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ESTIMATION OF HEAT TRANSFER COEFFICIENT IN SQUEEZE CASTING OF WROUGHT ALUMINUM ALLOY 7075 BY THE POLYNOMIAL CURVE FITTING METHOD

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Abstract

Numerical simulation is used to improve the productivity and optimize casting process in today's foundry. The accurate estimation of heat transfer coefficients (HTC) at the metal-mold interface is essential to simulate casting solidification processes. In this work, a 5-step casting mold was employed with section thicknesses of 2, 4, 8, 12, 20 mm. Wrought aluminum alloy 7075 was squeeze cast under an applied pressure of 60MPa in a hydraulic press. By placing the type-K thermocouples at different locations of each step in the mold, the casting-die interfacial IHTC in the 5-step casting were evaluated from the measured temperatures by applying the polynomial curve fitting method. The results from the estimation indicated that the wall thickness of squeeze cast wrought aluminum 7075 significantly influenced the value of IHTC. The peak IHTC value increased as the step thickness increased.

Introduction

Wrought aluminum alloys with their high strength properties have achieved widespread use in today's aerospace and automotive industries. Aluminum alloys of 7075 are known for its high strength and other good characteristics which allow them suitable for applications such as structural component or tooling plates [1]. Squeeze casting has the advantage of pressurized solidification, close dimensional tolerance and good surface finish. During the solidification process, the applied pressure feed the liquid metal into the air or shrinkage porosities effectively. It makes castings free of porosity and excellent as-cast quality [2-3]. There is limited open literatures or research activities that focus on casting wrought aluminums. It is interesting to combine the advantages of wrought aluminum with its excellent properties and squeeze casting process with its novel shaping techniques. The cast version of wrought aluminum might fill the gap between wrought and cast.

In today's foundry, numerical simulation improved the productivity significantly. However, one of the most important parameter, the interfacial heat transfer coefficients (IHTCs) at the metal-mold interface is usually roughly set in the available finite element method (FEM) and finite difference method (FDM) commercial code [4]. To ensure to accurately determine the solidification path, microstructure development and shrinkage porosity formation etc., it is necessary to have a precise prediction of boundary conditions. In the real-life casting process, the imperfection of the contact between the mold and liquid metal due to the air gap caused by the application of coating on die surface may decrease the heat transfer between metal and die as well as cooling rate of the casting surface. This thermal barriers could degrade casting quality and properties significantly [5, 6]. Therefore, an accurate prediction of IHTC is critical to simulate the solidification process.

For decades, researchers have done extensive works to obtain heat transfer coefficients for difference metal-mold interfaces by different kind of casting processes experimentally or analytically. Dour et al. [7] reported their work to evaluate IHTC of a thin wall aluminum casting by the application of HPDC technique. The results showed that the lower preheat die temperature and a faster shot velocity led to a higher IHTC value. Rajaraman and Velraj [8] estimated IHTC by the Beck's and control volume methods. The results indicated that the calculated results by these two methods have a maximum percentage deviation of around 40 and 57%, respectively. The control volume technique produced more accurate and reliable results, since it does not involve iteration and step by step computation. Hao et al. [9] used FDM to solve thermal conduction equation. They used the temperature recovery method to calculate the latent heat of fusion. They found that the IHTC of ductile iron increased gradually and it indicated that the metal-die interface stay in close contact condition. This showed a different result in comparison to those estimated in steel and other nonferrous alloy castings. Also, most of the casting products involve various section thicknesses, difference in section thicknesses could result in significant variation of the heat transfer coefficient. Also, as the section become thinner, the evaluation of IHTC becomes vital due to the limitation in solidification time. Thus, it is important to examine the influence of casting section thickness on the IHTC [10-12].

However, most of the work has been focused on permanent mold casting processes and casting aluminum alloys. There is very limited knowledge about IHTC during squeeze casting by using wrought aluminum alloys.

In this work, 5-step squeeze casting mold was designed for evaluation casting thickness-dependent IHTC. The temperature at the die surface was estimated by the polynomial extrapolation method, which required the temperature values at different locations inside the die. With the temperature measurements and the estimated die surface temperatures, the heat flux and interfacial heat transfer coefficient were calculated at the casting /die interface.

Experimental Procedures

Die Design

Figure 1(a) illustrates the 3-D model of a 5-step casting die. There were totally six steps, of which the first step (top step) was designed as an overflow to entrap impurities in the upfront stream of the liquid melt during cavity filling. The vent was located on the top of the overflow, which could discharge the air inside the die. The dimensions for the rest of the 5 steps (from the second

Table I Thermo-physical parameters of Al 7075-T6 alloy.

