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Solidification Simulation of Aluminum Alloy Casting – A Theoretical and Experimental Approach

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ABSTRACT: *Aluminium alloy castings are extensively used in general engineering, automotive and aerospace industries due to their excellent castability, machinability and high strength-to-weight ratio. The major problem with aluminium castings is relatively high shrinkage of between 3.5 to 8.5% that occurs during solidification. This study aims to theoretically analyze shrinkage behavior of cast aluminium alloy and to conduct solidification simulation of casting using finite element technique based on the experimental findings. A detailed finite element solidification simulation of A356 aluminum alloy casting in sand mould is performed, and numerical simulations are carried out considering interface resistance and with out interface resistance. Few test castings are poured with ordinary riser and insulated riser, and time - temperature history is plotted with the help of thermocouples to verify the results. It is observed that the results obtained by the solidification simulation are helpful in optimizing casting yield, predicting shrinkage, reducing number of trials and rejections.*

Keywords: *Aluminium, Casting, Shrinkage, Solidification and Simulation.*

I. Introduction

A detailed literature survey has shown that even after having more than fifty years of data and the use of computers to solve complex heat flow in mould, still manufacturing a critical casting is difficult. An attempt has been made to imitate the actual solidification process that occurs in sand mould. In this study, A356 - Aluminum alloy (AlSi7Mg) is used since large quantities of sand castings and gravity die castings are manufactured using this alloy. Solidification simulation of aluminum alloy casting is carried out using finite element analysis. The problem is assumed to be a two-dimensional axis symmetric transient heat transfer with latent heat generation. Simulation is carried out to study the capability of heat flow in casting, considering thermal resistance at the casting and mould interface, with interface resistance and with out interface resistance. The theoretical formulation and analysis is carried out by finite element techniques and comparative experimental tests are conducted. Temperature history is plotted at selected locations with the help of thermocouples for verification of results.

II. Background

During past 50 years, significant work has been done in the area of producing sound aluminum alloy castings [1-5], computer application in casting technology [6-10], theoretical heat transfer [11-15, 31]and its application to model casting solidification. Few analytical solutions are available to solve solidification problems and are limited to simple geometries. Therefore various numerical methods, such as finite difference [16-20], finite element [21-25] and boundary element methods [26, 27] have been widely applied with their own limitations for modeling of heat flow, fluid flow and thermal stress during solidification. Some of the numerical simulations are presented in the references at the end.

A major complexity of solidification process is release of latent heat of solidification during phase change, which occurs at the fixed melting temperature (in pure metal) or at the mushy zone (in alloy) depending upon the material used. Among different techniques that have been proposed to handle latent heat, the enthalpy method [24, 28-30] and modified specific heat method [31] are perhaps the most widely used in practical casting solidification modeling. Su and Tsai [30] have shown through experimentation, how latent heat is released during alloy solidification which was neglected in previous studies. Usually in the literature, for many alloys, only total amount of latent heat released during solidification is given, actually it is released over a temperature zone depending upon alloy composition and microstructure.

The thermal resistance caused by improper contact, mould coating, air gap formed due to shrinkage, moisture and additives are other important factor in solidification process. Significant work has been done to track the formation of air gap [32-34].

III. Governing Equation

The equation of conservation of energy considered in this study can be written as:

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kz\frac{\partial T}{\partial z}\right)+q_g=\rho C_P\frac{\partial T}{\partial t} \quad (1)$$

where K_x, K_y, K_z, T, t, q_g, ρ, C_p are thermal conductivities in x, y, z direction, temperature, time, internal heat generation, density and specific heat respectively. Considering a general problem as shown in Fig.1 the initial and boundary conditions are:

