DEVELOPMENT OF A NON INTRUSIVE HEAT TRANSFER COEFFICIENT GAUGE AND ITS APPLICATION TO HIGH PRESSURE DIE CASTING

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Abstract

This paper presents a design for a robust sensor suitable for determining heat flow and heat transfer coefficient in high pressure die casting. A design methodology for the sensor is presented, together with the conclusions of this analysis. A sensor has been manufactured to these principles and some typical results from its operation are introduced.

INTRODUCTION

It is well-known that the microstructure and therefore the properties of cast components strongly depend on the heat transfer conditions. In die casting processes, the heat transfer path is mostly controlled by the casting/die interface. Therefore it is of crucial importance to know the heat transfer coefficient at this interface and how it varies with time and with the process parameters.

Many attempts have been made to evaluate the heat transfer coefficient in laboratories [1-4]. These investigations involve the instrumentation of the die and the cavity with temperature sensors (such as thermocouples) to obtain direct temperature measurements. These measurements are then analysed using inverse methods or extrapolations to determine (1) the surface temperatures on both sides of the interface and (2) the heat flux density flowing though the interface. These data are then used to evaluate the heat transfer coefficient. However these are laboratory-scale experiments and these types of investigations cannot reliably be applied in a real die casting production facility, because of either limited robustness, modification to the casting shape or temperature sensors remaining embedded in the casting. Further, there is often the need to analyse data off-line. Therefore it was decided to design, manufacture and test a device that could measure the relevant temperatures in order to evaluate the heat transfer coefficient in an industrial environment. Central to the design of the device were the requirements that the measurement process had to be without any intrusion into the casting cavity and that it should make minimal change to heat flow patterns in the die. Ideally, it should also be transferable between different dies. Because the device was going to be used in high pressure die casting, it was also decided that its external diameter (12 mm) should be the same as direct pressure sensors made by Kistler and that are commonly used when a die is instrumented. The heat transfer phenomena in high pressure die casting are typically very brief. For this reason, rapid response time and measurement accuracy were critical concerns in the sensor design.

Concept of the heat transfer coefficient gauge

The heat transfer sensor incorporated a number of features required to determine both the temperature of the surface of the casting and the temperature at the surface of the die. The primary aim of the non intrusive heat transfer coefficient gauge was to determine the heat flux density from a series of temperature measurements obtained at different depths in a commercial die using an inverse method [1]. Knowing the heat flux density, it is possible to evaluate the temperature on the surface of the die. The surface temperature on the casting side was measured with a pyrometer connected to an optical fibre and a sapphire light pipe (2 mm dia.) that goes through the gauge and looks straight into the cavity. This casting surface temperature measurement along with the heat flux density can then be used to determine the heat transfer coefficient values during the casting process.

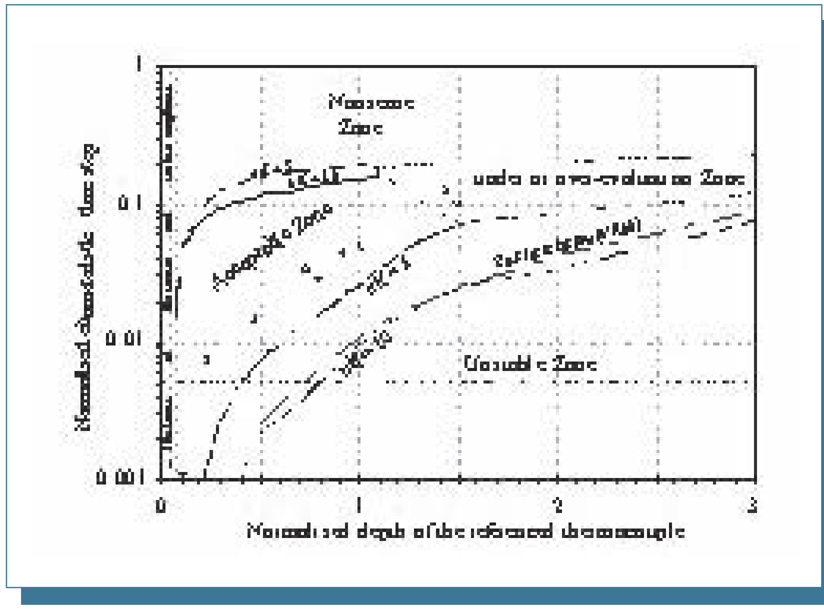

Fig. 1: Map of relevance of the inverse method. The different zones indicate the quality of solution to the simplified problem. The values of ntf show the effect of changing the number of future instants in the inverse solution

