Journal of Materials Processing Technology 211 (2011) 1510–1515

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Gas content in high pressure die castings

Laihua Wang*, Peter Turnley[1], Gary Savage

CAST Cooperative Research Centre, CSIRO Process Science and Engineering, Gate 5, Normanby Road, Clayton, VIC 3168, Australia

ARTICLE INFO

Article history:
Received 10 January 2011
Received in revised form 29 March 2011
Accepted 30 March 2011
Available online 8 April 2011

Keywords:
High pressure die casting
Gas content
Gas level
Gas entrapment
Gas porosity
Casting quality
Gas measurement
Vacuum fusion method

ABSTRACT

This paper presents the results of a quantitative study of the gas level in various types of castings from the high pressure die casting (HPDC) process using a vacuum fusion method. It was found that the major part of the gas was from the air entrapment during cavity filling. Other sources such as air entrapment during ladling, residual die lubricant and quenching water were also noticeable. Measurements of a large casting and castings from a multi-cavity die showed that the gas content was unevenly distributed. The modified vacuum fusion method has been proved to be a valuable tool for evaluating and quantifying the level of gas in castings as well as for an assessment of the influence of different process parameters on gas evolution in castings.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

High pressure die casting (HPDC) is a cost-effective process widely used to produce components with high productivity and high dimensional accuracy for automotive and other industries. A disadvantage of this process is the gas entrapment due to the highly turbulent flow of metal in the cavity. The entrapped gas remains in the casting in the form of gas porosity which hinders the casting's suitability for conventional heat treatment and deteriorates the casting quality sometimes to such a degree that it must be rejected.

In the cold-chamber HPDC process, air can be entrapped during the metal pouring, plunger advance, and metal injection. Lindsay and Wallace (1972) reported that the fill ratio of the metal in the shot sleeve has a significant influence on the gas entrapment. This is caused by the wave formation and propagation during the plunger advance as demonstrated with a simulation by Wang et al. (2003). In this case of half-filled shot sleeve, the air in the shot sleeve plus the air in the cavity is approximately three times of the volume of the metal poured into the shot sleeve. Clearly it could be a significant source of gas.

Oil is used in the process to lubricate the plunger tip in the shot sleeve, and other forms of die lubricant are used to assist in the casting removal from the dies. These lubricants can evaporate or burn once in contact with the molten metal. Lindsay and Wallace (1972) reported that lubricant evaporation did not play an important role in the porosity generation. It is envisaged that their conclusion was based on a casting having a simple shape used in the study. With a complex casting the lubricants can be more difficult to be flushed out by the metal into the overflows. So it is not clear that Lindsay and Wallace's conclusions could be applied to all castings.

Die lubricants used in the die casting industry mostly have a formulation comprising polymer wax, silicone oil and some surfactant, and are usually diluted with water. Some diecasters also use external water to quench the die surface for a complex casting. This water, when not removed either by evaporation or with compressed air before die closure, turns into steam in an explosive expansion when metal arrives in the die cavity according to Walkington (1997). As was argued above for lubricants, more complex dies would be expected to increase the likelihood of retaining water in pockets of the die.

The amount of gas present in a high pressure diecasting varies both with part geometry and casting parameters. Typically, the gas contents inside high pressure diecast parts are reported to vary between 10 and 50 cc/100 g (cubic centimeter per 100 g of aluminum at standard temperature and pressure) according to Badini et al. (2002). By the use of vacuum diecasting, gas contents below 10 cc/100 g and even as low as 1 cc/100 g may be achievable,

* Corresponding author. Tel.: +61 395458449; fax: +61 395458444.
E-mail address: Laihua.Wang@csiro.au (L. Wang).
[1] Former vacation student from RMIT, 98 Uplands Road, Yarra Glen, VIC 3775, Australia.

0924-0136/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmatprotec.2011.03.024

facilitating conventional heat treatment and allowing parts to be welded.

Due to the difference of hydrogen solubility between the liquid phase and the solid phase of aluminum, hydrogen in the metal will be released during the metal solidification. The maximum release of hydrogen can only account for less than 3% (1 cc/100 g) of the casting volume (calculated from Campbell, 1991). In the practice, the liquid metal is either degassed or protected to minimize the hydrogen intake. So the hydrogen content is minor when compared to the gas from other sources, for example, air in the cavity as discussed above.

