

State-of-the-art characterization tools for Al foundry alloys

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ABSTRACT

In this manuscript we review some characterization tools for Al foundry alloys. Castability is the ability of an alloy to be cast without formation of defects such as cracks, pores or misruns. Being able to measure, hence to control, these defects is fundamental and plays a critical role for the development of numerical models for castability. Also melt quality influences these defects formation. Alloy dependent phenomena that determine castability are, among others, fluidity and porosity. This manuscript focuses on the main characterization tools for measuring fluidity, porosity and melt quality.

RIASSUNTO

In questo lavoro, presentiamo alcuni dei metodi per la caratterizzazione delle leghe di alluminio per fonderia. La castabilità di una lega è definita come la sua abilità di essere colata senza la formazione di difetti, come cricche e pori. La possibilità di misurare, e quindi controllare questi difetti, è fondamentale ed è un passo critico per lo sviluppo di modelli numerici per prevedere la castabilità di una lega. Anche la qualità del fuso influenza questi difetti e la loro formazione. Aspetti della castabilità che dipendono dalla composizione della lega sono, per citarne alcuni, la fluidità e la porosità. L'attenzione di questo lavoro è dedicata a presentare e descrivere i principali strumenti per valutare la fluidità, la porosità e la qualità del fuso delle leghe di alluminio per fonderia.

KEYWORDS

Characterization, Al alloys, fluidity, porosity, melt quality.

INTRODUCTION

Castability is the ability of an alloy to be cast to a given shape with a given process without formation of casting defects [1, 2]. Alloy dependent phenomena that determine castability are fluidity, macrosegregation, hot tearing and porosity.

Being able to precisely measure alloy composition and casting defects plays a key role to quantify and control the casting product performances. Moreover, characterization tools for measuring these properties provide data for improving their modelling tools.

The modelling tools currently available need to be further improved. They do not have, for instance, modules for fluidity prediction/calculation. However, some attempts in this direction were recently carried out [3]. Stoppage criteria were based on dendrite coherency determinations. In this work the experimental data from fluidity measurements by spiral-shaped sand moulds were used to determine some key parameters for modelling, e.g., heat transfer coefficient and optimal mesh-size [3]. Furthermore, a model for porosity formation and growth based on micro-/macro-scale gas diffusion/transport in the melt, coupled with a model for feeding flows and pressured during solidification, is under development [4]. This modelling approach is intended to be valid for both gravity- and low pressure die castings. Experimental validation is essential for assisting and further developing the modelling tools. One of the major challenges to formulate a porosity criterion is to take into account the permeability in the interdendritic regions. Extensive investigations have been carried out in Norway at SINTEF/NTNU in order to measure permeability and elaborate a model to account for the variations in permeability with solid fraction and microstructure [5-7].

This paper will review properties such as fluidity and porosity as well as melt quality, and describe state-of-the-art characterization methods to measure them.

FLUIDITY

In the foundry, the term fluidity is used to indicate the distance a molten metal can flow in a mould of a constant cross-sectional area before it solidifies [8]. Fluidity is a complex technological property and it depends upon many factors [9] which can be categorized as follows:

- Metal variables: Chemical composition, Solidification range, Viscosity and Heat of fusion
- Mould and mould/metal variables: Heat transfer coefficient (coating), Mould and metal thermal

conductivity, Mould and metal mass density, Specific heat and Surface tension

- Test variables: Applied metal head, Channel diameter, Casting temperature (superheat) and Oxide/particle content