To make sure that the temperatures were measured correctly, the effect of the penetration depth of the thermocouple through the gauge diameter and the impact of the emissivity of the casting alloy (Al-12Si) on the pyrometer measurement were assessed. A careful examination of the first consideration led to the conclusion that only ultrafine (0.25 mm) sheathed thermocouples could give accurate data without being influenced by the surroundings of the gauge. The dominant error was uncertainty in the emissivity, which experiment showed could introduce a maximum error of 12¡C in the casting temperature measurements (with a pyrometer sensor measuring at a wavelength of 0.9 mm).

The heat flux density at the casting-die interface varies very rapidly in high pressure die casting. Therefore we had to investigate the sensitivity of the inverse method to the data acquisition conditions (sampling rate, noise), to the location (distance from the interface) of the thermocouples and to the dynamic effect of the thermocouples. Based on a review of the relevant literature an experimental strategy was developed [5-11]. The strategy for this sensitivity analysis used a normalised representation of the 1D heat conduction equations and a simplified simulation of heat transfer in the die. The heat input from the mating surface of the die was a square function of time with a maximum value f_{max} and a duration t. The rear face of the die was taken to be in contact with a cooling fluid maintained at a fixed temperature equal to the initial temperature of the die.

A number of simulated temperature response curves were created over a matrix of depths and sampling time conditions. An inverse solution was then found to each of these curves and the solution obtained was compared with the input heat function. From those simulations a map of the capability of the inverse method was established (Figure 1). This Figure plots the conditions of sampling rate and thermocouple location under which it would be possible to get a good inverse solution. If the sampling interval were too long or too short then no useful result would be obtained. The boundaries between these zones depend on the number of future instants (*ntf*) that are used for the computation. Beyond a normalised thermocouple depth of 1 the results become less precise, leading to over- or under-evaluation. A correct choice of thermocouple positions and sampling rate can result in very precise evaluations. It is therefore strategic to choose the location and the sampling rate in points 1, 2 or 3 of the map of relevance shown in Figure 1. The application of the inverse method at point 1 of the map of relevance resulted in the generation of substantial noise in the heat flux density evaluation. Furthermore, placing thermocouples very close to the surface exacerbated experimental uncertainties such as knowing the exact thermocouple depth, as well as increasing the errors due to surface irregularities and heat flow distortion. As a result position 3 on the map of relevance provided the most suitable choice of parameters for the inverse model.

The dynamic response of the thermocouples has also been investigated through simulation studies. The response of thermocouples was simulated as a first order filter with a time response t_{Tcple}. The inverse method evaluation at point 3 of the heat flux density is given in Figure 2 for different normalised time responses t_{Tcple}/t of the thermocouples. The most important consideration with respect to the effect of thermocouple response time on measurement accuracy is that thermocouples with a time response longer than 20% of the heat input duration give a poor evaluation of the heat flux density.

In order to finally design the heat transfer coefficient gauge for application to high pressure die casting, the duration of the heat input was required. In order to approximate this period of time it was assumed that the bulk of the heat transfer could be correlated with the period over which maximum pressure was being applied to the casting. Direct pressure measurements with Kistler pressure sensors (with fast response times, 7 ms) were used to measure the duration of time over which pressure was applied in the cavity.: it was assumed that the heat transfer coefficient would decrease at the same time at which the pressure in the cavity starts decreasing (see Figure 3). The duration was therefore estimated to be around 0.5 s. This meant that the strategic choice of parameters should be:

- location of first thermocouple, 1 mm;
- sampling rate, f = 200 Hz;

time response of the thermocouples should be less than 0.1 s.

