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EVALUATION OF SOME SQUEEZE CAST PARAMETERS OF ALUMINIUM

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Abstract

Effects of applied pressures and die pre-heat temperatures on the heat transfer coefficients of aluminium were determined using the solidification temperature histories of the cast metal. The heat transfer coefficients at the cast metal/steel mould interface during solidification of squeeze cast aluminium were investigated using the inverse heat conduction method. The heat transfer coefficients were determined by both experimental and numerical methods. The results show an increase in the value of heat transfer coefficients with applied pressure and a decrease with high die pre-heat temperatures. The numerical heat transfer coefficients were in good agreement with the experimental values.

Keywords

Squeeze casting, temperatures, applied pressure, die pre-heat

1. Introduction

Aluminium is a product with unique properties, making it a natural partner for the building and other manufacturing industries. Aluminium is valuable as an electrical conductor and as a material for handling, processing and packaging foods, pharmaceuticals, chemicals and variety of other products. Its strength, durability, corrosion resistance and recyclability, has made it to become an essential product for the building industry and over the years. Its use in building applications has shown continuous and consistent growth.

In buildings, aluminium panels are corrosion resistant and therefore virtually maintenance free. Aluminium's lightness means easy construction, while its thermal insulation properties derived from the ability to design thermal breaks in extrusions, and from aluminium foil's reflectivity, conserve heating energy. Aluminium has advantage as a lightweight material for some structural elements in buildings and in the aero-industry. A large amount of waste building materials go to landfill sites at a cost to both the economy and the environment. In contrast aluminium is recycled in a way that pays for itself and is sustainable.

Aluminium in packaging preserves food quality and avoids waste, and its low weight reduces fuel consumption and emissions during transportation.

Aluminium's high conductivity makes it an excellent material for electrical power transmission over long distances. The use of aluminium cables reduces power losses significantly and therefore conserves energy.
Aluminium extruded, rolled, and cast products are commonly used for window frames and other glazed structures ranging from shop fronts to large roof superstructures for shopping centres and stadia; for roofing, siding, and curtain walling, as well as for cast door handles, catches for windows, staircases, heating and air-conditioning systems. Most recently, aluminium has played a significant role in the renovation of historic buildings (Radlbeck, C el al 2004). The characteristics and properties of aluminium as a material have led to revolutionary and innovative changes in building techniques, architectural and engineering projects.

Remelting used aluminium requires only 5 per cent of the energy needed to produce primary metal (Radlbeck, C el al 2004). Thus, rather than contributing to society's growing waste problem, aluminium can be remelted and reformed to produce a new generation of building parts.

Aluminium in general has always been recycled at a higher rate than most other raw materials. Given the necessary infrastructure, it is possible to recycle all aluminium construction industry applications, for several reasons. First, there is a relatively high level of scrap aluminium available. Second, aluminium has a high scrap value, which can contribute significantly towards covering demolition costs. Finally, the infrastructure required for the collection of scrap metals is already well established and will continue to grow on its own economic merit as it has done in the past to provide an increasingly efficient recycling system. Nearly 40 per cent of all aluminium used today is remelted metal (Radlbeck, C el al 2004).

In general, however, aluminium construction products do not need to be protected by organic coatings used to safeguard some alternative materials. They therefore offer a source of good metal which can be recycled without any pre-processing.
The commercially pure aluminium metal used for this research work finds extensive use in the building, manufacturing and process industries, both as a material of construction and household goods. Products of squeeze casting are

of improved mechanical properties and could be given heat treatment. Heat abstraction through the process of solidification in squeeze casting is fast thus producing products of fine grains as compared to slow cooling in sand casting, which results in large grains. Products obtained through squeeze casting are with improved mechanical properties.

