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The Accurate Determination of Heat Transfer Coefficient and its Evolution with Time During High Pressure Die Casting of Al-9 %Si-3 %Cu and Mg-9 %Al-1 %Zn Alloys**

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High pressure die casting (HPDC), in which molten metal is injected into a die at high velocity and pressure, is an efficient method for the rapid production of low cost components requiring high dimensional accuracy.[1] In high pressure die casting an intensification pressure is applied to the solidifying casting after the cavity filling stage is complete. Higher heat transfer rates result in higher productivity in the die casting process along with finer microstructure with superior part qualities. A sound knowledge of the interfacial heat transfer coefficient is a critical consideration in understanding and Modelling the development of microstructure during high pressure die casting.[2] Solidification Modelling is used extensively in the design of suitable tooling for the die casting process. Tooling represents a significant cost to the die casting process. An effective die design is critical to production of high quality components and an optimized cycle time. Good die design will ensure optimum cycle times and extended tool life. Numerical simulation in the form of solidification Modelling has become an increasingly important tool in the design of dies for pressure die casting in order to reduce rework and provide a deeper understanding of the thermal conditions present throughout the die. The effectiveness of this simulation is however highly dependent on the accuracy of the heat transfer data utilized by the model.[3]

Currently heat transfer measurements are rarely performed in high pressure die casting and the heat transfer data is both difficult to find and the data that is available may be in a form that is not suitable for numerical simulation or the Modelling of microstructural development.[3–6] The large number of complex and often interrelated physical phenomena occurring during every production cycle makes the analysis of heat flow during the die casting process very difficult. Some measurements of interfacial heat transfer parameters during gravity permanent mould casting have been performed in experimental studies[4–7] but the heat transfer coefficient from permanent mould casting under atmospheric conditions (typically ~ 5 kW/m^2K for Al-Si alloys) are much lower than that which could be expected for high pressure die casting conditions. A small number of temperature measurements related to the determination of heat flux have been attempted in high pressure die casting.[8–11] One investigation reported only on heat transfer in the shot sleeve before the die filling process had commenced.[11] Others have reported single values for the Heat Transfer Coefficient (HTC) with no determinations of HTC or heat flux variation with time.[10] Some heat flux determinations have been reported but these investigations have also been limited in scope with no calculation of heat transfer coefficients or determination of the change of HTC and heat flux with time.[8,9] Most importantly none of these studies have provided an accurate determination of the evolution of the heat flux and heat transfer coefficient with time and in particular have not measured concurrently in-cavity pressures at the same locations as the heat transfer measurements. Other investigators discussing microstructural development during solidification during high

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pressure die casting have taken a peak interfacial heat transfer value and simply reduced it linearly as temperature decreases.[2] This takes into account none of the in-cavity dynamics associated with rapid high pressure filling processes. More detailed knowledge of the variation of these heat transfer values with time is therefore critical for the development of models which more accurately represent the solidification environment during die casting.

No measurements utilizing a pyrometric chain to accurately determine the melt surface temperature have previously been reported, except those of the current authors. Accurate determinations of die temperatures and heat flux density and how these values change with time is also highly dependent on the size and position of thermocouples used in any sensor/probe. A detailed review of the literature and description of the correct procedures to be followed when conducting heat transfer measurements in rapid forming processes like high pressure die casting has been previously discussed in detail by the present authors.[12] This present paper describes the application of the new non-intrusive and highly accurate measurement method to the determination of the heat flux density and heat transfer coefficient in the high pressure die casting of an Al-9 wt%Si-3 wt% Cu alloy and the magnesium AZ91 Alloy. The accurate heat transfer coefficient data obtained through these investigations has broad application to a wide range of materials for scientists and engineers concerned with the formation of microstructure during high pressure die casting and particularly in the development of accurate interfacial heat transfer models and numerical simulation techniques.

