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The Influence of In-Cavity Pressure on Heat Transfer and Porosity Formation During High-Pressure Die Casting of A380 Alloy

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This paper is concerned with the measurement of thermal properties and in-cavity pressures in cold chamber high-pressure die casting. The influence of in-cavity pressure on the casting porosity, heat flux, and heat transfer coefficient has been investigated during die casting of an A380 alloy. The die was instrumented with heat transfer and pressure sensors to measure these values directly. Direct measurement of the in-cavity pressure was found to be more reliable than the metal pressure calculated from pressure measurements in the hydraulic system. Variations on the intensification pressure directly affect the in-cavity pressure. Changing the intensification pressure between 17 MPa and 90 MPa had little effect on the heat flux and heat transfer which likely reach saturation at a lower pressure during the rapid filling stages. Increases in intensification pressure reduced the level of porosity within the castings, being most effective up to a value of 67.4 MPa.

INTRODUCTION

Radio frequency (RF) filter bodies, gearboxes, transmission cases, and cam covers are examples of components suitable for production using high-pressure die casting (HPDC).¹ This range of light-weight aluminium structural parts are ideal candidates for HPDC,² because this casting method is highly suitable for the production of components with a good surface finish in reasonable volumes. The mechanisms of heat transfer during the process control both the life and the condition of the die and part quality.^{3,4} Dies being used in HPDC are generally made of tool steels of type 1.2344 (AISI H13) or 1.2343 (AISI H11). These types of tool steels are used for their dimensional stability and high mechanical strength at elevated temperatures along with good toughness and resistance to thermal shock and thermomechanical fatigue.

Good thermal balance within the die can only be maintained with a sound understanding of processing and its relationship with productivity while reducing the thermal stresses within the tool.³ Over time, these thermal stresses result in heat checking and deterioration in the quality of the die surface. This in turn results in deterioration in the surface quality of the part and shortens its lifespan. In the case of RF filter bodies, this results in a dramatic decrease in the performance of the part. It is important, therefore, to change the processing conditions so as to minimize the effects of thermal stresses on the die, while still maintaining a highly reproducible and productive process. In practice, this has been a difficult task within a manufacturing environment, without a dedicated sensor to measure heat transfer characteristics during the real production process and over the large number of production cycles.

Die casting is a rapid and dynamic process which makes it difficult to characterize and control the heat transfer and pressure environment. Despite this, a number of studies have been undertaken

using thermocouple arrays to measure thermal gradients and heat fluxes in dies during HPDC.⁵⁻⁷ Using the configurations described in such studies, the die surface temperature can be measured at all times during the casting cycle. From the measured data, the die surface temperature and the heat flux delivered to the die can be calculated. Performing accurate thermal measurements in HPDC tools is a difficult task, very dependent on the size, location, and orientation of thermocouples used in the heat transfer measuring devices. The incorrect selection, assembly, and analysis of data from such probes can lead to significant errors.^{8,9}

In the present investigations, a specifically designed high-temperature probe reported previously by the present investigators⁸⁻¹¹ has been used to analyze the heat transfer environment during HPDC. The probe utilizes an array of fine thermocouples with fast response times located at different locations within the die to determine the temperature on the surface of the die. This is combined with a pyrometer connected to a fiber optic cable that can be used to determine the temperature of the surface of the casting.¹²

HPDC involves the application of pressure at a number of stages of the process, with a particular intensification in the final stage which is considered essential for the production of high-quality parts.¹³⁻¹⁵ However, the actual pressure encountered by the casting is rarely measured, but is expected to be much lower than machine-set values.^{13,16} The effect of pressure on the quality of cast components has also been investigated by several authors.^{6,15,17-19} The current authors have also reported on the effect of pressure on porosity in castings.²⁰ Other investigators have recently presented studies examining the effect of filling velocity on heat transfer properties.²¹ However, these previous studies have not concurrently accurately measured both heat transfer parameters, pressure, and porosity. The current investigations presented in this paper show that in-cavity pressure and heat transfer sensors can be used as a tool to maintain optimum in-cavity conditions, which are necessary to maintain high-quality castings. In-cavity pressures have also been recorded during the measurement of heat transfer data during the die-casting process. This enables actual in-cavity pressure measurements to be compared with heat transfer measurements directly, rather than inferred from

metal pressure readings calculated from hydraulic pressures, as is commonly provided through standard machine control and process monitoring equipment. Previous research has also shown that there is significant variation of in-cavity pressure (lower than the tip pressure) for a given set of intensification pressures.²⁰

The coupling of in-cavity pressure and heat transfer measurements enables a much more accurate determination of the effect of process parameters, such as set intensification pressure on heat transfer. A study directly correlating pressure with heat transfer and porosity using accurate sensors has not been reported. Therefore, the prime focus of these investigations was to determine the relationship between in-cavity pressure and heat flux and heat transfer during die casting. In addition, the in-cavity pressure measurements were correlated against porosity levels within the casting.