Reliable fluidity data for both pure and commercial aluminium foundry alloys are not readily available. However, such data are important in the optimization of mould filling calculations during solidification [10]. Fluidity testing can be carried out in different ways. Since the first fluidity test in 1902 [11], several equipments for fluidity testing have been developed and modified [12-14]. Currently, the most popular fluidity tests are the spiral-shaped mould test and the vacuum fluidity test. The former measures the length the metal flows inside a spiral-shaped mould. The latter measures the length the metal flows inside a narrow channel when sucked from a crucible by using a vacuum pump. Traditionally, the spiral test has been extensively used because it is compact and portable, and hence can be used easily in the foundry. Comprehensive reviews of the fluidity tests currently available have been recently presented [14]. The authors [14] also reports on the accuracy of these methods and compare both laboratory- and commercially available tests. Figures 1 and 2 show a schematic of a laboratory spiral test

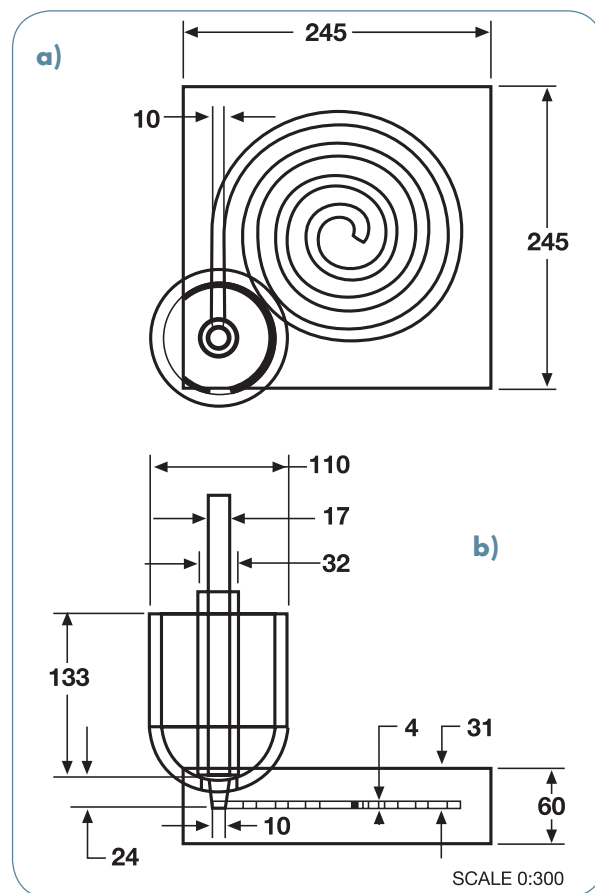


Fig. 1: a) Top and b) side views of the spiral-shaped fluidity test.

mould and commercial mould by N-Tec, respectively. The laboratory spiral test mould consisted of a pouring cup which is closed by a stopper. The stopper can automatically lift and open the gate when the melt in the cup achieves the selected temperature. This method allows for a good control of the casting temperature prior to enter the spiral-shaped sand mould (Fig. 1). The commercial fluidity mould consists of a permanent mould with five channels. It has a drag and cope (A and B in Fig. 2), a gating system split into two semi-cylinders (C), a Kalpur sleeve (D) held in place by a clamp ring (E), and a thermocouple (F). The total fluidity of the alloy is measured as the total volume of the melt that has entered the mould (i.e. the total volume of the five channels). Casting temperature and alloy chemistry are the major parameters affecting fluidity. Figure 3 shows the variation of fluidity with the alloy system [10] measured by the commercial N-Tec mould. Increasing the silicon content of the alloy will increase its fluidity with a maximum at around 17-18wt%Si. This is because primary silicon has a higher (approximately 4.5 times) heat of fusion than pure aluminium. Among the minor alloying elements, magnesium was found to decrease fluidity of the A356 alloys decrease the fluidity of the 356 alloys (6.6 wt% Si, 0.4 wt% Cu and 0.2 wt % Fe) whilst there was no significant influence of iron and titanium additions [9].

