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The effect of increased pressure on interfacial heat transfer in the aluminium gravity die casting process

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Abstract Contraction and distortion of a casting during cooling within a mould can force their respective surfaces together, with the associated increased interfacial pressure resulting in increased interfacial heat transfer. This problem has been examined for the case of gravity and low pressure die casting of an Al alloy, where an insulating coating is applied to the die cavity to assist filling of the mould. The degree of interfacial pressure was estimated to be, for a typical small die casting, at most about 21 MPa. Repeated applications of a compressive load showed that a freshly applied die coating became thinner and smoother, until a stable situation was reached after about ten applications. The interfacial heat transfer coefficient was estimated to be increased by about 20%, with an increase in the applied pressure by a factor of two, from 7 MPa to 14 MPa, and increased by about 40%, with an increase in the applied pressure by a factor of three, from 7 MPa to 21 MPa. The heat transfer mechanisms between the casting and the die surfaces were evaluated to produce a simple model of interfacial heat transfer which included conduction through the points of actual contact, in parallel with conduction through the interfacial gas between the points of actual contact, both mechanisms being in series with the heat transfer by conduction through the die coating. Evaluation of the model produced agreement with experimentally determined values of the interfacial heat transfer coefficient to within about 15%.

Introduction

Modelling has improved the productivity of the casting process greatly in the last few decades [1]. Initially simulations were concerned with modelling casting solidification, and then developed further to embrace mould filling and are currently being expanded to produce improved defect predictions, and improved microstructural and mechanical property models. For such models to be accurate they must utilise the correct thermophysical property data for the alloy concerned, specifically density, specific heat capacity and thermal conductivity (for both the liquid and the solid phase), and also use the latent heat of fusion appropriate for the specific alloy composition being modelled. It is also necessary to employ the correct boundary conditions for the heat transfer model, which means using a good estimate of the interfacial heat flux or interfacial heat transfer coefficient, to accurately describe the transfer of heat out of the casting and across the casting–mould interface.

The ease of interfacial heat transfer depends upon the conditions occurring at the casting–mould interface. Ho and Pelhke [2] explained how the surface of a casting develops by solidification of the liquid metal, initially on the peaks of the mould surface roughness on which it came to rest, with the casting skin gradually thickening and deforming as solidification progressed, leading to reduced contact with the mould surface.

The interfacial heat transfer therefore depends upon the amount of actual contact between the rough surfaces of the mould and the casting, and the mean separation of the two surfaces. The mechanism of heat transfer, in the case of

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relatively low melting point non-ferrous alloys, would be by conduction through the points of interfacial contact, and by conduction through the interfacial gas in the regions between the contact points. Radiation would not be expected to be a significant heat transfer mechanism in the case of Al or Mg alloys, but in the case of higher melting point ferrous alloys may account for around 50% of the interfacial heat transfer [3].

The effect of many casting parameters on the interfacial heat transfer coefficient have been investigated experimentally. Sahin et al. [4] measured heat transfer coefficients for steel and Cu chills. O'Mahoney and Browne [5] examined the effect of alloy freezing range and head height during solidification of an Al alloy in investment casting. Ferreira et al. [6] analysed the effect of alloy composition, melt superheat, mould material, mould roughness and mould coatings on the interfacial heat transfer coefficient, and Cheung et al. [7] determined the effect of the initial melt temperature profile, the wettability of the cast alloy on the chill surface and the effect of orientation of the casting with respect to gravity. Ferreira et al. [8] showed how assumptions about initial temperature distribution could affect the calculated heat transfer coefficients. Arunkumar et al. [9] examined two-dimensional heat transfer in gravity die casting, and also looked at how taking into account the initial nonuniform temperature field that typically results after filling of the mould made the distribution of heat flux and initiation of air-gap formation around a casting–mould interface occur nonuniformly.

As Ho and Pehlke [2] described earlier, as the solidification front of the casting progresses inwards the solid casting skin thickens and distorts, causing it to move relative to the surface of the mould. This reduces the amount of actual contact and increases the mean interfacial gap distance. As the solidified skin cools further, contraction normal to the interface may occur, which can also increase the thickness of the layer of gas at the casting–mould interface. This contraction can be such that a significant gap can occur between the casting and mould surfaces which, filled with low thermal conductivity mould gases and air, can create a considerable barrier to the transfer of heat across the interface. Nayak and Sundarraj [10] showed, for example, that a coupled thermo-mechanical model could be used to accurately describe the development of such an air gap, and that taking into account such variations in interfacial heat transfer led to more accurate solidification models.

In shape casting there would also be a natural tendency for a casting to drop into the lower part of its mould, under the action of gravity (although the position of the casting in the mould may also be constrained by its attached running and feeding system). In this case a gap would open up between the upper part of the casting surface and the upper part of the mould surface, decreasing the rate of heat transfer there, but the casting would be in better contact with the lower parts of the mould surface upon which it rested [11]. For example, Cheung et al. [12] measured heat transfer coefficients for an Al alloy solidifying in a rotary continuous caster, and noted an increased heat transfer coefficient where gravity caused the ingot to fall onto the bottom surface of the curved mould. Spinelli et al. [13] also measured the interfacial heat transfer coefficient for Al–Si alloys in upwards and downwards solidification orientations, and noted that the former were greater than the latter, due to the casting surface being pressed against the chill surface.

