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The Mechanics Of Casting Conditions And Quality Of As-Cast Products Interrelationships During High Pressure Die-Casting Of Al-Si Alloys

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Abstract

The effects of casting conditions, including fluid flow rate, casting and ingate thickness, and melt and die temperatures, were studied on the microstructure of A380 high pressure die casting alloy using a fully-controlled cold chamber high-pressure die-casting machine coupled with an experimental die set of a rectangular die cavity shape of 65x130x(2, 4, 8) mm. All castings showed a bimodal distribution of dendrites in which the morphology of dendrites was completely different from the classic tree shape characteristic. It was found that the casting parameters influence the quality of the coupons surface finish, porosity size and percentage, volume fraction and size of dendrites, but have no effect on the silicon morphology and percentage of Al-Si eutectic.

1. Introduction

Casting is the most economical route to transfer raw materials into readily usable components. The major drawbacks for castings include the formation of hot tears, gas and shrinkage porosity, non-uniform structures, and segregation [1-12]. Such defects are more pronounced in semi-finished products, ingots, slabs, billets, and some conventional shaped casting routes such as sand casting. These defects are potential causes of failure in the cast components during further processing or service operation. For shaped casting, the advent of more advanced casting techniques such as die and squeeze castings has compensated for casting shortcomings. They are further mitigated by improving the mechanics of casting routes through the employment of more advanced and sophisticated machinery and control systems. The introduction of CAD/CAM and solidification based software packages have further widened the vision of casting engineers. Therefore, it is possible to design and manufacture defect-free engineering components comparable or even better than those currently fabricated by forging [13].

The other alternative to compensate casting problems was the introduction of semi-solid processing of alloys, i.e. rheocasting and thixocasting. The process takes advantage of specific characteristics of the alloy when cast at a temperature between solidus and liquidus [14-16]. The obtained globular structure allows the slug to be handled like a solid but behaves like a non-Newtonian fluid upon shearing during the shaping stage within a die casting or forging machine.

The introduction of advanced casting processes such as high pressure die casting, HPDC, may be attributed to two main constraints of conventional casting routes, namely low production rate and minimum thickness of cast product, together with restrictions on the choice of casting alloy and its cleanliness. HPDC may be employed to cast thin sections of about 1 mm for aluminum alloys and production rates as high as 2000 per hour on certain components [17]. It also enables the fabrication of simple to very complex shapes using a wide range of alloys, including lead, tin, zinc, aluminum, magnesium and copper. The main drawback of HPDC is the cost of equipment, which should be compensated by higher productivity. Furthermore, it is important to understand the precise thermal history of the molten alloy once it is poured into the shot sleeve. This is rather complex and marked chilling of the molten metal may occur within the shot sleeve and runner. The actual temperature of molten metal entering the die cavity can drop to very low values where the concept of liquid injection is no longer a valid assumption [18].

For HPDC, the important casting parameters include; die cavity, runner, gate and shot sleeve temperatures, alloy superheat and injection velocity, casting thickness and complexity, runner and gate/ingate size, and geometry, and intensification, i.e. degree, rate, and the time delay between the end of injection and the start of intensification [19].

The current research program was undertaken to study the effect of casting conditions on the quality of as-cast products. The outcome would be of particular interest to die casting industry and should clarify certain ambiguities currently encountered during high pressure die casting.

2. Experimental Procedures

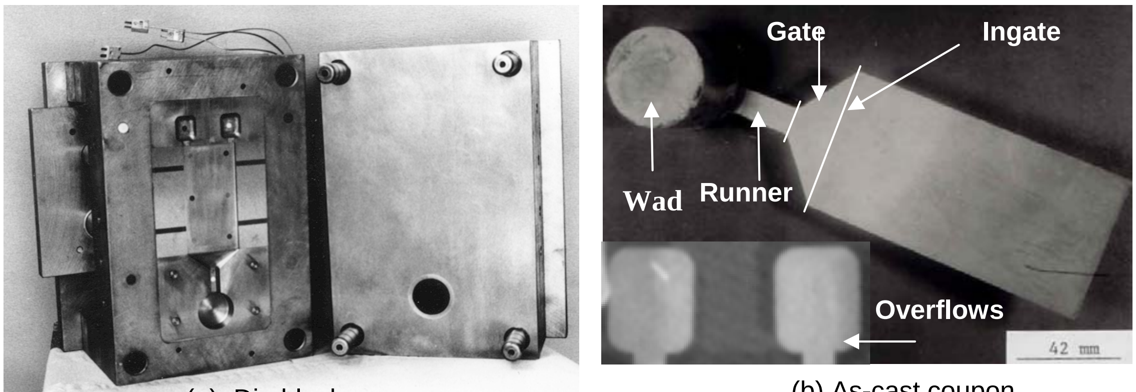
The alloy used in this investigation is classified as A380 and the chemical analysis shown in Table 1. Castings were produced in a fully controlled experimental die, using a 220-ton locking force cold chamber die casting machine. The die set was designed to have a simple rectangular shape of 65x130x (4, 8, 16, thickness) mm. The photographs in Figure 1 shows the actual experimental die set and the as-cast coupon with the runner, fan-shaped gate, overflows and wad sections. Three ingate thicknesses of 0.8, 1.6 and 3.2 mm were used with the fan gate geometry. The die was heated to the casting temperature, i.e. 200 C, using electrical cartridge heaters. The temperature of die block, shot sleeve, gate, cavity and overflow, was monitored and controlled to an accuracy of ±5^{o}C using K-type (chromel-alumel) thermocouples.

