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The influence of pressure during solidification of high pressure die cast aluminium telecommunications components

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Abstract

The effects of process variables on the quality of high-pressure die cast components was determined with the aid of in-cavity pressure sensors. In particular, the effects of set intensification pressure, delay time, and casting velocity have been investigated. The in-cavity pressure sensor has been used to determine how conditions within the die-cavity are related to the process parameters regulated by the die casting machine, and in turn the effect of variations in these parameters on the integrity of the final part. Porosity was found to decrease with increasing intensification pressure and increase with increasing casting velocity. The delay time before the application of the intensification pressure was not observed to have a significant effect on porosity levels.

Keywords: Pressure sensors; Die casting; Porosity; Pressure

1. Introduction

High-pressure die casting involves injecting molten metal into a die at high velocity and pressure. High pressure die casting is an economical and efficient method for producing components requiring low surface roughness and high dimensional accuracy. High pressure die casting is widely used in the production of aluminium automotive components. Many telecommunication components, such as radio frequency (RF) filter box housings (Fig. 1), have traditionally been produced by high speed machining operations. A case study examining the development work undertaken to migrate the production of RF filter body housings from a high speed machining route to a high pressure die casting process is contained in [1]. High speed machining has been acceptable for small production volumes. However, the relatively low productivity makes costs prohibitive when higher production volumes are required. The die casting route has the potential to substantially reduce the manufacturing cost per component and provide the required productivity. High pressure die casting was found to offer superior productivity at substantially reduced cost, compared to machining [1]. However, specifications for these components are more demanding than the specifications for typical die-cast automotive components. Specifications for telecommunications components call for much tighter control of dimensional tolerances; lower and more consistent porosity levels; and a higher quality surface finish.

After the injection of molten metal into the die, rapid heat transfer into the die causes the casting to solidify at very high rates. After solidification the die halves open and the casting is ejected. The quality of a die cast part is defined by a multitude of parameters, including the material properties of the alloy, the process parameters and the design of the die and component. A die was designed and manufactured for the production of the filter box housing. A description of the component and die design process is included in [1,11].

The die was mounted on a Buhler 53 D Evolution 530 ton cold chamber high pressure die casting machine, using the Buhler Shot Control system [2]. The Buhler Shot Control system is based around a two-phase control system. Process optimisation with this type of control system allows for the variation of a wide range of operating parameters. The injection phase is reg-

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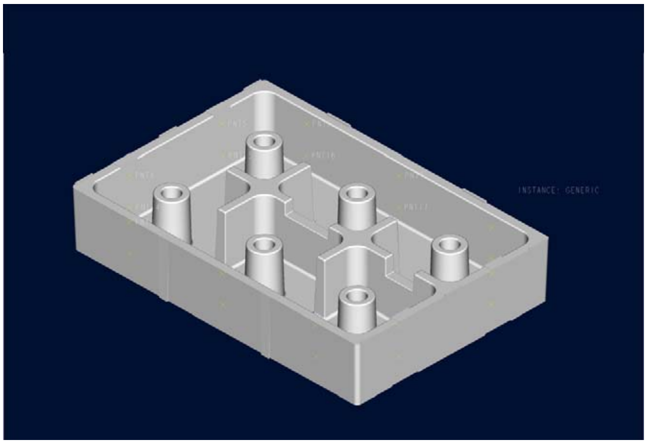

Fig. 1. A high pressure die cast radio frequency filter body (CAD Model).

ulated on the rod side ("meter-out") to control the metal velocity and subsequently, the cavity fill characteristics. In this system, the piston velocity is measured with a position/velocity sensor mounted directly on the injection ram. The injection profile can be defined with a large number of different set points. In the standard high pressure die casting process, cavity fill times are generally very short (0.020–0.100 s). Once the injection cycle is complete, the second pressure control phase of the operation is triggered from pressure built up in the hydraulics. It is during this pressure control phase that the high pressures characteristic of pressure die casting are applied to the casting.

