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The effect of varying chill surface roughness on interfacial heat transfer during casting solidification

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Abstract Experiments to investigate interfacial heat transfer mechanisms during casting solidification were carried out by varying the surface roughness of a Cu chill used to bring about unidirectional solidification of an Al-4.5 wt.% Cu alloy. Little variation in interfacial heat transfer coefficient with varying chill surface roughness was found, confirming previously published results. Examination of the as-cast surface of the casting showed the presence of predendritic contact areas, and also that the casting surface roughness did not form as a replica of the chill surface, as has often been proposed. Rather, the casting surface roughness was consistently greater than that of the chill, but varied little in the experiments. A sum surface roughness parameter was devised to characterise the casting–chill interface that included the roughness of both surfaces. The value of this parameter was strongly influenced by the greater roughness of the casting surface, rather than the chill surface roughness, and therefore also varied little in the experiments. This lack of variation in the casting surface roughness and hence the sum surface roughness parameter showed how interfacial heat transfer should be more strongly influenced by the greater roughness of the casting surface than of the chill surface, and explains why the interfacial heat transfer coefficient was not strongly influenced by the chill surface roughness in these types of experiments.

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Introduction

In the computer simulation of casting solidification an accurate value for the rate of heat transfer at the interface between the casting and the mould is essential. Heat transfer through the casting–mould interface is controlled by the relationship between the two surfaces and this involves two important parameters, the actual area of contact between the surfaces, and the distance between them [1], both of which are difficult to determine. While there have been many published measurements of the interfacial heat transfer coefficient and the interfacial heat flux, there has been limited success in interpreting these values quantitatively.

To understand the nature of the interfacial heat transfer mechanisms past studies have involved measurement of the heat transfer coefficient during solidification against chills with varying surface roughness. These results showed a decrease in heat transfer coefficient with increasing chill surface roughness [2, 3], although the decrease was slight compared to the increase in the chill surface roughness. For example, Muojekwu et al. [2], using Al–Si alloys, increased chill surface roughness from R_a = 0.018 μm to R_a = 10.56 μm, (i.e., by more than 500 times), but their measured heat transfer values decreased only 1.5 times. Assar [3] reported similar results from the casting of zinc against steel chills, with R_a values ranging from 43 μm to 866 μm, (an increase of 20 times).

In experiments involving the solidification of droplets, rather than bulk castings, the relationship between interfacial heat transfer and substrate surface roughness has been more clearly defined. Wang and Matthys [4] carried out solidification of splats of molten Cu and Ni on substrates of different surface roughness, and found a 50% reduction in heat transfer coefficient with a 100 times increase in surface roughness. However, they reported this to be true only for what was described as "the initial melt cooling period", and no relationship between surface roughness and heat transfer coefficient was found for the subsequent solidification and cooling stages. Loulou et al. [5], investigating the solidification of 3.5 g droplets of Sn, similarly found an increased thermal resistance, i.e., decreased heat transfer coefficient, with increasing substrate surface roughness. They reported a decrease in thermal resistance by a factor of about ten, for a decrease in surface roughness of about fifty times.

The reason why the interfacial heat transfer coefficient varies only slightly with large variations in chill or substrate surface roughness has not yet been explained. In this study further investigation of the mechanisms of interfacial heat transfer during casting solidification was carried out, by measuring heat transfer coefficients during the solidification of an Al-4.5 wt.% Cu alloy on the surface of water-cooled cylindrical copper chills with varying surface roughness. To establish any relationship between the chill and casting surfaces and the interfacial heat transfer coefficient, both were characterised by measurement of their respective surface roughness and planeness, and examined using optical and electron microscopy.

