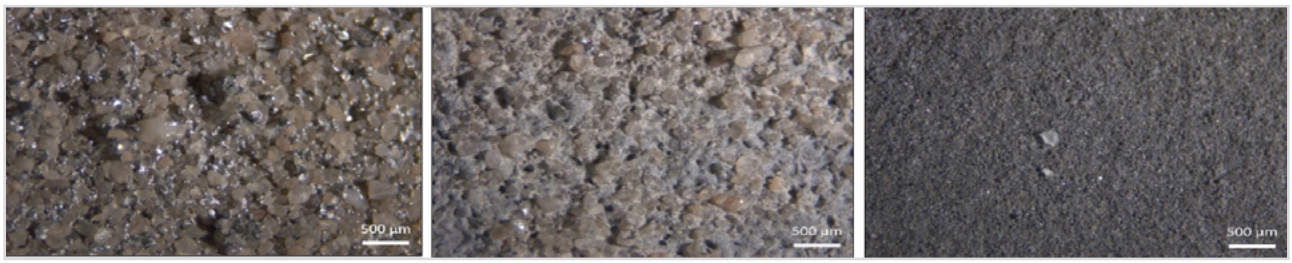


Figure 5: The inner surface of three casting pieces: left – a casting made with an uncoated core; centre – a casting made with the incorrect coating type; right – a casting made with an optimised coating.

Surface roughness of these castings was also measured by using a Keyence non-contact profilometer: In this case, the surface of a casting made with an uncoated sand core and one made with the optimised coating were measured. The value, Sa, is the extension of Ra (the arithmetical mean height of a line) to a surface, and expresses, as an absolute value, the difference in height of each point compared to the arithmetical mean of the surface. The uncoated core showed a relatively high roughness of Sa = 123µm (Figure 6); this confirmed the visual observation shown in Figure 5 (left). The application of a well-developed coating resulted in a significant improvement; the surface was much smoother with an average Sa of just 14 µm (Figure 7).

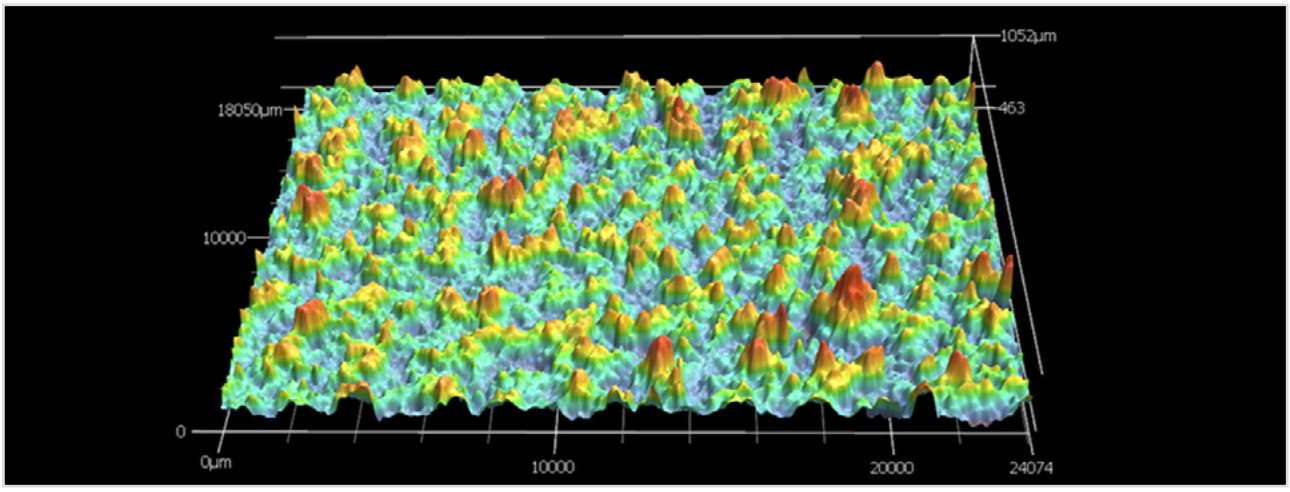


Figure 6: Keyence non-contact profilometer 3D image of a casting using an uncoated sand core (Sa – 123µm).

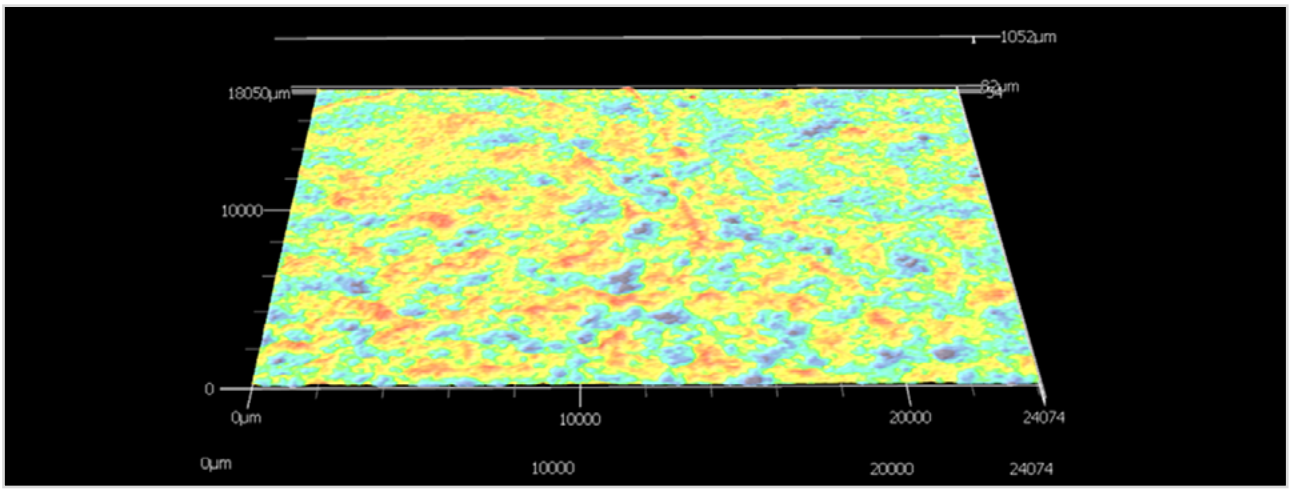


Figure 7: Keyence non-contact profilometer 3D image of a casting using a coated core (Sa – 14µm).

MAIN ADVANTAGES

Laboratory tests, as well as testing trials in the field, have demonstrated the strong potential of the new WASCO* system to meet a wide range of customer requirements, showing very promising results not only for liquid HPDC, but also gravity die casting and Rheocasting for aluminium.

CONCLUSIONS

The new WASCO* systems developed by the Foseco Foundry R&D Centre in Enschede, The Netherlands, have demonstrated their high strength in various applications. Even in severe processing conditions, such as HPDC, with the use of an appropriate coating, these innovative sand cores can withstand high pressures and high temperatures, whilst facilitating easy core removal from internal cavities by flushing water, leaving a smooth and sand-free surface.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the complete R&D Mould and Core team of the Foseco R&D Centre in Enschede, The Netherlands. Special thanks to Rafael Wattimena and Marco Huusken for their extensive experiments and measurements.