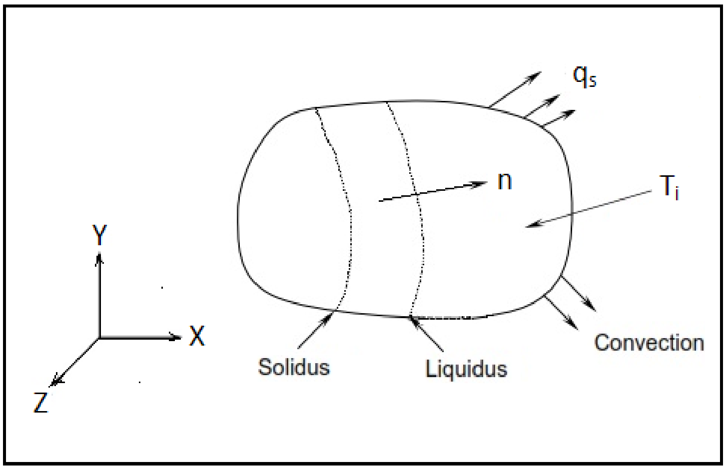

Fig. 1: Solidification in three dimensions, interface is moving in the direction n.

3.1 Initial condition

Initial temperature of metal poured in mould - T_i.

3.2 Specified heat flux

Heat flow inputs may be prescribed at the specific points or surface of the body - q_s.

3.3 Convective boundary condition

$$K\frac{\partial t}{\partial n}=h(T-T_\infty) \quad (2)$$

Where n, h are unit outward normal vector and convective heat transfer coefficient respectively.

3.4 Phase change boundary condition at the interface

$$K_S\frac{\partial T_S}{\partial x}-K_L\frac{\partial T_L}{\partial x}=\rho L\frac{\partial f_S}{\partial t} \quad (3)$$

Where subscripts s and L are used for solid and liquid respectively, L is latent heat, $\partial f_s/\partial t$ rate of solid formation.

3.5 2-D Heat Transfer

The enthalpy form of energy equation for a two dimensional case without heat generation is given by

$$\frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\frac{\partial T}{\partial y}\right)=\rho\frac{\partial H}{\partial t} \quad (4)$$

Where K, T, H, t, ρ are thermal conductivity, temperature, enthalpy, time and density respectively. The advantage of enthalpy form of equation is that a single energy equation becomes applicable in both phases; hence there is no need to consider liquid and solid phases separately. Therefore any numerical scheme such as the finite difference or finite element method can readily be adopted for the solution. In addition, the enthalpy method is applicable both in a distinct phase change at a discrete temperature Fig.2 (a) as well as phase change taking place over an extended range of temperature Fig.2 (b).

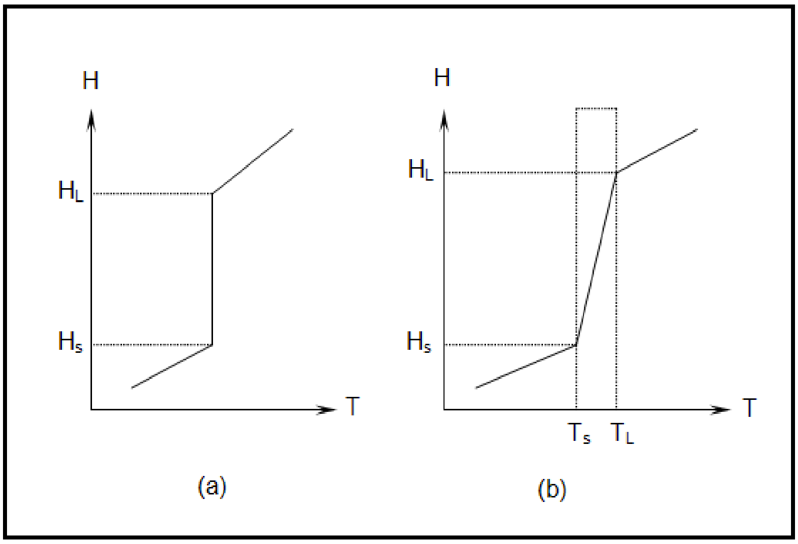

Fig. 2 (a) Enthalpy-Temperature relationship for pure crystalline substance and eutectic.
(b) Enthalpy – Temperature relationship for alloy.