Other work aimed at examining the effect of increased pressure on interfacial heat transfer includes that by Mirbagheri et al. [14, 15] who cast varying heights of Pb onto a solidifying Al alloy casting, producing changes in interfacial pressure of from 5 kPa to 50 kPa. The castings were made against an uncoated cast iron chill surface and the results showed a 3-fold increase in heat transfer coefficient, from about 4.5 kW m^{-2} K^{-1} at 10 kPa to 12 kW m^{-2} K^{-1} above 30 kPa (but being relatively insensitive to pressure outside of this range). An empirical expression to determine the variation of interfacial heat transfer coefficient with pressure was suggested [15]. Meneghini et al. [16] also examined the effect of metal head height, and therefore interfacial pressure, on the interfacial heat transfer coefficient between an Al alloy and an Al chill. It was concluded that increased metal head increased the interfacial heat transfer coefficient, and delayed the onset of air-gap formation.

Measurements have also been made of interfacial heat transfer, for cases where the casting-mould interface is compressed together, in the squeeze casting and high pressure die casting (HPDC) processes. In the case of squeeze casting, Aweda and Adeyemi [17] found only a small effect with applied pressure, with only a 14% increase in interfacial heat transfer coefficient with the application of 86 MPa pressure. Chattopadhyay [18] numerically simulated the squeeze casting process, using variable heat transfer coefficients, and noted no effect on the solidification model when heat transfer coefficients above values of 20–40 kW m^{-2} K^{-1} were used. He listed heat transfer coefficient values of 100 to 125 kW m^{-2} K^{-1} for applied pressures of 25–100 MPa, respectively, and suggested that pressures of up to 60–100 MPa were optimal for the squeeze casting process.

Research into interfacial heat transfer in Al and Mg alloy high pressure die casting (HPDC), using measurements made within the casting process itself, includes work by Guo et al. [19–21], who found a heat transfer coefficient that initially reached a maximum value of about 10–20 kW m^{-2} K^{-1} (depending on alloy and section thickness), followed by a rapid decline to low values of about a few hundred W m^{-2} K^{-1}. Guo et al. [22] examined the high pressure die casting of Mg alloy in H13 tool steel dies, obtaining an initial peak interfacial heat transfer coefficient of just over 12 kW m^{-2} K^{-1}, again then decreasing to less than 1 kW m^{-2} K^{-1} over about 7 s. Increasing pressure increased the interfacial heat transfer coefficient at all times (Applied pressures of 24, 44, and 67 MPa were used).

Dour et al. [23] measured the interfacial heat transfer coefficient and found values of 45–60 kW m^{-2} K^{-1}, in the 33–90 MPa pressure range, but observed they were relatively insensitive to pressure. A "saturation effect" where increased pressure did not lead to increased heat transfer, was suggested to occur above about 5 MPa. Hamasaiid et al. [24] and Dargusch et al. [25], for the HPDC of a Mg alloy, also reported initial peak heat transfer coefficients of up to about 90–112 kW m^{-2} K^{-1}, declining to low values within a few tenths of a second.

In high pressure die casting the typical behaviour of the heat transfer coefficient is to increase to a peak value, which is then followed by a rapid decline. This has been explained by increasing solidification and fraction solid in the mould cavity causing a reduction in the pressure transmitted from the piston to the casting–mould interface [19–25].

The heat transfer mechanisms for an Al alloy solidifying in contact with a coated die steel surface, representative of conditions in the gravity and low pressure die casting processes, have also previously been explored. This has led to empirical equations describing the interfacial heat transfer, e.g. Sun [26], Kumar and Prabhu [27] and Trovant and Agyropoulis [28], and simple expressions that attempt to model the thermal resistances recognised as playing a part in heat transfer from the casting to the mould. Griffiths produced a model of an Al casting solidifying whilst in contact against a Cu chill, which took into account heat transfer by conduction at the points of interfacial contact and through the interfacial gas [29, 30], and this was extended to the case of gravity and low pressure die casting, in which an insulating coating is applied to the die surface, by assuming resting contact between a solid casting skin and the die coating [31]. This meant that heat transfer through points of contact could be neglected, with the interfacial thermal resistances assumed to be due only to conduction through the interfacial gas and the insulating die coating. Further examples of these types of models were produced by Isaacs et al. [32], Chiesa [33], Lee et al. [34], Hamasaiid et al. [35] and Martorano and Capocchi [36].

An opposite effect to the formation of an air gap can occur, where the casting surface is forced into better contact with the mould surface. Different parts of a casting with different section thicknesses would cool unevenly, and this may cause distortion of the casting leading to a variation in the degree of contact between the casting and mould surfaces at different points in the mould. This means that parts of the interface may have an air-gap, whilst other parts will be in light contact, whilst yet other parts will be forced against the mould surface. If the casting surface is semi-solid, then it should easily deform. But once the casting surface has completed solidification, pressing the casting surface into the mould would lead to a localised enhancement of the interfacial heat transfer, as the area of actual contact would be increased and the mean separation of the two surfaces would be reduced. A further example of enhanced heat transfer would occur in the case of a casting surrounding a core, where contraction of the casting would cause it to shrink onto the core, again increasing the interfacial contact and the interfacial heat transfer rate. For the solidification of the casting to be modelled accurately, and for such internal defects as solidification shrinkage to be predicted confidently, the interfacial heat transfer between the casting surface and the mould must be understood at all points. If the casting is distorting in the mould as it solidifies, and the already-solidified casting skin is pressed against the die surface, this will enhance the heat transfer locally.

