jmr&t Journal of Materials Research and Technology
www.jmrt.com.br

Original Article

Quantification of volume deficit of rectangle shaped cast aluminium alloys

Samavedam Santhi[a,*], *Dharwada Hanumantha Rao*[b], *Srinivasan Sundarrajan*[c]

[a]*MGIT, Hyderabad, India*
[b]*MVSR Engineering College, Hyderabad, India*
[c]*National Institute of Technology, Trichy, India*

ARTICLE INFO

Article history:
Received 13 September 2012
Accepted 13 November 2012

Keywords:
Aluminium alloys
Casting
Volume deficit
Solid model
X-ray Computer Tomography

A B S T R A C T

Volume deficit of rectangular shape US 413 and US A356 cast aluminium alloy has been estimated in the present study. The decrease in specific volume directs to a volume deficit in castings and it has been shown as a defect. The volume deficit can be classified as macro cavities, internal porosity, surface sinking and volumetric contraction and measured using mathematical formulae; the actual volume deficit of the given casting was obtained by adding all the defects. Quantification of internal closed porosity has been addressed through X-ray computer tomography. The information regarding the volume deficit and its distribution is critical in minimizing casting defects.

1. Introduction

Shrinkage has been occurring due to the volumetric change that occurs when a liquid metal solidifies. Shrinkage occurs when a liquid metal solidifies and the density of the solidified metal is greater than the density of the liquid. The cast aluminum alloys are prone to defects, such as shrinkage, one of the chronic problems, which impact the quality of the castings. With increasing use of aluminum alloy castings, volume deficit characterization is useful for improving mechanical properties of the castings. By Volume deficit characterization study, will reduce in process rejections of aluminium alloy foundry.

Volume deficit or shrinkage occurs in metallic materials during freezing and cooling due to reduction in specific volume. The volumetric reduction that occurs when a liquid solidifies is the reason for volume deficit and it has been seen in the form of defects as discussed in ASM Metals Handbook [1]. Li et al. [2] stated that the tendency for the formation of shrinkage porosity relates to both the liquid or solid volume fraction at the time of final solidification and the solidification temperature range of the alloy. A number of significant factors influence episodes of shrinkage in cast products as quoted by Sundarrajan et al. [3]. They are the thermal cooling conditions or use of chills, pouring temperature, casting shape, mould coat, mould type and alloy composition. As stated by Reis et al. [4] and Heine et al. [5], the shrinkage porosity formation follows the physics principles and interactions among many physical phenomena such as heat transfer, fluid flow in the liquid

*Corresponding author.
E-mail address: santhi_samave@yahoo.com (S. Santhi).

2238-7854
http://dx.doi.org/10.1016/j.jmrt.2013.03.008

stage including natural convection, flow in the mushy zone, solidification shrinkage, deformation of the solid skin due to the formation of less pressure and so on. Thermal contraction of solid during subsequent freezing also increase the risk of shrinkage if proper care is not taken in casting as observed by Eady and Smith [6].

When molten metal is poured at a particular pouring temperature into the mould, the metal cools to certain extent before the mould is filled so during pouring itself shrinkage occurs to a small extent. The effects of mould dilation and mould deformation which occur during the cooling of molten metal are to be considered. The volume deficit depends on both casting conditions and casting material. The volume deficit classification has been given at Fig. 1.

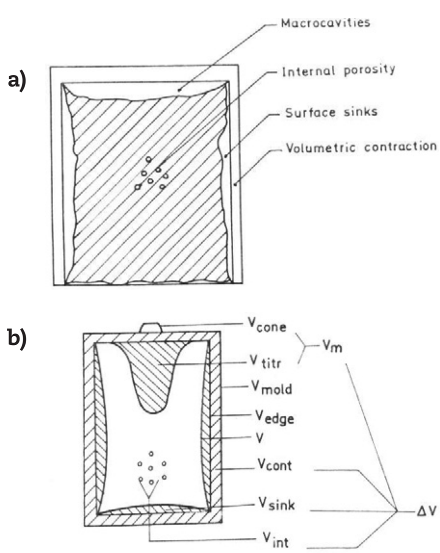


Fig. 1 – Classification of volume deficit. (a) Description of volume deficit; (b) depiction of volume deficit.