Experimental procedure

The experimental arrangement used to obtain the interfacial heat transfer coefficient during unidirectional solidification of an Al-4.5 wt.% Cu alloy is shown in Fig. 1. Cylindrical calcium-silicate fibre tubes were used as moulds, of length 300 mm, into one end of which a water-cooled cylindrical copper chill of length 100 mm was inserted, supplied with cooling water at a rate of about 0.6 L s^{-1}. The internal diameter of the refractory fibre tube was 25 mm. The surface of the chill exposed to the mould cavity was of varying surface roughness, obtained by using different grades of SiC papers. These were, from smooth to rough, P4000, P2400, P1200 and P400 grades. The chill was roughened before each casting, and the resulting roughness measured using a Surtronic 200 stylus-type surface profile measurement instrument, with an assessment length of 2.5 mm. The planeness of the chill surfaces was also measured using a stylus-type surface profile measurement instrument that produced a graphical output. Eight castings were obtained with each chill surface roughness, and their surface roughness and planeness measured also.

Two orientations of the experiment were used. With the chill placed in the base of the refractory fibre tube solidification occurred in an upwards direction. With the chill placed in the top of the tube, and a suitable arrangement fitted for running the liquid metal into the mould, solidification occurred vertically downwards.

Al-4.5 wt.% Cu alloy was melted in a clay-graphite crucible in a resistance-heated furnace with no fluxing or degassing of the molten alloy. The alloy was poured at 810 °C, (160 K superheat), directly from the melting furnace into the mould, which was initially at room temperature. The pouring distance between the furnace launder and the top of the cylindrical mould was about 100 mm.

Six type-K thermocouples were used to monitor temperature changes in the casting and the chill. Three of these were reusable thermocouples with a stainless steel sheath that were inserted into holes drilled into the chill and that reached the central axis, (of 0.55 mm diameter and 12.5 mm depth). Three more were inserted into the refractory tubes so that their hot junctions were also located on the vertical axis of the chill-mould arrangement. These three thermocouples were not reusable, and were made from 0.2 mm diameter wire, threaded into twin-bore alumina tubes, and had fused hot junctions of about 1 mm diameter. The thermocouples were located at 5, 37.5 and 75 mm from the interface of the casting and the chill, respectively, and were read at 0.5 s intervals using a PC-controlled data logging system.

To obtain the heat transfer coefficients from the measured temperature data the one-dimensional transient heat conduction equation was solved using an explicit finite difference technique for both the solidifying casting and the water-cooled Cu chill [6]. The boundary conditions 75 mm away from the casting–chill interface for the finite difference calculations were obtained from the temperatures of the thermocouples at those positions in the casting and the chill. Boundary conditions for the casting–chill interface were derived from estimated casting and chill surface temperatures, obtained by iterating the calculated temperatures in the casting and the chill at

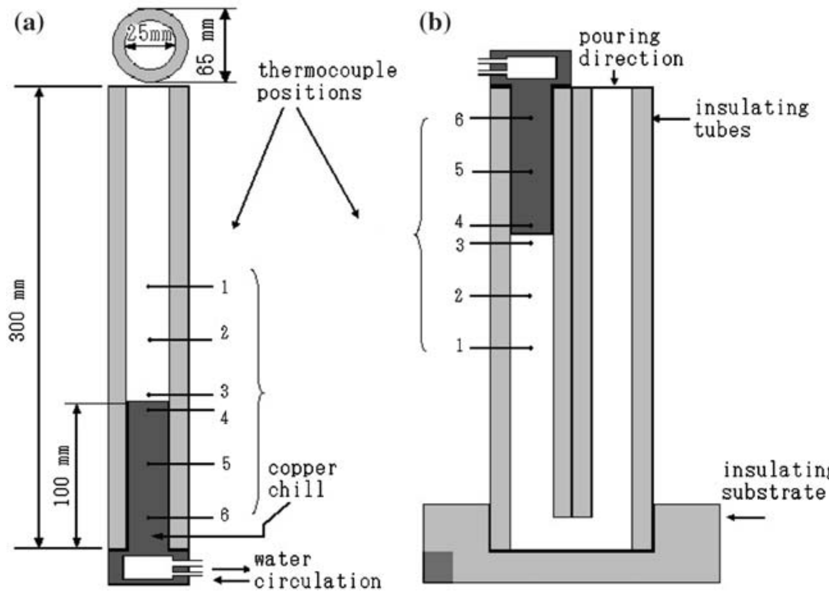


Fig. 1 Experimental arrangement to obtain unidirectional solidification (**a**) vertically upwards and (**b**) vertically downwards

