International Journal of Mechanical Engineering and Robotics Research

ISSN 2278 – 0149 www.ijmerr.com
Vol. 1, No. 1, April 2012

Research Paper

CALCULATION OF SHRINKAGE CHARACTERISTIC OF US 413 CAST ALUMINIUM ALLOY USING CASTING SIMULATION

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Shrinkage characteristic of US 413 cast aluminium alloy has been discussed in the current study. The decrease in specific volume leads to shrinkage in castings and it can be envisaged as a defect. The shrinkage porosity has been studied using finite difference based casting process simulation software. The shrinkage characteristic has been quantified using arithmetical formula. A three dimensional solid model of the shrinkage defect has been constructed using CAD. Shrinkage characteristic has also been quantified through experimental validation studies and compared well with casting process simulation. Influence of casting shape on the shrinkage characteristic has been studied in this paper.

Keywords: Shrinkage, Aluminium alloy, Casting shape, Process simulation, Solid model

INTRODUCTION

Metals and alloys are prone to defects, especially aluminium alloys, such as shrinkage, one of the chronic problems, which impact the quality of the castings. Quantitative and qualitative analysis of shrinkage characteristic has been helpful in improving the mechanical properties of castings (ASM Metals Handbook). 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 (Reis *et al.*, 2005) declared by Reis *et al.* (2005) determination 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 surface

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(Calcom, 2001). The thermal cooling conditions, the alloy content and the casting temperature have been influencing the quantity and quality of shrinkage and porosity.

The casting process simulation is temperature and time dependent. Freezing of castings is a non-linear transient phenomenon and it involves modification of phase with liberation of latent heat from an affecting liquid-solid boundary. The casting simulation programmes have been predicting temperature distribution or hot spots in the castings. The casting process simulation has been considering the thermophysical data of the alloys as the input and suitable boundary conditions data. In order to estimate shrinkage and porosity the thermal properties are defined as a function of the temperature (Arno and Matti, 1994; and Scarber and Littleton, 2008). Shrinkage porosity has been predicted by detecting open, partially closed and closed liquid regions by utilising appropriate boundary conditions. Casting process simulations have been carried out using Virtual Casting software. It is a program for the simulation of the solidification process of industrial castings using Finite Difference Method. This software has been developed by Regional Research Laboratory, Thrivandrum. This casting simulation software has been installed at Institute of Indian Foundrymen (R&D) Center, Hyderabad.

EXPERIMENTAL PLAN

The influencing parameters for shrinkage characteristics are alloy composition, shape of casting, mould coat, bottom chill, pouring time, mould sand and pouring temperature (Sundarrajan *et al.*, 1984).

For the present study casting shape, bottom chill, pouring temperature and alloy composition have been considered as the process parameters.

Alloy composition affects casting characteristics, mechanical properties, defects and structure of the cast product. The chemical composition of the alloy considered for the present study has been given at Table 1.

Table 1: Chemical Composition (%wt)

Alloy	Si	Fe	Cu	Mn	Mg	Ni	Zn	Pb	Ti	Each	Total	Al
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

Three basic casting shapes have been considered for the present study (John, 2008). They are rectangular, cube and cylinder. Generally industrial casting shapes follow either of these shapes. The dimensional details, volume and pouring technique of the castings have been provided at Table 2.

Pouring temperature or super heat (Kielbus, 2007) influences fluidity, porosity, strength and structure of the casting. Hence pouring temperature and pouring temperature with 50 °C of super heat is considered as one of the process parameter for the present study.

Another processing parameter is bottom chill which shows significant influence in the casting characteristics and promotes directional solidification. Mild steel chills are considered for the present study the details of the number of experiments conducted have been given at Table 3.

