International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-9 Issue-4 November 2020

Simulation of lead Antimony Alloy Solidification and its Experimental Validation

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Abstract: The solidification of metals continues to be a phenomenon of great interest to physicists, metallurgists, casting engineers, and software developers. It is a non-linear transient phenomenon, posing a challenge in terms of modeling and analysis. During the solidification of a casting in a mould, the heat-transfer between the casting and the mould plays a vital role. This paper attempts to study heat flow within the casting, as well as from the casting to the mould, and finally obtains the temperature history of some points inside the casting. The most important instant of time is when the hottest region inside the casting is solidifying. ProCAST software has been used to obtain the temperature distribution in the casting process by performing Transient Thermal Analysis. In this research work, solidification of lead-2wt%antimony alloy has been carried out in the different sizes of metallic mold to predict the formation of shrinkage during solidification. Theoretical results have been validated experimentally for a particular case of lead-2wt%antimony alloy solidification. Results obtained by simulation software are compared with the experimental reading of temperature and found to be in good agreement. Voids appeared at the top and isolated area of castings for the defect-free direct method used in this study.

Keywords: Solidification; Shrinkage; Simulation; Lead-2wt.%antimony alloy.

I. INTRODUCTION

Metal casting is one of the direct methods of manufacturing the desired geometry of components. Casting rejections are of major concern in the foundry industry. Great saving of materials, energy, and time can be achieved if the casting design can be corrected before moulding based on defects prediction [1, 2]. These facts make solidification simulation, a powerful tool to help the foundrymen in predicting casting defects. To identify the process parameters and their optimum values, simulation of the solidification process is done by running indigenously developed computer software for the casting process selected for investigation. The program output provides the details of the time-temperature profile which plays a key role in the effective design of castings [3]. Solidification of any metal leads shrinkage but in the case of lead alloy, shrinkage is more because of the low melting point and a large difference in liquidus and solidus density **[4]**. Shrinkage may be macro and micro porosity types in the casting.[5]Jiaqi Wang et al. reported the centreline shrinkage porosity of a heavy ingot which is used by the nuclear power plant as a low-pressure rotor. He compared the experimental results with FEM based simulated results utilizing the optimized design to get the porosity free castings. [6]C Zhang et al. observed the depth of the shrinkage cavity of steel ingot taking different casting parameters such as the height of insulation, taper, pouring rate, and pouring temperature. He found that the depth of the shrinkage cavity reduces by increasing the height of insulation and other parameters influence a small extent.[7]Gao Yong et al. predicted the shrinkage porosity of ingot using different mold height and vertical temperature gradient on mould wall. He found that the shrinkage porosity increases by increasing the mold height and significant improvement in porosity on applying temperature gradient.[8]Lokendra et al. investigated the melting of lead in a stainless steel cuboid. The vertical wall of the cuboid was maintained at a constant heat flux and movement of the solid-liquid interface was captured using neutron radiography. The enthalpy-porosity method was applied for numerical investigation using the numerical tool Fluent.[9]Sarkar et al. studied the visualization of melting front propagation in real-time for convection-driven melting and solidification of lead using neutron radiography. He observed two-dimensional radiographs of the propagation of the interface defined by solid and liquid lead concerning time and heat flux. He used an imaging system to capture the propagation of the interface of solid and liquid lead. He also compared the impure lead melting time with pure lead and found less time taken than pure lead.[10]Many researchers have done research work on the lead-antimony alloy to investigate the formation of dendritic structure on behalf of solidification conditions (alloy composition, solidification velocity, and cooling rate).[11, 12]Therefore, it is essential to study the solidification characteristics of lead-2wt.%antimony alloy to understand the phenomenon of formation of shrinkage/voids theoretically and experimentally. In this work, simulation has been carried out for the different height of cylindrical moulds with a fixed diameter.

Revised Manuscript Received on September 25, 2020.
Manuscript Received On October 06, 2020

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II. MATHEMATICAL MODELLING

The domain of solution with boundary condition is shown in Figure 1.