2. Modelling

2.1 Squeeze Casting Method

Squeeze casting is a comparatively newly developed manufacturing method for producing commercial castings (Liu A et al 1993, Franklin J. R. and Dass A.A 1983, Suresh K. V. and John L. D 1988, Aweda, J.O. 2006, Das, A and

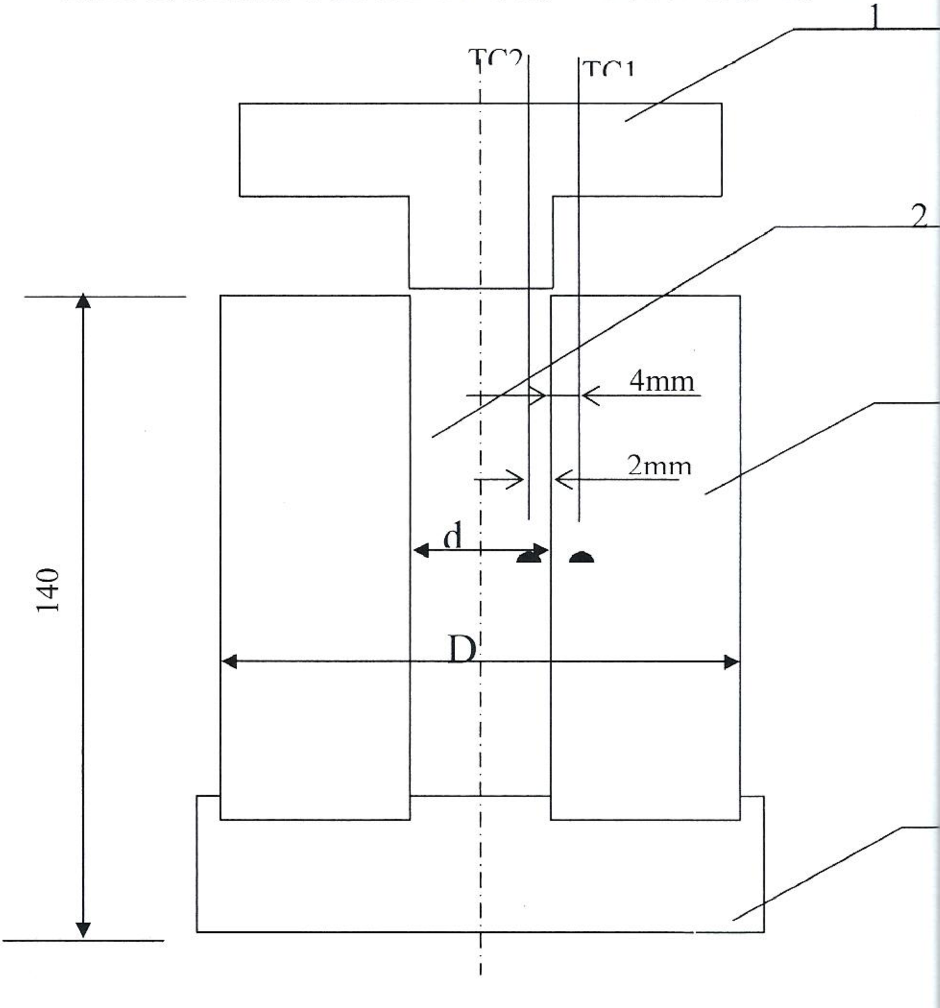

Figure 1 Schematic diagram of rig used for producing aluminium specimens for electrical test
1-moveable punch, 2-cavity for cast specimen, 3-cylindrical split steel container, 4-die support

Chatterjee S. 1981). Squeeze casting is a process in which liquid melt 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 Fig.1).

Squeeze casting consists of two stages, the first of which is mould filling-the mould is filled with the required quantity of 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 the fundamental parameters such as the occurrence of 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 (Donald S. C and Wilbur R.V. 1962, Robert E.R and Reza A. 1973). 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. 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 (Donald S.C and Wilbur R.V. 19627, Raymon A. H. 1983). 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.

Squeeze casting parameters that can be controlled for the production of sound products include; melt quality, pressure level and duration, time of pressure application, press speed, molten metal temperature, tooling temperature.

In studying the effect of chill thickness and superheat on casting-chill interfacial heat transfer during solidification of commercially pure aluminium, Gafur et al (2003) concluded that higher superheat had a significant effect than the chill thickness. Santos et al (2001) noted that the transient heat transfer coefficients profiles increase with increasing melt superheat. Evaluating the interfacial heat transfer coefficients using gap formation and inverse methods, Krishna M. and Sharma D.G.R. (1996) observed that heat transfer coefficients derived through temperature measurements using inverse methods were higher than that obtained by gap measurement method.

Consideration has not been given to the effects varying applied loads, the delay time and period of application of pressure on the heat transfer coefficients. This paper evaluates the heat transfer coefficients with varying applied pressures, delay times (time between die closure and pressure application) and die pre-heat temperatures on the heat transfer coefficients of squeeze cast aluminium.

