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Hydrogen pick-up during mould filling in the lost foam casting of Al alloys

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Abstract In the Lost Foam casting of Al alloys the foamed polystyrene pattern is broken down by the heat of the advancing liquid metal as it fills the mould. This has led to discussion about the possibility of increased hydrogen pick-up by the liquid metal from the gaseous pattern degradation by-products accumulating at the liquid metal—foam pattern interface, leading to detrimental porosity in the final casting. The results presented here were derived from comparisons of the initial measured hydrogen content of the liquid Al alloy before mould filling, and the hydrogen content of the final castings, coupled with real-time X-ray imaging of the filling of the mould to determine whether entrainment of the foam pattern degradation by-products was occurring. This showed that increased hydrogen content in Al Lost Foam castings was attributable to the entrainment of degrading pattern material, and not due to increased absorption of hydrogen from the interfacial atmosphere.

Introduction

Lost Foam casting involves the use of a foamed polymer pattern (usually of polystyrene in the case of aluminium casting), coated with a thin permeable layer of refractory, placed in a moulding box filled with loose unbonded silica sand which is then compacted by vibration. Since the foamed pattern is not removed from the mould, but degraded by the heat of the cast liquid metal during mould filling, the design of the casting is freed from the constraints placed upon conventional casting processes such as sand and die casting, where there is a need to strip the pattern from the mould, or the casting from the die. However, in situ degradation of the pattern in the mould creates casting defects not experienced in conventional casting processes. These include misrun, if the liquid metal solidifies prematurely without filling the mould, and fold defects caused by carbon-rich films on advancing liquid metal fronts preventing their fusion. In the case of Al alloy castings the polystyrene pattern degrades partly to a vapour by-product but principally to a liquid by-product. Incorporation of these degradation by-products into the liquid metal results in porosity in the final casting. This paper examines the role of hydrogen pick-up by the liquid metal in causing porosity in the Lost Foam casting of Al alloys.

Wang et al. [1], using density measurements and image analysis to study pore size, observed that alterations in casting practise that affected the transport of gaseous degradation by-products had no effect on porosity, and inferred from this that porosity in Al castings was probably related to the entrainment of the liquid pattern degradation by-products. Guoha et al. [2] attributed porosity to a slower cooling rate in Lost Foam castings compared to conventional castings, resulting in a wider mushy zone, but also to the entrainment of liquid pattern degradation by-products, although no evidence for this was offered. Shin et al. [3] demonstrated that the hydrogen content of liquid Al alloy was increased in a laboratory experiment in which vapour degradation by-products were held in contact with the liquid metal for a length of time. In their casting experiments, the hydrogen content of liquid metal poured into a cup

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containing expanded polystyrene was measured using a reduced pressure test, an indirect test that would not have discriminated between genuine hydrogen-induced porosity, formed due to dissolved hydrogen in the liquid metal being rejected during solidification, and porosity formed due to the entrapment of foam pattern degradation by-products. To distinguish between different pore formation mechanisms SEM examination coupled with EDX analysis was used to detect carbon-rich residues in the pores. It was argued that high C values indicated porosity due to entrapment of liquid polymer by-products, low C values indicated porosity due to entrapment of gaseous by-products and no C indicated the formation of hydrogen-induced porosity. Their results were interpreted to suggest that all three causes of porosity could occur; entrapment of liquid degradation by-products (most pronounced at the advancing liquid metal tip), entrapment of gaseous degradation by-products, and increased hydrogen content in the liquid metal due to absorption of H from the local atmosphere at the metal front caused by the degrading polystyrene pattern.

Finally, Sun and Littleton used real-time X-ray radiography to study the mould filling process, and concluded that porosity was largely due to the incorporation of by-products from the decomposition of the foam pattern [4] (no hydrogen measurements were carried out). In their work, examination of the colour of the pore, supported by Auger analysis to obtain the C content, was used to infer that porosity was probably due to the entrapment of gaseous degradation by-products.

