IMPROVING THE ELECTRICAL PROPERTIES OF ALUMINIUM METAL THROUGH SQUEEZE CASTING PROCESS

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ABSTRACT

*Squeeze casting is a new permanent mould casting process that produces products with improved mechanical and electrical properties. The effects of squeeze casting processing conditions (applied pressure and die temperatures), on the heat transfer coefficients and electrical properties of squeeze casting of aluminium have been investigated. Interfacial heat transfer coefficients were determined experimentally from measured values of heating and cooling temperatures of steel mould and cast metal respectively. A computer programme was developed to compute the temperature distributions in both the cast metal and steel mould and heat transfer coefficients in squeeze casting of aluminium. The predicted results show that high applied pressures and low die temperatures result in a high heat transfer coefficients across the casting / steel mould interface, which leads to increase in solidification and cooling rates of the cast metal. The experimental obtained values were compared with the numerical values and found to show good agreement between the predicted results **and the experimental measured data.***

Keywords: pre-heat temperature, delay time, applied pressure and heat transfer coefficients

INTRODUCTION

Aluminium is the second most abundant metallic element in the Earth's crust after silicon. If high strength of the highest priority is required, aluminium alloy can be transformed to have structural strength as the steel, and even more stronger. Aluminium is a light metal and can be given great strength by alloying, heat treatment and in the process of casting thus improving its mechanical and electrical properties [1,2]. Squeeze casting is one of the processes to improve the mechanical and electrical properties of aluminium. Thickness ranges between 0.3mm to 50mm and weighing 0.125mg to

35kg have been produced through squeeze casting [3]. This process was first applied to aluminium alloy, but the procedure can be applied to other non-ferrous metals as well [4,5]. Squeeze casting is a comparatively new developed manufacturing method for producing commercial castings [4,6]. Squeeze casting is a process in which liquid molten metal is metered into the permanent mould cavity usually made of metal and pressure applied through the upper punch on the solidifying molten metal so as to produce good soundness and dimensionally accurate product (see figure 1). Squeeze casting consists of two stages, the first of which is mould filling in which the mould is filled with the required quantity of liquid molten metal; the second is cooling, which continues until the part has solidified. Controlling both stages is of major importance for obtaining sound parts with the required geometry and mechanical properties. The prediction of temperature distribution and solidification rate in metal casting is very important in modern foundry technologies. This helps to control defects, as well as, the influence on final properties of cast products and the mould wall / cast metal interface contact surface. The rate at which molten metal solidifies affects the grain size that forms [7,8]. A slow cooling rate that leads to a small degree of undercooling at the onset of solidification yields a large grain size. A rapidly cooling rate on the other hand leads to a high degree of undercooling, leading to the formation of small grains [9]. The grain size of squeeze cast specimen is small as compared to that of sand casting. Sand casting cools slowly, due to the insulating properties of the sand mould. Squeeze casting solidifies quickly because of the contact of the molten metal with the metal mould [7,10]. Heat is rapidly dissipated to the steel mould in contact with the molten metal, which is convected out at the outer surface of the steel mould.

Solidification of metal castings inside mould is dependent on the rate of heat abstraction from the cast metal to the mould. The pattern of heat flow across the cast metal and mould surfaces affects the evolution of solidification and determines the freezing conditions within the metal. The thermal behaviour of the interface is characterized by the interfacial heat transfer coefficient that varies with time and location of the interface.

This work evaluates the variation of the heat transfer coefficients with varying applied pressures and delay times (time between die closure and pressure application) on the heat transfer coefficients and electrical resistivity of squeeze cast aluminium.