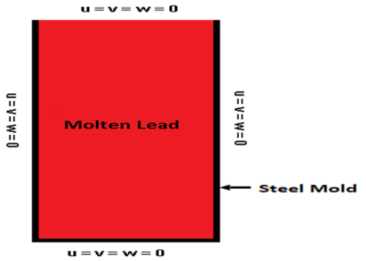


Fig1. The domain of solidification of lead-2wt.% antimony alloy

The fluid flow module solves the filling of mold, fluid flow, natural and forced convection, dynamic liquid pressure, and entrapped gasses by the solution of the Navier- Stokes equation.

The Navier-Stokes equations are given by:

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial (u_j \rho u_i + P\delta_{ij} - \sigma_{ij})}{\partial x_j} = \rho g_i$$

Where, ρ = density of liquid metal, P = pressure, δ_{ij}= Kronecker delta, σ_{ij}= Stokes viscous stress tensor,

g_i = gravitational acceleration

The conservation of mass is balanced through the continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0$$

Where, ρ = density of liquid metal, u_i= f_l $u_{i,liq}$ = component of superficial velocity, f_l = liquid fraction, $u_{i,liq}$ = Actual liquid velocity

The heat flow calculation, latent heat release during solidification is obtained by solving the Fourier heat conduction equation. Temperature distribution, Fraction of solid evolution, Heat flux and thermal gradients, Solidification time, Hot spots, Porosity prediction are obtained by solving the energy equation along with the fluid flow. The energy equation according to the characteristics of casting the three-dimensional unsteady temperature field was adopted as per the Eq. (1). Transient non-linear conduction equation is:

$$\rho \frac{\delta H}{\delta T}\frac{\delta T}{\delta t} - [k\nabla T] - q(x) = 0 \quad (1)$$

Where, H= Enthalpy, k = conductivity, T = nodal temperatures, q(x) = volumetric heat source

Transient heat transfer analysis of casting is given by enthalpy; Enthalpy of liquid metal is given by

$$H_{(T)} = \int_0^T C_p dT + L[1 - f_s] \quad (2)$$

Where, C_p= specific heat, L = latent heat, f_s= Solid fraction

Niyama criterion (N_y) was used in near the end of solidification to predict shrinkage micro porosity [13].

$$N_y = {}^{G}\!/\!_{\sqrt{\dot{T}}}$$

Where, G is temperature gradient, $\dot{T}$ is cooling rate.

In this modelling work it was assumed that solidification of metal start only after complete feeling of stainless steel mold.

Boundary conditions are shown in the domain Figure 1.

The following boundary and initial conditions were used to simulate the lead-2wt% antimony alloy solidification.

A. Boundary conditions

1. There is no movement of liquid metal around the wall of mold.
2. Mold is stationary.
3. Heat transfer will start after complete filling.
4. The top of the liquid metal is in direct contact with atmosphere.

B. Initial Conditions

1. Mold is initially at room temperature (30 ^{o}C)
2. The ambient temperature is also 30 ^{o}C and heat transfer coefficient between mold wall and surrounding is 25 $Wm^{-2}K^{-1}$.
3. Metal is filled at 350 ^{o}C.

The only movement of liquid metal is due to natural convection.

Convective heat flux boundary condition

$$-k\,\nabla T \cdot \hat{n} = h\,[T - T_a] \quad (1)$$

Where, $\hat{n}$ =unit vector normal to the surface, h = convection heat transfer coefficient between mold to surrounding also known as convective film coefficient, T_a = ambient temperature

C. Solution Method

The finite element Method (FEM) was used to solve differential equations. The solution domain, Ω was divided into a set of non-overlapping elements which completely fill the space. The temperature in each of these elements interpolated from discrete nodal temperature. This computes a temperature field which approximates the exact solution.

