Hydrogen gas pick-up mechanism of Al-alloy melt during Lost Foam Casting

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The hydrogen gas pick-up problem that can occur during Lost Foam Casting was investigated with reduced pressure tests and real castings.

The initial hydrogen concentration of the melt and the contact time between melt and polystyrene had a main effect on the hydrogen gas pick-up of Al melt. The hydrogen gas pick-up of Al alloy depended also on pouring temperature and a proper metal front temperature gave the minimum hydrogen pick-up. At a low pouring temperature, the hydrogen went into the melt mainly from entrapped liquid product of polystyrene but at high pouring temperature it was by the gas as well as the liquid product. The mold flask evacuation down to 710 torr decreased the gas porosity down by around 0.4 vol%. The permeability of coating thickness had a great effect because it affects the filling time and the easy removal of liquid polystyrene. © *2004 Kluwer Academic Publishers*

1. Introduction

The application of Lost Foam Casting (LFC) is increasing worldwide as it can make complex shaped castings in one step and requires no sand binders resulting in cost savings and less environmental problems. Although LFC has a high production cost per kg casting it can save cores, finishing and assembly costs. LFC has been used mostly to cast Al alloy automobile parts, such as intake manifolds, brake pump housings, cylinder heads, engine blocks, etc. The polystyrene used for LFC pattern consists of 92 wt% C, 8 wt%H [1]. The C_6H_5 Benzene ring in polystyrene is relatively stable and $-CH=CH_2-$ chain tends to decompose first. The benzene ring remains as liquid phase and reacts with melt causing casting defects. The copolymer of PS (Polystyrene) and PMMA (Polymethylmethacrylate) was developed to reduce the carbon related defects in ferrous castings [2, 3]. PMMA decomposes mostly into gas phase, like 80% at 700°C while PS only 40% at 700°C [4]. Both polymers, PS and PMMA, have many carbon and hydrogen atoms but PS seems to do more harm in terms of casting defects because it decomposes more into liquid phase. The reaction between alloy melt and liquid polymers can be more intensive producing more concentrated reaction products causing casting defects.

As Al-melt has a high solubility of hydrogen the hydrogen atoms in the gas or liquid phase of decomposed polymers can diffuse into Al melt, which can cause hydrogen gas pores in castings. However there seems to be no systematic work on this hydrogen pick-up during Lost Foam Casting of Al alloys. Therefore, the hydrogen gas pore formation behavior during LFC of Al alloy was investigated in this study.

2. Experimental details
2.1. Reduced pressure test and hydrogen content calculation

Reduced pressure test was used to investigate the hydrogen gas content after the reaction of Al-alloy melt with polystyrene. A schematic of the test apparatus is shown in Fig. 1. Sample was poured in the preheated stainless steel cup with 1 mm thickness, which had 170 cm³ volume and was coated with BN powder to around 0.2 mm thickness. The prepared mold was placed in the chamber and varying amounts of Expanded Poly Styrene (EPS) piece were inserted into the cup. Al-alloy (A356) melt of about 100 g (37 cm³) was poured into the cup. The glass cover was then closed and the chamber was evacuated immediately down to the optimal reduced pressure, which gave reproducible and consistent hydrogen gas content for the same melt [8]. The optimal pressure was determined by trial and error and it was selected to be 260 mmHg for the hydrogen levels of the samples investigated. At an optimal pressure the sample should have low open porosity to prevent bubbles escaping from the sample but also

❶ glass cover
❷ stainless steel cup
❸ vacuum chamber
❹ insulating block
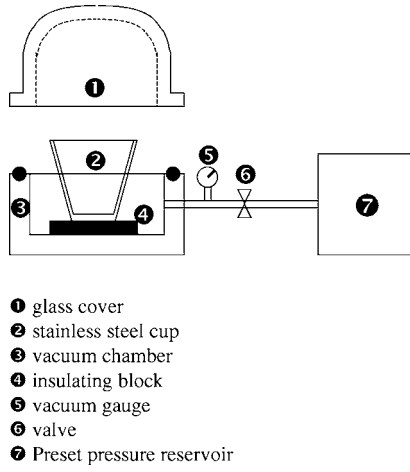❺ vacuum gauge
❻ valve
❼ Preset pressure reservoir

Figure 1 The schematic apparatus of reduced pressure test set.

sufficient porosity to measure the hydrogen gas volume with a high accuracy. The optimum porosity range for reduced pressure test samples was about 7 to 20 vol% [8]. The time to reach the final set pressure was about 5 s and the solidification time of the melt in this cup was about 8 min. The gasification of EPS seemed to finish in several seconds after pouring melt into the cup with EPS.

