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TECHNICAL PAPER

Estimating the Effective Metal-Mould Interfacial Heat Transfer Coefficient via Experimental-Simulated Cooling Curve Convergence

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Abstract The design of improved casting systems requires accurate modeling of metal cooling processes. This can only be accomplished after determining the interfacial heat transfer coefficient (IHTC) between a solidifying casting and its mould. In the current work, a simple and robust inverse heat conduction technique was applied for the estimation of the effective IHTC between an aluminum alloy casting and a steel permanent mould during solidification. The solidification of the alloy at varying mould preheating temperatures was monitored using a thermocouple, and the experimental cooling curves were compared with curves simulated by casting solidification modeling software. The IHTC value applied to the software was varied until its output converged with the experimental data, leading to an estimation of 6000 W/m^{2}K for this system. This technique is useful as a preliminary tool in materials modeling, and it will promote the development of improved casting processes without the need for excessive experimentation.

Keywords Interfacial heat transfer coefficient · Simulations · Permanent mould casting · Aluminum alloy

1 Introduction

Advances in metallurgy rely on the fundamental relationship between processing, microstructure and material properties. During metal-casting, controlling the metal cooling rate can affect the relative refinement of its solid microstructure, influencing many properties such as strength and thermal conductivity [1]. Hence, effective casting procedure design leads to enhanced material performance; yet, this requires a precise understanding of the heat transfer processes that occur during metal solidification. In gravity permanent mould casting, metal cooling occurs primarily via heat transfer from the metal to the mould, due to their large difference in temperature and thermal mass. While heat transfer from both the metal and the mould to the surroundings also occurs, accurately describing the metal-mould interfacial heat transfer is essential for modeling and producing systems for castings with predictable properties.

The metal-mould interfacial heat transfer coefficient (IHTC) is one of the most important parameters encapsulating the heat transfer from the solidifying metal to the permanent mould. The IHTC is defined as the proportionality variable between the heat flux and the temperature difference between the metal and the mould, and therefore it represents the overall thermal resistance across the metal-mould interface. The IHTC is a very complex parameter which is influenced by numerous factors, such as the metal and mould compositions, the area and geometry of heat transfer, surface roughness, interfacial contact, the casting system pressure, temperature, and time [2–6]. Nonetheless, IHTC is often approximated as constant, which may be valid over specified temperature ranges [7]. Peak IHTC values have been reported in the literature to vary within a range of 50–18,000 W/m^{2}K [8, 9].

It is possible to directly measure IHTC as the quotient of heat flux and the temperature gradient by measuring the variation in temperature with time at several positions in the system. For instance, direct measurements of IHTC have been performed for quenching solid steel in water, by

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quenching a steel cylindrical probe with an internal thermocouple to record its instantaneous cooling rates [7]. However, such measurements are usually only practical for simple one-dimensional systems. For more complicated casting systems, inverse heat conduction methods are typically utilized. In these methods, temperature evolution curves for some points in the casting and/or mould are both measured empirically and calculated using a theoretical heat transfer model. The unknown variable (IHTC) can then be varied in the model until converging to a value that satisfies a suitable correlation between the calculated and experimental data. Many techniques have been developed in the literature to apply the inverse heat conduction method to numerous casting systems, including lost-foam casting aluminum alloys [2], sand-casting aluminum alloys with metal chills [10, 11], and high-pressure die-casting aluminum and magnesium alloys [12].

In each of these studies, an intricate numerical model was developed that was specific to the system of interest, and precise thermocouple placement was required inside the mould and the casting. While suitable in a controlled lab environment, these approaches might not be practical in modern manufacturing companies, especially in the initial stages of product design or technological improvements when significant variation can be considered for system parameters. The objective of this paper is to present a simpler, faster and more robust technique for estimating the IHTC in casting systems, in which a single thermocouple is inserted within a solidifying casting for comparison with a cooling curve calculated by typical casting solidification modeling software. This technique is more suitable for integration into industrial research and development, and it will promote the development of moulds, carefully designed to produce superior castings.

