



Al-Si and Al-Si-Mg Cast Alloys Shrinkage Porosity Estimation

S. Samavedam*, S. Sundarrajan

MGIT, Hyderabad,

National Institute of Technology, Trichy

*Corresponding author. E-mail address: santhi_samave@yahoo.com

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Abstract

US A356 and US 413 cast aluminium alloys shrinkage characteristic have been discussed in the present study. Specific volume reduction leads to shrinkage in castings and it can be envisaged as a casting defect. Finite difference based casting process simulation software has been used to study the shrinkage characteristic and it is quantified using mathematical formulae. The three dimensional model of the shrinkage defect has been constructed using CAD application software. Shrinkage characteristic has also been quantified through experimental validation studies and compared well with casting process simulation. Shrinkage characteristic study and control is essential for producing defect free castings. Influence of casting shape on the shrinkage characteristic has been studied in this paper.

Keywords: Shrinkage characteristic, Cast aluminium alloy, Rectangular shape, Process simulation, Solid model

1. Introduction

The cast aluminium alloys are prone to shrinkage defects, one of the chronic problems and impacts the quality of the product [1,2]. The physics of formation of shrinkage porosity has been involving interactions among many physical phenomena such as heat transfer, fluid flow in the liquid stage including natural convection, flow in the mushy zone, solidification shrinkage, deformation of the solid skin due to the formation of under pressure and many more as stated by A. Reisetal [3]. Prediction of the behaviour of the liquid metal during solidification has been important to consider the different modes of shrinkage and trace the evolution of the liquid metal free surface⁴. The quantity of shrinkage and porosity has been depending on the thermal cooling conditions, the alloy content and the casting temperature [5,6].

The casting process simulation is time and temperature dependent¹. Solidification or freezing of castings is a non-linear transient phenomenon and it involves modification of phase with liberation of latent heat from a moving liquid-solid boundary. The

casting simulation programmes have been predicting temperature distribution or hot spots in the castings and use material data [7]. In order to predict shrinkage and porosity the thermal properties are defined as a function of the temperature [8,9]. Shrinkage porosity has been predicted by detecting open, partially closed and closed liquid regions by utilising appropriate boundary conditions [10]. Casting process simulations have been carried out using Virtual Casting software [11], based on solving the transient heat transfer equation with solid-liquid phase changes using finite difference method (FDM). This software has been developed by Regional Research Laboratory, Thrivandrum and has been installed at Institute of Indian Foundrymen(R&D) Center, Hyderabad.

2. Experimental plan

It has been observed from the literature that some of the influencing parameters for shrinkage characteristics are alloy


composition, shape of casting, mould coat, bottom chill, pouring time, mould sand and pouring temperature [1,5,12]. For the present study the process parameters considered were casting shape, bottom chill, pouring temperature and alloy composition.

Table 1.
Chemical composition (%wt)

Alloy	Si	Fe	Cu	Mn	Mg	Ni	Zn	Pb	Sn	Ti	Each	Total	Al
US A356	6.5-7.5	0.55	0.2	0.35	0.2-0.65	0.15	0.15	0.15	0.05	0.05-0.25	0.05	0.15	Rem
US 413	10.5-13.5	0.65	0.15	0.55	0.1	0.1	0.15	0.1	-	0.2	0.05	0.15	Rem

Rectangular casting shape has been considered for the present study. The rate of heat exchange depends on wall thickness of casting, its shape and thermo-physical properties of liquid metal¹². The dimensional details and pouring technique of the castings have been provided at table 2.

Table 2.
Dimensional details of the casting shapes for shrinkage characteristic

S.No	Shape	Dimension, mm	Pouring technique	Volume, cc
1	Rectangular	115x100x48		552

Pouring temperature [13,14] influences fluidity, porosity, strength and structure of the casting. Hence pouring temperature with 50°C of super heat was considered as one of the process parameter for the present study.

Another processing parameter is bottom chill which shows significant difference in the casting characteristics, promotes directional solidification, help in eliminating shrinkage porosity defects [15]. Mild steel bottom chill is considered for the present study. The details of the number of experiments conducted have been given at table 3.