3. Experimental Method

3.1 Materials Used and Squeeze Cast Rig

The material used for the present investigation was commercially pure aluminium, of percentage composition of 99.81% of aluminium and traces of other elements such as silicon, manganese phosphorous and nickel in small amount. Chromel-Alumel thermocouples, TC1 positioned on the sides of the cylindrical steel mould monitored the heating temperature of the steel mould while, TC2 positioned in the cast aluminium metal in the cylindrical surface monitored the solidifying temperature of the cast metal as shown in Figure 1.

3.2 Melt Preparation and Pouring

Aluminium used as overhead cables was procured, cut into sizes and melted in an electric furnace at a temperature of 720 ^0C (a super heat of 60^0C). The melt pouring was carried out fast enough into the steel mould using the crucible pot (i.e. between 3 to 5 seconds) while avoiding turbulence. The inner surfaces of the die were initially lubricated with used engine-oil, so as to allow for easy removal of the cast specimen after solidification.

3.3 Temperatures Versus Time Curves Determinations

Thermocouples of chromel-alumel type K, 3mm in diameter, were used to determine the solidifying temperatures of the cast molten metal (TC2) and heating temperatures of the steel mould (TC1) with time, Figure 1. The temperature versus time curves at positions TC1 to TC2 were obtained by connecting the thermocouple through a cold junction (thermo flask) maintained at the temperature of melting ice, 0^0C to a chart recorder. The millivolt readings versus time curves were recorded by the chart plotter pen on the graph paper. From the graph, the millivolt readings were converted to temperature using the conversion table.

3.4 Temperature Measurement Vithout Pressure Application on the Cast Metal

A metered quantity of molten metal was poured into the steel mould cavity to attain a height of about 36.8mm. The upper die was released to close the mould cavity without applying any load on the upper die. Thermocouples TC2 (penetrating 2mm into the cast metal) measured the solidification temperatures with times of the cast metal. The other thermocouple, inserted into the blank hole in the steel mould, measured the heating temperatures with time of the cylindrical wall of the die. 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 ^{0}C throughout the measuring period.

3.5 Temperature Measurement with Pressure Application on the Cast Metal

The procedure for no pressure application was repeated, except for the application of pressure on the solidifying molten aluminium metal. The molten aluminium was carefully poured into the mould cavity within five seconds, so as to avoid turbulence of molten metal flow. 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. The compression loads were applied at a delay time of about seven seconds after pouring molten aluminium metal and retained on the solidifying molten metal for a period of between 50 and 60 seconds, until total solidification was achieved. During pressure applications, the solidification temperatures with times were recorded on the chart recorder by thermocouples positioned at the cylindrical steel mould and the cast metal.

3.6 Determination of Heat Transfer Coefficient

Computer simulations of solidification in permanent mould castings have been developed (Hu h et al 2002). Heat flow across the casting and through the interface to the mould directly affects the evolution of solidification and plays no small role in the determination of the freezing conditions of the cast metal. In squeeze casting, soundness of casting is directly affected by heat transfer at the cast metal-mould interface and it is time dependent. With the formation of air gap at the metal/mould interface during solidification, the value of heat transfer coefficient will decrease. The heat transfer coefficient is affected by the roughness of the mould surface, the coating and squeeze casting conditions. The heat flow across the cast metal/mould interface can be characterised by equation 1. To determine h_{al} in the equation, all other terms of the equation must be known. To determine T_{al} and T_M accurately becomes difficult because of the difficulty in locating the exact thermocouples' positions. To overcome this experimental problem, the method of calculating h_{al} is based on the knowledge of temperature histories at the interior points of the casting together with the mathematical formulation of heat flow during solidification. This method, based on the solution of inverse heat conduction problem, has been used to determine heat transfer coefficients in this work. The inverse heat conduction problem is the determination of the surface temperature (or heat flux) from the measured transient temperatures inside a heat conducting body [Krishna M. and Sharma D.G.R. 1996, Tae-gyu and

Zin-Hyoung Lee 1992, Beck J.V. 1970). 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.