The results reported in this article aim to resolve the issue of the origin of porosity in Lost Foam casting of Al alloys, by a combination of direct measurement of hydrogen content in the liquid metal and the final castings and real time X-ray imaging of mould filling, a combination of techniques not previously used.

Experimental procedure

Two patterns consisting of vertically oriented foamed polystyrene plates, with dimensions 440 mm in length, 180 mm width and 10 mm thickness, were cast under controlled conditions using a counter-gravity mould filling technique. This allowed some control of the metal front velocity to be achieved, and hence some control over the amount of entrainment of the degrading foam pattern by-products.

Casting was carried out by placing a crucible containing 8 kg of liquid metal in a sealed cylindrical steel chamber, over which was placed a vertically oriented moulding box containing the foamed polystyrene plate pattern, with the mould consisting of loose unbonded silica sand compacted by vibration. The arrangement of the casting process has been shown schematically in Fig. 1. The density of the foam patterns used was 27 kgm^{-3}, and the moulds were cast with a Sr pre-modified 2L99 Al alloy (nominal composition Al–7Si–0.3 Mg), at a temperature of 785 °C.

Filling of the mould was achieved by pressurising the chamber with compressed air, forcing the liquid metal from

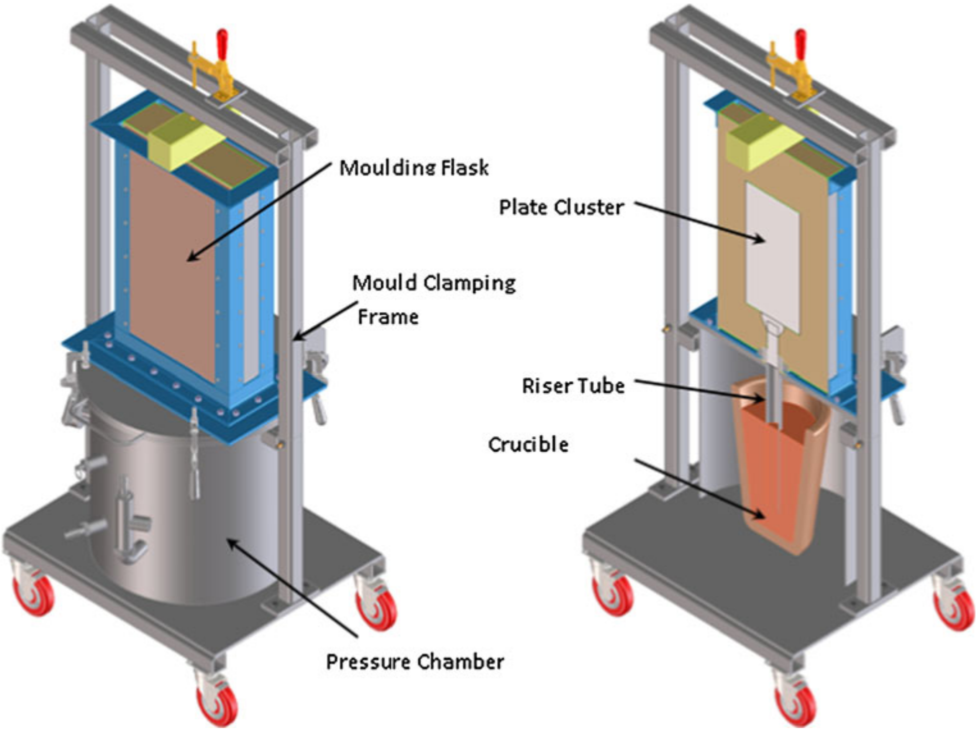

Fig. 1 Schematics showing the mould-filling arrangement for counter-gravity filling of Lost Foam castings

the crucible up a connecting tube to fill the vertically oriented plates from below. This was carried out inside a real-time X-ray machine, so that the advancing liquid metal front could be observed, and its velocity determined. In one experiment a velocity of approximately 5 mm s^{-1} was obtained, and this resulted in a planar advancing liquid metal front, with no entrainment of the decomposing pattern into the advancing liquid metal observed (see Fig. 2). In a second experiment, the pressure inside the steel chamber was increased to obtain a slightly higher velocity of 8 mm s^{-1}. This resulted in an alteration of the advancing liquid metal front morphology to produce a "fingering" effect (see Fig. 3), which was accompanied by the incorporation of degrading pattern material into the liquid metal. (The reasons for this fingering effect are thought to be caused by an interfacial instability, as has been discussed elsewhere [5, 6]).