Sakamoto and Sose (1985) reported that the gas contents were 3–5 cc/100 g for castings made using a GF (Gas Free) valve with vacuum applied, and 6–10 cc/100 g for those when the GF valve was used as an air vent. Brevick and Cheng (1995) reported that the gas content in an experimental casting was on average 2.6 (in the range of 2.05–2.73) cc/100 g for vacuum assisted and 6.3 (5.12–21.5) cc/100 g when the Fondarex vacuum system was used as an air vent.

A number of methods may be used to quantify the gas level in castings. The Archimedes test is commonly used as a non-destructive method to measure casting density. While the average density is a good measure of pore volume fraction, it does not accurately reflect the amount of gas in a casting. The gas pores would typically be merged with shrinkage pores and their relative contributions difficult to separate. The density measurement is therefore considered to be inadequate for an accurate estimation of gas content in the castings.

Yamamoto et al. (1989) estimated the gas content by heating and remaining the castings at 495 °C for 4 h and then measuring the casting density when blisters were formed on the surface of the castings. However, the mechanism of the blister generation was very complicated and could be affected by many factors, such as the casting shape, the location of gas pores in the casting (a gas pore in the centre might not show up) and even the way the casting was placed in the furnace during heating. Again, this method is considered not ideal to estimate the gas content in the casting.

Vacuum fusion (Sakamoto and Sose, 1985; Murray et al., 1991) is a more accurate method to determine the gas content. With this method, a small sample sectioned from a casting was placed in a container under vacuum and heated until molten. The gas in the sample was then released and the gas content could be calculated from the pressure increase due to the gas release. In a variation of this technique, Brevick and Cheng (1995) placed the whole casting in a bell jar and heated it in a furnace.

Gas content in a casting is an effective indicator of casting quality and in general, provides a good indication of the suitability for post casting processes such as welding and heat-treatment. The current study describes a vacuum fusion rig, together with measurements of the gas contents in complex castings produced under varied industrial conditions.

2. Experimental

The principle of the vacuum fusion method is that a sample is placed in a sealed vessel and melted under vacuum. The gas content in the sample is determined from the pressure increase due to gas released from the casting. In the method, sealing of the vacuum vessel at the melting temperature is critical to minimize the error due to the air ingress into the vacuum vessel. Effort was made to achieve the best sealing under the operational temperature and pressure. The vacuum vessel was made of mild steel and consisted of two halves. Each half had a shape like a flat pan and had a wall thickness of 20 mm to reduce distortion. The two halves were fastened together using mechanical fastening. A copper ring was used as a gasket between the mating faces. A knife-edge rim was machined on the mating face of each half of the vessel, but slightly offset. The rims would therefore bite into the copper ring to seal the vessel when the two halves were tightly engaged together. A stainless steel pipe from the top of the vessel was connected to a vacuum pump and an argon supply. The pipe passed through a water tank to release the heat conducted from the furnace. A pressure transducer was connected to the pipe to record the gas pressure. A 1.5 m long by 2 mm diameter thermocouple was inserted through the pipe into the vacuum chamber to monitor the temperature inside the vessel. By sharing the same port with the pipe on the lid, the potential leak using an extra port for the thermocouple was eliminated. Swagelok fittings were used for all pipe joints. With all of these measures applied, the leak rate of the vessel at the melting temperature could be controlled at less than 6 mbar/h with an average of 4 mbar/h. The pressure increase of a typical test was approximately 300 mbar and the melting process took less than 2 h. The error due to the air leak was calculated to be less than 4% on average. A schematic diagram of the apparatus is shown in Fig. 1.

