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# Sampling Tool for In-Depth Study of Furnace Processes

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## Abstract

The need for ever more efficient and reproducible processes in furnace operations is increasing. Conversely the development trend is towards more complexity in furnace technology and flexibility in input material capability. These demands have produced a startlingly large number of furnace designs and operational strategies. To better understand the various metallurgical processes occurring in the furnace and the potential operational and economic impact of changes to the furnace technology, operation or input material, a simple, but robust technology to selectively take samples throughout the three dimensional geometry of the melt has been developed. This allows the construction of a time dependent 3-D performance map of the furnace which can be used to optimize operational performance, economics or in combination with simulation techniques compare different furnace technologies and operational strategies. This paper introduces the sampling technology and presents results of a small demonstration study

## Introduction

To date understanding of inclusion generation and behaviour in industrial furnaces is based on:

- Theoretical chemistry and physics
- Computational simulations
- Limited results from physical sampling from easily accessible areas of the bath surface

The manual sampling of melt surface using a ladle severely limits the ability to gain knowledge about important furnace processes:

- requires protective clothing with limited movement and visibility
- only easily accessible areas can be sampled – melt surface at doors and pouring spouts
- limited number of samples and volume can be sampled due to weight of equipment and heat exposure

Furthermore in some cases it is questionable whether such a sample is truly representative of the bulk of the melt as layers of dross or sludge can distort the results obtained when only the surface of the melt is sampled. This is demonstrated in Figure **1** which compares two PoDFA samples taken using a ladle from the same charge of an Al-3Mg alloy. The first sample was taken after skimming of the melt surface through the furnace door and the second sample was taken from the launder at the furnace exit during casting. Clearly the first sample taken with a ladle through the furnace door after charge preparation is not representative of the melt that is cast into the product. Representative samples can thus only be obtained by sampling of the melt during casting. This situation severely limits the ability to investigate the time dependent furnace processes (e.g. particle generation, transformation and transport). A better understanding of these processes is important as these are the processes which determine the overall melt quality obtained in the furnace.

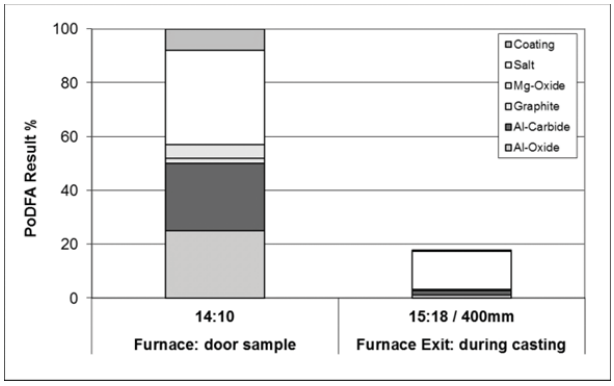



Figure 1. Comparison of two PoDFA samples taken from the same charge: first sample taken after skimming of the melt surface through the furnace door, second sample taken from the launder at the furnace exit during casting.

This limited understanding and the restrictions imposed by the standard investigation methods currently available are insufficient to deal with the increasing complexity of modern furnace design and operation:

- Multiple chambers or rotary furnaces
- Stirring with mechanical and electromagnetic pumps
- Increasing scrap content with tramp elements and organic content
- Scrap form – loose or compacted
- Pyrolysis (partial) of organics and submergence
- Changes in type and concentration of typical inclusions due the increasing use of post-consumer scrap

More knowledge of particle generation, transformation, transportation and agglomeration is required to fully understand and control modern Aluminium melting furnaces. It is therefore necessary to be able to sample throughout the three dimensional space of the liquid metal bath within the furnace. Using the currently available ladle sampling technique it is not possible to sample metal at specific positions and depths in the furnace.
An improved sampling capability is needed to be able to map the melt within the furnace with respect to the above parameters

Two vacuum based methods for sampling beneath the melt surface are available [1, 2]:

1. LAIS – Liquid Aluminium Inclusion Sampler
2. Classic “lollipop” sampler used in steel production

These methods were implemented many years ago but would need to be adapted to be able to function within the harsh environment

within an Aluminium melting or casting furnace. In their current form these devices also suffer from limited reach into the furnace and minimal submersion depth. The LAIS system has not proved to be as popular as the PoDFA system due at least in part to its more complicated design and corresponding time consuming assembly and maintenance requirements. More care is also required to successfully operate this equipment in the production environment. The "lollipop" sampling method is well established in the steel industry but in this case only a relatively small volume is required mainly for chemical analysis purposes. Due to the low level of inclusions present in Al-melts a pre-concentration step is often required. This principle is employed in both the PoDFA and Prefil methods [3, 4]. Typically 1kg of Aluminium is necessary to obtain a sufficient inclusion density. Both the LAIS and "lollipop" methods require the use of a vacuum system which adds an additional level of complexity as materials must not only be resistant to molten Aluminium but also non-porous and thermal shock resistant. Adequate maintenance and careful assembly are required to ensure adequate sealing in order to generate sufficient vacuum. The method proposed in this work being mechanical in nature aims to avoid these disadvantages while at the same time delivering a sample volume in excess of 1kg.

## Furnace Sampling and its Contribution to Continuous Improvement and R&D Programs

The furnace sampling tool (FST) was developed to overcome the limitations of the current ladle sampling procedure. This tool will be used to generate knowledge about and develop a better understanding of the following processes:

Melting furnaces

- Rate of sludge formation
- Identify dead zones – areas of chemical inhomogeneity or high particle concentration
- Study segregation of particles based on location, depth and type of particle
- Effectiveness of melt stirring in homogenizing the melt
- Optimization of furnace practices (cleaning and alloying) to minimize inclusion concentration in the melt
- Generate information for improved furnace design

Holding and casting furnaces

- Optimization of furnace practices (cleaning, alloying, settling) to minimize inclusion concentration in the melt
- Minimizing holding time to achieve specific melt quality
- Avoiding unwanted reactions and reaction products in the furnace

A more comprehensive understanding of furnace process is also necessary to be able to assess which of the available melt treatment technologies could provide the most effective and economical process to remove inclusions in the furnace. The wide range of options available have various advantages and potential disadvantages in term of performance, operating and investment cost and environmental impact [5-9]. An important aspect of this research program will be to generate data showing which melt refining technology would achieve the optimum cost/benefit result for each combination of furnace technology, input material and alloy/product spectrum.

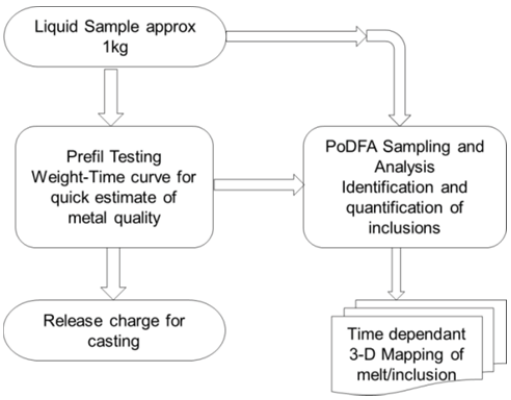



Figure 2. Furnace melt sampling in combination with Prefil and PoDFA measurements can contribute to efficient furnace operations and increase understanding of physical and chemical processes occurring within the furnace.

The FST and its operation will be presented in the following chapters of this paper. The aim of the FST is to obtain a liquid metal sample from a specific position (Cartesian coordinates x, y, z) within the melt, remove this sample from the furnace and deliver it to the subsequent analysis processes. In the first instance the FST can be combined with the well-known PoDFA and Prefil tests as shown in Figure **3**. In this way the FST in combination with Prefil equipment can be used to give immediate information about a charge (e.g. ready to cast) [10] or used with PoDFA to increase knowledge and optimize furnace processes.

