Magnesium Technology 2011
Edited by: Wim H. Sillekens, Sean R. Agnew, Neale R. Neelameggham, and Suveen N. Mathaudhu
TMS (The Minerals, Metals & Materials Society), 2011

ESTIMATION OF HEAT TRANSFER COEFFICIENT IN SQUEEZE CASTING OF MAGNESIUM ALLOY AM60 BY EXPERIMENTAL POLYNOMIAL EXTRAPOLATION METHOD

Zhizhong Sun[1], Xiaoping Niu[2], Henry Hu[1]
[1]Dept. of Mechanical, Automotive & Materials Engineering, University of Windsor; 401 Sunset Ave.; Windsor, Ontario N9B 3P4, Canada
[2]Promatek Research Centre, Cosma International; Brampton, Ontario L6T 5R3, Canada

Keywords: Heat transfer coefficient, Squeeze casting, Magnesium alloy, Inverse method

Abstract

In this work, a different wall-thickness 5-step (with thicknesses as 3, 5, 8, 12, 20 mm) casting mold was designed, and squeeze casting of magnesium alloy AM60 was performed in a hydraulic press. The casting-die interfacial heat transfer coefficients (IHTC) in 5-step casting were determined based on experimental thermal histories data throughout the die and inside the casting which were recorded by fine type-K thermocouples. With measured temperatures, heat flux and IHTC were evaluated using the polynomial curve fitting method. The results show that the wall thickness affects IHTC peak values significantly. The IHTC value for the thick step is higher than that for the thin steps.

Introduction

The squeeze casting process with high applied pressures is a promising solution for magnesium castings. Compared to other conventional casting processes, the most attractive features of squeeze casting (SC) are slow filling velocities and the pressurized solidification. Before the solid fraction of the casting is high enough, the applied pressure squeezes liquid metal feed into the air or shrinkage porosities effectively. Therefore, squeeze casting can make castings virtually free of porosity and usually have excellent as-cast quality, and are heat treatable, which is difficult to achieve with other conventional casting processes [1]. Although many research activities on squeeze casting process, some fundamental questions still need to be answered and the process must be optimized so as to expand its application, especially for emerging magnesium alloys.

Numerical simulation improved the productivity and optimized casting process greatly in the last decade. Beside the correct thermophysical property data, the estimating of the interfacial heat transfer coefficients (IHTCs) at the metal-mold interface is also necessary to simulate the solidification process accurately. IHTCs are usually very roughly set in the available FEM/FDM commercial codes. An accurate prediction of the boundary conditions is required to determine temperature distribution, solidification path, formation of shrinkage porosity, microstructure development, and residual stress. The pressure-transfer path is affected by applied hydraulic pressures, pouring and die initial temperatures, alloy and die materials, and casting orientation. Thermal barriers include coating applied on the die surface and air gap caused by shrinkage. The process parameters, such as the applied hydraulic and local pressures, pouring temperatures, and die initial temperatures, have an influence on the formation of pressure-transfer path, which consequently affects heat transfer at the metal-mold interface and the finial quality of squeeze castings [2,3]. In various casting process, the contact between the liquid metal and mold die is imperfect because of the coating applied on the die surface and air gap caused by shrinkage [4]. These thermal barriers may decrease the heat transfer between metal and die and cooling rate of the casting surface, which affect microstructure and quality of the casting significantly. Hence, precise determination of heat transfer coefficients at the metal-mold interface is a critical consideration to simulate the solidification process and model the microstructure of die castings accurately [5-10]. Especially, for thin-wall castings, the evaluation of IHTC becomes vital due to very limited solidification time.

However, many studies only focused on the simple shape die casting [11-14]. Little attention has been paid to variation of casting thicknesses and hydraulic pressures. Actually, in the die casting practice, various section thicknesses at different locations of castings result in significant variation of the local heat transfer coefficients. Therefore, it would be essential to investigate the influence of casting thickness, pressure value, and process parameters on the IHTC. In this study, a special 5-step squeeze casting was designed for understanding casting thickness-dependant IHTC, and the temperature measuring units and the pressure transducers were employed to accurately measure the temperatures and the local pressures during squeeze casting of magnesium alloy AM60.