It is generally believed that the effective application of this intensification pressure is crucial to the production of high integrity parts [3,4]. In production environments, in-cavity pressure is not often measured even though it is clear that actual in-cavity pressures can be much lower than those provided from the hydraulic system [3,5,10]. In the production of the filter box, it was clear that the demands for high product integrity required that the die casting process be optimised using in-cavity pressure measurements to ensure that a set of process operating parameters were adopted that resulted in optimum in-cavity conditions. In order to achieve this goal, a detailed industrial experiment has been carried out by modifying the production tooling to incorporate in-cavity pressure sensors and measuring the density of the RF filter body components after production. This paper describes the methodology and results of this investigation. A wide range of process parameters were investigated to determine an optimum set of operating parameters. Once the critical operating parameters were established, the in-cavity pressure sensors remained in the tooling for the production life of the component (∼30,000 parts). This enabled real time feedback to machine operators during manufacturing.

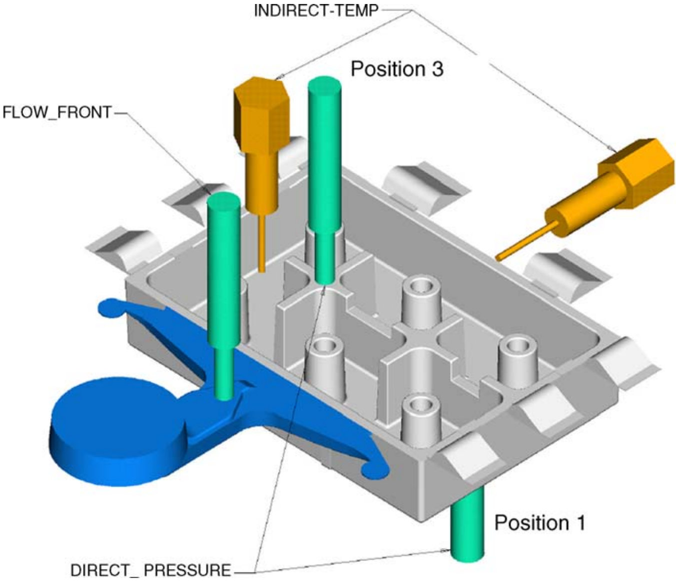

Fig. 2. Location of pressure sensors on the RF filter body casting.

2. Experimental procedure

A series of experiments was conducted to measure in-cavity pressure during the casting of aluminium alloy DA 401 and aluminium alloy CA 313 metal in a commercial high pressure die casting die used for the production of filter body casings. The nominal compositions of the alloys are presented in Table 1. Subsequent to these initial trials, a number of experimental production runs were completed to focus on the development of porosity as a result of in-cavity pressure.

In the current investigation, the effect of maximum applied pressure on the porosity levels of the final components is of primary interest. Consequently, after optimisation of the filling process, the pressure applied to the casting after cavity fill (so-called intensification pressure) was varied, along with the time delay before application of the intensification pressure. The injection velocity was varied over a range appropriate to the production of components. Three different set casting velocities were utilised during experimentation. These included set piston velocities of 1, 1.8, and 3.8 m/s. Set intensification pressures of 322, 674, and 900 bar (32.2, 67.4, and 90.0 MPa, respectively) were used for alloy DA 401, while for alloy CA 313 the set intensification pressures were 322, 674, and 866 bar (32.2, 67.4, and 86.6 MPa, respectively). In this paper, a "set" value refers to a value set by the Buhler SC control system.

