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An ultrasonic technique for the determination of casting-chill contact during solidification

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Heat transfer between a solidifying aluminium alloy casting and a mould is dominated by the thermal resistance created by the interface. Interfacial heat transfer occurs by conduction through the atmosphere between the two surfaces and by conduction through the points of actual contact. (Heat transfer by radiation is probably significant only for ferrous castings.) The extent of real physical contact between two surfaces is difficult to quantify. This paper explains a method, using ultrasonic flaw detection techniques, whereby an estimate of the propagation of an ultrasonic signal through a casting-chill interface is used to infer the degree of actual contact occurring between them.

In experiments involving casting and solidification of an aluminium alloy onto a copper chill the technique was found to give information for the first two seconds of the casting process only. In this time a peak in ultrasound transmission was observed, correlating to a maximum in the area of casting-chill contact, followed by a decrease in the ultrasound transmission that corresponded to actual contact areas between the casting and the chill in the region of 5 to 10%.

1. Introduction

The solidification of a casting begins when the cast molten metal first contacts the mould surface and extraction of heat from the liquid metal commences. At this moment the surface of the molten metal is, on the microscopic scale, in partial contact with the rough mould surface. The area of actual contact depends upon the surface tension of the liquid metal, the contact angle of the liquid metal with the mould surface, the surface roughness of the mould, the local metallostatic pressure and the pressure of any entrapped gases [1].

This stage of initial contact of the liquid alloy with a mould surface is poorly understood but is important. The amount of actual contact will affect the amount of heat extracted from the liquid metal during mould filling, which has two results. Firstly, this will influence the ability of the liquid metal to fill the mould cavity. Secondly, the distribution of temperature in the liquid metal once the mould cavity is full will influence the subsequent solidification pattern of the casting.

Heat transfer during this stage also affects the formation of features such as casting surface roughness and perhaps localised deformation of the casting skin [2, 3]. These factors then, in turn, influence the heat transfer mechanisms through the casting-mould interface during the later stages of solidification and cooling of the casting.

In real casting situations the interfacial heat transfer mechanisms are complicated because of the presence of coatings, e.g., in diecasting. However, a case of direct contact between liquid metal and a mould surface occurs in the upper part of the mould in a DC casting process, and in the high pressure diecasting process, for example.

To investigate this stage is difficult as any effects occur on the microscale and are transient—perhaps of only a few seconds duration or less. Any examination must be as unintrusive as possible. This paper reports an exercise to learn something about the degree of contact between metal and mould by using an ultrasonic flaw detector.

In this technique an ultrasound signal is transmitted into a body and is reflected from a discontinuity in the material such as a defect. The reflected ultrasound is detected and the position of the defect located. In this experiment a casting-chill interface is the discontinuity. The work reported here represents an attempt to determine whether the ultrasound signal obtained by reflection from the casting-chill interface can be interpreted to yield an estimate of the extent of the physical contact between a cast Al alloy and a Cu chill during the initial contact stage, in which the liquid metal first comes into contact with the mould surface.

2. Experimental procedure

In this section some background information is first given, followed by an account of the experiments carried out. This is followed by an explanation of how the experimental results are interpreted to obtain a measure of the actual contact area.

2.1. Reflection and transmission of ultrasound at an interface

The characteristic acoustic impedance of a material is given by [4];

$$z_0 = \rho_0 c \tag{1}$$

where ρ_0 = density and c = the velocity of sound in the material.

Sound waves in solids consist of longitudinal waves, which oscillate in the direction of propagation, and transverse waves, which oscillate at an angle of 90°.

The sound velocity of a longitudinal wave in a solid, c_L, is given by;

$$c_L = \sqrt{\frac{E}{\rho}\frac{1-\nu}{(1+\nu)(1-2\nu)}} \tag{2}$$

and the velocity of a transverse wave, c_T, by;

$$c_T = \sqrt{\frac{E}{\rho}\frac{1}{2(1+\nu)}} \tag{3}$$

where E, ρ and ν are Youngs' Modulus, density and Poissons Ratio respectively.