EXPERIMENTAL SET-UP AND RESULTS

A gauge was designed and manufactured according to the criteria described previously. The sensor was manufactured to incorporate 6 thermocouples (configured in pairs for redundancy), a light pipe and optical fibre assembly. Figure 4 is an image of the gauge taken after it had been removed from the die. The 6 thermocouples were laid in grooves along the cylinder and exited through holes in the shoulder.

The gauge was installed in a commercial die at Ferra Engineering in a location previously designed to accommodate a Kistler pressure sensor (see Figure 5). The cable running from the base of the sensor was able to follow the route provided for the cable of a standard block temperature sensor which had also been present. Some minor modifications to this cable groove were required in order to accommodate the limited radius of curvature (130 mm) of the optical fibre. The cable then continued through the ejector plates and block. After emerging from the die the cable was connected to the pyrometer, which was mounted on the top of the die in a protective housing.

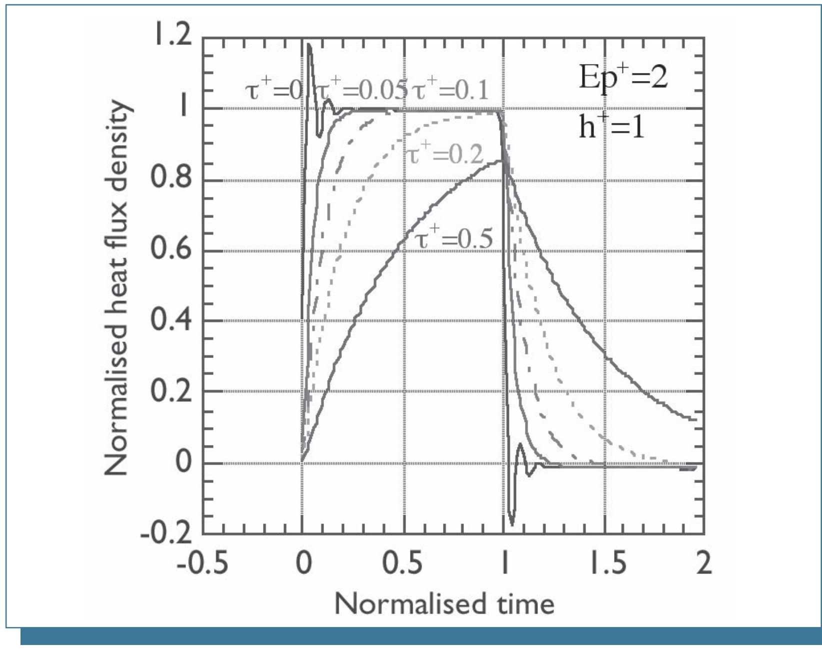

Fig. 2: Effect of the dynamic of the thermocouple on the heat flux density evaluation