A review of the work carried out so far shows that the interfacial heat transfer in the casting process can therefore vary with both time and position in the mould. It is necessary to understand the effects of this on interfacial heat transfer, so that future casting simulations can incorporate variable heat flux and heat transfer coefficients, resulting in improved accuracy. As the casting solidifies, its solid skin can move relative to the mould, and the heat transfer mechanisms between the respective surfaces vary. The case of resting contact and the formation of an air-gap in gravity and low pressure die casting has been examined earlier [31]. In the work reported here the interfacial heat transfer between a solid casting surface and a coated die surface has been examined under conditions of increased interfacial pressure, leading to increased interfacial contact, and enhanced interfacial heat transfer.

Experimental procedure

The procedure to measure the effect of pressure on the interfacial heat transfer mechanisms required the measurement of unidirectional heat transfer through an interface between a cast Al alloy surface and a coated die steel surface, maintained under pressure and at a temperature typical of the operation of the gravity and low pressure die casting processes.

Solidification models of cylindrical castings, freezing onto a cylindrical core, were carried out using MAGMASoft casting simulation software [37], and these models suggested an interfacial pressure of up to 22 MPa might be obtained in the case of a typical (small) die casting (about 100 mm in diameter and 10 mm wall thickness), cooling to 300 °C (at which temperature it would be removed from its die). This value would obviously vary with casting size, geometry and alloy, but was accepted as a guide in deciding what pressures to apply during the experiment.

In industrial practice dies used in the gravity and low pressure die casting processes are coated with a thin layer of a refractory slurry to improve fluidity of the cast alloy. In use these die coatings degrade after their initial application, but often last for several days before requiring repair or replacement. A correctly applied coating could be used for anywhere between 100 and 1000 mould fillings before requiring maintenance or replacement. Therefore, before any experiments were carried out, changes to a freshly-applied die coating due to repeated use were initially investigated, firstly by determining the effect of repeated mould filling, and then by determining the effect of repeated compression of a die coating.

To determine the effect of die filling, a 200-μm thick commercial die coating was applied to a preheated (200 °C) cast iron die (a thickness representative of typical die casting practice). This was then heated to 300 °C and cast with Al–7Si–0.3Mg alloy 30 times. The surface roughnesses of the coating and casting surfaces were measured after each casting was made (by measuring R_z), which showed a decrease in die coating roughness of about 30% over the 30 castings made. The corresponding decrease in casting surface roughness was about 10%.

To determine the effect of repeated compression, a commercial die coating was similarly applied to H13 die steel discs, of height 7 mm and diameter 30 mm, again with a coating thickness of 200 μm. As-cast Al alloy samples, of diameter 15 mm, and height 7 mm, were made from Al–7Si–0.3Mg alloy which were then placed on the coated die steel surfaces. These cast Al alloy surfaces were obtained by previously casting the alloy against a similarly coated die steel surface. The casting and coated die steel surfaces were placed, in contact with one another, in a resistance-heated furnace in a tensile testing machine, and heated to 300 °C, monitored by a thermocouple inserted in the cast sample. Compressive loads were applied via the tensile testing machine to give interfacial pressures of 7, 14 and 21 MPa, with the loads applied for a period of 60 s, and then released. The application of the load was repeated twelve times, each time using a fresh as-cast casting surface, but the same coated die steel surface, to mimic the case where a freshly-coated die surface can become abraded due to use. The change in die coating thickness and surface roughness were measured before and after each application of the load.

These experiments showed that a coating on a die surface changed its thickness as a result of filling of the die, and of being compressed, at least for the first 10 applications of pressure, although there was no effect of repeated compression detected thereafter. Therefore, to duplicate the effect of use of a die coating in this experiment, the coated die steel chill used was compressed 10 times, and then a new as-cast surface inserted before proceeding with the measurement of the interfacial heat transfer.

The macroscopic surface profile was also determined, to check whether the surfaces in contact were plane. A lack of planeness, i.e. waviness, would mean that heat transfer through the interface would preferentially occur through the highest areas of the surface, which would be in greater contact with the opposing surfaces. No waviness, greater than the measured surface roughness, was detected in these experiments, on either the coated die steel surfaces or the casting surfaces used.

The effect of compression on the interfacial heat transfer was determined by the same method, compression of a heated casting–coated die interface using a tensile testing machine. The experimental arrangement used has been shown in Fig. 1. In this case the die was represented by a H13 water-cooled die steel chill, of height 100 mm and diameter 30 mm, coated with the same commercial die coating with a thickness of about 200 μm. The casting was represented by an as-cast cylindrical bar of a commercial eutectic P-refined Al–Si alloy (AE413P), also of height 100 mm and 30 mm diameter. The as-cast surface at the interface was obtained by solidification of the casting against a similarly coated die steel surface, to create an interface representative of die casting conditions. The

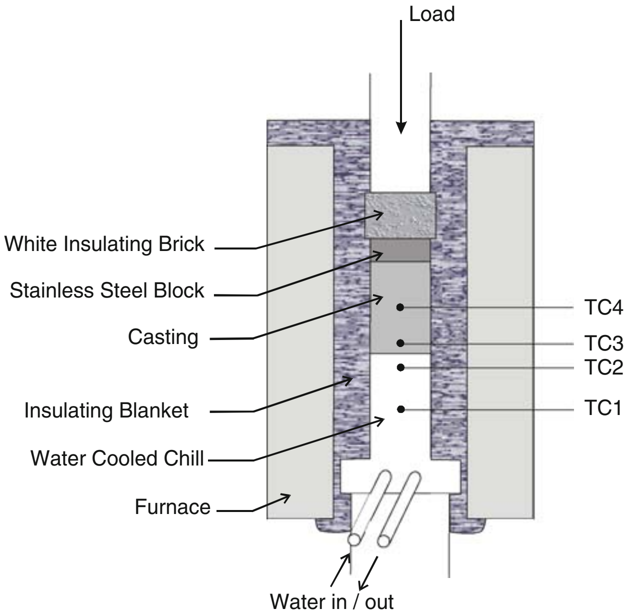

Fig. 1 Sketch of the apparatus used to determine the interfacial heat transfer coefficient for a casting–coated die interface under compression

upper part of the cast cylinder was insulated, to prevent loss of heat to the tensile testing machine. Type K thermocouples (0.5 mm diameter) were inserted in both the casting and the die steel chill, so that their hot junctions lay on the axis of the cylinders, at distances of 5 mm and 37.5 mm from the interface.