POROSITY

Porosity in a casting is attributed to both solidification shrinkage and high gas content. The inability of the liquid metal to feed through the interdendritic regions to compensate for the volume shrinkage during solidification causes porosity. The rejection of hydrogen gas from solution during solidification can also cause porosity. It is recognized that homogenous pore nucleation is not possible. Non-metallic inclusions and oxide films entrained in the liquid state influence porosity formation and mechanical properties in aluminium and its alloys [15, 16]. Understanding the mechanisms of porosity formation requires reproducible laboratory experiments where key parameters, such as hydrogen levels and melt quality, can be carefully controlled. Recently an investigation was made where the effect on porosity of two hydrogen levels (low and medium) were investigate on a step-mould

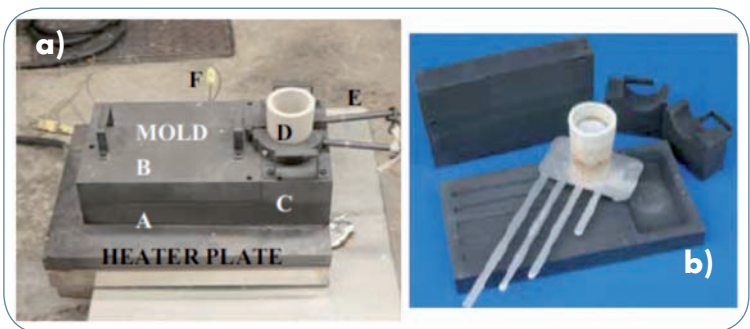


Fig. 2: a) Components of the commercial N-Tec fluidity mould (A- drag, B- cope, C- gating system split into two semi-cylinders, D- Kalpur sleeve, E-clamp ring, F- thermocouple); and b) view of the open mould with a fluidity test sample.

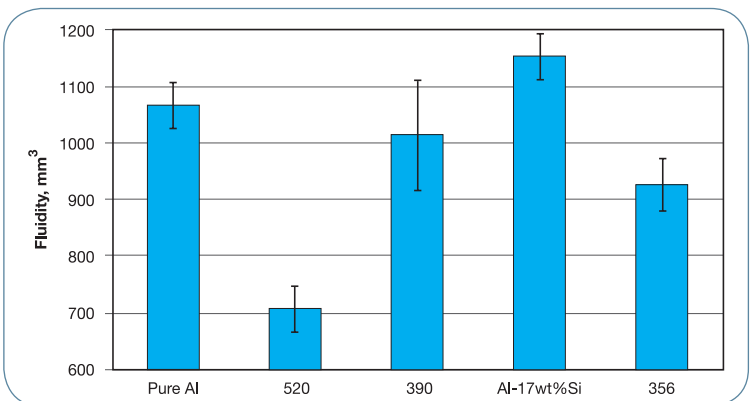


Fig. 3: Fluidity measurements as a function of alloy system measured by the N-Tec mould [10]. Comparison between pure Al, 520 (9.6 wt% Mg, 0.2 wt% Fe and 0.2 wt% Cu), 390 (16 wt% Si, 0.4 wt% Fe and 4 wt% Cu), Al-17wt%Si, and 356 (6.6 wt% Si, 0.2 wt % Fe and 0.4 wt% Cu) alloys.

die [17]. Also the effect of degassing and upgassing procedures on porosity levels was investigated. It was shown that the presence of oxides and inclusions, hence melt quality, has a more significant effect on mechanical properties and porosity than the hydrogen content [18]. The reproducibility of this experimental approach was assessed by repeating a series of two casting experiments under identical conditions on two different days. The relative reproducibility was measured to vary in the range 5-10% [17]. One of the most used methods to measure porosity is weighing the sample in air and water and calculating the density by Archimede's principle. The density of fully dense A356 alloy is estimated to be 2678 kg/m³.