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(K_{al} r \frac{\partial T}{\partial r} \right) \quad (1)$$

Equation (1) holds with the boundary condition at the interface expressed as:

$$q = K_{al}(T)\frac{\partial T}{\partial r} = h_{al}(T)\left[T_{al} - T_M\right] \quad (2)$$

The heat transfer coefficient h_{al} at the interface is estimated by minimizing the errors between numerically estimated and measured temperatures defined by:

$$F(h) = \sum_{i=1}^{n}\left(T_{est} - T_{\exp}\right)^2 \quad (3)$$

4. Computational Method

Heat transfer equations were obtained by developing an algorithm to monitor the solidification front and temperature distribution with time of squeeze cast aluminium in a cylindrical steel mould. Differential heat transfer equations with internal heat generation were generated and solved using finite difference method (FDM). In the differential equations generated, squeeze casting parameters such as applied pressure, die pre-heat temperature, delay and retention times of applied pressure were taken into consideration. Set of heat transfer equations were generated in the cast region and the interfaces with appropriate boundary conditions. These equations were converted to the finite difference forms and used for computation. Computation of solidification fronts and temperature distribution in the mould and cast metal began after a metered quantity of molten metal was poured into the mould cavity. The time of pouring of molten aluminium metal, t_p was fast and was within 5 seconds. The steel mould, the solid metal and the liquid melt regions were the three distinctive regions that existed in the process of solidification of molten aluminium metal. Each of these regions was separately discretized into a number of gridal points. The discretization started from the outer surface of the steel mould and terminated at the adiabatic centre wall in the liquid melt. Lines separating each of the interfaces were defined. As solidification progresses, temperatures were monitored in the steel mould, the cast metal and the interfaces.

5. Discussion of Results

Figure 2 shows the variation of heating and cooling temperatures of steel mould (obtained 4mm into the steel mould) and solidifying aluminium metal (obtained 2mm into the cast metal) respectively with time under pressure application. The maximum temperatures obtained increase with increase in applied pressures. The maximum temperatures obtained in the cast metal are 639^{0}C and 652^{0}C without pressure application and with pressure application of 70.68MPa on the solidifying metal respectively.

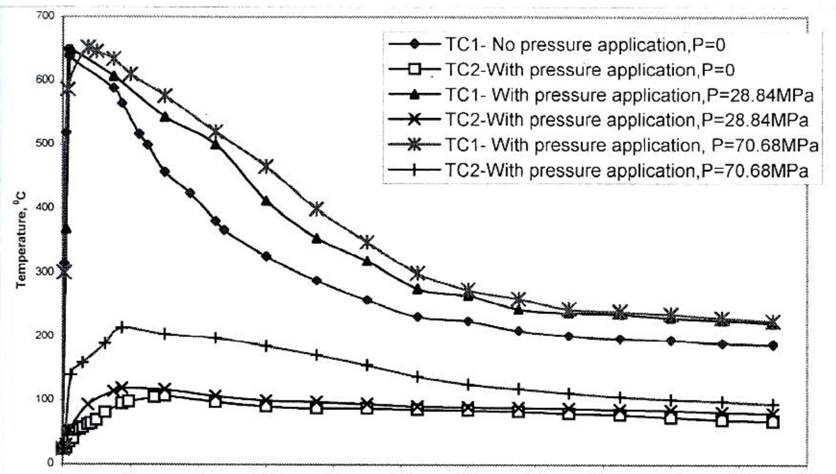

Figure 2 Effect of applied pressures on the measured temperatures of solidification of aluminium without die heating

The effects of die pre-heat temperatures on the heating and cooling temperatures of the steel mould and the solidifying aluminium with time is shown in figure 3. With increase in the die pre-heat temperature, the maximum temperatures attained in the cast metal are 638^{0}C and 659^{0}C at die pre-heat temperatures of 95^{0}C and 260^{0}C respectively. These values become 290^{0}C and 311^{0}C at die temperatures of 95^{0}C and 260^{0}C respectively in the steel mould wall.