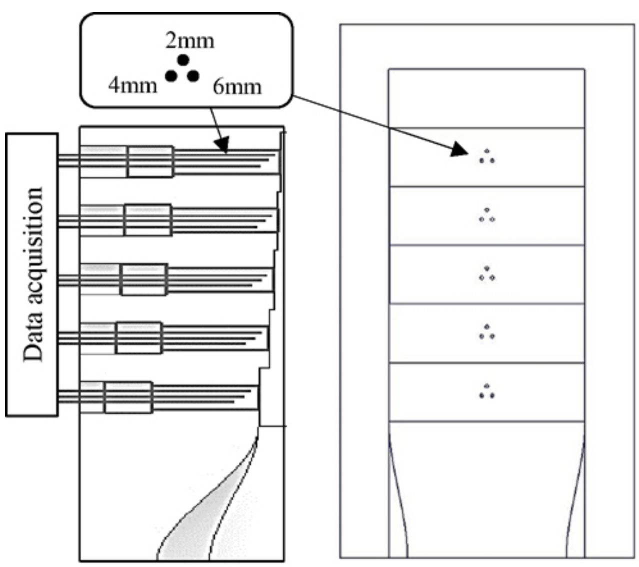
Material	Density g/cm^3	Specific heat J/g K	Thermo conductivity 130 W/m K	Solidus temperature °C	Liquidus temperature °C
Al 7075	2.81	0.96	130	477	635

Table II Chemical composition of Al7075 alloy (in weight percent).

Al	Zn	Mg	Cu	Cr	Fe	Si	Mn	Ti
88~92	5.1~6.1	2.1~2.9	1.2~2.0	0.18~0.28	Max 0.50	Max 0.40	Max 0.30	Max 0.20

top) were 100x20x2 mm, 100x30x4 mm, 100x30x8 mm, 100x30x12 mm and 100x30x20 mm, accordingly. Figure 1(b) gives the side view of a 5-step casting sample of Al7075, of which chemical composition is given in Table 2.

Figure 1 a) 3-D model of step casting mold, and b) side view and c) front view of 5-step casting sample of Al 7075 by squeeze casting under an applied pressure of 60MPa.



(a) (b)

Figure 2 a) side view and b) front view of the step die illustrating the locations of the thermocouples in each step.

To acquire the temperature history of each step, three K-type thermocouples (totally 15 thermocouples) were placed at each steps with the distance of 2mm, 4mm, and 6mm away from the cavity surface, as shown in Figure 2. The cavity is filled from the bottom sleeve (with diameter of 100mm) to the top.

Casting Process

A 75-ton- hydraulic press and wrought aluminum 7075 were used in the experiment, the thermo-physical parameters for the alloy are summarized in Table 1. The metal was firstly melt in an electric resistance furnace with the protection of nitrogen gas on the top. The holding temperature of the furnace was 800°C. As shown in Figure 3, the two half upper dies opened along the centeral parting line. The lower die had a diameter of 100 mm and a height of 200 mm. Both of the upper and lower dies were preheated by cartridge heaters. The upper die was preheated to 250 °C and the lower die at 300 °C. Liquid metal at 710°C was poured into the lower die. At last, the liquid metal was squeeze casted under an applied pressure of 60MPa and kept holding at this pressure for 20 seconds.

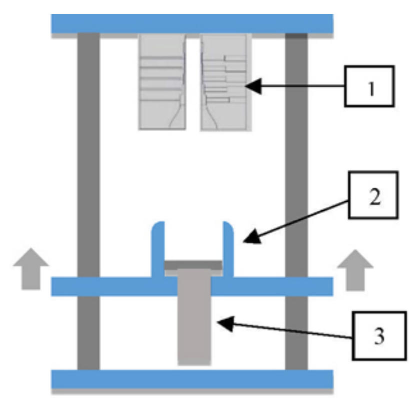


Figure 3 Schematic diagram of squeeze casting machine 1) upper die, 2) lower die and 3) piston.