Hence;

$$\frac{c_L}{c_T} = \sqrt{\frac{2(1-\nu)}{1-2\nu}} \tag{4}$$

For a sound wave reaching a boundary with a second medium in which the velocity of sound is c' and with acoustic impedance Z'_0 the coefficients of reflection, R, and transmission, T, for the interface are given by (with normal incidence assumed);

$$R = \frac{Z'_0 - Z_0}{Z'_0 + Z_0} \tag{5}$$

$$T = \frac{2Z'_0}{Z'_0 + Z_0} \tag{6}$$

where,

$$T = R + 1 \tag{7}$$

2.2. Use of the ultrasonic flaw detector in the experiment

To measure the contact area upon first contact of the molten alloy with a cold surface the experimental

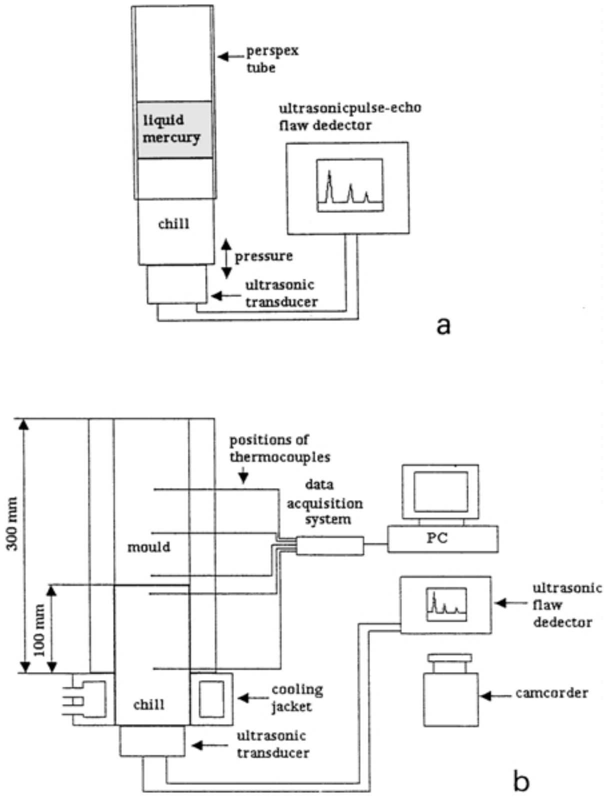

Figure 1 Experimental apparatus used to investigate the ultrasonic reflection from the casting-chill interface. (a) For the experiment with liquid Hg cast onto a Cu chill. (b) For the experiment with Al-4.5 wt% Cu alloy cast onto a Cu chill.

apparatus shown in Fig. 1 was used. A Cu chill of diameter 25 mm and length 100 mm was inserted into the bottom of a 300 mm long refractory tube. The base of the Cu chill was surrounded by a water cooled Cu jacket and the transducer of an ultrasonic flaw detector was applied to the base of the chill. The water cooling prevented the base of the chill becoming hot, which might cause degradation of the coupling gel applied between the transducer and the base of the chill and a consequent loss in efficiency in the ultrasonic signal transmission.

The liquid alloy used was an Al-4.5 wt% Cu alloy made from commercial purity Al (minimum purity 99.8% Al) and electrical conductivity grade pure Cu. This was melted in a resistance heated furnace and cast at 810°C into the open mouth of the refractory fibre tube and onto the upper part of the water cooled Cu chill.

Experiments were also carried out at room temperature, using the same Cu chills but with liquid Hg (99.9% purity), and therefore with the water-cooling arrangement removed. The liquid Hg was poured from heights of 150 mm and 280 mm and varying amounts were used to give different heights of the final static Hg column, namely, 10, 50 and 100 mm.

Experiments were carried out with the chill oriented vertically but with solidification taking place either upwards or downwards from the chill. The Cu chills used were of varying surface roughness, as shown in Table I.

The transducers used for the experiment with liquid Hg were of 2, 5 and 10 MHz frequencies whereas for the experiments with the cast Al-4.5 wt% Cu alloy only a 2 MHz frequency was employed.

TABLE I The surface roughness of the Cu chills used in the experiments

Grade of emery paper	R_a (μm)	R_z (μm)	S_m (μm)
4000	0.02	0.17	314
2400	0.06	0.60	93
1200	0.17	1.6	52
400	0.47	4.4	37

R_a is a measure of the mean deviation of the surface roughness, R_z is a measure of the mean peak-to-valley height of the surface roughness and S_m is a measure of the mean peak-to-peak distance of the surface roughness.

In the casting experiments with the Al-4.5 wt% Cu alloy a video camera was used to continuously record the output of the monitor of the ultrasonic flaw detector and the recording re-examined with stop-motion to determine the varying height of the echo from the chill surface displayed on the screen. With the liquid Hg it was sufficient to measure the amplitude of the echo before and after the experiment.