The experiment was heated to 320 °C (i.e. both the casting sample and the die steel sample had reached this temperature), and then the required load was applied and the water cooling to the die steel chill turned on, in order to draw heat through the cast alloy—coated die steel interface, and create a temperature gradient across it. The temperature of the thermocouples either side of the interface was measured by a data-logger every 2 s during the period in which the temperature measured by the thermocouple in the casting 5 mm from the interface decreased from 320 °C to 280 °C. Determination of the interfacial heat transfer coefficient from the measured temperatures was carried out by using a finite difference solution to the one-dimensional heat conduction equation, as described elsewhere [38]. The experiments were carried out with three loads applied, 7, 14 and 21 MPa, and each experiment was carried out twice at each load.

Results

The effect of repeated compression of the die coating

The effect of application of pressure to a 200-µm commercial die coating applied to a die steel surface, has been shown in Fig. 2. The unaffected coating surface is on the left-hand side of the Figure, whilst on the right-hand side can be seen the same coating surface after a sequence of 20 compressions of 14 MPa, showing considerable flattening. One effect of the applied pressure was to embed particles of the coating in the casting surface, as shown in Fig. 3. Three-dimensional representations of the effect of repeated application of a compressive load have been shown in Fig. 4. Figure 4a shows the applied coating, whilst Fig. 4b shows that after 20 applications of a compressive pressure of 14 MPa, the surface of the die coating comprised of fewer, more widely spaced peaks and valleys.

The coating surface roughness was characterised by determination of its mean peak-to-valley height, R_z, and its thickness, and the results have been shown in Fig. 5a and b,

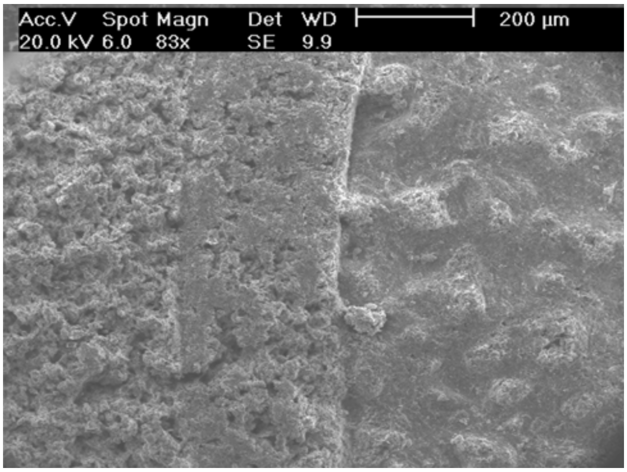

Fig. 2 The effect of repeated compression of a die coating. The left-hand side shows the original, unaffected die coating. The right-hand side shows considerable flattening of the coating surface (after a sequence of 20 compressions at a pressure of 14 MPa)

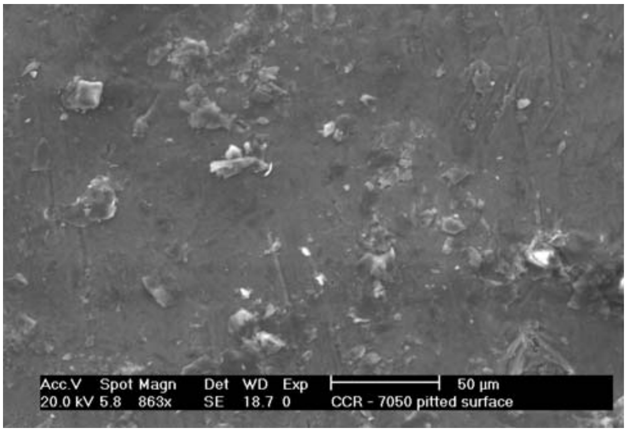

Fig. 3 The casting surface after contact with a coated die steel surface, subjected to a compression of 7 MPa

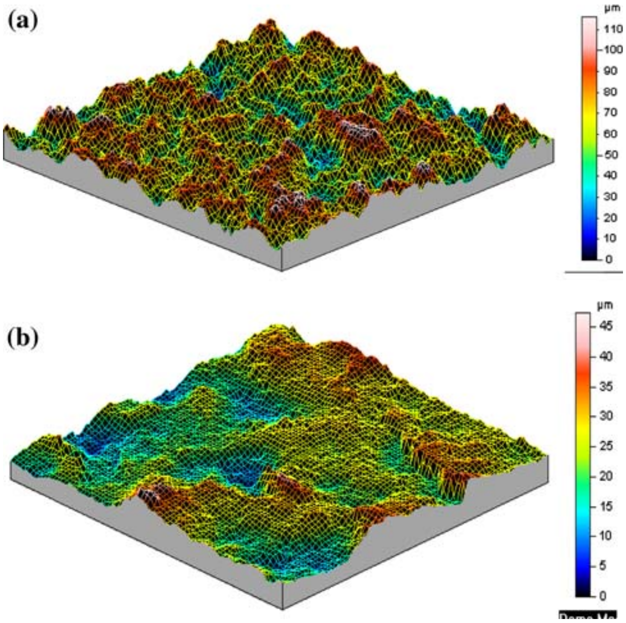

Fig. 4 Three-dimensional scans of the coating surfaces. **a** Before compression. **b** After a sequence of 20 compressions at 14 MPa

