Heat Transfer through Die Coatings in the Aluminium Die Casting Process

Introduction

Numerical modelling of heat transfer in the casting process can reveal the likely occurrence of defects such as solidification shrinkage. However, for accurate models of solidification it is necessary to have accurate data with which to solve the problem. This means not only accurate values for the thermal conductivity, specific heat capacity, density and latent heat for the particular alloy under consideration, but also accurate values for the heat transfer coefficient, h, that describes the boundary condition of the mathematical problem, ie, how the heat is transferred from the casting to the mould.

During the solidification process the cast liquid alloy cools and solidifies thus the casting-mould interface changes from an initial stage, characterised by the liquid metal in contact with the solid mould surface, to a solid-solid contact situation once a solid skin has formed on the cast alloy. This leads to a variation in the rate of heat transfer across the interface between the casting and the mould. In the later stages of solidification a casting may, locally, lose contact with the mould altogether if a local air-gap forms causing a further significant reduction in heat transfer. Alternatively, the solidifying casting could shrink onto a mould feature, such as an internal core, bringing the casting and the mould into a more intimate contact and causing a local increase in the heat transfer.

Recently the University of Birmingham has investigated heat transfer during the die casting of Al alloys where the dies are coated with a porous refractory coating. Measurement of the interfacial heat transfer coefficient is a very laborious, difficult and time consuming process. The particular aim of this work was to model the interfacial heat transfer mechanisms in the die casting process and in this way to obtain an estimate of the heat transfer coefficient. Its focus was to determine an equation that could be used to estimate the interfacial heat transfer coefficient in order to provide values for use in the simulation of casting solidification and which could be applied to a range of alloys in a range of conditions.

Modelling of the heat transfer coefficient

This research was begun by Hallam and Griffiths [1], who measured and modelled the interfacial heat transfer coefficient between a solidifying Al-Si alloy and a coated die steel chill. It was realized that during the filling of the die the thermal conductivity of the die coating should be the major factor in the heat transfer from the liquid metal since the liquid metal would be in intimate contact with the die coating. Once the casting surface had solidified and formed its own surface roughness the nature of the interface would change to two rough surfaces in contact. In this case the decrease in casting surface temperature would cause contraction of the casting surface, and the heating of the die would cause expansion of the die surface causing the two surfaces to move laterally over each other naturally trapping a layer of air between them, (It should be pointed out that this is a different effect to the usual explanation for the formation of an air-gap, referred to above, where thermal contraction of the casting, normal to the mould surface leads to a gap forming between the casting and the mould.)

The role of thermal contraction causing lateral movement between the casting and mould surfaces had previously been pointed out by de L Davies [2]. These considerations led to the following equation to predict the interfacial heat transfer coefficient, h, during solidification [equation 1];

$$h = \frac{1}{\dfrac{x_{max} + 0.5R_{y(sub)} - 0.5R_{y(coat)}}{k_c} + \dfrac{R_{z(X)}}{2k_a}}$$

Equation 1

Where k_c was the thermal conductivity of the coating, k_a the thermal conductivity of air, R_z the mean peak-to-valley height of the surface roughness, R_y the maximum peak-to-valley height of the surface roughness and x_{max} the measured thickness of the coating. The subscripts (coat) and (sub) refer to surface roughness measurements carried out on the coating and on the substrate, (eg, the uncoated but shot-blasted die steel surface), respectively. $R_{z(\Sigma)}$ refers to the sum of the coating and casting surface roughnesses, thus;

$$R_{z(\Sigma)} = \sqrt{R^2_{z(coat)} + R^2_{z(casting)}}$$

Equation 2

The insulating effect of a material can be assessed by determining its thermal resistance, R = k/x, where k is the thermal conductivity of the material and x is its thickness. Thus Equation 1 sums together the two principle resistances to heat transfer from the casting to the die, namely, the thermal resistance due to the coating itself, (represented by the left-hand side of the denominator), and, secondly, the thermal resistance due to the gas, (which was assumed to be air), trapped between the casting and coating surfaces by virtue of their respective surface roughness, (represented by the right-hand side of the denominator).