In order to obtain accurate heat transfer data at high temperatures, a new non-intrusive sensor was designed that uses an infrared probe incorporated into a Pyrometric chain (light pipe + optical fiber + pyrometer) (Fig. 1). The pyrometers used in the present investigations were chosen for their rapid response time of 2 ms. In addition, the sensor was manufactured to incorporate six fine thermocouples (configured in pairs for redundancy) located at various depths below the die surface. These thermocouples were laid in grooves along the cylinder and exited through holes in the shoulder. The Infra-Red(IR) lightpipe/pyrometric sensor system has a precision of ± 0.1 °C and the thermocouple system is designed to record at up to 1 kHz. The theoretical considerations critical to the design of the sensors have been discussed in detail by Dour et al. 2006.[12–13]

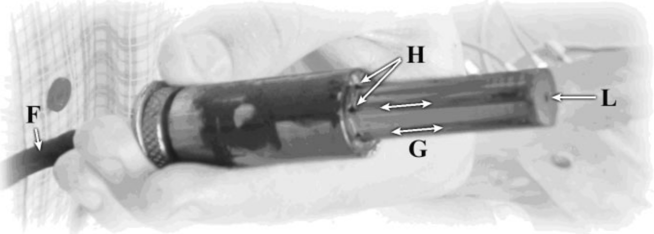

Fig. 1. Photo of the heat transfer coefficient gauge, showing tip of light pipe(L), Thermocouple guide holes (H) and grooves (G) and Optic Fibre/thermocouple bundle (F).

The temperature data obtained from the thermocouple arrays was analyzed with an inverse model as described by Dour et al.,[12–14] in order to determine the die surface temperature and the heat flux density. The heat transfer coefficient was then calculated using the heat flux density data and the measurements of the casting surface temperature data obtained from the Pyrometric chain.[12–13] The middle thermocouple (located at 9.5 mm from the die surface) is used to verify the soundness of the inverse method results. See[14] for the detail of the inverse method used in the present work.

Experimental Design

A series of experiments were conducted to concurrently measure heat flow and in-cavity pressure during the high pressure die casting of an A380 aluminium alloy and AZ91 magnesium alloy into an experimental high pressure die casting die (Fig. 2). The experiments were designed to measure both in-cavity pressure and heat flow in the die concurrently. The die was mounted on a commercial Toshiba 250 ton cold chamber high pressure die casting machine and 502 castings