In order to optimize cast shop operations it is necessary to understand where the current and future technical challenges and production bottlenecks exist and what measures are necessary to reduce or eliminate them. A strategy to use the FST to investigate these processes and implement improvements in the production environment is also required as depicted schematically in Figure **3**. In this strategy the FST is used in parallel with standard furnace operations to quantify furnace performance and evaluate the effectiveness of process changes on key melt quality parameters in accordance with the well-known Plan-Do-Check-Act cycle of Demings [11]

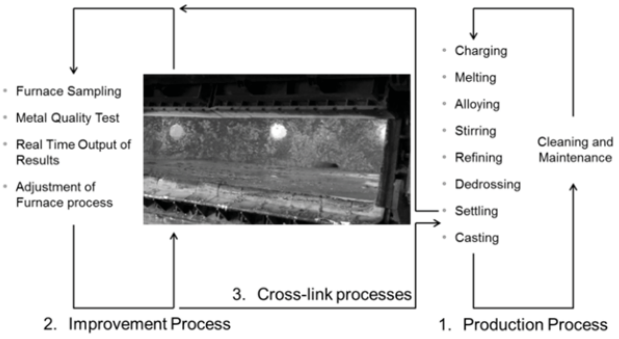



Figure 3 Strategy to combine furnace sampling and analysis with standard production processes to assist with the continuous improvement process.

**Furnace Sampling Tool (FST)**

In order to be able to take a sample from a specific position (x, y, z) within the melt a robust mechanical positioning system and sampling container is required. The positioning system must be variable to enable its use with a wide range of furnace designs and geometries. It must function accurately and reliably and withstand the hot and dusty cast house environment. The sampling arm and container must be resistant to heat and liquid metal and chemically and mechanically robust so as not to introduce particles into the melt. The sampling system must also ensure that only melt from the desired sampling point can enter the sampling container. It should also be designed so that the liquid metal sample can be quickly and easily transferred to another container for further processing. It should be possible to assemble and disassemble the system and transport it between measurement locations within the cast house and even between different cast houses.

The construction of the FST is shown in Figure **4**. The unit consists of a stable stand with a vertical rail system. By means of a small electric winch the sampling arm and container can be raised and lowered. The horizontal movement of the sampling arm into and out of the furnace is performed using a guide roll system. In this way a sliding movement of the arm is accomplished with very little force required. The sampling container is constructed from refractory material and is easily attached to and removed from the sampling arm. The equipment is thus very flexible can be applied both in the preparation of wrought and foundry alloys. It would also be possible to use this equipment to sample furnaces containing other non-ferrous metals such as copper or lead or zinc.

The procedure to obtain a melt sample using the FST is as follows:

1. Establish relationship between melt level in furnace and height of furnace sill (=required container-arm off-set)
2. Position FST in front of furnace chamber to be sampled (so that the desired (x, y) coordinates can be reached
3. Fit sampling container with desired siphon length (determines z coordinate)
4. Open furnace door
5. Slide FST sampling arm into furnace to desired position (x, y coordinates)
6. Lower into melt until sampling depth is obtained (z coordinate)
7. Wait until sampling container fills with metal
8. Raise and slide sampling arm out of furnace
9. Remove sampling container and perform test procedure e.g. PoDFA or Prefil
10. Clean and prepare equipment for next sample

This process (Steps 2-9) is completed in only a few minutes and can be integrated into the standard production process without causing significant delays to the production schedule. Cleaning and preparation activities can be conducted “off-line” and remote from the furnace.

To ensure that only metal from the desired sampling position enters the sampling container a siphon system was employed. This system and its function is shown schematically in Figure **5**. In these trials the siphon length was approximately 50cm but this length can be increased or decreased to sample material from different depths in the melt. In this way also samples can be taken from a wide range of furnace types such as relatively shallow reverbatory furnaces or deep crucible furnaces. The Al-plug seals the siphon during the immersion phase preventing unwanted entrainment of surface metal or dross.

