A MODEL OF THE INTERFACIAL HEAT TRANSFER COEFFICIENT DURING THE SOLIDIFICATION OF AN AL-SI ALLOY

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ABSTRACT A model was developed to predict the heat transfer coefficient during the unidirectional solidification of an Al-7wt.%Si alloy casting. An important feature of this model was that once the casting skin had solidified it was assumed to deform into a spherical shape. This implies that during solidification heat was transferred at the interface with the chill through a central area where the plane chill surface and the spherical casting skin were in contact, surrounded by an outer annulus where a local gap existed between the casting and the chill surfaces. The model produced values of the interfacial heat transfer coefficient which were comparable to those measured.

Keywords: *casting, solidification, interface, heat transfer coefficient.*

1. INTRODUCTION

Modelling of casting solidification requires a knowledge of the heat transfer coefficient at the casting-mould interface and many experiments have been carried out to measure this. These have shown that the heat transfer coefficient varies greatly with variations in the casting conditions, such as alloy superheat, chill material, etc., used in each experiment. It is apparent that the values obtained by experiment can only serve as a guide. Modelling of the processes that govern heat transfer at the casting-mould interface would offer a method of obtaining the boundary conditions necessary for improved modelling of casting solidification.

It is generally held that upon pouring a molten alloy into a die it comes to rest upon the peaks of the die surface asperities. Heat is extracted by conduction through areas of contact between the rough surfaces of the chill and the casting skin and also by conduction through the atmosphere in the voids between the actual areas of contact[1]. Thereafter, the relative expansion and contraction of the chill and the casting may result in their separation and a reduction in the heat transfer coefficient as the resulting air gap creates a strong thermal resistance.

In unidirectional solidification experiments to measure the interfacial heat transfer coefficient with Al-Si[2] and Al-Cu[3] alloys it was found that the casting surfaces were convex towards the chill by amounts of around 10-20 μm. The convexity of the casting surface was thought to have been caused by the accumulation of thermal stress in the solidifying skin of the casting as proposed by Niyama and co-workers[4,5]. A model has been developed of the change in the interfacial heat transfer coefficient with time during the unidirectional solidification of an Al-Si alloy in which the deformation of the initial solidified skin was included.

2. THE EXPERIMENTAL CASTING

The heat transfer coefficient was measured during the solidification of Al-7wt.%Si alloy castings poured at 780°C into cylindrical refractory fibre moulds containing a water cooled Cu chill to induce unidirectional solidification. Before casting the surface of the Cu chill was prepared using 240 grade SiC paper to obtain a reproducible surface finish and the refractory fibre tubes were preheated to 900°C and allowed to cool to drive off any volatile material. The casting dimensions were 200 mm in length and 25 mm in diameter and the experiment was carried out with solidification taking place both vertically upwards and downwards. Figure 1 shows a sketch of the experimental arrangement. The heat transfer coefficient was calculated from thermocouple data recorded in the casting and the chill using an explicit finite difference solution to the one dimensional heat transfer equation[2].

3. THE MODEL OF THE HEAT TRANSFER COEFFICIENT DURING UNIDIRECTIONAL SOLIDIFICATION

One dimensional explicit finite difference models of the temperature distributions within the chill and the casting were coupled together by calculating the interfacial heat transfer coefficient between them for the duration of the experiment (about 1000 s). The initial temperatures of the cast Al-Si alloy and the Cu chill were assumed to be 1000 K and 293 K respectively. The end of the casting away from the interface was assumed to have a boundary condition of perfect insulation while measured temperature data obtained in the experiments to calculate the interfacial heat transfer coefficient was used for the boundary condition away from the interface in the chill.

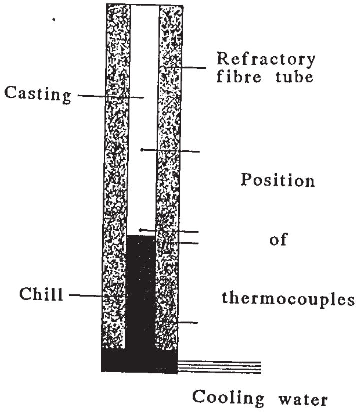

Figure 1. The experiment used to measure the interfacial heat transfer coefficient.