3. Component geometry

The present investigations were carried out on a production die used to produce RF filter body components. The geometry of the RF filter body is illustrated schematically in Fig. 1. The piezo-electric quartz pressure transducers were designed for use up to temperatures of 700 °C and pressures of 2000 bar (200 MPa) [6]. The positions of the sensors on the filter body casting are illustrated in Fig. 2. The first set of investiga-

Table 1
Nominal alloy compositions by element wt.%

Alloy	Element wt.%											
	Al	Si	Fe	Cu	Mn	Mg	Pb	Ni	Zn	Ti	Sn	Cr
DA 401	Base	13.4	0.77	0.31	0.04	0.22	0.01	0.01	0.06	0.07	0.01	0.01
CA 313	Base	8.6	0.90	3.68	0.19	0.18	0.11	0.08	2.4	0.04	0.06	0.04

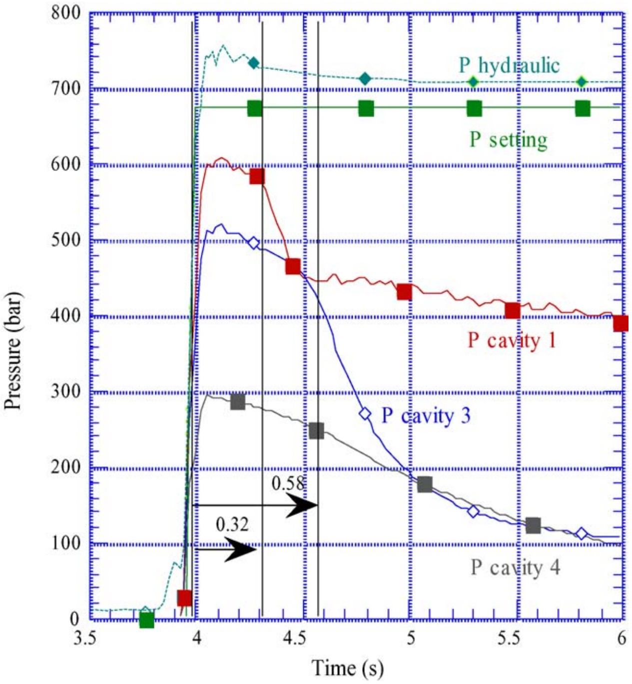

Fig. 3. Typical direct pressure measurement results from the sensors within the die cavity.

tions was undertaken with pressure sensors in both location 1 and 3. All pressure sensors were mounted flush with the cavity.

The response time of the pressure sensors is very short (7 μs according to the manufacturer [6]) and can provide the required information independent of the sensor's own dynamics. Fig. 3 is an example of typical pressure–time curves acquired from the pressure sensors.

The experimental method outlined in the following section was used to determine the fraction of porosity present in a collection of approximately 230 high-pressure die-castings, manufactured under the optimised process parameters. As part of this analysis, the data produced was used for the quality assessment of the filter body casting. In this instance, the components were cast from two different alloys; DA 401 and CA 313 (See Table 1 for compositional details). The most relevant information to be gained from this analysis is the effects of pressure, delay time, and casting velocity on the development of porosity within the castings.

4. Comparison between set and actual values of process parameters

The pressure sensors made it possible to determine the actual pressure within the castings and compare these readings to those set by the machine. Most notable from such a comparison is the amount of variation observed between set and actual measured intensification pressures. A graphical representation of the variation achieved between set intensification pressures and measured cavity pressures in location 1 for alloy CA 313 is shown in Fig. 4. The variation between the set pressure and the measured pressure increases as the pressure increases. The measured cavity pressure is much less than set pressure at a set pressure of 866 bar (86.6 MPa).

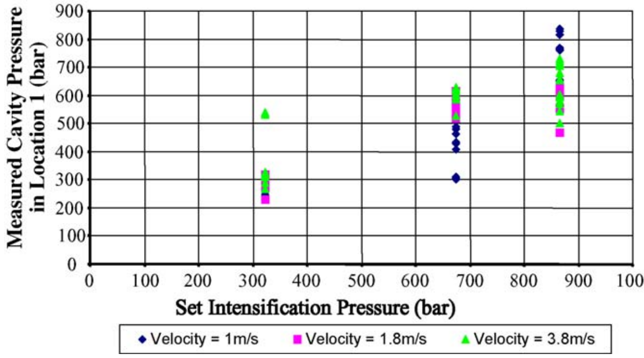

Fig. 4. Set pressure vs. maximum measured cavity pressure in location 1. (Alloy CA 313).