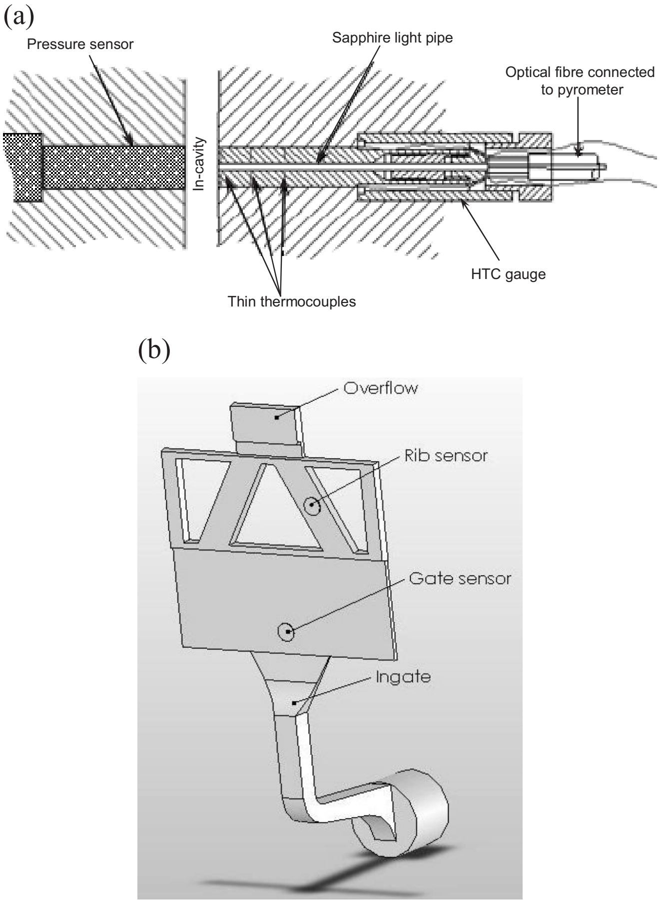

Fig. 2. (a) Vertical cross section of the die, showing the Heat Transfer Coefficient gauge (HTC gauge) and pressure sensor. (b) Experimental casting, showing location of sensors. The plate region is slightly over 2 mm thick and the rib region is 5 mm thick. The pressure sensor locations are visible here, and the heat-flow sensors were located precisely opposite the pressure sensors. The pressure sensors were situated in the moving half of the die while the heat transfer measurement configuration was placed in the fixed half of the die.

of the A380 alloy and 328 castings of the AZ91D alloy were produced. Precise measurements (resolution 1 µm) were made of the position of the piston tip that injects the molten metal into the cavity. Piston velocity was calculated from these measurements. Pressure within the die cavity was measured using commercially available piezo-electric quartz pressure transducers which were designed for use in molten metal contact at temperatures up to 700 °C and pressures of 200 MPa. The pressure sensors have been shown to be an effective tool to measure in-cavity pressure during die casting.[15] The die is modified to incorporate these sensors such that the measuring surface of each sensor is flush with the die cavity surface. The heat transfer sensors that were also incorporated into the die were used to detect the arrival of the liquid alloy and measure its temperature. The temperature and pressure sensors were located opposite each other (Fig. 2) so that measurements from each sensor could be directly correlated.

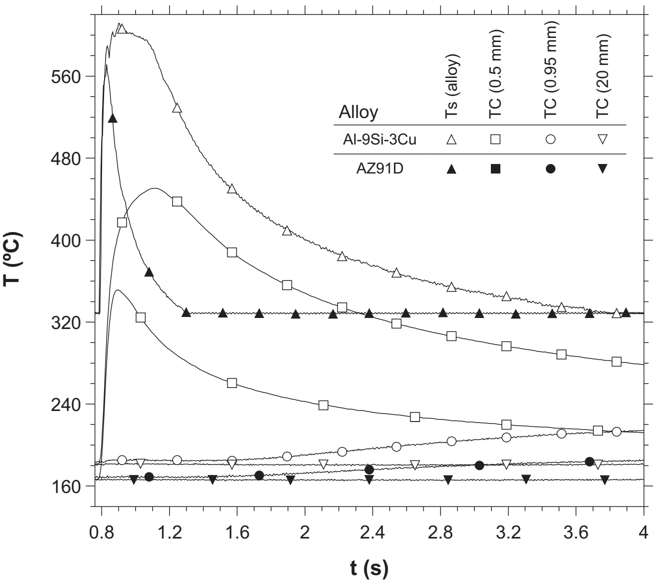

Fig. 3. Typical temperature data measured by both the light pipe pyrometric chain and the thermocouples contained in the heat transfer sensor. The symbols mark only one data point in every 50 or 75 of the total number of data points that were collected. For the aluminium alloy the melt temperature was 680 °C; shot speed was 0.84 m/s; nominal intensification pressure was 80 MPa. For the magnesium alloy the melt temperature was 700 °C, shot speed was 1.54 ms^{-1} and the nominal intensification pressure as 80 MPa.

Results

Unprocessed data obtained from the heat transfer sensor is shown in Figure 3 which compares one cycle from each alloy with the same process parameters except alloy pouring temperature (680 °C for Al-9Si-3Cu and 700 °C for AZ91). Figure 3 shows the temperature variation with time for the two alloys. The curves labeled T_{alloy} refer to the temperature of the casting surface at both the rib and gate positions obtained by the lightpipe/pyrometric chain. These curves show clearly that AZ91 cools much more rapidly than the Al-9Si-3Cu alloy. The lower temperature curves correspond to the die temperature measurements obtained from the thermocouples situated at different depths from the die cavity surface (0.5, 9.5 and 20 mm – described in detail in[13]). When a thermocouple is further away from the interface, it is colder and has a slower response, as would be expected from the diffusion of a short peak of heat according to Fourier's Law.