Experimental Setup

5-Step Casting

A 5-step shape casting was designed special for this study. Figure 1 shows the 3-D model of 5-step casting, which consists of 5 steps (from top to bottom designated as steps 1 to 5) with dimensions of 100x30x3 mm, 100x30x5 mm, 100x30x8 mm, 100x30x12 mm, 100x30x20 mm accordingly. The molten metal fills the cavity from the bottom cylindrical shape sleeve with diameter 100 mm.

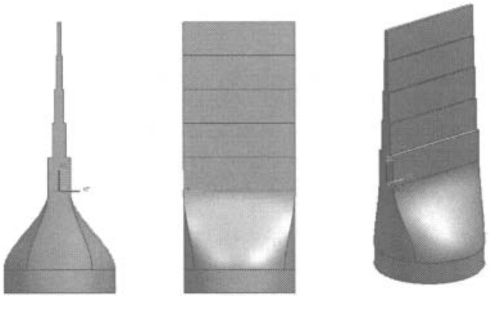

Figure 1. 3-D model of 5-step casting with the round-shape gating system. (A) XZ view; (B) YZ view; (C) isometric view.

Die Assembly

The integrated system included a laboratory hydraulic press, upper-lower die, an electric resistance furnace and a data acquisition system. As Figure 2(a) shows, the mold assembly was composed of three parts. The two upper die of casting cavity split along the center. The bottom sleeve has a diameter of 0.1016 m and a height of 0.127 m. The chill vent was located on the top of the step casting, which can discharge the gas inside the upper die cavity. Both the upper die and the bottom sleeve were heated by cartridge heaters, in which the temperatures were separately controlled by Shinko Temperature Controllers.

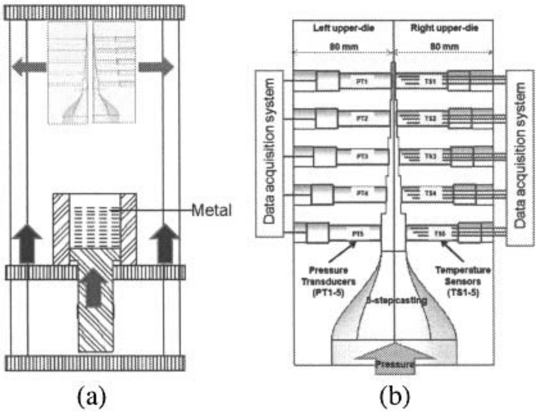

Figure 2. Schematic diagram of (a) squeeze casting machine and (b) upper-die configuration.

To measure the temperatures and pressures at the casting-die interface accurately and effectively in the 5-step squeeze casting, a special thermocouple holder was designed and developed to enable the proper placement of the thermocouples in the upper die. The thermocouple holder was manufactured using the same material as the die to ensure that the heat transfer process would not be distorted. Figure 2 illustrates schematically the configuration of the upper die (left and right parts) mounted on the top ceiling of the press machine. It also included the installation of pressure transducers, thermocouple holders and thermocouples. Local pressures within the die cavity were measured using Kistler pressure transducers 6175A2 with operating temperature 850^{0}C and pressures up to 200MPa.

As Figure 2 shows, the pressure transducers and temperature thermocouples were located opposite each other so that measurements from each sensor could be directly correlated. Five pressure transducers and temperature measuring unit were designated as PT1 through PT5, TS1 through TS5, respectively. Each sensor unit was adjusted into the die until the front wall of the sensor approached the cavity surface. The geometry shape of the temperature measuring unit was purposely designed to be the same as the pressure transducer, so that they could be exchangeable at different positions.

Casting Process

The 75- ton heavy duty hydraulic press made by Technical Machine Products (TMP, Cleveland, Ohio, USA) used in the experimental study. The die material was P20 steel. Commercial magnesium alloy AM60 was used in the experiment. The chemical composition of AM60 is shown in Table I. Table II gives the thermal properties of the related materials in this study.

Table I. Chemical composition of magnesium alloy AM60.

Mg	Al(%)	Mn(%)	Si(%)	Cu(%)	Zn(%)
balance	5.5-6.5	0.13	0.5	0.35	0.22

Table II. Thermophysical properties of magnesium alloy AM60.