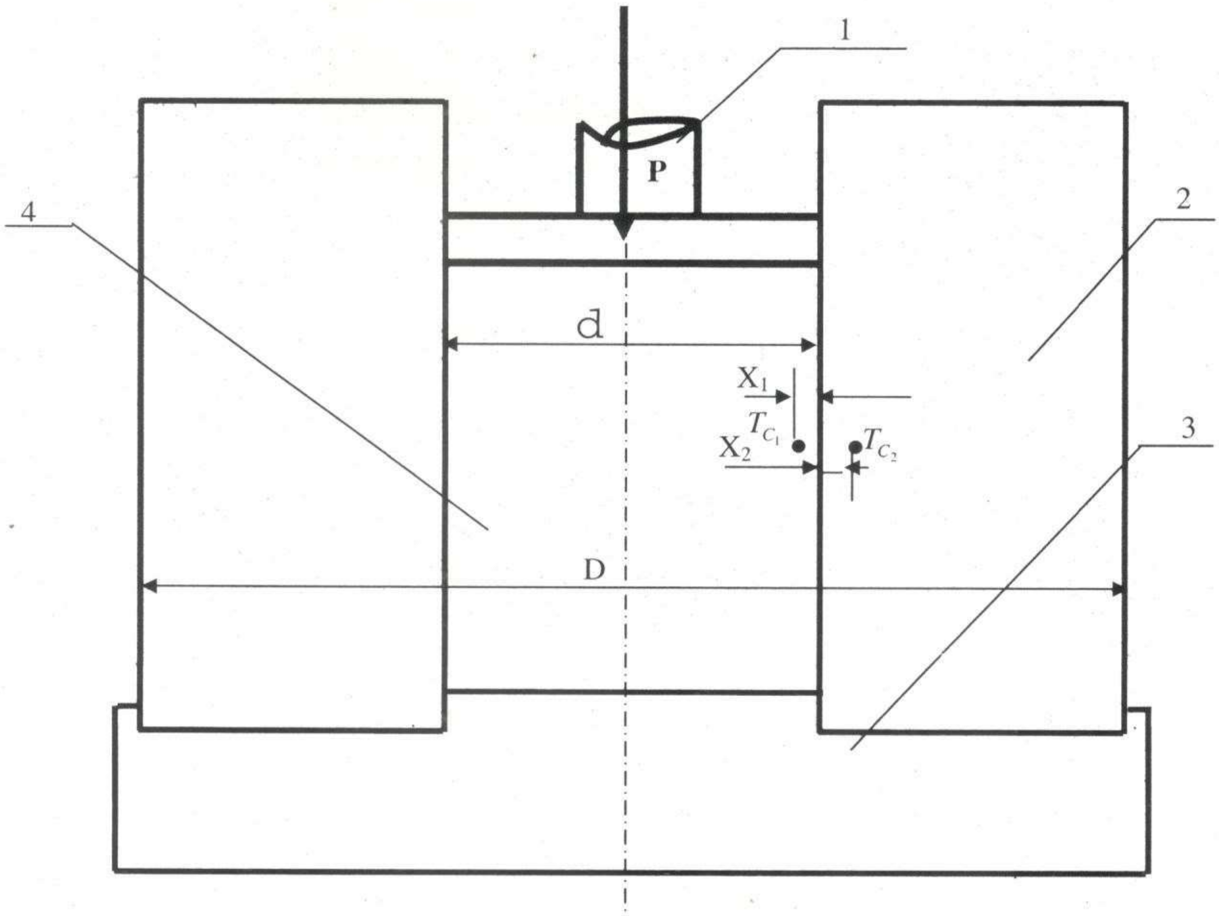

Figure 1 Schematic diagram of squeeze casting test rig
1-upper punch, 2-cylindrical steel mould, 3-die support, 4-die cavity (specimen), ($X_1 = 2$, $X_2 = 4$, (mm))

Experimental Method

The material used for the present investigation was commercially pure aluminium, of percentage composition of 99.8% of aluminium and traces of other elements (see table 1).

Table 1. Chemical composition of aluminium metal

Al	Cu	Si	Mn	S	P	Ni	Cr	Zn
99.847	0	0.06	0.03	0.002	0.03	0.001	0.00	0.03

Two chromel-alumel thermocouples were positioned to monitor both the cast metal temperature and the steel mould temperature during the solidification of molten aluminium metal in the steel mould. One thermocouple T_{C_2} was positioned on the side of the cylindrical steel mould, which monitored the heating temperature of the steel mould and the other T_{C_1}, in the cast aluminium metal that monitored the solidifying temperature of the cast aluminium metal as shown in figure 1. A metered quantity of molten metal was poured into the steel mould cavity at a temperature of about 720^{0}C (super heat of 60^{0}C). The punch was lowered to close the die and the Vega Compression Machine, model UTM 3C, serial No 1061 with a capacity of 89,000 N, was actuated to compress the solidifying molten metal. As cast metal solidifies in the mould, the solidification temperature of the cast metal and heating temperature of the steel mould were recorded with time on the chart recorder through the thermocouples positioned in the cast metal and the mould.

Varying magnitudes of loads were applied on the cast metal observing different delay and retention times.

Squeeze cast aluminium specimens were also produced with die pre-heating temperatures of 50^{0}C at temperature increments of 50^{0}C to 300^{0}C without pressure application on the solidifying aluminium metal. The die heating process was carried out, using three electric heater rods (100Watts each) that were connected to a.c supply. The required die temperatures were set and controlled, using a bimetallic thermostat attached to the steel mould. The purpose of the experimental method was to determine the electrical behaviour of aluminium metal during squeeze casting while varying the mould initial temperature. The solidifying temperature of the cast metal at the cylindrical surface was monitored at a position X_1=2mm (from the surface of the steel mould/cast aluminium metal interface) into the cast molten aluminium metal. The heating temperature of the steel mould was monitored X_2=4mm (from the cast metal/steel mould interface) into the mould. The terminals of the thermocouples were connected to the chart recorder/plotter (set at the highest speed of 10mm/s and voltage 100mV) passing through the cold junction apparatus, maintained at $0\ ^0C$ *throughout the* measuring period.