$$T(x,t) = N_i(x)\, T_i(t) \quad (2)$$

Where, N_i = interpolating or "shape" functions

T_i = nodal values of temperature

The approximate solution of Eq. (2) was taken as input for the governing field and boundary condition of Eq. (1). This resulted into a residual error. This error was minimized by the Method of Weighted Residuals, applying the Galerkin procedure [14] of using the shape functions, N_i, as the weighting functions. This results in the symmetric matrix system

$$C\dot{T} + KT = F \quad (3)$$

Where, $\dot{T}$ = Time derivative of the vector of nodal temperatures, C = capacitance matrix with terms

$$C_{ij} = \int_\Omega \left(\rho \frac{dH}{dT}\right) N_i N_j \, d\Omega$$

K = conductivity matrix with terms

$$K_{ij} = \int_\Omega \nabla N_i . (k \nabla N_j) d\Omega + \int_{\Gamma_2} h N_i . N_j d\,\Gamma_2$$

F = source vector with terms

$$F_i = \int_{\Gamma_2} N_i . (q - hT_a) d\,\Gamma_2$$

The integrations were performed on an element-by-element basis and assembled to form the global matrices. The first order differential equation system of Eq. (3) was numerically integrated by a two level predictor-corrector method. The solution of Eq. (3) determines temperature distribution of the domain. The above solutions were carried out on the FEM based commercial software ProCast 2014.0 [15].Mathematical modelling of solidification of lead-2wt.% antimony alloy was carried out to understand the formation of voids and shrinkages.

III. THERMO-PHYSICAL PROPERTIES

Thermo-physical properties of lead-2wt.% antimony alloy and stainless steel grade 304 are given in Table 1 and Table 2, which were used as an input for simulation of lead-2wt% antimony alloy casting.

Table1: Thermophysical data for lead-2wt.% antimony alloy [11]

1	Solidus Temperature, (^{0}C) Liquidus Temperature, (^{0}C)	295 322
2	Thermal Conductivity, (W/mK) at 295 ^{0}C 322 ^{0}C	32.8 29.5
3	Density of solid (g/cc) Density of liquid (g/cc)	11.251 10.598
4	Latent heat of fusion, kJ/kg	28.80
5	Specific heat, kJ/kg.K	0.1401

Table 2: Thermophysical data for Stainless steel 304 [16]

1	Thermal Conductivity, (W/mK)	14.85
2	Density of solid (g/cc)	8.02
3	Specific heat, kJ/kg.K	0.49

IV. EXPERIMENTAL VALIDATION OF MODEL

A Cylindrical mold of grade 304 stainless steel 70 mm internal diameter and 210 mm height with shell thickness 3 mm was selected for validation. K-type thermocouples were attached to the surface of the mold wall and at the centre of mold cavity to obtain the temperature profile during solidification of mold wall and liquid metal using data acquisition system. A Schematic sketch of experimental set up is shown in Fig. 2. Experimentally obtained temperature v/s time plot was also used to finalize the heat transfer coefficient between liquid metal and mold wall. The induction furnace was used to melt the lead-2wt.% antimony alloy. Molten lead-2wt.% antimony alloy was poured into the mold at 350 °C. The mold was kept in open atmosphere at room temperature (30 °C).