A stainless steel pan was placed in the vessel to contain the casting sample. The pan could load 2 kg of aluminum, which was slightly more than the weight of the whole castings mostly investigated in this study. For castings larger than 2 kg, segments were sectioned from the casting to fill the pan as much as possible. Having a larger ratio of metal filling the open space of the system meant that the pressure gain due to the gas release would be relatively higher. The total volume of the pipe lines in this test rig was less than 2% of the vacuum vessel. For a pressure sensor having an error of ±0.2% of the full range, the accuracy is calculated to be ±0.02 cc/100 g. The whole vacuum vessel was placed in a furnace in which a uniform temperature was maintained. The temperature inside the vessel was used in the calculation of the gas mass. The error caused by the difference of temperatures between the gas in the pipes and the vessel was negligible due to the small volume of the pipe compared with the vessel.

In the test, the vacuum vessel loaded with the sample was preheated in the furnace at 150 °C for 4 h with the vacuum pump continuously on. During this period of time, the system was flushed with argon twice. The casting was then held at 450 °C in the furnace for another 1–2 h to remove any surface volatiles. Having been checked to meet the leak criteria mentioned above, the furnace was then set to 630 °C until the casting became completely molten. During this melting process, the vessel chamber was isolated from vacuum by manually switching off the valves. The temperature and pressure in the chamber were recorded online. The total gas released from the sample could therefore be determined from the difference between the maximum and the initial pressure.

The casting investigated in this study was a pump cover with a complex geometry, as shown in Fig. 2. The casting was produced in an industrial die-casting machine, with vacuum applied during normal production. To investigate the gas contribution from different sources, the machine operational parameters were varied from the normal conditions. These included eliminating combinations of the following steps: vacuum, tip oil, die spray and external quench water. In order to maintain the thermal balance of the die, each of these samples was collected between the normal production shots. Samples were also collected by ladling the metal from the holding furnace directly into the stainless steel pan, and also by pouring and solidifying the metal in the shot sleeve with the plunger tip remaining stationary between two normal production shots.

3. Results and discussion

A typical result with the traces of pressure, $P(T)$, and temperature, T, is shown in Fig. 3. The time was counted from the end

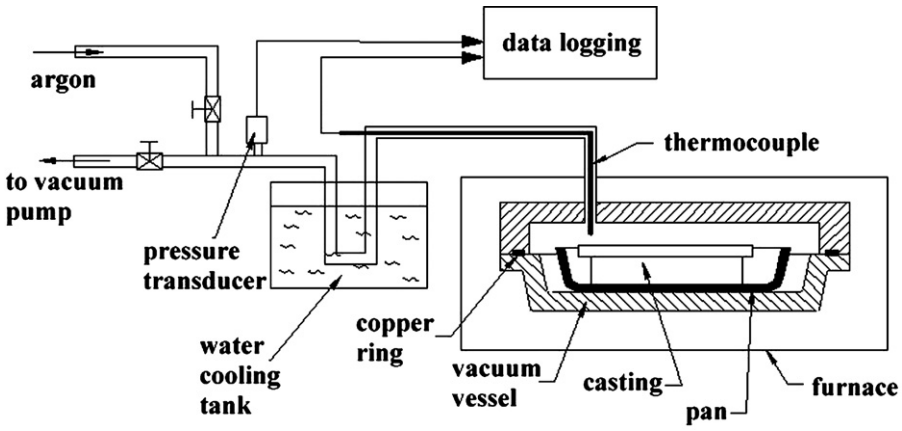

Fig. 1. A schematic drawing of the new test rig.

Fig. 2. The pump cover casting (~1700 g in weight, ~215 mm in diameter and 2–12 mm in thickness with alloy ADC12) made in an industrial die-casting machine with a vacuum system used.

of holding at 450 °C when the vacuum chamber was isolated from the vacuum source prior to heating continuously to, and holding at 630 °C. As shown in Fig. 3, when the temperature approached approximately 540 °C, the gas contained in the casting started to rapidly release as indicated by the pressure increase. Some tests were run for 7 h to determine a minimum heating time. As shown in Fig. 3, the maximum gas pressure $P(T)$ was reached at approximately 2 h after isolating the vacuum source. It was thus decided that two and half hours of holding time was sufficient to melt the alloy and have all gas released for a normal run.