2 Materials and Methods

2.1 Experimental Castings

The two permanent moulds used in this study were fabricated from 160 mm × 225 mm × 64 mm (6.25 in × 8.875 in × 2.5 in) blocks of H13 tool steel. The moulds contained three casting cavities each, allowing the production of six geometrically-identical castings (as illustrated in Fig. 1) from the same alloy batch. For each production run (two moulds, six castings), approximately 2.2 kg of 319 aluminum (Al) alloy was melted in a silicon-carbide crucible. The crucible was heated in an electric-resistance furnace at 750 °C for at least 1.5 h until the alloy was molten. Next, commercial purity magnesium (Mg) (99.8 wt%) was added to raise its concentration in the alloy to approximately 0.40 wt%. Thin slices of Mg were added by manually plunging and stirring for approximately 30 s under a CO_2 cover gas, after which the melt was allowed to settle for 20 min to ensure effective dissolution. The melt was then skimmed and treated with 0.25 wt% sodium fluorosilicate degasser and flux (powder) to reduce inclusions and entrained hydrogen. The degasser and flux was manually stirred and then allowed to settle for 5–10 min.

Concurrently, the moulds were heated in an electric furnace to at least 150 °C above the maximum desired mould preheating temperature for the production run for a minimum of 1 h to ensure complete soaking. The moulds were then removed from the furnace and allowed to cool on a firebrick in still air to homogenize in temperature and reach the desired mould temperature before pouring. During this time, four K-type thermocouples with 3.175 mm diameter ceramic sleeves were inserted into the holes in the four sides of the mould, each at the centre length of the side and 30 mm from the top. The holes extended into the mould such that there was about 15 mm of mould material between the thermocouple and the nearest casting cavity. Furthermore, three more thermocouples were suspended at centre length and width of each cavity, 30 mm from the top of the mould, to capture the cooling curves of each casting. These thermocouples were suspended by placing a steel cover plate over half of the top of the mould with three holes in it, in which they were secured using steel stoppers. The thermocouples were attached to a Daytronic System 10 data acquisition unit for temperature monitoring and recording at a rate of 5 measurements per second. The thermocouple placement and labeling can be seen in Fig. 2. Each time the mould reached a desired preheating temperature, the melt was skimmed, removed from the furnace, and poured into a single mould cavity, and the remaining metal was returned to the furnace. The cavities were filled in order of ascending casting thermocouple number. For each casting, the pouring temperature was approximately 715 °C.

For these experiments, each mould cavity was considered isolated for the purpose of producing a casting with particular solidification characteristics. This was achieved by assigning the closest thermocouple(s) to each casting cavity as an indicator of its effective mould temperature, since heat transfer to the mould was most significant in the area directly surrounding the casting. Referring to Fig. 2, the effective mould temperature for Casting 2 and Casting 3 were determined from thermocouples Mould 1 and Mould 3, respectively. For Casting 1, at the centre of the mould, the lowest of the temperature readings between thermocouples Mould 2 and Mould 4 was taken as the effective mould temperature. Therefore, during casting, all four mould thermocouples for each of the two moulds (denoted “A” and “B”) were monitored, and molten metal was poured into a given cavity once its assigned