The experiment was adapted from a similar one to determine the interfacial heat transfer coefficient, hence the inserted thermocouples in the chill and the casting and the long refractory fibre tube used. From these the temperature distribution in the chill and the casting could be determined by an explicit finite difference method [5]. In adapting this experiment in this way the temperature dependence of the density and velocity of sound of the materials, and their effect on acoustic impedance, could be taken into account to obtain a more accurate estimate of the actual contact area. The relationships for Youngs Modulus and density used for calculating the longitudinal sound velocity are shown in Table II. (Room temperature values for Hg were used.)

2.3. Interpretation of the output from the ultrasonic flaw detector

With the ultrasonic transducer placed at the base of the chill the monitor showed a strong echo from the upper surface of the chill. The amplitude of this echo, H_0, corresponded to a condition of complete reflection of the ultrasonic signal from the upper surface of the chill. Upon contact of the cast liquid metal with the chill surface some of the ultrasonic signal would be transmitted through the areas of contact between them, resulting in a reduction in the amplitude of the initial echo to a new amplitude, H_1. (This is shown schematically in Fig. 2.) The coefficient of reflection implied by this is given by;

$$R = \frac{H_1}{H_0} \tag{8}$$

TABLE II Expressions to describe temperature dependant Youngs Modulus and density

Material	Density	Youngs modulus
Cu	$9095.11 - 0.46292T$	$129.8 \times 10^9 \times (1 - 3 \times 10^{-4} \times (\theta - 15))$
Al-4.5% Cu alloy	$2570 - 0.175(600\text{-}T)$	$213 - 0.35\,\theta$

T = temperature in Kelvin; θ = temperature in degrees centigrade.

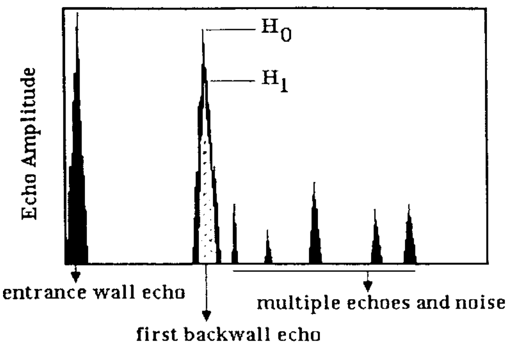

Figure 2 Schematic of the output from the ultrasonic flaw detector showing H_0, the amplitude of the echo from the surface of the chill and H_1, the amplitude of the echo from the upper surface of the chill after pouring.

If the casting and chill surfaces are assumed to be in perfect contact the maximum reflection coefficient (R_t) is given by Equation 5 where Z_0 and Z_0' are the acoustic impedances of the chill and the casting material respectively (given by Equation 1).

The hypothetical height of the echo if the Cu chill surface was in perfect contact with the cast liquid metal would therefore be given by $R_t H_0$ (from Equation 8). Thus the actual contact area, upon pouring of the liquid metal onto the chill surface, was given by the ratio (expressed as a percentage) of the real change in amplitude of the echo from the surface of the chill ($H_0 - H_1$) to the change in amplitude if perfect contact was assumed to occur ($H_0 - R_t H_0$).

In other words the actual contact area, A_c, was obtained from the experimentally observed amplitudes of the ultrasonic reflections using;

$$A_c = \left(\frac{H_0 - H_1}{H_0 - R_t H_0}\right) \times 100 \tag{9}$$

More details of this approach are given in References 6, 7 and 8.

3. Results

3.1. The Hg-Cu interface

Figs 3 and 4 show the estimated contact areas for liquid Hg upon a Cu chill, for different surface roughnesses

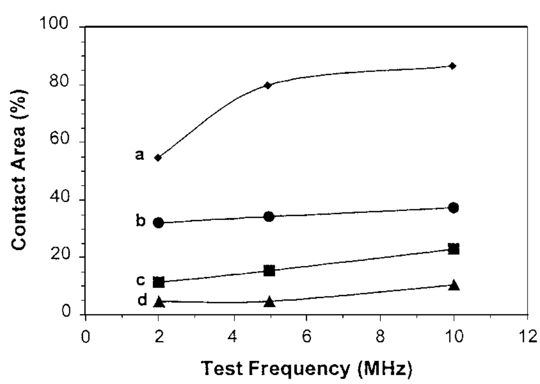

Figure 3 Variation in estimated contact area for liquid Hg cast onto a Cu chill with varying chill surface finish, for three different test frequencies. a—4000, b—2500, c—400 and d—280 grade emery papers. (Pouring height of 28 cm from chill surface.)