The gas pressure $P(T)$ was temperature dependent as it was obtained at a varied temperature. A correct representation of the

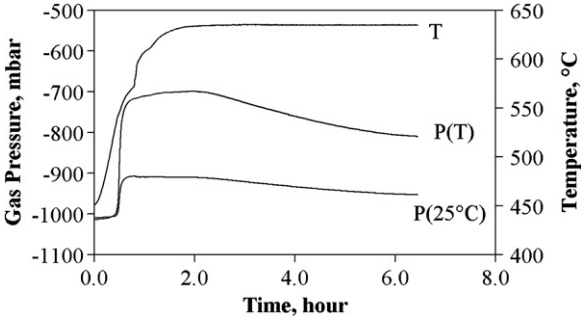

Fig. 3. Typical traces of gas pressure and temperature in the vacuum vessel during melting a sample.

gas release should be the mass of the gas. According to the gas law, the gas pressure at a constant temperature in a given volume represents the mass of the gas in the system. The gas pressure $P(T)$ may therefore be converted to the pressure at a standard temperature of 25 °C, and is plotted in the same chart in Fig. 3.

As shown by the curve of gas pressure at 25 °C, $P(25\,^{\circ}C)$, in Fig. 3, the gas mass reached its maximum in less than 1 h and remained almost unchanged for nearly 1 h after. Following that, the gas mass began decreasing. This indicated consumption of gas to form a solid, through reaction of the gas with the molten metal, which may have involved the formation of oxides or nitrides of aluminum.

3.1. Gas content in the holding pot and from the shot sleeve

The gas content for the sample of metal collected from the holding pot was 0.053 cc/100 g (Table 1) whereas the average of the samples taken from metal in the shot sleeve was 0.96 cc/100 g. These values can be used as a baseline for the comparison of gas contents with different conditions. Taking the baseline of ~0.05 cc/100 g for the alloy, the increase to ~0.96 cc/100 g by pouring metal into the shot sleeve was considered to result mainly from the tip oil and the air entrapment during metal pouring.

3.2. Gas contents from production parts

The results from the measurement of gas content for the standard production condition of the pump cover are listed in Table 2. The data in the table varied from 6 to 13 cc/100 g. The standard deviation of the gas content is 1.5 cc/100 g for an average gas content of 8.2 cc/100 g. It should be pointed out that the castings were collected from different production days. The process parameters such as the die spray, melt temperature, alloy composition as well as the external water quench and tip oil could be reasonably expected to be different for each sample taken. All of these factors may have contributed to the relative standard deviation of around 18%.

The gas contents of the castings made either with vacuum and natural venting (without vacuum) are illustrated in Fig. 4. The data for 'without vacuum' in the figure was averaged from 3 sample castings produced under the conditions with the vacuum hose off to air. The data for 'reject with vacuum' was from 4 castings scrapped by X-ray inspection as a routine quality monitoring. It can be seen that the castings made without vacuum contained more gas than those made with vacuum. The castings rejected by X-ray inspection exhibited little difference in the gas content from the accepted castings. In a normal practice of the X-ray inspection in a diecasting plant the castings were rejected based on either the location or the size of the porosity. In most of the cases the gas porosity co-

Table 1
Gas content of metal from the holding pot and shot sleeve.

Samples	Weight (g)	Gas (cc/100 g)	Leak (mbar/h)
Holding pot	2718	0.053	1.5
3 samples from shot sleeve	1354 (on average)	0.96 (on average)	3.1–6.3

Table 2
Gas contents following vacuum diecasting of the pump cover.

Sample number	Weight (g)	Gas (cc/100 g)	leak (mbar/h)
1	1693.75	5.51	5.54
2	1701.95	5.93	5.48
3	1700.85	8.37	5.11
4	1692.70	10.01	5.88
5	1686.15	8.38	1.50
6	1693.85	9.75	3.59
7	1706.20	7.51	4.79
8	1708.65	7.15	3.53
9	1700.85	9.34	5.93
10	1698.65	10.76	2.92
11	1642.95	6.20	3.44
12	1645.35	7.60	2.41
13	1647.30	6.57	5.84
14	1700.00	10.77	5.81
15	1697.75	6.74	2.56
16	1678.20	11.67	0.33
17	1705.25	13.16	1.94
18	1708.30	7.07	5.11
19	1713.20	6.02	5.71
20	1707.90	6.93	4.49
21	1647.50	7.27	5.49
22	1667.30	6.65	5.27
Average	1688.39	8.15	4.21
SDEV		1.49	

exists with shrinkage porosity, and it is just as likely the castings were rejected on the basis of the shrinkage and combined porosity, rather than the gas porosity by itself.