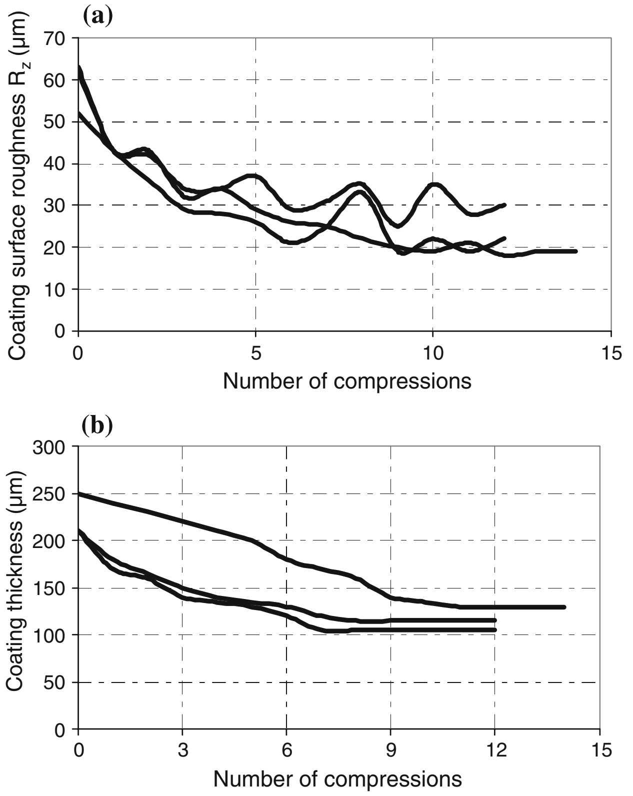

Fig. 5 Effect of repeated compression on properties of the die coatings; in each case three repeated experiments have been shown. **a** Mean peak-to-valley height, as measured by the parameter R_z. **b** Mean coating thickness

respectively. Repeated compression resulted in a reduction in the R_z value to about 30–50% of its original value (about 60 µm), whilst the coating thickness was reduced to about 50% of its original value of 200–250 µm.

The effect of compression on the heat transfer coefficient

The heat transfer coefficients determined at the different applied pressures have been shown in Fig. 6 (with the coatings having previously been subjected to a series of compressions until it was expected that the coating surface was no longer affected, as the results shown in Fig. 5a and b suggested). Figure 6 also includes an estimated heat transfer coefficient, for the casting and the coated die steel surfaces in resting contact, determined by evaluating the different interfacial heat transfer mechanisms, according to the method described in Ref. [31].

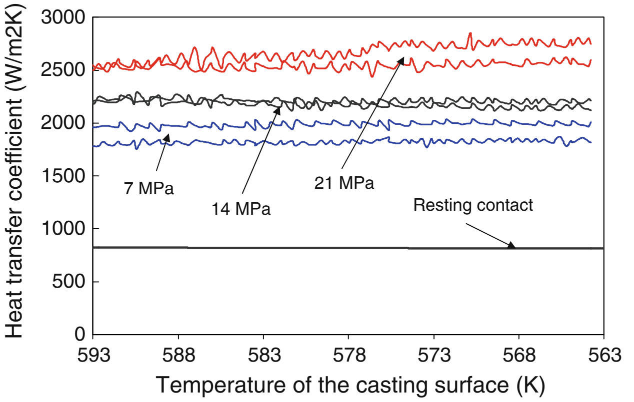

Fig. 6 Effect of applied pressure on the interfacial heat transfer coefficient

For the measured surface roughness parameters and coating thicknesses obtained in the experiment, the heat transfer coefficient without an applied pressure was estimated to be about 830 W m^{-2} K^{-1}. With an applied pressure of 7 MPa, the heat transfer coefficient was experimentally determined to be about 1870 W m^{-2} K^{-1}, and was increased to about 2230 W m^{-2} K^{-1} with a pressure of 14 MPa, and about 2650 W m^{-2} K^{-1} with a pressure of 21 MPa. Therefore, increasing the pressure by a factor of two, from 7 MPa to 14 MPa, increased the experimentally determined heat transfer coefficient by about 20%. Increasing the applied pressure by a factor of three, from 7 MPa to 21 MPa, increased the experimentally determined heat transfer coefficient by about 40%.

Discussion

The assessments of the effects of repeated compression of the die coating, shown in Fig. 5a and b, showed embedding of coating particles in the casting surface, which suggested that there would be considerable contact between the peaks of the coating surface roughness and the casting surface, due to the applied load forcing the two surfaces together. The heat transfer mechanisms from the casting surface to the die surface should be (i) the conduction through the points of actual contact between the casting and coating surfaces, in parallel with (ii) the conduction of heat through the interfacial gas in the gaps between the points of actual contact, with both mechanisms being in series with (iii) the conduction of heat through the coating to reach the die surface.