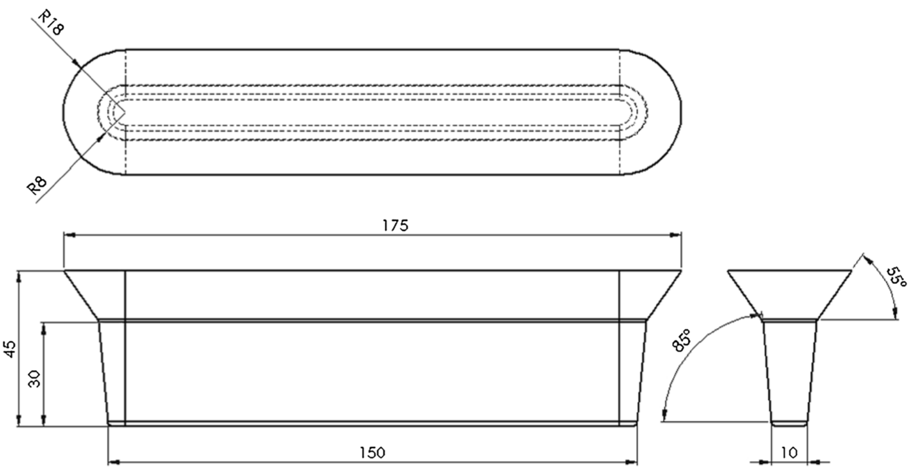

Fig. 1 Casting geometry (units in mm), omitting 1.6 mm radius fillets on corners for clarity

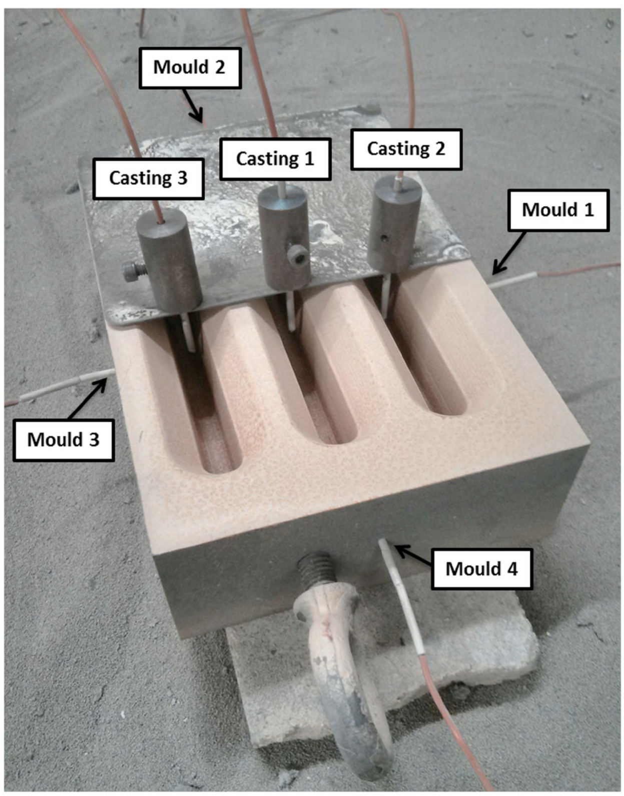

Fig. 2 Thermocouple placement and labeling in the permanent mould

thermocouple indicated a desired mould temperature. The intended initial mould temperatures for the experiments were between 200 and 700 °C in 50 °C intervals. The achieved mould temperatures for the castings are presented in Table 1.

The average composition of the castings, as determined from optical emission spectrometry on four samples per casting, is presented in Table 2.

The primary solidification rate was determined for each casting condition using the alloy cooling curves recorded by the suspended thermocouples (Casting 1, 2 and 3 in Fig. 2). Referring to a typical experimental 319 alloy cooling curve from this study in Fig. 3, the primary solidification rate can be calculated as follows:

Table 1 Initial mould temperatures for experimental castings

Production Run	Initial mould temperature at pour (°C)			
		Casting 1	Casting 2	Casting 3
1	Mould A	690	647	497
	Mould B	588	545	–
2	Mould A	449	349	250
	Mould B	397	300	200

$$SR_P = \frac{\Delta T_{L \to E}}{\Delta t_{L \to E}} \quad (1)$$

where SR_P is the primary solidification rate, $\Delta T_{L \to E}$ is the primary freezing range (temperature difference between liquidus and Al–Si eutectic reactions), and $\Delta t_{L \to E}$ is the primary solidification time (time difference between liquidus and Al–Si eutectic reactions).