Table 2: Dimensional Details of the Casting Shapes for Shrinkage Characteristic

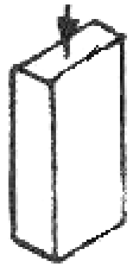
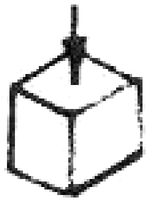
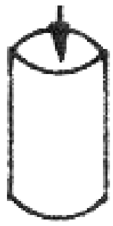
S. No.	Shape	Dimension, mm	Pouring Technique	Volume, cc
1.	Rectangular	115 × 100 × 48		552
2.	Cube	82 × 82 × 82		551.368
3.	Cylinder	Ø90 × 90		572.265

Table 3: Shows the Details of the Number of Experiments

Exp Run Order	Alloy	Chill	Pouring Temperature (°C)	Casting Shape
1.	US 413	Chill	T	Rectangular
2.	US 413	Chill	T	Cylinder
3.	US 413	Chill	T	Cube
4.	US 413	Chill	T+50	Cylinder
5.	US 413	Chill	T+50	Cube
6.	US 413	Chill	T+50	Rectangular
7.	US 413	N	T	Cylinder
8.	US 413	N	T	Cube
9.	US 413	N	T	Rectangular
10.	US 413	N	T+50	Cylinder
11.	US 413	N	T+50	Cube
12.	US 413	N	T+50	Rectangular

SIMULATION STUDIES

Simulation studies on shrinkage characteristics of aluminium alloy have been conducted using the Virtual casting commercial software (Virtual Casting User Manual) and test piece for cube shape casting in Figure 1.

Virtual Casting is based on finite difference method and the simulation process is following Pre-processing, Solving the Governing Equations and Post-processing or visualization of results. Thermo-physical properties of alloy, bottom chill and silica sand for the present study are given at Table 4.

Figure 1: Test Piece for Cube Shape Casting

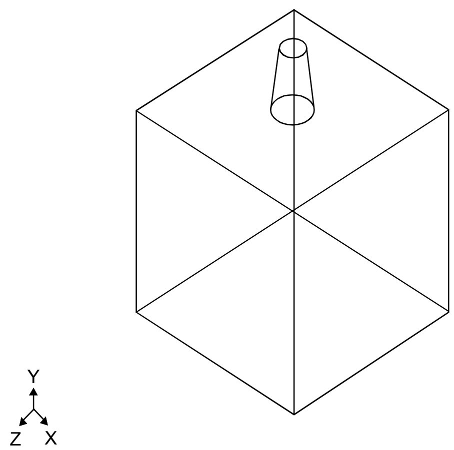


Table 4: Thermophysical Data for Casting Process Simulation

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

The heat transfer coefficient is the rate of the heat loss through the metal/mould interface and it is an important aspect to be considered during simulation. The selection of heat transfer coefficient values as well as boundary conditions at the metal/mould interface influences the accuracy of the simulation studies. In the present investigations, interfacial heat transfer coefficient values were approximated such that the casting simulations and the experimental measurements are in conformity.

The Thermo-physical properties of the US A 413 alloy, bottom chill and silica sand (Pani and Prasanna, 2004) for the casting simulation have been given at Table 4 (Michael, 1998; Cellini and Tomesani, 2008; and Venkataramana *et al.*, 2008).

Mesh has been generated by importing the solid model in the form of stl file and divides the casting and mould into small finite cells. Each cell is assigned a material id. Boundary Conditions like Interfacial heat transfer coefficient and temperature at all material interfaces like metal, mould, ambient, chill and coating have been considered.

Shrinkage occurs in metallic materials during freezing and cooling due to reduction in specific volume, a physical characteristic. The defects can be reduced by reducing the shrinkage, controlling the distribution of shrinkage and balance it using feeders and chills. The information regarding the shrinkage and distribution is thus essential in minimizing casting defects.

The contour plots of the location and magnitude of porosity formed during the solidification for simulation run order number 9 are shown below in Figures 2a and 2b.