The main advantages of the new systems are:

- Core residue is easy to remove, even after longer times at 700°C
- Uses cost-effective materials
- High flexibility in the use of additives
- Manufacturing uses standard hot box core shooters
- Strength values exceeding 1000 N/cm² are achievable
- Thermal resistance up to 750°C is possible

ABOUT THE AUTHOR

Mark has worked for Foseco since 2020 and is currently Global Product Director for the non-ferrous foundry market. In this role, he is responsible for developing and implementing our growth strategy for current and future non-ferrous products. It's a job that regularly takes him around the world to learn about regional market dynamics and needs from our network of experts. In his free time, Mark enjoys spending time with his wife and children, walking, reading, and playing cricket, golf, and football.

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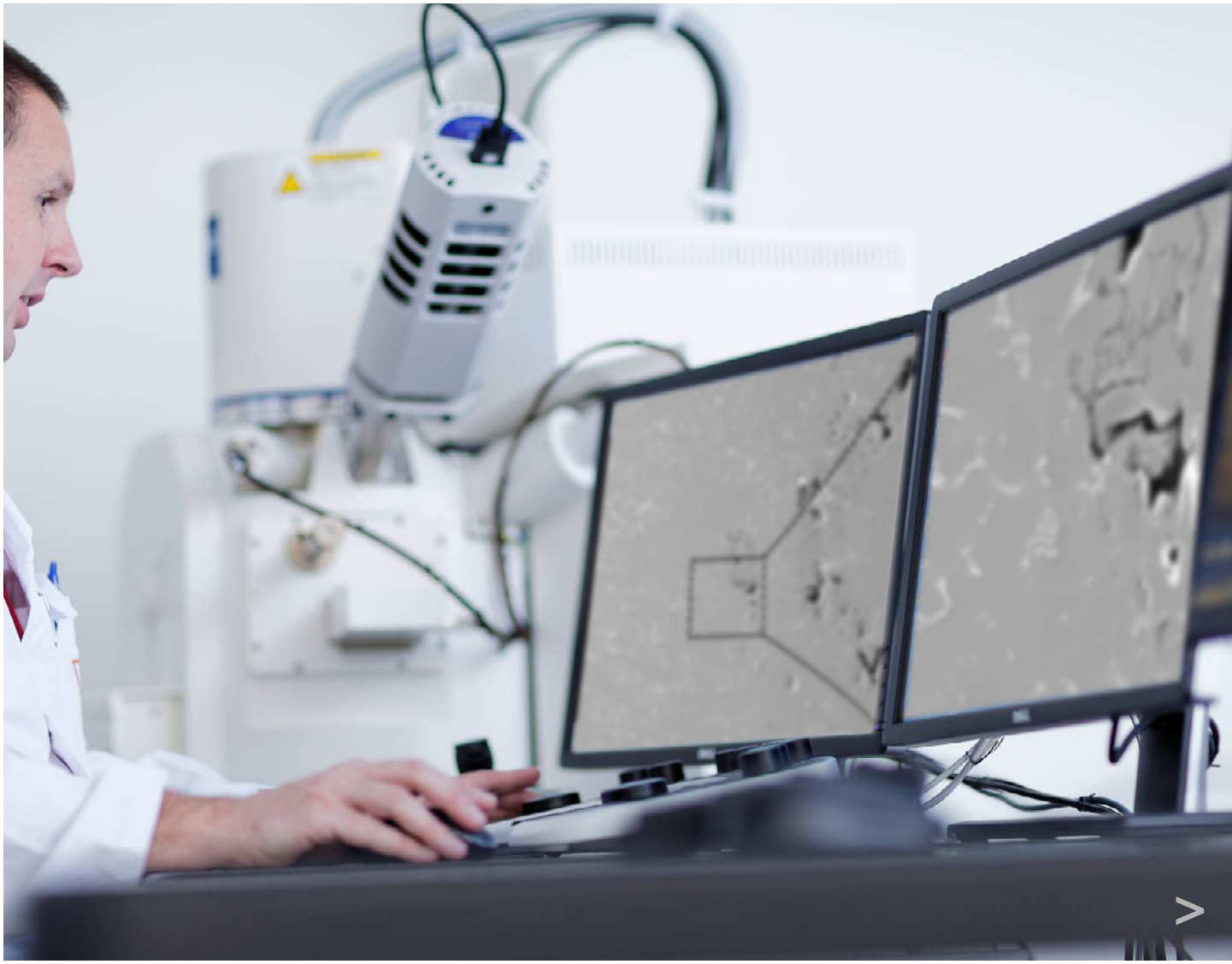
R&D Manager Binders



A COMPARISON OF DIFFERENT SAMPLING TECHNIQUES FOR ALUMINIUM METAL CLEANLINESS INVESTIGATIONS

Author: Mert Kurttepeli, Foseco Nederland BV

K-mold sampling is the traditional method of choice for obtaining aluminium samples for Vmet melt cleanliness investigations. The K-mold sampling process involves pouring liquid metal into a mould; however, this can negatively impact melt quality of the sample by introducing shrinkage pores into the cast metal. To overcome this, different sampling methods for Vmet were tested and compared, including K-mold, copper mould and immersion sampling. It was found that by using new sampling methods, such as copper mould and immersion sampling, with different geometries and mould materials, the shrinkage pore volume fraction and density can be lowered, without observing any clear negative impacts on the melt quality. The results suggest that, with the correct sampling technique, Vmet remains a viable method for determining the cleanliness of an aluminium melt in high detail.

INTRODUCTION

Aluminium alloys account for an increasing proportion of global castings production, notably in the casting of high-quality automotive parts (Kordas, Soiński and Skurka 2016). Melt treatment is a critical part of such casting processes in order to ensure appropriate standards of metal quality and cleanliness. This in turn requires a precise understanding of the melt properties.

There are essentially three main approaches to measuring metal cleanliness: chemical analysis, metallographic evaluation, and techniques based on physical principles (Doutre 2016). One example of chemical analysis is Vmet. Developed by Vesuvius, this technique uses a specialized scanning electron microscope (SEM) that is set-up to record the size, morphology, and composition of defects (pores and oxides) using energy-dispersive x-ray spectroscopy (EDXS), together with pre-defined rules and image processing algorithms adjusted for aluminium (Shi 2018).

To achieve representative monitoring of metal cleanliness with Vmet, a reliable melt sampling technique is required. Sampling should highlight any defects for image processing and reflect the effects of melt treatment on the casting quality. In the past, K-mold sampling has been widely used to obtain Vmet samples (Shi 2018). Although the geometry of the K-mold is quite simple, there are some drawbacks in the design that influence the efficacy of the mould to produce clear and repeatable results. For example, the K-mold design introduces shrinkage pores in the cast metal because certain sections solidify more slowly than surrounding areas, and so do not have enough metal flow or feed to fill completely.

To address this problem, this study tested and compared three sampling methods in range of conditions: K-mold sampling, copper mold sampling, and immersion sampling (Figure 1). It is shown that, by using the new sampling methods, the shrinkage pore volume fraction and density can be lowered, without observing any clear negative impact on the melt quality. With the correct sampling technique employed, Vmet therefore remains as a viable technique for measuring the cleanliness of the aluminium melt in high detail.