Surface roughness measurements showed that the roughness of the casting and coating surfaces was such that the air layer had a depth of some tens of microns while the applied die coating would have a thickness that was about 100-300 μm. However, the thermal conductivity of air, (~0.06 $Wm^{-1}K^{-1}$), would be an order of magnitude lower than the thermal conductivity of the die coating, (measured to be ~0.8 $Wm^{-1}K^{-1}$). Accordingly the air layer would offer a greater barrier to heat transfer than the coating, (during solidification of the casting).

The validity of the formula to estimate the heat transfer coefficient was assessed by comparing measured values with values estimated with Eq. 1 in the case of a die steel chill coated with a 200 μm thick layer of DYCOTE* 2000, a potassium silicate bonded insulating refractory coating. The chill was heated to 300 °C to represent typical die casting practice and the alloy cast was a commercial eutectic Al-Si alloy. Results from two experiments are shown in Figure 1.

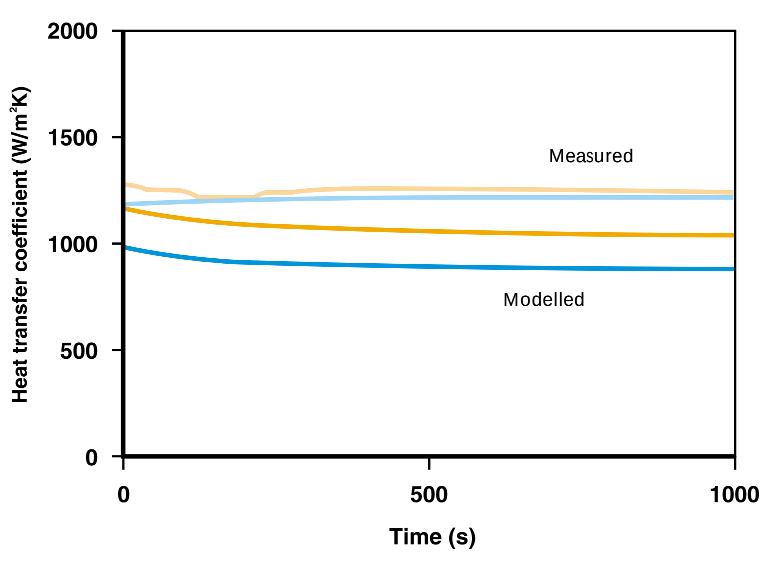

Figure 1: Graph comparing measured and modelled heat transfer coefficients for the solidification of an Al-Si eutectic alloy upon a die steel chill coated with a 200 μm thick layer of DYCOTE 2000 at 300 ^{o}C

The measured values of the heat transfer coefficient were about 200 $Wm^{-2}K^{-1}$ greater than the estimated values in both experiments, but the estimated values were within the estimated accuracy of the experiment, (about ± 20%), verifying the use of Equation 1 for determining the heat transfer coefficient.

Heat transfer through die coatings

Using this approach several coatings were assessed by determining the heat transfer coefficients associated with their use by measuring casting and coating surface roughness and using Equation 1. Figure 2 shows comparisons between different commercial coatings. In each case, the thermal resistance of the air layer between the coating and the casting surfaces was found to have a significantly higher value than the thermal resistance of the coating itself; these relative thermal resistances are compared in Table 1 and are also shown graphically in Figure 3.