The initial hydrogen content of the liquid metal before mould filling was sampled by casting into a steel mould, while the hydrogen content of the cast plates was determined from three samples taken from each plate, one from just above the ingate, one from a height one-third of the way up the plate, and one from a height two-thirds of the way up the plate (i.e., about 150 and 300 mm from the ingate, respectively). The hydrogen content of these samples was measured using the Inert Gas Fusion

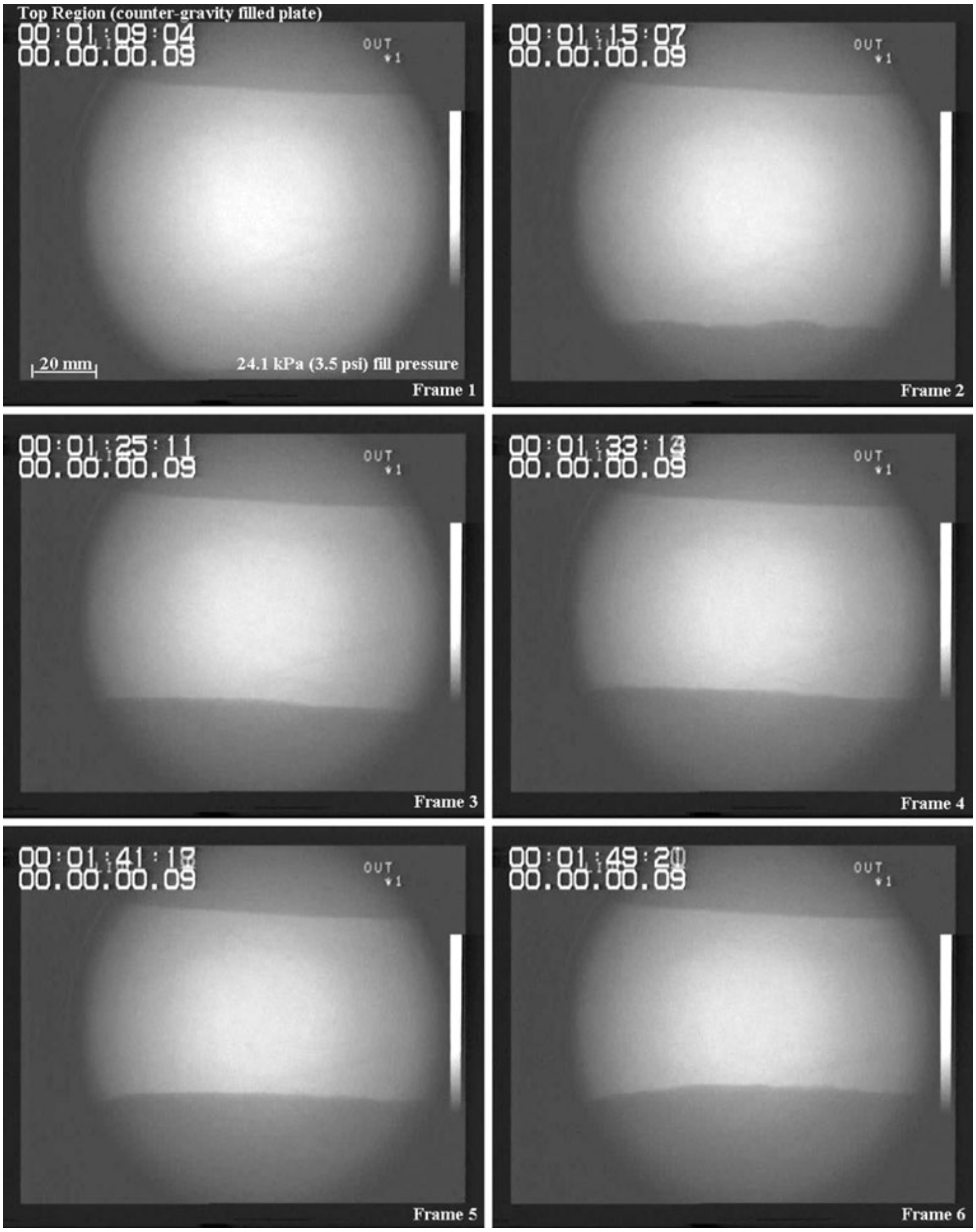

Fig. 2 X-ray images of the advancing metal front with velocity of 5 mm s^{-1}, showing a planar liquid metal-pattern interface