Properties	Mg Alloy AM60	
	Solid	Liquid
Thermal Conductivity (W/m K)	62	90
Specific Heat (J/kg K)	1020	1180
Density (kg/m^3)	1790	1730
Latent Heat (KJ/kg)	373	
Liquidus Temperature at 0 MPa (^{0}C)	615	
Solidus Temperature at 0 MPa (^{0}C)		540

Before the pouring, the dies were pre-heated to 275^{0}C using four heating cartridges installed inside the dies. The experimental procedure included pouring molten magnesium alloy AM60 into the bottom sleeve with a pouring temperature 720^{0}C, closing the dies, cavity filling, squeezing solidification with applied pressure, lowering the sleeve die, splitting the two parts of the upper die, and finally the 5-step casting was shaken out from the cavity. The temperatures inside the die and casting were measured by Omega KTSS-116U thermocouples with response time below 10 ms, which could be applied in the squeeze casting process properly. Real-time in-cavity local pressures and temperature data were recorded by a LabVIEW- based data acquisition system. Figure 3 shows a typical 5-step casting poured under above mentioned process condition with applied hydraulic pressure of 30 MPa.

Figure 3. A 5-step casting solidifying under applied pressure 30 MPa.

Determination of IHTC

Based on the principle of heat transfer, the interfacial heat transfer coefficients (IHTC) between metal and die surface can be determined by Equation 1:

$$h(t) = \frac{q(t)}{T_{cs} - T_{ds}} \tag{1}$$

where h is IHTC; q is heat flux at the metal-die interface; T_{cs} and T_{ds} are the casting surface temperature and die surface temperature, respectively; and t is the solidification time. With the known boundary conditions in the form of temperatures or the heat fluxes, the temperature field inside the die or casting can be obtained by the direct heat conduction method.

But, it is almost impossible to measure T_{cs} and T_{ds} because the insertion of thermocouples of finite mass at the interface may distort the temperature field at the interface. Further, the heat flow at the interface may not be unidirectional due to the complex geometry. Therefore, determination of IHTC using measurements of T_{cs}, T_{ds}, and $q(t)$ directly is difficult. As a result, a polynomial curve fitting method needs to be employed to determine the IHTC based on the temperatures measured inside the die or casting [10,12,15]. The direct heat transfer modeling also was involved to calculate heat flux at the casting-die interface, which requires numerical or analytical methods to be solved.

From the measured interior temperature histories, the transient metal-die interface heat flux and temperature distribution were estimated by the polynomial extrapolation method, coupled with the finite difference method (FDM).

Because solidification of magnesium alloy AM60 during squeeze casting involves phase change and its thermal properties are temperature-dependent, the inverse heat conduction is a non-linear problem. To evaluate the IHTC effectively as a function of solidification time in the squeeze casting process, the finite difference method (FDM) was employed as follows based on the heat transfer equations [16].

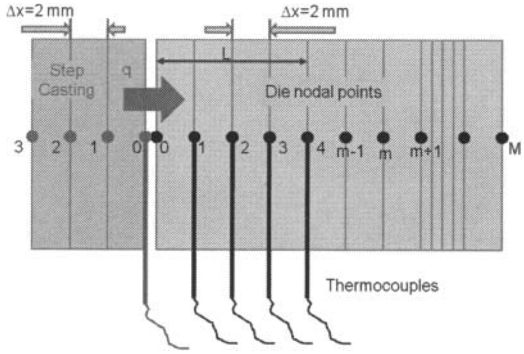

Figure 4. One-dimensional heat transfer at the interface between the casting and die, where temperature measurements were performed.

Since the thickness of each step is much smaller than the width or length of the step, it can be assumed that the heat transfer at each step is one-dimensional. The heat transfer across the nodal points of the step casting and die is shown in Figure 4. The temperatures were measured at 2, 4, 6, 8 mm beneath die surface and the heat flux transferred to the die mould can be evaluated by heat transfer equations.

Heat Transfer Model

The heat transfer inside the die at each step is transient conduction through one-dimensional body which can be described by Equation 2:

$$\rho c \frac{\partial T(x,t)}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T(x,t)}{\partial x} \right) \tag{2}$$

where ρ is density of conducting die, T is the temperature, t is the time and x is the distance from the die surface to the node point; c, k are specific heat capacity and thermal conductivity of the die.

The initial and boundary conditions are described by the following equations 3 to 5:

$$T(x,0) = T_i(x) \tag{3}$$

$$q(0,t) = -k(T)\left.\frac{\partial T}{\partial x}\right|_{x=0} \tag{4}$$

$$T(L,t) = Y(L,t) \tag{5}$$

Where T_i is the initial temperature of the die; q is the heat flux at the casting-die interface; L is the distance from the last temperature measurement point to the die surface; Y is the measured temperature at distance L from die surface.

