

EFFECTS OF SQUEEZE CASTING PARAMETERS ON TEMPERATURE DISTRIBUTION DURING CASTING OF ALUMINIUM

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ABSTRACT

The effects of squeeze casting parameters, such as delay time and retention time of applied pressure and die pre-heating, on temperature distribution during casting of aluminium were investigated. Increased applied pressure and die pre-heating produced higher peak solidifying temperatures during squeeze casting of molten aluminium. Longer pressure retention time and shorter delay time gave higher peak solidifying temperature and product of excellent cast properties. The correlation between experimental measurements and computed numerical values of applied pressure, die heating temperature, delay times and retention times was very good.

1. INTRODUCTION

Solidification of metal castings is dependent on rate of heat abstraction from the metal to the mould and ambient; and is controlled by the mode of heat extraction from the casting metal/mould interface. The thermal behaviour of the interface is characterized by interfacial heat transfer coefficient that varies with time and location of the interface.

For simulation of casting temperature, heat flow pattern in the cast metal is required. Experimental measurements of temperature distribution at discrete locations with time are prone with errors. Therefore, numerical methods become more appropriate [1], where the heat transfer equations for cast metal, mould and interfaces, coupled with boundary and initial conditions are solved by Finite Difference Method (FDM).

Solidification of molten aluminium (Al) in steel mould is a complex process [2], since the 3 modes of heat transfer (conduction, convection and radiation) are involved, while the solidifying metal undergoes phase changes. The final structure and properties of the cast product depend on the casting parameters of applied pressures, period of pressure application and die pre-heating [3, 4].

Prediction of temperature distribution and solidification rate in metal casting is very important in foundry operations, especially for the control of defects, microstructure, mechanical properties and interfacial debonding of cast metal from the mould.

The effects of casting parameters on squeeze casting of commercially pure Al investigated are presented in this paper. In particu-

lar, the effect of plastic flow stress of imposed pressure on the cast was studied. Initial temperature distribution in both the cast metal and steel mould were used to predict the temperature distribution in the solidifying metal. The simulated temperatures were compared with the experimental values.

2. SQUEEZE CASTING PROCESS

Squeeze casting is a process in which molten metal is metered into a permanent mould cavity, and pressure applied through an upper punch on the solidifying molten metal to produce product of dimensional consistency and high integrity. The process consists of filling the mould with the liquid molten metal, followed by cooling until solidified. Controlling the two processes is critical for obtaining products of the required geometry and mechanical properties.

2.1. Physical domain

A one-dimensional heat transfer problem of squeeze casting of Al in a cylindrical steel mould is illustrated in Fig. 1. The problem involved a moving boundary of solidifying metal and by symmetry, only half of the geometry was analysed. In Fig. 1, solidification was assumed to start from steel mould/liquid molten metal interface, $i = G$, and progressed inwards into the liquid molten metal, $i = N$.

2.2. Metallurgical process

Sand casting cools slowly, due to insulating properties of the sand mould, but squeeze casting solidifies quickly because of contact