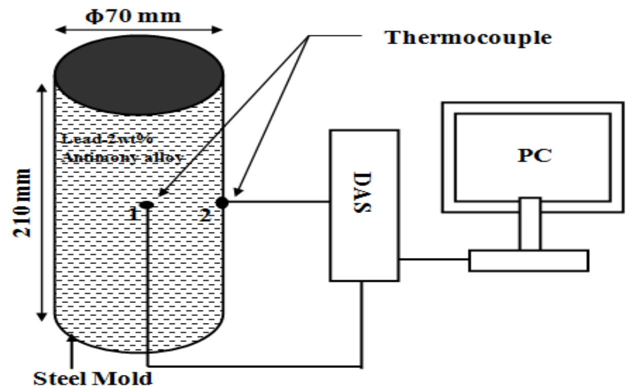


Fig.2. Schematic two dimensional view of the experimental setup

V. RESULTS AND DISCUSSIONS

A. Determination of heat transfer coefficient between mold wall and liquid metal

It is essential to give an input of the heat transfer coefficient between the wall of the mold and molten lead-2wt.% antimony alloy for simulation of solidification of molten lead-2wt.% antimony alloy in a stainless steel mold. The value of heat transfer coefficient between liquid metal and mold wall was determined by matching the simulated temperatures vs. time plot at the centre of liquid metal and the wall of the mold wall. Locations of temperature determination with respect to times are shown in Fig. 2. Simulated and experimental plots of temperature and time of both points were similar for the value of heat transfer coefficient 300 $Wm^{-2}K^{-1}$. Therefore, 300 $Wm^{-2}K^{-1}$was taken as a fixed value of the heat transfer coefficient for further simulation of lead solidification. Fig. 3 shows the experimental and simulated temperatures vs. time plots for the wall. The temperature vs. time plot for liquid metal experimental and simulated is shown in Fig. 4.

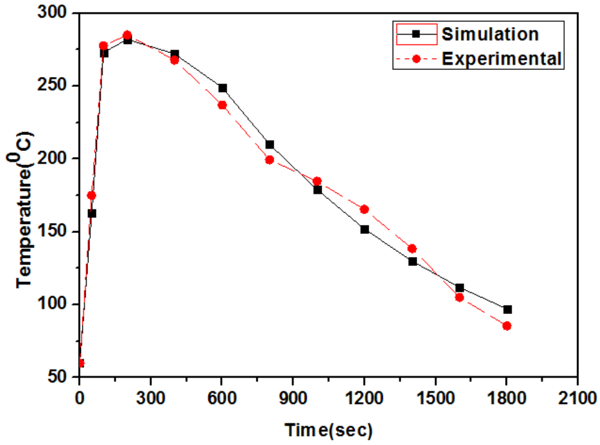


Fig.3. Simulated and experimental temperatures vs. time plot at a point on mold wall

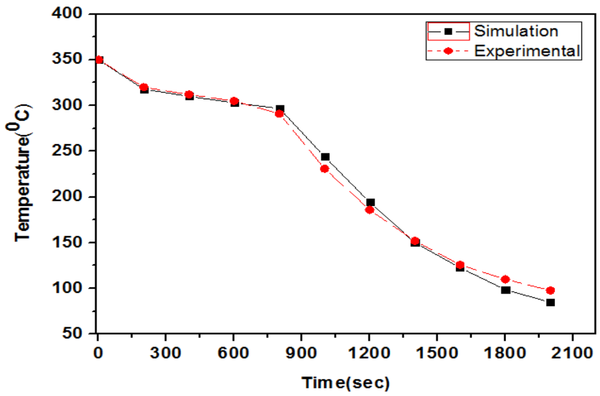


Fig.4. Simulated and experimental temperatures vs. time plot at a point inside molten lead-2wt.% antimony alloy

B. Simulation of Lead-2wt.% Antimony Alloy Casting

Studies on shrinkage characteristics of lead-2wt.% antimony alloy were conducted theoretically. The solid models for shrinkage simulations were created using the CATIAV5R19 software. A virtual environment for the casting solidification process is created based on FEM. It predicts and analyses the occurrence of shrinkage defects. The input for the casting process simulations is a solid model of the casting, material properties, boundary conditions, and initial conditions. The software consists of three major processes; Pre-processing, Solving the Governing Equations, and Post-processing or Visualization of results.

In the present research work, the interfacial heat transfer coefficient between mold wall and molten lead-2wt.%antimony alloy was taken experimentally and theoretically determined value 300 $Wm^{-2}K^{-1}$ for simulation. The solid model domain of lead-2wt.% antimony alloy casting and mold were divided into small elements. Every element was assigned to boundary conditions, initial conditions, and thermo-physical properties. Based on the above boundary conditions and initial conditions grid-independent tests were carried out. The relative mesh size 5 out of 1 to 10 was selected for simulation based on a grid-independent test. The minimum time step was 0.01second. Solidification simulation was carried out till 100% liquid solidified i.e. solid fraction from 0 to 1. Simulations were carried out for the lead-2wt.% antimony alloy casting to study the formation of shrinkage/defect formation.