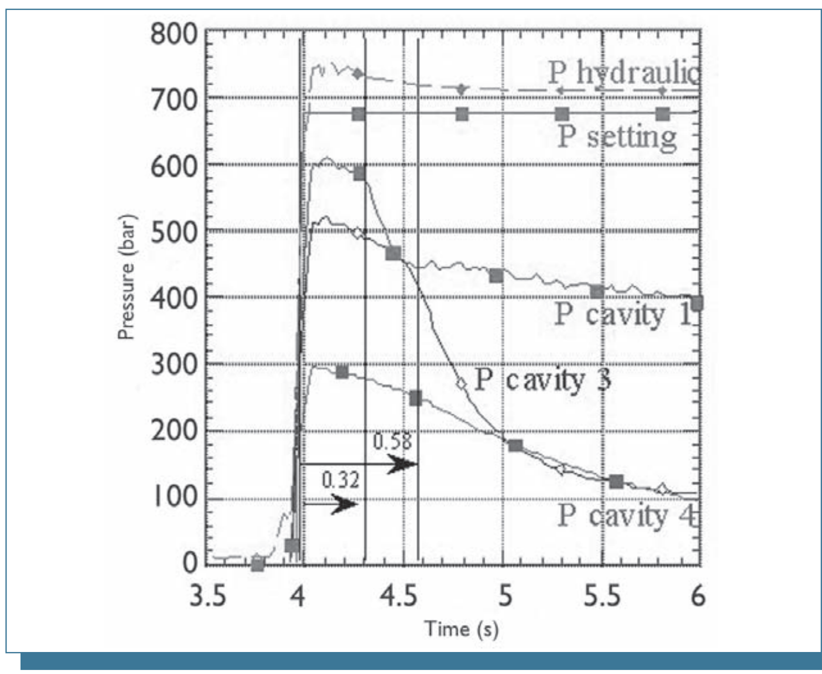

Fig. 3: Evaluation of the duration of the heat input with pressure measurement

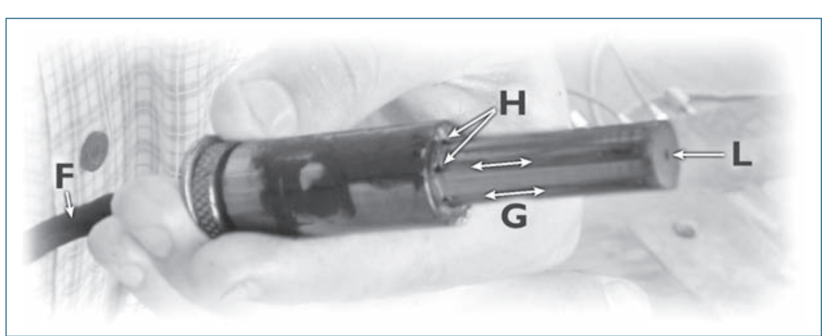

Fig. 4: Photo of the heat transfer coefficient gauge, showing tip of light pipe(L), Thermocouple guide holes (H) and grooves (G) and Optic Fibre/thermocouple bundle (F)

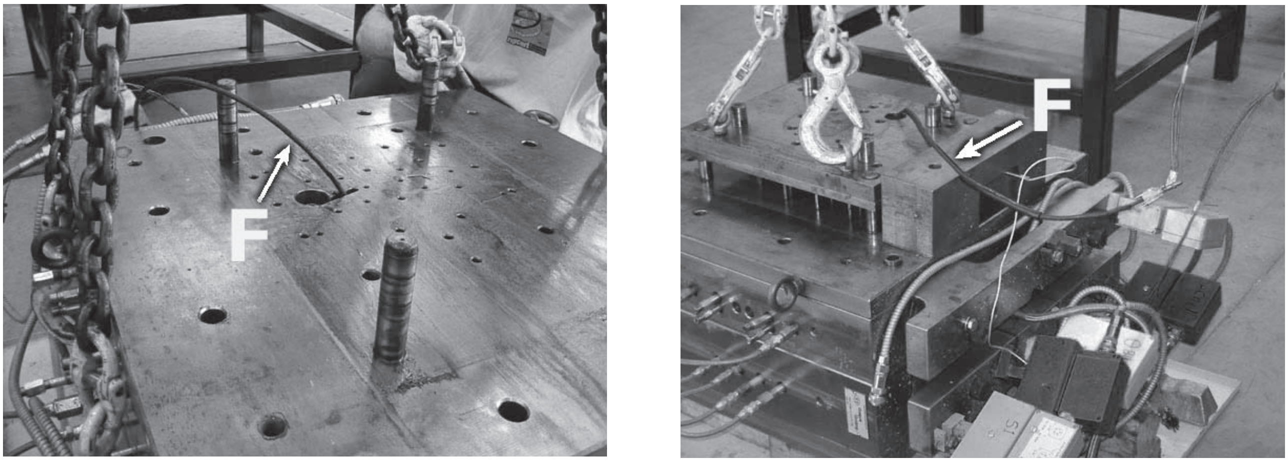

Fig. 5: Mounting of the gauge in the die. The fibre-thermocouple bundle, indicated by the "**F**", is fed through the bolster (a) and then through the ejector plate (b)