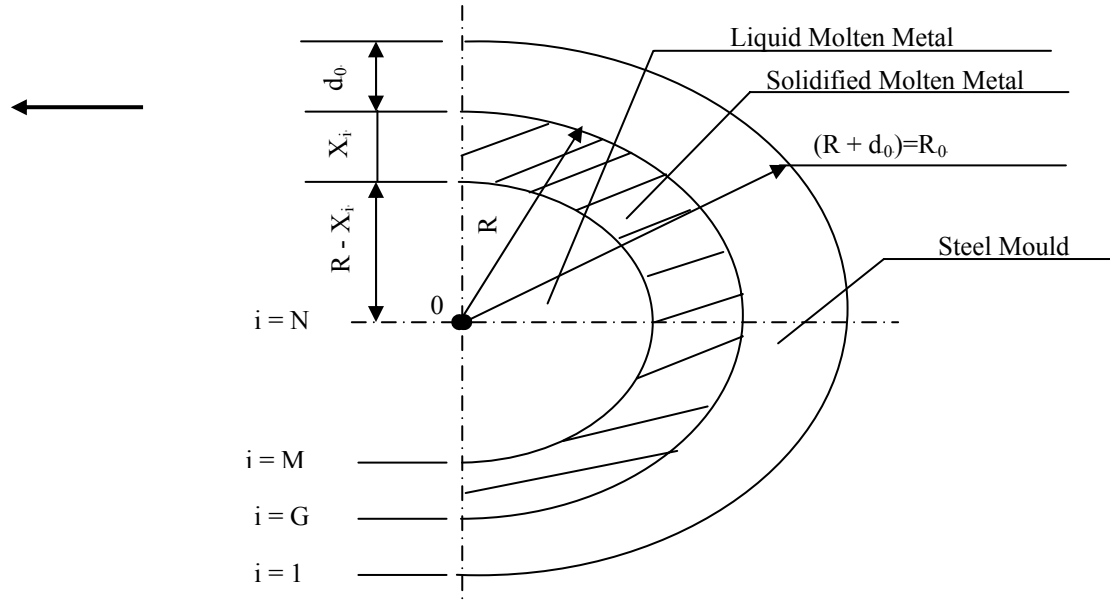


Fig. 1. Schematic representation of solidification front in one dimension (radial direction)

of molten metal with the metal mould [5].

Heat is rapidly dissipated to the steel mould in contact with the molten metal, which is convected out of the surface of steel mould (Fig. 1). The rate at which molten metal solidifies affects the grain size, since the grain size of squeeze cast specimen is smaller as compared with that of sand casting.

3. MODELLING SQUEEZE CASTING (Without Applied Pressure)

3.1. Assumptions

Heat transfer in molten Al cast zone was by both conduction and convection, but heat transfer in the steel mould was by conduction, while in the outer surfaces, the heat transfer was by convection. The differential heat transfer equations were solved numerically by explicit FDM and simulated to monitor the solidification front and temperature distribution.

The height of the cast specimen was assumed to be much smaller than the diameter, for one dimensional heat transfer. The solidification process was assumed symmetrical and only one half of the specimen's thickness was analysed. The base of the casting rig was lagged and heat losses were neglected. The density of molten and solidified Al was assumed to be same and independent of temperature. Thermal conductivity and specific heat of cast Al were considered to be dependent on the solidifying temperatures.

3.2. Heat transfer equations

The governing heat transfer equations were based on 1-D conduction and convection. The principle of energy balance and phase changes were considered in formulating the heat transfer equation and appropriate boundary conditions. The steel mould, solidified molten Al and liquid molten Al portions were discretized separately to establish the rate of change of temperature with time.

For cylindrical steel mould in region

$R \leq r_{st} \leq (R + d_0)$ of Fig. 1,

$$\rho_{st} C_{st} \frac{\partial T_{st}}{\partial t} = K_{st} \left[\frac{\partial^2 T_{st}}{\partial r^2} + \frac{1}{r_{st}} \frac{\partial T_{st}}{\partial r} \right] \quad (1)$$

where ρ_{st} is density, T_{st} is temperature, C_{st} is specific heat, and K_{st} is thermal conductivity of steel mould material.

In the solidified molten Al region

$(R - X_r^j) \leq r_s \leq R$,

$$\rho_s C_s \frac{\partial T_s}{\partial t} = K_s \left[\frac{\partial^2 T_s}{\partial r^2} + \frac{1}{r_s} \frac{\partial T_s}{\partial r} \right] \quad (2)$$

ρ_s is density, T_s is temperature, C_s is specific heat, and K_s is thermal conductivity of solid Al, with boundary condition $T_s = T_{mm} = 660^\circ\text{C}$, where T_{mm} is the melting temperature.