Table 1 – Details of volume deficit.

ΔV	Total volume deficit
ΔV	*Vm + V sin k + Vint + Vcont*
V_m	*Vcone + Vtitr*
V	$G_{air} - G_{water}$
V_{edge}	Casting edge volume
V_{sink}	*Vedge – (Vm + V)*
V_{mould}	Mould volume
V_{theor}	Theoretical volume
V_{int}	*V Vtheor*
V_{cont}	*Vmould – Vedge*

Patterson and Engler have classified the volume deficit into four types, namely macro cavities, V*m*; internal porosity, V*int*; surface sinks, Vsinks; and volumetric contraction, V*cont* as discussed in Sundarrajan et al. [3]. These are explained in Table 1.

2. Experimental plan

For volume deficit the influencing parameters are alloy composition, shape of casting, mould coat, chill and pouring temperature. Alloy composition influences the casting characteristics, mechanical properties, defects and structure of the cast product. The chemical composition of the alloys has been given in Table 2.

Casting shape is controlling the quality of the alloy [7] by influencing the amount of volume shrinkage. The rate of heat exchange depends on wall thickness of casting and its shape. Rectangular shape is considered for the present study. The dimensional details and pouring technique are provided at Table 3.

Another processing parameter is bottom chill which shows significant influence on the casting characteristics and promotes directional solidification. Mild steel chill is considered for the present study. Table 4 provides the details of the number of experiments.

Table 3 – Dimensional details of the casting shape for shrinkage characteristic.

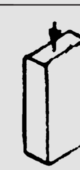
S.No	Shape	Dimension, mm	Pouring technique	Volume, cc
1	Rectangular	115 × 100 × 48		552

Table 4 – Experimental plan.

Exp run order	Alloy	Chill
1	US 413	Chill
2	US 413	No Chill
3	US A 356	Chill
4	US A 356	No Chill

Table 2 – Chemical composition of alloys (%wt).

Alloy	(%wt)											
	Si	Fe	Cu	Mn	Mg	Ni	Zn	Pb	Sn	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
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

3. Experimental studies

Alloys used in the present investigation are US 413 and US A356, the testing arrangement and schematic of the pouring basin and overflow core is given in Fig. 2. Tooling for experiments overflow core, pouring basin and other details for this experiment and the assembled mould for volume deficit experiment is shown in Fig. 3. 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.

The moulds are provided with dowel pins for perfect matching of cope and drag. Moulds are prepared with slight ramming. The patterns have been stripped after 3 hours. Moulds are prepared using green sand process consisting of bentonite (5%-6% of sand weight) and water (5%-8% of sand weight). The moisture level is adjusted in such a way that compatibility measured with + GF + compatibility meter is maintained between 45% and 50%, permeability is maintained between 400 and 500 and green compression strength is in the range of 700-900 g/cm^2. The mould hardness is in the range of 75-80 on B scale.

The alloys are melted in an electric resistance furnace of capacity 20 kg provided with mild steel crucible. Each alloy melting is done with their respective batch (belonging to same heat). 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. The pouring height is maintained constant to avoid turbulence and difference in surface oxidation and oxide pick-up. Fig. 4 shows the solidified casting of volume deficit characteristic experiment.

a) b) c)