Where T_S and T_L are solidus and liquidus temperatures, and H_S and H_L are enthalpies at solidus and liquidus temperature respectively. In case of alloys with long freezing range [2, 35] there is no discrete melting point temperature, because the phase change takes place over the extended range of temperature. Such relationship between H (T) and T is obtained from either experimental data or standard physical tables. In general enthalpy is a non-linear function of temperature therefore an enthalpy versus temperature variation need to be available. Assuming linear release of latent heat over the mushy region, the variation of H (T) with temperature can be written as:

$$H = C_P T \qquad \text{(For } T < T_S \text{ Solid zone)} \tag{5}$$

$$H = C_P T + \frac{T - T_S}{T_L - T_S} L \qquad \text{(For } T_S \le T \le T_L \text{ Mushy zone)} \tag{6}$$

$$H = C_P T + L \qquad \text{(For } T \ge T_L \text{ Liquid zone)} \tag{7}$$

Where C_p, L are specific heat and latent heat respectively.

IV. Finite Element Formulation

A Finite element analysis of a two dimensional axis-symmetric casting is presented in this section. The problem is defined as a transient heat transfer with phase change [31], where a temperature gradient is assumed to be present at each element. As in every FEM the casting is divided into a number of basic elements depending on the type of interpolation employed. The temperature at every nodal point is first determined and than interpolated over the entire element region. Thus the temperature distribution is obtained at regular intervals. A good description of the solidification pattern can be obtained by treating the problem as a non-linear transient heat transfer in the casting mould assembly and by incorporating the energy release at the liquid-solid interface in the heat capacity function C_pT.

4.1 Theoretical Formulation

The following assumptions are usually made while formulating the model for solidification simulation:

- Only conductive mode of heat transfer is operative during the entire solidification process.
- The heat flow is assumed to be two dimensional axis symmetric transient heat with phase change.
- Pouring is completed in no time and there is no drop in metal temperature during pouring.
- The mould temperature is instantaneously raised to some constant higher value.
- Heat flow across mould/metal interface is governed by a constant heat transfer coefficient.
- The outer surface of the mould looses heat by convection.
- Thermal conductivity remains constant and specific heat varies with temperature for metal, mould and air gap.

A general procedure of finite element model for unsteady heat conduction with phase change for 2-D axis symmetric problem is described here.

The differential equation can be written as:

$$\frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\frac{\partial T}{\partial y}\right)+q_g=\rho C_P\frac{\partial T}{\partial t} \quad (8)$$

4.2 Boundary Conditions

$$K\frac{\partial T}{\partial x}+h(T_m-T_\infty)=0 \qquad \text{(Convective)} \quad (9)$$

$$K_S\frac{\partial T_S}{\partial x}+K_L\frac{\partial T_L}{\partial y}=\rho L\frac{\partial f_S}{\partial t} \qquad \text{(at the phase interface)} \quad (10)$$

Where K, C_p, ρ, Q_g, T, t, T_m, T_∞ and L are thermal conductivity, specific heat, density, heat generation, temperature, time, mould temperature, ambient temperature and latent heat of generation respectively. Subscripts s, L is for solid & liquid and ∂fs /∂t is rate of solid fraction.

Following the standard finite element formulation procedure the unknown temperature 'T' can be approximated over the domain, by a combination of interpolation function:

$$T(x,t)=\sum_{i=1}^{m}T_i(t)N_i(x) \quad (11)$$

$$[T]=[T_i][N_i] \quad (12)$$

Where 'm' is the number of nodes, $N_i(x)$ are the shape functions and $T_i(t)$ are the nodal temperatures. The resulting semi- discrete equations can be written as:

$$[C][\check{T}]+[K][T]=[F] \quad (13)$$

Where [C] is heat capacitance matrix, [K] is conductivity matrix, [T] is temperature matrix, [F] is load matrix, Ť= ∂T/∂ t, 'F' is internal heat generation vector.

$$C=\rho C_P\int N^T N dv \quad (14)$$

$$K=K^e+h\int N^T N ds \quad (15)$$

$$F=q_g\int N dv \quad (16)$$

Where K^e- is element conductivity, h-coefficient of heat transfer, q_g - is heat generation. The symmetric and banded system matrix is converted into arrays to minimize computation time and storage requirements. The problem therefore, can be solved numerically as a system of algebraic equations in 'T', unknown nodal temperatures. The time dependence of equation (9) can be faced by considering the problem as a succession of steady states.