The heat flux for both the casting and die interface can be calculated from the temperature gradient at the surface and sub-surface nodes by Equation 6:

$$q(t) = -k\frac{dT}{dx} = -k\frac{T_m^t - T_{m-1}^t}{\Delta x} \tag{6}$$

where k is thermal conductivity of the casting or die materials. The superscript t is solidification time. The subscript m means the number of the discrete nodal points. With the heat flux value, the segregated IHTC value can be evaluated from Equation 1.

For the surface node of the die, Equation 2 can be rearranged as Equation 7a:

$$(1+2F_0)T_0^{p+1} - 2F_0T_1^{p+1} = 2F_0\frac{\Delta x}{k}q_0 + T_0^p \tag{7a}$$

For any interior node of the die, equation 3 can be solved as Equation 7b:

$$(1+2F_0)T_m^{p+1} - F_0(T_{m-1}^{p+1} + T_{m+1}^{p+1}) = T_m^p \tag{7b}$$

where the superscript p is used to denote the time dependence of T. F_0 is a finite different form of the Fourier number:

$$F_0 = \frac{a\,\Delta t}{(\Delta x)^2} = \frac{k}{c\rho}\frac{\Delta t}{(\Delta x)^2} \tag{7c}$$

The heat flux at the casting-die interface (q) at each time step was obtained by applying Equation 7a and 7b. Thus, with T_{ds} estimated by the polynomial curve fitting method, the IHTC values were evaluated by Equation 1.

Polynomial Curve Fitting Method

For example, beneath the step 4 die surface, as Figure 4 showed, thermocouples were positioned at X1 = 2mm, X2 = 4mm, X3 = 6mm, and X4 = 8mm away from the die surface. From the temperature versus time curves obtained at each position inside the die, the temperature at the die surface (X0 = 0mm) can be extrapolated by using a polynomial curve fitting.

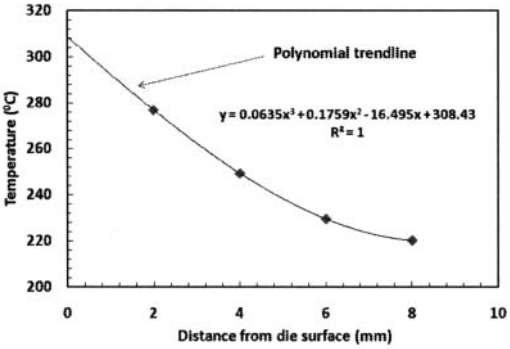

Figure 5. Polynomial curve with various measured temperatures at a time of 4.1 seconds after pressurized solidification.

By selecting a particular time of solidification process, for example *t = 4.1 seconds*, the values of temperatures were read from the temperature-time data at position X1, X2, X3, and X4. Figure 5 shows the temperature values against distance X which were fitted by the polynomial trendline. The temperature at the die surface (*T0=308.43* ^0C) was determined by substituting the value of x=0 in the polynomial curve fitting Equation 6 obtained from the temperature values at various distances inside the die at a chosen time of 4.1 seconds after pressurized solidification.

$$y = 0.0635\, x^3 + 0.1759\, x^2 - 16.495\, x + 308.43 \qquad (6)$$

This procedure was repeated for a number of time increments to get series of such temperatures with corresponding times. As Figure 6 shows, for the step 4 under pressure 30 MPa, the temperature curve versus time at the die surface(X0 = 0mm) was extrapolated as "Die-surf-T0-0mm-polynomial" based on the experimental data T1(X1=2mm), T2(X2=4mm), T3(X3=6mm), and T4(X4=8mm) beneath the die surface. By extrapolation, the evaluated peak temperature value of the die surface is 333.39^{0}C at the solidification time *t=6.1* seconds.

