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Effect of melt superheat on heat transfer coefficient for aluminium solidifying against copper chill

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Solidification of metal castings inside moulds is mainly dependent on the heat flow from the metal to the mould which is in turn proportional to an overall heat transfer coefficient h which includes all resistances to heat flow such as the presence of an air gap. In the present work the heat transfer coefficient is determined using a directional solidification set-up with end chill for solidifying commercial-purity aluminium with different superheats (40 K and 115 K) against copper chill. A computer program solving the heat conduction and convection in the solidifying metal is used together with the experimental temperature history in order to determine the heat transfer coefficient at the interface. The variation of h as a function of time, surface temperature and gap temperature for each melt superheat is found. The results indicate that h reaches a maximum value for surface temperature close to the liquidus. The analysis of heat flux from the metal to the mould indicates that it is mainly by conduction. The air gap size is evaluated with time, surface temperature and with melt superheat. It is found that higher h values and smaller gap sizes are obtained with higher superheats.

1. Introduction

In the last decade a trend towards improving casting quality and controlling solidification of metals inside the moulds and predicting casting defects has attracted great interest based on the use of computer simulation of solidification. Models for solving solidification of metals and alloys have been successfully developed [1]. However, an accurate application of these models and computer programs implies accurate knowledge of thermal parameters of alloys and moulds in use, as well as thermal resistance or heat transfer coefficients at the metal mould interface.

It is the purpose of this work to determine the heat transfer coefficient between the metal and mould for aluminium of commercial purity during cooling and solidification against copper chill and the effect of melt superheat on it.

2. Previous work

Several attempts to determine the heat transfer through the metal–mould interface have been reported in the literature. The methods of determination are either purely analytical [2, 3]; semi-analytical and empirical [4–7]; or numerical, based on finite difference or finite element techniques [8–11]. It is reported by Ho and Pehlke [9] that the last method is the most suitable because of the high dynamic changes which occur at the metal–mould interface, such as the rapid change from initial contact to gap formation accompanied by a rapid drop in interfacial heat transfer coefficient. Therefore a time-dependent heat transfer coefficient is necessary for solving solidification of metals especially in permanent moulds or die casting and in sand castings involving chills.

The results obtained from numerical simulation and experiments [8–11] indicate that in general the heat transfer coefficient, h, decreases with time, first rapidly then much more slowly until an almost constant value is reached. Similar behaviour for h with time was found in aluminium [8], aluminium alloys [10] and lead [11]. This behaviour was related to the formation of an air gap at the metal–mould interface upon shrinkage of the metal and or due to mould displacement [10]. It was also found that heat transfer through the air gap is mainly by conduction for small gap sizes (less than 0.5 mm) [9] and that h increases as the mean interfacial temperature increases for a given gap width [8].

The position of the chill, either at the top or bottom of the casting or surrounding it affects the value of h as the air gap formed is different in each case [10, 11]. The mould shape was found to affect the heat transfer coefficient and the formation of the air gap. Engler [10] found by monitoring mould and casting movements during solidification that in the case of cylindrical moulds the mould moves outwards away from the casting, while in rectangular moulds the mould surface moves first inwards towards the casting then outwards. It was also found that for weakly constrained rectangular moulds, the inward movement is even larger than for strictly constrained moulds.

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It is noticed from previous results on aluminium castings that the solidification time can vary from a few seconds to several minutes which makes the application of the heat transfer coefficient values versus time inaccurate in different solidification problems. It is the purpose of this work to study the effect of melt superheat on h, and on the history of formation of the air gap and to represent the results in a way applicable to different casting conditions.

3. Experimental procedure

In order to evaluate the metal chill heat transfer coefficient the experimental set-up shown in Fig. 1 is used. The specimen has a cylindrical shape 12.5 mm inner diameter 170 mm length of commercial-purity Al (99.7% Al) inserted in a stainless steel crucible. The specimen is seated on a copper chill which can be cooled by water spray. In order to avoid radial heat losses as well as error in thermocouple readings at the start of the cooling process both crucible and chill are inserted into a cylindrical electrical resistance furnace where the specimen is molten and reaches the required superheat. After a steady-state temperature is reached in both specimen and chill, cooling is started on the chill by turning on the water spray and by turning off the furnace. Three thermocouples (Cromel–Alumel 0.5 mm diameter) are inserted along the specimen at 10, 90 and 166 mm from the chill to monitor temperature variation versus time. Another thermocouple is inserted in the chill, 2 mm below the metal–chill interface. The experiments are run several times for liquid superheats of 40 and 115 K.