Table 3:
The details of the number of experiments

Exp run order	Alloy	Chill	Pouring temperature (°C)	Mould coat
1.	US A356	MS	T+50	Graphite
2.	US A356	MS	T+50	No coating
3.	US A356	MS	T	No coating
4.	US A356	No	T+50	Graphite
5.	US A356	No	T	Graphite
6.	US A356	No	T	No coating
7.	US 413	MS	T	No coating
8.	US 413	MS	T	Graphite
9.	US 413	MS	T+50	No coating

Alloy composition influences the shrinkage characteristics, mechanical properties and structure of the cast product. The chemical composition of the alloys considered for the present study has been given at table 1.

Exp run order	Alloy	Chill	Pouring temperature (°C)	Mould coat
10.	US 413	No	T	Graphite
11.	US 413	No	T+50	No coating
12.	US 413	No	T+50	Graphite

3. Casting Process Simulation

3.1. Solid model

Simulation studies on shrinkage characteristics of aluminium alloy have been conducted using the Virtual casting commercial software [11]. The solid models for shrinkage simulations were created using the SolidWorks. The solid model or test piece for rectangular shape casting is given in Figure 1.

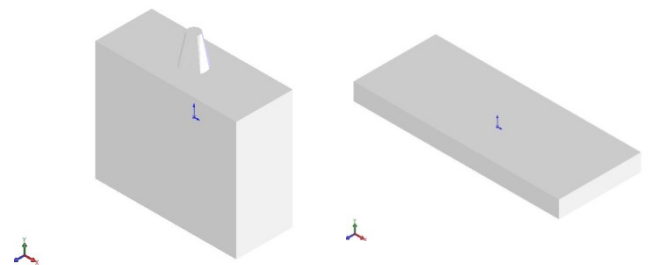


Fig. 1. Solid model of Shrinkage studies

3.2. Simulation studies

Virtual Casting is based on finite difference method. Virtual casting software has been creating a virtual environment for casting solidification process [11], predicting and analysing the occurrence of shrinkage defects. The input data for the casting process simulation are solid model of the casting, material properties and boundary conditions. Virtual Casting consists of three major processes; Pre-processing, Solving the Governing Equations and Post-processing or Visualization of results. The simulation output / results are displayed as contour plots of

temperature, porosity, solid fraction (Fs), solidification time and cooling rate.

For accurate results, the process simulation requires introduction of boundary conditions. The boundary condition values to be described at the beginning of the process are thermal data of metal and casting mould, conditions of heat exchange between a casting and individual parts of mould and between mould and surroundings.

The interfacial heat transfer coefficient is the rate of heat loss through the metal/mould interfaces which influence the casting characteristics [16]. However, interfacial heat transfer coefficient is not a simple material property and is dependent upon chemical, physical interfacial conditions, mould and casting material properties and casting geometry [17]. The selection of interfacial heat transfer coefficient values as well as boundary conditions at the metal/mould interface affect the accuracy of the simulations. In the present investigations, interfacial heat transfer coefficient values for conformity of computer simulation and the experimental measurements are in consistency. The thermo-

physical properties of both alloys, bottom chill and silica sand [11] for the casting simulation have been given at table 4 [18,19].

The solid model of shrinkage characteristic which is imported in the stl file format as the solution domain, divides into small finite cells of casting and mould with a material id. Boundary Conditions are assigned at all material interfaces like metal, mould, ambient and mould coat.

Critical liquid fraction (a parameter used by the solver for calculation of porosity) is the value of liquid fraction below which a neighbouring cell does not feed to pay off for shrinkage. During solidification of a location, liquid is pulled in from neighbouring locations to pay off for solidification shrinkage. If the neighbouring location has a high percentage of solid, liquid cannot flow through it. The Exit solid fraction is the total volume percent of solid at which the solver exits. For example, a value of 1 for exit solid fraction means that the simulation will be done till the casting is 100% solidified. The contour plot for simulation run order 10 is shown in figure 2.

Table 4.
Thermophysical data for casting process simulation

S.No	Parameter	US A 356	US 413	Sand	MS Chill
1.	Melting point, (°C)	660	574	-	-
2.	Thermal conductivity, W/mm.K	0.159249	0.121338	90.27×10^{-5}	4.5×10^{-2}
3.	Density of solid (g/cc)	2.68496	2.65772	1.5219	7.84
4.	Liquidus temperature (°C)	613	574	-	-
5.	Freezing range (°C)	127.8	30.6	-	-
6.	Latent heat of fusion, J/Kg	388442	389112	-	-
7.	Specific heat, J/Kg.K	962.944	1170	1076.0076	460.548
Heat Transfer Coefficient, HTC, W/m ² K					
8.	Metal-mould	0.0035	0.0025		
	Metal- coating mould	0.0015	0.0012		