Figure 1. Three different sampling techniques were compared in this study: a) K-mold, b) copper mould (left: with coating and right: without coating), and c) an immersion sampler.

EXPERIMENTAL PROCEDURES

A number of samples were taken using each of the three techniques across three distinct trials as summarized in Table 1. It should be noted that the copper mould was specifically designed for this study to overcome the challenges observed during K-mold sampling. For this, a simple design was chosen that allows easy sampling and safe removal of the sample upon solidification (see Fig. 1-b). The immersion sampler used in this study was provided by Vesuvius Sensors and Probes division under the article code "HSF-DDX-NK-SCA-HO-12MM-EXP/TB39,5" (see Fig. 1-c).

The first trial aimed to observe the effect of different moulds or sampling techniques (K-mold vs copper mould vs immersion sampler) on the metal cleanliness results in a straightforward manner. Four samples were collected from each mould: one before degassing, and three after degassing, with samples collected at five minute intervals. This understandably caused a temperature increase at the surface of the K-mold and copper mould, which was recorded via a pyrometer so the effect on the Vmet results could be seen. The usual practice when using a K-mold includes the application of a coating on its pattern surface (HeBoCoat 401E Boron Nitrite Spray coating from Henze was used in this study), and this coating was applied on the K-mold for the first trial. Since the use of a copper mould is new for this study, no coating was applied to see if there were any detrimental effects when molten aluminium interacts with the copper surface. The immersion sampler does not require a coating due to its design and use.

The second trial focused specifically on the copper mould to establish whether mould temperature had any effects on the Vmet results. In this trial, three samples were collected using the copper mould and two with the immersion sampler before degassing. After degassing, four samples were collected using only the copper mould. All samples were collected at five minute intervals. As in the previous trial, this caused a temperature increase at the mould surface, which was again recorded with a pyrometer so the effect on the Vmet results could be seen. HeBoCoat 401E Boron Nitrite Spray coating from Henze was used to coat the copper mould, since it was observed during the previous trial that the interaction between the molten aluminium and mould surface had resulted in etching of the mould surface, which caused difficulties when removing the sample.

Trial	Before Degassing			After Degassing			Total Number of Samples			Coating applied		
	K-Mold	Copper Mold	Immersion Sampler	K-Mold	Copper Mold	Immersion Sampler	K-Mold	Copper Mold	Immersion Sampler	K-Mold	Copper Mold	Immersion Sampler
1st	1	1	1	3	3	3	4	4	4	Yes	No	N.A.
2nd	N.A.	3	2	N.A.	4	0	N.A.	7	2	No	Yes	N.A.
3rd	N.A.	12	1	N.A.	12	1	N.A.	24	2	No	Yes	N.A.

Table 1.
Summary of trials that were conducted with different conditions. The number of samples collected is also indicated (N.A. = not applied)

The last trial was conducted to confirm the findings on the first two trials. 12 samples were collected using the copper mould, and one with the immersion sampler, before and after degassing. All samples were collected at five minute intervals. As previously, the temperature increase at the surface of the copper mould was recorded with a pyrometer, and HeBoCoat 401E Boron Nitrite Spray coating from Henze was used to coat the copper mould.

During the trials, several K-mold, copper mould and immersion samples were cast with AlSi7Mg0.3 alloy, before and after rotary degassing, using Foseco's XSR rotor. A Stotek 500 kg aluminium furnace was used at the following temperatures:

+ 1st trial: 745°C
+ 2nd trial: 742°C
+ 3rd trial: 747°C

Degassing with the XSR rotor was done for 600sec at 450rpm, with argon at 10 l/min. The sampling sequence was as follows:

+ Measure the temperature at bottom of the K-mold or copper mould.
+ Pour the sample.
+ Wait 1 min for its solidification.
+ Remove the sample.
+ Wait five minutes and then measure temperature at bottom sample holder again.

After considering all the parameters involved, as explained above, Table 2 summarizes the sample IDs.

All samples were sectioned using a diamond saw with continuous water cooling. Sectioned samples were mounted into 32mm sample stubs with a heat set resin, and mounted samples were polished using a Buehler auto-polisher.

Optical microscopy (Zeiss Axiocam) was used to determine the morphology of the samples upon polishing. SEM (at 20kV) was then performed on the samples to determine metal cleanliness. An area of 10x10 mm2 per sample was investigated using Vmet parameters. In summary, this involves the selection of a feature for EDXS quantitative analysis by the microscope's software, due to its contrast level being under the threshold set. Such a feature then appears darker on the image than the rest of the sample (the aluminium matrix in this case). A spectrum is collected from the centre of that feature for a short amount of time (within seconds). The centre of the feature is chosen as the contrast centre. Further details on Vmet experimental procedures can be found in earlier reports (Shi 2018).

< >

Sample ID

1st Trial
K-Mold
1-1KM-B
1-2KM-A
1-3KM-A
1-4KM-A
Copper Mold
1-1CuM-B
1-2CuM-A
1-3CuM-A
1-4CuM-A
Immersion Sampler
1-1ImS-B
1-2ImS-A
1-3ImS-A
1-4ImS-A

2nd Trial
Copper Mold
2-1CuM-B
2-2CuM-B
2-3CuM-B
2-4CuM-A
2-5CuM-A
2-6CuM-A
2-7CuM-A
Immersion Sampler
2-1ImS-B
2-2ImS-B

3rd Trial	
Copper Mold	
3-1CuM-B	3-13CuM-A
3-2CuM-B	3-14CuM-A
3-3CuM-B	3-15CuM-A
3-4CuM-B	3-16CuM-A
3-5CuM-B	3-17CuM-A
3-6CuM-B	3-18CuM-A
3-7CuM-B	3-19CuM-A
3-8CuM-B	3-20CuM-A
3-9CuM-B	3-21CuM-A
3-10CuM-B	3-22CuM-A
3-11CuM-B	3-23CuM-A
3-12CuM-B	3-24CuM-A
Immersion Sampler	
3-1ImS-B	3-2ImS-A

Table 2. Summary of all sample IDs referred in this study. Letters B and A indicate before (B) and after (A) degassing/treatment.

RESULTS & DISCUSSIONS

3.1 FIRST TRIAL

Figure 2 shows SEM images taken of samples from the first trial, before Vmet analysis, for each sampling method. In addition, images of the samples before and after degassing are given for each sampling method (A indicates after and B indicates before degassing).

From the images of the K-mold samples (Figures 2a-d), pores with different sizes can be seen as dark spots against the grey aluminium matrix background. In general, porosity is attributed to either hydrogen or shrinkage in aluminium castings (Sabau 2002): the former usually results in rounded, isolated, and well-distributed pores, whereas the latter results in interconnected or clustered pores of an irregular shape, corresponding to the shape of the interdendritic region. The occurrence of microporosity in aluminium alloys is usually assigned to the combined effects of solidification shrinkage and gas precipitation (Sabau 2002). From a detailed observation of the morphology of the pores hereby detected (Figures 2a-d), it is likely they are a result of shrinkage.