In the liquid molten Al region

$0 \leq r_L \leq (R - X_r^j)$,

$$\rho_L C_L \frac{\partial T_L}{\partial t} = K_L \left[\frac{\partial^2 T_L}{\partial r^2} + \frac{1}{r_L} \frac{\partial T_L}{\partial r} \right] \quad (3)$$

where ρ_L is density, T_L is temperature, C_L is specific heat, K_s is thermal conductivity of molten Al, with boundary conditions,

$$K_s \frac{\partial T_s}{\partial r} = 0; r = 0; T_L = 720^\circ \text{C}$$

At the phase-change boundary,

$$r = R - X_r^j, \text{ and}$$

$$\rho_L L_f \frac{dX_r^j}{dt} = K_L \frac{\partial T_L}{\partial r} - K_s \frac{\partial T_s}{\partial r} \quad (4)$$

where L_f is latent heat of fusion of liquid molten Al.

3.2. Energy balance equations

The energy balance equation was derived from the amount of heat lost by solidifying molten Al and amount of heat gained by steel mould at the interfaces.

For steel mould-atmosphere interface ($i = 1$);

$$\frac{\partial T_{st}}{\partial t} = \frac{2K_{st}}{\rho_{st} C_{st} d_{st}} \frac{\partial T_{st}}{\partial r} - \frac{2H^*}{\rho_{st} C_{st} d_{st}} (T_i^j - T_\infty) \quad (5)$$

In the solidified molten Al-steel mould interface ($i = G$);

$$K_s \frac{\partial T_s}{\partial r} + \frac{1}{2} \rho_s C_s d_s \frac{\partial T_s}{\partial t} = K_{st} \frac{\partial T_{st}}{\partial r} + \frac{1}{2} \rho_{st} C_{st} d_{st} \frac{\partial T_{st}}{\partial t} \quad (6)$$

In the liquid molten Al-solidified molten Al interface ($i = M$);

$$K_L \frac{\partial T_L}{\partial r} - \frac{1}{2} \rho_L C_L d_L \frac{\partial T_L}{\partial t} = K_s \frac{\partial T_s}{\partial r} + \frac{1}{2} \rho_s C_s d_s \frac{\partial T_s}{\partial t} \quad (7)$$

3.3. First time analysis and completion of solidification, $i = G$ to N

The situation when the steel mould was filled with quantity of molten Al and just before the pressure was applied was represented by;

$$\rho_L C_L \frac{dT_L}{dt} = K_L \left[\frac{\partial^2 T_L}{\partial r^2} + \frac{1}{r_{FL}} \frac{\partial T_L}{\partial r} \right] \quad (8)$$

while at completion of solidification (entire cast Al solidified), was expressed by,

$$\rho_s C_s \frac{\partial T_s}{\partial t} = K_s \left[\frac{\partial^2 T_s}{\partial r^2} + \frac{1}{r_{CS}} \frac{\partial T_s}{\partial r} \right] \quad (9)$$

3.4. Discretization

The stability criteria were such that the coefficients of T_i^{j+1} did not contribute negatively to the finite difference equations.

3.4.1. Heat transfer equations

The steel mould and cast Al regions (Fig. 1) were discretized using Crank-Nicolson method of finite difference to solve the partial

differential heat transfer equations developed for each region and interface.

In the steel mould, the finite difference representation (FDR) of eqn. (1) was,

$$T_i^{j+1} = \left[1 - \frac{2\delta\alpha_{st}}{d_{st}^2} - \frac{\delta\alpha_{st}}{r_{st}d_{st}} \right] T_{i-1}^j + \left[\frac{\delta\alpha_{st}}{d_{st}^2} + \frac{\delta\alpha_{st}}{r_{st}d_{st}} \right] T_{i+1}^j + \frac{\delta\alpha_{st}}{d_{st}^2} T_{i-1}^j \quad (10)$$

where $i = 1, 2, 3, \dots (G-1)$, δ is time interval, and α_{st} is thermal diffusivity of the steel.