The velocity and pressure of the molten metal injected into the die cavity were calculated using displacement and pressure transducers to monitor the piston, i.e. plunger, movement and hydraulic pressure of the die casting machine respectively. The velocity of molten metal was calculated at the gate and varied between 20-70 m.s^{-1} for 0.8 mm thick ingate. The die temperature was kept at about 200^{o}C at the start of the casting operation, but increased to 250-300^{o}C during casting depending on the number of castings made. A few selected castings of different gate velocities were X-ray radiographed for internal quality inspection.

Conventional metallography was carried out on both longitudinal and transverse cross-sections for microstructural analysis. All specimens were etched in 10% sodium hydroxide solution.

Table 1: Chemical analysis of the A380 alloy used.

Element	Cu	Si	Mg	Fe	Mn	Ni	Zn	Pb	Sn	Ti	Al
Wt%	3.54	8.96	0.30	1.05	0.27	0.17	2.81	0.17	0.05	0.07	Balance



(a) Die block (b) As-cast coupon

Figure 1: Experimental die set and the as-cast coupon.

Optical and scanning electron microscopes were used for microstructural analysis of the castings. The volume fraction of the various microconstituents of the as-cast structure was measured using Weibel graticule and point counting method.

3. Results and Discussion

3.1 Surface Quality

In order to establish the effect of gate velocity on the casting surface finish, all coupons were initially inspected visually for surface defects such as cold shut, flow line and blister. As shown in Figure 2, castings with low gate velocity, 20 m.sec^{-1} for a gate thickness of 0.8 mm, did not have good surface finish and generally contained flow line, cold shuts and a rough surface in general. As the gate velocity increased, the quality of casting surface finish improved as shown in Figure 3, where the casting surface is a replica of the die surface. It was reported that there is a linear relationship between the molten metal gate velocity and the extent of “defect free zone” along the casting surface [20]. As the die and molten metal temperatures were raised to 350^{o}C and 740-750^{o}C respectively, the cold shuts were still pronounced at low gate velocities. However, there were a few blisters and the flow lines were easily detectable.

The introduction of cold shuts and poor surface finish may be related to the nature and geometry of molten metal flow. It is also related to the excessive chilling effect of the shot sleeve, which causes temperature drop of the liquid metal stream as it enters the die cavity. The low metal temperature coupled with irregular filling pattern has resulted in lack of liquid fusion, Figure 2.

Figure 2: Optical photograph to show surface quality at low gate velocity. (20 $m.s^{-1}$)

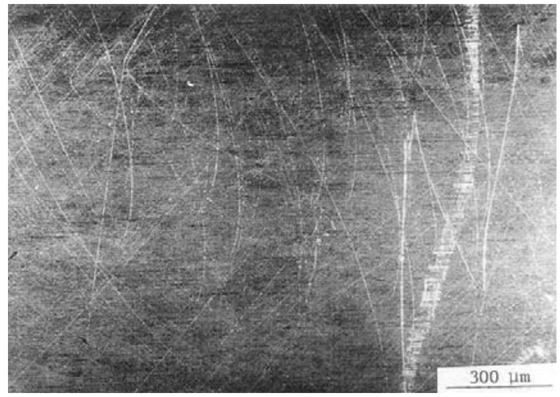


Figure 3: Optical photograph to show surface quality at high gate velocity. The lines are the replica of the scratches on the die surface.