Figure 4 shows the data after analysis by the inverse model. The top curves are the interfacial heat flux density q and the heat transfer coefficient h versus time. The lower set of curves are the die temperatures as measured and as recalculated with the $q(t)$ data as a boundary condition. This analysis gives information about the die surface temperature and also about the reliability of the temperature calculation obtained using the inverse model. For the aluminium alloy the die surface temperature never reached 500 °C, heat flux densities peak at around 16 MWm^{-2} and the heat transfer coefficient reaches close to 90 kWm^{-2}K^{-1}. The estimations give rise to residuals of less than 10 °C (typically below 3 °C in the first 5 s) on the die temperatures around 10mm from the surface. The temperatures close to the surface were used to derive q and so have much lower residuals. For the magnesium alloy AZ91 the die surface temperature never reaches 440 °C, peak heat flux densities are around 11–17 MWm^{-2} and the peak heat transfer coefficient is close to 100 kWm^{-2}K^{-1} at the gate and 85 kWm^{-2}K^{-1} at the rib position.

It is worth noticing that the peak value of heat transfer coefficient is fairly comparable for the two alloys. So the heat transfer at the beginning is about the same. But because the

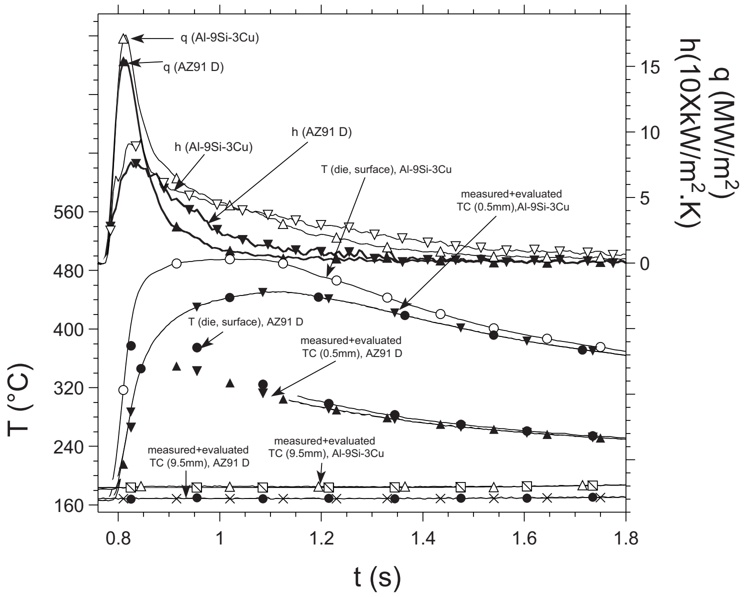

Fig. 4. Results derived from inverse modelling evaluations of the data shown in Figure 3.

volumetric latent heat of AZ91 is much smaller than that for Al-9Si-3Cu (A380), the casting solidifies and cools down much quicker as discussed before. This results in a more rapid decrease of h for AZ91 as the quality of the casting-die contact degrades rapidly. As a result the heat flux density also decreases quickly, while the temperature gap at the interface remains constant at around 50 °C (after 1.3 s, the temperature of the casting surface for the AZ91 alloy measured by the pyrometer reaches its lower limit of 320 °C).

The final consequence of this rapid evolution of the interfacial heat transfer is that the maximum die surface temperature reached for AZ91 (about 440 °C) is lower than that reached for the Al-9Si-3Cu alloy (around 500 °C). Similarly the temperature within the die measured by the thermocouple installed 0.5 mm from the die surface reaches 350 °C and 450 °C for AZ91 and A380 respectively.

As shown in Figure 5 increasing piston velocities resulted in an increase in the maximum heat flux densities for both alloys but particularly for the magnesium alloy AZ91 while the heat flux density showed little dependence on intensification pressure (Fig. 6).