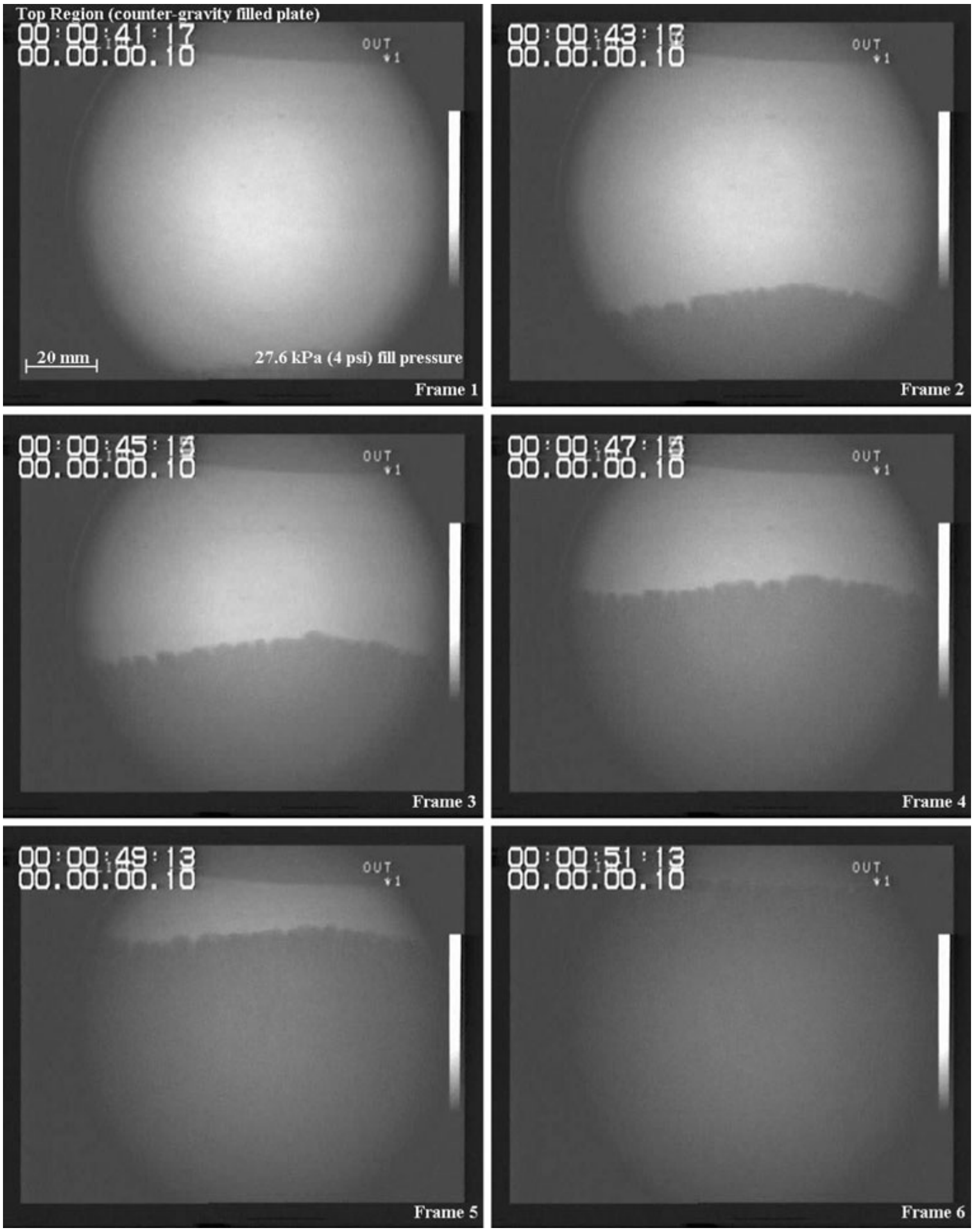

Fig. 3 X-ray images of the advancing metal front with velocity 8 mm s^{-1}, showing a nonuniform liquid metal-pattern interface

technique[1] by Sci-Lab Analytical Ltd. (Chester, UK). Two measurements of hydrogen content were made on each sample.

Results

The initial hydrogen content of the melt used to cast the plate at 5 mm s^{-1}, with the planar advancing metal front (shown in Fig. 2), was 0.41 ppm (see Fig. 4a for a summary of H content). This may be considered rather high, but may be expected considering the higher pouring temperatures required for Lost Foam casting. The hydrogen contents of the final plate casting, were measured to be 0.38 ppm near the ingate, 0.50 ppm in the central region of the plate, and 0.33 ppm in the upper part of the plate, giving a mean hydrogen