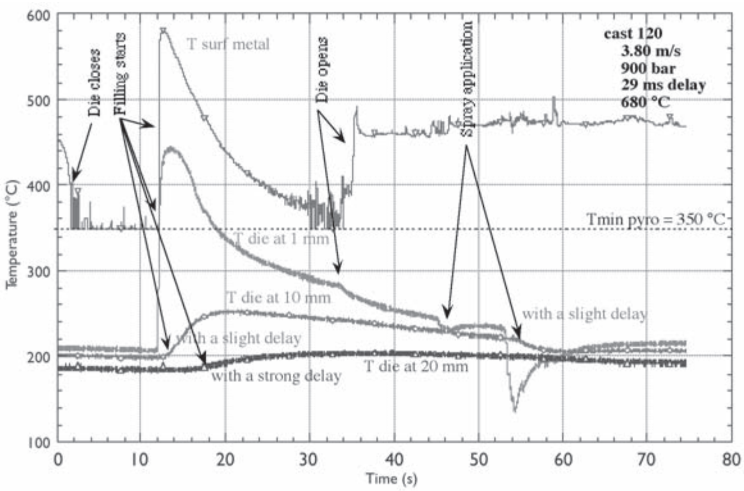

Fig. 6: Raw data from the gauge. Arrows indicate thermal responses to:die closure (2 s); and events labelled: A - metal injection (12 s); B - casting ejection (~35s); and C - die spray (~46 and 54s)

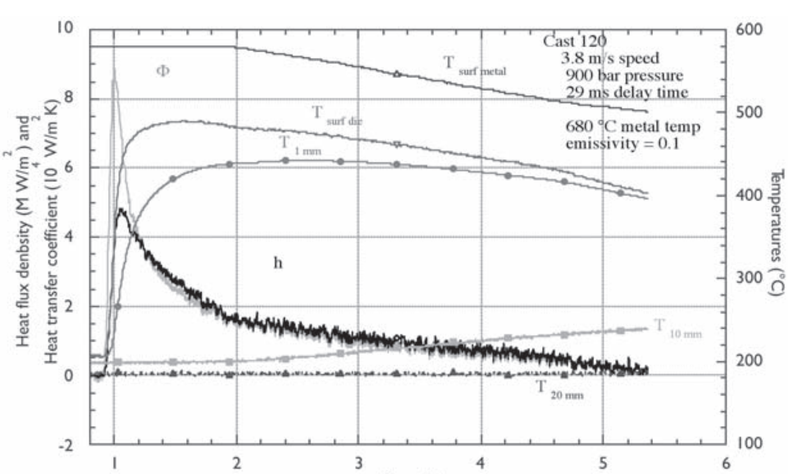

Fig. 7: Processed data from the Gauge (see text for details)

Several hundred castings were made with various process parameters as part of a wider program of process optimisation at Ferra Engineering Pty. Ltd. The heat transfer gauge performed without pause for the entire run. An example of the typical data obtained from the sensor over one shot cycle is shown in Figure 6. The pyrometer readings (e=0.1 and T_{min} = 350°C) show the evolution of the casting temperature from about 11 to 35 s. The readings from the pyrometer before the die closed and after the die opened were not used in the subsequent analysis, as those readings were not from the casting. The three sets of temperature readings from the thermocouples at distances of 1, 10 and 20 mm from the casting surface of the die exhibited responses ranging from very sensitive at 1 mm to a minor response at 20 mm. This was a clear effect of the transient heat conduction through the die with brief heat input: at the 20 mm depth the response to the metal injection took approximately 4 seconds to be observable, while the cooling transient due to the die spray was not detectable at all.

HEAT TRANSFER EVALUATIONS AND INFLUENCE OF PROCESS PARAMETERS

The raw data has been used to determine the heat flux density (f in orange), the die surface temperature ($T_{surf\ die}$ in red) and the heat transfer coefficient (*h*, in black). Figure 7 shows a typical result after optimisation of the inverse method parameters. An examination of the heat flux density curve shows that the heat input duration was closer to 0.2 than to 0.5 s.