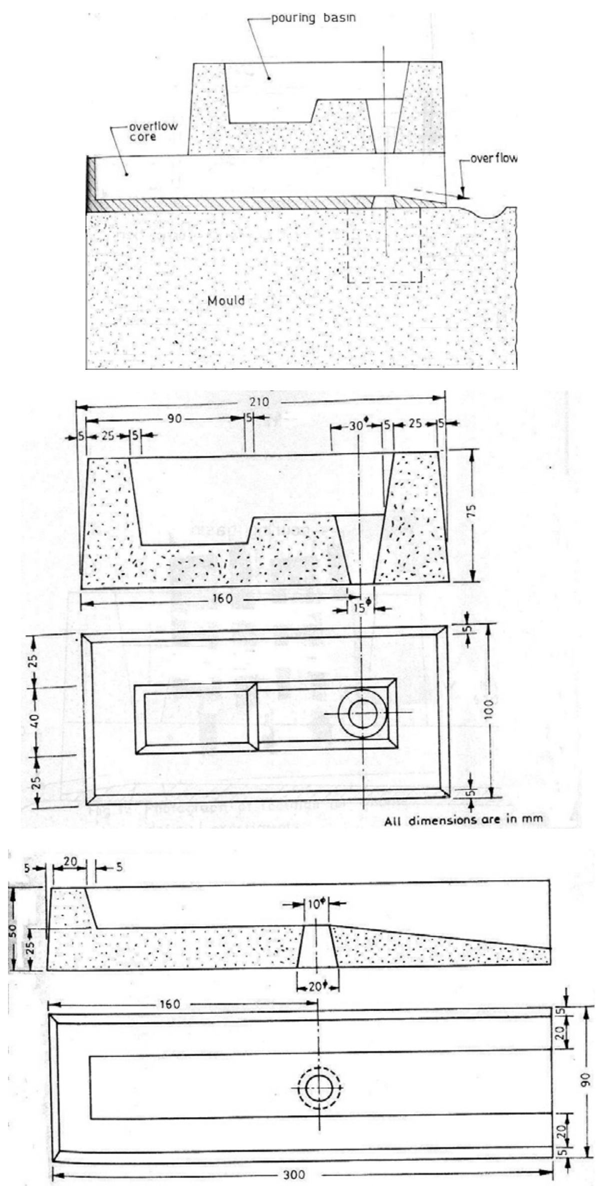


Fig. 2 – (a) Testing arrangement for the volume deficit experiment and (b) schematic of the pouring basin and (c) overflow core.

4. Results

Planned study of volume deficit is essential to minimize the casting defects. The defects occurred due to volume deficit have formed a large portion of rejections. The information regarding the total volume deficit and distribution is thus critical in minimizing casting defects. The defects can be minimized by

a) b)

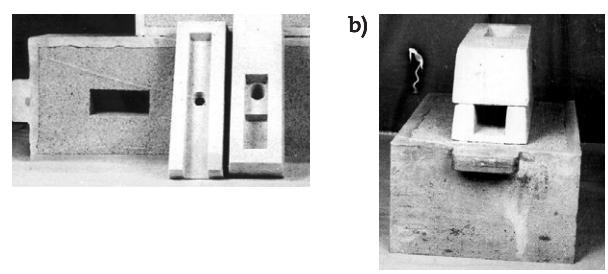


Fig. 3 – Details for experiment and the assembled mould for volume deficit. (a) Mould for rectangular, overflow core and pouring basin; (b) assembled mould.

Fig. 4 – Solidified casting of volume deficit experiment.

reducing the total volume deficit, controlling and balancing the distribution of volume deficit using feeders and chills.

4.1. Estimation of volume deficit

The volume deficit is calculated by considering the following parameters:

a. When molten metal is poured at a particular pouring temperature into the mould, the metal cools to certain extent before the mould is filled. The assumption of instantaneous filling of mould is not realistic since shrinkage occurs to a small extent during pouring itself.
b. The effects of mould dilation and mould deformation which occur during the cooling of molten metal are taken into consideration in the volume deficit calculation.

Planned study of volume deficit is essential to avoid occurrence of defects/rejections. The defects can be minimized by reducing the volume deficit and also by controlling and balancing the distribution of volume deficit using feeders and chills. To minimize the casting defects information regarding the total volume deficit and its distribution is critical. Test castings were analyzed to determine the volume deficit and its distribution by using the following procedure.

1. The test casting is taken out of the mould and the cone portion is cut off. The volume of the pipe is 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 macro cavity, V_m is given by

$$V_m = V_{cone} + V_{titr} \quad (1)$$

2. The average length, width and thickness of the test casting is measured using a vernier caliper

$$V_{edge} = \text{length} \times \text{width} \times \text{thickness} \quad (2)$$

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

$$V = (\text{weight in air} - \text{weight in water}) \quad (3)$$

The surface sink is given by $V_{sink} = V_{edge} - (V_m + V)$ (4)

4. The theoretical volume, V_{theor} is obtained as follows

$$V_{theor} = \frac{\text{Weight in air}}{\text{Theoretical maximum density}}$$

is obtained from the chill specimen

The internal porosity V_{int} is computed as

$$V_{int} = V - V_{theor} \quad (5)$$

The volumetric contraction V_{cont} is calculated as

$$V_{cont} = V_{mould} - V_{edge} \quad (6)$$

V_{mould} is the volume of the mould which has been calculated before pouring.