content of 0.43 ppm, very similar to the initial hydrogen content of the metal cast. This suggested little or no hydrogen had diffused into the liquid metal during mould filling, as the foam pattern degraded. Figure 4b shows a fracture surface of a tensile test bar from the plate filled at 5 mm s^{-1}, which had some small regions of porosity.

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[1] http://www.lecouk.com.

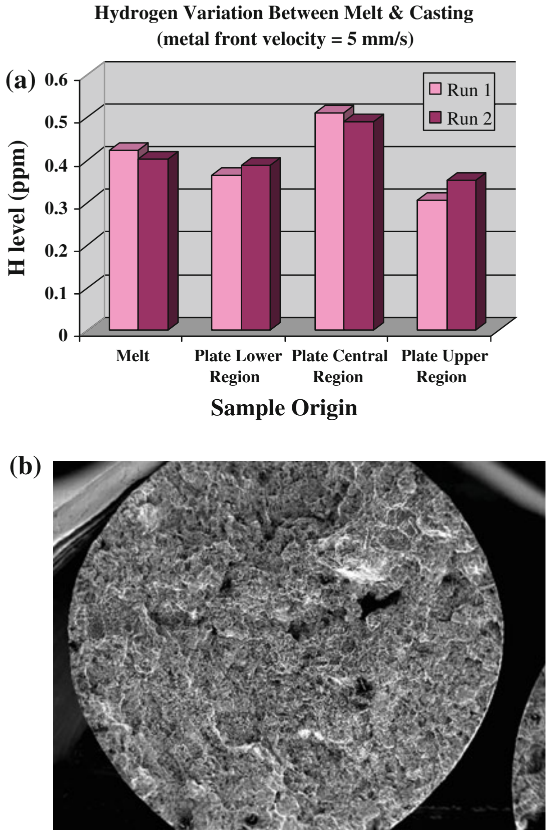

Fig. 4 **a** Hydrogen content of the melt and the casting made with a filling velocity of 5 mm s^{-1}. (Run 1 and Run 2 refer to two different hydrogen measurements carried out on the same sample). **b** Example of a fracture surface of a test bar taken from the cast plates filled with a metal front velocity of 5 mm s^{-1}. The diameter of the test bar was 6.75 mm