Therefore the strategic point is not point 3 but point A on the map of relevance (Fig 1), which is still in the acceptable zone. The time response of the thermocouple has been evaluated to be 40 ms, which is close to 20 % of t. This means that the evaluations were relevant. The uncertainty of the values derived from the sensor has been determined to be 3 % for the heat flux density and up to 30% for the heat transfer coefficient. Collection of data over multiple cycles has shown the data from the sensor to be highly reproducible.

The influence of the process parameters has been tested. The most influential parameters on the peak heat flux are the die temperature and secondly the maximum plunger velocity (2nd phase). More surprisingly, variations of the intensification pressure in the range 300 to 900 bar and of the delay before application of the intensification stage in the range 29 to 200 ms had little measurable effect. Figure 8 illustrates that, during the peak heat flux, the influence is negligible, while a slight effect appears later (2s after the peak) when the heat flux was already low.

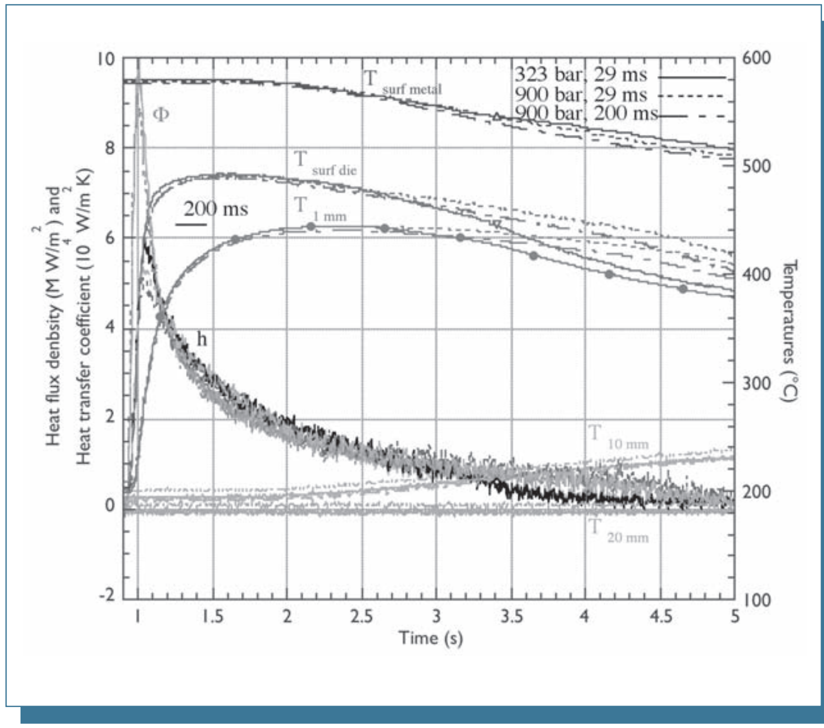

Fig. 8. Effect of pressure and delay on the heat transfer and temperatures curves during the first 4 seconds of the process

CONCLUSIONS

This project has involved extensive collaboration between EMAC, CAST, UQ, CSIRO and Ferra Engineering. The project has included all aspects of the development of the gauge: from conception of the new gauge and optimisation of the sensor design right through to the manufacture, calibration and testing of the sensor within an industrial environment. Conception through to industrial trials took one year.

The device has proven to give reliable evaluations of the heat transfer coefficient. It has been tested on production tooling for castings and has shown the influences of a range of process parameters on the peak heat transfer rates.

Future work will include improvements to the design of the sensor housing so as to make the device more robust and easily used by industry. Improvements to the response time of the pyrometer and the integration of real time inverse method signal processing into the sensor package are other features on which work is currently underway.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the CRC for Cast Metals Manufacturing (CAST), Ecole des Mines d'Albi-Carmaux and Ferra Engineering for supporting this work. The authors are also grateful to CAST for permitting the publication of this paper, which has previously been presented in the Light Metals Technology 2003 conference held in Brisbane, Australia in September 2003.

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