EXPERIMENTAL PROCEDURE

Temperatures in two high-pressure die-casting dies were measured at different locations in the die when casting the common A380 alloy (Al-8.9 wt.% Si-3.68 wt.% Cu-2.4 wt.% Zn-0.9 wt.% Fe-0.19 wt.% Mn-0.18wt.% Mg). Pressures within the cavity and the surface temperature of the casting were also measured by the heat transfer sensor.

The experiments were designed to measure concurrently both in-cavity pressure and temperatures at different depths in the tool steel and on the surface of the casting. The experiments were conducted with a prototype die mounted on a cold-chamber HPDC machine. The die was built from X38CrMoV-5 (EN/DIN 1.2344, AISI H13) hot-work tool steel. The chemical composition of the die is shown in Table I.

The experiments were conducted on an experimental die mounted on a TOSHIBA 250-tonne clamping force cold-chamber machine. The die was used to produce the prototype casting shown in Fig. 1. During casting, the position of the piston tip that injects the liquid metal into the die was measured to a resolution of 1 μm , and these displacement measurements were used to calculate piston velocity. The die was modified to incorporate two pressure sensors and two heat transfer sensors in the positions shown in Figs. 1 and 2.⁸ The heat transfer and pressure sensors were located opposite each other in order to accurately compare both the

Table I. Chemical composition of X38CrMoV-5 steel (EN/DIN 1.2344, AISI H13)

| Element % | C | Mn | Si | S | P | Cr | Mo | V | Fe |
|------------|-------|------|------|---------|-------|------|------|------|---------|
| X38CrMoV-5 | 0.396 | 0.36 | 0.94 | < 0.003 | 0.009 | 5.05 | 1.25 | 0.47 | Balance |

local in-cavity pressure and the heat transfer data at the gate and rib locations within the casting, as illustrated in Fig. 2.

Die fill times are very short (0.020–0.100 s) during HPDC, followed by a longer high-pressure intensification stage. Special pressure sensors with rapid response times have been incorporated into

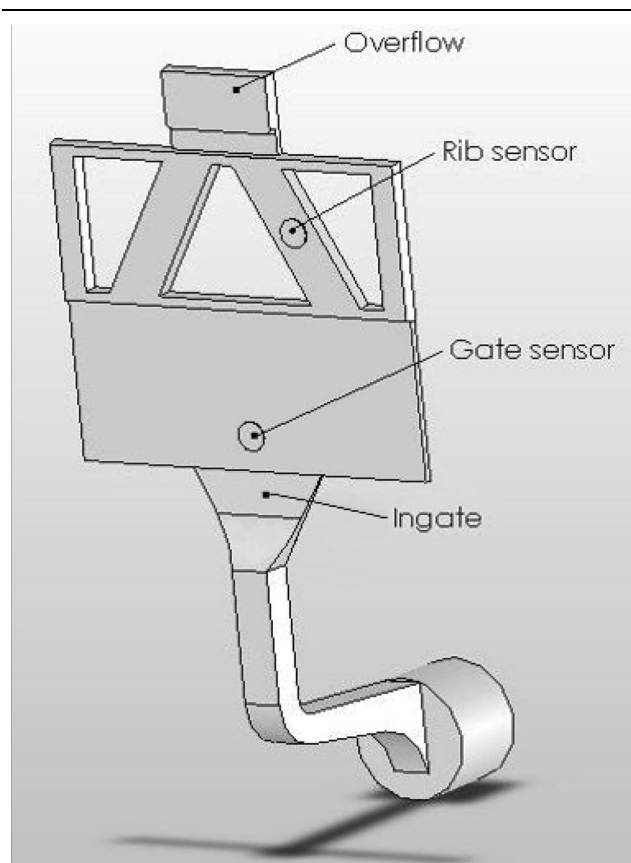


Fig. 1. Sensor locations in the instrumented die having a plate thickness of 2 mm and the rib region thickness of 5 mm, showing the location of the sensors. The pressure sensors were in the moving die, while the heat-flow sensors were directly opposite in the fixed half of the die (Reprinted with permission from Ref. 12).