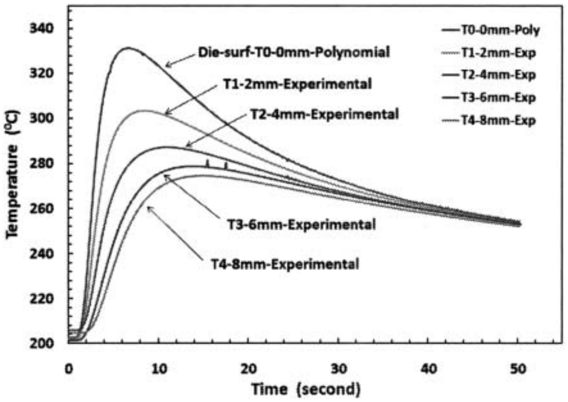

Figure 6. Extrapolated temperature curve at the die surface (T0) by the polynomial curve fitting method with applied pressure 30 MPa.

Results and Discussion

Experimental Cooling Curve

Figure 6 and 7 show typical temperatures versus time curves at the metal-die interface of Step 4 for solidifying magnesium alloy AM60 and the steel die respectively with an applied hydraulic pressure of 30 MPa. The measured locations are described in Figure 4, which include casting surface temperature (Metal-surface-Experimental), T1, T2, T3, and T4 inside the die. Since molten metal filled the cavity from the bottom, pre-solidification occurred upon the completion of cavity filling. No die surface temperatures exceeded 350^{0}C, and metal surface temperature (532.97^{0}C) was also lower than the liquidus temperature of the melt. From Figure 7, it can be observed that the temperature curve at casting surface increases abruptly and drops faster than the temperature measurements obtained at different depths under the die surface. The curves indicated the dynamic temperature change at the metal-die interface.

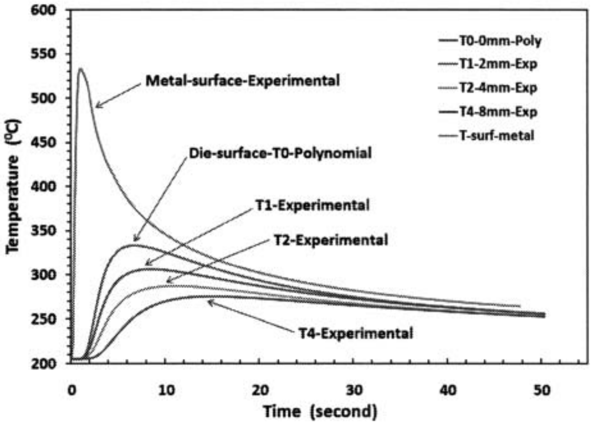

Figure 7. Typical temperature versus time curves (Step 4, 30 MPa) at metal surface, die surface, and various positions inside the die.

Typical Heat flux(q) & IHTC(h) Curves

Substituting the estimated die surface temperature (*T0*) and the measured temperature at T1=2 mm to Equation 2, the interfacial heat flux (*q*) was calculated. Figure 8 shows the interfacial heat flux (*q*) and the heat transfer coefficient (IHTC) versus solidification time of step 4 with applied pressure 30 MPa. The curves were estimated by extrapolated fitting method based on the data in Figure 7. For step 4, the peak heat flux value was 3.4E+05 W/m^2, and the peak value of IHTC was 6,450 W/ m^{2}K. From Figure 8, it can be observed that the heat flux (q) curve reached its peak value abruptly within 2.3 seconds and decreased rapidly to a lower level (5.0E+04 W/m^2) after 20 seconds. While the heat transfer coefficient (h) curve reached its peak value gradually at 12.3 seconds and vibrated around that peak value for about 6.5 seconds, then decreased slowly to the level 3,000 W/ m^{2}K after 28 seconds. Notably, the uncertainty and error of the polynomial extrapolated method should be responsible for the significant variation presented in the heat flux & IHTC curve in Figure 8.

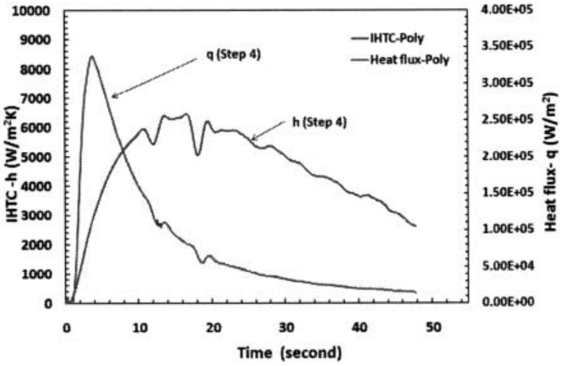

Figure 8. Interfacial heat flux (q) and the heat transfer coefficient (IHTC) curves for step 4 with applied pressure 30 MPa.