A K-mold is made from cold rolled steel. Additionally, the pattern is designed almost like a thin slab. Upon pouring, solidification takes place rapidly. As noted earlier, the K-mold design damages sampling quality by introducing shrinkage pores into the cast metal. This is due to sections that solidify more slowly than surrounding areas upon pouring. For such sections, there is not enough metal flow – or the chance to feed more into them – for them to be filled completely. As Vmet is based on recognising features that appear with darker contrast in comparison to the background matrix, all these shrinkage pores are recorded and contribute to the results. Since, microporosity in aluminium alloys can be related to both solidification shrinkage and gas precipitation, this makes it difficult to consider K-mold sampling further in such investigations.

When the images of samples obtained using the copper mould or immersion sampler are considered, however, it is clearly seen that there are no such areas of highly-concentrated porosity, as are caused by shrinkage and are present in the K-mold samples.

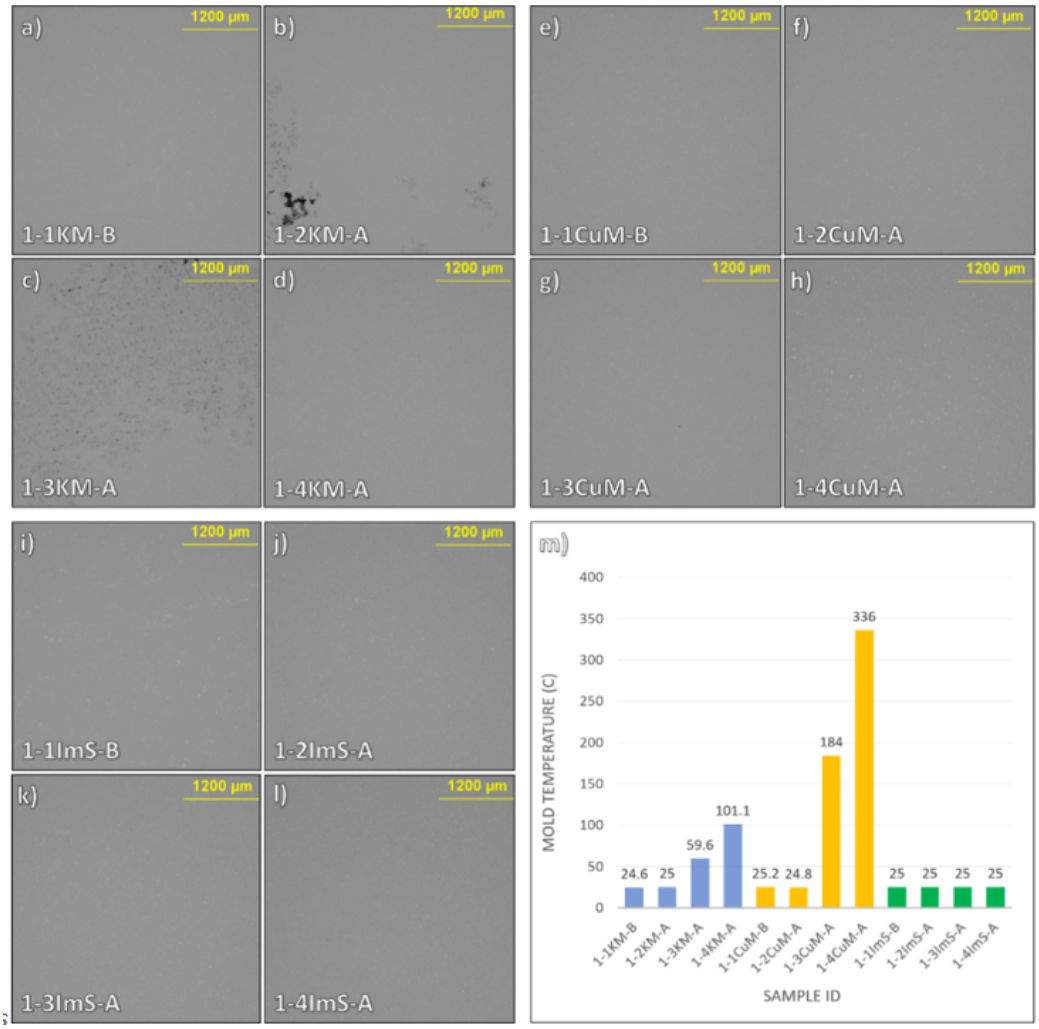


Figure 2.
SEM images taken from samples of the 1st trial, before Vmet analysis, for each sample method: a-d) K-mold, e-h) copper mould, and i-l) immersion sampler. Sample IDs given on images indicate before and after degassing with MTS 1500 (A indicates after and B indicates before degassing). The graph (m) shows sample IDs vs mould temperature (°C) taken by a pyrometer.

To demonstrate the effects of mould design on metal cleanliness, a Vmet analysis was conducted. The results of this experiment are shown in Table 3. One of the key parameters when measuring metal cleanliness via Vmet is to calculate the number of total number of features analysed, which includes all pores, aluminium oxides, and other inclusion types. As can be seen in Table 3, the K-mold samples showed a significantly higher number of total features than the samples taken with both the copper mould and immersion sampler. When the total number of pores, aluminium oxide and other type of inclusions are considered individually, similar conclusions can be drawn.

Inclusions with large dimensions (>15 micrometre) are of particular concern for the mechanical properties of the castings. In the K-mold samples, the number of such inclusions fluctuates significantly before and after degassing. This runs contrary to normal expectations of degassing to lower the number of inclusions and thus result in a cleaner metal. However, such an interpretation cannot be easily made on the basis of K-mold samples. On the other hand, the results from copper mould and immersion sampling indicate that degassing has a clear positive effect on the melt quality. Using any of these two samples methods therefore makes it easier to show that rotary degassing can improve melt cleanliness.

Sample IDs	1-1KM-B	1-2KM-A	1-3KM-A	1-4KM-A	1-1CuM-B	1-2CuM-A	1-3CuM-A	1-4CuM-A	1-1ImS-B	1-2ImS-A	1-3ImS-A	1-4ImS-A
Mold Type	K-Mold				Copper Mold				Immersion Sampler			
Mold Temperature C	24.6	25	59.6	101.1	25.2	24.8	184	336	25	25	25	25
Treatment	untreated Al	degassing	degassing	degassing	untreated Al	degassing	degassing	degassing	untreated Al	degassing	degassing	degassing
Total Features	8793	7754	7583	1800	323	161	19	318	412	248	62	72
Area Analyzed (mm^2)	100.44	100.44	100.44	100.4	100.44	100.44	100.44	100.44	100.44	100.44	100.44	100.44
Total Pores	7649	6535	6662	1121	267	111	17	194	93	169	51	56
0.5 – 15 µm	7646	6480	6662	1121	262	111	17	194	93	169	51	56
15 – 30 µm	3	34	0	0	4	0	0	0	0	0	0	0
30 – 75 µm	0	18	0	0	1	0	0	0	0	0	0	0
> 75 µm	0	3	0	0	0	0	0	0	0	0	0	0
Total Aluminum Oxides	453	392	339	62	14	16	0	15	62	28	2	3
0.5 – 15 µm	453	378	339	62	14	16	0	15	62	28	2	3
15 – 30 µm	0	6	0	0	0	0	0	0	0	0	0	0
30 – 75 µm	0	7	0	0	0	0	0	0	0	0	0	0
> 75 µm	0	1	0	0	0	0	0	0	0	0	0	0
Total Other Inclusions	691	827	582	617	42	34	2	109	257	51	9	13
0.5 – 15 µm	681	816	581	616	42	34	2	108	255	49	6	13
15 – 30 µm	9	11	1	1	0	0	0	1	2	2	3	0
30 – 75 µm	1	0	0	0	0	0	0	0	0	0	0	0
> 75 µm	0	0	0	0	0	0	0	0	0	0	0	0

Table 3. Vmet analysis of samples taken during the 1st trial, before and after treatment with MTS 1500 degassing.