To determine the actual velocity of the piston during the second stage of metal injection, the machine incorporates a position/velocity sensor mounted directly onto the injection ram. This allows the actual piston velocity to be related to the development of porosity within the casting and it also allows comparison between the velocities actually encountered in the shot cavity and those supposedly set by the machine. Fig. 5 illustrates the relationship that exists between set injection velocity and measured injection velocity. In this instance, the variation witnessed is not excessive and it can be assumed that the small differences encountered do not affect the development of porosity.

The fraction of porosity in each casting was determined using Eq. (1) and (2).

$$\%P = \frac{\rho_{\text{apparent}} - \rho_{\text{th}}}{\rho_{\text{th}}} \tag{1}$$

$$\rho_{\text{apparent}} = \left(\frac{M_{\text{casting in air}}}{M_{\text{casting in air}} - M_{\text{casting in water}}}\right) \times \rho_{\text{water}} \tag{2}$$

where ρ_{apparent} is the apparent density of the casting; ρ_{th} the theoretical density of the alloy, $M_{\text{casting in air}}$ the mass of the casting in air; $M_{\text{casting in water}}$ the mass of the casting in water; and ρ_{water} the actual density of water at the specified temperature.

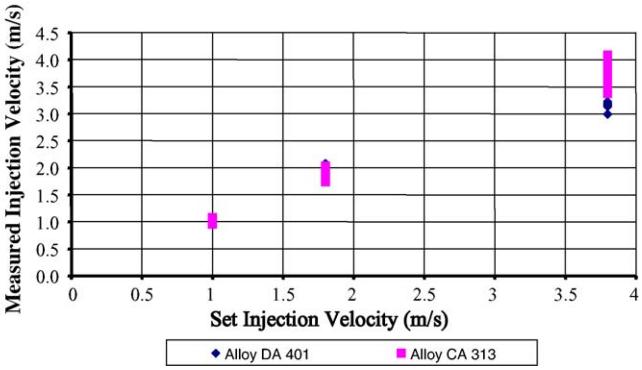

Fig. 5. Set injection velocities vs. measured injection velocities.

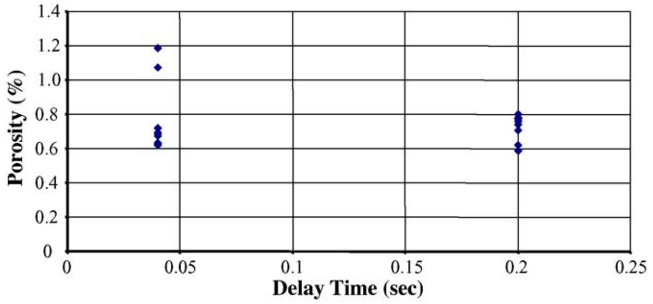

Fig. 6. Delay time vs. fraction of porosity in DA 401 castings produced with a set intensification pressure of 900 bar and an injection velocity of 1 m/s.

5. Results

The results presented in the following sections outline the trends that exist between important variables contributing to the development of porosity in high-pressure die-castings.

5.1. Delay time trends

Figs. 6 and 7 display the measured porosity levels associated with the two delay times for a DA 401 casting batch and a CA 313 batch, respectively. It is evident from the data in Figs. 6 and 7 that delay time has little effect on porosity levels for the range of delay times investigated. Despite this Fig. 7 appears to indicate a trend of increasing porosity with increasing delay time although the correlation is not obvious. Although these plots depict the behaviour exhibited by different alloys, the trends are representative of the entire experimental catalogue.

5.2. Pressure and velocity effects

5.2.1. Pressure in mould cavity location 1

Figs. 8 and 9 illustrate the trends associated with porosity levels over a range of maximum pressures measured in the mould cavity at location 1 for alloy CA 313 and DA 401, respectively. It appears that for all three piston velocities, porosity decreases with increasing pressure in the cavity. It is expected that as pressure increases the fraction of porosity should decrease [3]. The data for alloy CA 313 appears more variable than the data for alloy DA 401, perhaps indicating the presence of secondary effects, possibly related to the formation of copper-containing phases at relatively low temperatures.