Figure 2a: Output for Simulation

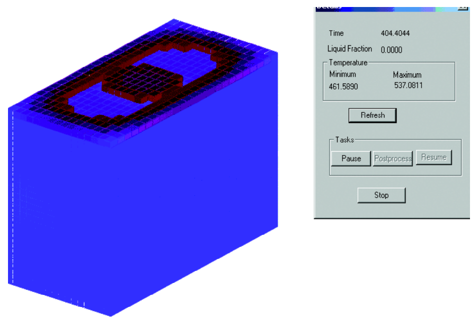
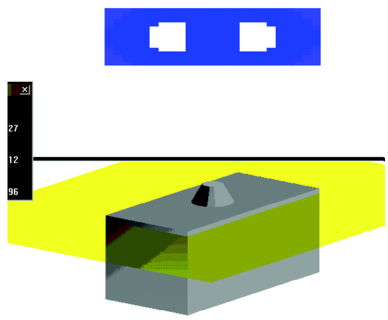


Figure 2b: Typical Contour Plots Showing Porosity Distribution for

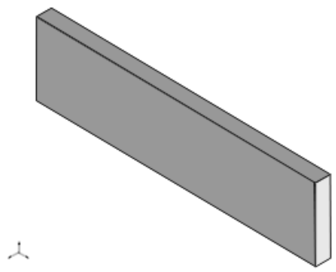


Simulation Run Order 9

It is difficult to output the volume of the shrinkage porosity in the casting because it is 2D. Therefore, the shrinkage pore areas of the image at various locations are imported into solidworks software. The large tolerance level typical of (0.1 mm) foundry process has been considered for the present study (Fiorello *et al.*, 1999). The

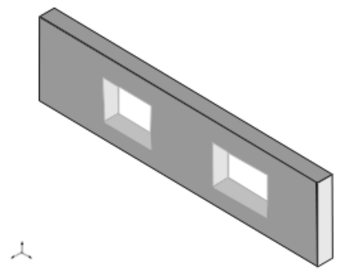
Figure 3: Shows Constructed Porosity of the Simulation Run Order 9

103 mm from Bottom



Volume is 10.399 cc

108 mm from Bottom



Volume is 9.4899 cc

contour plot data for simulation run order 9 at four locations starting from 103 mm from the flat bottom to 108 mm have been converted to solid model part (sldpart). Figure 3 shows constructed porosity of the simulation run order 9 using Solid Works software is given below.

Shrinkage porosity distributed for simulation run order 9 from 103-108 mm from the flat bottom is given at Table 5.

Porosity distribution in these four locations is 0.636 which is obtained from the contour plot for this particular simulation run order 9. The amount of shrinkage porosity distribution in these regions has been calculated and given at Table 6.

Table 5: Shrinkage Porosity for Simulation Run Order 9

S. No.	Distance from the Flat Bottom, mm	Volume cc
1.	103	10.39935
2.	108	9.48990
Total Volume		19.88925

Table 6: Shrinkage Porosity Distribution in the Regions for Simulation Run Order 9

Total volume of shrinkage porosity	19.88925
Amount of shrinkage porosity distribution in these regions	Total volume × maximum porosity distribution in these regions
	19.88925 × 0.636
	12.64956
Amount of shrinkage porosity in the casting	12.64956/volume of the casting from table
	12.64956/552
	0.022916
% amount of shrinkage porosity in the casting for simulation run order 9	2.29

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.