If the designs of K-mold and copper mould are compared to each other, some similarities are observed (Figure 3). For instance, sample volume in both cases is significantly higher than that of immersion samples. In the case of the K-mold, however, a thinner slab-like geometry is prominent; whereas for the copper mould, a thick cup shape is to be seen. It is this geometry that causes the above mentioned issues with inconsistent solidification and shrinkage, which is illustrated well in Figure 3a.

To discover whether shrinkage pores also exist in the copper mould sample due to its bulky geometry, a cross section was cut directly from the middle of the sample. It was further polished by hand until a scratch free surface was obtained for microscopic imaging. Figure 4 was acquired using the tiles and stitching module of the optical microscope, which enables the user to zoom in and observe the microstructure and defects of a sample in detail. As can be seen, the top part of the copper mould sample contains a large area where shrinkage pores are present. For the rest of the sample, round-shaped pores are seen, which indicates pores with a gas origin. Since the Vmet section is cut from the bottom of the sample, this makes the area that is to be characterized through Vmet falls far away from the region where a high density of shrinkage pores is seen.

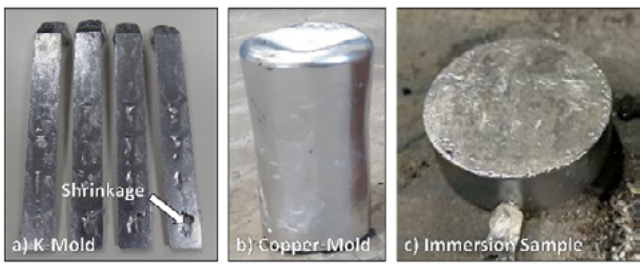


Figure 3. Samples taken using a) a K-mold (back side), b) a copper mould, and c) an immersion sampler. Note the shrinkage prominent defects in the K-mold sample.

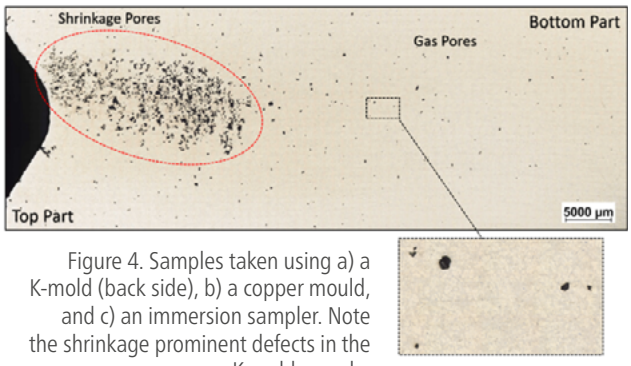


Figure 4. Samples taken using a) a K-mold (back side), b) a copper mould, and c) an immersion sampler. Note the shrinkage prominent defects in the K-mold sample.

3.2 SECOND TRIAL

The details of the second trial are given in Tables 1 and 2, and Vmet results can be seen in Table 4.

This trial aimed to investigate the effect of an increase in copper mould temperature during sampling. As can be seen, taking consecutive samples increased the copper mould temperature from room temperature to a value slightly higher than 300 °C, at which it stabilised. During the trial, it was observed that such temperatures are usually reached with a sample interval time of five minutes; whereas decreasing the sample interval time increased the mould temperature to a maximum of 450 °C. The trials therefore showed that it is not advisable to decrease sample interval times to less than five minutes, as this results in overheating of the mould and negatively impacts the mould coating, causing the aluminium sample to stick onto the walls of the mould.

When Vmet results of this trial are considered, the first collected sample has a high number of pores (751 in total); this number decreases and mostly stabilises when a temperature above 150 °C is reached. Although this number is considered high, it is significantly lower than those obtained with K-mold samples (see Table 3 for comparison). When sampling continued after degassing, there is a further decrease in the number of pores, as expected. A decrease in the number of aluminium oxide and other types of inclusion was also observed after degassing. Although the melt was not treated with a flux – and keeping in mind that the initial status of the melt was already rather clean, with almost no inclusions larger than 30 micrometres – the positive impact of degassing on melt quality is still clearly seen.

If the results from the copper mould and immersion sampler are compared, the immersion sampler shows a clear advantage over the copper mould, as both immersion samples give similar results, with very low number of pores, aluminium oxide, and other type of inclusions. This is probably due to the negative impact of mould geometry on the sample. Although a much better candidate than the K-mold, there are negative impacts of a bulky sampling mould on sample quality due to the introduction of shrinkage pores into the cast metal.

Sample IDs	2-1CuM-B	2-2CuM-B	2-3CuM-B	2-4CuM-A	2-5CuM-A	2-6CuM-A	2-7CuM-A	2-1ImS-B	2-2ImS-B
Mold Type	Copper Mold							Immersion Sampler	
Mold Temperature C	28	167	201	288	314	315	317	28	28
Treatment	untreated Al	untreated Al	untreated Al	degassing	degassing	degassing	degassing	untreated Al	untreated Al
Total Features	854	346	620	363	326	278	232	193	125
Area Analyzed (mm^2)	100	100	100	100	100	100	100	100	100
Total Pores	**751**	**313**	**348**	**325**	**285**	**258**	**192**	**154**	**111**
0.5 – 15 µm	749	313	344	323	274	248	189	153	108
15 – 30 µm	2	0	4	0	9	6	2	1	2
30 – 75 µm	0	0	0	2	2	4	1	0	1
> 75 µm	0	0	0	0	0	0	0	0	0
Total Aluminum Oxides	**41**	**14**	**37**	**18**	**24**	**13**	**22**	**24**	**8**
0.5 – 15 µm	41	14	37	18	22	12	22	24	8
15 – 30 µm	0	0	0	0	2	1	0	0	0
30 – 75 µm	0	0	0	0	0	0	0	0	0
> 75 µm	0	0	0	0	0	0	0	0	0
Total Other Inclusions	**62**	**19**	**235**	**20**	**17**	**7**	**18**	**15**	**6**
0.5 – 15 µm	58	19	232	20	17	3	15	12	4
15 – 30 µm	3	0	3	0	0	4	3	3	1
30 – 75 µm	1	0	0	0	0	0	0	0	1
> 75 µm	0	0	0	0	0	0	0	0	0

Table 4. Vmet analysis from the second trial, before and after degassing of the melt with MTS 1500.

The third trial aimed to compare the copper mould vs. immersion sampler. In particular, the goal was to confirm the effect of copper mould temperature on the observed total number of pores. Vmet results for this trial can be observed in Table 5. As can be seen again, taking consecutive samples increased the copper mould temperature from around room temperature to slightly higher than 300°C. One of the main common findings in each of these trials is that sampling tends to increase the copper mould temperature to a value between 300-350°C, before it stabilizes within that temperature range.