The following experiments were also determined:

(i) Determination of Interface Heat Transfer Coefficients

The inverse heat conduction problem based on non-linear estimation technique described by Beck and Browne and O'Mahoney [11,12] has been adopted to determine the values of interface heat transfer coefficients, as a function of time during solidification of squeeze casting. Solidification of squeeze casting of aluminium involves phase change and therefore thermal properties of aluminium are temperature dependent, making the inverse heat conduction problem non-linear. The governing heat transfer equation in one dimensional cylindrical coordinates holds with the boundary condition at the interface expressed as:

$$q = K_{al}(T)\frac{\partial T}{\partial r} = h_{al}(T)[T_C - T_M] \quad (1)$$

The thermal conductivity K_{al} [13,14] of aluminium is dependent upon casting temperature as expressed:

$$K_{al}(T) = 241.84 - 0.041T_C \quad (2)$$

(ii) Determinations of Electrical Properties

The electrical circuit diagram used for the measurement of voltage across the specimens as shown in figure 2 was used. The circuit consists mainly of a variable resistor, ammeter, voltmeter and energy source supply from the mains, see figure 2. The potential difference (voltage) across the specimen was read in millivolt by the digital voltmeter and the corresponding reading of the current taken in ampere. Repeated readings of voltage were taken for each selected current and average values of voltage and current were used for the determinations of electrical resistivity, using equation (3a) and equation (3b) used when direct measurement of resistance was taken.

$$\rho_e = \frac{VA}{IL} \quad (3a)$$

$$\rho_e = \frac{A}{L}R_e \quad (3b)$$

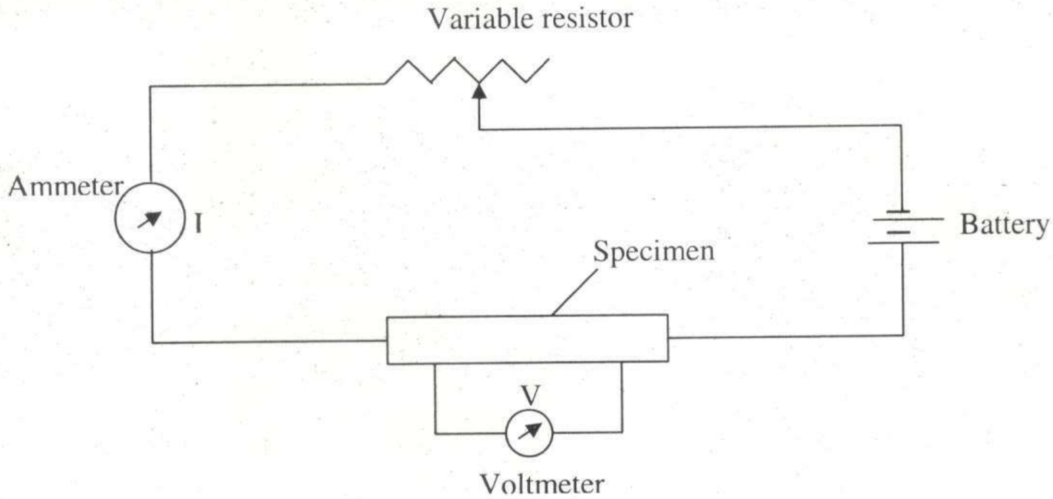

Figure 2 : Electric circuit used to measure voltage and current across the specimen

(iii) Developing the Model

The theoretical analysis, which is basically computer simulation of differential heat transfer equations, was carried out by developing an algorithm to monitor the solidification front and temperature distribution of squeeze cast aluminium, (see figures 3 and 4). Differential heat transfer equations with internal heat generation described by Aniyi [15] were generated and solved using finite difference method (FDM). The relevant heat transfer equations in the cast region, interfaces and appropriate boundary conditions were derived and solved using finite difference method. Due to the cylindrical nature of the cast specimen , one-half of was analysed, (see figure 3).