The bulk density (ρ_b) and the total porosity including open pores of specimens were calculated by Equations 1 and 2 respectively:

$$\rho_b = \frac{W_d \times \rho_w}{W_s - W_b} \ (\text{g/cm}^3) \qquad (1)$$

$$\text{Porosity in vol.\%} = \left(1 - \frac{\rho_b}{\rho_{th}}\right) \times 100 \qquad (2)$$

where W_d = dry weight, W_b = suspended weight in water, W_s = weight with open pores filled with water (wetted weight), ρ_{th} = theoretical density of A356 alloy = 2.658 g/cm^3, and ρ_w = density of water.

The hydrogen content of the melt, C_H, was then obtained from the Equation 3 using the density results assuming that all pores are 100% hydrogen pores formed at the solidus temperature and under the ambient pressure [5–7].

$$C_H[\text{ml H}_2/100 \text{ g Al}] = \frac{P_2}{P_1} \times \frac{T_1}{T_2} \times 100 \times \left(\frac{1}{\rho_b} - \frac{1}{\rho_{th}}\right) \qquad (3)$$

where P_2 = the pressure during solidification, (here 260 mmHg), P_1 = 760 mmHg, T_2 = the alloy solidus temperature in °K, and T_1 = 273°K.

The errors in measuring bulk density ρ_b and hydrogen concentration C_H were calculated by Equations 4 and 5 obtained by differentiating Equations 1 and 3.

$$\begin{aligned} d\rho_b = & \left|\frac{dW_d \times \rho_w}{W_s - W_b}\right| + \left|\frac{d\rho_w \times W_d}{W_s - W_b}\right| \\ & + \left|\frac{W_d \times \rho_w \times dW_s}{(W_s - W_b)^2}\right| + \left|\frac{W_d \times \rho_w \times dW_b}{(W_s - W_b)^2}\right| \end{aligned}$$
$$(4)$$

$$dC_H = \left|\frac{P_2}{P_1} \times \frac{T_1}{T_2} \times 100 \times \frac{d\rho_b}{\rho_b^2}\right| \qquad (5)$$

The error estimation is shown in Table I. The error depends on the accuracy of the scale, the density variation of the water with temperature and the diameter of the wire to hold the sample in water and the wetted degree of water in measurement of wetted weight. Here, $d\rho_w$, the error of water density has the biggest impact. By measuring the water temperature each time the error in bulk density could be maintained within 0.0015 g/cm^3. Usually, the errors of hydrogen concentration were around 0.0028 in Reduced Pressure test specimen.

Another test apparatus (Fig. 2a) was used to investigate the effect of the reaction of the melt with the formed gas only from the decomposition of EPS. Two variation of the test were:

(1) Partial decomposition in the flask: EPS was partially decomposed in a quartz flask at temperature of 650°C and 700°C until transparent liquid residue was collected at the bottom as shown in Fig. 2b, during which the formed gas flowed into the melt. Reduced Pressure test was then performed with this melt.

(2) Complete decomposition in the flask: The decomposed gas was allowed to flow through the melt until the liquid residue turned into black carbon and then Reduced Pressure test was performed with the melt.