5. The volume deficit is given by

$$\Delta V = \frac{V_m + V_{\sin k} + V_{cont} + V_{int}}{V_{mould}} \quad (7)$$

The volume deficit calculation for experimental run order 1 has been given below

S.No	Parameter	Exp run order 1
1	*Gair* (Wt), gm	1429.5
2	*Vtheor*	539.4339623
3	V = (*Gair* – *Gwater*), cc	540
4	*Vtitr*, cc	18
5	*Vm* (*Vcone* + *Vtitr*), cc	18.73018868
6	*Vint* (V – *Vtheor*), cc	0.566037736
7	*Vm* + V, cc	558.7301887
8	*Vegde* (lxbxt)	v560.175
9	*Vsink* (*Vedge* – (*Vm* + *V*))	1.444811321
10	*Vmould*, cc	574.084
11	*Vcont* (*Vmould* – *Vedge*)	13.909
12	*Vshrink*	*Vm* + *V sin k* + *Vint* + *Vcont* 34.65003774
13	Total volume deficit	*Vshrink* / *Vmould* 0.060357087
14	%Total volume deficit	6.0357087
15	%*Vmacro*	*Vmacro* / *Vshrink* = 53.7
16	%*Vint*	*Vint* / *Vshrink* = 1.6
17	%*Vsink*	*V sin k* / *Vshrink* = 4.1
18	%*Vcont*	*Vcont* / *Vshrink* = 40.14

Volume deficit values for experimental run orders for 1, 3 and 4 were calculated in similar manner. The volume deficit values for 1, 3 and 4 have been tabulated in the Table 5.

Table 5 – Volume deficit values for 1, 3 and 4 experimental run orders.

Parameter	Exp run order 1	Exp run order 3	Exp run order 4
V_{shrink}, cc	34.65	38.42678	39.009
Total volume deficit	0.06	0.066	0.067
%Total volume deficit	6	6.6	6.7
$\%V_{macro}$	53.7	36.69	33.94
$\%V_{int}$	1.6	1.4	2.3
$\%V_{sink}$	4.1	4.4	7.06
$\%V_{conc}$	40.14	57.1	56.61

4.2. X-ray computer tomography

All the 4 castings were subjected to X-Radiography. For experimental run order 2, the macro shrinkage value or V_{macro} is much less X-radiography revealed that this casting is showing internal gas porosity round 4, Grade 5 as per ASTM E155 [8]. By using the X-ray computer Tomography, quantification of internal closed porosity of castings was obtained.

Quantification of internal closed porosity of the given casting was addressed using the XCT, non-destructive evaluation. XCT is a quantitative, NDE technique for reconstructing three dimensional models of defects using CAD. Quantifying internal closed porosity in foundry industry is quite an important aspect for which XCT can provide an effective evaluation means to improve product quality. The majority of common defects found in castings were porosity, both isolated and diffuse. XCT, modern tool has been utilized for quantification and morphology of casting pores. XCT was done using DRDL's indigenously developed 450 kV X-ray industrial computer tomography system. The system consists of a 450 kV X-ray source, 256 channel detector array with 18 bit dynamic range and a 6 axis mechanical object manipulator. The resolution of the system is 500 μm with 1 mm slice thickness [9,10].

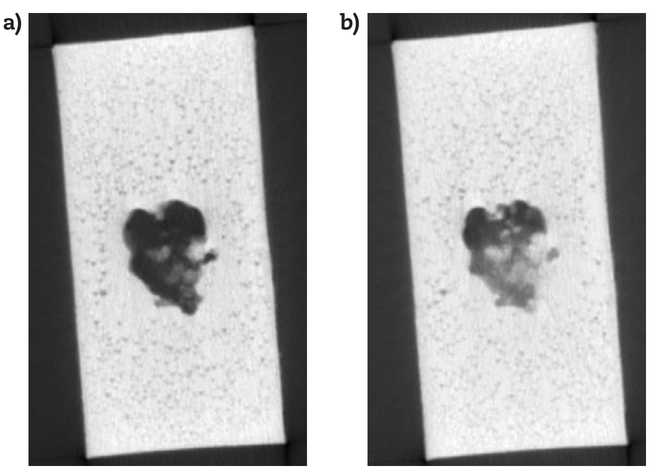


Fig. 5 – Computed tomographic Images of Exp run order 2. (a) S32: 32 mm from the bottom. (b) S34: 34 mm from the bottom.