In the solidified molten Al region, FDR of eqn. (2) was;

$$T_i^{j+1} = \left[1 - \frac{(I-G)}{(M-G)} \frac{(X_r^{j+1} - X_r^j)}{d_s} - \frac{2\delta\alpha_s}{d_s^2} - \frac{\delta\alpha_s}{r_s d_s} \right] T_i^j + \left[\frac{(I-G)}{(M-G)} \frac{(X_r^{j+1} - X_r^j)}{d_s} + \frac{\delta\alpha_s}{d_s^2} + \frac{\delta\alpha_s}{r_s d_s} \right] T_{i+1}^j + \frac{\delta\alpha_s}{d_s^2} T_{i-1}^j \quad (11)$$

where $r_s = R - \frac{X_r^j(I-G)}{(M-G)}$; $d_s = \frac{X_r^j}{(M-I)}$; $\alpha_s = \frac{K_s}{\rho_s C_s}$;

$i = G+1, G+2, G+3, \dots, (M-1)$, and α_s is thermal diffusivity of solid Al.

In liquid molten Al region, FDR of eqn. (3) was;

$$T_i^{j+1} = \left[1 - \frac{(I-M)}{(N-M)} \frac{(X_r^{j+1} - X_r^j)}{d_L} - \frac{2\delta\alpha_L}{d_L^2} - \frac{\delta\alpha_L}{r_L d_L} \right] T_i^j + \left[\frac{(I-M)}{(N-M)} \frac{(X_r^{j+1} - X_r^j)}{d_L} + \frac{\delta\alpha_L}{d_L^2} + \frac{\delta\alpha_L}{r_L d_L} \right] T_{i+1}^j + \frac{\delta\alpha_L}{d_L^2} T_{i-1}^j \quad (12)$$

where $r_L = (R - X_r^j) \frac{(I-M)}{(N-M)}$; $d_L = \frac{(R - X_r^j)}{(N-I)}$; $\alpha_L = \frac{K_L}{\rho_L C_L}$;

$i = M, M+1, M+2, M+3, \dots (N-1)$, and α_L is thermal diffusivity of molten Al.

At the phase change boundary, FDR of eqn. (4) was;

$$X_r^{j+1} = X_r^j - \left[\frac{\delta K_L}{\rho_L L_f h_{PL}} + \frac{\delta K_s}{\rho_L L_f h_{PS}} \right] T_i^j + \frac{\delta K_L}{\rho_L L_f h_{PL}} T_{i+1}^j + \frac{\delta K_s}{\rho_L L_f h_{PS}} T_{i-1}^j \quad (13)$$

where $h_{PL} = \frac{(R - X_r^j)}{(N - M)}$; and $h_{PS} = \frac{X_r^j}{(M - G)}$

3.4.2. Energy balance equation

For the steel mould-atmosphere interface ($i = 1$), the FDR of eqn. (5) was

$$T_i^{j+1} = \left[1 - \frac{2\delta K_{st}}{d_{st}^2 \rho_{st} C_{st}} \right] T_i^j + \frac{2\delta K_{st}}{d_{st}^2 \rho_{st} C_{st}} T_{i+1}^j - \frac{2\delta H^*}{d_{st} \rho_{st} C_{st}} (T_i^j - T_\infty^i) \quad (14)$$

In the solidified molten Al-steel mould interface (i = G), FDR of eqn. (6) was;

$$T_i^{j+1} = a \left[\frac{2\alpha_s}{d_s} + d_s \rho_s C_s + \rho_s C_s \frac{(I-G)}{(M-G)} (X_r^{j+1} - X_r^j) + \frac{2\alpha_{st}}{d_{st}} - d_{st} \rho_{st} C_{st} \right] T_i^j + a \left[\rho_s C_s \frac{(I-G)}{(M-G)} (X_r^{j+1} - X_r^j) - \frac{2\alpha_s}{d_s} \right] T_{i+1}^j - \frac{2a\alpha_{st}}{d_{st}} T_{i-1}^j \quad (15)$$