If the number of total pores is observed, it is clear that the collected samples before degassing have a high number of pores (171 min. and 731 max.), while this number decreases after the degassing to a minimum of 110 and maximum of 652. When the total number of aluminium oxide and other inclusions are observed, the positive impact of degassing on these values is much more obvious. It is observed that, in most of the cases, both numbers are significantly lower after degassing than before treatment.

In addition, when the results from the copper mould and immersion sampler are compared, the immersion sampler gives similar results across samples, with very low number of pores, aluminium oxide and other type of inclusions. The samples taken with immersion sampler show the lowest number of pores (untreated or degassed at room temperature) when compared to copper mould. This is due to the fact that the immersion samples are much smaller than the copper mould samples and so solidify more rapidly. Because shrinkage is caused by inconsistent solidification through the mould, the rapid solidification of a small volume of metal explains the lack of shrinkage pores within.

Sample IDs	3-1CuM-B	3-2CuM-B	3-3CuM-B	3-4CuM-B	3-5CuM-B	3-6CuM-B	3-7CuM-B	3-8CuM-B	3-9CuM-B	3-10CuM-B	3-11CuM-B	3-12CuM-B	3-1Im5-B
Mold Type	Copper Mold												Immersion Sampler
Mold Temperature C	21.5	246	266	275	293	299	308	305	310	309	316	319	21
Treatment	untreated Al												untreated Al
Total Features	804	752	243	359	248	288	186	274	223	215	627	214	171
Area Analyzed (mm^2)	100	100	100	100	100	100	100	100	100	100	100	100	100
Total Pores	**731**	**668**	**219**	**294**	**223**	**262**	**171**	**237**	**189**	**190**	**575**	**194**	**148**
0.5 – 15 µm	729	659	219	292	222	260	168	236	188	190	575	194	147
15 – 30 µm	2	8	0	2	1	2	2	1	1	0	0	0	0
30 – 75 µm	0	1	0	0	0	0	1	0	0	0	0	0	1
> 75 µm	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Aluminum Oxides	**66**	**68**	**23**	**34**	**22**	**25**	**11**	**19**	**26**	**23**	**47**	**19**	**9**
0.5 – 15 µm	66	67	23	34	22	24	11	19	26	23	47	19	9
15 – 30 µm	0	1	0	0	0	1	0	0	0	0	0	0	0
30 – 75 µm	0	0	0	0	0	0	0	0	0	0	0	0	0
> 75 µm	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Other Inclusions	**7**	**16**	**1**	**31**	**3**	**1**	**4**	**18**	**8**	**2**	**5**	**1**	**14**
0.5 – 15 µm	7	16	1	29	3	1	4	15	6	0	4	1	10
15 – 30 µm	0	0	0	2	0	0	0	3	2	2	1	0	3
30 – 75 µm	0	0	0	0	0	0	0	0	0	0	0	0	1
> 75 µm	0	0	0	0	0	0	0	0	0	0	0	0	0

Sample IDs	3-13CuM-A	3-14CuM-A	3-15CuM-A	3-16CuM-A	3-17CuM-A	3-18CuM-A	3-19CuM-A	3-20CuM-A	3-21CuM-A	3-22CuM-A	3-23CuM-A	3-24CuM-A	3-2Im5-A
Mold Type	Copper Mold												Immersion Sampler
Mold Temperature C	27.5	206	300	312	325	306	322	326	320	329	319	320	21
Treatment	degassing												degassing
Total Features	475	180	204	115	214	207	746	134	148	150	224	144	163
Area Analyzed (mm^2)	100	100	100	100	100	100	100	100	100	100	100	100	100
Total Pores	**336**	**167**	**182**	**110**	**181**	**186**	**652**	**118**	**135**	**139**	**206**	**132**	**149**
0.5 – 15 µm	336	167	181	110	178	186	649	118	134	139	204	131	149
15 – 30 µm	0	0	1	0	3	0	3	0	1	0	2	1	0
30 – 75 µm	0	0	0	0	0	0	0	0	0	0	0	0	0
> 75 µm	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Aluminum Oxides	**42**	**8**	**20**	**5**	**24**	**15**	**73**	**12**	**11**	**11**	**12**	**8**	**9**
0.5 – 15 µm	42	8	19	5	24	15	69	12	11	11	12	8	8
15 – 30 µm	0	0	1	0	0	0	4	0	0	0	0	0	0
30 – 75 µm	0	0	0	0	0	0	0	0	0	0	0	0	1
> 75 µm	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Other Inclusions	**97**	**5**	**2**	**0**	**9**	**6**	**21**	**4**	**2**	**0**	**6**	**4**	**5**
0.5 – 15 µm	94	5	0	0	4	6	21	2	2	0	5	4	4
15 – 30 µm	3	0	2	0	0	0	0	2	0	0	1	0	0
30 – 75 µm	0	0	0	0	5	0	0	0	0	0	0	0	1
> 75 µm	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5. Vmet analysis from the third trial before and after degassing with MTS 1500

CONCLUSIONS

Metal cleanliness is an important parameter that plays a vital role in determining the final quality of aluminium castings. In this study, it is demonstrated that metal cleanliness can be determined with high precision (i.e., at the micrometre scale) using the Vmet technique. Vmet enables one to optimise melt quality by adjusting melt treatment procedures, which in return will ensure castings with good physical properties.

For Vmet to reflect the precise condition of the melt, different sampling methods for Vmet were investigated. Three sets of trials, before and after rotary degassing, with different sampling techniques (K-mold, copper mould and immersion sampling), were undertaken. Based on the results of these trials, it can be concluded that copper mould and immersion sampling techniques are superior to the traditional K-mold sampling method, both in terms of replicability and the elimination of shrinkage in the final samples. Specifically, the results demonstrate immersion sampling to be slightly more reliable than the copper mould sampling; however, both were shown to be trustworthy techniques for investigating samples through Vmet.

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

Author: Wolfram Stets, Foseco Nederland BV

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

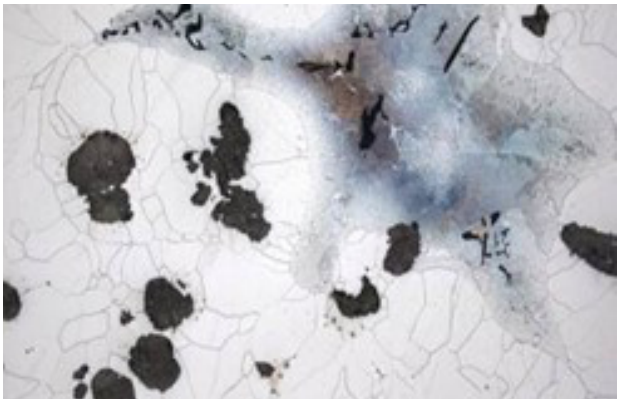

Figure 2. Endogenous MgO inclusion in ductile cast iron.

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.