similar experimental measurements, as described previously.⁸ The response time of the pressure sensors was very short ($\sim 7 \mu\text{s}$). A schematic of the heat transfer sensor and its geometry is shown in Fig. 2. The geometry of the heat transfer sensor was designed to be the same as the pressure sensor, in order that the two types of sensors could be easily interchanged in the same production die. The pressure sensors and the heat transfer sensor were installed opposite each other in the cavity, at movable and fixed die sections. This allowed for a direct comparison of the in-cavity pressure with the heat transfer data. All the sensors were mounted flush with the cavity and calibrated before use. The set intensification pressures were 32.2 MPa, 67.4 MPa, and 90.0 MPa, which were based on the hydraulic pressures. These pressure values are expected to differ substantially for actual pressures experienced by the casting.

The heat transfer sensor consists of a pyrometric chain (optical fiber + pyrometer) for measurement of the surface temperature of the aluminium casting, along with an array of very fine thermocouples (K-type, 0.25 mm in diameter having a response time of 10 ms). The thermocouples are located at different depths from the die cavity surface (1 mm, 10 mm, and 20 mm using a graphite or silver-based thermal paste) and orthogonal to the direction of the maximum heat flow, as illustrated in Fig. 2. The sensor housing is fabricated from the same H13 Tool steel (temper and composition) as the parent die. The temperature data from the thermocouples contained in the sensor were analyzed using an inverse model in order to determine the heat flux density and the die surface temperature.^{8,22} The alloy surface temperature data obtained with the pyrometric chain are then combined with the die surface temperature data to produce values for the heat transfer coefficient h according to the relationship shown in Eq. 1:

$$h(\phi(x, t), T_c, T_{\text{die}}) = \frac{\phi(x, t)}{T_c - T_{\text{die}}} \quad (1)$$

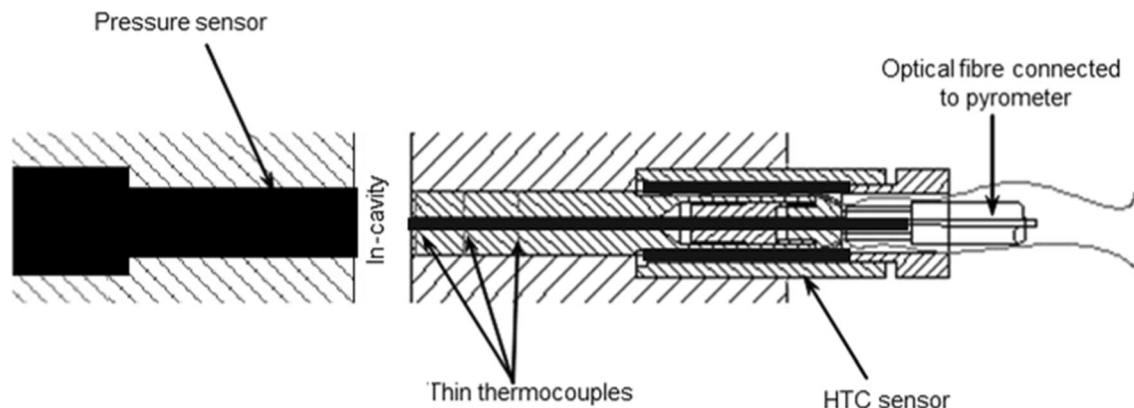


Fig. 2. The configuration of the heat transfer sensor and pressure sensor in both rib and gate positions (Reprinted with permission from Ref. 12).

RESULTS

where (x, t) is the heat flux through the interface and T_c and T_{die} are the surface temperatures of the casting and the die, respectively. A detailed description of the sensor and the data analysis process has been provided in previous publications.^{8,22}

A total of 502 castings of alloy A380 (Al-9wt.%Si-3wt.%Cu) were produced during this second series of experiments. The data obtained from all castings were analyzed and the density of each casting measured. The die cavity filling process was first optimized using standard techniques, and then the maximum pressure applied to the casting during solidification was varied in order to determine the influence of in-cavity pressure on porosity formation and heat transfer characteristics during casting.