In the liquid molten Al-solidified molten Al interface, (i = M), FDR of eq. (7) was;

$$T_i^{j+1} = b \left[d_L \rho_L C_L - \rho_L C_L \frac{(I-M)}{(N-M)} (X_r^{j+1} - X_r^j) - \frac{2\alpha_L}{d_L} + d_s \rho_s C_s - \frac{2\alpha_s}{d_s} + \rho_s C_s \frac{(I-G)}{(M-G)} (X_r^{j+1} - X_r^j) \right] T_i^j + b \left[\frac{2\alpha_s}{d_s} - \rho_s C_s \frac{(I-G)}{(M-G)} (X_r^{j+1} - X_r^j) \right] T_{i+1}^j + b \left[\frac{2\alpha_L}{d_L} + \rho_L C_L \frac{(I-M)}{(N-M)} (X_r^{j+1} - X_r^j) \right] T_{i-1}^j \quad (16); \text{ where } b = 1/(d_s \rho_s C_s + d_L \rho_L C_L)$$

3.4.3. First time analysis and Completion of solidification

Finite difference representation of eqn. (8) was,

$$T_i^{j+1} = \left[1 - \frac{2\delta\alpha_L}{d_{FL}^2} - \frac{\delta\alpha_L}{r_{FL} d_{FL}} \right] T_i^j + \left[\frac{\delta\alpha_L}{d_{FL}^2} + \frac{\delta\alpha_L}{r_{FL} d_{FL}} \right] T_{i+1}^j + \frac{\delta\alpha_L}{d_{FL}^2} T_{i-1}^j \quad (17); \text{ where } r_{FL} = \frac{(N-I)}{(N-G)} R, d_{LF} = \frac{R}{(N-G)}$$

The FDR of eqn. (9) at completion of solidification was,

$$T_i^{j+1} = \left[1 - \frac{2\delta\alpha_s}{d_{cs}^2} - \frac{\delta\alpha_s}{r_{cs} d_{cs}} \right] T_i^j + \left[\frac{\delta\alpha_s}{d_{cs}^2} + \frac{\delta\alpha_s}{r_{cs} d_{cs}} \right] T_{i+1}^j + \frac{\delta\alpha_s}{d_{cs}^2} T_{i-1}^j \quad (18)$$

where $r_{cs} = \frac{(N-I)}{(N-G)} R, d_{cs} = \frac{R}{(N-G)}$; i = G+1, G+2, G+3, ..., (N-1).

4. SQUEEZE CASTING WITH APPLIED PRESSURE

The governing heat transfer equation for squeeze casting under applied pressure was developed for solidified molten Al as [6, 7],

$$\frac{\partial T_s}{\partial t} = \alpha_s \frac{\partial^2 T_s}{\partial r^2} + \frac{\alpha_s}{r_{cs}} \frac{\partial T_s}{\partial r} + \frac{\Delta q}{\rho_s C_s} \quad (19)$$

where Δq is internal energy generated upon pressure application.

Using upper bound theory, the internal energy generated by application of pressure on the cast metal was deduced by Aweda [8] as,

$$\Delta q = \left[2 \int_0^{R h_0} \int_h^{\sqrt{3 + \frac{r_o^4}{r^4}}} r_o dr dh + m V_o \int_h^{h_0} \left(1 - \frac{h_c}{h_0} \right) r_o dh \right] \frac{\pi \bar{\sigma}_T}{\sqrt{3}} + \frac{2m V_o}{h_c} \int_{R_0}^R (r_o^2 - r^2) dr \quad (20)$$

where h_0 is initial height of specimen, h_c is cast specimen height, σ_f is plastic flow stress, P_i is applied pressure, r is elemental radius, and T_M is die temperature. The FDR of eqn. (20) with the energy change converted to temperature change was,