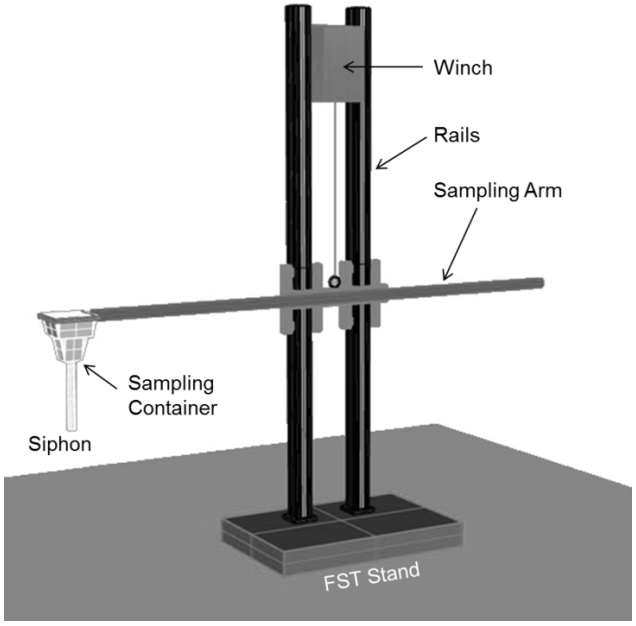



Figure 4. Schematic diagram of the FST developed to enable sampling throughout the three dimensional space of the liquid metal bath within the furnace.

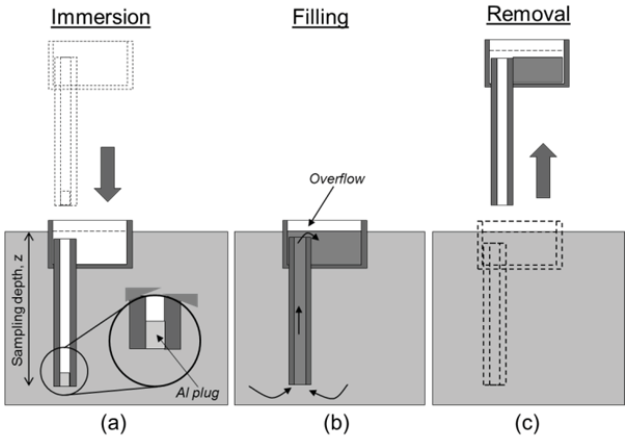



Figure 5. Siphoning system used to obtain sample of melt from desired bath depth z. By means of the FST the sampling container is positioned in the furnace and lowered into the melt (a), a metal plug seals the siphon until the correct depth has been achieved. It then melts, the metallostatic pressure causing metal to flow through the siphon into the sampling container (b). Here it is trapped in the sampling container and removed with the container from the furnace (c).

## Results and Discussion

To investigate the functionality and potential of this tool for industrial application first trials were conducted under laboratory conditions in a 300kg electrical resistance heated crucible furnace.

Trial 1 Commercial Purity Al

Trial 1 was conducted using 300kg of commercial purity Aluminium. 3kg of 3:1 TiB grain refiner was added to this melt in order to ensure enough particles were present in the melt to clearly show the effect of particle settling. The melt temperature was maintained between 720 and 760°C. Melt samples were taken from this melt:

1. from the surface using a ladle
2. from a depth of 50cm using the FST

The bath depth in this furnace was approximately 70cm. After the addition of grain refiner (at 10:30) the melt was well stirred and samples taken at regular intervals (11:00, 11:40 and 12:00). The samples were evaluated using the standard PoDFA analysis method. The normalized (inclusion concentration expressed as percentage of sample with highest inclusion concentration) PoDFA results are shown in Figure **6**.