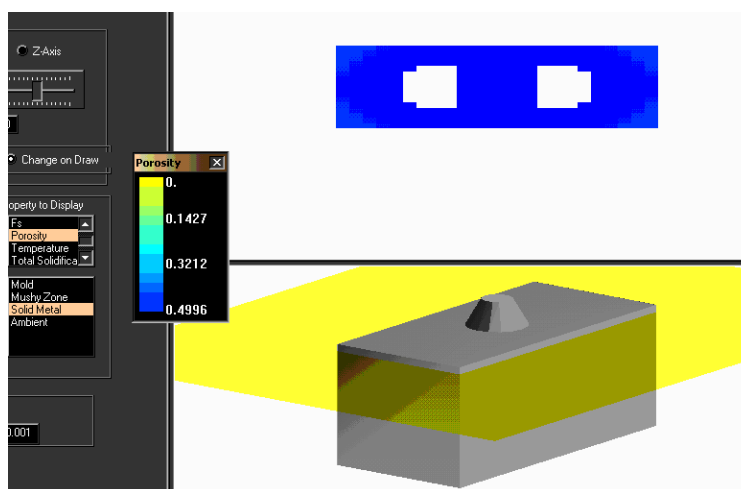


Fig. 2. Typical contour plots showing porosity distribution for simulation run order 10

The transformation from liquid to solid state is accompanied by a decrease in volume in most of the metals. Though metal casting process has greatly advanced, porosity, shrinkage and gas bubbles remain as inherent by-products of the casting process. These by-products, though not detrimental to the structural integrity of a casting, lead to product failures. The defects can be reduced by reducing the shrinkage, controlling the distribution of shrinkage and balancing it by using feeders and chills.

The tendency for formation of shrinkage is associated to both liquid and solid volume fraction and solidification temperature range of the alloy. Volume deficit or shrinkage occurs in metallic materials during freezing and cooling due to reduction in specific volume, which is a physical characteristic.

3.3. Construction of 3D shrinkage porosity

The present study shows the volume of the shrinkage porosity of the casting at various locations, which is difficult to measure in 2D. Hence 3D SolidWorks software has been used for generating 3D model of the images. The large tolerance level typical of (0.1 mm) foundry process has been considered for the present study [14]. The contour plot data for simulation run order 10 (fig. 2) at four locations starting from 103 mm from the flat bottom to 115 mm have been converted to solid model part (sldpart). Figure 3 shows constructed porosity of the simulation run order 10 using SolidWorks software is given below.

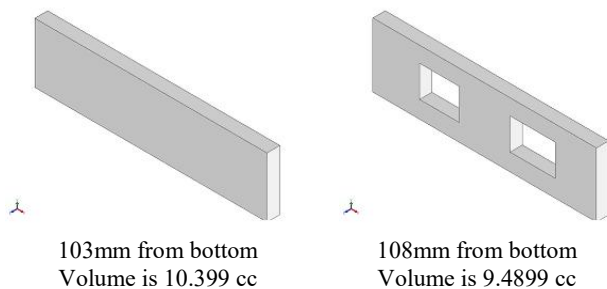


Fig. 3. shows constructed porosity of the simulation run order 10

Shrinkage porosity distribution for simulation run order 10 from 103-115 mm from the flat bottom is given at table 5.

Table 5. Shrinkage porosity for simulation run order 10

S.No	Distance from the flat bottom, mm	Volume cc
1	103	10.399
2	108	9.4899
3	115	5.412
Total volume		25.3018

Porosity distribution in these four locations is 0.499 which is obtained from the contour plot for this particular simulation run order 10. The amount of shrinkage porosity distribution in these regions has been calculated and given at table 6.

The porosity distribution for all the 12 simulation runs has been calculated in the similar way. The results are tabulated and given at table 7.