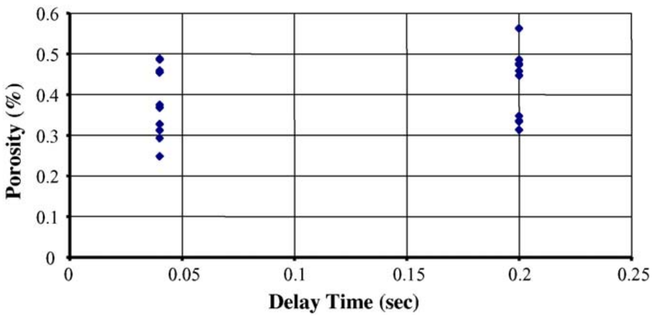

Fig. 7. Delay time vs. fraction of porosity in CA 313 castings produced with a set intensification pressure of 674 bar and an injection velocity of 1 m/s.

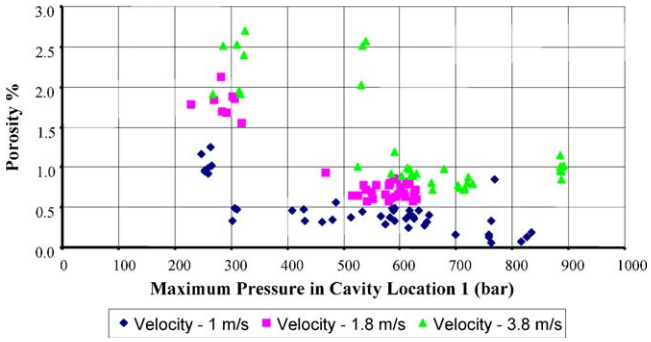

Fig. 8. Fraction of porosity as a function of maximum in-cavity pressure at location 1 (CA 313).

5.2.2. Pressure in mould cavity location 3

Figs. 10 and 11 show the effect of maximum pressure in the mould cavity at location 3 on the fraction of porosity present for the three piston velocities. Location 3 is a region of the casting that is to be subsequently drilled and tapped, and therefore provides important parameter information to ensure casting integrity. The data appears to indicate the trend of decreasing porosity with increasing intensification pressure. No convincing trends relating porosity to casting velocity are evident. In

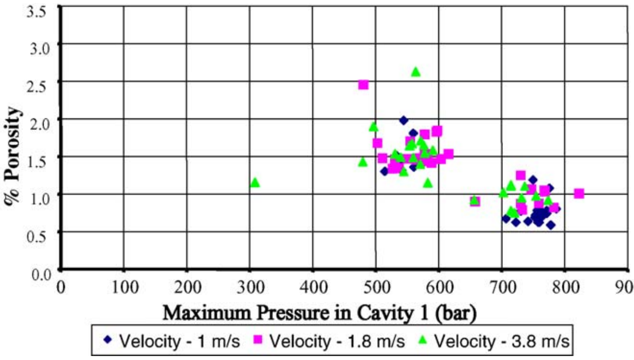

Fig. 9. Fraction of porosity as a function of maximum in-cavity pressure at location 1 (DA 401).

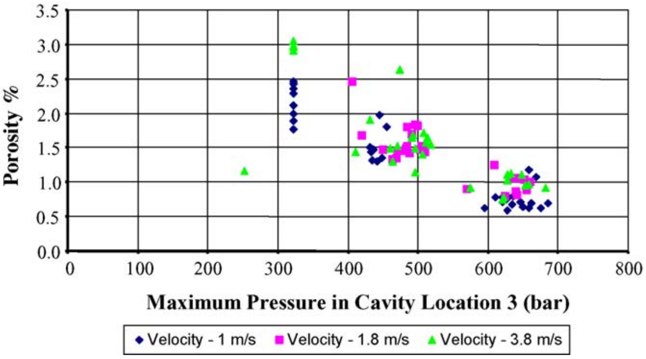

Fig. 10. Percentage porosity as a function of maximum in-cavity pressure at location 3 (DA 401).