2.2. Lost Foam Casting

The test casting shown in Fig. 3 (Test Casting-T) was made by Lost Foam Casting to examine the hydrogen gas pick-up in a real casting. The foam pattern for Test Casting-T had three legs of different

TABLE I Error estimation in bulk density and hydrogen concentration of reduced pressure test specimen

$\frac{\rho_w}{W_s - W_b}$	$\frac{W_d}{W_s - W_b}$	$\frac{W_d \times \rho_w}{(W_s - W_b)^2}$	$\frac{W_d \times \rho_w}{(W_s - W_b)^2}$	Typical values:
0.023	2.454	0.056	0.056	$W_d = 106.5118$ g
dW_d	$d\rho_w$	dW_s	dW_b	$W_s = 106.7027$ g
0.001	2.6×10^{-4}	0.01	0.005	$W_b = 63.2982$ g

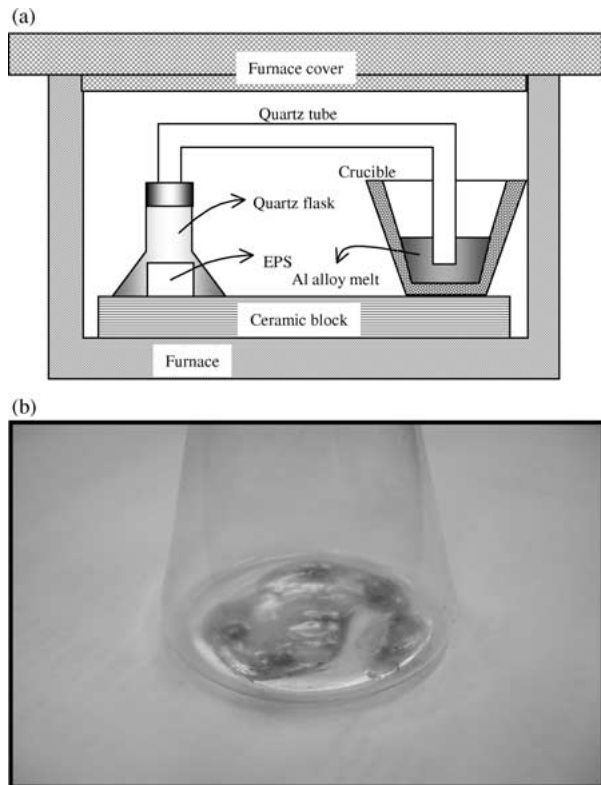| $\frac{dW_d \times \rho_w}{W_s - W_b}$	$\frac{d\rho_w \times W_d}{W_s - W_b}$	$\frac{W_d \times \rho_w \times dW_s}{(W_s - W_b)^2}$	$\frac{W_d \times \rho_w \times dW_b}{(W_s - W_b)^2}$	Total $d\rho_b$ [g/cm^3]
2.29×10^{-5}	6.38×10^{-4}	5.64×10^{-4}	2.82×10^{-4}	0.0015
	$dC_H = \frac{260 \text{torr}}{760 \text{torr}} \times \frac{273°K}{828°K} \times 100 \times \frac{(0.0015)}{(2.449)^2}$			dC_H [ml H$_2$/100g Al]
				0.0028

Figure 2 (a) The schematic apparatus to introduce the gas product of EPS into Al-melt and (b) the liquid product of EPS remained in the flask after initial decomposition of EPS.
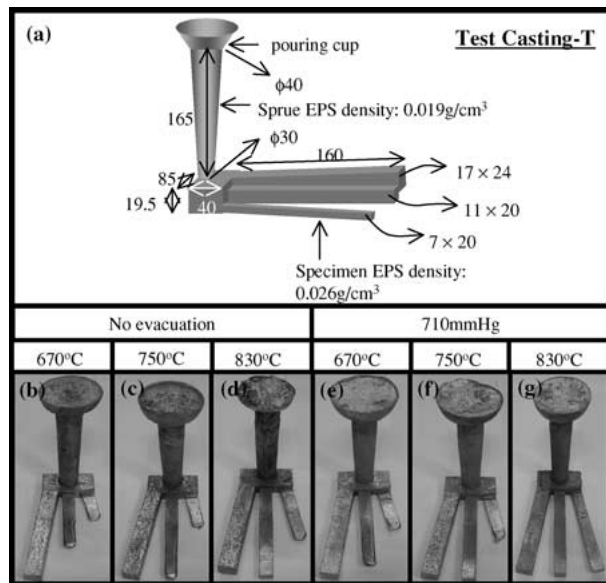