5 mm from their interface against the measured temperatures at these points until agreement to within ± 0.5 K was reached. The heat flux from the casting to the chill, and the interfacial heat transfer coefficient, were then determined from this calculated temperature distribution. Temperature dependent thermophysical property data were used in these calculations, with the thermal conductivity of the liquid alloy being increased to represent the effect of heat transfer by fluid flow using the following expression;

$$k_{LT} = 2k_L + (2(T - T_{sol})) \tag{1}$$

where k_{LT} = thermal conductivity of the liquid alloy, enhanced by convection, k_L = thermal conductivity of the liquid alloy, T = liquid alloy temperature and T_{sol} = solidus temperature.

The thermocouples at 37.5 mm from the interface were used to provide an additional check of the calculated temperature distributions. This approach produced heat transfer coefficients that were estimated to have an accuracy of ± 20% [7]. Further experimental details can be obtained from reference [8].

Results

Mean values of the chill and casting surface roughnesses obtained from the experiments are given in Table 1. R_a represents the arithmetical mean value of the departure of the profile about a mean line and R_z is a measure of the mean distance between the highest surface roughness peaks and the deepest valleys in a measured profile. The scatter of the surface roughness measurements were such that 1 standard deviation was about 10–20% of the mean surface roughness values.

The mean values of the measured roughness parameters for the chill surfaces increased approximately three times between each successive grade of SiC paper used, from P4000 to P400 grade, and by twenty-four times over the whole range. In comparison, the surface roughness of the castings was greater than that

Table 1 Mean values of the surface roughness parameters of the Cu chills and the associated Al-4.5 wt.% Cu alloy castings

SiC grade	Chill surface roughness parameters		Casting surface roughness parameters				Sum surface roughness	
			Upwards solidified castings		Downwards solidified castings		Upwards solidified castings	Downwards solidified castings
	R_a (μm)	R_z (μm)	R_a (μm)	R_z (μm)	R_a (μm)	R_z (μm)	$R_{z(\Sigma)}$ (μm)	$R_{z(\Sigma)}$ (μm)
4000	0.02	0.17	2.8	12.4	1.0	4.8	12.4	4.8
2400	0.06	0.60	2.6	11.6	1.1	4.9	11.6	4.9
1200	0.2	1.6	1.7	10.6	0.6	3.0	10.7	3.4
400	0.5	4.5	1.1	4.9	0.8	3.8	6.7	5.9

of the chill, especially in the case of solidification upwards, but less so with solidification downwards. The mean roughness values of the castings solidified upwards were larger than those of the castings solidified downwards by a factor of up to 3.5. This implied that the mould filling had an effect on the casting surface roughness, and with upwards solidification there would be an increased likelihood of entrapped gases at the casting–chill interface. The surface roughness of the castings solidified upwards decreased with increasing chill surface roughness, but only over a range of 2.5 times, while in the castings solidified downwards the casting surface roughness was largely unchanged. In general, it was apparent that, despite the large variation in roughness of the chill surfaces, the roughness of the casting surfaces showed considerably less variation.

Typical examples of the as-cast casting surfaces, for smooth to rough chill surfaces, are shown in Fig. 2. The small point-like features in the central region of each grain were identified as ''pre-dendritic areas'' by Biloni and Chalmers [9, 10] who suggested that these were formed when the cast liquid metal rested on the peaks of the mould surface roughness leading to localised rapid solidification. Close examination of these pre-dendritic contact areas using angled illumination revealed that they formed peaks on the as-cast surface, with the areas between forming valleys. A clearer example of this is shown in Fig. 3, obtained by casting the same alloy onto a roughened Cu plate. (The surface roughness of the Cu plate was measured to be R_a = 3.1 μm and R_z = 23.7 μm).