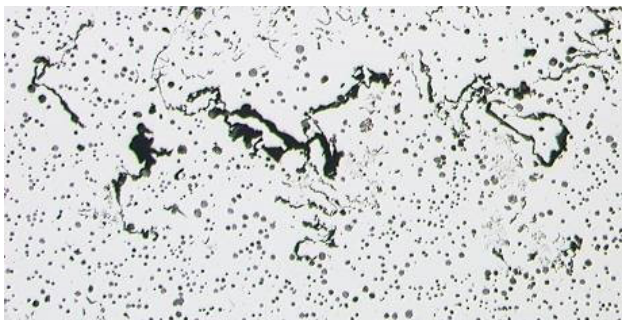

Figure 3. Dross defect in ductile cast iron.

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.

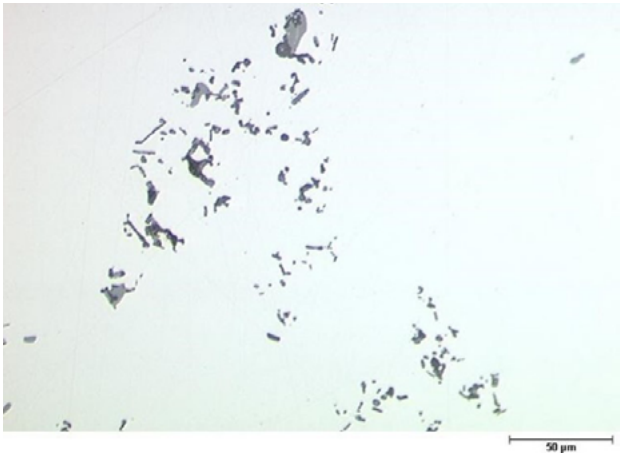

Figure 4. Non-metallic inclusions in cast steel may aggregate into larger clusters.

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.

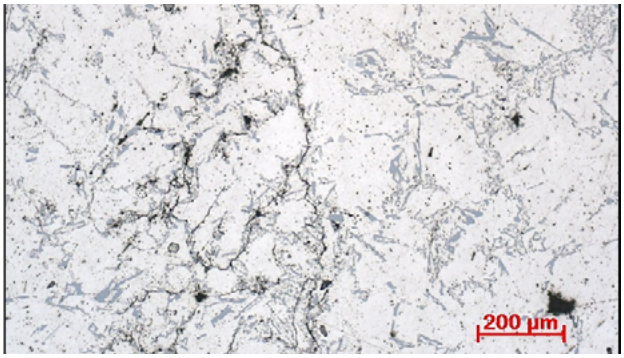

Figure 5. Oxide skin in an aluminium casting.

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.

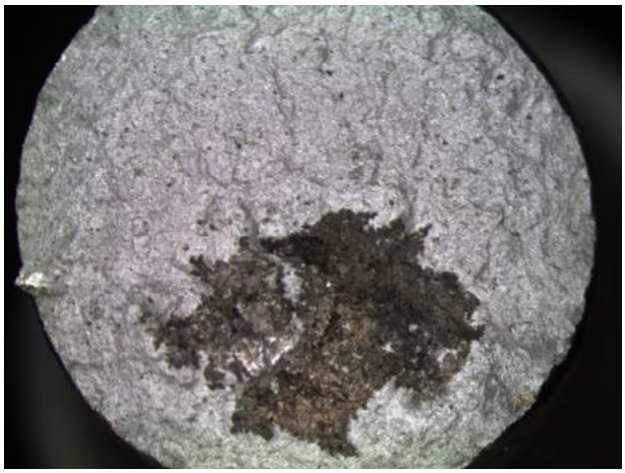

Figure 6. Large oxide skin in the fracture surface of an aluminium casting

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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DR. WOLFRAM STETS
International Technology Manager
Metal Treatment

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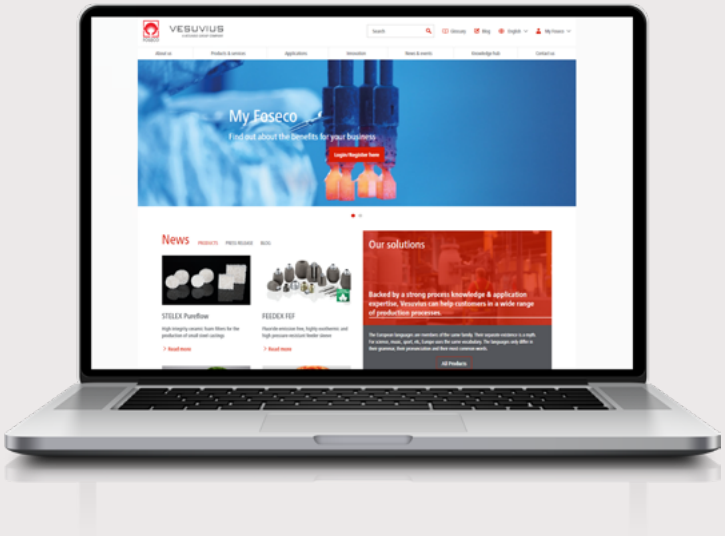

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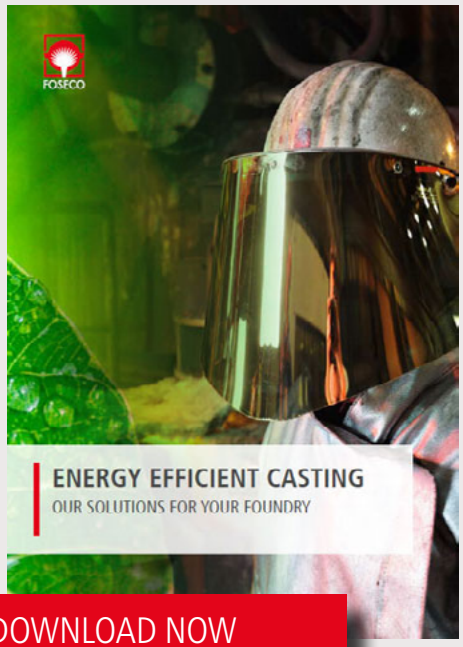

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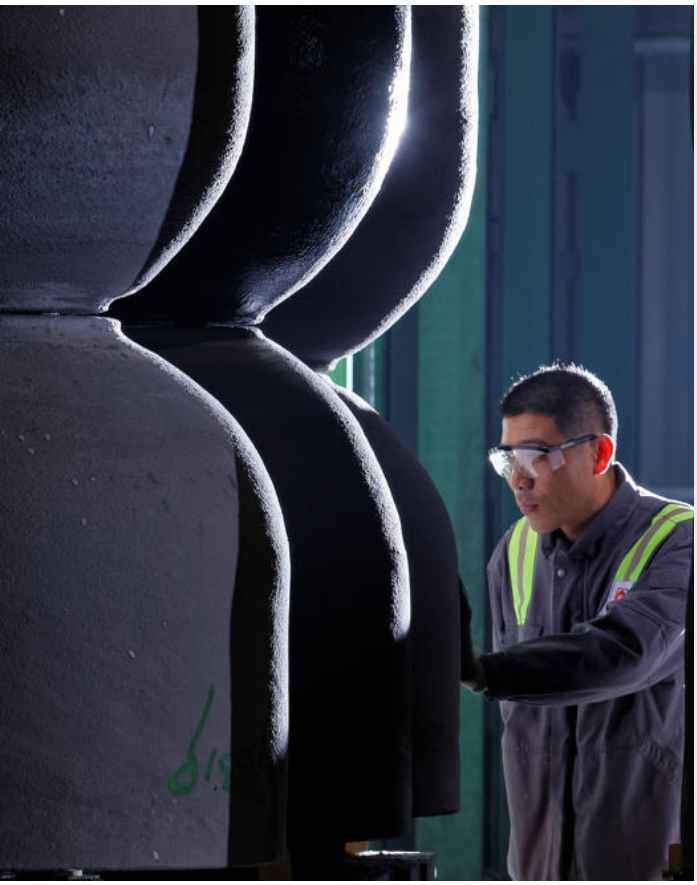