$$T_i^{j+1} = \left[1 - \frac{2\delta\alpha_s}{d_{cs}^2} - \frac{\delta\alpha_s}{r_{cs} d_{cs}} \right] T_i^j + \left[\frac{\delta\alpha_s}{d_{cs}^2} + \frac{\delta\alpha_s}{r_{cs} d_{cs}} \right] T_{i+1}^j + \frac{\delta\alpha_s}{d_{cs}^2} T_{i-1}^j + \Delta T \quad (21)$$

where $\Delta T = \frac{\Delta q \beta}{J C_p V_o \rho_s C_s}$, β (= 90 %) is percentage

of deformation energy transformed into thermal energy, ρ is density of workpiece, C_s is specific heat of workpiece, J_h is mechanical equivalent of heat (4.2 kJ/cal), Δq is power dissipated due to pressure application, and V_o is volume of the workpiece.

5. COMPUTATIONAL METHODS

A dynamic program code was developed in Quick Basic ver. 45 to simulate numerical values of heating and solidifying temperatures of the steel mould and cast Al with time at positions i = G and i = M (Fig. 1).

At onset of solidification, a thin solidified layer was assumed to be forming at inner cylindrical surface of the mould (i = G), followed by another thin layer at inner surface of the formed solidified layer in the mould. The solidification continued and extended inwards into the core of cast Al until convergence criteria of 90 % solidification were achieved.

6. EXPERIMENTS

6.1 Molten and Mould temperature

Commercial grade Al (99.81 % purity) was melted in an electric furnace. A metered quantity of the molten Al was poured into a steel mould cavity at molten temperature of 720 °C. The temperatures were measured by chromel/alumel thermocouples with cold junctions

at 0 °C, and connected to a plotter, set at speed of 10 mm/s and voltage of 100 mV to obtain temperature-time curves. The mould was pre-heated using 3 electric heater rods (100 W each) that were connected to 240 Vac supply. The mould temperatures were controlled by bimetallic thermostat.

6.2. Casting with pressure and pre-heat

As the cast Al was solidifying, the mould pressurization was achieved using a 8.9×10^4 N Vega compression machine. Pressure was applied at the pre-heat temperatures, and at different delay and retention times.

7. RESULTS

7.1 Applied Pressure

Figure 2 shows temperature-time curves for solidifying molten Al in steel mould without applied pressure. The numerical computation and experimental values are indicated. The maximum temperature by computation was 709.5 °C, while the maximum from experimental measurement was 649.0 °C. The cast Al and steel mould temperatures decreased in similar trend with time.

Figure 3 shows the temperature-time curves of solidifying molten Al under applied pressure. At delay time of 20 s, retention time of 55 s, and pressure of 85.9 MPa, peak temperature of 720.0 °C was obtained by computation, and 690.0 °C by experimental measurement.

The temperatures attained before pressure application were 661.4 °C and 648.0 °C for numerical and experimental values, but increased under pressure application to maximum values of 673.0 °C and 640.0 °C after 20 s of pouring the molten metal into the mould for pressure retention time of 55 s.

7.2. Die Heating

Effect of die pre-heating on solidification temperature-time curves of Al is shown in Fig. 4. Under an applied pressure of 85.86 MPa, delay time of 20 s and pressure retention time of 55 s, the peak temperatures were higher with increased die temperatures. At die temperature of 150 °C, the maximum solidification temperature was 708.4 °C, compared to 682.0 °C for die temperature of 50.0 °C. With

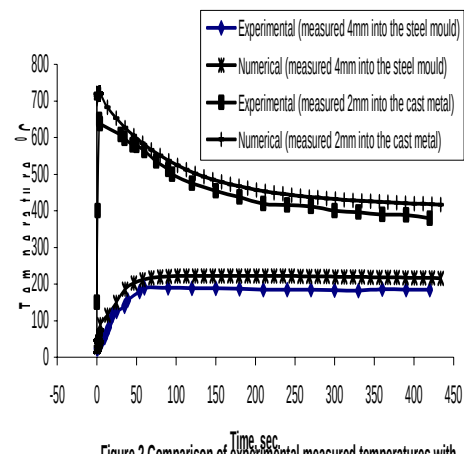


Figure 2 Comparison of experimental measured temperatures with numerical values of aluminium metal without pressure application and die heating ($P=0, T_w=30^\circ\text{C}$)