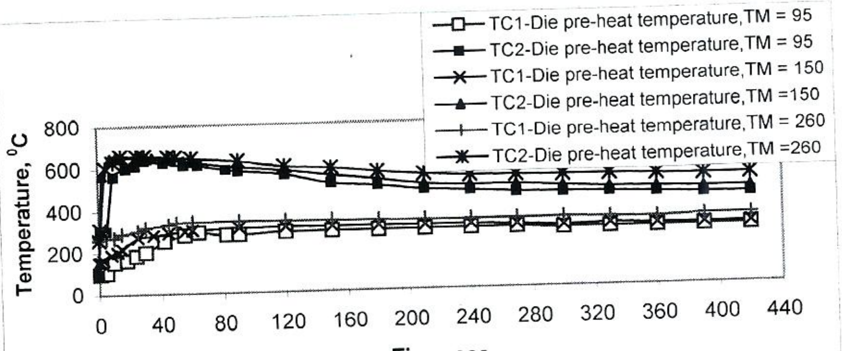

Figure 3 Effect of die pre-heat temepartūre on the measured temperatures of solidification of aluminium without pressure application

The peak values of the heat transfer coefficients are $2927.92 W/m^2K$ and $3223.00 W/m^2K$ respectively without and with pressure applications, see figure 4. For solidification times of less than 40 seconds, the heat transfer coefficients fall drastically and further falling in heat transfer coefficients afterwards is gradual. At solidification times of 150 seconds, the heat transfer coefficients are $575.08 W/m^2K$ and $906.37 W/m^2K$ at no pressure and with pressure application of 70.68MPa. These values drop to $313.92\ W/m^2K$ and $593.30 W/m^2K$ in another 150 seconds.

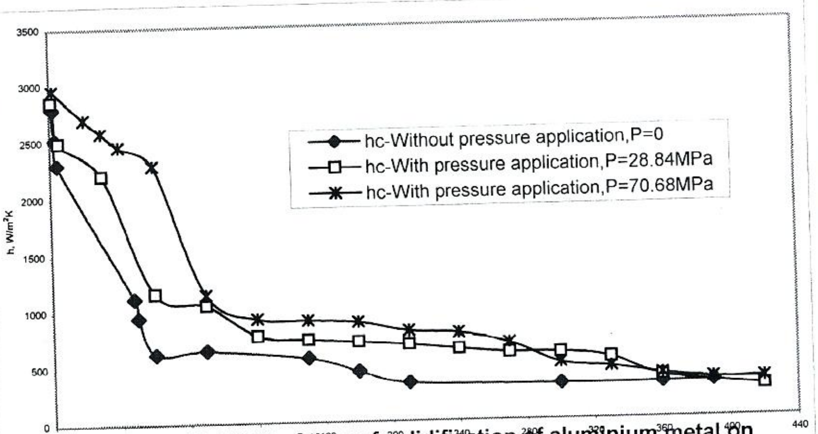

Figure 4 Effect of time of solidification of aluminium metal on heat transfer coefficients with pressure application and no die heating

Figure 5 is the effects of die pre-heat temperatures on the heat transfer coefficient's values of aluminium metal with casting temperature without the application of pressure. From figure 5, the heat transfer coefficients become lower with increase in die temperatures. At die temperature of 95°C, the peak heat transfer coefficients are 2994.53W/m^{2}K and drop to a peak value of 2644.30W/m^{2}K at die pre-heat temperature of 260°C. For all the die temperatures investigated, there is a drop in the heat transfer coefficients' values as solidification progresses.

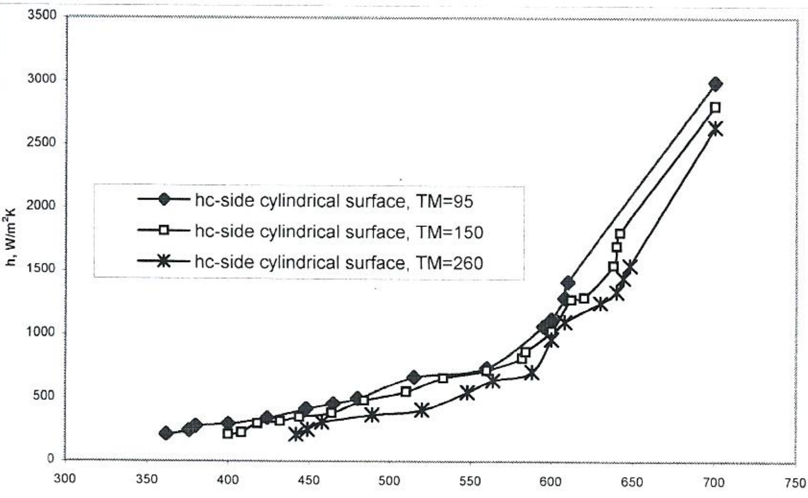

Figure 5 Effect of die pre-heat temperature on the heat transfer coefficients of aluminium metal without pressure application