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Improving the energy efficiency of foundry operations reduces both energy costs and carbon emissions. It's a vital win-win for foundries under pressure to reduce their environmental impact, while staying cost competitive. Foundries should therefore consider switching to energy-efficiency crucibles, such as the ENERTEK crucible range from Foseco, even if this means challenging traditional price-based purchasing decision-making.

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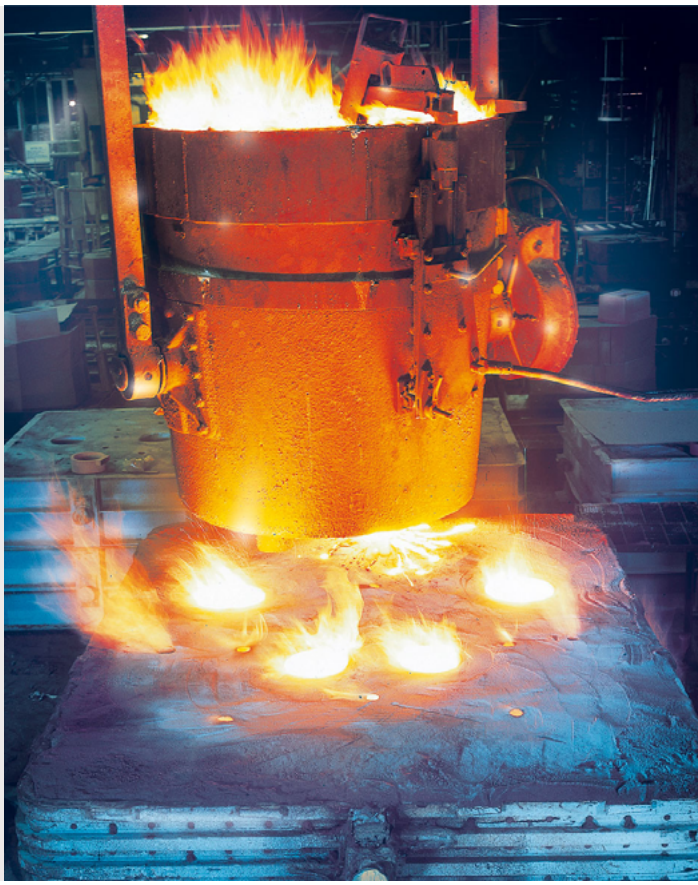

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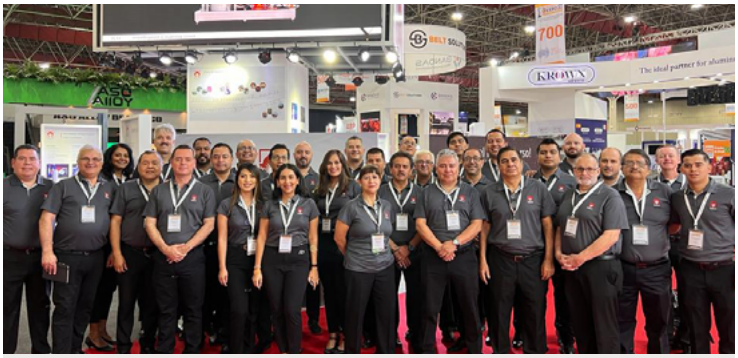

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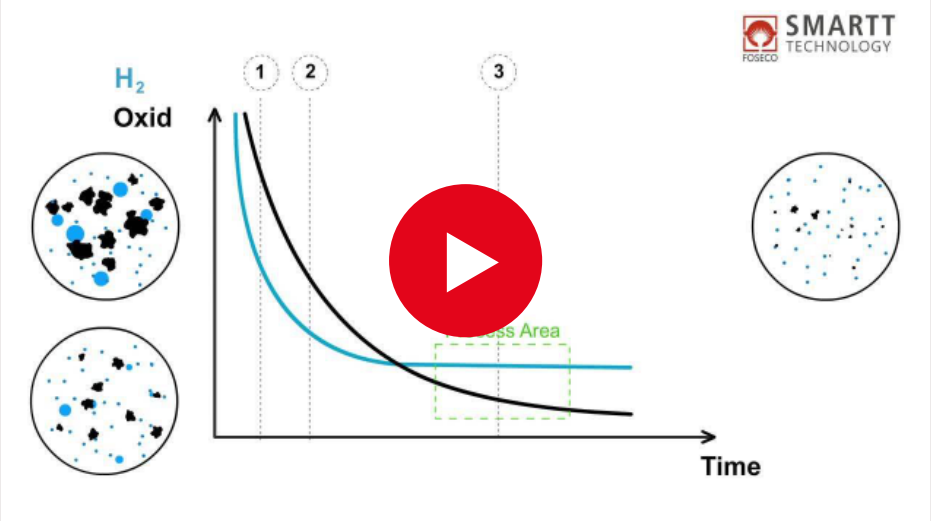

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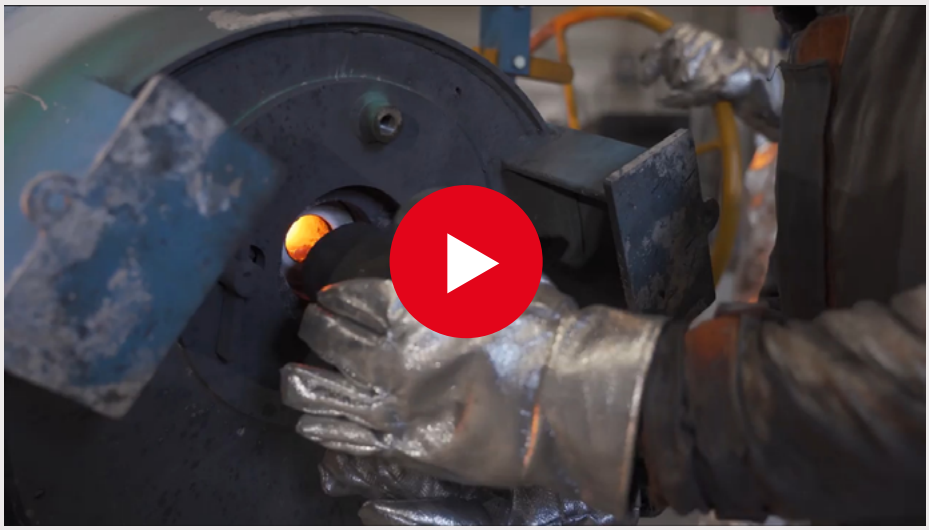

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