The effectiveness of the intensification process in minimizing defects in the castings was determined by measuring the porosity (Eqs. 2 and 3):

$$\%P = \frac{\rho_{th} - \rho_{apparent}}{\rho_{th}} \times 100 \quad (2)$$

$$\rho_{apparent} = \left(\frac{M_{casting\ in\ air}}{M_{casting\ in\ air} - M_{casting\ in\ water}} \right) \times \rho_{water} \quad (3)$$

ρ_{water} is the room temperature density of water, $\rho_{apparent}$ is the measured density of the casting, ρ_{th} is the theoretical density of the alloy, $M_{casting\ in\ air}$ is the mass of the casting in air, and $M_{casting\ in\ water}$ is the mass of the casting in water.

Examples of the typical sensor measurement curves produced during the 502 A380 casting cycles are presented in Fig. 3. The data provided are comprehensive, with pressures and temperatures recorded at high sampling rates, as labeled in Fig. 3. The sensor reliably records detailed information during the filling and intensification cycles from slow liquid/semi-liquid metal entry into the cavity, followed by rapid fill and pressure intensification. The filling of the die cavity corresponds to a sharp increase in the in-cavity and tip pressure curves, as can be seen in Fig. 3, which also shows a rapid rise in temperature for thermocouples close to the die surface, followed by a delayed temperature rise for the thermocouples at a distance from the casting/die interface. The pressure drop with time is due to the effectiveness of the pressure transmission to decrease. The rib position solidified before the gate positions, according to the design of the casting. This is the reason for which the pressure drops firstly and more sharply at the rib position and then at the gate, as can be seen from Fig. 3. The pressure applied by the piston (the tip pressure) does not change significantly with time.

Heat Transfer Results

The temperature data presented in Fig. 3 were further analyzed using a previously reported

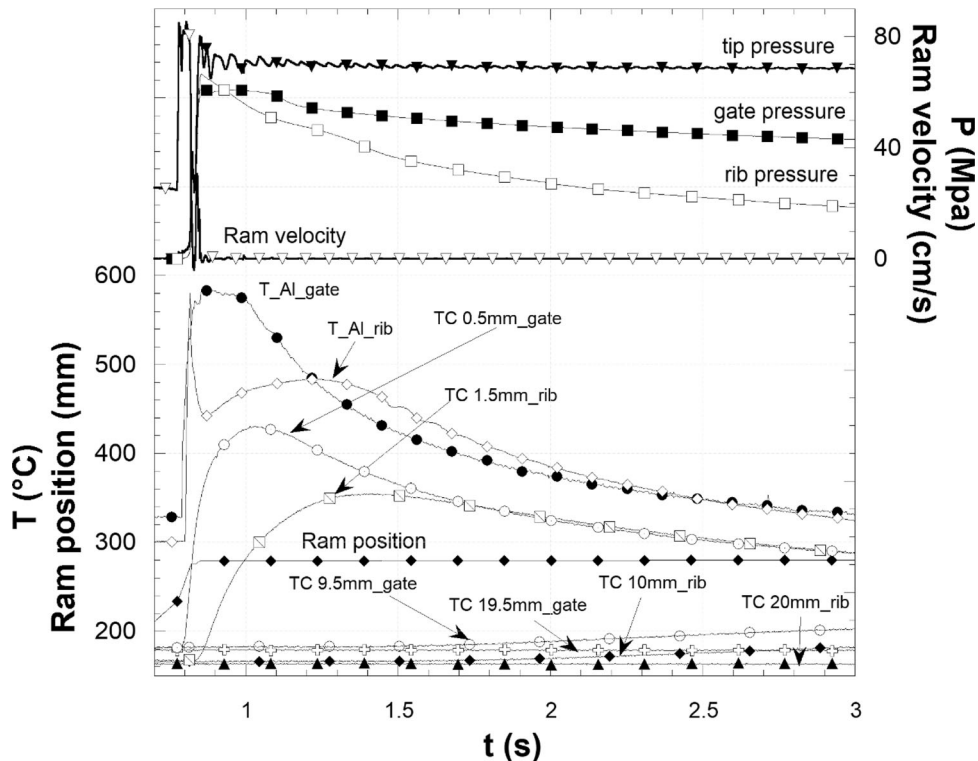


Fig. 3. Some typical raw results for the A380 alloy. Initial alloy temperature was 680°C; shot speed = 0.84 m/s; ingate velocity = 50 m/s; nominal intensification pressure = 80 MPa.

inverse model approach,⁸ and the processed data of the interfacial heat flux density, q , and the heat transfer coefficient, h , versus time are presented in Fig. 4.²³ The analysis clearly shows good agreement between the measured and the recalculated temperatures. Table II also summarizes the results in terms of peak values.