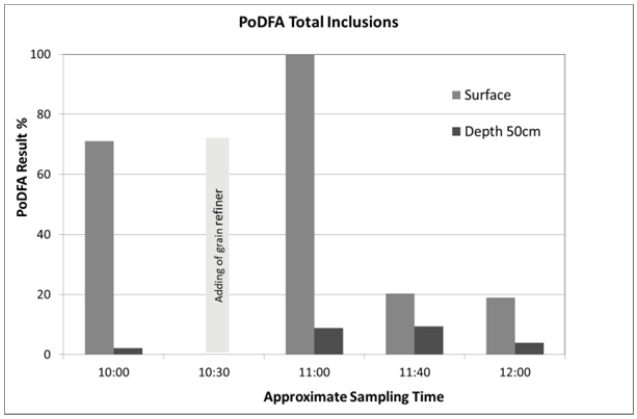



Figure 6. PoDFA results for samples taken at the surface and at a depth of approximately 50cm. The effect of the sampling position on the reported melt quality is quite strong especially for the measurements taken directly after stirring. Inclusions were identified as Al-Oxides or Ti-Borides.

It is clear that the reported concentration of inclusions is a function of the sampling position in this case. Samples taken from the surface with a ladle always had a higher concentration of inclusions than those taken from a depth of 50cm under the melt surface. This difference was largest shortly after stirring of the melt (Sample 11:00) however, a large difference was also observed for the sample taken at 10:00. This sample was taken before the melt was stirred and in fact the melt had been quiescent for several hours previously. The reason for the large difference between the surface and depth samples for the case before and immediately after stirring and those samples taken after an intermediate time is not clear at this stage but may be related to differences in the amount of oxidation present on the surface of the melt (different sampling times after the surface skimming operation). A second round of stirring and sampling showed low inclusion concentration for both a freshly skimmed surface and 50cm depth samples but high inclusion levels in the surface sample after stirring. Unfortunately due to technical difficulties it was only possible to obtain the one surface sample after stirring. It would be preferable to conduct several repeats of this trial in order to assess the repeatability of this result. Time and cost constraints prevented this in the current study however. The other disadvantage of such tests is the absence of any real time information on inclusion level. The delay in obtaining the PoDFA results means that one cannot react to any anomalies occurring during the trials.

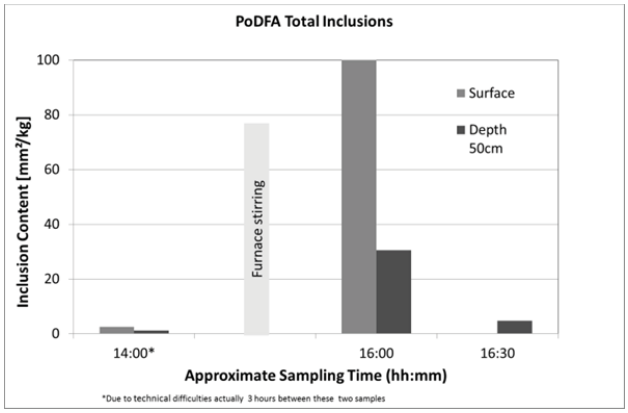



Figure 7. Similar trial as in Figure 6 but with low inclusion concentration found in the surface sample taken from a freshly skimmed melt surface.

Clearly the variation in results that can result in samples taken from the surface is unsatisfactory. Success here depends on both the condition of the surface of the melt and the sampling technique itself. By sampling below the melt surface the FST should avoid some of these problems and provide a more reproducible indication of inclusion concentration in the melt.

Trial 2 Al-5Mg Alloy

For the second trial approximately 15kg of Magnesium was added to the melt to produce a binary Al-5Mg Alloy. The actual Magnesium content varied between 4.8 and 4.6 wt.% over the course of the trial. To commence the trial the melt was vigorously stirred and then sampled at regular intervals using the same procedure as described above. The results of the PoDFA analysis of these samples are shown in Figure **8**. Again in this trial the surface samples showed higher inclusion concentrations than the depth samples but the difference here was much smaller than in the previous trial. A gradual reduction in inclusions for both sampling positions was observed until approximately 1½ hours after stirring. At this time the inclusion concentration at the surface of the melt appeared to increase again. Due to the high reactivity of this alloy the rate of oxidation was much higher than for the previous trial so that a thick layer (approx. 2-3cm) of dross formed on the surface of the melt in this time.