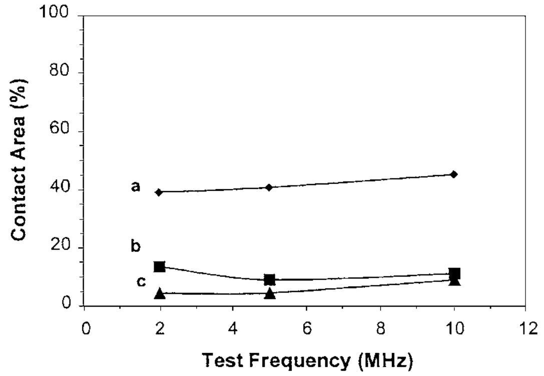

Figure 4 Variation in estimated contact area for liquid Hg cast onto a Cu chill with varying chill surface finish, for three different test frequencies. a—4000, b—2500 and c—400 grade emery papers. (Pouring height of 15 cm from chill surface.)

and test frequencies, and for pouring heights of 280 mm and 150 mm respectively. The measured contact area decreased with increasing surface roughness but was not greatly affected by test frequency except with the smoothest surface finish, where the contact area tended to increase with increasing test frequency, (curve a in both figures).

With the lower pouring height (Fig. 4), lower contact areas were measured. This suggested that some wetting of the Cu chill surface had taken place with the higher pouring height (and therefore greater impact velocity) that affected the subsequent values of measured contact area. This is clearly a factor that needs to be controlled in future experiments.

The different amounts of liquid Hg used, producing different metallostatic pressures at the base of the column of liquid upon the chill surface, produced similar contact areas, so no results are shown for these experiments.

3.2. The solidifying Al/Cu alloy interface

Experimentally determined contact areas for three casting experiments are shown in Fig. 5 (upwards solidification, prepared with 400 grade paper), Fig. 6

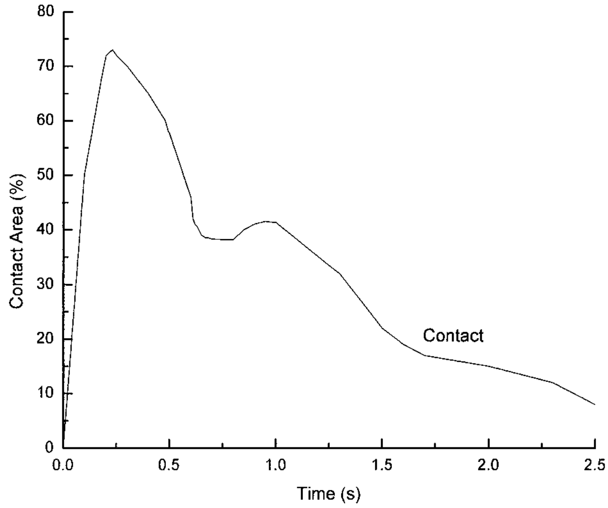

Figure 6 Variation in estimated contact area for Al-4.5 wt% Cu alloy cast onto a chill prepared with 4000 grade emery paper. (Casting solidified vertically upwards.)

(upwards solidification, prepared with 4000 grade paper), and Fig. 7 (downwards solidification, prepared with 400 grade paper).

In each case the estimated contact area rose from zero to a maximum and then declined. The peak occurred about 0.1–0.3 s from the time of impact of liquid metal upon the chill surface and varied from around 25% to 70% contact area. Thereafter the contact area tended to decline to a minimum of around 10% or less. From around 2 s onwards the contact area rose to extremely unlikely values. Therefore the results were considered to be reliable for the first 2 s of the test only and presumably thereafter some of the assumptions underlying the approach to estimate the contact area were no longer valid.

4. Discussion

Repeated experiments showed little agreement between results from different experiments so a few selected results have been presented to which the following general remarks apply.

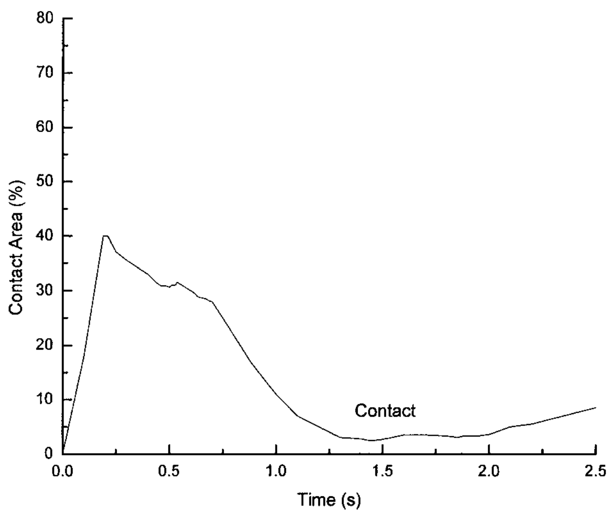

Figure 5 Variation in estimated contact area for Al-4.5 wt% Cu alloy cast onto a chill prepared with 400 grade emery paper. (Casting solidified vertically upwards.)