4. Heat transfer coefficient by simulation

The heat transfer coefficient is evaluated as a function of time using an explicit finite difference model for solving the one-dimensional heat conduction problem along the axis of the specimen. The method is explained elsewhere [11]. Both metal and chill are considered in the model and are divided into small space intervals 4 mm long in both metal and chill. The thermocouple readings in the chill are input as lower boundary conditions and those of the upper thermocouple are input as upper boundary conditions. An approximate heat transfer coefficient is first assumed by which the temperature distribution in the metal is obtained. The computed temperatures at definite points, where thermocouples 1 and 2 are placed, are compared with those of the experimentally obtained values. The computations are repeated until the best fitting between experimental and computed cooling curves is obtained.

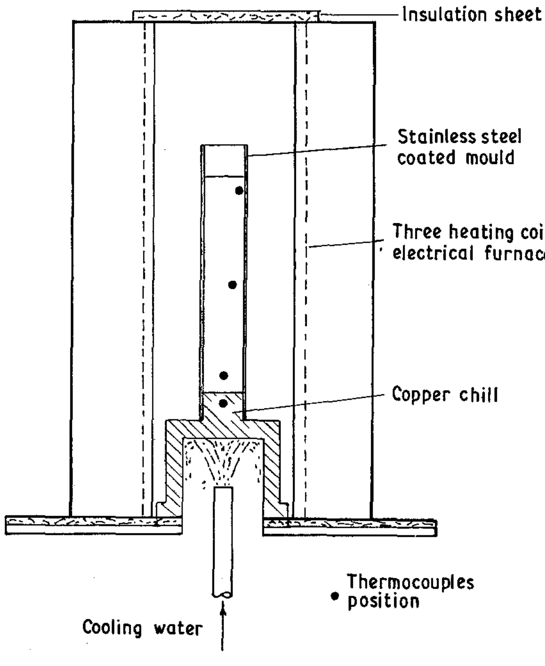

Figure 1 Schematic drawing of the experimental set-up used in the present work.

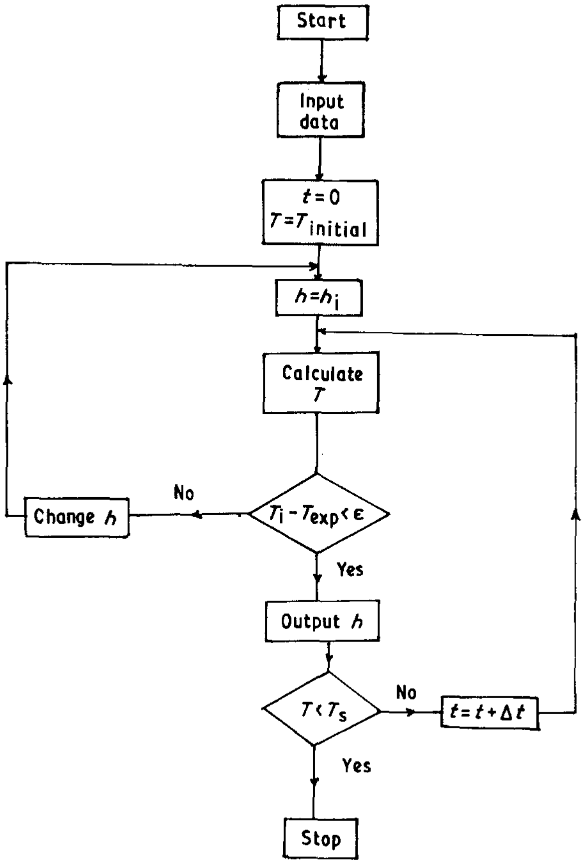

Figure 2 Flow chart for calculating the heat transfer coefficient.

The thermal properties of metal and chill considered in the computations are given in Table I. The simplified flow chart for the calculation of heat transfer coefficients is given in Fig. 2.