Solidification of lead-2wt.% antimony alloy was carried out in different sizes of a stainless steel mold. Simulations were carried out for 100 mm, 150 mm, 210 mm, 250 mm, and 300 mm height of stainless steel mold for a fixed diameter of mold i.e. 70 mm. The temperature profile and shrinkage porosity profile are shown in the Figs. 5 and 6 for different height of casting. The least solidification time was observed 525 seconds for the lowest height casting (100 mm mold height), while maximum solidification time (661 Seconds) was observed in the case of the longest height (300 mm) of mold. The variations of solidification time for different molds are different because of the difference in material content. The heat content is directly proportional to the mass, not the pouring temperature or initial temperature of molten metal. Temperature profiles show the temperature distribution in the casting concerning colour gradient as shown in Fig. 5. The maximum temperature after solidification is just below the top of the casting as presented in the temperature profile. It means the last liquid to solidify at that point. Therefore, there is an appearance of shrinkage porosity just below the top solidified region. Lower height castings do not show isolated shrinkage, it may be due to the high cooling rate from wall to centre as shown in Fig. 5. Therefore, it did not appear in the experiment as shown in Fig. 9(b). But isolated shrinkages were observed for casting for height 300 mm as presented by simulated results shown in Fig. 5.

Simulated results of voids are shown in the depth of the void and height of the casting graph in Fig. 7. The tendency for the formation of shrinkage is related to liquid temperature, freezing range, and materials. Volume deficit or shrinkage happens in metallic materials during solidification and cooling due to a reduction in specific volume, which is a physical characteristic of materials. The molten metal volume decreases during solidification due to the atoms drawing nearer and coming to fixed lattice positions resulting in shrinkage. This shrinkage occurs in three stages as shrinkage of the molten metal during cooling, shrinkage due to solidification, shrinkage from solidification temperature to room temperature. The amount of shrinkage is large in the lead-2wt.% antimony alloy casting because of a large variation in density with temperature particularly solid to liquid condition. That is why it is necessary to study the lead-2wt.% antimony alloy casting to avoid any kind of shrinkage.

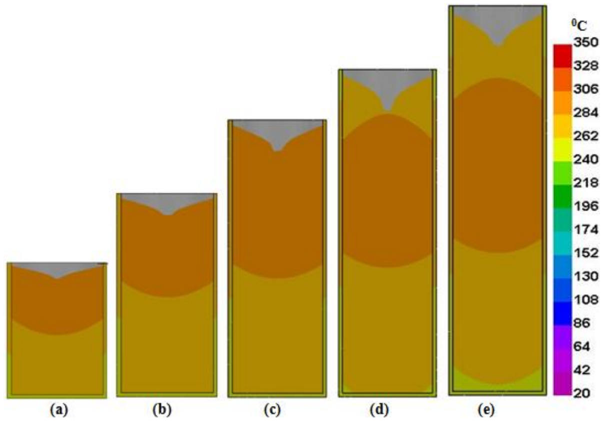


Fig.5. Temperature profile for lead-2wt% antimony alloy casting of (a) 100 mm, (b) 150 mm, (c) 210 mm, (d) 250 mm and (e) 300 mm casting height

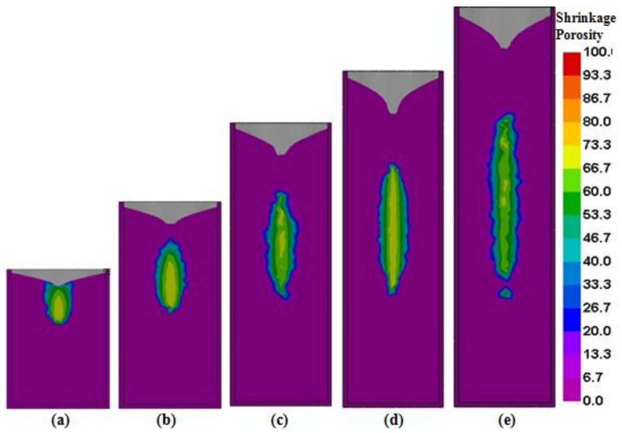


Fig.6. Shrinkage Porosity profile for lead-2wt% antimony alloy casting of (a) 100 mm, (b) 150 mm, (c) 210 mm, (d) 250 mm and (e) 300 mm casting height