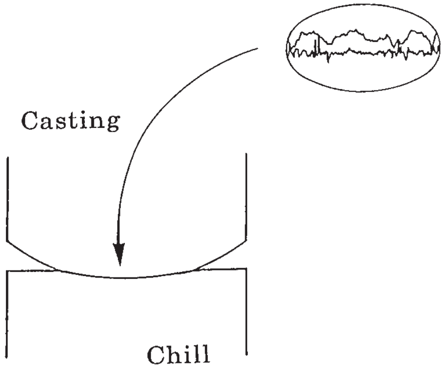

Figure 2. Schematic diagram of the contact between the casting and the chill surfaces assumed in the model.

3.1 The initial contact stage

Initially the liquid alloy was assumed to rest upon the peaks of the chill surface roughness. Negligible conduction of heat through the points of contact between the liquid metal and the asperities of the chill surface was assumed and the heat transfer coefficient, h, for this stage estimated from;

$$h=\frac{k}{x+g} \tag{1}$$

where k was the thermal conductivity of the gas in the interface, (assumed to be air), and x was the mean interfacial gap, obtained from the measurement of R_z, a vertical dimension of surface roughness which was used as an estimate of the mean peak to trough height of the surface roughness of the chill; hence $x = R_z/2$. g represented a temperature jump coefficient which reflected the difficulty of gas molecules in exchanging thermal energy with a solid surface[6]. This was equivalent to an increase in the mean gap distance of about 0.8 μm. With the surface roughness of the chill surfaces used in these experiments x+g was about 7 μm.

3.2 The deformation of the initial solidified skin

Once the temperature of the casting element at the interface decreased to the equilibrium eutectic temperature for Al-Si alloys (850 K), it was assumed that the casting skin had formed and then underwent deformation by thermal stress into a spherical shape with a radius of curvature, R, which was determined from[5];

$$R=\frac{1}{\alpha\left(\dfrac{\theta_{sol}-\theta_{chill}}{k/h}\right)} \tag{2}$$

θ_{sol} and θ_{chill} were the casting and chill surface temperatures at that time respectively and α and k were, respectively, the coefficient of thermal expansion and thermal conductivity of the solid alloy. h was the interfacial heat transfer coefficient calculated using Eq.1. However, since the casting skin was now assumed to have formed the interfacial heat transfer coefficient used was obtained from the mean interfacial gap determined from the measured surface roughnesses of both the casting and the chill. Heat transfer due to conduction between the contact areas of the casting and chill surfaces was again neglected. The two rough surfaces in contact were equated to a sum rough surface in contact with a perfectly smooth surface[7] obtained from the measured surface roughness values for both surfaces as follows;

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

and h calculated using Eq.1 with $x=R_{z(\Sigma)}/2$.

Following the deformation of the casting skin into a spherical shape heat transfer through the casting-chill interface was now assumed to occur through a central contact region surrounded by an annular gap. This is shown schematically in Figure 2. At each time step in the finite difference calculations the interfacial heat transfer coefficient was obtained from the sum of the heat transfer coefficients of the mechanisms, weighted by their area, governing heat transfer at the interface. The three mechanisms being, (i) conduction through the annular gap where deformation of the initial solidified skin had created a local separation, calculated using Eq.1., (ii) conduction through the asperities in contact within the central nominal contact area and (iii) conduction through the atmosphere in the intervening voids. Both radiation and convection were assumed to contribute negligibly to heat transfer through the interface.

3.3 The nominal contact area

The relative expansion and contraction of the casting and the chill were determined from their calculated temperature distributions and the geometrical overlap of the two surfaces, assuming no deformation, calculated (w). The nominal contact area, A_{nc}, between the spherical casting skin and the plane chill surface was calculated, with elastic deformation assumed, from[8];

$$A_{nc}=\pi R w \tag{4}$$

and the force, W, between a parabolic and a plane surface in elastic deformation obtained from[8];

$$W=(4/3)E'R^{1/2}w^{2/3} \tag{5}$$

where E′ was a modified Youngs Modulus which included the elastic properties of both the alloy and the Cu chill, R was the radius of curvature of the casting skin and w was the geometrical overlap between the casting and the chill surfaces.