Figure 3 (a) The shape of the test casting-T by lost foam casting (unit: mm); (a) Dimension of casting; (b)–(g) shape of each casting under various casting conditions.

thickness (17, 11, 7 mm), which were glued to the sprue base. It was coated with a commercial coating material (EBACOTE) with a thickness of about 0.18 mm, which was determined by weight measurement. The coated pattern was dried and placed in a flask and compacted with un-bonded sand by vibration to get sufficient strength of the sand mold. The upper part of the flask was sealed with a vinyl foil to inhibit the leakage of vacuum. Al-alloy (A-356) melt was then poured into the pouring cup on top of
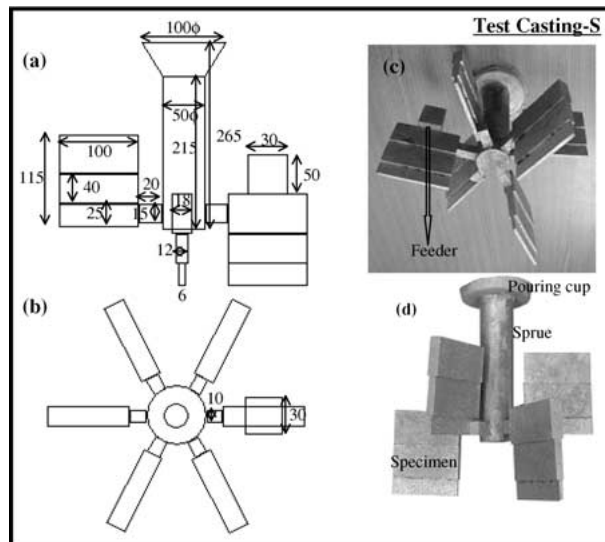

Figure 4 The shape and dimension(unit:mm) of the step test casting-S with 6 stepped plates, 3 of them with top gating and 3 of them with bottom gating; (a) side view, (b) top view; photographs of the casting: (c) view from bottom, (d) view from side.
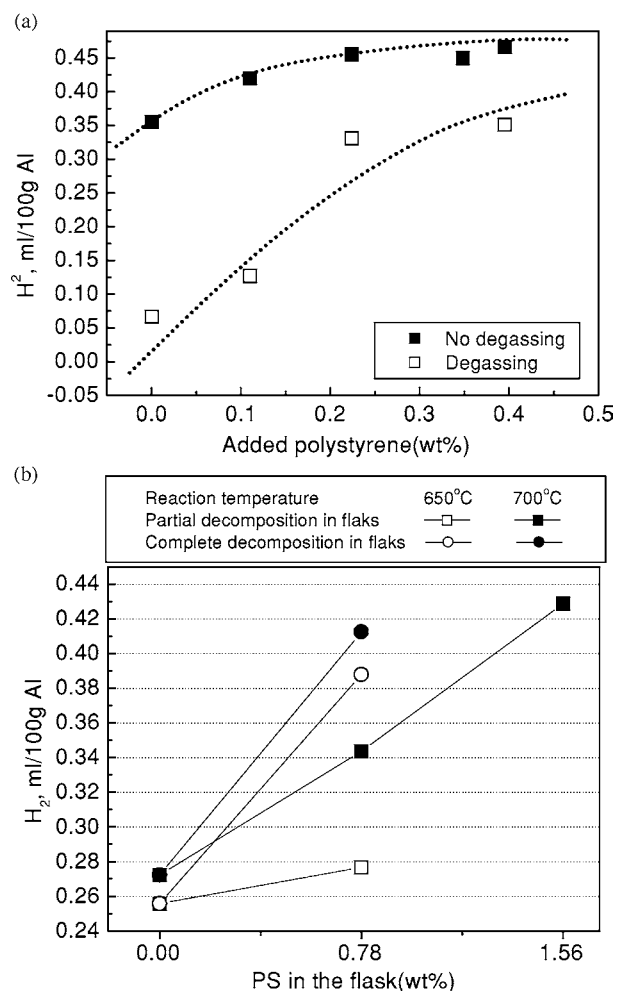