2.2 SOLIDCast Simulations

The same casting system was modeled using SOLIDCast software with add-on flow modeling module FLOWCast, simplified to only include one casting in the centre cavity of the mould (Fig. 4). The software used FDM (finite difference method) and CFD (computational fluid dynamics) to simulate liquid metal flow and solidification. The built-in casting material Al 319.0 was selected, whose properties are listed in Table 3 [13]. The mould material was selected as H13 tool steel with thermal conductivity, specific heat, and density values of 24.5 W/m-K, 460 J/kg-K, and 7800 kg/m^3, respectively [14]. The initial mould temperature was varied from 100 to 800 °C in 100 °C intervals, as

Table 2 Average experimental chemical composition of 319 alloy

Component	Si	Cu	Mg	Ti	Fe	Mn	Zn	Ni	Other	Al
wt%	6.37	3.35	0.40	0.13	0.66	0.34	0.79	0.05	0.22	Bal.

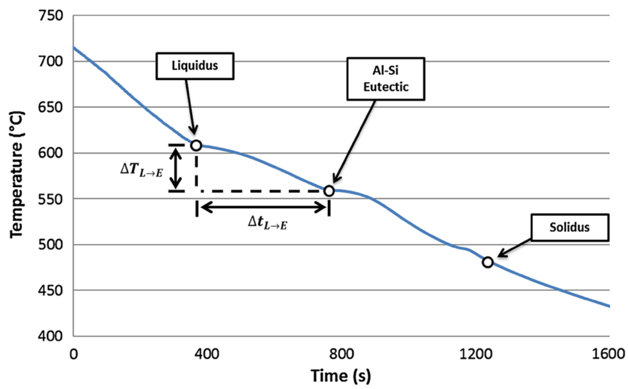

Fig. 3 Typical experimental cooling curve for 319 alloy

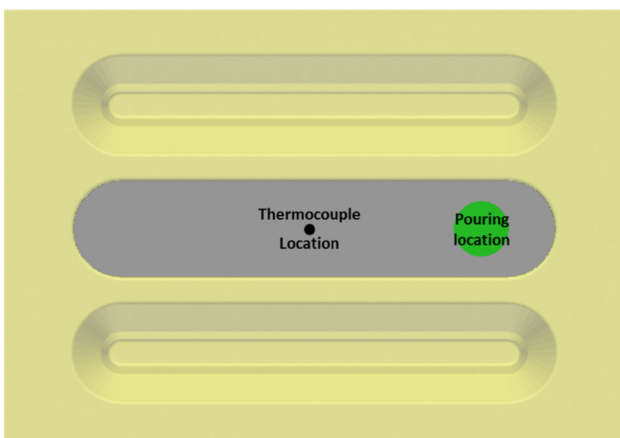

Fig. 4 Top view of the SOLIDCast simulated mould and casting geometry

to capture the practical mould temperature limits of the experimental casting facility. The heat transfer coefficients for the Al alloy and ambient air, for the H13 mould and ambient air, and for the Al alloy and the H13 mould were suggested by the software as 8.5 W/m^{2}K, 48.8 W/m^{2}K, and 1135 W/m^{2}K, respectively. The ambient temperature was selected as 20 °C, the casting initial pouring temperature was set at 715 °C, and the pouring time was estimated as 4 s based on preliminary experiments. The castings were simulated using a 2 mm node size mesh for each initial mould temperature.

For each simulation, the temperature profile of the molten alloy was recorded during solidification as function of time at the absolute centre of the main section of the casting (i.e. at centre length, centre thickness, and 30 mm from the top of the mould). A typical 319 alloy cooling curve is shown in Fig. 3, yet the time scale on the abscissa was correlated to the initial mould temperature. From these curves, the primary solidification rate was calculated for each condition according to Eq. (1), above. The simulations were repeated, varying the input metal-mould IHTC while keeping all other parameters constant, in order to find a close fit between the simulated and experimental primary solidification rates for each initial mould temperature.