Influence of the Fill Velocity, Intensification Pressure, and the Delay on Heat Transfer Measurements

The results summarized in Figs. 4, 5 and 6 show that the heat transfer properties are predominantly determined by the velocity and the die temperature, and that the effect of intensification pressure on heat transfer is very small compared to these parameters.

The effect of intensification pressure on heat transfer was performed with the A380 alloy. The maximum heat transfer coefficient and heat flux values have been plotted against the maximum in-cavity pressures, as shown in Fig. 5a and b. These plots show that, for a large number of castings, increasing the pressure has no significant effect on the heat transfer coefficient.

Effect of Pressure on Porosity

In-cavity pressure sensors have also been used to measure in-cavity pressures which are then

correlated against porosity content in the A380 alloy castings. Measured pressures are always lower than hydraulic pressure at the piston tip, as shown in Fig. 5, and previously reported with a different die geometry.²⁴ The results presented in Fig. 6 show that increasing intensification pressure decreases the porosity in the castings, which is most likely because the applied pressure restricts pore formation and growth.

DISCUSSION

These investigations show that the metal pressures calculated from the pressure measured in the hydraulic system of the HPDC machine are inaccurate for use as a process control variable. There is an appreciable deviation between pressures measured at the shot end (tip pressure) compared to actual pressures measured within the die cavity during solidification of aluminium alloys. Figure 3 compares the calculated metal pressure derived from a force measurement at the shot end of the die-casting machine compared to the actual pressure measured at two positions within the cavity. This figure shows quite clearly that in-cavity pressures are significantly lower than that measured at the piston tip and that the pressure at the gate position is higher than that at the rib for a substantial time after the cavity is full. A clear relationship between in-cavity pressures and component quality was identified with higher in-cavity pressures corresponding to a

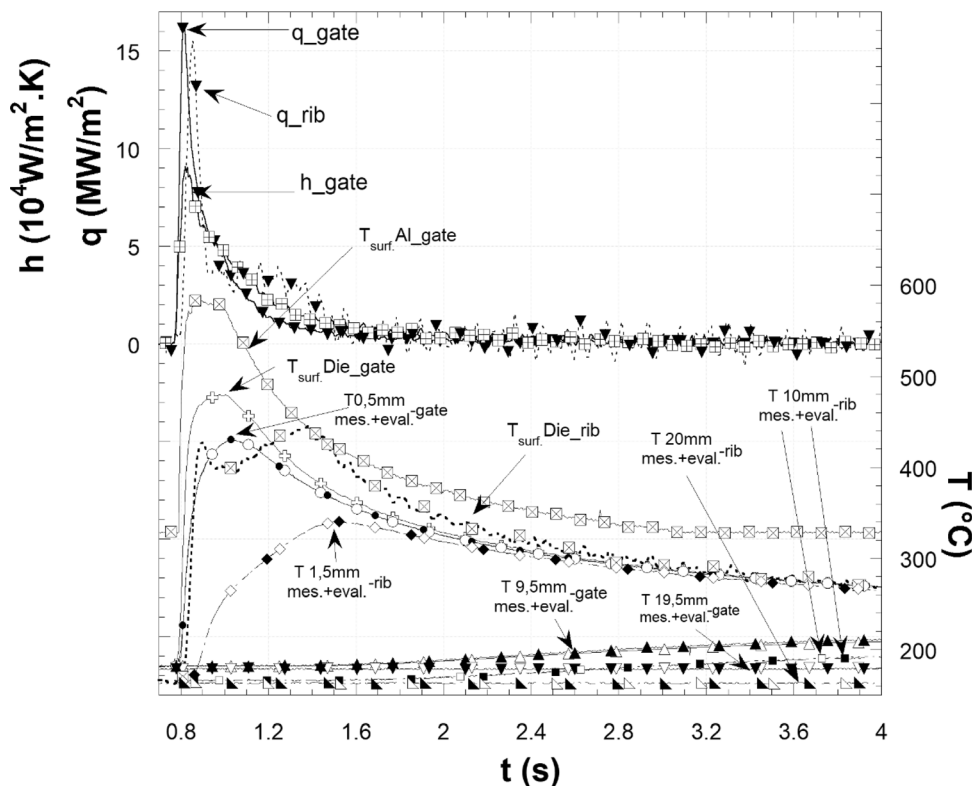


Fig. 4. Heat transfer results for the A380 alloy calculated using the inverse model approach. Data correspond to the casting shown in Fig. 1 (produced from data presented in Fig. 3).