Heat Transfer Model

Since the thickness of each steps was much smaller than the width, it could be assumed that the heat transfer was one dimensional at each step. The IHTC can be characterized by the following equation (Eq.1).

$$h(t) = \frac{q(t)}{\quad} \qquad \text{(Eq.1)}$$

where h is IHTC, q is average heat flux at the metal-mold interface, A is the cross section area, T_C is casting temperature and T_d is die surface temperature, respectively. The heat flux for both of the casting and die interface could be evaluated from Eq.2 with the temperature gradient at the surface and sub-surface nodes (2, 4, and 6mm form the surface).

$$q(t) = -k(T)\frac{dT}{dx} = -k(T)\frac{T_m^t - T_{m-1}^t}{\Delta x} \quad \text{(Eq.2)}$$

where k is thermal conductivity of the casting or die materials. The superscript t is solidification time. The subscript m is the number of the discrete nodal points. The heat transfer at each step is unsteady conduction transfer through one-dimensional body which can be described by Eq.3.

$$\rho c(T)\frac{\partial T(x,t)}{\partial t} = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T(x,t)}{\partial x}\right) \quad \text{(Eq. 3)}$$

For the heat transfer at the surface of the die, Eq. 3 could be rearranged as Eq.4:

$$(1 + 2F)\,T_0^{p+1} - 2F\,T_1^{p+1} = 2F\frac{\Delta x}{k}q_0 + T_0^p \quad \text{(Eq. 4)}$$

For the heat transfer inside of the die, Eq. 3 could be rearranged as Eq. 5:

$$(1 + 2F)\,T^{p+1} - F\,(T_{m-1}^{p+1} + T_{m+1}^{p+1}) = T_m^p \quad \text{(Eq. 5)}$$

where the superscript p denotes the time dependent of T. F is a finite different form of the Fourier number:

$$F = \frac{\alpha\Delta t}{(\Delta x)^2} = \frac{k}{c\rho}\frac{\Delta t}{(\Delta x)^2} \quad \text{(Eq. 6)}$$

The heat flux at the metal-die interface at each time step was obtained by applying equation 4 and 5.

Polynomial Curve Fitting

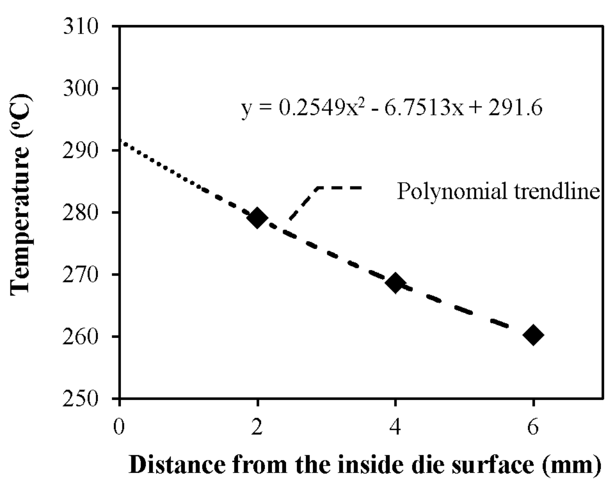


Figure 4 Polynomial curve fitting with the temperature readings from step 2 at 1.1 seconds after pressurized solidification.

The metal-die interface temperature T_c was estimated by the polynomial curve fitting method. Thus, the IHTC values can be calculated by Eq. 1 with the measured casting temperature. Three K-type thermocouples were located at X_1= 2 mm, X_2= 4 mm and X_3= 6 mm away from the inside die surface for each steps. Using the temperature reading from thermocouples at different locations, a temperature versus time curve can be obtained. The temperature at the inside die surface (X_0= 0 mm) can be estimated by using polynomial curve fitting method.

During solidification (after completion of filling), the data could be plotted on a temperature versus time plot by selection of the temperatures readings from the three thermocouples at the same time step, for example t=1.1, as shown in Figure 4. The temperature values versus distance X were then fitted by the polynomial trendline. To obtain the temperature at the inside die surface, the value X_0= 0 mm was substituted in the polynomial curve fitting equation (Eq. 7).

$$y = 0.2549x^2 - 6.7513x + 291.6 \quad \text{(Eq. 7)}$$

This procedure was repeated for different time increments to obtain a series of die surface temperature data.