V. Experiment

Experiments are conducted using the test casting shown in Fig. 3. The test casting is divided into number of two dimensional axis symmetric elements for numerical analysis.

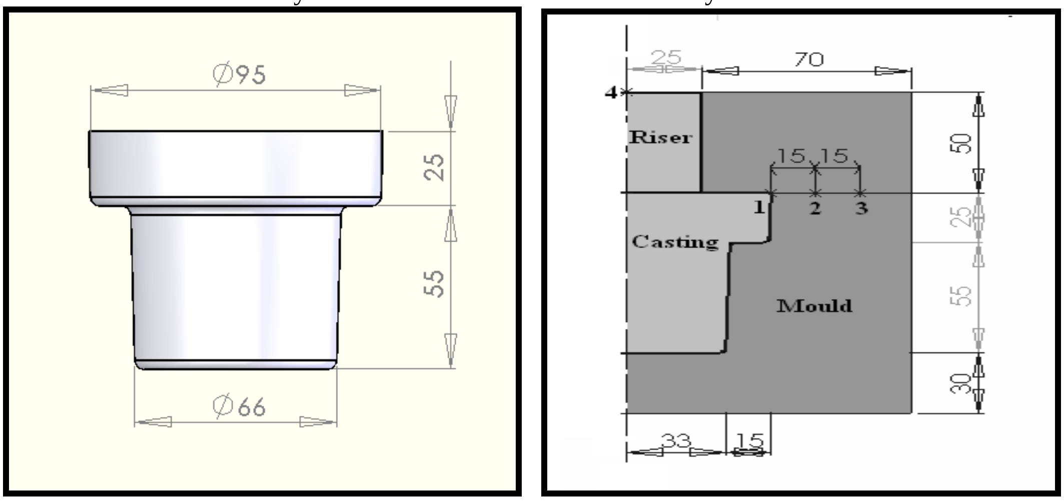

Fig. 3(a) Test casting with dimensions, (b) Schematic representation of the casting geometry and the selected locations for plotting temperature history.

5.1 Boundary conditions

- Initial Temperature of the casting is considered to be 1023°K.
- Initial Temperature of the mould is considered to be 298°K.
- Convective boundary condition is given at the mould – atmosphere interface.

5.2 Material Properties

5.2.1 Casting: The metal selected in the present study is aluminum alloy A356 (Al 7% Si, 0.3% Mg). The solidus and liquidus temperature are 793°K and 853°K respectively. The freezing range is 60°K hence the alloy is long freezing range alloy. Considering constant thermal conductivity and density since enthalpy method is selected for analysis. Enthalpy versus temperature data is given in the form of curve [36] shown in Fig. 12. Properties of aluminium alloy used [38-40] are also mentioned below.

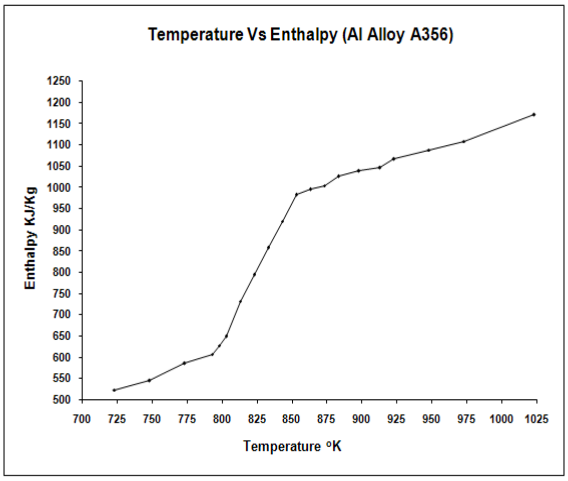

Fig.12: Temperature Vs Enthalpy for A356 alloy.