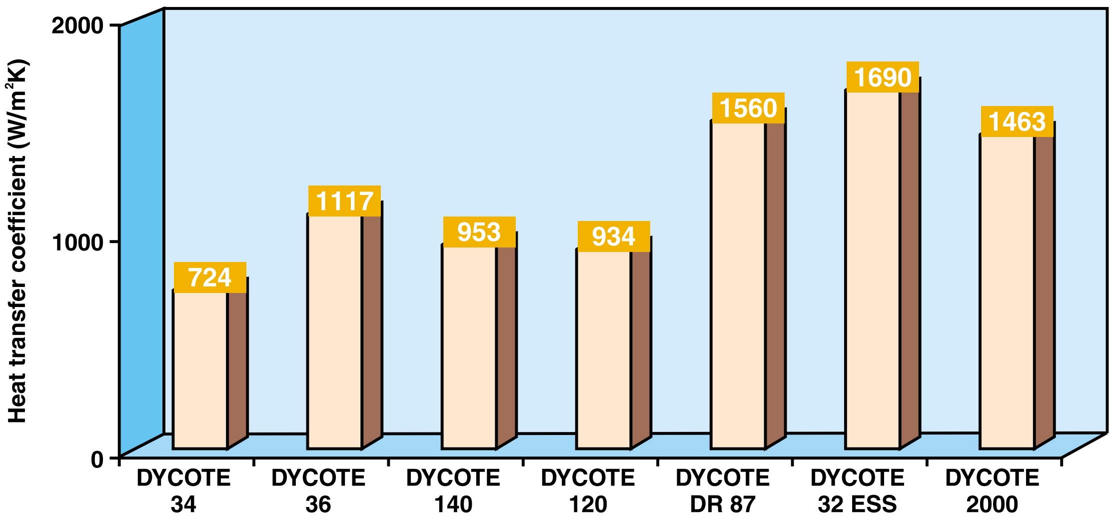

Figure 2. Relative values of the heat transfer coefficient associated with different commercial die coatings predicted using Equation 1

Die-coating (DYCOTE...)	32 ESS	34	36	DR 87	DBN 120	140	2000
Ratio of thermal resistances Air layer : coating	1.7 : 1	7.1 : 1	5.5 : 1	1.7 : 1	4.4 : 1	4.0 : 1	1.9 : 1

Table 1: The ratio of the thermal resistances of the coating and the air layer for several commercial die coatings

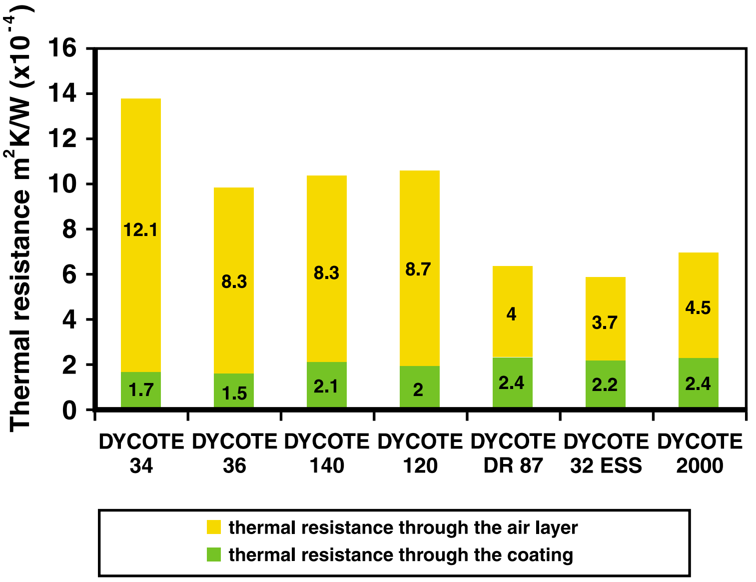

Figure 3: Comparison of the thermal resistances of the die coating and the air layer for several commercial die coatings

These results therefore show that, during casting solidification, the surface roughness of the coating should have a greater influence on the heat transfer coefficient than the coating itself. A smooth coating surface should result in a smoother casting surface and hence a reduced depth of the air layer between them and therefore a higher rate of heat transfer, while a rough coating surface would result in a more insulating effect from the coating. It has been suggested that coating surface roughness can have an effect on the mould filling stage also but the nature of this effect has yet to be determined.

Determination of the point of casting solidification

For better understanding of the role of coatings in die casting it was considered important to establish a method to determine when the casting surface solidified and formed its associated surface roughness. The roughness of the casting surface is dependent upon the pressure experienced during solidification. Figure 4 shows an SEM picture of the surface of a DYCOTE 140 coating; the greater the pressure experienced by the liquid metal the more it will penetrate into the valleys of the coating surface roughness.

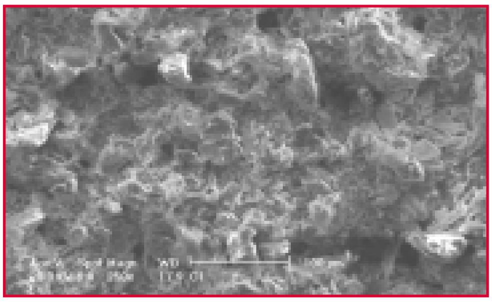

Figure 4: SEM image of the surface of a DYCOTE 140 insulating die coating. The scale marker indicates a length of 100μm

To study this problem an ideal coating surface was created by placing a thick layer of die coating on a die steel block and then machining the coating layer to give it the characteristics of a DYCOTE 140 coating. A 3D image of the resulting machined coating surface is shown in Figure 5.