Results and Discussion

Cooling curves

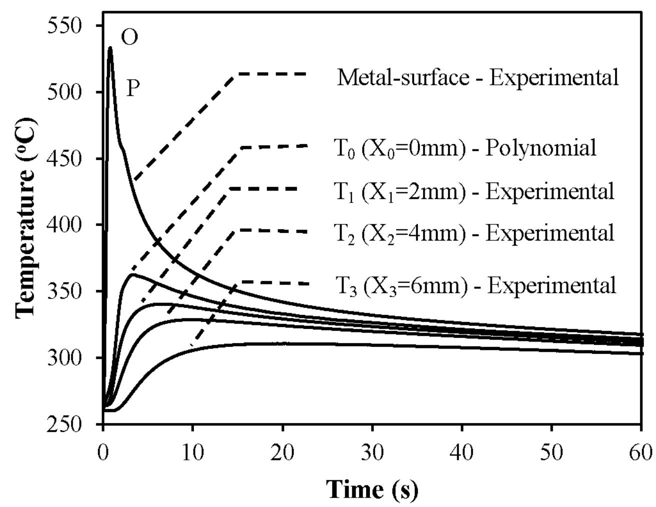


Figure 5 Typical temperature versus time curve (step 2, 60MPa) at the casting metal surface, die surface and various positions inside the die.

Figure 5 shows an example of the typical temperature versus time curve (at step 2), which includes estimated die surface temperature T_0 by polynomial curve fitting, measured temperature at the casting surface and T1, T2 and T3 at distances of X_1= 2 mm, X_2= 4 mm and X_3= 6 mm away from the inside die surface. The molten metal was poured at 710°C. As the molten metal filled from the bottom to the top of the die, the temperature was decreased to 529°C at step 2. From Figure 5, a dynamic temperature change occurred at the metal-die interface, since the temperatures of the casting surface increased and dropped much faster than the temperatures in the locations at different depths under the die surface. Segment OP of metal-surface temperature curve represented the period immediately after liquid metal pouring. The abrupt negative slope indicates a fast heat transfer behavior at the metal-die interface. Also, the rapid decrease in temperature took only 0.9s after metal solidification which indicates a high cooling rate occurs at step 2. Corresponding to the decrease in metal surface temperature, there was an increase in die surface temperature T_0 (X_0=0mm) which was estimated by the polynomial curve fitting method. The casting continued to lose heat until it reached the solidus temperature and completely solidified at point Q on the metal-surface curve.

Heat Flux and IHTC Curves

Figure 6 represent the determined step-2 heat flux (q) and IHTC (h) profiles associated with the results in Figure 5. The rapid decrease in temperature at segment OP of the metal surface leads to an abrupt increase in heat flux until its maximum value ($3.08Ex10^5$ W/m^2) is reached. Corresponding to the rapid decrease in temperature at segment OP, the abrupt increase in IHTC is observed at segment EF on IHTC curve. Then, the IHTC keeps increasing until reaches its maximum 2.3 KW/m^2 K. After the peak is reached (point G), the IHTC values starts to fluctuate until point J is reached, after which the IHTC falling rapidly to point K. The uncertainty and error of the polynomial extrapolated method should be responsible for the fluctuation presented in IHTC or q values. The rapid decrease in IHTC (segment JK) at step 2 could be caused the fact that the casting surface is not firmly contact with the die surface due to the lack of pressure present at step 2 as the solidification process proceeded.

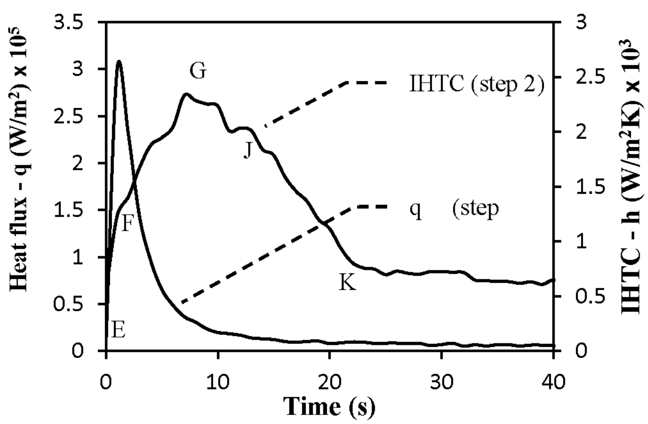


Figure 6 Interfacial heat flux (q) and interfacial heat transfer coefficient (IHTC) curves for step 2 with the applied pressure of 60 MPa.

Figures 7 and 8 show the estimated q and IHTC at step 1 to step 5 by the extrapolated fitting, respectively. All the q and IHTC profiles varies in a similar manner with step 2 as discussed before. They all initially increased abruptly right after the pressure was applied until the peaks were reached and then decreased until their values became steady state.