Convection in the superheated liquid is taken into consideration by raising conductivity in the liquid by a factor of 1.5 in case of 115 K superheat and 1.1 for 40 K superheat.

5. Results

Typical cooling curves obtained from computations and experiments are given in Fig. 3 for different superheats at three points along the specimen. The curves indicate the excellent agreement between experimental and computed temperatures based on which the heat transfer coefficient is evaluated. The experimental readings of the chill temperature shown in the figures

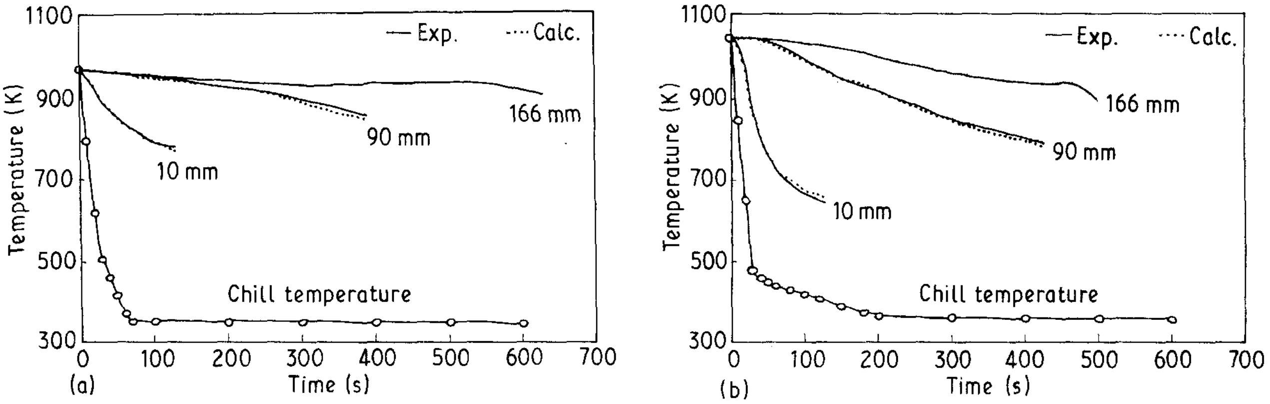

Figure 3 Experimental and computed cooling curves of three points along the specimen (10, 90, and 166 mm from the chill) together with chill temperature: (a) for 40 K superheat, (b) for 115 K superheat.

indicate that it has reached that of the metal before the cooling is started and that it decreased rapidly from 973 K or 1048 K to about 500 K after about 30 seconds.

The variation of the heat transfer coefficient, h, as a function of time is presented in Fig. 4. It is found that h increases sharply from about 3000 W/m^2 K to a maximum value in the first 20 or 50 seconds according to the superheat, then drops rapidly and tends to a steady-state value after the first 100 seconds. A similar behaviour between h and time was previously found by Engler [10] for aluminium. Fig. 4 also indicates that in general, the higher superheat is accompanied by a higher heat transfer coefficient where a maximum of 9000 and 12000 W/m^2 K was reached for 40 K and 115 K superheat values, respectively. The steady-state heat transfer coefficient was about 2000 and 6000 W/m^2K for 40 K and 115 K superheats used. This indicates that the superheat plays an important role in determining the heat transfer coefficient value. The decrease in h with time is expected to be due to the effect of thermal contraction which takes place in both chill and metal in opposite directions resulting in increasing the air gap between them. A comparison with previous results indicates that the present steady-state value of h for low superheat (40 K) is close to that obtained by Pehlke [8, 9] and Engler [10] where the superheat was relatively low (30–40 K). On the other hand the maximum values for h reached in the present work are higher than those obtained previously, probably due to the effect of the specimen/chill arrangement and to the superheat. The higher superheat increases the fluidity of the liquid metal therefore allowing better conformity with chill surface irregularities leading to better heat flow at the interface. In Pehlke's work a cylindrical specimen with a chill either on top or on the bottom of the specimen indicated that h is smaller in the top chill case where a larger air gap is formed. In Engler's work a cylindrical specimen indicated that a radial air gap is formed and increased with time, while for a flat casting the mould movement is first towards the casting which increased the heat transfer coefficient in the first time period. The present results indicate that in the first few seconds h increases rapidly. This behaviour is also found in Engler's results, but no clear explanation is yet to be found. Engler mentioned that it could be due to the use of a coating material or due to thermocouple effects. But in the present case this behaviour is found while no coating is used and the thermocouple was heated up with the metal and chill and its temperature only decreases with cooling.