A detailed investigation of the PoDFA samples revealed a strong growth of Al-Mg-oxide clusters with embedded Aluminium-Nitride phases after an initial incubation period of about 60 minutes as shown in Figure **9** and Figure **10**. This acceleration in

oxidation rate has been reported previously and was associated with a loss of coherency of the oxide layer and hence loss of passivation [12]. In these trials however, the oxidation occurred under a Helium-Oxygen atmosphere which would of course exclude the formation of Nitrides. From approximately 60 minutes after stirring small amounts of Nitrides were also observed in the last three samples taken from a depth of 50cm under the surface of the melt. It is assumed that these particles were entrained in the melt by thermal convection currents which would establish a vertical mass transport pattern in the quiescent melt after a certain amount of time.

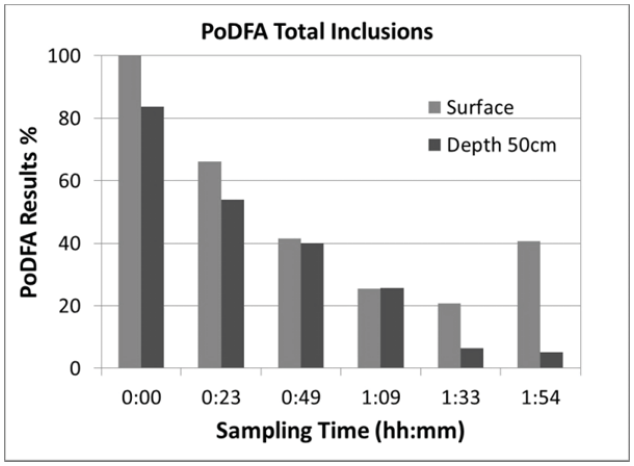



Figure 8. Results of PoDFA analysis taken from the surface of the melt and at a depth of approximately 50cm. Note strong increase in inclusion concentration at the surface after initial reduction.

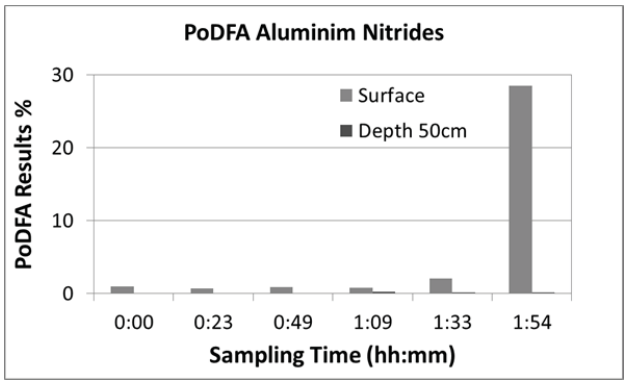
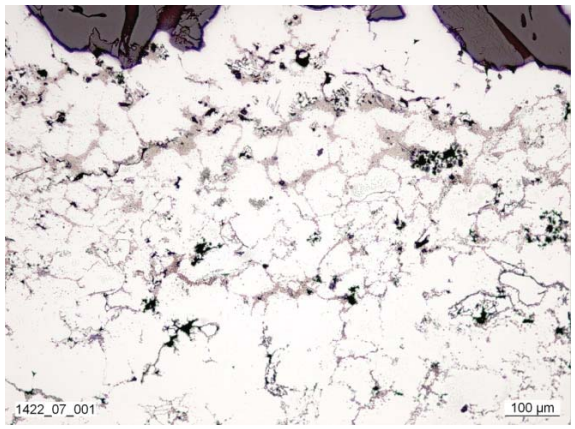
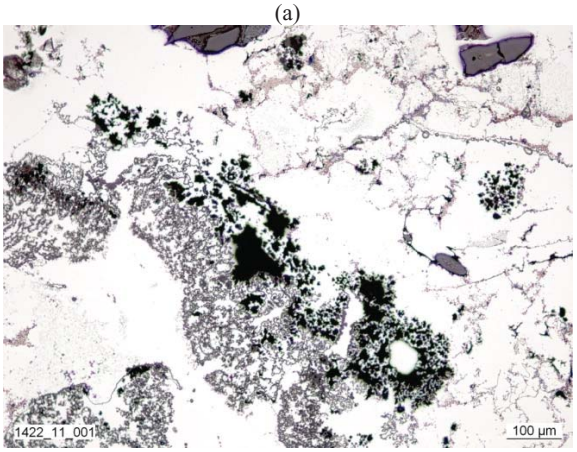



Figure 9. Aluminium nitride growth in the dross layer of an Al-5Mg alloy in electrically heated crucible furnace. An incubation period may be required for the formation of this phase.