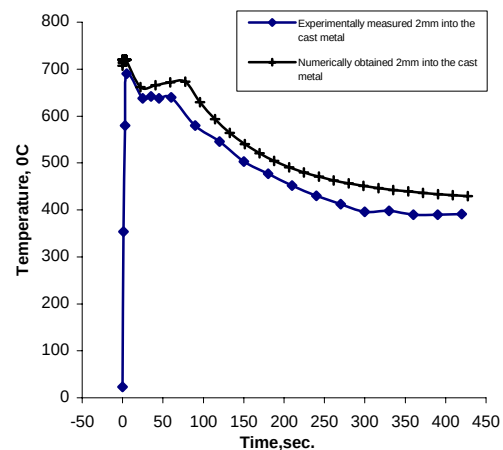


Fig. 3. Effect of applied pressure on solidification temperature of Al ($P=85.86\text{MPa}$) (delay time=20 s, retention time=55 s, $T_M=300^\circ\text{C}$)

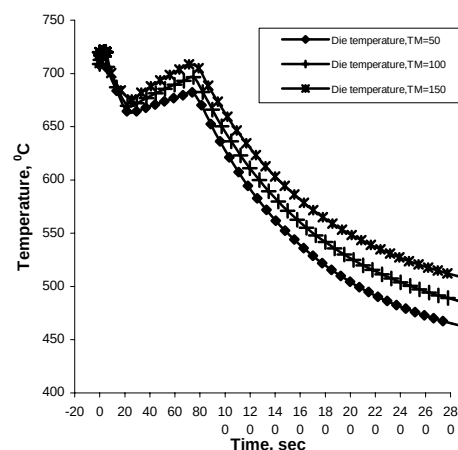


Fig. 4 Effect of die pre-heat temperatures on casting temperatures of Al obtained 2mm into the cast metal (Numerical method) $P = 85.86\text{MPa}$, delay time=20s., retention time=55 s)

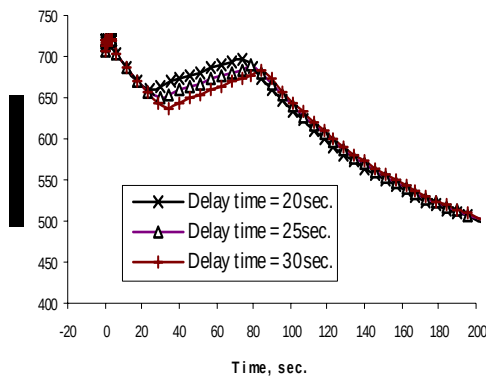


Fig. 5. Effects of delay times on solidification of Al, 2mm into the cast metal with die at room temperature and pressure application (Numerical method) ($T_w=30^\circ\text{C}$, $P=85.86\text{MPa}$)

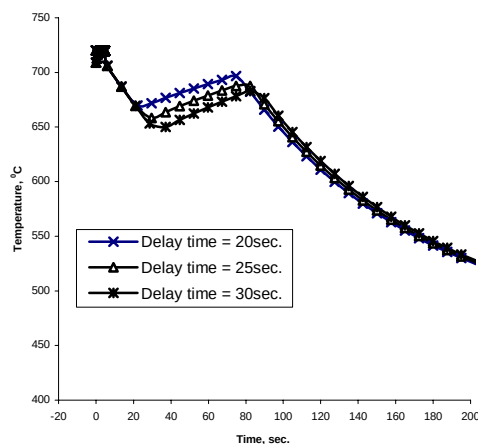


Figure 6 Effects of delay times on the solidification temperatures of aluminium metal with die heating (Numerical method) ($T_w=100^\circ\text{C}$, $P=85.86\text{MPa}$)