By plotting h versus surface temperature, as shown in Fig. 5, it is found that h has a peak value when the surface temperature is at the liquidus. Below the liquidus temperature, h decreases rapidly until a steady-state value is reached. This value is higher for the higher superheat. The figure also indicates that h is low when the metal is above liquidus even when the

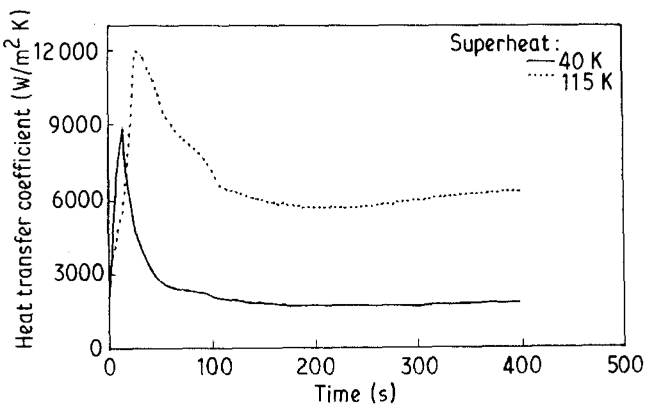

Figure 4 Variation of heat transfer coefficient with time for 40 K and 115 K superheat.

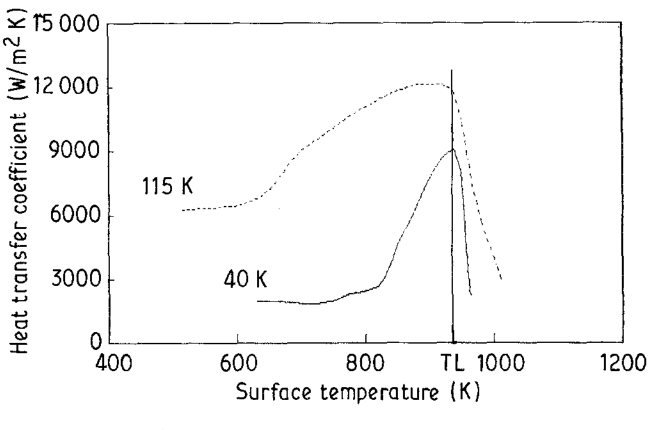

Figure 5 Variation of heat transfer coefficient with surface temperature for 40 K and 115 K superheat.

contact area between the liquid metal and chill is expected to be maximum.

6. Analysis of the heat transfer coefficient *h*

The heat transfer from the metal to the mould through the air gap is in general a combination of conduction, convection and radiation. The gap is usually small so that the convection part as indicated by the corresponding Grashof number can be neglected [8]. The heat flux by conduction and radiation are then considered and the heat transfer is given by a conduction term h_{cond} and a radiation term h_{rad} as follows

$$h = h_{\text{cond}} + h_{\text{rad}} = K_{\text{gap}}/X_{\text{gap}} + \frac{\sigma(T_c^3 + T_c T_m^2 + T_m T_c^2 + T_m^3)}{(1/\varepsilon_m) + (1/\varepsilon_c) - 1}$$

where K_{gap} is the average thermal conductivity of the gas in the gap evaluated from the average temperature of metal surface (T_m) and chill surface temperatures (T_c); X_{gap} is the gap size; ε_m and ε_c are the corresponding emmisivities; and σ is the Stefan–Boltzmann constant. The variation of h_{cond} and h_{rad} is plotted versus gap temperature in Fig. 6. It is found that the radiation heat transfer coefficient is so small with respect to the conduction coefficient that it can be neglected. These results are in agreement with previous comments made by Pehlke [8] and with heat flux computations made by Engler [10]. It is also noticed that the superheat affects the conduction coefficient significantly while it has a negligible effect on the radiation coefficient. According to these results the heat transfer is considered to be by pure conduction and the gap size can be evaluated using the relationship