(a)




(b)

Figure 10. PoDFA samples taken from the surface of the melt (a) 60 minutes and (b) 90 minutes after stirring. In micrograph (a) the dominant inclusions are oxides and borides. Micrograph (b) shows large Al-Mg-oxide clusters with embedded Aluminium-Nitride phases.

To conclude the experimental verification of the FST reference will again be made to the trial discussed in Figure **1**. This Al-3Mg charge was produced with a high content of recycled scrap as evidenced by the variety of inclusion types identified. In addition to the standard ladle sampling through the furnace door an early industrial prototype of the FST was used to sample the melt through the furnace door before casting but in this case at a depth of 50cm below the melt surface. These results are shown in Figure **11**. The correlation between the FST sample and the casting sample is very good both in terms of inclusion concentration and inclusion type. In this case it would clearly be preferable to sample the furnace using the FST rather than use the standard ladle sampling method.

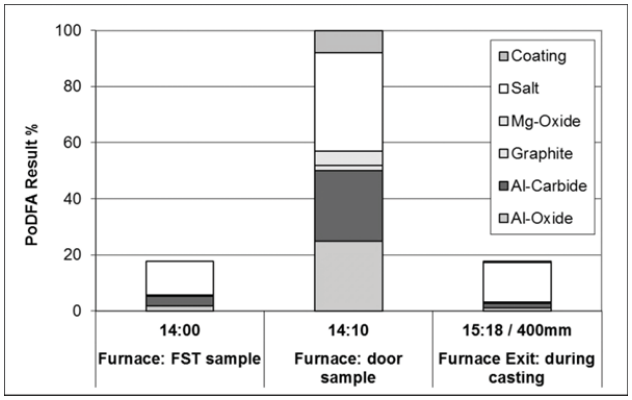



Figure 11. Repeat of Figure 1 but with the inclusion of the PoDFA results of the FST sample taken at a bath depth of 50cm. The correlation between the FST sample and the casting sample is very good both in terms of inclusion concentration and inclusion type.

## Conclusions

Equipment to enable the sampling of the melt within a melting or casting furnace in three dimensional space has been built and its functionality confirmed.

The equipment can be used to:

- obtain melt samples from various positions in a 3-D matrix within the furnace
- study the 3-D time dependent behavior of important processes occurring within the melt and reaction interfaces

Using standard PoDFA and Prefil analysis techniques the equipment can:

- Provide a rapid indication of the furnace melt quality with improved reproducibility compared to the previously employed ladle sampling technique
- Provide in depth analysis of inclusion concentration and type from various positions and depths within the bath and hence increase knowledge and understanding of critical furnace processes.

## Future Work

The next stage in the FST development process is to gain more experience in the use of the equipment under production conditions in additional cast houses. Initial work will be limited to using the FST to take samples in conventional single chamber casting furnaces but the aim is to expand its application to multi chamber furnaces and use this technique to investigate the effects of

- Forced convection in the furnace on particle generation, transformation and transport
- Increasing amounts and varieties of recycled scrap on furnace operations and melt quality. This is of increasing importance as the available volumes of post-consumer scrap are increasing and use of such raw materials is expected to positively influence financial performance of such furnaces.
- Key parameters influencing sludge formation and accumulation within the furnace
- Furnace treatments to remove inclusions and sludge – particularly important in light of the above mentioned market developments

This work should also provide important information to help refine furnace simulation models. These models are now important tools used to asses various aspects of furnace performance and provide insight into improvement potentials.

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