A quantitative prediction of porosity requires the consideration of several effects on porosity formation, such as hydrogen content, pores number and -size, permeability etc. An extensive review of the research progress on porosity modelling can be found in [19]. The authors addressed the need for (i) a more accurate measure of the hydrogen solubility

in the eutectic, (ii) an improved model for the pore number density variations, and (iii) a better accuracy of the local finite-rate hydrogen diffusion sub-model. Figure 4 shows the porosity values measured in two different days (Day1 and Day2), and compare them with the predicted values (Simulation). The method used in this experiment to assess porosity is a permanent mould consisting of 5 channels of different cross section, more details about this porosity test method are given in reference [17].

Prediction of porosity defects in castings is important to prevent them and, hence, has a great economical benefit. Porosity on a macroscopic scale resulting from shrinkage during solidification can be avoided with the use of well-established practical rules. The formation of micro-pores dispersed within the dendritic structure constitutes a complex phenomenon which depends on the liquid metal feeding, shrinkage and gas segregation. The use of modeling tools for microporosity prediction in aluminum alloy system is hampered by the lack of physical data, such as mushy zone permeability, and the lack of careful experimental validation. Akhtar et al. [4] reported that microporosity simulation results were quite promising and there was good agreement between the measured and simulated microporosity distribution (Fig. 4).

MELT QUALITY

Aluminum casting industry is using significant amounts of primary, secondary and master alloys in order to produce high quality cast products. This quality depends on the quality of molten metal from which the products are cast. Comprehensive understanding of the melt quality is of vital importance for the control and prediction of the casting properties.

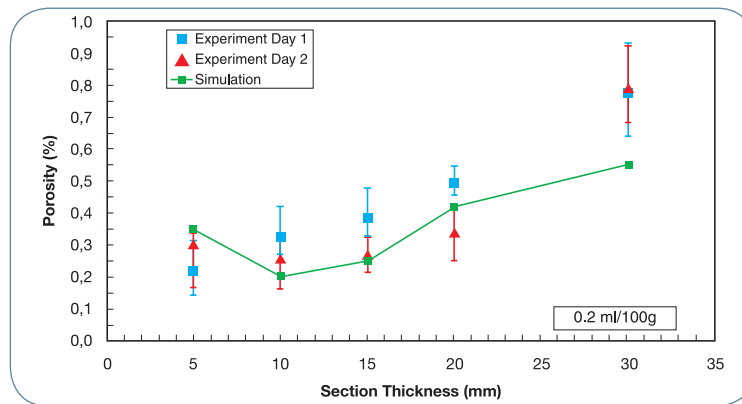


Fig. 4: Porosity (%) vs section thickness (mm) for hydrogen levels 0.2 ml/100 g melt. The porosity measurements carried out on castings made in two different days (Day1 and Day2) as well as the predicted porosity are shown.

Any defect added or created during the melting and transfer stages will appear in the final microstructure, and certainly, affect the quality of the cast products. There is no unique apparatus in the market that can be used for a complete assessment of the aluminum melt quality. Therefore, combinations of several equipments have to be used [20]. Some tools commonly used in aluminum casting plants are: (i) Reduced pressure test, (ii) Porous disc filtration apparatus (PoDFA) /Pressure filtration (PREFIL), (iii) Liquid metal cleanliness analyzer (LIMCA), and iv) ALSPEC Hydrogen (H). For daily melt quality control, aluminum casting plants normally use at least one of the above mentioned methods. In addition, a new concept for melt quality assessment has been presented and is called “*bifilm index*”. Some details of these methods are given below.

Reduced Pressure Test

It is well recognized that inclusions nucleate hydrogen porosity. In the reduced pressure test, the presence of inclusions will assist any hydrogen present to develop an exaggerated visualization of pores, which is evident when the sample is