The relationships between these three heat transfer paths have been shown as thermal resistances in Fig. 7. The interfacial heat transfer coefficient (h) can be obtained by evaluating the individual thermal resistances, and then combining them as two thermal resistances in parallel, in series with a third resistance, as follows:

$$\frac{1}{h} = R = \left(\frac{R_{\mathrm{air}}R_{\mathrm{contact}}}{R_{\mathrm{air}} + R_{\mathrm{contact}}}\right) + R_{\mathrm{coat}} \tag{1}$$

Here, $R =$ the total interfacial thermal resistance, $R_{\mathrm{contact}} =$ the thermal resistance associated with heat

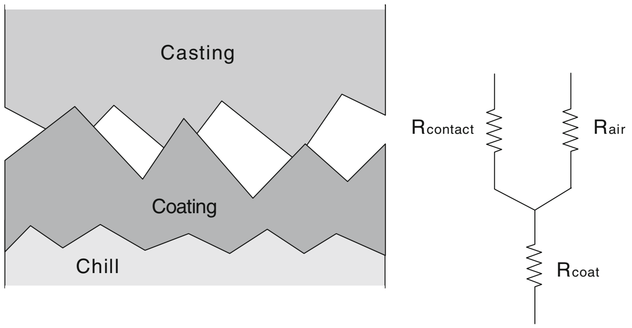

Fig. 7 Schematic model of the heat transfer mechanisms between a casting surface compressed onto a coated die steel surface. R_{contact} represents the thermal resistance associated with the transfer of heat through the points of actual contact. R_{air} represents the thermal resistance associated with the transfer of heat through the interfacial gas between the points of actual contact. R_{coat} represents the thermal resistance associated with the transfer of heat through the (compressed) die coating

transfer by conduction through the points of actual contact, R_{air} = the thermal resistance associated with heat transfer by conduction through the atmosphere in the interface between the points of actual contact, and R_{coat} = the thermal resistance associated with heat transfer by conduction through the die coating. Heat transfer by convection and radiation were assumed to be negligible for the case of die casting of Al alloys.

The thermal resistance of the air in the interface (R_{air}), was obtained by determining the mean thickness of the air layer, deduced from the surface roughness of the casting and coating surfaces, but deducting from this the amount of penetration of one surface into another due to the applied pressure. This was then divided by the thermal conductivity of air, expressed at the temperature appropriate for the interface:

$$R_{\mathrm{air}} = \frac{x}{k_{\mathrm{a}}} = \frac{0.5(R_{\mathrm{z}(\Sigma)} - d_{\mathrm{p}})}{k_{\mathrm{a}}} \tag{2}$$

where x = the mean estimated thickness of the air layer and k_{a} = thermal conductivity of the gas in the interface (presumed to be air). $R_{\mathrm{z}(\Sigma)}$ = the mean distance between the coating and casting surfaces, expressed as the square root of the sum of the squares of the mean peak-to-valley heights of the respective surfaces (where the subscripts (cast) and (coat) refer to the casting and coating surfaces, respectively):

$$R_{\mathrm{z}(\Sigma)} = \sqrt{R^2_{\mathrm{z(cast)}} + R^2_{\mathrm{z(coat)}}} \tag{3}$$

Here, $R_{\mathrm{z}(\Sigma)}$ represents an estimate of the mean thickness of the layer of air in the interface, if the two surfaces were in simply resting upon each other. A sketch, in which the surface roughness parameters used in this estimation have been defined, has been given in Fig. 8.

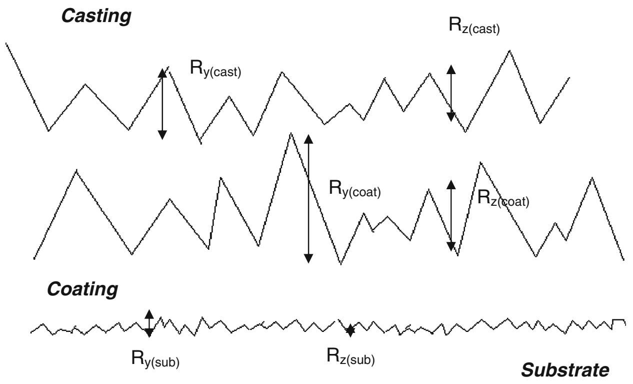

Fig. 8 Schematic showing the surface roughness parameters used in the evaluation of the interfacial heat transfer coefficient. R_{y} is the maximum peak-to-valley height in the surface profile assessment length. R_{z} is the mean of the ten greatest peak-to-valley height measurements in the surface profile assessment length

If a pressure is applied, the peaks of the harder surface would be forced into the softer surface, and the mean thickness of the layer of interfacial gas would be correspondingly reduced. The amount of this reduction, denoted d_{p}, was estimated by assuming the surface roughness of the harder surface could be represented by pyramidal shaped indentors, having a geometry obtained from the surface roughness measures of mean peak spacing and mean peak height, giving, for a known applied pressure, the following expression (further details of the derivation of this expression are given in Ref. [39]):

$$d_{\mathrm{p}} = \cos\beta \sqrt{\frac{P(S^2_{\mathrm{m}(\Sigma)})}{12Y\tan\beta}} \tag{4}$$

where β = the mean semi-angle of the peaks forming the indenting surface, P = the applied pressure, and Y = the yield stress of the softer surface, assumed, from Fig. 3, to be the alloy. $S_{\mathrm{m}(\Sigma)}$ = the measured mean spacing between the surface roughness peaks (taken as the square root of the sum of the squares of the measured mean spacings of the surface roughness peaks of the coating and casting surfaces):

$$S_{\mathrm{m}(\Sigma)} = \sqrt{S^2_{\mathrm{m(cast)}} + S^2_{\mathrm{m(coat)}}} \tag{5}$$

The reduction in the mean distance between the two surfaces owing to the applied compression was estimated to be about 7 μm, for an applied pressure of 7 MPa, about 10 μm for an applied pressure of 14 MPa, and about 13 μm for an applied pressure of 21 MPa. These values corresponded to reductions in the estimated spacing distance between the two surfaces of about 20%, 26% and 32%, respectively.