Table 6. Shrinkage porosity distribution in the regions for simulation run order 10

Total volume of shrinkage porosity	25.3018
Amount of shrinkage porosity distribution in these regions	Total volume x maximum porosity distribution in these regions 25.3018 x 0.499 12.6408
Amount of shrinkage porosity in the casting	12.6408/ volume of the casting from table 12.6408/552 0.0229
% Amount of shrinkage porosity in the casting for simulation run order 10	2.29

Table 7. Shrinkage porosity for 12 casting process simulations

Exp run order	%Shrinkage porosity	Exp run order	%Shrinkage porosity
1	2.628	7	2.1
2	2.7	8	2.19
3	2.8	9	2.0
4	2.895	10	2.29
5	3.1	11	2.18
6	3.13	12	2.12

3.4. Results and discussion

For the present investigation, short freezing alloy US 413 and long freezing US A356 alloy have been considered. Shrinkage normally occurs during the freezing process due to increase in density (when liquid metal solidify). Hypothetically, if there were no nuclei to let shrinkage to initiate at internal sites, all the contraction is generally seen on the outside surface. But there are plenty of internal sites for the nucleation of shrinkage, and this internal shrinkage appears as porosity. Oxide films and non-metallic inclusions are primary causes for porosity [20].

Macro shrinkage occurs when the liquid metal is surrounded by significant amount of solid material, which is strong enough to resist the depression of the contracting liquid [21]. Macro shrinkage is a concentrated zone of shrinkage holes or single shrinkage cavity in cast products that can be detected through non-destructive tests such as radiography, ultrasound, and magnetic particle method.

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 - shrinkage of the molten metal during cooling, shrinkage due to

solidification, shrinkage from solidification temperature to room temperature.

The influence of temperature on specific volume for pure metal is shown in Figure 4. The liquid contraction occurs from the pouring temperature to liquidus temperature which can be avoided by pouring extra liquid metal. The solidification contraction is caused by phase change from liquid to solid state. The solid contraction causes overall contraction of the solidified casting and results in residual stresses. The shrinkage pores are basically due to solidification shrinkage.

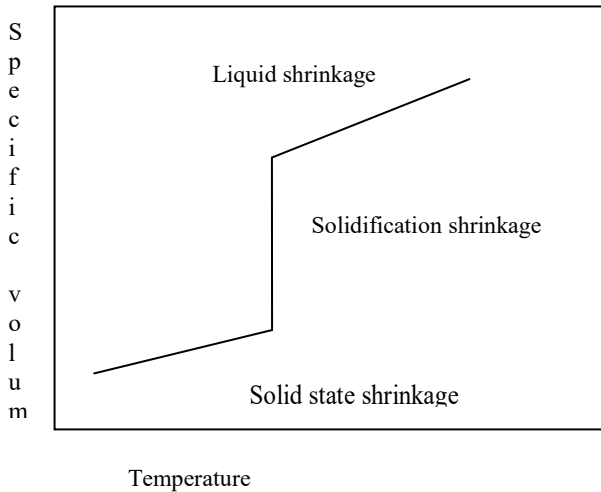


Fig. 4. Variation of specific heat with temperature

Porosity is generally rounded, isolated, and well distributed. Porosity that is interconnected or clustered and of an irregular shape corresponding to the shape of the interdendritic region is usually termed as shrinkage. However, in general, the occurrence of microporosity in aluminum alloys is due to the combined effects of solidification shrinkage and gas precipitation.

3.4.1. Influence of chill

Bottom chill reduces the shrinkage porosity for all the shapes of castings rectangle, cube, cylinder. Bottom chill extracts heat locally. However, there is an increased rate of heat extraction from the liquid metal and compensation of solidification shrinkage during the pouring time of molten metal increases. This shows a reduction in shrinkage porosity.

The rate of heat extraction and the temperature gradients inside the solidifying metal influence the solidification. Change in temperature gradient by the presence of chill has no effect on macro solidification and hence macro cavities are not influenced. Chill promote faster temperature gradient in the solidifying metal and increase its feeding capacity thus reducing internal porosity and pore size. The influence of bottom chill on the shrinkage porosity is given in Figure 5.

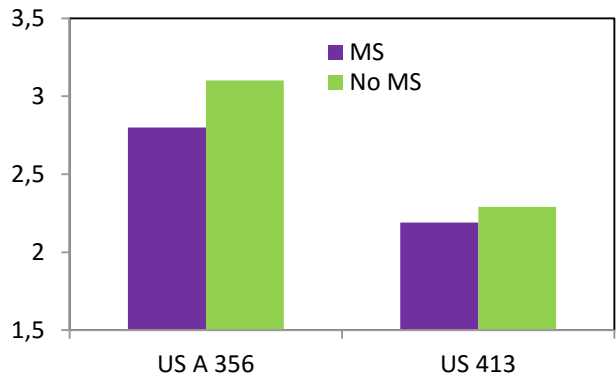


Fig. 5. Influence of bottom chill on the shrinkage porosity

3.4.2. Influence of pouring temperature

Pouring temperature is an important parameter in foundry for manufacturing quality castings. In order to study the affect of pouring temperature on shrinkage porosity, pouring temperature and pouring temperature +50°C have been considered. Superheat is (additional heat) essential for melting. Additional pouring temperature or super heat increases the fluidity and considers the allowance for heat losses before they are in their final position in the mould. Increase in pouring temperature results in lower rate of heat extraction by the mould. This causes a normal plane or rough wall morphology to pasty type. So with increased tendency towards pastiness, the strength of the solidifying shell decreases. Higher pouring temperature leads to decreased macro cavities and internal porosity as shown in the Figure 6.