$$h = K_{\text{gap}}/X_{\text{gap}}$$

The evaluated gap sizes are plotted versus time in Fig. 7 and versus gap temperature in Fig. 8. The results indicate that the gap size increases rapidly in the first few seconds, then decreases slightly and reaches an almost constant value. It is also noticed from these results that the gap size for the higher superheat is more than two times less than that formed for the lower superheat. This is probably due to high fluidity and better conformity of the liquid metal with the surface irregularities of the chill before the starting of solidification. These results explain the higher heat transfer coefficient for the higher superheat used. The values of chill temperature, surface temperature and thickness solidified are plotted versus time in Fig. 9 in order to find which of these parameters more significantly affects the heat transfer coefficient value. It can be deduced from the figure that the rapid variation in chill temperature and *h* occur simultaneously in the first few seconds. The figure also indicates the less rapid decrease in surface temperature which keeps decreasing while the thickness solidified increases and *h* reaches an almost constant value. This value of *h* is started when the thickness solidified is 32 mm and 55 mm for 40 K and 115 K, respectively, and the surface temperature is 800 K and 650 K for 40 K and 115 K, respectively. These results suggest that the air gap is first (and mainly) formed due to contraction of the chill then to the contraction of the metal which is expected to be compensated by the downward movement of the metal column due to gravity.

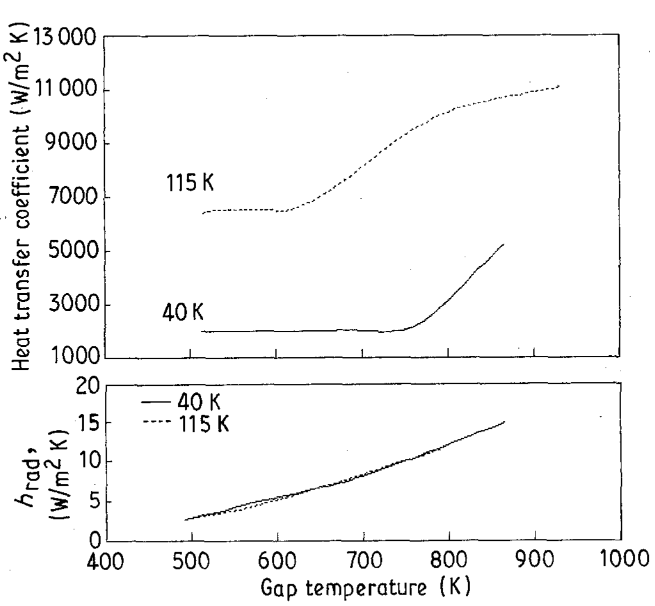

Figure 6 Conduction (h_{cond}) and radiation (h_{rad}) heat transfer coefficient for different gap temperature.

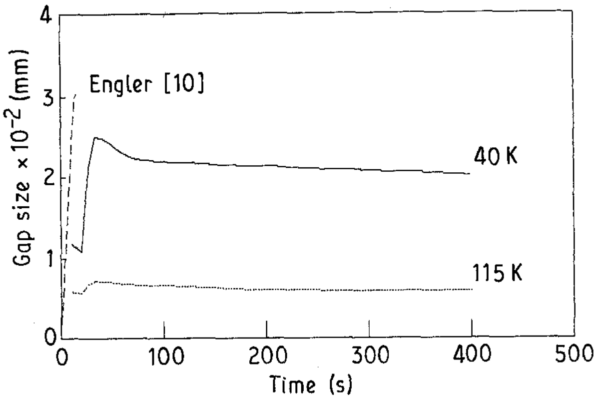

Figure 7 Variation of gap size with time.