Properties of Aluminum Alloy used

K (W /m °K) = 160
C (KJ/Kg °K) = 0.963
ρ (kg/m³) = 2710
L (KJ/Kg) = 389
Pouring Temperature, T_i (°K) = 1023
Solidus temperature, T_s (°K) = 793
Liquidus temperature, T_L (°K) = 853

5.2.2 Air gap: Thermal resistance occurred between the casting and mould interface due to improper contact, mould coating, oxide formation, shrinkage of metal, and mould gases. In present study analysis is carried with and without air gap considering the curve [37] shown in Fig.13. If air gap [32-34] is considered apparent density and thermal conductivity have to be given. Properties of interface resistance used are given below.

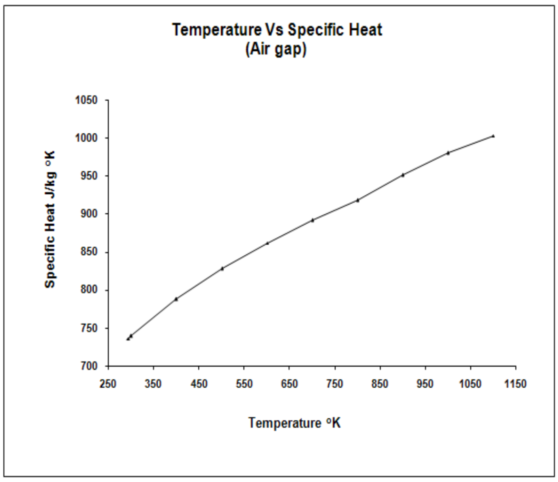

Fig.14: Temperature Vs Specific Heat (apparent) for air gap.

Properties of interface resistance (air gap) used

K (W/m°K) = 0.009
Density (kg/m³) = 1490

5.2.3 Mould: Constant thermal conductivity and density is considered. Data for specific heat versus temperature is given in the form of curve [37] shown in Fig. 14. Properties of silica sand used are also mentioned.

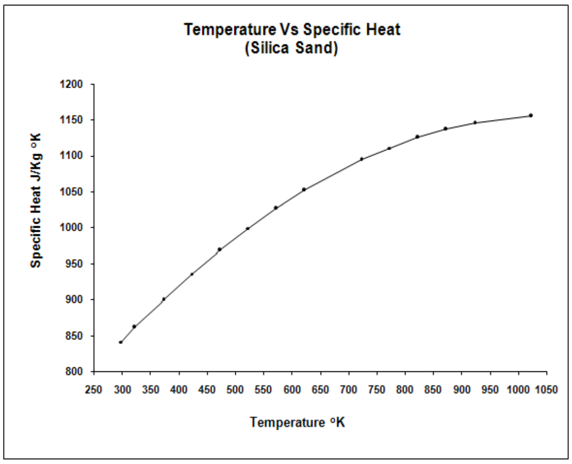

Fig.13: Temperature Vs Specific Heat for silica sand.

Properties of silica sand used

Density (Kg/m^3) = 1540
K (W/m^oK) = 0.602
Apparent specific heat of sand
(KJ/Kg^oK) = 1.16

5.3 Time Step

The phase change model is highly non-linear and the crossing of the phase change should be done carefully. If the time steps [27] are too large, some elements of the model could go from liquid to solid without having contributed with all of its latent heat. The time step can be calculated as follows:

$$\Delta t = \frac{(\Delta x)^2}{4\alpha} \qquad (17)$$

Where Δx is the conducting length of the element in the region over which largest temperature gradient acts, and ∝ is the thermal diffusivity of the medium. In case of a casting solidifying in a mould, there is a high non-linearity at the beginning of the simulation, due to a large temperature differential across the interface. The time step for the initial region should be fairly small.

$$\Delta t = \frac{(0.2)^2}{4*0.358} = 0.0279 \text{ sec.} \qquad (\text{Where } x = 2 \text{ mm}, \ \alpha = 0.358 \text{ cm}^2/\text{sec}).$$

Time step for initial region is considered as 0.005 sec to obtain better results. Numerical analysis is run for a solidification time of 10 sec without air gap and for 20 sec with air gap.