3.3. Varying casting parameters

The gas contents for the five conditions tested are illustrated in Fig. 5. These conditions include

1. 'tip oil only', a condition with the external water cooling and die spray eliminated,
2. 'water + tip', with the die spray eliminated,
3. 'spray', with the tip oil and external cooling water eliminated,
4. 'water + spray', with the tip oil eliminated,
5. 'normal', with the tip oil, external cooling water and die spray applied.

Here it is important to note that it was a difficult exercise to collect the samples by varying the normal production conditions, since this could result in long machine stoppages if the casting stuck in the die. As a result, only 2–3 samples were collected for each of conditions.

As can be seen in Fig. 5, the gas contents were in general reduced by eliminating sources of gaseous porosity. In the "normal" condition, the gas contents were of the order of 8.2 cc/100 g. If the tip oil was eliminated ("water + spray" condition), then the average gas content was reduced to 7.9 cc/100 g. If both the tip oil and external water cooling were eliminated ("spray" condition) the average gas content was reduced to 6.6 cc/100 g. If the die spray alone was eliminated ("water + tip" condition), the gas content was reduced to 6.2 cc/100 g, and when both the die spray and external water cooling were eliminated ("tip oil only" condition), the gas content was reduced further to 5.8 cc/100 g.

As may be appreciated, each of the abovementioned parameters will have an influence on the casting quality and Fig. 5 shows that each of the sources had a contribution to the total gas content, and the air entrapment probably had the most contribution.

3.4. Application of the technique to other parts

Three other types of castings were also investigated using the vacuum fusion method. They were (1) a structural sump, (2) a side cover and (3) a cam cap. All of these castings were made with natural venting using chill blocks, and without applying vacuum.

Fig. 6 shows an image of the structural sump casting with the runner. The part was made on a 2000 t UBE machine with a chill block sitting on the top. The cavity was gated in the middle on one side as shown in Fig. 6. Three samples were sectioned from the casting. The gas contents in these samples are also shown in Fig. 6. The sample extracted from the middle section (first filled) had the least gas, whereas the top and bottom sections (last filled) had higher gas. The last filled regions contain the most gas because these are the locations that air, moisture and die lubricant are moved to during cavity filling.

Fig. 7 shows the side cover casting. It was made from a twin-cavity die and with chill blocks as shown in the figure. The gas content in the left hand casting was measured to be 3.7–4.4 cc/100 g from 3 samples (excluding overflows and vent) and the right hand one 2.8–3.6 cc/100 g. The reasons for this difference were unclear.

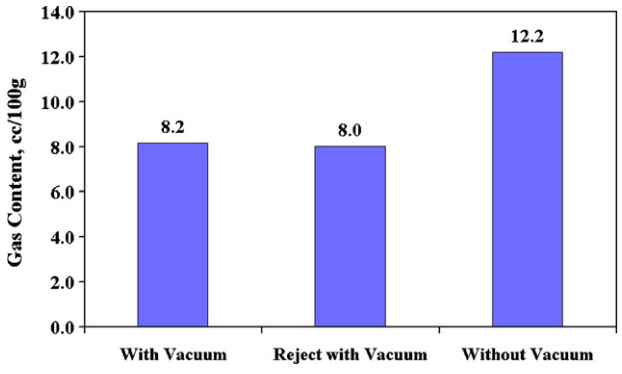

Fig. 4. Gas contents of castings with or without vacuum.

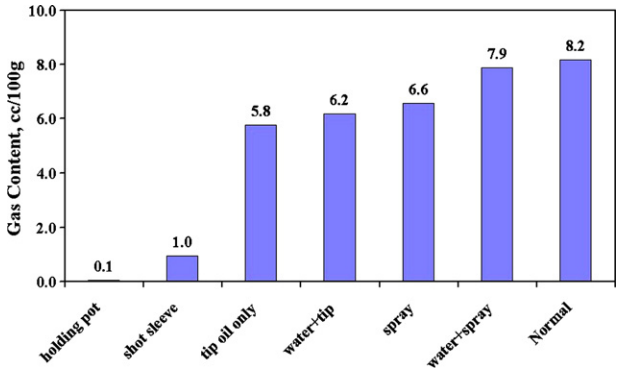

Fig. 5. Gas contents of castings showing the effects of various casting parameters (see text for details).