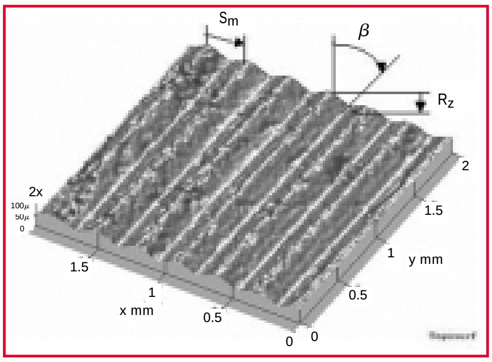

Figure 5: A 3-D "image" of a machined coating surface with parallel grooves and with surface roughness characteristics similar to an as-sprayed DYCOTE 140 coating. The image shows a 2.5mm x 2.5mm square

This "ideal" coating surface had a thickness of 200 μm, the depth of the grooves was 80 μm, (R$_Z$), and the distance between the grooves was 300μm, (S$_m$). Thus the angle of the apex of the grooves, (2β), was representative of a real coating surface.

To determine when the casting surface solidified the measured casting surface roughness was used to calculate the pressure on the casting surface that occurred during its solidification. If the surface solidified after pouring the pressure experienced by the casting would be due to metallostatic pressure alone whereas if the casting surface solidified during pouring the pressure would be due to both the pouring height and the metallostatic pressure.

Figure 6, shows an example of the topography of the casting surface obtained by solidification of a commercial purity Al alloy on the machined coating surface shown in Figure 5.

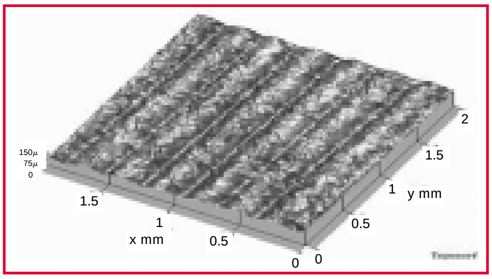

Figure 6: A 3-D image of a casting surface obtained by casting commercial purity Al onto the coating surface shown in Figure 5

Measurement of the depths of the grooves on the casting surface showed that the casting surface formed when only metallostatic pressure was experienced, that is, after pouring had been completed. Approximately in the middle of the casting surface, however, a much rougher patch had occurred (figure 7). Measurement of the

Figure 7: Photograph of a casting made on the "ideal" coating surface shown in Figure 5 showing a central rough patch, corresponding to the point of impact of the metal stream. (The parallel-sided feature on the casting surface shows the region where grooves were machined in the coating of the die steel block)

surface roughness of this patch showed that it experienced a greater pressure during its solidification corresponding to both metallostatic pressure and the pressure due to the impact of the metal stream. i.e. this rough patch was the point of impact of the liquid metal on the coated die steel surface.

Modelling of the coating surface roughness

To produce an estimate of the heat transfer coefficient using Equation 1 measured surface roughness parameters of both the casting and coating surfaces are required, however, it would be useful to have a model that did not require any measurement. The method used in the previous experiment could be used to predict the casting surface roughness from the measured surface roughness of the coating and the modelling package MacroPac [3] could be used to predict the coating surface roughness. This shows how a range of particle sizes can be packed into a specific volume thus duplicating how a die coating is built up by spraying a slurry onto a die surface. Modelling of a coating surface profile was carried out using a particle size distribution for DYCOTE 140 obtained from FOSECO GmbH and the programme was executed 5 times to obtain five different surface profiles. This was considered to be equivalent to measuring a surface profile of a coating at five randomly selected positions. Figure 8 shows a typical surface profile obtained in this way, with an assumed porosity of the coating of 30%, and how the surface roughness parameters were obtained from the model. Good agreement was found between measured coating surface roughness parameters and values obtained by modelling the coating formation in this way.