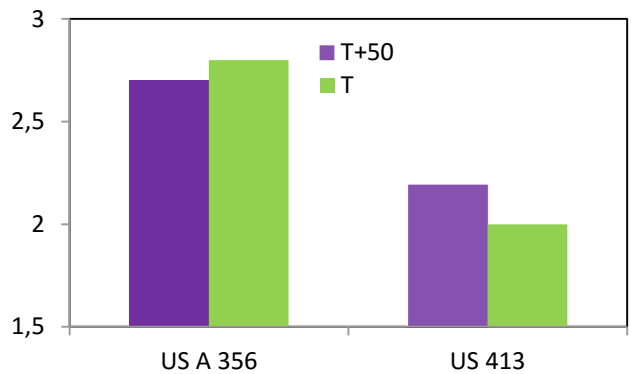


Fig. 6. Influence of pouring temperature on the shrinkage porosity

4. Experimental validation studies

The experimental validation studies have been conducted to validate the casting process simulation results. On the basis of experimental validation studies it is possible to compare and validate the simulation processes results with reality and optimize. To evaluate the influence of process parameters 4 (simulation run order 1,5,7 and 10) experiments have been conducted and schematic diagram of the testing arrangement for cube shape

casting as shown in figure 7. These experiments have been designated as exp run order 1 to 4. Prepared mould, overflow core and pouring basin for rectangular shape castings have been shown in figure 8. The overflow core is placed over the mould in order to ensure that a fixed quantity of metal only is poured each time into the mould.

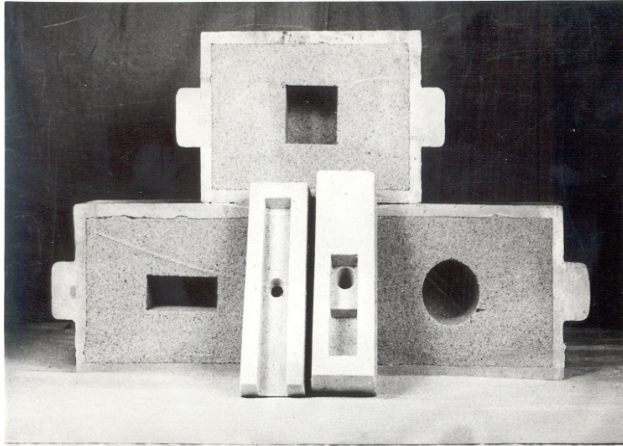


Fig. 7. The assembled mould for volume deficit experiment

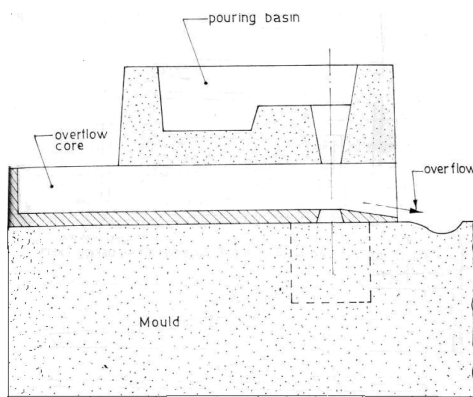


Fig. 8. Schematic diagram for the volume deficit experiment for cube shape casting

4.1. Moulding, melting and pouring

Moulds are prepared using green sand process. The sand composition consists of Bentonite 5-6% of sand weight and water is 5-8% of sand weight. Moulds are prepared with slight ramming. The patterns have been stripped after 3 hours. The alloy is melted in an electric resistance furnace of capacity 20 kg provided with mild steel crucible. Temperature is measured with the help of a thermocouple.

The furnace is put off and the crucible is lifted and put in a tilting device. The metal is tapped into a smaller crucible for pouring into the mould. Figure 9 shows the rectangular shaped solidified casting of the experimental validation studies.