Interface resistance between casting and mould is modeled by placing a layer of small elements between the casting and mould elements, which corresponds to the interface distance between the casting and mould, which in the present study is 0.1 cm. The interface effective heat transfer coefficient is converted to conductivity that could be assigned to interface elements. Riser is insulated by removing the sand elements near the riser in the model.

5.4 Experimental Setup

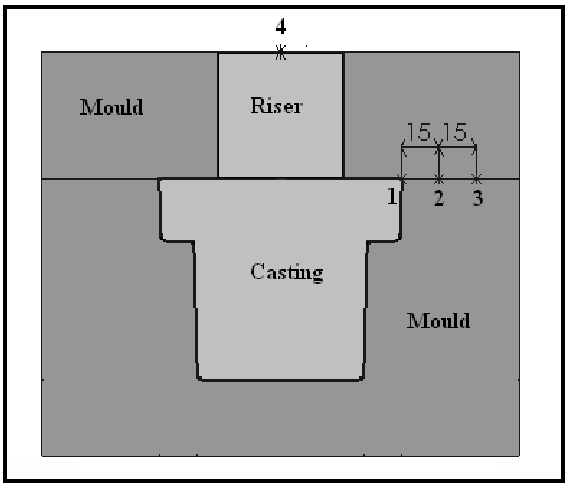

Fig.4: Schematic representation of test casting with mould and locations of thermocouples used in the experiment.

5.5 Casting Details

Volume of casting = 376 cc.
Weight of casting = 1.01 Kg.
Cooling surface area of casting = 324 Sq.cm.
Modulus of casting (Mc) = 1.16
Modulus of riser (Mr) = 1.2 Mc = 1.39
Diameter of riser = 6.96 cm
Cooling surface area reduces once the riser is located on casting therefore the diameter of riser is recalculated.
Revised cooling surface area = 285.92 Sq.cm.
Modulus of casting = 1.315
Modulus of riser = 1.578
Diameter of riser (ordinary sand riser) = 7.89 cm ≈ 8 cm.
Diameter of insulated riser = 5cm.

In order to verify the riser requirements four-test castings were poured.

1. The first casting is made with ordinary sand riser having diameter 50 mm and height 80mm, it is found that centerline shrinkage is extending from the riser top into the casting up to a depth of 35mm. The reason is the under sized riser Fig.5.
2. Second casting is poured with an ordinary riser having diameter 80mm and height 80mm as calculated. The shrinkage spot is shifted from casting to riser thus eliminating the defect, but the yield of the casting is 43% Fig.6.
3. In order to improve the yield of casting, the next casting is made by insulating riser (insulating sleeve of 2"x 3" is provided) the diameter of riser is 50 mm and height is 75mm. The casting is found to be free from shrinkage and yield is improved from 43 % to 61% Fig.7.
4. Insulating sleeves are of standard sizes (2"x 3") 50 x75mm. In order to improve yield further riser height to diameter ratio is made one (i.e.; height = diameter = 50mm) the yield is improved from 61% to 67% Fig.8.

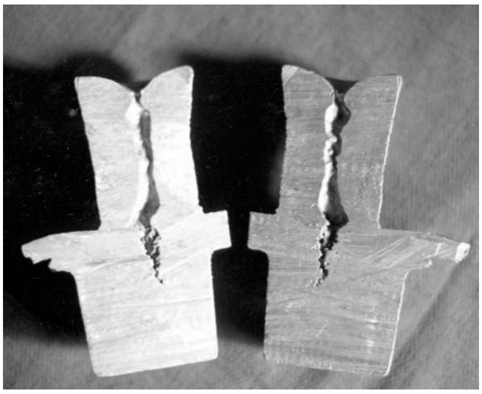
Fig.5: Section of test casting showing Shrinkage

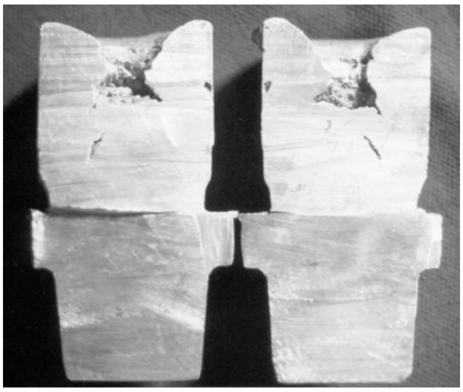
Fig.6: Section of casting with adequate riser Diameter