The casting step thickness influenced the IHTC significantly. For step 1, with the section thickness of 2mm, IHTC reached its peak (1.33 $Ex10^3$ W/m^2 K) 5s after the pressure applied. And then, it decreased to its lower level (444.32 W/m^2 K) at 21s. For step 2, with the section thickness of 4mm, IHTC reached its peak (2.33 $Ex10^3$ W/m^2 K) 7s after the pressure applied. It then decreased to its lower level (699.4 W/m^2 K) at 25s. For step 3, with the section thickness of 8 mm, IHTC reached its peak (4.36 $Ex10^3$ W/m^2 K) 8s after the pressure applied. It decreased to its lower level ($1.69Ex10^3$ W/m^2 K) at 30s. For step 4, with the section thickness of 12mm, IHTC reached its peak (8.2 $Ex10^3$ W/m^2 K) 10s after the pressure applied. It decreased to its lower level ($4.12Ex10^3$ W/m^2 K) at 23s. For step 5, with the section thickness of 20mm, IHTC reached its peak (11.7 $Ex10^3$ W/m^2 K) 11s after the pressure applied. It decreased to its lower level ($4.5Ex10^3$ W/m^2 K) at 31s.

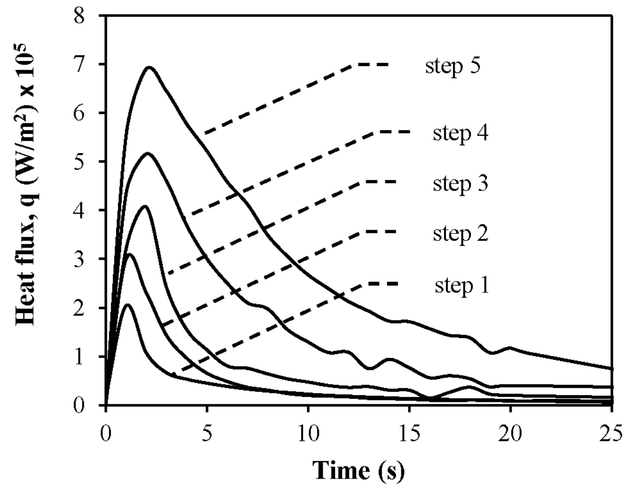


Figure 7 Heat flux (q) curves for steps 1-5 estimated by the extrapolated fitting method.

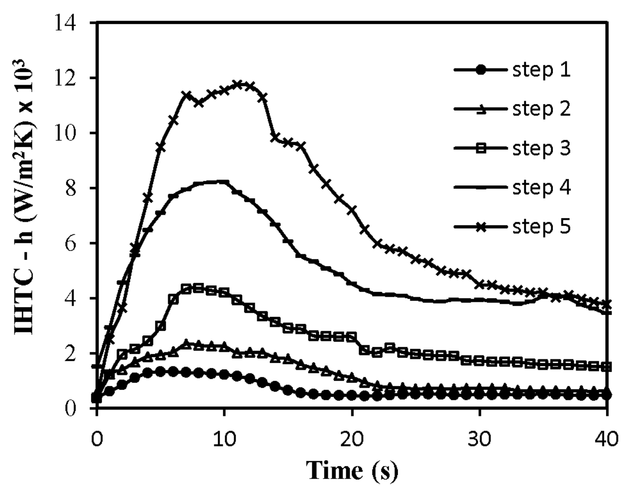


Figure 8 Interfacial eat transfer coefficient (IHTC) curves for step 1-5 estimated by extrapolated fitting method.

Also, the IHTC curve profiles expanded vertically, were elevated, and became tall and steep as the step thickness increased. Also, as the step thickness increased, it took more time for the IHTC to climb to its maximum value. For example, it took almost 3s longer for step 5 to reach its peak (11.75 $x10^3$ W/m^2 K) in comparison with step 3.

Conclusion

The wrought aluminum 7075 alloy was successfully cast by the squeeze casting technique under an apply pressure of 60 MPa. The IHTC between the wrought alloy and steel die was estimated by the extrapolation method based on the temperature measurements during squeeze casting.

All the IHTC curves presented a similar pattern. After the pressure was applied, the curves increased rapidly until their peak were reached and then decreased until they arrived at their plateaus. The step thickness had a significant influence on the shape of the IHTC curves. Their profiles became expanded, tall and steep as the step thicknesses increased. The step thickness also varied the IHTC values. It increased as the section thickness increased. Comparing the IHTC curves for step1 to step 5, the IHTC values varied form 1.33×10^3 W/m^2 K to 11.75×10^3 W/m^2 K. It took almost 6s longer for step 5 to reach its peak compared with step 1.

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