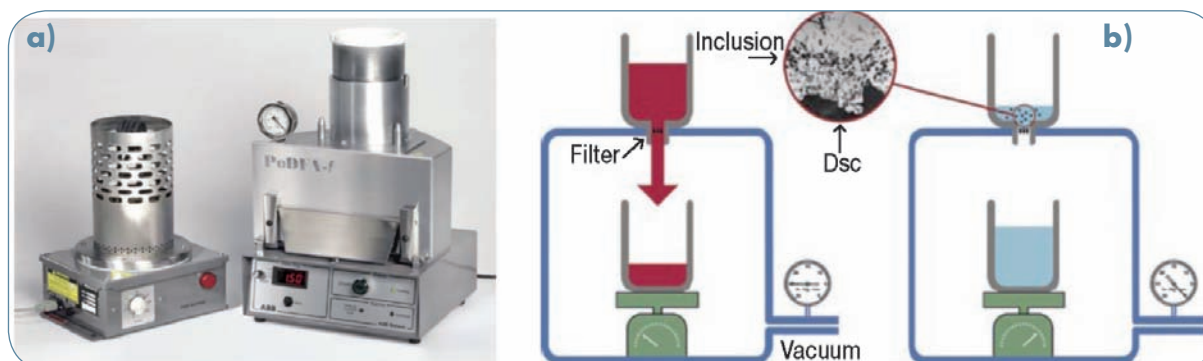


Fig. 5: a) PoDFA apparatus and b) schematic view of its principles of operation.

sectioned after solidification. The reduced pressure test (RPT) consists of taking a sample from the aluminum melt, let it solidify under vacuum conditions and then visually analyse a cross section of the sample. This is the most common method which many foundries use today, and it is becoming increasingly prevalent in diecasting industry as a simple means of evaluating metal quality. It provides a semi-quantitative measure of overall melt cleanliness, as well as the hydrogen content.

PoDFA/PREFIL test

PoDFA (Porous Disc Filtration Apparatus) and its successor PREFIL are equipments used for qualitative and quantitative evaluation of the melt cleanliness. Approximately 1.5 kg of the molten metal is poured into a preheated crucible which had a fine-grade test filter at the bottom as shown in Figure 5.

A vacuum is applied to cause the molten metal to flow through the filter. Any inclusion in the melt is then collected on the surface of the test filter. The metal cleanliness can then be determined by metallographic examinations of the “cake” area.

The working principle of PREFIL test is the same as previously described for the PoDFA test. Throughout the test, the system continuously weighs the metal in the weight ladle and displays a curve of the accumulated weight versus the elapsed time [20]. The cleaner the metal, the higher the slope of this curve. Inclusions in the metal, such as oxide films, quickly build-up on the filter surface during the test, reducing the flow rate through the filter. The slope and overall shape of the weight filtered versus time curve indicate the level of inclusions present in the metal. The metal residue above the filter can be saved for supplementary metallographic analysis. Typical PREFIL curves are shown in Figure 6.

Liquid Metal Cleanliness Analyzer (LIMCA)

LIMCA is an on-line technology, though its cost has limited its use in the foundry industry. The LIMCA is based on the principle of allowing liquid metal to pass through a small orifice in a tube which measures the voltage potential between two electrodes as shown in Figure 7. When an inclusion enters the orifice, it displaces liquid and creates a rise in electrical resistance. The subsequent voltage change observed can be correlated with the actual inclusion size and concentration. This information can be displayed on a computer screen

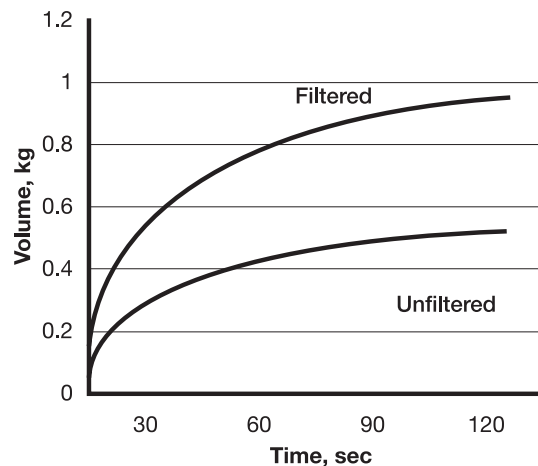


Fig. 6: Typical PREFIL curves for clean (filtered) and dirty (unfiltered).