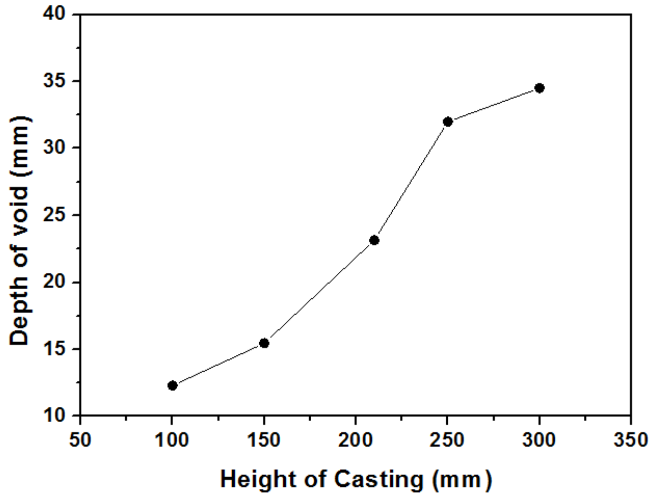
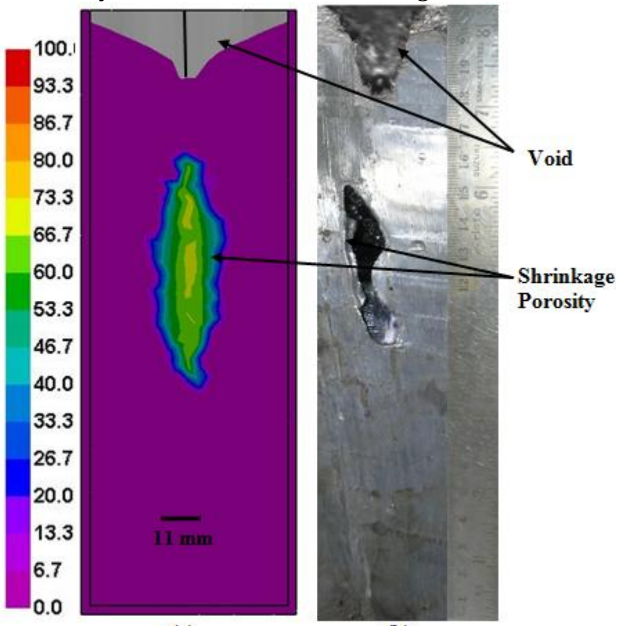


Fig. 7: Graph between depth of void and casting heights

VI. EXPERIMENTAL VALIDATION

To validate the mathematical model, experiments were carried out as shown in Fig. 2. The lead-2wt.% antimony alloy melt was poured into the stainless steel mold of height 210 mm.

The casting was cut throughout the cross-section to observe the exact depth of void/shrinkage at the top of the casting. The simulations were carried out for solidification of lead-2wt.%antimony alloy in the same size of mold under the same boundary and initial conditions as per the experimental. Simulated and experimental shrinkage porosity observed similar which validating the simulation work. Shrinkage porosity for 210 mm height and 70 mm diameter of mold casting is shown in Fig. 8. The maximum depth of voids at the top of casting was observed 24 mm as indicated by the vertical line shown in Fig.8.



(a) (b)

VII. CONCLUSIONS AND SUMMARIES

In the present work the shrinkage porosity of lead-2wt.% antimony alloy was analysed. The most important conclusions that can be drawn are:

1. Mathematical model has been developed.
2. This model can predict temperature profile, voids/shrinkage profile in casting.
3. Model predicts formation of voids and shrinkage in lead-2wt.% antimony alloy Castings.
4. Experimental profile of Void and shrinkage matched well with the simulated result.
5. It also can be seen that the depth of void increases with heights.

ACKNOWLEDGMENT

This study was financially supported by Bhabha Atomic Research Centre, Mumbai, India. We also thank for their continuous suggestions and improvement.

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