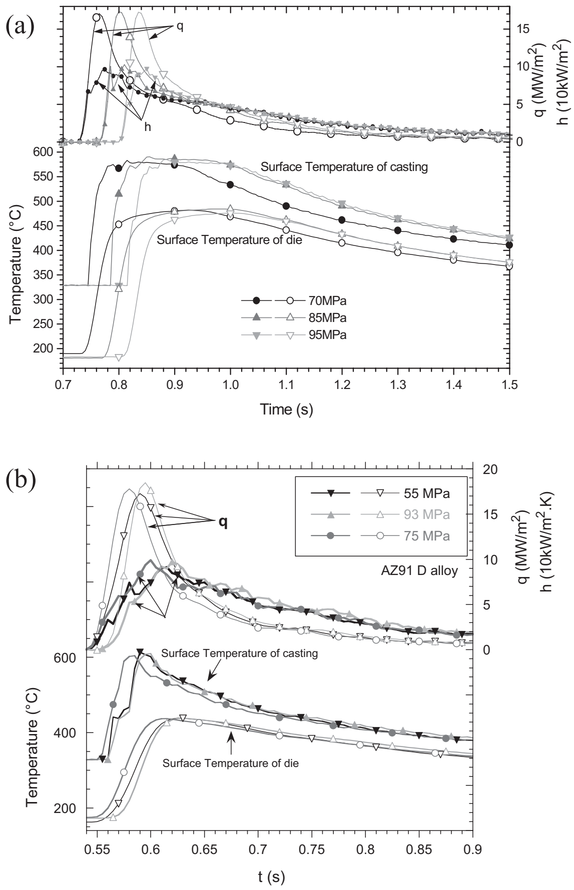

Fig. 6. Effect of intensification pressure (second stage piston velocity was 0.87 m/s, alloy melt temperature was 680 °C for the aluminium alloy and 1.5 ms^{-1} (a) and 700 °C for the magnesium alloy (b)). Representative curves at different peak pressures with the curves offset for clarity.

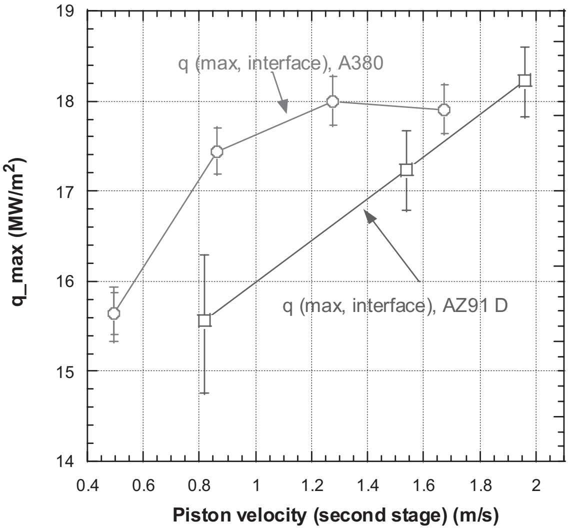

Fig. 5. Variation of Heat Flux density values with second stage piston velocity. Each data point shown is the average value for 10 castings. Error bars represent standard deviation.