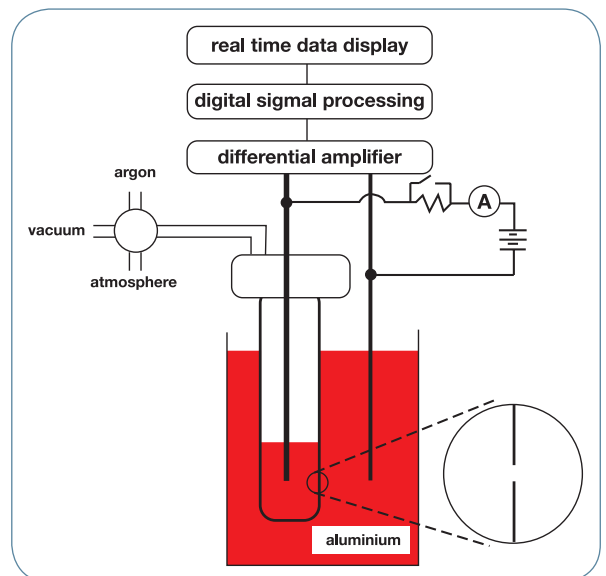


Fig. 7: Principle of operation of LIMCA.

[21]. The continuous measurement of inclusion size distribution provides a monitoring technique most useful for continuous flow processes such as in the launder.

ALSPEC Hydrogen (H)

The ALSPEK H (shown in Figure 8) is based on the electrochemical principle [22]. It is used to measure the total concentration of hydrogen in the melt and, hence, is an indirect measure of the melt quality. Fast and accurate spot measurements of hydrogen concentrations can be performed in ladles and furnaces, or the probe can be left immersed in one location to provide continuous real-time measurement of hydrogen levels. It is

also possible to carry out real-time hydrogen measurements during a degassing treatment. All measured values are automatically logged and can be downloaded later to provide important data for quality control and certification purposes.

Bifilm Index

The two important interactions that take place between an aluminum melt and its environment are the absorption of hydrogen and the formation of oxide films. It is impossible to prevent the formation of oxide on the liquid aluminum surfaces. The formation of the alumina oxide film is an important part of the melting process for the reason that it protects the metal from further oxidation. The problem occurs when an oxide film is entrained in the melt during foundry operations like charging, fluxing, and degassing, skimming, transferring, mould filling. The entrainment events are surface folding actions in which a non-wetting surface film is folded over against itself with gas trapped in between two halves. This is a defect that will act like a crack in the liquid and is known as double oxide film defect or *bifilm*. Campbell and Dispinar [23, 24] have thoroughly described this method. It consists of taking RPT (Reduced Pressure Test) samples and measuring the total length of the pores, which is expressed as the bifilm index:

$$\text{Bifilm Index} = \Sigma(\text{total pores length})$$

Figure 9 shows a sketch of the method, i.e. an RPT (Reduced Pressure Test) sample with colored pores which have been reassured to calculate the Bifilm Index. Recently Akhtar et al. [25] have used this method to assess and compare the quality of the different aluminum foundry alloys and found good agreement with other quality control methods.