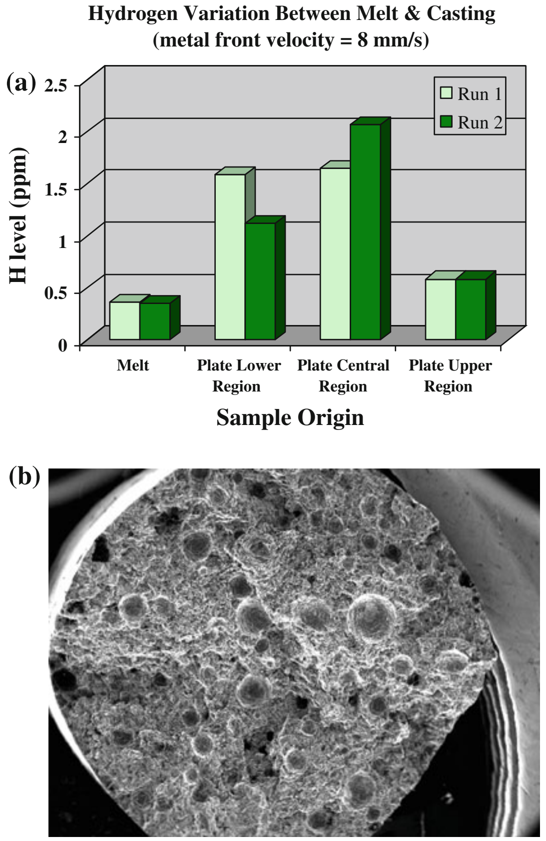

Fig. 5 **a** Hydrogen content of the melt and the casting made with a filling velocity of 8 mm s^{-1}. (Run 1 and Run 2 refer to two different hydrogen measurements carried out on the same sample). **b** Example of a fracture surface of a test bar taken from the cast plates filled with a metal front velocity of 8 mm s^{-1}. The diameter of the test bar was 6.75 mm

The initial hydrogen content of the melt used to make the plate with a metal front velocity of 8 mm s^{-1} was determined to be 0.36 ppm. During filling, perturbations were observed on the advancing metal front which were about 4 mm in length and had a wavelength of about 5 mm (see Fig. 3). The mean hydrogen content of the cast plate was measured to be 1.36 ppm in the region above the ingate, 1.86 ppm in the central region, and 0.585 ppm in the upper region of the plate, giving a mean hydrogen content of 1.27 ppm (summarised in Fig. 5a. The measured hydrogen contents in the lower and central regions of the plate were therefore considerably higher than the value of the maximum solubility of hydrogen in liquid pure aluminium, 0.69 ppm [7]. These high hydrogen contents must therefore be due to the entrapment of H-rich foam pattern degradation residues, entrained in the liquid metal due to the nonuniform nature of the advancing metal front during filling. The fracture surfaces of test bars taken from these regions revealed numbers of spherical porosity defects (see Fig. 5b).

The pores on the fracture surfaces from both castings were examined in an SEM using EDX to determine their carbon content, with analyses also taken at the adjacent matrix, free of porosity. Figure 6 shows that the EDX results suggested carbon was to be found in all of the pores examined, but also in the surrounding matrix as well, where the amount measured could be the same as in a neighbouring pore, although such large amounts of carbon were not expected in the matrix. Also, there was little difference in the amount of C in the results obtained from the two plates. Since traces of hydrocarbons are not uncommon contaminants in the atmosphere of an SEM, these results suggest that the detection of carbon may not be a good indicator of the origins of pores, whether due to hydrogen precipitation or entrapment of degrading pattern material.