The thermal resistance associated with the transfer of heat through the points of actual contact between the casting and the contact surface (R_{contact}) was evaluated from:

$$R_{\text{contact}} = \frac{S^2_{\text{m}(\Sigma)}}{2k_{\text{t}}}\sqrt{\frac{\pi}{A_{\text{i}}}} \tag{6}$$

where A_i = the area of actual contact, estimated by the same method used to determine d_p, and k_t = the harmonic mean thermal conductivity of the two materials in contact:

$$k_{\text{t}} = \frac{2k_{\text{coat}}k_{\text{cast}}}{k_{\text{coat}} + k_{\text{cast}}} \tag{7}$$

where k_coat = the thermal conductivity of the coating, and k_cast = the thermal conductivity of the casting.The thermal resistance of the die coating (R_coat) was estimated from the mean thickness of the die coating, divided by its thermal conductivity.

$$R_{\text{coat}} = \frac{x_{\max} + (0.5R_{\text{y(sub)}}) - (0.5R_{\text{y(coat)}})}{k_{\text{c}}} \tag{8}$$

where x_max = the measured thickness of the coating, where the measurement was taken from the peaks of the coating surface roughness, $R_\text{y(sub)}$ = a measure of the maximum peak-to-valley height of the surface roughness of the substrate upon which the coating was deposited (i.e. the shot-blast die surface before application of the coating), and $R_\text{y(coat)}$ = a measure of the maximum peak-to-valley height of the surface roughness of the coating. Surface roughness and thickness values were measured for each coating used in the experiments, after the experiments had been carried out. k_c was the thermal conductivity of the coating, which was corrected for the effect of being compressed.

The thermal conductivity of a die coating had been previously measured, using a laser flash diffusivity technique, to be 0.8 W m^{-1} K^{-1}, and possessed 32% porosity, determined by image analysis [31]. In the compressed coatings used in these experiments, image analysis measurements showed the degree of porosity had been decreased to about 23%, and the thermal conductivity of the coating was therefore estimated to be increased to about 0.93 W m^{-1} K^{-1}. The harmonic mean thermal conductivity was estimated from the thermal conductivity of the cast alloy at 300 °C (the temperature at which the experiments were carried out), which had been measured by laser flash diffusivity to be 160 W m^{-1} K^{-1} [31], whilst the constituent of the coating that would form the peak in contact with the casting surface, was estimated to have a thermal conductivity of 1.3 W m^{-1} K^{-1}. These values produced a harmonic mean thermal conductivity for the areas of actual contact of 2.6 W m^{-1} K^{-1}.

Table 1 shows the values of the parameters used in evaluating the thermal resistances described, whilst Table 2 shows the effect of increasing pressure on the actual contact area of the interface. The agreement between the interfacial heat transfer coefficients evaluated by Eq. 1 and experimentally determined has been shown in Fig. 9a–c, for the different applied pressures. The agreement was within 15% and suggested that a good understanding of the mechanisms of interfacial heat transfer in the gravity and low pressure die casting processes had been obtained.

Table 1 Properties and parameters used to evaluate the model of interfacial heat transfer for a casting-coated die interface under pressure

	Symbol		Units
Thermal conductivities			
Thermal conductivity of porous coating after compression	k_c	0.93	W m^{-1} K^{-1}
Harmonic mean thermal conductivity	k_t	2.6	W m^{-1} K^{-1}
Thermal conductivity of casting surface	k_cast	160	W m^{-1} K^{-1}
Thermal conductivity of coating surface	k_coat	1.3	W m^{-1} K^{-1}
Thermal conductivity of air (at 300 °C)	k_a	0.045	W m^{-1} K^{-1}
Alloy properties			
Yield stress of (as-cast) AE413P alloy (at 300 °C)	Y	80	MPa
Typical surface roughness parameters			
Maximum peak-to-valley height of the substrate surface profile	$R_\text{y(sub)}$	60	μm
Maximum peak-to-valley height of the coating surface profile	$R_\text{y(coat)}$	69	μm
Mean peak-to-valley height of the coating surface profile	$R_\text{z(coat)}$	50	μm
Mean peak-to-valley height of the casting surface profile	$R_\text{z(cast)}$	58	μm
Mean peak-to-valley height of the surface profile of the sum rough surface	$R_{\text{z}(\Sigma)}$	77	μm
Mean peak spacing of the coating surface profile	$S_\text{m(coat)}$	295	μm
Mean peak spacing of the casting surface profile	$S_\text{m(cast)}$	308	μm
Mean peak spacing of the surface profile (sum rough surface)	$S_{\text{m}(\Sigma)}$	426	μm
Mean semi-angle of the surface roughness peaks and valleys	β	70	°

Table 2 The mean separation and actual contact area for the interface under pressure

Parameter	Applied pressure (MPa)		
	7	14	21
Reduction in the mean distance between the casting and coating surfaces (d_p) (μm)	7	10	13
Estimated contact spot size (A_i) (mm^2)	0.006	0.013	0.02
Estimated area of actual contact (mm^2)	21	41	62
Estimated area of actual contact (%)	3	6	9