Table II. Summary of the key results

| Position | Die surface temp. (°C) | Peak h (kW/m ² .K) | Peak q (MW/m ²) | Residual (°C) |
|----------|------------------------|---------------------------------|-------------------------------|---------------|
| Gate | 475 | 90 | 17 | < 3 |
| Rib | 440 | Not measured | 16 | < 2.5 |

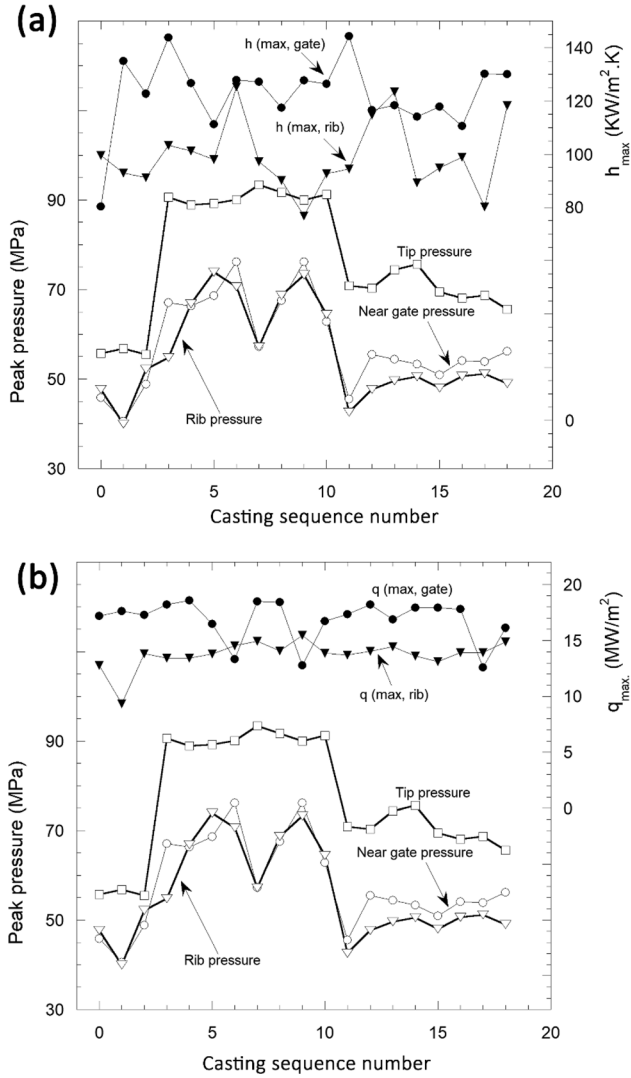


Fig. 5. Maximum heat flux and heat transfer coefficient versus maximum in-cavity pressure values at (a) the gate position and (b) the rib position. Data correspond to the casting (A380 alloy) shown in Fig. 4.