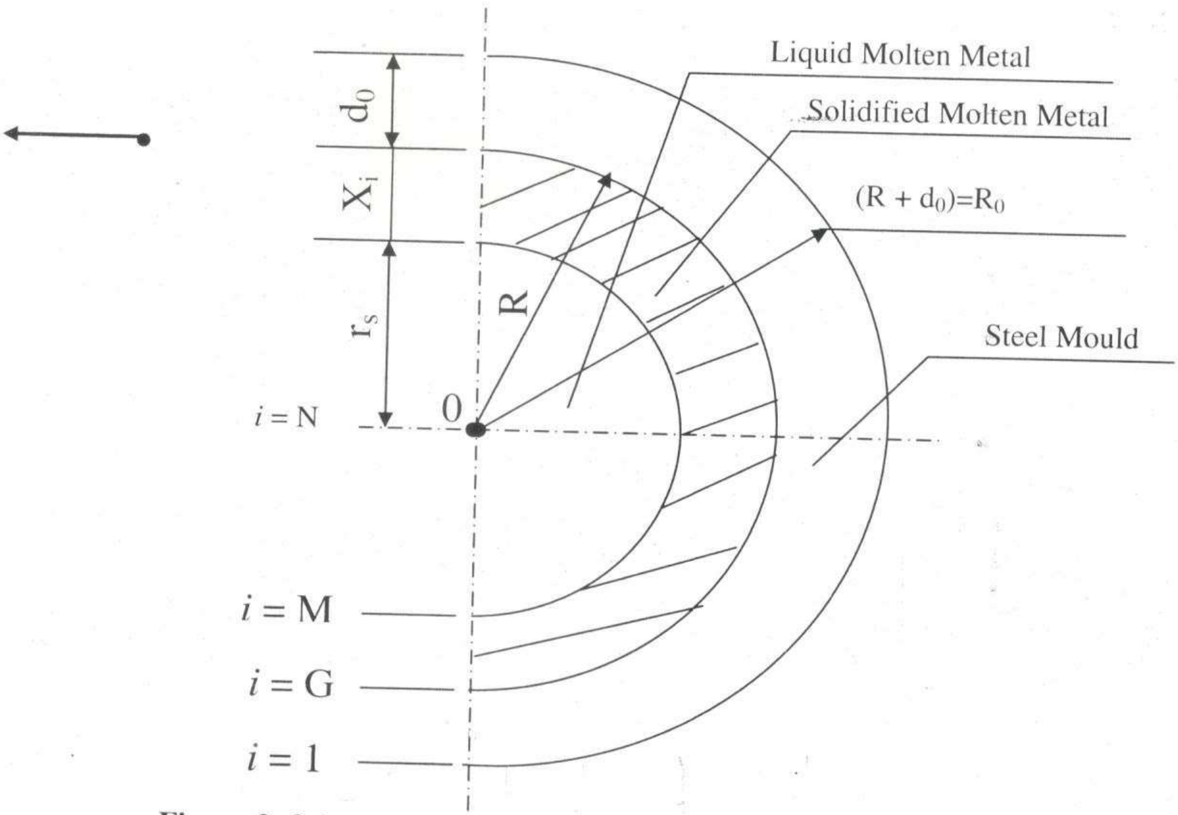

Figure 3: Schematic representation of solidification front in a cylindrical mould in one dimension (sectional view)

With pressure application on the cast metal, an internal energy, Δq was generated within the solidified molten metal, (see figure 4). The internal energy generated was due to the plastic strain energy and frictional energy at the interfaces. The rate of work done, Δq on the solidified molten metal is as a result of plastic strain energy and frictional energies both at the punch / solidified molten metal interface and die / molten metal interfaces. These were taken into consideration.

The conduction heat transfer equation for the solidified metal takes the form;

$$\frac{dT_S}{dt} = \alpha_S \frac{\partial^2 T_S}{\partial r^2} + \frac{\alpha_S}{r_S}\frac{\partial T_S}{\partial r} + \frac{\Delta q}{\rho_S C_S} \qquad (4)$$