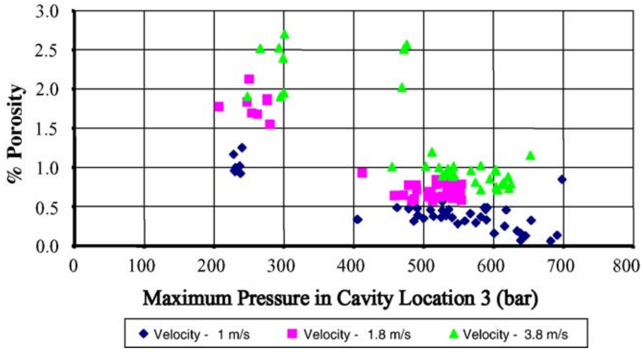

Fig. 11. Fraction of porosity as a function of maximum in-cavity pressure at location 3. (Alloy CA 313).

Fig. 11, at low pressures, porosity increases with velocity. However at high pressure velocity does not affect porosity.

5.2.3. *Set pressure trends*

As indicated previously, there is appreciable deviation between set casting pressures and measured casting pressures in some instances. It is necessary to determine if the deviation affects the trends observed in porosity levels. This may indicate whether set pressure can be reliably used as a process control variable.

Fig. 12 illustrates the dependence of porosity on the set casting pressure for alloy DA 401. These data appear to indicate a trend of decreasing porosity with increasing pressure for various set intensification pressures. The relationship appears almost linear and is in good agreement with trends observed for the measured pressure levels. These data also appears to show that casting velocity does not significantly affect porosity at higher pressure. However, it appears that, for lower pressures, porosity may increase with casting velocity.

The plot in Fig. 13 demonstrates the relationship between porosity and set casting pressure for alloy CA 313. The data appear to show that porosity decreases when set casting pressure is increased from 322 to 674 bar (32.2–67.4 MPa) but plateaus as the pressure is increased to 866 bar (86.6 MPa), in general agreement with the results from the measured pressure. These data appear to show that porosity may increase as the injection velocity increases. To fully describe the effect of casting velocity on porosity, more data needs to be collected using a greater variety of casting velocities.

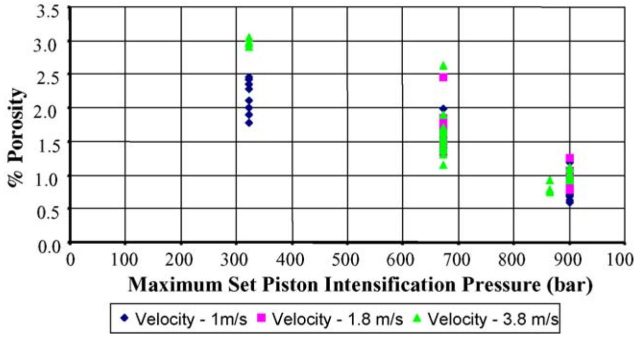

Fig. 12. Percentage porosity as a function of maximum set intensification pressure (DA 401).

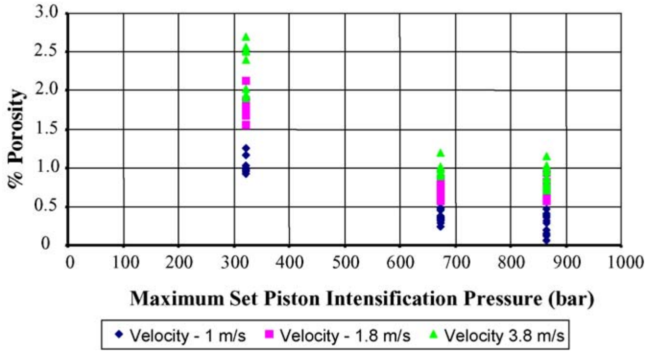

Fig. 13. Fraction of porosity vs. set intensification pressure for Alloy CA 313.