Profiles taken across the chill and the casting surfaces showed that the as-cast surfaces possessed a curvature that was consistently convex towards the chill surface, although the chill surfaces were plane. Examples of these profiles are shown in Fig. 4(a–c). The extent of the curvature was found to be up to 50 μm at the circumference of the casting surface, (12.5 mm from the center), but was of average size 20 μm. (Similar effects have been found in Al–Si alloy castings [6]). No significant relationship was found between the casting surface curvature and the chill or casting surface roughness, or the direction of solidification of the castings.

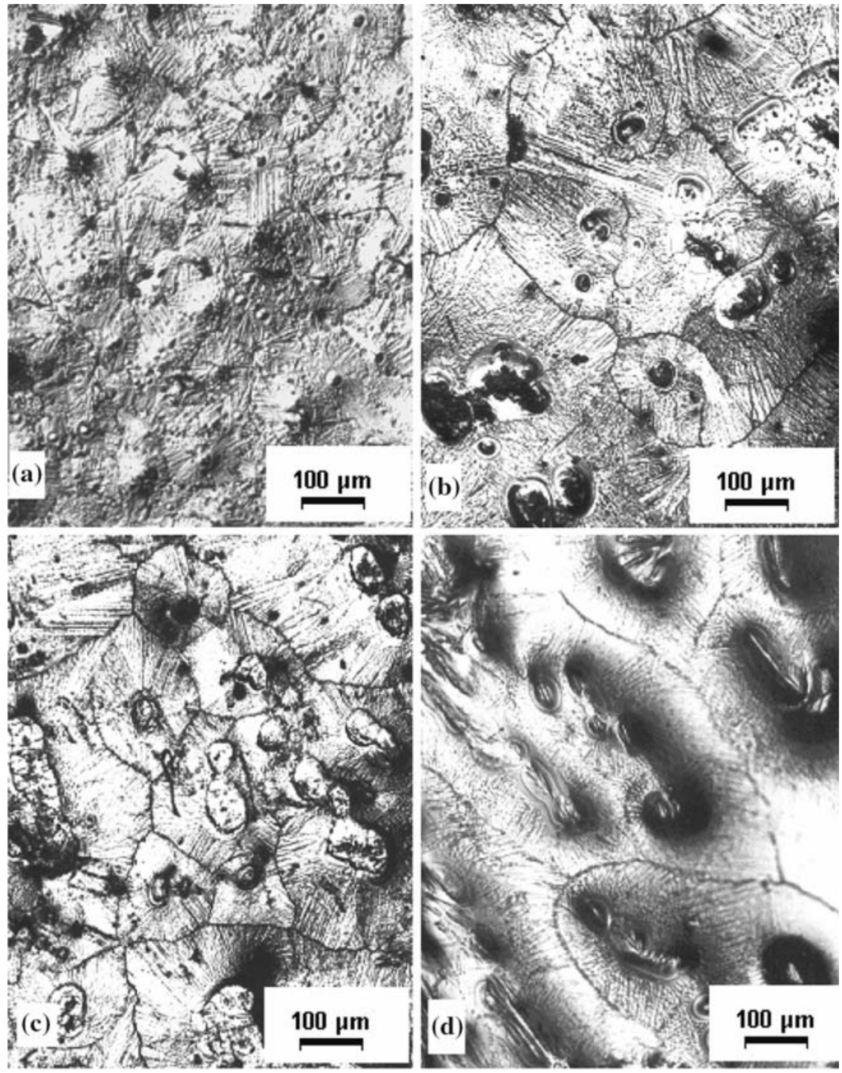
An example of cooling curves obtained from the temperature measurements in the casting experiments has been shown in Fig. 5, for the case of a casting solidifying vertically downwards. In this case the heat transfer coefficient, (superimposed in Fig. 5), began with a sharp decrease from a higher value to around 10 kW m^{-2} K^{-1} at 25 s. This was followed by an increase for about 100 s, and then a decrease again until it fell sharply at 200 s to a value of below 1 kW m^{-2} K^{-1}. The latter decrease in the heat transfer coefficient was characteristic of the formation of a complete air-gap between the casting and the chill where the two surfaces separated completely [11]. The formation of the air-gap resulted in an increase in the casting temperatures adjacent to the interface that was due to the flow of heat into this region from the hotter parts of the casting, furthest away from the interface with the chill. In previous research, for example by Ho and Pehlke [12], the air-gap was attributed to the casting retreating from the chill under the action of gravity, (and this is probably a factor here). However, the air-gap occurred in upwardly-solidified castings as well, where gravity should cause the casting to rest upon the chill. It is likely that an air-gap can occur for many reasons, and in this case it probably occurred due to the chill expanding upon heating, which would push the casting away. The casting would then be held in the refractory tube forming the mould, (helped by the presence of the thermocouples), and the air-gap formed as the chill contracted as it subsequently cooled.