Discussion

A sound knowledge of the interfacial heat transfer coefficient is a critical consideration in understanding and modelling the development of microstructure during high pressure die casting. Accurate heat transfer measurements are particularly important for solidification modelling using numerical simulation techniques. The effectiveness of these simulations is highly dependent on the accuracy of the heat transfer data utilized by the solidification models. The significance of the findings presented in this investigation arise from the uniqueness of the measurement methods applied to the determination of heat transfer during the high pressure die casting of both magnesium and aluminium alloys resulting in highly accurate heat transfer data. In particular the reported experiments provide detailed knowledge of the thermal characteristics occurring at the cavity fill stages of the die casting process achieved through the application of an array of fine rapid-response thermocouples integrated in one sensor along with the light pipe/pyrometric chain which have enabled the accurate measurement of both the die and metal surface temperatures through the entire die casting cycle. The rapid response time of the sensors (less than 20 ms) and their sensitivity (± 0.1 °C) along with the application of an inverse method,[2–4] have enabled the accurate determination of both the heat transfer coefficient and heat flux along with their variation with time during the die filling and intensification stages of the high pressure die casting process. The relevance, accuracy and reproducibility of the processed data from the sensor has been confirmed elsewhere.[13] Based on the analysis undertaken by Dour et al.,[13] the precision in evaluation of heat flux density and die surface temperature is 3 %. By calibrating the pyrometric chain according to a black body and alloy emissivity the accuracy of the casting temperature measurements in the investigations discussed in the paper following the analysis of Dour et al.,[13] was found to be 5 % . The precision in evaluation of the heat transfer coefficient was found to be 15 % at the beginning of solidification and 30 % at the end of the process.

The heat transfer coefficient values reported here have wide application in the modelling of the development of microstructure during solidification of light alloys along with the development of engineering software used to predict the filling and solidification of light alloys during high pressure die casting. Very little data for heat flux and no direct determinations of the heat transfer coefficient using an actual casting surface temperature measurement have been reported for high pressure die casting.[3] The present work enables a much higher resolution of the evolution with time of heat flux and heat transfer coefficient than any measurements previously reported for high pressure die casting. The work differs from prior work also in that it has enabled a direct correlation with in-cavity pressures through concurrent measurement of both in-cavity pressure and heat flux/heat transfer coefficient. An examination of the curves outlined in Figure 6 shows that intensification pressure has little effect on maximum values for the heat flux and interfacial heat transfer coefficient.

This piece of work compares the evolution of heat flux and heat transfer coefficient during the high pressure die casting of the two alloys. It is well known that magnesium alloys have a smaller volumetric latent heat than aluminum alloys. It was therefore expected that the total heat flux would be smaller and that the casting would cool faster for the magnesium alloy. The results from the present study show clearly that under similar casting conditions, the peak value of heat transfer coefficient and the heat flux density are fairly close for the two alloys used in this work. This is because the peak value of heat transfer coefficient (h) is more dependent on interface characteristics such as die surface roughness, contact conditions and some process parameters than on latent heat and that the peak of heat flux density depends mostly on the peak value of h and the initial temperature difference between the die and the casting surface (which is also comparable for the experimental conditions reported here). Moreover, the slight difference in the peak value of heat transfer for both alloys may be related to the difference in thermal conductivity of the magnesium alloys compared to aluminum alloys since it has been previously determined during investigations on the Thermal Contact Resistance during solid-solid contact that the effective thermal conductivity at the interface (derived from the thermal conductivities of the two contacting bodies) can play a significant role in determining the peak value of the Thermal Contact Resistance.[16] In addition the evolution of the temperature of the casting strongly depends on its latent heat. Therefore the heat transfer coefficient and as a consequence, the heat flux density at the casting-die interface tend to decrease much more rapidly for magnesium alloys.

Conclusions

The heat transfer coefficient (h) and heat flux (q) have been determined during the high pressure die casting of magnesium alloy AZ91 and an Al-9 %Si-3 %Cu alloy using a new measurement and analysis technique incorporating infra-red probes and thermocouple arrays that accurately determine both casting and die surface temperatures. This technique provides the most accurate heat transfer coefficient and heat flux data obtained to date. The evolution of this data with time therefore provides important new knowledge for both materials scientists and engineers enabling a better understanding of the thermal processes occurring and therefore an enhanced ability to control the development of microstructure and alloy properties during solidification in high pressure die casting.

The peak value of the heat transfer coefficient have been determined to be around 90 $kWm^{-2}K^{-1}$ for the aluminium alloy and 100 $kWm^{-2}K^{-1}$ for the magnesium alloy. Peak heat flux densities were determined to be around 16 MWm^{-2} for the aluminium alloy and 18 MWm^{-2} for the magnesium alloy.

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