In order to determine whether or not porosity levels are affected by the metal injection velocity, Figs. 14 and 15 have been formulated. These figures present the same data as Figs. 12 and 13, however the porosity levels are shown as a function of the casting velocity rather than the intensification pressure.

Figs. 14 shows the effect of metal injection velocity on porosity levels for two different set pressures using alloy DA 401. Measured casting velocities at a set pressure of 322 bar (32.2 MPa) are not available and therefore cannot be included on the plot. These data appear to indicate that porosity increases with increasing casting velocity. However, the variability in the

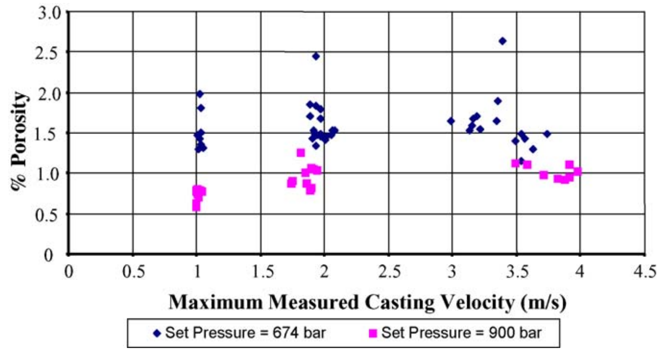

Fig. 14. Percentage porosity as a function of maximum measured casting velocity. (DA 401).

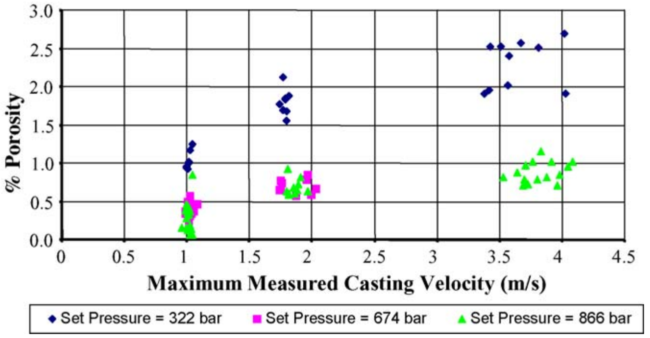

Fig. 15. Fraction of porosity as a function of measured casting velocity. (Alloy CA 313).

data is large and more data would be required to accurately demonstrate this trend.

Figs. 15 shows the effect of metal injection velocity on porosity levels for alloy CA 313. This data appears to indicate that increasing casting velocity increases porosity at the lower set pressure. At the higher set pressures, the results are less conclusive.

6. Discussion

This experimental programme has shown that cavity-mounted pressure sensors provide useful data to optimise the high pressure die casting process. Strategic placement of pressure sensors in the cavity can enable parameters such as piston velocity, intensification pressure and delay time to be optimised for a particular die design. Once the optimal operating window for the process parameters has been determined, the pressure sensors provide a reasonably inexpensive method to perform on-line process control and verification of the quality of the cast components. The divergence in the machine settings and the measured values of parameters make in-cavity pressure sensors a necessary feature to perform rational optimisation of the die-casting process. Further, without in-cavity sensors, the divergence of set and actual parameters makes on-line process control less straight forward.

Fig. 4 shows that the actual measured pressure is lower than the set intensification pressure. The measured pressure should be maintained within the die cavity provided the intensification can be transmitted into the die cavity. This is dependent on the solidification time of the gate [7]. Once the gate becomes fully solid, the pressure from the die casting machine hydraulic system can no longer be transmitted to the metal in the die cavity. This is probably the reason for the measured pressure being lower than the set pressure.

The lack of a relationship between delay time and porosity levels may be a result of gate freezing affecting pressure in the die cavity as well. It would be expected that as the delay time increases the porosity would increase. However, no relationship between delay time and porosity was observed in Figs. 6 and 7. This suggests a more important process variable may be the gate freezing time. More work is required to better understand the relationship between these variables.