The interfacial heat transfer coefficients for the upwards and downwards solidified castings are shown in Figs. 6 and 7, respectively. Results from four repeated experiments have been shown for the case of solidification vertically upwards, and from two repeated experiments in the case of solidification vertically downwards, for each chill surface roughness. The heat transfer coefficients showed significant scatter within the range of 10–40 kW m^{-2} K^{-1}. The values of the heat transfer coefficient associated with the downwards solidified castings, (Fig. 6a–d), were in general smaller than those from the upwards solidified castings, and the time interval for air-gap formation generally shorter, consistent with results obtained from other investigations of the effect of orientation where, if the casting was below the chill, lower values of the heat transfer coefficient and earlier occurrences of the air-gap, were found [6, 12]. However, no consistent relationship between chill surface roughness and heat transfer coefficient was observed.

Discussion

It has been generally supposed that during filling of a mould the liquid metal comes to rest in contact with the high points of the mould surface roughness, and that the liquid surface between the contact areas hangs down into the intervening ''valleys'' [4, 5, 9, 10, 14]. In this case, where the surface of the cast alloy solidifies

Fig. 2 As-cast surfaces obtained by solidification vertically upwards against the water-cooled Cu chill surfaces prepared with (**a**) P400, (**b**) P1200, (**c**) P2400 and (**d**) P4000 grade SiC papers



while suspended between the peaks of the mould or chill surface roughness, the casting surface roughness, and hence the distance between the two surfaces, should be largely defined by the roughness of the chill surface. If the casting surface roughness is derived from the mould (or chill) surface roughness in this way, the heat transfer between the two surfaces should be a function of mould or chill surface roughness, until a complete air-gap forms and the two surfaces lose contact.

However, examination of the as-cast surfaces in the experiments reported here revealed pre-dendritic contact areas that formed peaks on the casting surface, (see Figs. 2, 3), with the casting surface between the contact areas forming valleys, the reverse of the situation previously described. In other words, the casting surfaces were not replicas of the Cu chill surfaces against which they had solidified, (as has generally been supposed), but the opposite, in that the peaks of the Cu chill surface roughness were associated with the peaks of the casting surface roughness. Therefore no systematic relationship between the chill surface roughness and casting surface roughness is to be expected, and this explains why the casting surface roughness varied little with variations in chill surface roughness, (see Table 1).

Incidentally, when Al castings were made against die steel surfaces to which a refractory die coating had been applied, the casting surface roughness formed in the manner described, with peaks of the casting surfaces corresponding to troughs in the die coating surface, and vice versa [7]. It appears that with chill surfaces with higher thermal conductivity, i.e., uncoated surfaces, the mechanism of formation of the casting surface changes.