where,

$$\alpha_S = \frac{K_{al}(T)}{\rho_S C_S} \qquad (5)$$

α_S - thermal diffusivity of solidified aluminium metal,

T_S -solidifying temperature of cast metal,

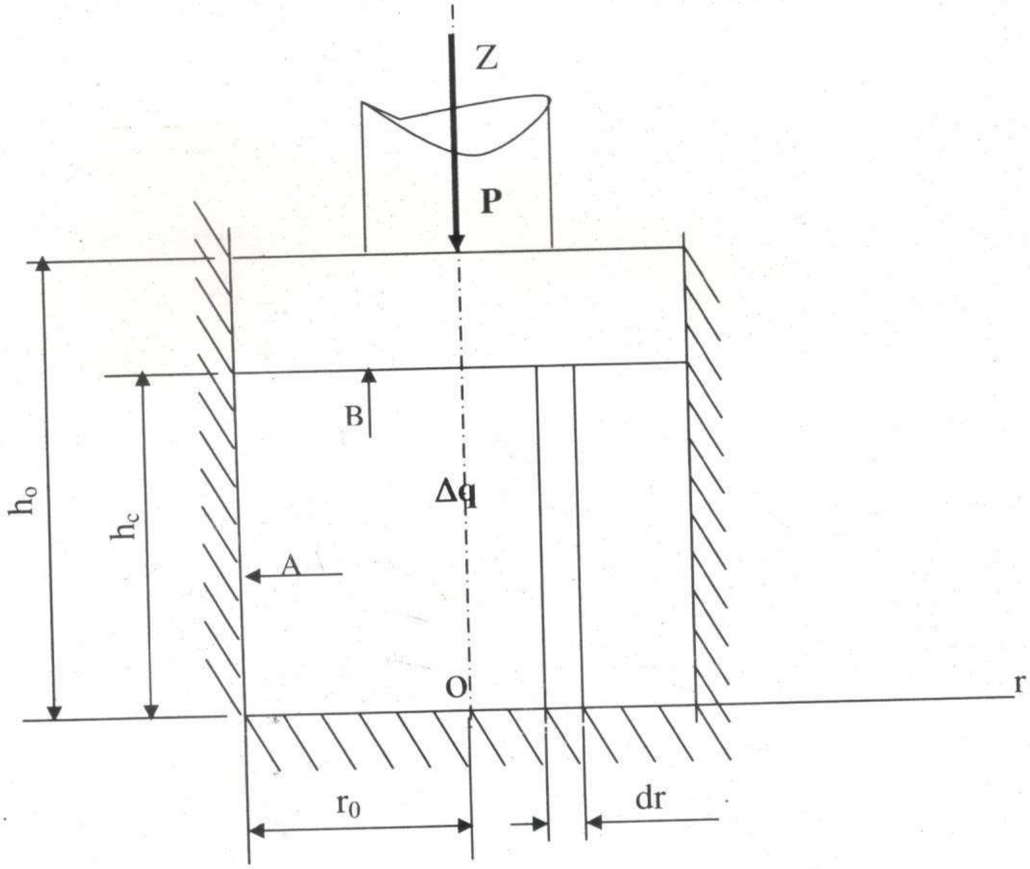

Figure 4 Specimen under pressure

$$\nabla q = \nabla q_P + \nabla q_f \tag{6}$$

Δq - internal energy generated due to pressure application,

Δq_P - energy due to plastic strain within the solidified molten metal material,

Δq_f - frictional energy generated during pressure application,

$$\nabla q_f = \nabla q_{fP} + \nabla q_{fm} \tag{7}$$

Δq_{fP} - frictional energy due to punch - solidified molten metal interface, surface B in figure 4.

Δq_{fm} - frictional energy due to steel mould cylindrical surface - solidified molten metal interface, surface A in figure 4.

$$\nabla q = \nabla q_p + \nabla q_{fm} + \nabla q_{fp} \tag{8}$$

$$\nabla q = \frac{\pi \bar{\sigma}_T}{\sqrt{3}}\left[2\int_0^{R}\int_h^{h_0}\sqrt{\left(3+\frac{r_0^4}{r^4}\right)}\, r_0\, dr\, dh + \mu V_0\int_h^{h_0}\left(1-\frac{h_C}{h_0}\right) r_o\, dh + \frac{2\mu V_0}{h_C}\int_{R_0}^{R}\left(r_0^2 - r^2\right) dr\right] \tag{9}$$

The cast specimen height h_c is pressure dependent and the relationship is expressed with equation (10) after performing five experiments of variation of pressure with cast specimen's height as shown in table 2, with various applied pressures;

$$h_c = -0.00007P_i + 0.036833 \tag{10}$$

R^2 = 0.996, at α = 0.05, p-value for variable Pressure = 0.000,

The plastic flow stress σ_T, is dependent on both the applied pressure, P_i and die pre-heat temperature T_M, and expressed with the equation;

$$\sigma_T = 0.244P_i - 0.0407T_M + 18614 \tag{11}$$

R^2 = 0.955, at α = 0.05, p-value for variable Pressure = 0.000,

P-value for temperature = 0.002

Table 2. Cast specimen heights with applied pressures

Pressure, MPa	Specimen's height, h_c mm
0	36.83
7.67	36.08
28.84	34.50
50.0	33.04
70.0	31.40
85.86	30.93