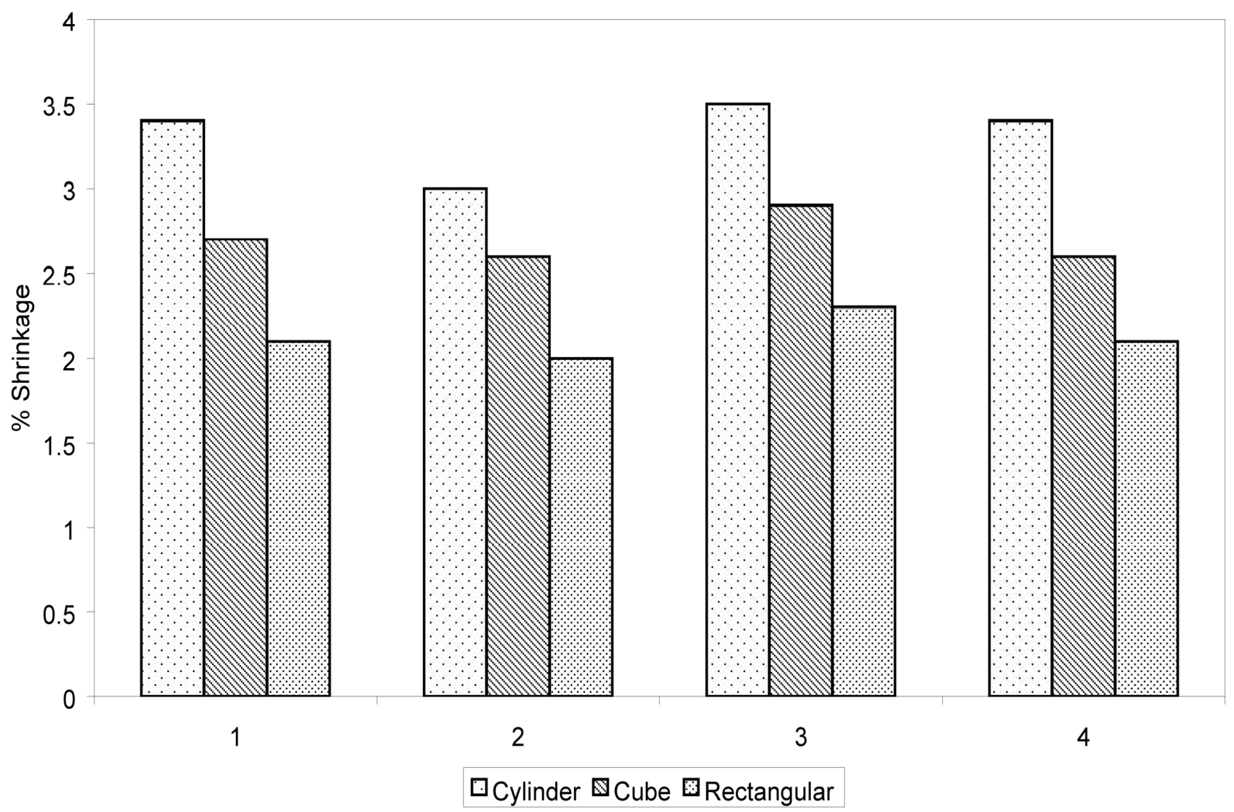
Table 7: Shrinkage Porosity for 12 Casting Process Simulations

Exp Run Order	% Shrinkage Porosity	Exp Run Order	% Shrinkage Porosity
1	2.18	7	3.40
2	3.34	8	2.88
3	2.71	9	2.29
4	3.04	10	3.30
5	2.60	11	2.61
6	2.00	12	2.12

Influence of Casting Shape on Shrinkage Porosity

Macro cavities decrease with casting shape changes from thick to flat castings. This can be explained based on the solidification behaviour of the casting shape. The solidification morphology of the casting in the localized areas has been influenced by the shape of the casting because the edges play a considerable role in the heat extraction. The edges of the test casting combined with the relative composition of the alloy decide the variation of formation of macrocavities. Relative solidification time affects the macrocavities, with increase in solidification time, the macro cavities increases. Cylindrical shape castings are promoting maximum cavities and it has been shown in the figure. The influence of casting shape on shrinkage porosity has been shown in Figure 4.

Figure 4: Influence of Casting Shape on Shrinkage Porosity of US 413



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 to optimize them.

To evaluate the influence of process parameters 3 experiments have been conducted using test piece as shown in figure 1 and these are 1, 4 and 5. These experiments have been designated as exp run order 1 to 3.

Testing arrangement for shrinkage characteristics for cube shape casting is shown Figure 5. Prepared mould, overflow core and pouring basin for rectangular, cube and cylinder shape castings have been shown in Figure 6. 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.

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 h.