3 Results and Discussion

The experimental and simulated cooling curves each featured relatively constant phase evolution temperatures for each initial mould temperature condition. Experimentally, the liquidus, Al–Si eutectic, and solidus temperatures have been found to be approximately 608, 560, and 485 °C, respectively (± 1.5 °C). These values correspond well to the property data for Al 319.0 alloy found within SOLIDCast, yet the experimental Al–Si eutectic phase nucleation temperature is slightly higher than the value used for the simulations (547 °C). This is likely due to variation in the solidification reaction temperatures caused by compositional differences, by which Al–Si eutectic temperatures in the 545–565 °C range are typical [15, 16].

Although the primary freezing range of the alloy is invariant, decreasing the initial mould temperature results in progressive increase in the primary solidification rate for both the experimental castings and the simulations (Fig. 5). A lower mould temperature corresponds to a greater temperature gradient between the molten metal and the mould. According to Fourier's law of heat conduction and

Table 3 Built-in SOLIDCast property data for Al 319.0

Thermal conductivity (W/m-K)	Specific heat (J/kg-K)	Density (kg/m^3)	Latent heat of fusion (kJ/kg)	Liquidus temperature (°C)	Al–Si eutectic temperature (°C)	Solidus temperature (°C)
108.8	962.3	2768	388.2	609	547	482

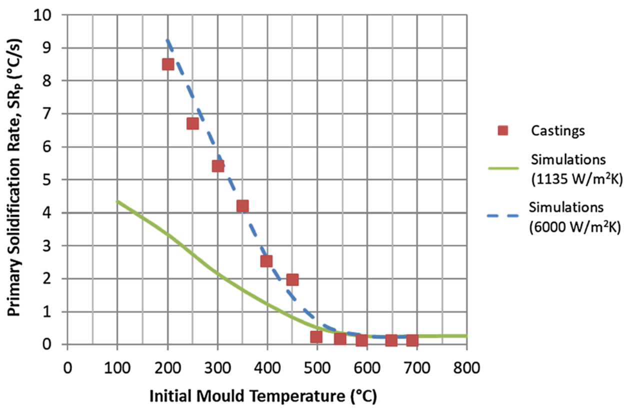

Fig. 5 Experimental and simulated primary solidification rate of 319 alloy as a function of mould temperature, using the suggested 1135 W/m^{2}K and a best-fitted 6000 W/m^{2}K metal-mould IHTC

analogous laws for convection and radiation [17], this promotes a greater heat transfer rate, which in turn causes faster metal cooling.

As shown in Fig. 5, the primary solidification rate of the experimental castings decreases almost linearly with increasing mould temperature in the 200–500 °C range. Yet, for higher initial mould temperatures, the rate remained relatively constant at about 0.13 °C/s. The simulation results using the suggested 1135 W/m^{2}K metal-mould IHTC (plotted as a solid line in Fig. 5) display a strong correspondence with the experimental results at initial mould temperatures near 500 °C and higher. However, with decreasing mould temperature below 500 °C, the simulations predict that primary solidification rate increases with a much shallower slope than that found for the castings. Given the very small thermal mass ratio between the castings and the mould (of the order of 1:25), this can be largely attributed to an underestimation of the amount of heat transfer that occurs between the metal and the mould in the simulations, characterized by the IHTC.

Varying the metal-mould IHTC while keeping all other parameters constant in repeated simulations indicate that increasing the IHTC increases the slope of the primary solidification rate–initial mould temperature curve for temperatures up to about 500 °C. A higher coefficient corresponds to more efficient heat transfer at the interface between the molten metal and the mould. At a given temperature gradient between the metal and the mould, a higher IHTC will lead to a more rapid solidification rate. Nonetheless, at mould temperatures above about 500 °C, the simulated primary solidification rates closely approximate the constant experimental values, regardless of IHTC.