However, the force between the casting and the chill in the nominal contact area was borne by the actual areas of contact between the surface asperities of the chill and casting surfaces. Two rough surfaces in contact was analyzed by Greenwood and Williamson[9] and, following this work, it was assumed in this model that the heights of the asperities of the combined sum rough surface of the casting and chill surfaces were exponentially distributed. It was further assumed that the asperities deformed with an ideal plastic behaviour. Tabor, from studies of indentation hardness measurements[10] showed that, for ideal plastic flow, the pressure, P, was distributed uniformly over the contact area and was described by;

$$P=cY \tag{6}$$

where Y is the tensile yield stress of the softer material and c was some geometry dependent factor which for hemispherical surfaces = 3. The exponential function describing the asperity heights was integrated over a range representing the mean separation of the casting and chill surfaces to give the following expressions for the number, n, area, A_t, and load, L_t, supported by the asperities in contact;

$$n=\eta A_{nc}e^{-h} \tag{7}$$

$$A_t=2\pi\beta\eta A_{nc}\sigma e^{-h} \tag{8}$$

$$L_t=6\pi\beta Y\eta A_{nc}\sigma e^{-h} \tag{9}$$

where η is the area density of asperities, estimated from S_m, the measured longitudinal characteristic of surface roughness and h is the dimensionless separation of the two planes = d/σ. d = mean separation of the two surfaces and σ = standard deviation of the asperity heights (of the sum rough surface) and was related to the measured surface roughness value, R_a, the arithmetical mean deviation of the surface profile. ß was the radius of curvature of the asperities, also calculated from the measured surface roughness data.

The heat transfer coefficient for the contact areas was then obtained from;

$$h=\frac{q/A_t}{\Delta T} \tag{10}$$

where q was the heat flux in the casting, estimated from the finite difference calculations, A_t was given by Eq.8 and ΔT was the temperature difference of the casting and chill surfaces, which were also obtained from the finite difference calculations for the chill and casting temperature distributions.

The separation of the two planes represented by the casting and the chill was determined iteratively by comparing the macroscopic load supported by the nominal contact area, given by Eq.5, with the sum of the microscopic loads supported by the asperities in contact within the nominal contact area, obtained from Eq.9.

In iterating to balance the macroscopic and microscopic loads at the interface, allowance must be made for the casting to be pushed forward by the expansion of the chill. In these type of unidirectional solidification experiments the movement of the casting would be restrained by the refractory fibre mould - an effect that would be difficult to model. In this model it was arbitrarily specified that the two planes may not approach closer than a distance of $0.5R_{z(\Sigma)}$ (in practice a separation of around 6 μm). If, in the iteration procedure, agreement between the macroscopic and microscopic loads was not obtained for separations greater than this then the geometric overlap between the two surfaces was reduced, ie, it was assumed that the casting had been forced away by the expansion of the chill. The macroscopic load at the interface was then recalculated and the iteration procedure repeated until agreement was obtained.

Once the iteration procedure was complete heat transfer by conduction through the voids within the nominal contact area could be determined, again using Eq.1., for which x was equal to d from h = d/σ in Eqs.7-9.

3.4 Expansion and contraction of the chill and casting

In the case of solidification vertically upwards casting contraction and solidification shrinkage were neglected and the casting was assumed to rest upon the chill surface until the chill contracted away to form an air-gap. With solidification vertically downwards both solidification shrinkage and casting contraction would operate to encourage the casting surface to withdraw from the chill surface so both were included in determining the relative position of the casting and chill surfaces.

As solidification within the model progressed with time a complete air-gap opened between the casting and the chill surfaces. The heat transfer coefficient in this stage was simply calculated by again using Eq.1 where x was determined from the relative expansion and contraction of the casting and the chill.

4. COMPARISON OF MEASURED AND MODELLED HEAT TRANSFER COEFFICIENTS

Comparisons between the measured and modelled heat transfer coefficients are shown in Figure 3. The measured values shown are those obtained in the experiments from which the boundary conditions for the finite difference model of the temperature distribution in the chill were obtained. The agreement shown between the two was, of course, dependent upon the amount of separation allowed between the casting and the chill surfaces when balancing the macroscopic and microscopically supported loads in the nominal contact area.