The amount of contact between the two surfaces, and the distance by which they were separated, should

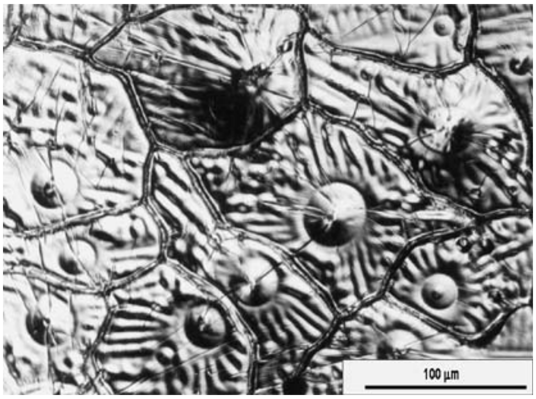


Fig. 3 An example of predendritic contact areas on the as-cast surface of an Al-4.5 wt.% Cu alloy solidified on a roughened Cu plate

therefore depend upon the characteristics of both surfaces, rather than of the chill surface alone, and a sum surface roughness parameter was accordingly devised to take into account the surface roughness of both the casting and the chill;

$$R_{z(\Sigma)} = [R^2_{z(casting)} + R^2_{z(chill)}]^{1/2} \quad (2)$$

Here R_z is the parameter that characterises the vertical dimension of the surface roughness, (being a measure of the peak-to-valley height of the surface roughness), and therefore the $R_{z(\Sigma)}$ parameter can be used to characterise the vertical dimension of the casting–chill interface, ($R_{z(\Sigma)}$ values are also shown in Table 1). A better description of the surfaces, to quantify the heat transfer mechanisms between them, might be obtained if the kurtosis of the surfaces was determined. However, the R_z value is a simple measure than can be more readily obtained.

Since the casting surface roughness was generally greater than the chill surface roughness, $R_{z(\Sigma)}$ was dominated by the rougher casting surface. Since the casting surface roughness varied little compared to the chill surface roughness, the sum surface roughness also varied little in comparison to the chill surface roughness. This implies that the distance between the two surfaces and the contact between them would not vary greatly, and little variation in heat transfer coefficient with varying chill surface roughness is, in fact, to be expected. As Figs. 6 and 7 show, no systematic variation of heat transfer coefficient with chill surface roughness was observed.

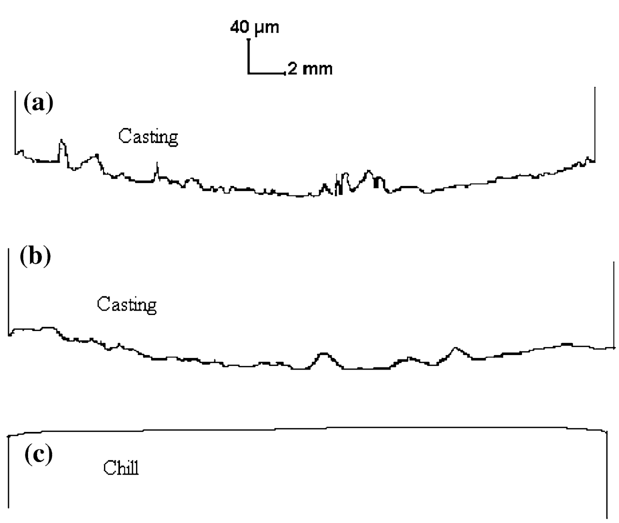


Fig. 4 Selected surface profiles taken across two castings solidified vertically upwards, (bottom-chilled), against chill surfaces prepared with (**a**) P400 and (**b**) P 2400 grade SiC papers, and (**c**) a Cu chill