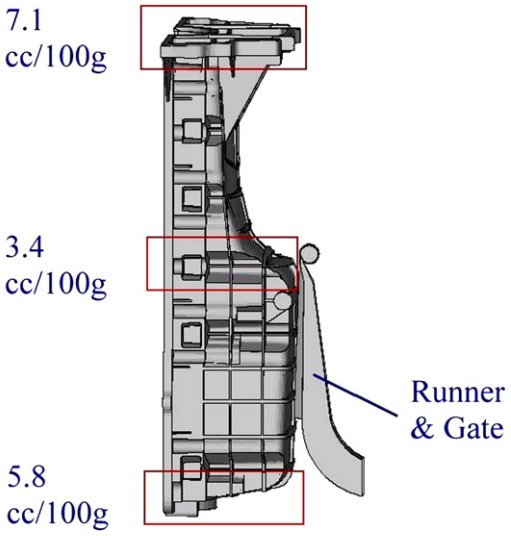

Fig. 6. This image shows the shape, gas content and fill position of the structural sump casting. The casting was 730 mm in length and 9.5 kg in weight with alloy CA313.

From the appearance of the full shot in Fig. 7, the casting on the right hand side containing less gas was better vented, as evidenced by the length of the vent metal in the figure. Since the runner system is asymmetrical, the cavity filling sequence is likely to have been asymmetrical and this would have had an influence too. As shown in the figure, the metal filling in the right hand side cavity could have benefitted from its shorter and thicker runner.

The cam cap castings were made from an 8-cavity die. The image in Fig. 8 shows a full shot of the castings and their gas contents. For the convenience of identification, the cavities are numbered as cavity 1 to cavity 4 from left to right in the top row and cavity 5 to cavity 8 in the bottom row. The top four are the front cam caps and the bottom four are the rear cam caps. In general, the top four contained more gas than the bottom four. This can be explained as a lack of venting for the top four because the chill vents designed for the top four were blocked off to avoid die flash in production. It is not clear why the side ones (cavities 1, 4, 5 and 8) have less gas than the middle ones (cavities 2, 3, 6 and 7). A hypothesis is that the

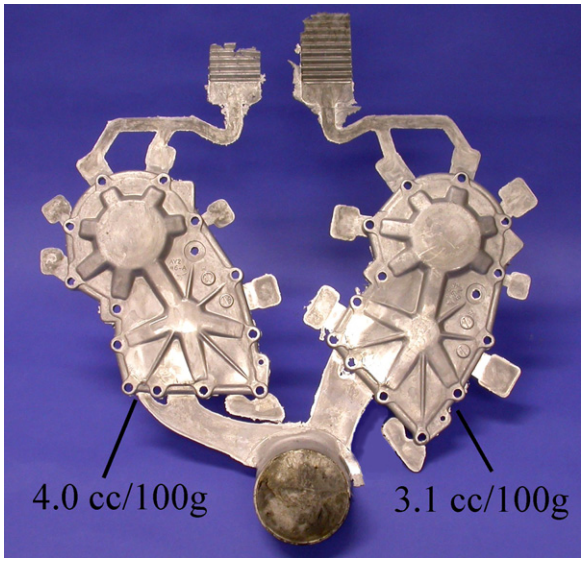

Fig. 7. This image shows a side cover casting and its average gas content with alloy ADC12.