CONCLUDING REMARKS

Significant progress has been made in the last decade in the understanding of castability of aluminium alloys. This understanding is being systematized in predictive models. Such models are still under development and needs reliable experimental data. Continued research must focus on:

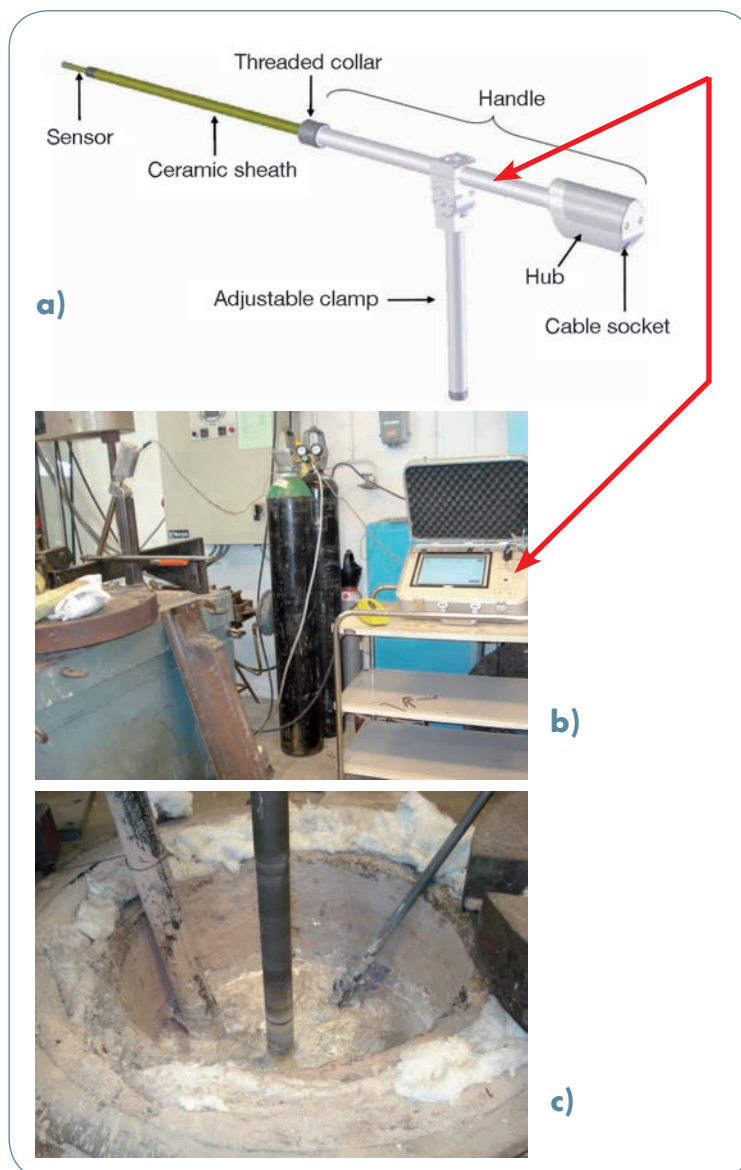


Fig. 8: a) Schematic view of ALSPEC H, b) control unit, and c) how it is used in the foundry to measure hydrogen. Concentration during melt treatment.

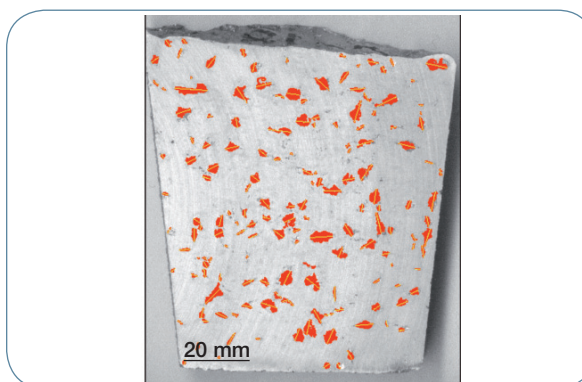


Fig. 9: Reduced pressure test sample with colored pores. The total length of the pores has been used to calculate the Bifilm Index.

- Improvements of the physical description of castability phenomena in order to improve the sophistication of the models
- Measurements of physiochemical and thermodynamic data, particularly mushy zone properties such as permeability and mechanical properties of semisolid metals
- Critical reproducible experiments and accurate measurement tools to validate the models
- Reproducible measurements and control of melt quality is of the key importance for high quality casting products.

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