Figure 5 (a) The Effect of the amount of polystyrene reacted with the melt on the hydrogen pick-up for Al-alloy (A-356) melt with different initial hydrogen content; pouring $T = 710°C$. (b) The effect of the reaction with only the gas phase of decomposed EPS.

the foam sprue at various pouring temperatures. In the case of mold evacuation, the absolute pressure of 710 mmHg was maintained in the flask during solidification.
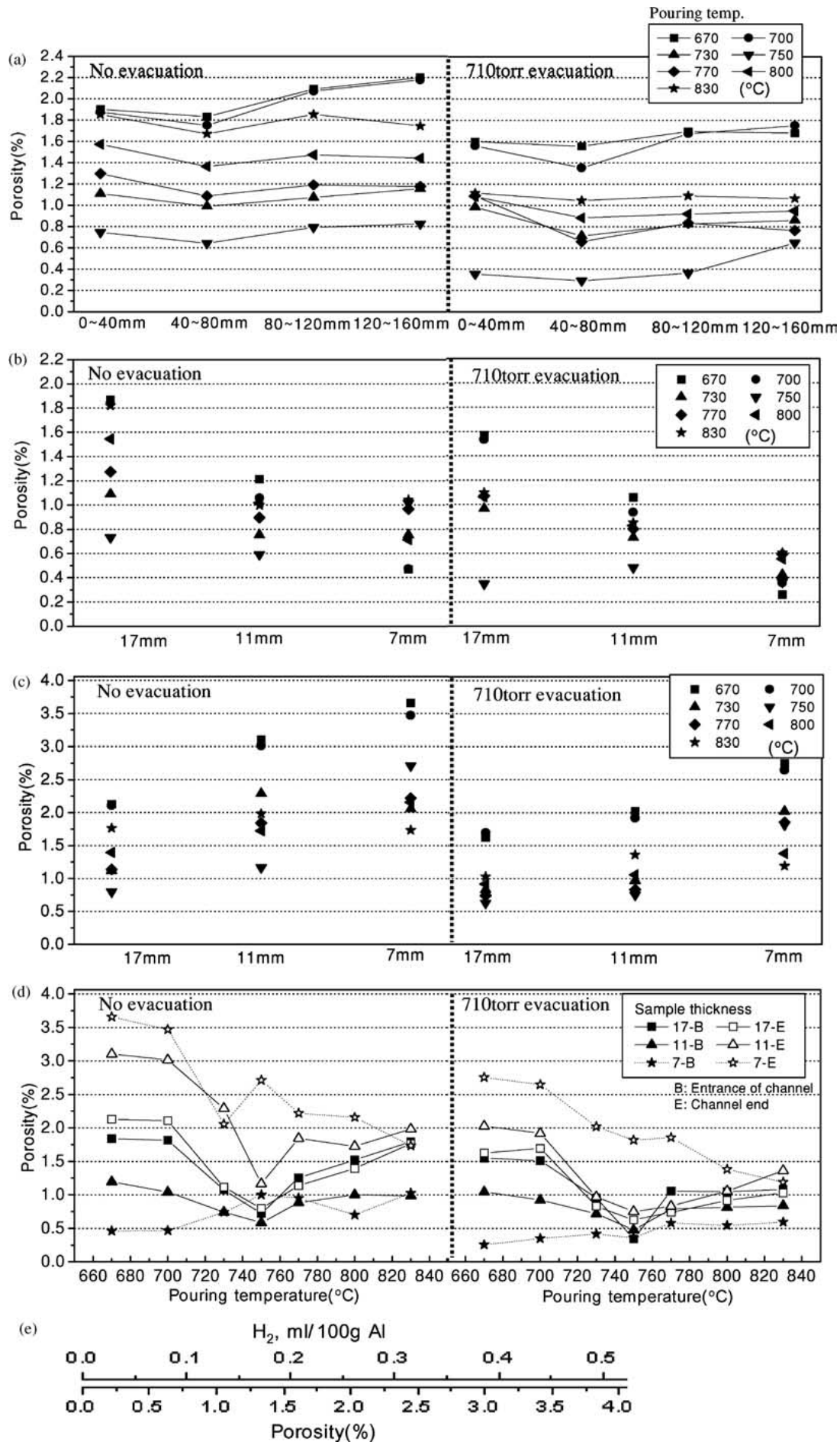
Figure 6 (a) Total porosity variation with pouring temperature and evacuation in the 17 mm thick leg of test casting-T, (b) porosity variations in initial part (0–40 mm) of each channel, (c) porosity variations in the end part of each channel, (d) porosity of the three channels in the beginning(-B) and end (-E) part vs. pouring temperature, (e) comparison of the scale between porosity and hydrogen content.