In addition to gate velocity, the die temperature has a distinctive effect on the surface quality where a high die temperature resulted in formation of blisters as detected for die temperature range of 350-400^{o}C. Metal temperature effects were determined by injecting the molten metal 1, 2 and 4 seconds after pouring into the shot sleeve. Surface quality deteriorated as delay time increased. This is attributed to the formation of a skin layer within the shot sleeve which was then peeled off, broken and mixed with molten metal as the plunger moved forward. These presolidified lumps disturb the metal flow through the ingate and within the die cavity and thus result in detoriating surface finish.

The effect of superheat was determined by increasing the melt temperature from 630^{o}C to 700-750^{o}C. Although the surface finish was better at higher temperatures for all respective gate velocities, the surface contained some blisters. It is well established that blisters are due to expansion of entrapped gas below the skin surface when the cast part is removed from die. Furthermore, the level of flash was higher. The formation of blisters was therefore attributed to the higher level of gas dissolution within molten metal and blockage of vents due to flash. A third factor, which is believed to contribute to the quality of surface finish, is the geometry. The very high surface area to volume ratio of the coupons in the present study may be responsible for rapid loss of heat in molten metal. Such heat loss should eventually reduce the ability of molten metal streams to join up effectively, i.e. an important reason for cold shut formation.

3.2 Microstructure

A full metallographic investigation was carried out on the experimental coupons. The optical and SEM micrographs presented in Figure 4 reveal the microstructure of die cast coupon. It is evident that the dendrite morphology is either rosette or spherical and there is a bimodal distribution of aluminum dendrites. The large dendrites are due to alloy solidification in shot sleeve or runner, while the fine ones are formed within the die cavity as reported before [1]. The volume fraction of large dendrites varied along the length of the coupons as shown in Table 2. It is also gate velocity dependent. A lower gate velocity resulted in higher percentages of large dendrites. The fact that the large dendrite content decreases with length is quite predictable since the probability of these dendrites to be entrapped within the initial solidified regions are higher and therefore would be separated from the metal stream before reaching the distances near the overflows. The porosity content however is the reverse where its volume fraction increased with distance, Table 2.

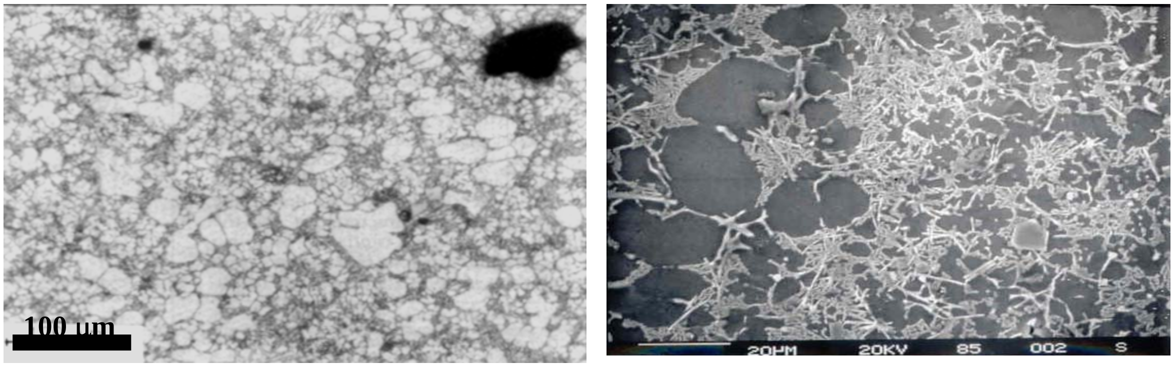


Figure 4: Optical and SEM micrographs to show the microstructure of the as-cast coupons.

Table 2: The Porosity and large dendrites contents along the length of a single coupon the as-cast.

	Vol. Fraction Large Dendrites			Vol. Fraction Porosity		
	Near ingate	Middle region	Near overflow	Near ingate	Middle region	Near overflow
High Gate Velocity	27.4± 1.5	22.5±1.5	24.1±1.4	1.4±0.4	4.6±0.7	4.8±0.6
Low gate Velocity	30.8±1.6	29.7±1.6	28.6±1.6	3.2±0.6	4.5±0.7	4.1±0.7

The die and metal temperatures also affected the quantity of large dendrites where lower volume fractions were detected with higher temperatures. This is directly related to the liquidus temperature of the A380 alloy. Since the injection of molten metal is a semisolid, the entire die casting operation is carried out within the mushy zone. Therefore, a higher melt temperature is closer to liquidus and thus the fraction of large dendrites formed in the shot sleeve is lower. The effect of lower die cavity and shot sleeve temperatures are shown in Figure 5. The formation of non-uniform structure is due to partial solidification of molten metal within the shot sleeve, which is then peeled off as the plunger moves. These dendrites eventually find their way into the die cavity and not only disturb the flow characteristics but also render a non-uniform structure.