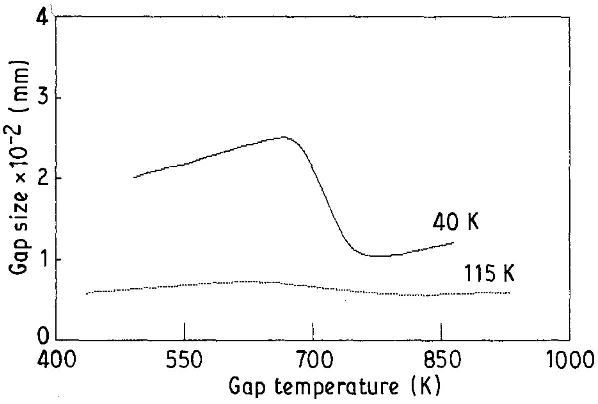

Figure 8 Effect of gap temperature on gap size.

The effect of gap size on the heat transfer coefficient is shown in Fig. 10. Previous results by Engler [10] on aluminium are superimposed. The figure shows that the higher the superheat the smaller the gap size. The

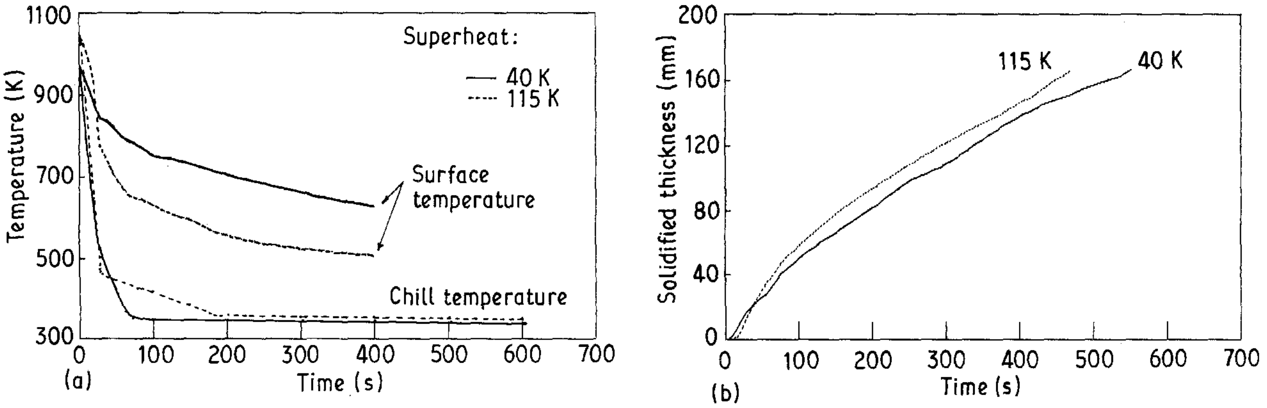

Figure 9 (a) Variation of chill and surface temperature with time, and (b) variation of thickness solidified versus time.

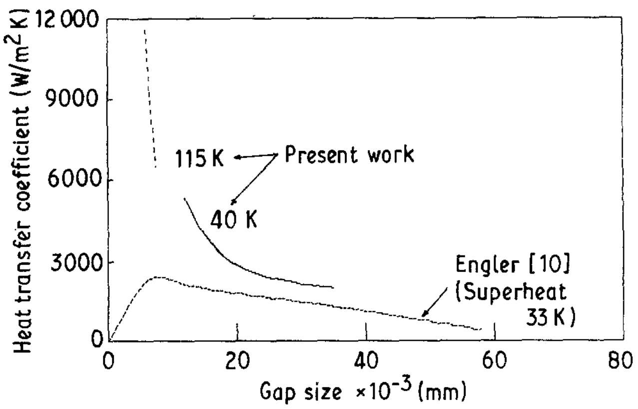

Figure 10 Effect of gap size on heat transfer coefficient.

present results for low superheat (40 K) are close to those obtained by Engler (33 K). It is important to mention that the heat transfer coefficient depends on the gap size which is larger for lower superheats as well as on the gas temperature within this gap for small gap sizes ($<$ 0.05 mm) given good chill surface conditions and no coating.

7. Conclusions

The following conclusions can be drawn from the present results.

1. The heat transfer coefficient, h, between metal and chill is found to be a function of time, and gap temperature. It reaches its maximum value when the surface temperature is equal to the liquidus of the metal.

2. The value of h increases as the melt superheat temperature increases.

3. The gap size formed between the metal and chill at the bottom of the ingot is smaller for higher superheats.

4. The heat transfer from the metal to the mould is mainly by conduction.

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