EDS analysis was performed in gas pores on polished specimens of Test Casting T to investigate the pore formation mechanism.

The effect of filling direction (upward filling and downward filling by arranging some of the plates above the ingate and some plates below) was also investigated with the Test Casting-S shown in Fig. 4. The whole pattern assembly was coated with refractory slurry to 0.12 or 0.21 mm thickness. The mold evacuation was applied for this test.

3. Results and discussion
3.1. The effect of reacted amounts of EPS with the melt

Fig. 5a shows the hydrogen concentration as a function of polystyrene weight reacted with melt at two different initial hydrogen contents. The high hydrogen concentration of the melt of about 0.35 ml/100 g Al was reduced to about 0.08 ml/100 g Al after degassing by Ar gas with flow rate of 5.0 l/min for 30 min [9]. The hydrogen concentration increased with increasing amount of EPS. The increase is more severe when the initial hydrogen level is low, which is the result of the increased driving force for hydrogen dissolution. Fig. 5b shows the results of the reaction with only gas phase of the decomposed EPS. The EPS weight in the quartz flask was varied to have the same volume (0.78 wt%) or the double volume (1.56 wt%) as the melt. The flask with EPS was put into the furnace beside the melt crucible. The partial and complete decomposition times were about 5 and 10 s respectively. The reaction with only the gas phase can cause hydrogen pick-up and hydrogen concentrations increased with the amount of EPS or reaction time. It is shown that the gas products of EPS alone can also cause the hydrogen gas pick-up, although it was believed that the gas defects of Al casting in LFC could be affected by liquid products of polystyrene [10].

3.2. Hydrogen gas pick-up during actual Lost Foam Casting

Fig. 6a shows the porosity distributions in the sample legs with the large cross section (17×24 mm) at various pouring temperatures. The minimum porosity of about 0.3 vol% was obtained at pouring temperature of 750°C with evacuation. Porosities of all samples had somewhat increasing tendency as the sample position approached the channel tip. The evacuation decreased the porosity of all sample generally around 0.4%. Fig. 6b–c show the porosity of the entrance and the end part of the three channels (thickness 17, 11, 7 mm) of test casting-T. As the casting thickness increased, porosity increased in the entrance part of the channel because of long solidification time (Fig. 6b). However the porosity in the end of the channel increased as the thickness decreased (Fig. 6c). Fig. 6d shows the porosity of the beginning part (-B) and end part (-E) of the three channels. There is a optimal pouring temperature for each thickness to obtain minimum porosity. For channels with thickness of 17 and 11 mm, 750°C gives minimum porosity, while for the thin (7 mm) channel the
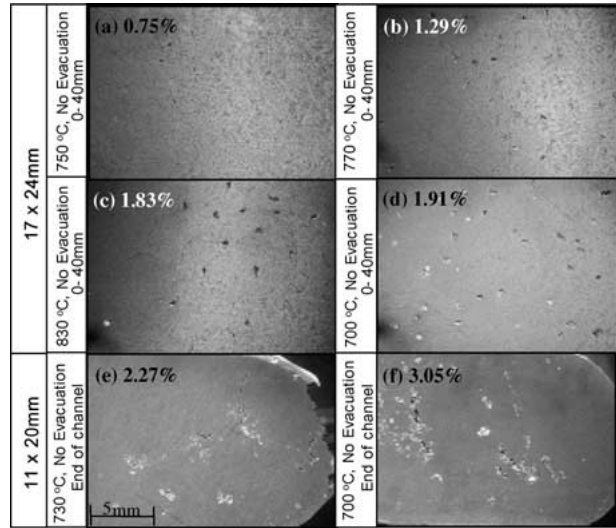