Another parameter, which has direct effect on the porosity content of high pressure die cast components, is the fill ratio, the ratio of molten metal volume to that of shot sleeve. A higher cavity thickness means a greater fill ratio. The fill ratios were 33% and 23% for 8 mm and 4 mm thick cavities respectively. The higher the fill ratio, the lower the porosity content as the possibility of wave front break down within the shot sleeve, due to plunger movement, decreases with higher fill ratio. Wave front break down results in more air pickup within the shot sleeve, which will eventually end up within die cavity. The effect of fill ratio on the porosity content is given in Table 3 and plotted in Figure 6. The wad length is directly related to fill ratio, since a larger wad means more molten metal within the shot sleeve and thus higher fill ratio.

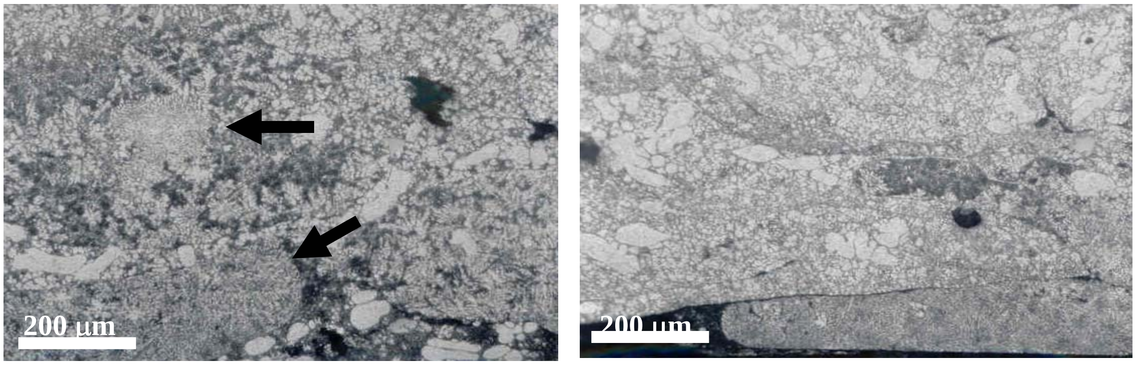


Figure 5: Optical micrographs to show the effect of low shot sleeve and die temperatures on microstructure.

Table 3: Effect of fill ratio on porosity content (4 mm thick cavity, 0.8 mm ingate, gate velocity ~60 $m.s^{-1}$).

Casting No.	Wad length	Porosity %
58	36.8	3.57± 0.41
61	41.7	3.09±0.40
60	47.8	2.56±0.34
57	54	2.47±0.33
59	63.7	2.85±0.36

The overflow in the die cavity also affects the porosity content since it is used as the location to absorb the initial metal stream, which is generally less clean than the rest of metal. Blocked overflows resulted in an average density of 2.62 $g.cm^{-3}$ compared with the normal, unblocked overflows casting of 2.68 $g.cm^{-3}$.

Intensification is usually applied to reduce porosity content, but the timing of intensification is crucial. The intensifier was applied during cavity fill, at the end of and few seconds after cavity fill. It was found that porosity was minimum if intensification was applied immediately after cavity fill, see Table 4.

Table 4: Effect of the timing of intensification on the density of the as-cast components. (4 mm thick cavity, 0.8 mm ingate, gate velocity ~20 $m.s^{-1}$, intensification duration = 4-8 sec.)

Intensification time set on the Machine (sec.)	Time after cavity fill and before activation of Intensifier (sec.)	Density $Mg.m^{-3}$
None	None	2.62±0.02
10	+8.70	2.62±0.02
6.0	+4.85	2.61±0.02
2.0	+0.25	2.62±0.02
1.75	+0.11	2.61±0.02
1.5	0.00	2.68±0.02
1.25	-0.03	2.60±0.02
1.0	-0.14	2.60±0.02
0.5	-0.40	2.62±0.02

4. Conclusions

It has been shown that the quality of as-cast products is dependent on the casting parameters and appropriate selection of these parameters is crucial. The parameters discussed here were cavity and ingate thickness, ingate velocity, die set temperature, overflows, and intensification.