Figure 5: Schematic Diagram for the Volume Deficit Experiment for Cube Shape Casting

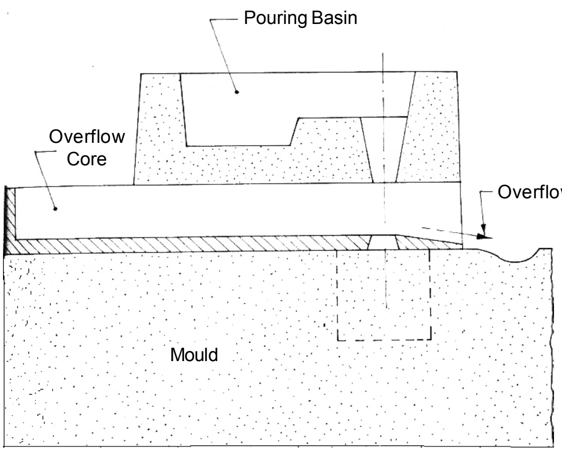
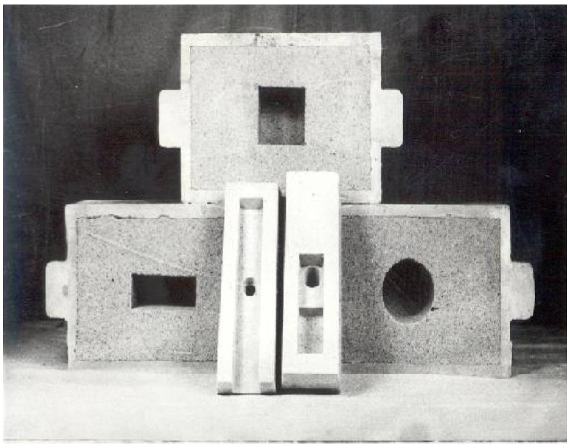
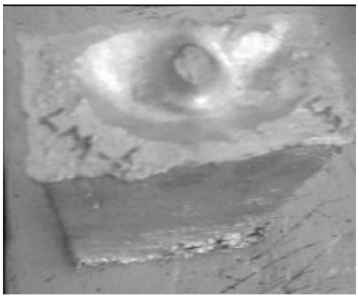


Figure 6: Details for Experiment and the Assembled Mould for Volume Deficit Experiment



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 7 has shown the rectangular, cylinder and cube shaped solidified castings of the experimental validation studies.

Figure 7: Solidified Castings of the Experimental Validation Studies



Rectangular

Cylinder

Cube

SHRINKAGE POROSITY CALCULATIONS FOR THE EXPERIMENTAL STUDIES

Shrinkage porosity calculations for the experimental studies have been given below

- 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 Vtitr is read from the burette. The macrocavity, Vm is given by:

Vm = Vcone + Vtitr

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

  V = (weight in air – weight in water)

- The theoretical volume, V theoretical is obtained as follows

  Vtheor = Weight in air/(Theoretical maximum density where the theoretical maximum density is obtained from chill specimen).

The internal porosity Vint is computed as follows:

Vint = V – Vtheor

Shrinkage porosity is given by = (Vm + Vint)/ Vmould.

Shrinkage porosity for experimental run order1 are given below at Table 8 using the above calculations.

The shrinkage porosity values for the remaining 2 experiments have been calculated in similar way using the above and there are given at Table 9.

CRITICAL ANALYSIS OF SIMULATION AND EXPERIMENTAL STUDIES

The results from the simulation runs and experiments have been compared. The simulation results are in agreement with experimental test data and it is shown in the Table 10 and Figure 8 also.