Figure 9 shows the heat flux (q) versus solidification time of step 3, step 4, and step 5 with an applied pressure of 30 MPa. The curves were estimated by extrapolation of the experimental data. For steps 3, 4, and 5, the peak heat flux values were 1.8E+05 W/m^2, 3.4E+05 W/m^2, 5.25E+05 W/m^2, respectively. From step 3 to step 5, the heat flux (q) curves reached to their peak value abruptly between 2.4, to 3.8 second and decreased rapidly to the lower level (5.0E+04 W/m^2) at 16, 28, and 42 seconds, respectively.

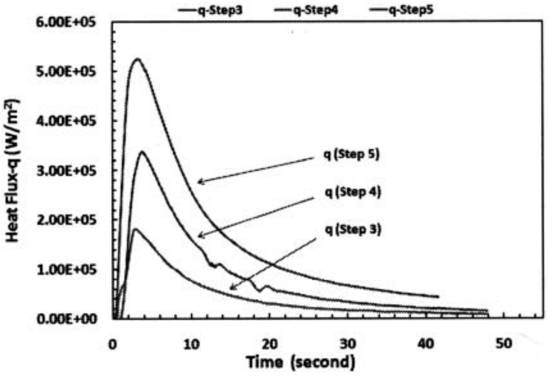

Figure 9. Heat flux (q) curves for step 3,4,5 estimated by the extrapolated fitting method.

Figure 10 shows that the heat transfer coefficient (IHTC) curves of steps 3,4,5 estimated by the extrapolated fitting. For step 3, IHTC began increasing, and reached its peak value of 3,200 W/ m^{2}K at 12.5 seconds, maintained that value for about 6 seconds, then decreased slowly to the level 1,600 W/ m^{2}K at 48 seconds. For step 4, IHTC value increased and reached its peak value (6,450 W/ m^{2}K) at about 12.3 seconds, remained at that value for about 6.5 seconds, then decreased slowly to the level 3,000 W/ m^{2}K at 48 seconds. For step 5, IHTC curve increased sharply to the peak value of 7,850 W/ m^{2}K at 8.2 seconds and then decreased to the lower level 5,500 W/ m^{2}K at 20.5 seconds. Finally IHTC increased again to high value. The up swinging tail of the IHTC curve for step 5 may be attributed to the stability of data collection, which needs to be further verified.

From steps 3 to 5, the peak IHTC value varied from 3,200 W/m^{2}K to 7,850 W/m^{2}K. Therefore, the wall thickness affects IHTC peak values significantly. The peak IHTC value decreased from the bottom to the top of the step casting as the step thickness reduced.

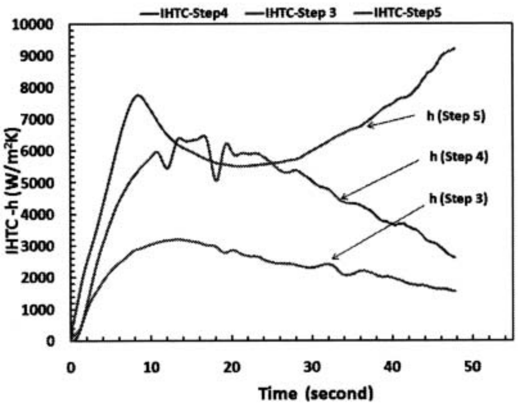

Figure 10. Heat transfer coefficient (IHTC) curves for step 3,4,5 estimated by the extrapolated fitting method.

Conclusions

1. The heat flux and IHTC at metal-die interface in squeeze casting were determined based on an extrapolation method.
2. For all steps, IHTC increased first, and reached its peak value, then dropped gradually until it arrived at a low value.
3. For steps 3, 4, and 5, the peak heat flux values were 1.8E+05 W/m^2, 3.4E+05 W/m^2, 5.25E+05 W/m^2, respectively.
4. For step 3, with a section thickness of 8mm, IHTC began with a increasing stage, and reached its peak value of 3,200 W/ m^{2}K at 12.5 seconds, maintained that value for about 6 seconds, then decreased slowly to the level 1,600 W/m^{2}K at 48 seconds. For step 4 of the thickness 12mm, IHTC value increased and reached its peak value (6,450 W/m^{2}K) at about 12.3 seconds, remained at that value for about 6.5 seconds, then decreased slowly to the level 3,000 W/m^{2}K at 48 seconds. From step 3 to 5, the peak IHTC value varied from 3,200 W/m^{2}K to 7,850 W/m^{2}K.
5. The wall thickness of squeeze cast magnesium alloy AM60 affected IHTC peak values significantly. The peak IHTC value decreased in a direction from the bottom to top as the step thickness reduced.