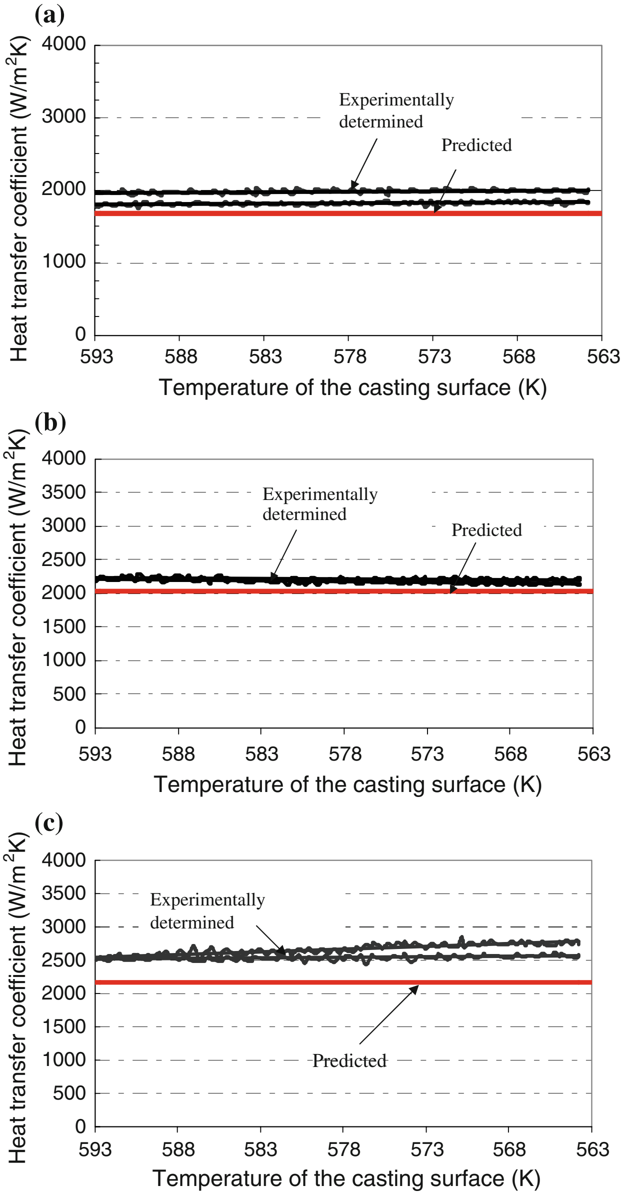

Fig. 9 Measured and predicted interfacial heat transfer coefficients at 300 °C for an applied pressure of **a** 7 MPa, **b** 14 MPa and **c** 21 MPa

The individual thermal resistances of the three different heat transfer paths have been shown in Table 3. The thermal resistances associated with heat transfer by conduction through the points of actual contact was similar to that associated with heat transfer by conduction through the interfacial gas between the points of contact, both being between about $\sim 5 \times 10^{-4}$ m^2 KW^{-1} to $\sim 10 \times 10^{-4}$ m^2 KW^{-1}. The thermal resistances associated with heat transfer through the coating itself was about one-quarter of these values, being about $\sim 1.3 \times 10^{-4}$ m^2 KW^{-1} to $\sim 2.2 \times 10^{-4}$ m^2 KW^{-1}.

Conclusions

1. The interfacial heat transfer coefficients have been determined for the case of an Al alloy casting surface forced against a coated tool steel die, as would occur during solidification and cooling of a casting in the gravity and low pressure die casting processes.
2. The interfacial heat transfer coefficients were estimated, for an interfacial temperature of 300 °C, to be increased (compared to a case of no applied pressure) to about 1900 W m^{-2} K^{-1}with an applied pressure of 7 MPa, 2200 W m^{-2} K^{-1} with a pressure of 14 MPa, and about 2650 W m^{-2} K^{-1} with a pressure of 21 MPa. Increasing the applied pressure by a factor of two, from 7 MPa to 14 MPa, increased the heat transfer coefficient by about 20%. Increasing the applied pressure by a factor of three, from 7 MPa to 21 MPa, increased the heat transfer coefficient by about 40%.
3. Evaluation of the interfacial heat transfer mechanisms was carried out, to produce a simple model in which interfacial heat transfer occurred by conduction through the points of actual contact between the die coating and the casting surface, in parallel with heat transfer by conduction through the interfacial gas between the points of actual contact, both mechanisms being in series with the heat transfer by conduction through the die coating. Evaluation of this simple model produced a predicted heat transfer coefficient which agreed with experimentally determined values to within about 15%.
4. The magnitude of the thermal resistances for the different heat transfer paths evaluated in the model

Table 3 Evaluated thermal resistances and estimated heat transfer coefficients for each experiment

Thermal resistances and interfacial heat transfer parameters	Applied pressure (MPa)					
	7	7	14	14	21	21
R_{air} ($\times$ 10^{-4} m^2 KW^{-1})	7.7	6.9	6.8	8.3	7.5	7.0
$R_{contact}$ ($\times$ 10^{-4} m^2 KW^{-1})	8.6	9.5	6.7	6.3	6.2	4.6
R_{coat} ($\times$ 10^{-4} m^2 KW^{-1})	2.2	1.6	1.5	1.3	1.7	1.4
Measured coating thickness (x_{max}) (μm)	220	160	160	145	175	150
Coating thickness after compression (x) (μm)	204	150	141	124	157	132
Overall thermal resistance (R) ($\times$ 10^{-4} m^2 KW^{-1})	6.2	5.6	4.9	4.9	5.1	4.2
Heat transfer coefficient (h) (W m^{-2} K^{-1})	1900		2200		2560	

showed that the heat transfer through the points of actual contact, and through the interfacial gas, had similar thermal resistances, and were approximately four times greater than the thermal resistance associated with the die coating itself.

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