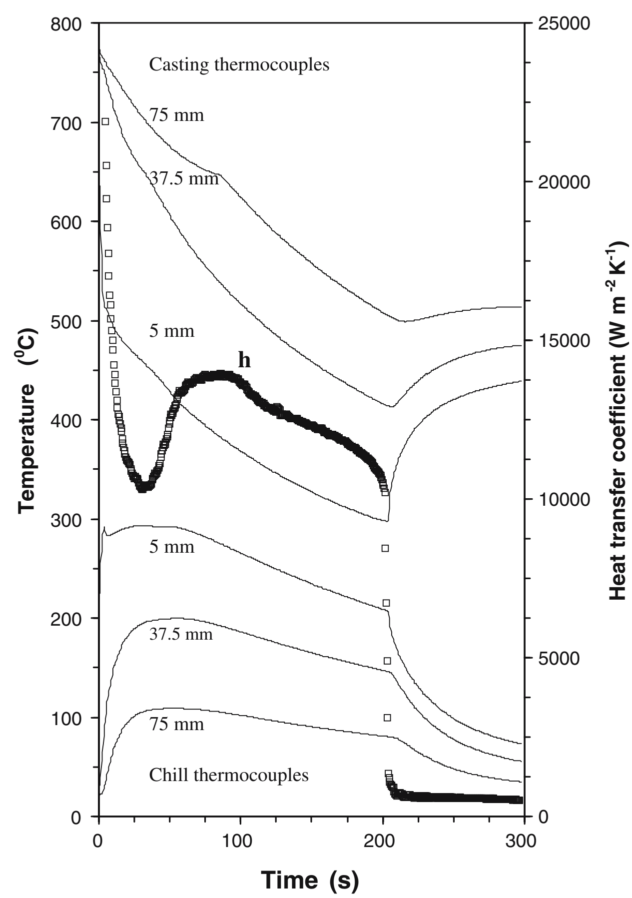
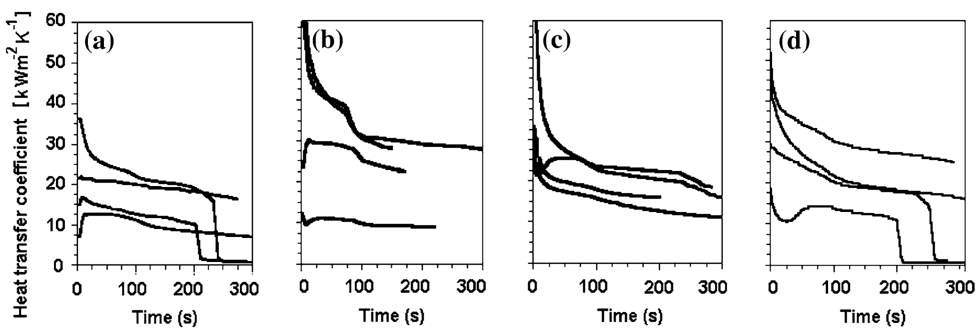


Fig. 5 A typical example of the time-temperature relationships obtained in a casting solidified vertically downwards, with the calculated heat transfer coefficient curve (denoted h) superimposed. The casting solidified against a chill surface prepared with P400 grade SiC paper

Fig. 6 Heat transfer coefficients obtained from castings solidified vertically upwards, against chill surfaces prepared with (**a**) P4000, (**b**) P2400, (**c**) P1200 and (**d**) P400 grade SiC paper



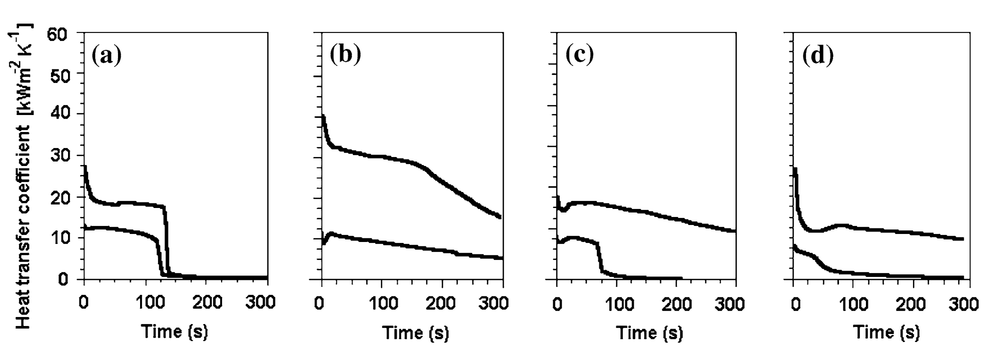
Similarly, Muojekwu et al., studying Al–Si alloys and using chills with R_a values that ranged over 500 times, found that the measured casting surface roughness varied between $R_a = 2.5$ µm to 3.5 µm, a range of less than two [2]. To duplicate the castings made in their experiments, castings of Al–Si alloys and commercial purity Zn, solidified against cast iron, Cu, steel and brass chills, were made, and examination of their as-cast surfaces also revealed predendritic contact areas that formed peaks, similar to those shown in Figs. 2 and 3. This suggests that the castings made by Muojekwu et al. [2] also solidified with the type of as-cast surfaces shown here, where no relationship between chill and casting surface roughness is to be expected. Calculating a sum surface roughness value for their experiments would also have shown little variation, and would explain the slight variation in the heat transfer coefficient that was found in their work.