Fig. 9. Rectangular Solidified casting of the experimental validation studies

4.2. Shrinkage porosity calculations for the experimental studies

Shrinkage porosity calculations for the experimental studies have been given below

1. The test casting is taken out of the mould and the cone portion is cut off. The volume of the pipe has been measured by keeping the casting under a burette and distilled water with wetting agent is dropped into the cavity till it is completely filled. The titration volume V_{titr} is read from the burette. The macrocavity, V_m is given by

$$V_m = V_{cone} + V_{titr}$$

2. The weight of casting in air and while immersed in water are determined using a sensitive balance of accuracy 0.001gm

$$V = (\text{weight in air} - \text{weight in water})$$

3. The theoretical volume, $V_{theoretical}$ is obtained as follows
 $V_{theor} = \text{Weight in air} / (\text{Theoretical maximum density where the theoretical maximum density is obtained from chill specimen})$

The internal porosity V_{int} is computed as follows

$$V_{int} = V - V_{theor}$$

Shrinkage porosity is given by $= (V_m + V_{int}) / V_{mould}$

Shrinkage porosity for experimental run order 1 is given below at table 8 using the above calculations. The shrinkage porosity values for the remaining 3 experiments have been calculated in similar way using the above calculations and are given at table 9.

Table 8.

Shrinkage porosity for experimental run order 4 for rectangular to be incorporated

S.No	Parameter	Exp run order 4
1.	Gair(Wt),gm	1429
2.	V_{theor}	539.245283
3.	$V = (Gair - G_{water})cc$	540
4.	V_{titr} , cc	10
5.	V_{cone}, gm	1.535
6.	V_{cone}, cc	0.579245283
7.	$V_{int} (V - V_{theor})cc$	0.7547
8.	$V_{titr} + V_{cone} + V_{int}$, cc	11.33394528
9.	V_{mould}, cc	574
10.	Shrinkage porosity	$\frac{(V_{titr} + V_{cone} + V_{int})}{V_{mould}} = 0.019745549$
11.	% Shrinkage porosity	1.97

Table 9.

Shrinkage porosity values for the remaining 2 experiments

Exp run order	%Shrinkage porosity
1	2.07
2	2.628
3	1.5

4.3. Comparison of simulation and experimental studies

The results from the simulation runs and experiments have been compared. The simulation results are in agreement with experimental studies data and it is shown in the table 10 & 11.

Table 10.

Correlation co-efficient for US A 356

N	X	Y	X x Y	X ²	Y ²
1	2.07	2.628	5.43996	4.2849	6.906384
2	2.62	3.1	8.122	6.8644	9.61
Σ	4.69	5.728	13.56196	11.1493	16.51638

Table 11.

Correlation co-efficient for US 413

N	X	Y	X x Y	X ²	Y ²
1	1.5	2.1	3.15	2.25	4.41
2	1.97	2.29	4.5113	3.8809	5.2441
Σ	3.47	4.39	7.6613	6.1309	9.6541

To establish the strength of association between the casting process simulation and experimental validation studies, correlation co-efficient between the two results is calculated using the formula

$$\text{Correlation}(r) = \frac{[N \sum XY - \sum X \sum Y]}{\sqrt{[N \sum Y^2 - (\sum X)^2][N \sum X^2 - (\sum Y)^2]}}$$

Where :

N = number of values (casting shape)

X = Shrinkage value of casting process simulation

Y = Shrinkage value of experimental validation study

The Value of Correlation Co-efficient for US A356 alloy is calculated and is equal to 0.99, indicating a strong association between the two studies.

The Value of Correlation Co-efficient for US 413 alloy is calculated similarly and is equal to 1, indicating a strong association between the casting process simulation and experimental validation studies.

The shrinkage porosity values from the simulation results are matching with the experimental studies data. Porosity is major concern for foundry industry which is to be addressed to reduce the in-process rejections in castings. Present study mainly focuses on predicting the porosity in aluminium alloy casting through process simulations which will help the foundry industry in predicting and controlling the porosity.

5. Conclusions

The correlation co-efficient values for casting process simulation and experimental validation studies are indicating a **positive relationship** between them. A novel technique for quantifying the porosity from casting process simulations is implemented with the help of CAD application programme. Chills promote faster temperature gradient in the solidifying metal and increase its feeding capacity thereby reduces shrinkage. Higher pouring temperature results in lower rate of heat extraction by the mould thereby decreasing shrinkage.

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