The finite difference form of equation (4) while converting the energy change, Δq into temperature becomes;

$$T_i^{j+1} = \left[1 - \frac{2\delta\alpha_S}{d_S^2} - \frac{\delta\alpha_S}{r_S d_S}\right] T_i^j + \left[\frac{\delta\alpha_S}{d_S^2} + \frac{\delta\alpha_S}{r_S d_S}\right] T_i^j + \frac{\delta\alpha_S}{d_S^2} T_{i-1}^j + \nabla T \tag{12}$$

where,

$$\nabla T = \frac{\nabla q \beta}{J C_P \rho V_{ol} \rho_S C_S} \tag{13}$$

$$r_S = \frac{(N-i)}{(N-G)} R \tag{14a}$$

$$\alpha_S = \frac{K_S}{\rho_S C_S} \tag{14b}$$

$$d_S = \frac{R}{(N-G)} \tag{14c}$$

i = G+1, G+2, …., N

Results and Discussion

Effects of Applied Pressures

Figure 5 shows typical temperature versus time curves for solidifying molten aluminium metal and steel mould respectively without die heating and pressure application. This figure shows the comparison of the numerical method usually applied by previous authors [5,10] to determine interface steel mould / cast metal temperature versus time curve.

Typical results obtained under pressure is shown in figure 6, indicating the cooling curves generated for solidifying molten aluminium metal which follow the same patterns as curves in figure 5. With the application of pressure at the delay time of 20 seconds and retention time of 55 seconds, the peak temperatures recorded are close in values 719.95°C and 648^{0}C for a pressure of 85.86 MPa for numerical and experimental methods respectively (see figure 6). The temperatures attained before pressure application are 661.42^{0}C and 648^{0}C for numerical and experimental values respectively and rose to a maximum of 672.96^{0}C and 660^{0}C with pressure application and retention time of 55 seconds respectively. The increase in the temperature is due to pressure application on the cast metal is as a result of the increase in the internal energy generated within the cast metal.

Interface Heat Transfer Coefficients with Solidifying Temperature

Figure 7 shows the numerical values of the variation of interface heat transfer coefficient with the solidification temperatures of aluminium metal at the cylindrical surface with the application of pressure. The maximum value of heat transfer coefficient of 3397.29 W/m^{2}K at applied pressure of 85.86MPa is obtained compared with 3351.08 W/m^{2}K obtained through the experimental procedure. At solidifying temperatures below 600°C, a sharp reduction in the interface heat transfer coefficients is noticed. For temperatures below 500^{0}C, the interface heat transfer coefficients' values for both no pressure and pressure applications are close in values. At temperatures of about 470^{0}C the heat transfer coefficients are 1108.45 and 1252.58 W/m^{2}K for no pressure application and at applied pressure of 85.86MPa respectively. This shows that at temperature below 500^{0}C, the effect of applied pressure is no longer significant on the interface heat transfer coefficient values. The high value in the interface heat transfer coefficient at temperature close to liquidus is probably due to good thermal contact at the cast metal-mould interface. However the decrease with solidification time is due to the rapid heat abstraction from the cast metal to the steel mould, leading to the minimal temperature difference between the cast metal and the steel mould [5,11].

Effects of Die Heating

Figure 8 shows a typical comparison of numerical casting temperature of aluminium metal with experimental measured values with die heating at 150^0C. From this figure it is observed that the cast metal looses heat (cooling) while the steel mould gains the heat (heating) and becomes heated up. The values obtained for both methods are close as is seen from the graphs.

Figure 9 is the graph comparing the voltmeter/ammeter and ohmmeter methods of measurement of electrical resistivity of aluminium metal with die heating temperatures. From this figure and table 3 there is an increase in the electrical resistivity of aluminium with an increase in die temperature from room temperature up to die temperature of 50^0C for both methods. Between die temperatures of 50 and 150^0C there follow a decrease in electrical resistivity to a value of 0.347×10^{-8} Ωm at die temperature of 150^0C for voltmeter method. Above this die temperature, electrical resistivity increases again to a value of 1.28×10^{-8} Ωm at die temperature of 310^0C. The increase in electrical resistivity at elevated die temperature is possibly due to high thermal conditions [1], which reduce die chilling effect on the molten aluminium metal that subsequently leads to lower thermal gradient during the process of metal solidification. This indicates that die temperature required for good electrical resistivity should not exceed 150^0C. From figure 9, the electrical resistivities as determined by the two methods were found to be close with voltmeter/ammeter method found to be higher by 8.8%.