The heat transfer measurements of Assar [3], with roughness variation $R_a = 43$ µm to 866 µm, also showed that heat transfer coefficients varied slightly, (unless a very rough chill surface was used). They did not report measured casting surface roughness values but it is likely that they would also have varied only slightly, explaining the lack of variation in their heat transfer coefficients.

The effect of the curvature of the casting surfaces shown in Fig. 4 must also be considered. An explanation for this effect was given by Dong et al. [13] and it seems to occur shortly after solidification of the skin of the casting. In this case, the casting surface would have deformed, soon after pouring, into the convex form shown. Heat transfer between the casting and the chill would have occurred preferentially through the central part of the interface, where the two surfaces were in contact, but would have been poor at the periphery of the interface, where a localized gap would have occurred, (of 20 µm on average). This is another reason not to expect a significant relationship between chill surface roughness and the interfacial heat transfer coefficient.

To summarise, in the case of the uncoated chills used here, no direct relationship between casting and chill surface roughness should be expected due to the manner of the formation of the casting surface, and therefore no relationship between chill surface roughness and the interfacial heat transfer coefficient should occur. Further work is required to understand the mechanism of the formation of the casting surface during solidification against these chill surfaces in which the pre-dendritic contact areas on the as-cast surfaces form peaks rather than troughs.

Fig. 7 Heat transfer coefficients obtained from castings solidified vertically downwards, against chill surfaces prepared with (**a**) P4000, (**b**) P2400, (**c**) P1200 and (**d**) P400 grade SiC paper



Conclusions

1. Al-4.5 wt.% Cu alloy castings solidified against Cu chills with a surface roughness of from $R_a = 0.02$–0.47 μm, a variation of about 25 times, showed little variation in casting surface roughness, which varied by a factor of about 2.5 times.
2. Examination of the casting surfaces revealed that the peaks of the casting surface roughness were in the form of predendritic contact areas. These showed that the formation of the casting surface was largely independent of the nature of the chill surface, explaining the lack of agreement between their measured surface roughness parameters.
3. Interfacial heat transfer coefficients for Al-4.5 wt.% Cu alloy castings solidified unidirectionally against Cu chills with various surface roughnesses were found to have a wide scatter, varying within the range of 10–40 kW m^{-2} K^{-1}. In general castings solidified vertically downwards were associated with heat transfer coefficients that were about half those associated with solidification vertically upwards. However, no consistent relationship was observed between measured heat transfer coefficients and chill surface roughness.
4. The casting–chill interfaces were characterised by a sum surface roughness parameter defined as $R_{z(\Sigma)} = (R^2_{z(\mathrm{chill})} + R^2_{z(\mathrm{casting})})^{1/2}$ which accounted for the roughness of both casting and chill surfaces. This sum surface roughness parameter was dominated by the rougher casting surface, which had varied only slightly in the experiments, and was therefore not strongly affected by the variation in the chill surface roughness.
5. The heat transfer through the casting–chill interface would have been dependant upon the sum surface roughness parameter, and the lack of variation in the casting surface roughness, and hence the sum surface roughness, accounted for the lack of variation in the interfacial heat transfer coefficient with varying chill surface roughness.

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