Figure 7 Photographs showing the distribution of gas-pores in section with different porosity %.

optimal temperature seems to be higher such as 800°C. It seems that there is a optimal metal front temperature that gives the minimum porosity in castings. Too high melt temperature will increase the hydrogen pick-up and prolong the solidification time, resulting in a higher porosity. On the other side, too low melt temperature will cause more liquid decomposition product and entrap liquid polymers, which will cause large pores. The mold flask evacuation decreased the porosity in all cases. Fig. 6e shows the comparison of the scale between porosity and hydrogen content assuming all pores were formed by hydrogen.

Fig. 7 shows the photographs of polished sections of the cast samples with different levels of porosity. Samples with a porosity as assessed by density, less than 0.7% showed no appreciable pores (Fig. 7a) and the samples with a porosity larger than 2% were all from the flow tips, most distant from the ingate, showing large pores (Fig. 7e–f). Samples with a porosity between 1 and 2% showed typical round gas pores. Large pores and open pores at the flow tip seemed to be formed from the gasification of captured liquid polymer [10].

In order to know if the gas pores originated from entrapped liquid polymer or supersaturated hydrogen, the pore surface was analyzed for carbon content. Fig. 8 shows the carbon concentrations on pore surfaces. In 17 mm-thick samples, the maximum carbon concentration was around 8 wt% in samples cast at 700°C and decreased down to around 3 wt% at pouring temperatures of 750 to 830°C. Many of the pores showed almost no carbon, comparable to the concentration measured on the polished matrix surface. The flow tip of 11 mm- or 7 mm-thick channels showed pores with even much higher carbon content such as 10 to 13%. These pores were usually the large pores at the end of the thin channels (Fig. 7e–f), which probably have formed from the entrapped liquid polymer. Pores can form in three different mechanisms in Lost Foam casting. First one is the pore formation by gasification of captured liquid products of EPS. Second one is the pore formation by the captured gas products of EPS. The last one is the
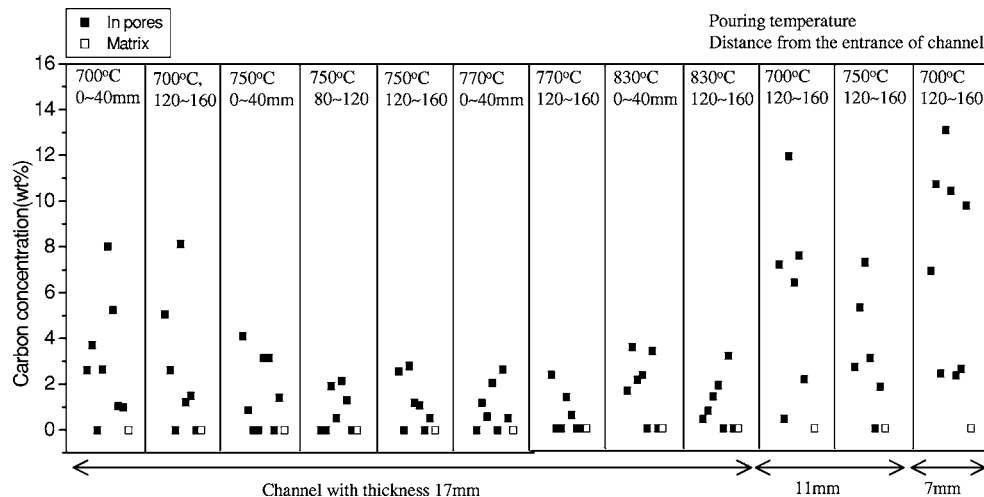
Figure 8 The carbon concentrations in pores at different locations of test casting-T. The pouring temperature and specimen thickness and location are shown.
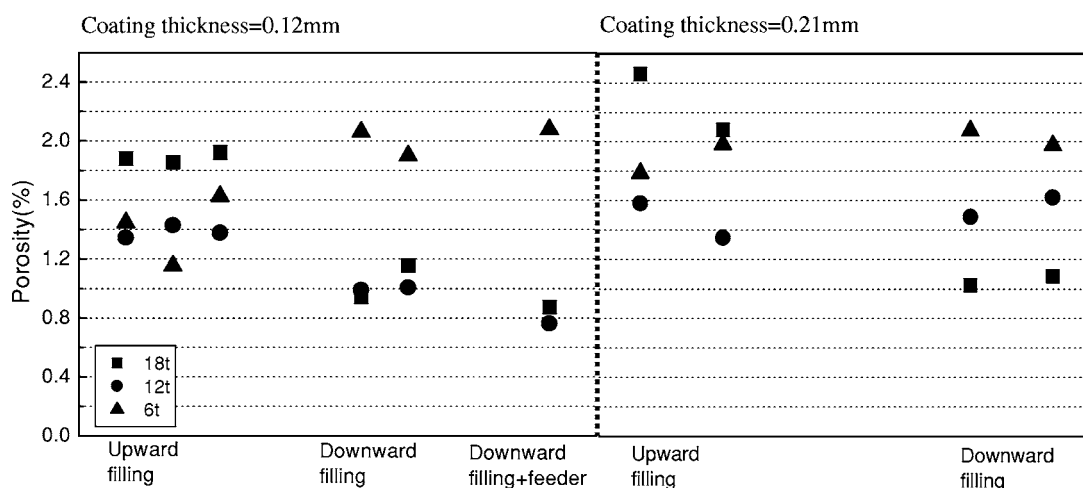