Table 3: Electrical resistivity of the cast specimen

Die pre-heat temperature, ^{0}C	Electrical resistivity, (x10^{-8} ohms.m), (P = 85.86MPa)	
	Ohmmeter method (by calculation using equation 3a)	Voltmeter/ammeter method (direct resistance measurement, equation 3b)
30	2.4237	2.63
50	2.5746	2.82
80	1.418	1.58
150	0.3014	0.325
245	0.5779	0.598
310	1.2014	1.28

Conclusions

Evaluation of heat transfer coefficients by pressure application and die pre-heat temperatures has been investigated using squeeze casting method which incorporated plastic flow stress that is pressure and die pre-heat temperature dependent. Therefore from this investigation, it could be concluded that;

- Applied pressure and die pre-heat temperature are found to have significant effects on the electrical resistivity of squeeze cast aluminium metal therefore, die pre-heat temperature of 150^{0}C is recommended for squeeze casting of aluminium metal for optimum electrical resistivity.
- The maximum values of heat transfer coefficients are 2956.73 W/m^{2}K prior to pressure application and increase to 3358.19 W/m^{2}K with the application of pressure. The delay time of about 5 seconds is recommended when the temperature of the cast metal is close to liquidus.
- With die pre-heat temperature, the maximum heat transfer coefficient decreases from a value of 3185.34 W/m^{2}K to 2476.73 W/m^{2}K at die pre-heat temperature of 95^{0}C and 300 ^{0}C respectively.
- There is a good agreement between the experimental and numerical obtained values of cooling and heating temperatures of both the cast specimen and the steel mould respectively.

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Nomenclature

A -cross-sectional area of the Specimen,

$h_{al}(T)$ -interfacial heat transfer coefficient of cast metal,

d_S -spatial step size in the solidified aluminium metal,

K -thermal conductivity of the steel mould,

$K_{al}(T)$ -thermal conductivity of the cast metal,

G -nodal point in the steel mould cast aluminium metal interface,

N -nodal point in the centre of the cast aluminium metal,

T_C -cast metal temperature,

T_M-die pre-heat temperature,

T_{C_1} -experimental measured temperature in the cast metal,

T_{C_2} -experimental measured temperature in the steel mould,

T_S-Temperature of solidified aluminium metal,

ΔT-temperature difference,

ρ_S-density of solidified aluminium,

C_S-specific heat of solidified aluminium,

P_i-applied pressure,

q-heat flux,

ρ_e-electrical resistivity,

V-voltage,

I - gridal point,

I-current,

L-specimen's length,

r_S-elemental radius of cast specimen,

R-radius of cast specimen,

R_e-specimen's resistance,

h_0-Initial height of cast specimen metal (no pressure application),

h_c-height of solidified specimen metal with pressure application,

σ_T-Plastic flow stress (temperature dependent),

μ-coefficient of friction,

Z-axial axis,

β-percentage of the deformation energy transformed into heat energy (90%),

α_S-thermal diffusivity of the solidified aluminium metal,

J-mechanical equivalent of heat (4185J/kal),

∇q -energy dissipated due to pressure application,

V_{ol} -volume of workpiece.

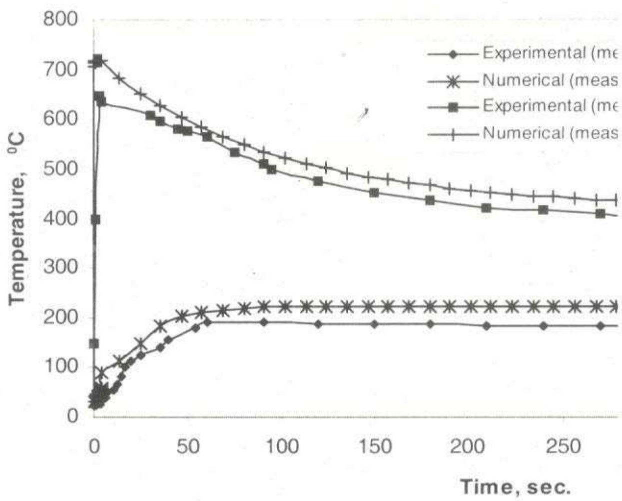

Figure 5 Comparison of experimental measu numerical values of aluminium metal without die heating (P=0,T_M=30⁰

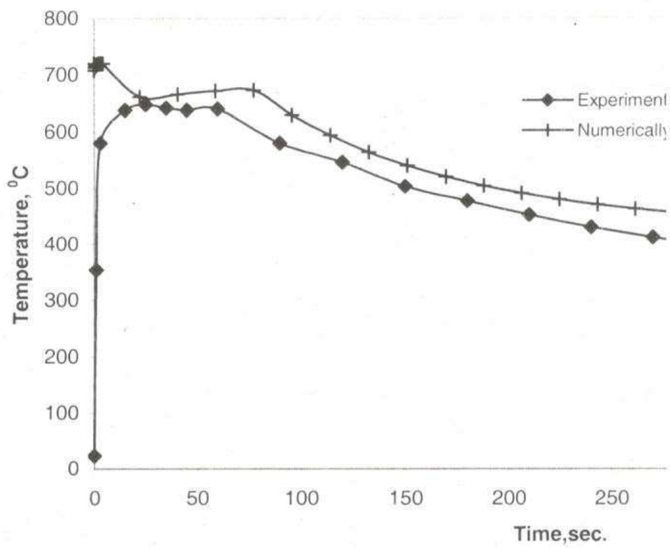

Figure 6 Typical comparison of the effect of applied p temperature of aluminium metal (P= (delay time=20 sec., retention time=55 s