Table 8: Shrinkage Porosity for Experimental Run Order 2

S. No.	Parameter	Exp Run Order 2
1.	Gair(Wt), gm	1492
2.	Vtheor	563.02
3.	V = (Gair-Gwater) cc	564
4.	Vtitr, cc	9.3
5.	Vcone, gm	5.8
6.	Vcone, cc	2.1887
7.	Vint (V-Vtheor) cc	0.981132
8.	Vtitr + Vcon + Vint, cc	12.46981
9.	Vmould, cc	591.553
10.	Shrinkage Porosity	12.46981/591.553
		0.02108
11.	% Shrinkage Porosity	2.108

Table 9: Shrinkage Porosity Values for the Remaining 2 Experiments

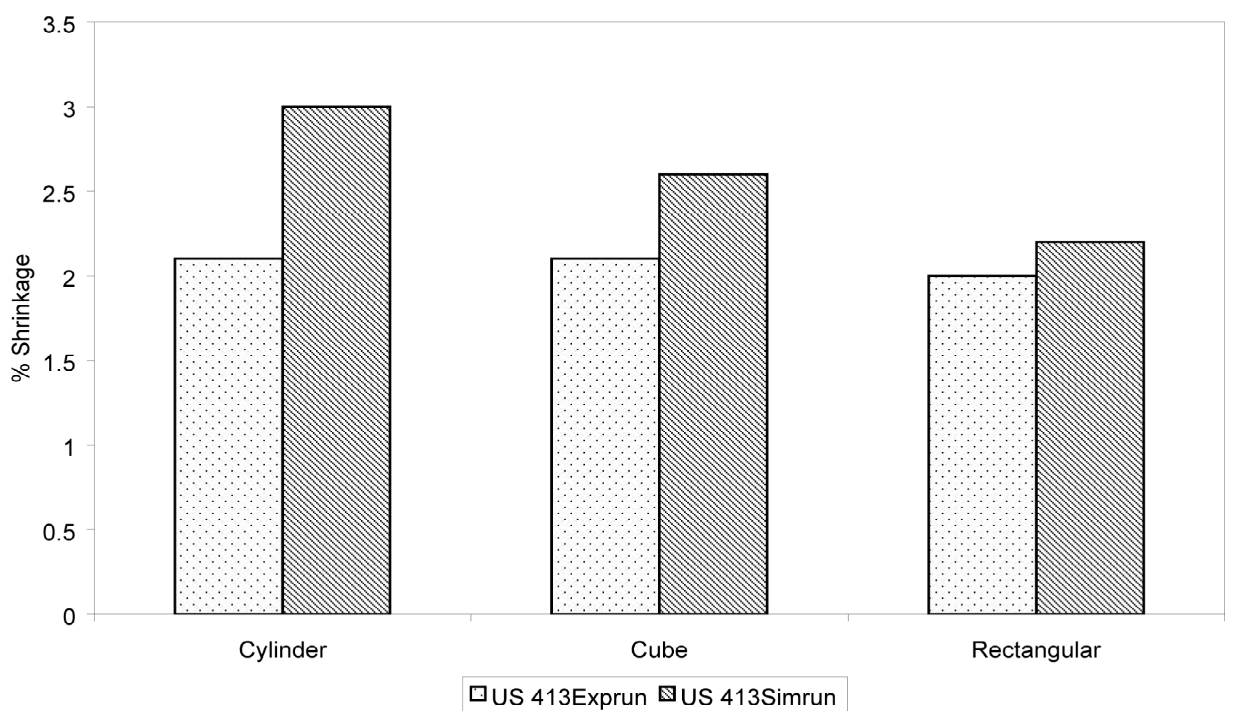
Exp Run Order	% Shrinkage Porosity
1	1.90
2	2.07

Table 10: Critical Analysis of Simulation and Experimental Studies

	US 413 Exp Run	US 413 Sim Run
Cylinder	2.108	3.04
Cube	2.070	2.61
Rectangular	1.900	2.18

The shrinkage porosity values from the simulation results are matching with the experimental studies data.

Figure 8: Shrinkage Porosity Values for Simulation and Experimental Studies



CONCLUSION

Shrinkage characteristic has been quantified using finite difference based casting process simulation. Cylindrical shape castings are promoting maximum shrinkage. The experimental validation has been carried out with the same process parameters. The simulation results are in agreement with experimental test data.

ACKNOWLEDGMENT

The authors reward their thanks to Directorate of Engineering and Director DRDL for providing support and permission for carrying out this R&D work.

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