Discussion

The results showed that when the advancing metal front was sufficiently slow (~5 mm s^{-1}) a planar liquid metal front was obtained, and the hydrogen content of the final casting was comparable with the initial hydrogen content of the

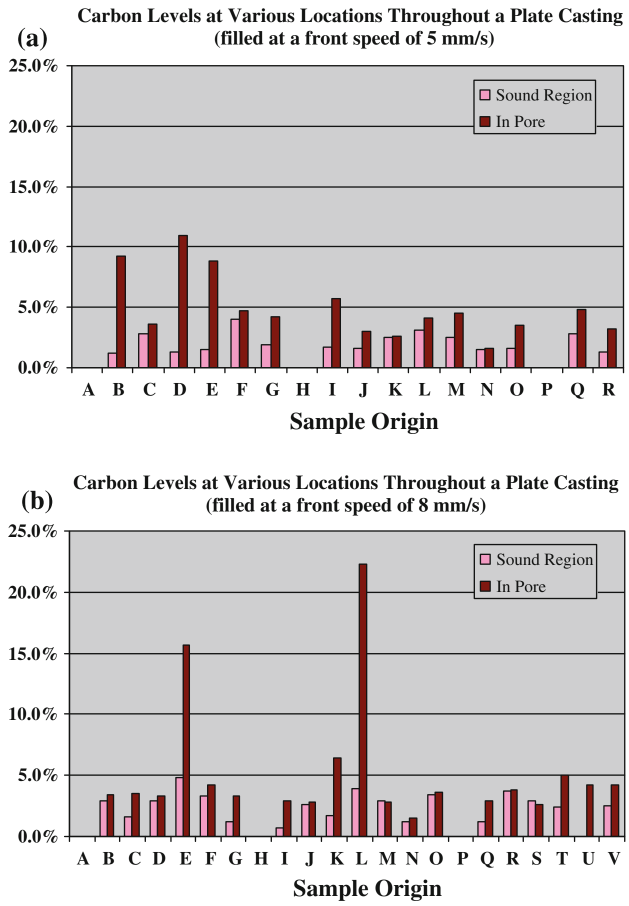

Fig. 6 Results of carbon determinations in pores and of the matrix material, (denoted Sound Material). The lettering of the Sample Origin refers to increasing height above the ingate. **a** plate cast at 5 mm s^{-1}. **b** plate cast at 8 mm s^{-1}

metal from which it was made. When the velocity of the liquid metal front was such that an irregular metal front was obtained (at ~8 mm s^{-1}), examination of the mould filling using real-time X-ray showed this was associated with entrainment of degrading pattern material, and the hydrogen content of the final casting was greatly in excess of the original hydrogen content, and could even be in excess of the maximum solubility of hydrogen in the alloy. Excessive hydrogen and large amounts of porosity in Lost Foam castings should therefore be attributed to entrainment of the degrading pattern material, probably in liquid form (since in Al casting liquid degradation by-products are principally formed), rather than diffusion of hydrogen from the metal-pattern interface into the liquid metal. In any event, hydrogen rejected during solidification would probably preferentially diffuse into a pre-existing pore formed by entrapped degrading pattern material, rather than forming a new pore.

Since a film of aluminium oxide on the surface of liquid Al is known to act as a barrier to the absorption of hydrogen [8, 9] it is presumably the case that hydrogen will pass with ease into the liquid metal from the surrounding environment only when its surface oxide film is ruptured during flow. That hydrogen is not so readily absorbed by the liquid metal in Lost Foam casting may therefore be due to the much slower velocity during mould filling. In conventional casting, the velocity of the liquid metal may be up to about 2.5 ms^{-1}, about 500 times greater than in the case of the mould filling examples shown in Figs. 2 and 3. This slower filling velocity in Lost Foam casting may result in a thicker oxide film on the surface of the advancing liquid metal, reducing the extent to which ruptures in the film may allow the ingress of hydrogen from the metal-foam pattern interface into the liquid metal. However, in the case of Mg, or Al–Mg alloys, where the surface oxide film may be expected to be porous MgO, greater hydrogen diffusion from the degrading pattern into the liquid metal may then occur.

Conclusions

Increased hydrogen content, and increased porosity of Al alloy Lost Foam castings has been shown to be due to the entrainment of degrading pattern material (probably in a liquid form), rather than due to increased absorption of hydrogen into the liquid metal from the degrading pattern with its subsequent precipitation of hydrogen porosity during solidification.

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