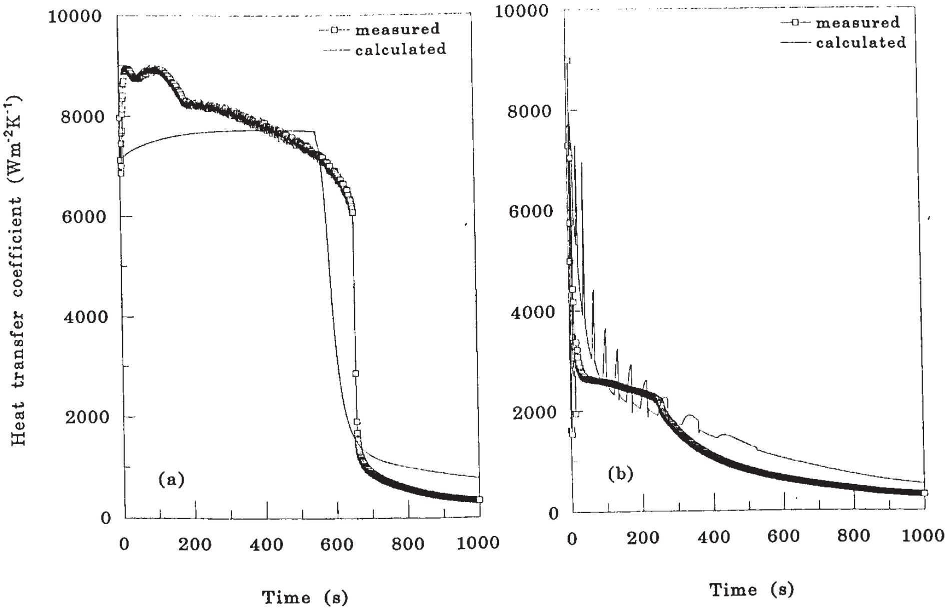

Figure 3. A comparison of measured and modelled heat transfer coefficients for the unidirectional solidification of an Al-7wt.%Si alloy (a) upwards, (b) downwards.

The initial heat transfer coefficient, before formation of the casting skin, was estimated to be about 8 kWm^{-2}K^{-1} and was dependent on the R_z values of the chill surface alone and independent of solidification orientation. The model predicted deformation of the initial casting skin with a radius of curvature of about 6 m. This was similar to the mean of the measured values of the actual casting surface curvatures of 6.4 m. The deformation was assumed to occur when the surface element in the finite difference model of the temperature distribution of the casting reached the solidus temperature of the alloy and this occurred at about 10 s from the beginning of the calculation with both orientations of solidification.

Expansion of the chill at first exceeded contraction of the casting and the model suggests that elastic deformation of the casting and chill surfaces occurs at the interface. Plastic deformation of the asperities in contact was assumed, and for this a simple ideal plastic behaviour was used. Examination of the contributions of the different mechanisms to the overall heat transfer through the interface suggested that the annular gap caused by the deformation of the initial solidified casting skin was a major factor in the overall thermal resistance of the interface. The extent of the annular gap and the size of the central contact region were subject to the specification of the minimum separation of the casting and chill surfaces. In this experiment the area of the nominal contact region was only a small percentage of the total casting-chill interface area and it made only a small contribution to the heat transfer through the interface.

The relative expansion and contraction of the casting and the chill eventually resulted in a complete air-gap occurring between the two. In upwards solidification the air-gap was predicted to form at 555 s, compared to about 660 s in the experiment with which comparison was made. With downwards solidification air gap formation began early in the calculation at 15 s.

SUMMARY

The model of the interfacial heat transfer coefficient for the simple case of unidirectional solidification of an Al-Si alloy on a chilled Cu surface was able to produce reasonable agreement with measured values. This was achieved, however, by the specification of the minimum distance which the casting and chill surfaces could approach. Nonetheless, the development of the model to this point has led to an improved understanding of the heat transfer mechanisms that can occur at a casting-die interface.

Surface coatings, commonly used in diecasting processes, have a great effect on the heat transfer process as does distortion of the die. Both effects could be included by further development of the model to predict heat transfer in three-dimensional cases.

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