Porosity levels in high pressure die cast radio frequency filter bodies have been shown to decrease with increasing intensification pressure. The relationship between porosity levels and intensification pressure appears to be dependent on the alloy composition. Alloy CA 313 appears to show more variable behaviour than alloy DA 401. This may reflect the longer freezing range of the former. The relationship between porosity levels and shot piston velocity is less clear.

The piston velocity may affect porosity levels through the flow properties of the liquid metal. As the velocity of the liquid metal front increases the flow becomes more turbulent. As a result gases and oxides may become entrapped in the liquid metal [8]. Porosity was observed to increase with increased piston velocity in the CA313 alloy at a set pressure of 322 bar (32.2 MPa). At the higher pressures, in both alloys, this trend appeared much less pronounced. This may indicate that the applied pressure reduces the driving force for pore nucleation and growth. Further, the higher applied pressure is likely to be significantly greater than the increase in the equilibrium pressure of the dissolved gases caused by the entrainment of air.

Pore growth is governed by Eq. (3). Theoretically, a pore will grow if the combined effect of the gas pressure and the solidification shrinkage is larger than the sum of applied pressure, metallostatic head and surface tension.

$$P_{\mathrm{g}} + P_{\mathrm{S}} \geq P_{\mathrm{app}} + P_{\mathrm{H}} + P_{\mathrm{s\text{-}t}} \tag{3}$$

where: P_{g} is the equilibrium pressure of dissolved gases; P_{S} is the pressure drop due to solidification shrinkage; P_{app} is the applied pressure; P_{H} is the pressure due to metallostatic head; and $P_{\mathrm{s\text{-}t}}$ is the pressure due to pore-liquid surface tension.

Further, a pore nucleus of radius, r, will only grow if it is larger than the critical radius r_{C}, Eq. (4) [9].

$$r \geq r_{\mathrm{C}} = \frac{2\sigma}{P_{\mathrm{g}} - (P_{\mathrm{app}} + P_{\mathrm{H}} + P_{\mathrm{S}})} \tag{4}$$

where: σ is the surface tension $\left(P_{\mathrm{s\text{-}t}} = \frac{2\sigma}{r}\right)$.

Thus, the amount of porosity is expected to be inversely proportional to the applied pressure increases (i.e. the intensification pressure). This is supported by the relationships observed between porosity and pressure. It appears that porosity decreases proportionately less for the increase in set intensification pressure from 674 to 900 or 866 bar than for the increase in set intensification pressure from 322 to 674 bar. If it is assumed that the number of heterogeneous pore nucleation sites remains constant over the range of experimental parameters, it is clear from Eq. (4) that the size of the pores, and hence the amount of porosity, is not linearly proportional to the applied pressure.

The final quality of a high pressure die cast component appears to be influenced by the interaction between the metal injection velocity and the pressure within the cavity. As the injection velocity increases the flow of metal into the die cavity becomes more turbulent, possibly leading to the entrainment of oxides and gases, and an increase in porosity. However, the application of intensification pressure may help to ameliorate the potential increase in porosity by restricting pore growth.

7. Conclusions

From the data collated and presented there are a number of observations that can be made. It appears evident that for the delay times studied, the delay time prior to application of intensification pressure has no significant effect on the development of porosity within castings. This is, however, assuming that the delay times utilised are within certain limits set by the solidification times characteristic of the particular alloy being cast. Typical delay times that were experimented with in this instance were only in the vicinity of 0–0.2 s.

It is apparent that the fraction of porosity present in a casting generally decreases as the pressure inside the die cavity increases. These trends conform to the expected outcome.

Although more data needs to be collected before one can make a confident statement about the effects of casting velocity on porosity development, the data available indicates that as casting velocity increases, so does the fraction of porosity present in a casting. The reasons for this may lie in the effects of turbulent flow causing the entrapment of oxides and gases and the rapid solidification in certain sections of the castings resulting in shrink or gas porosity.

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