Acknowledgements

The authors would like to thank the Natural Sciences and Engineering Research Council of Canada, and University of Windsor for supporting this work.

References

1. I. Cho, C. Hong, "Evaluation of heat-transfer coefficients at the casting/die interface in squeeze casting", Int. J. Cast Metals Res, 1996, Vol.9, 227-232.

2. J. Aweda, M. Adeyemi, "Experimental determination of heat transfer coefficients during squeeze casting of aluminum", J. of Materials and Processing Technology, 2009, vol.209, 1477-1483.

3. Z. Guo, S. Xiong, B. Liu, M. Li, J. Allison, "Effect of Process Parameters, Casting Thickness, and Alloys on the Interfacial Heat-transfer Coefficient in the High-pressure Die Casting Process", Metallurgical and Materials Transactions, Vol.39A, 2008, 2896-2905.

4. M. Trovant, S. Argyropoulos, "Finding boundary conditions: A coupling strategy for the modeling of metal casting processes: Part I. Experimental study and correlation development", Metallurgical and Materials Transactions B, Vol.31B, 2000, 75-86.

5. Alfred Yu, "Mathematical Modeling and experimental study of squeeze casting of magnesium alloy AM50A and aluminum alloy A356", Ph.D. dissertation, Department of Mechanical, Automotive & Materials Engineering, University of Windsor, 2007.

6. D. Browne, D. O'Mahoney, "Interface heat transfer in investment casting of aluminum", Metall. Mater. Trans. A, 32A, 2001, 3055-3063.

7. G. Dour, M. Dargusch, C. Davidson, and A. Nef, "Development of a non-intrusive heat transfer coefficient gauge and its application to high pressure die casting", J. of Materials and Processing Technology, 2005, vol.169, 223-233.

8. A. Hamasaiid, M. Dargusch, C. Davidson, S. Tovar, T. Loulou, F. Rezai-aria, and G. Dour, "Effect of mold coating materials and thickness on heat transfer in permanent mold casting of aluminum alloys", Metallurgical and Materials Transactions A, Vol.38A, 2007, 1303-1316.

9. M. Dargusch, A. Hamasaiid, G. Dour, T. Loulou, C. Davidson, and D. StJohn, "The accurate determination of heat transfer coefficient and its evolution with time during high pressure die casting of Al-9%si-3%Cu and Mg-9%Al-1%Zn alloys", Advanced Engineering Materials, 2007, Vol.9, No.11, 995-999.

10. J. Taler, W. Zima, "Solution of inverse heat conduction problems using control volume approach", Int. J. Heat Mass Transf., 1999, Vol.42, 1123-1140.

11. R. Rajaraman, R. Velraj, "Comparison of interfacial heat transfer coefficient estimated by two different techniques during solidification of cylindrical aluminum alloy casting", Heat Mass Transfer, 2008, Vol.44, 1025-1034.

12. J. Su, F. Geoffrey, "Inverse heat conduction problem of estimating time varing heat transfer coefficients", Numer Heat Transf Part A, 2004, Vol.45, 777-789.

13. D. Sui, Z. Cui, "Regularized determination of interfacial heat transfer coefficient during ZL102 solidification process", Transactions of Nonferrous Metals Society of China, 2008, Vol.18, 399-404.

14. S. Broucaret, A. Michrafy, G. Dour, "Heat transfer and thermo-mechanical stresses in a gravity casting die influence of process parameters", J. of Materials Processing Technology, 2001, vol.110, 211-217.

15. J. Beck, "Nonlinear estimation applied to the nonlinear inverse heat conduction problem", Int. J. Heat Mass Transfer, 1970, Vol.13, 703-715.

16. J. Beck, B. Blackwell, A. Haji-sheikh, "Comparison of some inverse heat conduction methods using experimental data", Int. J. Heat Mass Transfer, 1996, Vol.39, 3649-3657.