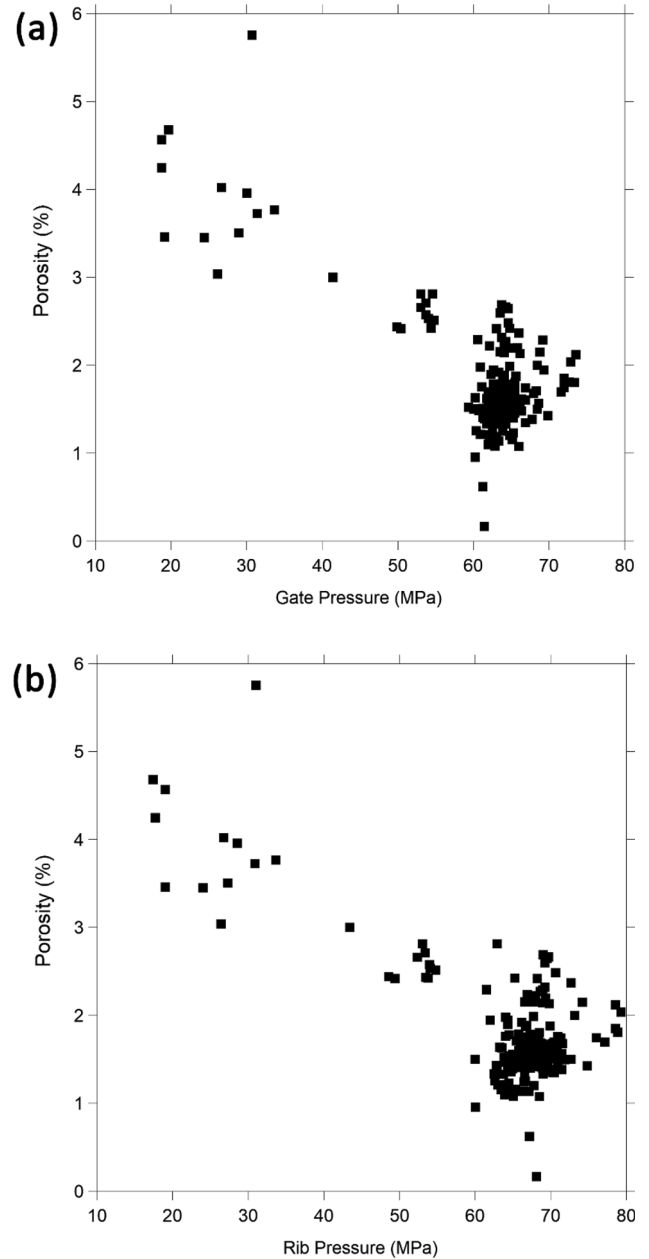


Fig. 6. Maximum in-cavity pressure versus porosity for A380 alloy castings at (a) the gate position and (b) the rib position.

decrease in porosity, as shown in Fig. 6a and b. These results and conclusions are supported by previously reported studies by other investigators.^{25,26}

It has been shown (Fig. 5a and b) that varying the intensification pressure during solidification has no measurable effect on either the heat transfer coefficient or the heat flux density. In the first 2.5 s of the casting process, the curves are very similar

whether the maximum pressure applied is around 33 MPa or 90 MPa (in the curves, it corresponds to around 20 MPa and 60–70 MPa, real pressure measured by the pressure sensor at the gate and rib positions of the cavity). It is clear from the results that there is very little effect of pressure on heat

transfer in this range, which is in agreement with the work by Özisik (Ref. 27), who has reported that saturation occurs at about 5 Mpa, which is much lower than the pressure values achieved during the high-speed filling cycles of high-pressure die casting presented in the present study. For the case of solidifying aluminium alloys, the saturation value also appears to be much lower than 17 Mpa, otherwise, an increase in heat transfer parameters with intensification pressure should have been observed in these experiments. This observation is most probably because the effect of pressure has been fully limited by the mechanical contact constraints imposed by the mushy zone and progressive solidification. This is a significant finding which casts doubt on the commonly held assumption that high intensification pressure improves heat transfer during HPDC, and therefore improves process efficiency.

This investigation has therefore shown that intensification pressure has a limited effect on heat transfer, which is a key driver for productivity, and that the velocity of the molten metal (this involves significant contact pressures but much lower than those encountered during solidification) and the die temperature dominate the heat transfer process. This study has also shown that the intensification pressure remains an important consideration in reducing porosity formation, by restricting pore formation and growth after solidification has commenced.

CONCLUSION

The effects of in-cavity pressure on heat transfer characteristics and porosity when high pressure die casting the A380 alloy has been reported in this paper. Measuring the in-cavity pressure directly by use of a pressure transducer is more reliable as a process control parameter than theoretical values calculated from pressures in the hydraulic system.

The heat flux density and heat transfer coefficient between the die and the melt during solidification could not be increased by applying higher intensification pressures in the range of 17–90 MPa. These heat transfer values are likely to have reached saturation at a lower pressure during the rapid filling stages of the casting process. Varying the delay between the die fill and applying intensification between 29 ms and 200 ms also had little effect on heat transfer. Increases in the intensification pressure within this range did, however, reduce the level of porosity, being most effective up to a value of 67.4 MPa.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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