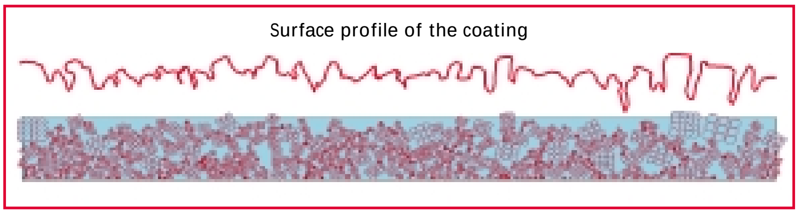

Figure 8. Modelled surface profile of a 200 μm thickness of DYCOTE 140 die coating. The surface profile of the coating was drawn by hand and used to obtain the surface roughness parameters of the coating

Thus it should be possible, by modelling the formation of the coating surface, to model the casting surface roughness and then derive a rough estimate for an interfacial heat transfer coefficient for a die casting process without making any experimental measurements.

Effect of increased pressure on the heat transfer coefficient

The effect of an air-gap, where the casting and mould surfaces retreat from one another, can be determined by estimating the distortion and contraction and expansion of the casting and the die. Alternatively the casting and the die surfaces could be forced together when, for example, the casting freezes onto a core or an internal die feature. This would cause an increase in the heat transfer coefficient which could have a marked effect on the solidification pattern of the casting.

Mathematical modelling of an Al automobile piston casting suggested that the interface in the gravity die casting process could experience a pressure that was a maximum of around 15 MPa which occurred shortly before the casting was released from the die. To duplicate the interfacial pressures found in casting, a cast Al surface was pressed against a coated die steel surface in a tensile testing machine. Subsequent examination revealed coating fragments embedded in the casting surface suggesting a model for the casting-coating interface represented in Figure 9. In this case the peaks of the coating surface are embedded in the casting surface to an extent that depends upon the pressure experienced. Heat transfer from the casting to the coating would occur by conduction through the areas of actual casting-coating contact and by conduction through the voids between the points of contact. Heat transfer to the die would then occur by conduction through the coating layer itself.

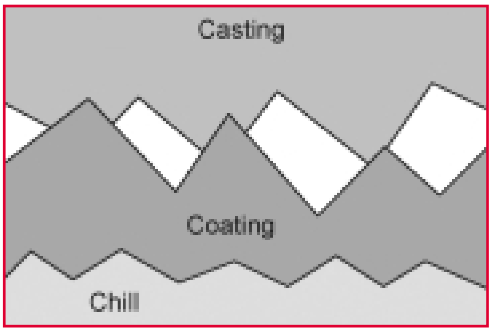

Figure 9: Sketch of the surfaces of a casting and a coated die in contact under pressure

The heat transfer for this situation has also been modelled resulting in an equation where the depth of the penetration of the coating surface roughness peaks, and their area of contact, was taken into account. Figure 10 shows a comparison of modelled and measured heat transfer coefficients in the case of a 200 μm DYCOTE 140 coating in contact with a commercial Al-Si alloy under a compressive load equivalent to a pressure of 14 MPa, at 300 ^{o}C. A heat transfer coefficient of around 2000 Wm^{-2}K^{-1} was measured and the modelled values showed good agreement with this.

In comparison the modelled heat transfer coefficient estimated by Equation 1, which reflected a situation where the casting-coated die interface experienced no pressure, was estimated to be 950 Wm^{-2}K^{-1} (figure 2). The application of the pressure therefore resulted in an approximately twofold increase in the heat transfer coefficient.

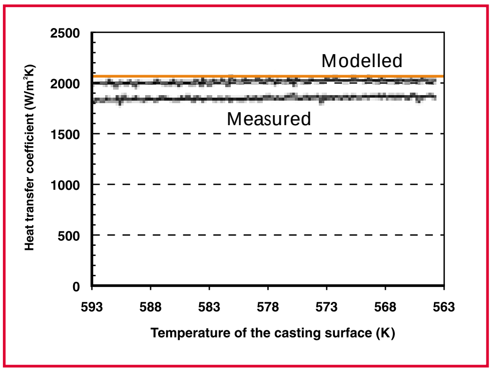

Figure 10: Graph showing a comparison between modelled and measured heat transfer coefficients for a 200 μm DYCOTE 140 coating with an applied pressure of 14 MPa at 300 ^{o}C

Summary

Examination of the casting – coated die steel interface in experiments intended to duplicate gravity die casting conditions has led to an improved understanding of the heat transfer mechanisms during casting solidification. Evaluation of these mechanisms has led to equations to predict the heat transfer coefficient in Al die casting that can lead to improved solidification modelling. This estimation of the heat transfer coefficient has shown the important role played by the occurrence of a layer of air trapped between the casting and