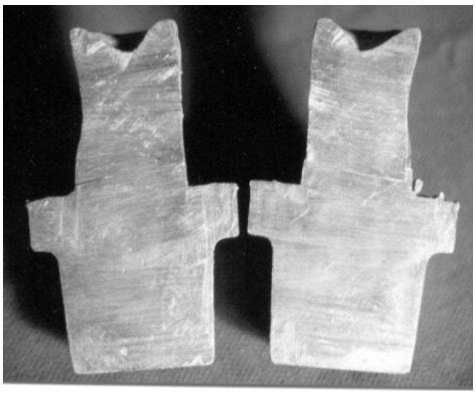
Fig.7: Section of casting with insulated Riser

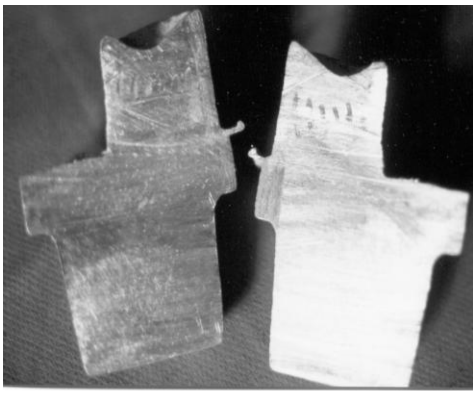
Fig.8: Section of casting with Insulated Riser of H/D=1

VI. Results And Discussions

6.1 Aluminum alloy A356 is simulated without interface resistance; it is found that casting is solidifying faster when compared to the expected theoretical value. The actual solidification time is noted by pouring the casting and Time-Temperature history is plotted as shown in the Fig.9.

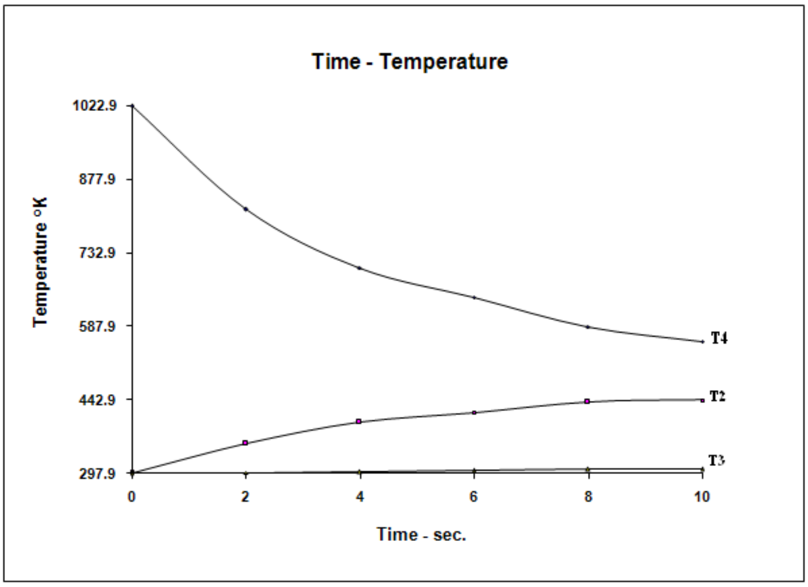

Fig.9: Temperature history at selected locations without interface resistance.

6.2 Same alloy is simulated assuming an interface resistance and a sand riser without insulation; it is found that solidification time of the casting is nearer to the estimated values. During the numerical analysis interface resistance is considered right from the first iteration. But in actual solidification process the formation of air gap occurs after few seconds from commencement of solidification. Since there is no method to track the formation of air gap and introduce it in the numerical analysis after few seconds from commencement of solidification the problem is assumed to have air gap right from beginning of solidification Fig.10.