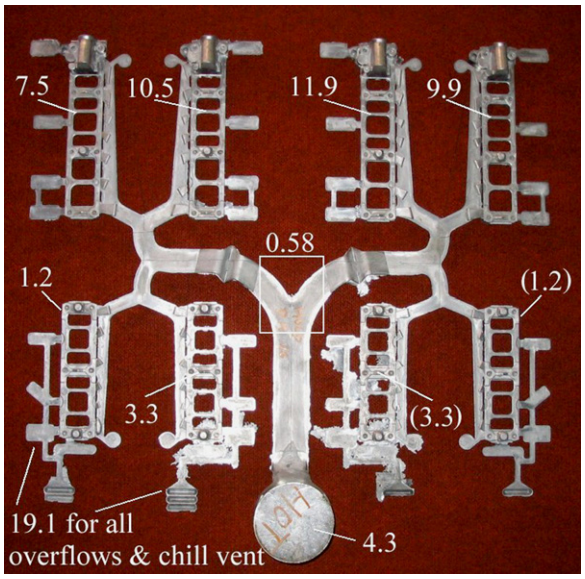

Fig. 8. This image shows a full shot of an 8-cavity die for cam caps casting made with alloy CA313.

side cavities had better venting than the middle ones. In one test, all of the overflows and chill vents were measured. Not surprisingly, the gas level in the overflows was extremely high (19.1 cc/100 g). It was also found that the gas content in the middle section of the runner was very low. This might be a result of the die lubricant and moisture being eliminated during cavity filling. A higher gas content in the biscuit than in the runner might be attributable to the tip oil and air entrapment in the shot sleeve.

4. Conclusions

A vacuum fusion test rig, which can accurately quantify the gas content in a casting, was used to measure the gas contents for various types of castings made under varied conditions. It appears that:

Gas sources such as air entrapment, tip oil, external cooling water and die lubricant all contributed to the total gas content in the complex pump cover casting used in this study.
Vacuum-casting assisted in the gas removal to a degree. However, for a complex casting, the sources other than the air entrapment could contribute to the gas content significantly. As a result, a complex casting does not necessarily contain less gas when cast using vacuum technology than a simple casting made without vacuum.
For a large casting like the structural sump (730 mm in length and 9.5 kg in weight) the section filled last contained most gas.
For a twin cavity die like the side cover, the gas contents in two castings in a shot were not identical. This could be due to the difference in the venting and asymmetrical feeding.
For an 8-cavity die, the gas content in the overflows and chill vent was substantially higher than in the castings, runner and biscuit. The castings with better venting had less gas than those with a lack of venting.

Acknowledgements

The authors would like to thank CAST Cooperative Research Centre for providing the funds to undertake this work, and our industrial partners for their support.

References

Badini, C., Bonollo, F., Cavatorta, M.P., La Vecchia, G.M., Panvini, A., Pola, A., Nicodemi, W., Vedani, M., 2002. Process simulation of microstructure and relationship with mechanical properties in diecastings. Metallurgical Science and Technology 20 (2), 14–21.

Brevick, J., Cheng, P., 1995. Evaluating the Quality of Vacuum Die Castings, NADCA Transactions, Paper No. T95-045.

Campbell, J., 1991. Castings. Butterworth-Heinemann Ltd., Linacre House, Jordan Hill, Oxford OX2 8DP, p. 176.

Lindsay, D., Wallace, J.F., 1972. Effect of Vent Size and Design, Lubricant Practice, Metal Degassing, Die Texturing and Filling of Shot Sleeve on Die Casting Soundness, Transactions 7th SDCE International Die Casting Congress, Chicago, Paper No. 10372.

Murray, M., Asquith, S., Smith, A., Gulizia, S., 1991. Gas Analysis in Aluminum Ingots, CSIRO Division of Manufacturing Technology, Report No. MTM220, September 1991.

Sakamoto, T., Sose, M., 1985. Air Content and its Effect on Casting Quality, SDCE 13th International Die Casting Congress and Exposition, June 3–6, 1985, Paper No. G-T85-034.

Walkington, B., 1997. NADCA Die Casting Defects – Causes and Solutions, p. 48.

Wang, L., Nguyen, T., Savage, G., Davidson, C., 2003. Thermal and flow modelling of ladling and injection in high pressure die casting process. International Journal of Cast Metals Research 16 (4), 409–417.

Yamamoto, Y., Iwata, Y., Nakamura, M., 1989. Gas pressure in finally filled region in die cavities and defects in aluminum die castings. Journal of the Japan Institute of Light Metals 39 (1).