Figure 9 Porosity in each plate with different thickness of the test casting-S for different filling directions, all with a mold evacuation (710 mmHg) and pouring $T = 730°C$; (■): upper part of plate (18 mm thick), (●): middle part (12 mm thick), (▲): lower part (6 mm thick).

pore formation by supersaturated hydrogen gas from the melt, which can originate from initial melt or from reaction with decomposed EPS. There can be differences in carbon content according to pore formation mechanisms. The carbon content from the first mechanism would be expected to be highest, and moderate or lowest from the second or the third mechanism. As Fig. 8 shows different levels of carbon content, suggesting that the pores can have formed in all three mechanisms.

The effect of filling direction (upward filling or downward filling) in the test casting-S with stepped plates (Fig. 4) was investigated. A feeder was attached to one of the three downward filled plates. Fig. 9 shows the porosity in each thickness of different stepped plates for different filling directions and coating thicknesses. In downward filling the 6 mm-thick part is farthest from gate and in upward filling the 18 mm-thick part is farthest. In all plates, the part farthest away from the gate showed highest porosity. Downward filling showed generally lower porosities in 12 and 18 mm thickness due to faster filling possibly because of the short reaction time between melt and EPS. The case of downward filling with riser showed a similar result to that 'with-

out' a riser. However the thick part showed a slightly lower porosity, which may be the result of the riser effect.

In the case of the thicker coating (0.21 mm) the porosity level was generally around 0.3% higher than that of the thinner coating (0.12 mm). The thicker coating delays the penetration of the pyrolysis products (gas + liquid) through the coating and increases the filling time and therefore the reaction time with EPS. Otherwise, the tendency is same as with thinner coating, i.e., the last filled part shows the highest porosity level.

4. Conclusions
The hydrogen gas pick-up problem that can occur during Lost Foam Casting was investigated with Reduced Pressure test samples and real castings, yielding the following conclusions:

1. The low initial hydrogen concentration in Al-melt increased the rate of hydrogen pick-up of the melt due to increased driving force for dissolution.
2. The hydrogen gas pick-up depended on pouring temperature or metal front temperature and there was an

optimal temperature that gave the minimum porosity in the casting. For example the optimal pouring temperature seemed to be 750°C for 17 to 11 mm-thick casting and 800°C for 6 mm-thick casting.

3. The mold evacuation decreased the porosity generally by around 0.4 vol% due to a faster filling and removal of EPS decomposition products.

4. The farthest part of a casting from the gate had highest porosity due to long reaction time between melt and EPS and possibly due to a too low melt temperature.

5. Downward filling together with the provision of a riser slightly reduced the porosity. Thicker pattern coating increased the porosity due to slower filling.

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