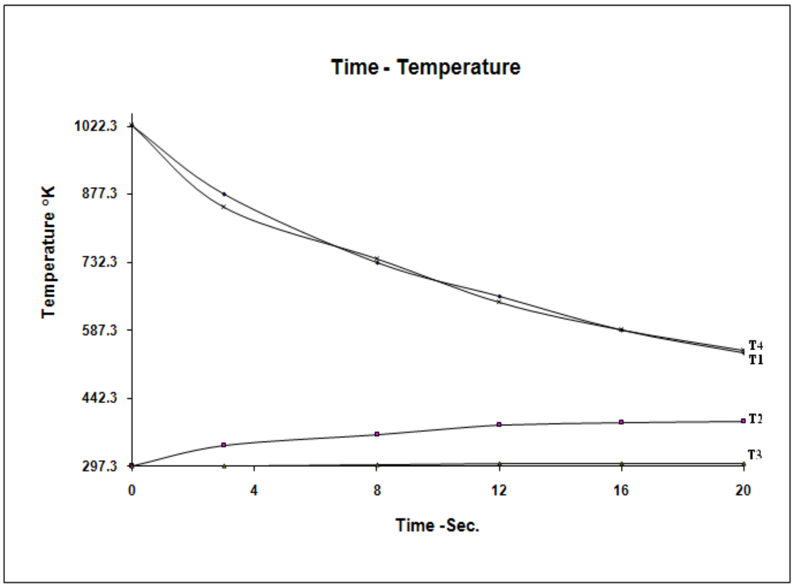

Fig.10: Temperature history at selected locations with interface resistance.

6.3 Four castings are poured to verify the results obtained from numerical solution. To study the effect of riser insulation a casting with ordinary sand riser is simulated and is found that maximum temperature zone (hot spot) is in the casting. In order to eliminate hot spot riser is insulated, results showed shifting of hot spot from the casting to riser. It is observed that the results obtained by numerical solution are within an error of 15%. The experimental temperature history plotted at selected locations is shown in Fig.11.

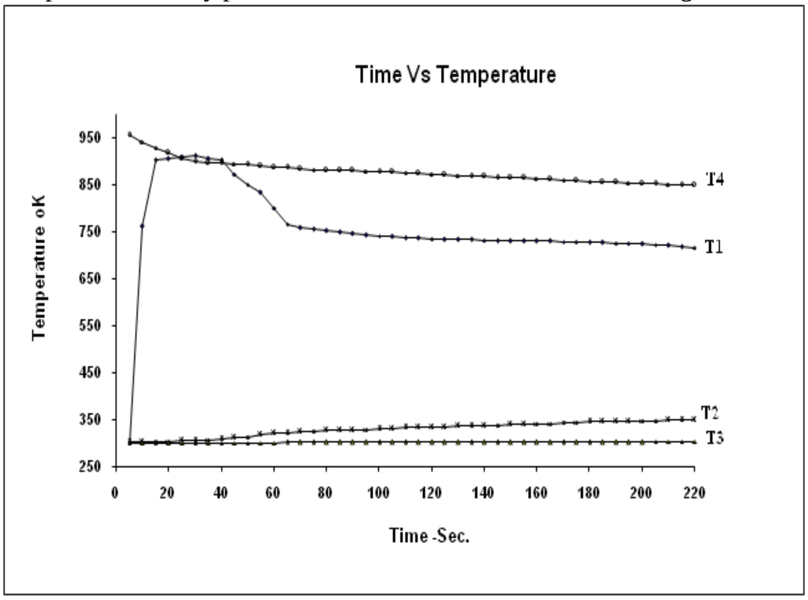

Fig.11: Temperature History at selected locations based on experimental data.

VII. Conclusions

Solidification simulation of aluminum alloy casting is carried out and the effect of riser insulation is studied. The results obtained by simulation and those obtained by experimental method are within an error of 15%. The differences in the results are due to improper method to track the formation of air gap during solidification. By using riser insulation the yield of the casting is improved from 43% to 67%. It is observed that the results obtained by the solidification simulation are helpful in optimizing casting yield, indentifying volume deficit locations, eliminating shrinkage and hence reducing number of trials and rejections in foundry.

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