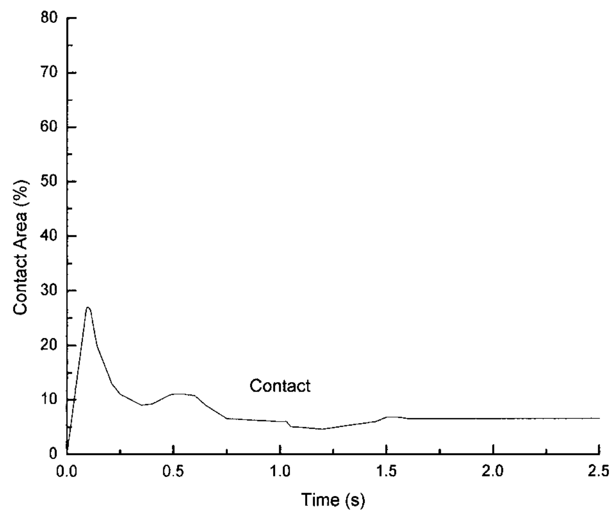

Figure 7 Variation in estimated contact area for Al-4.5 wt% Cu alloy cast onto a chill prepared with 400 grade emery paper. (Casting solidified vertically downwards.)

With the Al-Cu alloy castings the results showed an initial high contact area (high transmission of ultrasound) occurring within 0.25 s but which thereafter declined, indicating a reduction in contact between the chill and casting surfaces. The great variation in maximum contact area determined is probably due to the highly variable nature of the impact of the metal stream on the chill surface resulting in variations in wetting and differing measured contact areas, as was demonstrated by the results obtained with Hg.

The decline in contact area from its initial peak is probably due to several causes. With the formation of the casting skin its associated surface roughness would reduce the area of contact, as would the convex deformation of the chill surface due to thermal strain and/or the convex deformation of the casting surface referred to by Dong et alia [2] and by Thompson and Parkman [3]. The subsequent lateral thermal expansion and contraction of the casting and chill surfaces would also change the contact area between them.

The estimated contact areas obtained with the experiments using Hg suggested that smoother chill surfaces were associated with larger contact areas (Figs 3 and 4) (and therefore larger interfacial heat transfer coefficients), as would be expected. However, there was no consistent relationship between the measured contact area and the chill surface roughness observed with the Al-4.5 wt% Cu alloy castings.

The actual values of the initial (peak) contact areas are probably not very accurate. Initially high contact areas due to liquid metal impact, followed by a decline, would certainly be expected but the variation in values obtained shows a lack of reproducibility. Therefore the value of these observations lies in the estimated actual contact area after the decline from peak values, which was found to be around 5%.

The nature of the interface that these values relate to is probably that of a (just-solidified) casting skin in contact with the chill surface. With two surfaces in contact, a significant amount of ultrasound can be propagated if the gap between them is sufficiently small [4]. The R_z values for the chill surface (a measure of the peak-to-valley height of the surface roughness), are sufficiently low that this additional transmission may have occurred, particularly in the vicinity of the points of actual contact, (where the gap between the two surfaces would be at its smallest), and therefore these contact areas should be regarded as maximum values. The accuracy of the experimentally determined contact areas could probably be greatly improved with further refinement of the technique.

The use of an ultrasonic flaw detector could therefore be a viable technique to explore the actual contact area between casting and mould, if the technique could be refined to give a greater precision. The suggested initial actual contact areas of the molten alloy on the chill surface of between 25 to 70% are presumably highly transient and not particularly accurate. The estimates of the contact areas subsequent to the initial peak, values of below 10%, are more likely to be a true reflection of the nature of the interface during formation of the skin of the casting.

5. Conclusions

A technique has been developed for investigating the contact area between a cast liquid metal and a chill employing an ultrasonic flaw detector. Results could only be obtained for the first few seconds of casting but these suggested a peak in contact area, which could be as great as 70%, followed by a decline to values of around 5 to 10%.

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