This high mould temperature solidification behaviour is likely related to the alloy solidification temperature range and mould cooling. During casting, the metal cools by heat transfer to the mould and to the ambient surroundings (still air) but the mould also cools by transferring heat to the surroundings. For mould temperatures less than the solidus temperature (∼ 485 °C), the heat transfer to the mould, driven by the large initial temperature difference, promotes complete solidification that occurs fast enough that mould cooling is negligible. Hence, the initial mould temperature has a dominant influence on the solidification rate of the metal. However, for mould temperatures higher than the solidus, the melt is still semi-solid after approaching thermal equilibrium with the mould during the initial heat transfer. Therefore, complete solidification can only occur after the mould cools by heat transfer to the surroundings to below the solidus temperature. In this case, the heat transfer from the mould to the surroundings is more significant than the heat transfer from the metal to the mould, so increases in initial mould temperature past the solidus does little to decrease the solidification rate.

The simulations produces a primary solidification rate vs initial mould temperature curve that qualitatively fit the experimental data closest when 6000 W/m^{2}K is chosen as the metal-mould IHTC (plotted as a broken line in Fig. 5). This value closely resembles the 6578 W/m^{2}K value estimated by Paul and Venugopal [18], for which 6063 Al alloy is cast in a permanent mould under similar conditions of the present study. Yet, the identified IHTC of 6000 W/m^{2}K is not a precise evaluation of the true heat transfer coefficient in this system. For example, the heat transfer coefficients of the Al alloy and ambient air as well as for the H13 mould and ambient air suggested by the software are not varied in any of the simulations. Although changes in these other two coefficients will also influence the results, it is assumed to be less significant than changes in the metal-mould IHTC, given that the thermal mass ratio between the castings and the mould is very small and the metal-mould coefficient is several orders of magnitude higher than the other coefficients. Additionally, the simulations utilize constant thermal property and heat transfer coefficient values for calculating the heat transfer processes during casting, but the metal and mould thermal conductivities, specific heat capacities, densities, and heat transfer coefficients are all dependent on temperature and casting time [2]. Also, during casting, an air gap tends to form between the casting and the mould, reducing the rate of interfacial heat transfer. Even though the IHTC initially suggested by the software underestimate the effective value in this work, failure to consider the air gap may introduce error into such simulations.

Moreover, the estimated IHTC cannot be accurately generalized to other 319 alloy castings in H13 permanent moulds with any confidence. The value is specifically determined for these casting and mould materials and geometries, given the exact boundary conditions and calculations applied by this particular software. Any discrepancy in the boundary conditions or even the application of different simulation software can cause drastic changes in the result obtained. Therefore, the exact value determined in this study is not intended for universal application. Rather, this study demonstrates that a simple comparison of simulation data to experimental solidification rates can be used to calibrate a certain simulation software to enable reasonably-accurate modeling of heat transfer in a casting system. Given the widespread use of computer modelling in industrial research and development, this method is very useful as a preliminary tool in the initial stages of planning high-volume production, particularly for the iterative design of casting processes without the need for excessive experimentation.

4 Conclusions

Primary solidification rates of permanent mould castings were determined via experiments and SOLIDCast simulations as a function of initial mould temperature. A system-specific metal-mould internal heat transfer coefficient was estimated by its variation in the software to produce a primary solidification rate vs initial mould temperature curve that corresponded well to the experimental data. This has been a simple and effective method to enable basic simulations of heat transfer in casting systems for applications including solidification modeling as well as component research and development. For the most useful results in similar systems, this methodology was needed only to be applied for mould temperatures below the alloy solidus temperature. At higher temperatures, solidification rate was found to be relatively independent of mould temperature and heat transfer coefficient.

Some additional conclusions drawn from this study include:

1. Decreasing the initial mould preheating temperature resulted in an increase in primary solidification rate. However, the solidification rate did not noticeably affect the alloy liquidus, Al–Si eutectic, or solidus temperatures.
2. For higher metal-mould interfacial heat transfer coefficients, heat transfer at the interface between the molten metal and the mould was more efficient, such that a given temperature gradient would promote faster metal cooling. Consequently, for higher heat transfer coefficients, the slope of the primary solidification rate vs initial mould temperature curve was steeper.

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