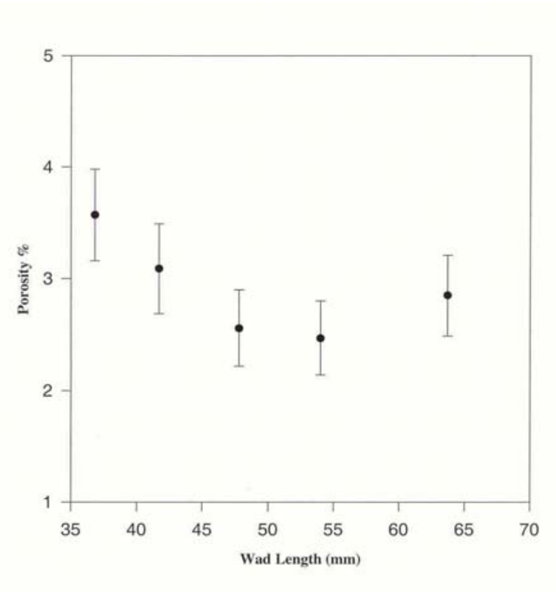


Figure 6: Effect of fill ratio, (wad length), on the porosity content.

References

[1] Ghomashchi, M.R. and Chadwick, G.A., Metals and Materials p. 477, Aug. 1986.
[2] Ghomashchi, M.R., Z. Metallkkunde, Bd. 78, H.11, P.784, 1987.
[3] Murray, M.T., Chadwick G.A. and Ghomashchi, M.R. Materials Australasia, P.20, June 1990.
[4] Ghomashchi, M.R., Scand. J. Metall., Vol.22, No. 2, Pp. 61-67, 1993.
[5] Ghomashchi, M.R. and Vikhrov, A., J. Mat. Proc. Tech., Vol. 101, Pp. 1-9, 2000.
[6] Flemings, M.C. "Solidification Processing" McGraw-Hill Publ. 1974.
[7] Kurz, W. and Fisher, D.J., "Fundamentals of Solidification" Trans. Tech. Publ. 3rd. Ed., 1989.
[8] Flemings, M.C., Mehrabian, R. and Nereo G.E., Met. Trans. AIME, Vol. 242, P.41, 1968.
[9] Flemings, M.C., Scand. J. Metall., Vol. 5, P. 1, 1976.
[10] Sarazin J.R. and Hellawell A., Met. Trans. A, Vol. 199, P. 1861, 1988.
[11] T.B. Abbott, and B.E. Davey, Proc. 74th Steelmaking Conf., Washington D.C. USA, 1991.
[12] P.R. Vince, T.A. Abbott, and R. Ghomashchi, "*The Generation of V-Segregates in the Ammonium Chloride - NH_4Cl-H_2O system*,", Workshop on "Modeling of Casting and Solidification Processes, BHP Research, Melbourne-Australia, 10th March, 1994.
[13] G.A. Chadwick, "Casting Technology", in "Future Developments of Metals and Ceramics", Ed. J.A. Charles, G.W. Greenwood and G.C. Smith, Inst. Materials, P180-199, 1992.
[14] Shahrooz Nafisi, Daryoush Emadi, Mahmoud Shehata, Reza Ghomashchi and Andre Charette, "Semi Solid Processing of Al-Si alloys: Effect of processing Parameters on Iron-based intermetallics", Int. Conf. Semi Solid Processing, Cyprus, S2P-2004
[15] Shahrooz Nafisi, Reza Ghomashchi, Andre Charette, and Bahadir Kulunk, "SEED Semi-Solid Processing of A356 Alloy: Morphological Evolution during Grain Refining", Int. Conf. Semi Solid Processing, Cyprus, S2P-2004.
[16] Reza Ghomashchi and co-workers, NSERC-ALCAN-UQAC industrial Research Chair, "Solidification and metallurgy of Al-Alloys", University of Quebec at Chicoutimi, 2002-2007
[17] B. Upton, "Pressure Die casting, Part I- Metals, Machines- Furnaces", Table 1.4, Pergamon Press, 1982.
[18] M.R. Ghomashchi, "Thermal history of molten metal during high pressure die casting", to be sent for publication, 2004.
[19] M.R Ghomashchi, and K.N. Strafford, "*Factors Influencing the Production of High Integrity Aluminum/Silicon Alloy Components by Die and Squeeze Casting Processes*", J. Mat. Processing Tech., Vol. 38, Nos. 1-2, P.303-326, 1993.
[20] M.R., Ghomashchi, "*High pressure die-casting: Effect of fluid flow on the microstructure of LM24 die-casting alloy*", J. Mat. Proc. Tech., Vol. 52, P 193-206,1995.