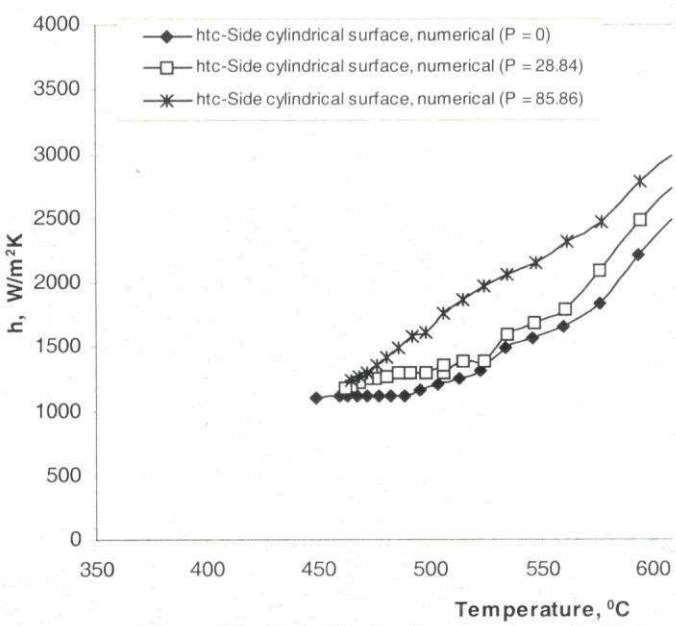

Figure 7 Typical effects of pressure application on with solidifying temperature of the side cylind numerical method

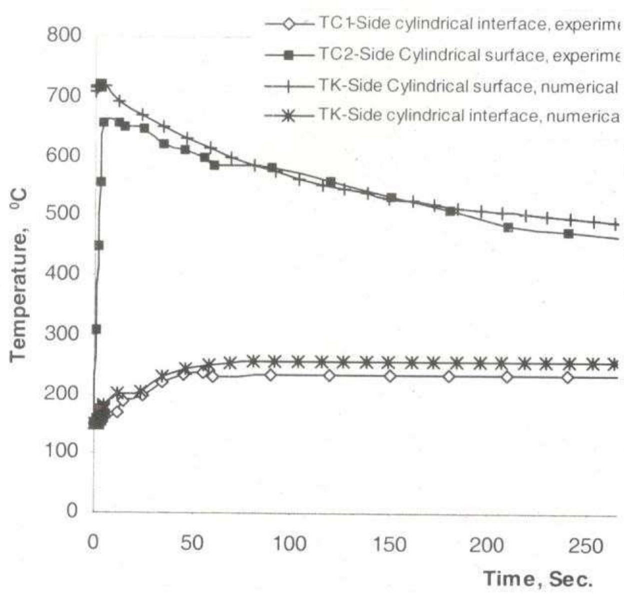

Figure 8 Typical comparison of experimental measured casting temperatures with numerical values of aluminium metal with die heating (T_M=150°C)

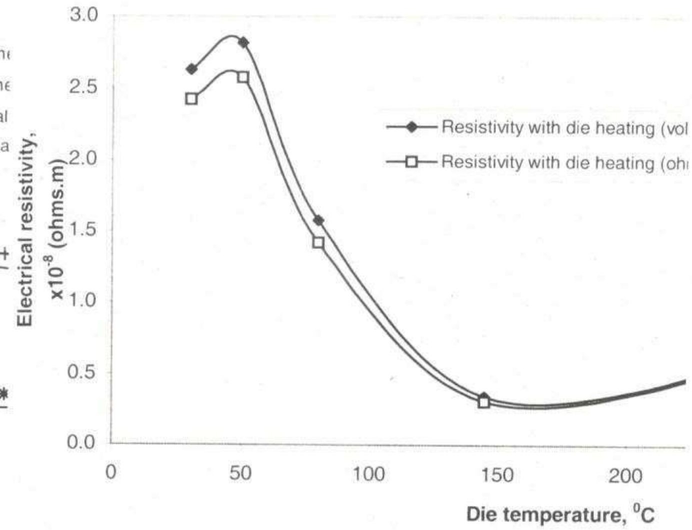

Figure 9 Comparison of calculated and direct resistance resistivity of aluminium metal with pressure applic

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