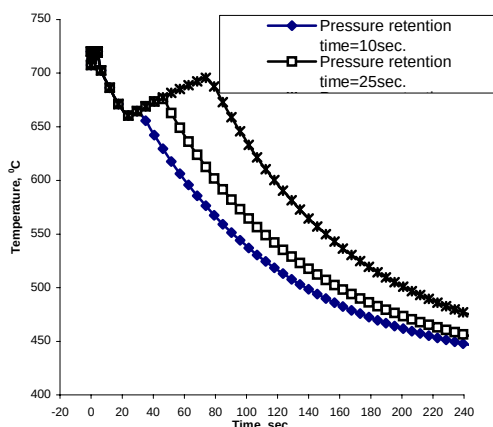


Figure 7 Effects of pressure retention times on the casting temperature of aluminium, obtained 2mm into the cast metal (Numerical method) ($P=85.86\text{MPa}$, delay time=20sec., $T_w=30^\circ\text{C}$)

higher die pre-heat temperatures, the peak of cast Al temperature was higher, leading to a decrease in solidification rate (Fig. 4).

7.3. Delay Times

Figures 5 and 6 show the effects of delay times (i.e. time before pressure application), on solidification temperatures-time curves of molten Al, for die heating and without die heating. With die heating, the solidification temperature of molten Al was higher than without die heating. Irrespective of the delay time, the effect of applied pressure became less significant after about 200 s of pouring molten Al (as solidification was completed).

7.4. Retention Times

Figure 7 shows the solidification temperature-time curves for different pressure retention times at a constant delay period of 20 s and applied pressure of 85.9 MPa. From the graph, retention time of 55 s produced maximum temperature of 695.5°C , as compared to 664.7°C when the retention time was 10 s.

8. DISCUSSION

With application of pressure, there was an increase in the maximum temperature, as confirmed by the findings of Kobryn and Semiatin [9] that high applied pressure led to high interface heat transfer. The increase in solidification temperature with pressure application was enhanced by good thermal contact at the casting/die interface. There was good agreement between numerical and experimental values of maxima temperatures.

An increase in die pre-heating temperature increased the peak temperature, which could be attributed to the relative low initial temperature difference between cast and die surface, a trend reported by Garfur et. al [10]. At higher die pre-heat temperature, the solidification time increased, as observed by Hu and Yu [11], that higher die pre-heat temperature resulted in extended total solidification time; and reduction would enhance the cooling rates to produce better cast products.

Increasing delay time of pressure application increased the maximum temperature with or without die heating, the solidification temperatures increased with pressure applicati-

on and decreased when the pressure was removed. The observation has been attributed to formation of a non-conforming solid skin at the interface, preventing direct contact between cast metal and die surface [12].

At imposed pressure retention times under a constant delay time of 20 s, the time to attain peak temperature increased with increasing retention time (Fig. 7). Prior to pressure application, the cast metal temperature decreased in all cases. Upon applying pressure, cast metal temperature was elevated, but decreased rapidly after removal of pressure on the solidifying metal for all retention times. The longer the retention time, the higher was the peak temperature leading to extended solidifying time, as confirmed by the findings of Cho and Hong [13], that longer period of pressure application led to longer solidifying time.

9. CONCLUSIONS

The effects of applied pressure, die heating, pressure retention and delay time on squeeze cast solid Al cylinders were investigated. Increasing the applied pressure resulted in higher peak solidifying temperature, which also increased with high die pre-heat temperature. Longer pressure retention times and shorter delay times led to higher peak solidifying temperatures for producing quality squeeze cast Al. Die pre-heat temperature of 150 °C enhanced the cooling rates by decreasing solidification period of the cast Al, thereby producing cast product of higher integrity. The predicted and experimental values of solidification and cooling temperatures were in close agreement.

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