Typical comparison of numerical and experimental measured cast aluminium solidification temperatures with die heating under no pressure application is shown in figure 6. With higher die pre-heat temperature, the cast aluminium solidification temperatures are higher and these remain higher at a given time to values obtained with lower die pre-heat temperature. There is a close agreement between the numerical and experimental measured temperatures at all die pre-heat temperatures investigated. The numerical results show higher values as compared to the experimental results by about 0.71%.

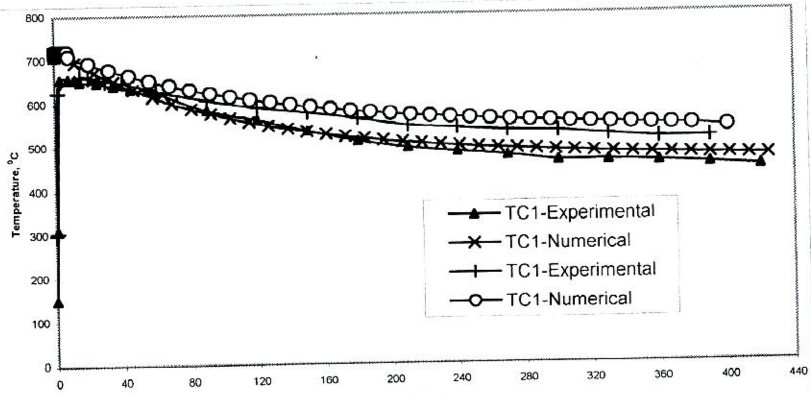

Figure 6 Typical comparison of experimental measured aluminium cast solidification temperatures with numerical values with die heating (P = 0)

Fig. 7 is the heat transfer coefficients as determined using both numerical and experimental values. The maximum heat transfer coefficients of 2927.92 W/m^2K is obtained for no pressure application, which is close in value to 2900 W/m^2K as obtained for pure aluminium by Tae-Gyu Kim and Zin-Hyoung Lee (1992). The values of heat transfer coefficient are found to decrease rapidly for both the numerical and experimental methods to a level of 1919.75 W/m^2K and 1498.74 W/m^2K respectively in 40 seconds.

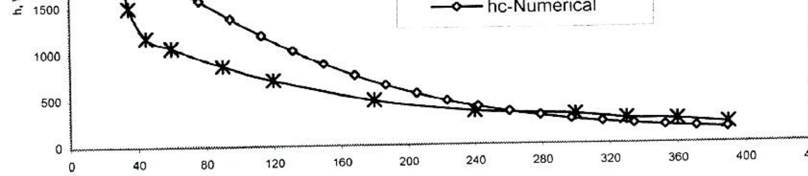

Figure 7 Comparison of numerical values of heat transfer coefficients with calculated values without pressure application and die heating

These values are further decreased to 408.95 W/m^2K and 361.77 W/m^2K at these surfaces in another 150 seconds, which continues decreasing until the decrease in values become unnoticeable. For times within 40 to 120 seconds, the values of the interfacial heat transfer coefficients obtained numerically and experimentally are found to show higher values deviations of 19.83 % maximum of numerical results from experimental results only at certain ends.

6. Conclusion

In the present work, applied pressures and die temperatures are found to have significant effects on the heat transfer coefficients of aluminium. Heat transfer coefficients decrease sharply when the casting temperature of the metal is near liquid. Therefore, effect of pressure application on the solidifying aluminium is more pronounced within the first 40 seconds of pouring molten aluminium metal into the mould cavity. With die pre-heat temperature, the heat transfer coefficients decrease with increase in die temperature and the maximum value of heat transfer coefficient were obtained while maintaining die at room temperature.

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8. Nomenclature

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

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

T_{al} -cast metal temperature
T_M -mould temperature
TC1 -measured temperatures in the cast metal
TC2 -measured temperatures in the steel mould
ρ -density of aluminium
C_P -specific heat
r -distance
q -heat flux
T_{est} and T_{exp} -the estimated and experimentally measured temperatures at various thermocouples location and times,
n -iteration stage