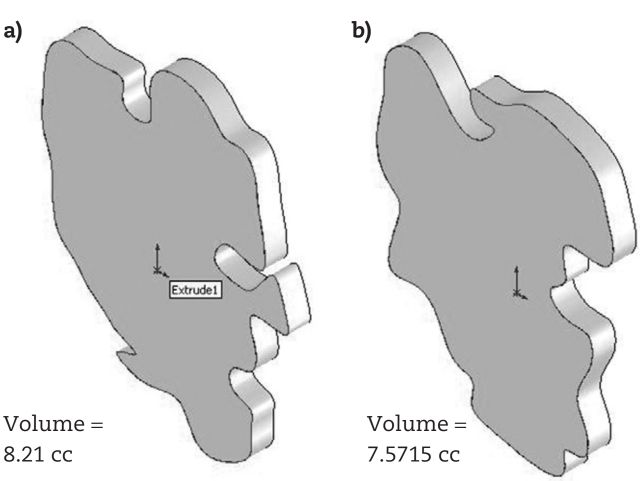


Fig. 6 – Constructed porosity of Exp run order 2. 2. (a) S32: 32 mm from the bottom. (b) S34: 34 mm from the bottom

The casting images produced from the XCT diagnostic analysis are not photographic images but digital reconstructions of XCT scan data. These images are thus capable of revealing features of interest on the surface or at any position within the interior bulk of the original casting. Shrinkage cavities are concentrated mainly around the center of the casting. XCT slices through several locations of both castings and is shown as a set of images. These images are projections of the casting, representing pixel by pixel the absorption coefficient of the material crossed by X-rays. From these scans, cross-section images (i.e., slices) of the material dimensions are obtained [11].

For Exp run order 2 the starting location of the shrinkage pore is 26 mm from the flat bottom and it spreads up to 36 mm from the flat bottom. The images of Exp run order 2 at 32 and 34 mm from the bottom are shown at Fig. 5. US 413 is a short freezing range alloy. The porosity or shrinkage for the experimental run order 2 is taking the form of large internal closed porosity. This is due to the inadequately feed thermal centers or because of the near the end of the solidification, the molten metal is cut off by the merging of parallel solidification fronts.

The XCT technique can visualize the porosity within the given slice and morphology of each individual pore. Typically pore sizes found in industrial casting are in the 10-10^3 μm size range. The XCT images may be imported into CAD software. It is difficult to output the volume of the internal closed porosity in the casting because it is 2D XCT. Therefore, the shrinkage pore areas of the XCT image at various locations are imported into solidworks software. The large tolerance level in (0.1 mm) foundry process is the same as that in XCT [11]. XCT data was converted to solid model part (sldpart) file format. Fig. 6 shows constructed porosity of the Exp run order 2 using Solid Works software.

Total volume of Internal closed porosity of the given casting from 26-36 mm is given below in Table 6.

The casting samples were sectioned based on the XCT data to show the actual Internal closed porosity. For measuring the volume of the Internal closed porosity of the casting it is kept under a burette and distilled water is dropped into the cavity till it is completely filled [3]. The titration reading gives the volume of the Internal closed porosity of the respective casting and these are in agreement with XCT data as shown in Table 7.

The internal closed porosity values of experimental run order 2 was used for calculating the total volume deficit of the same. The total volume deficit of this casting is given in Table 8.

Table 6 – Volume of Internal closed porosity for Exp order 2.

Distance from the flat bottom, mm	Volume cc
26	1.4842
28	5.5327
30	8.0228
32	8.2169
34	7.5715
36	12.9819
Total	4.381

Table 7 – Comparison of Volume of Internal closed porosity, cc.

S.No	Part Identification	Volume of Internal closed porosity, cc		% variation
		Using XCT	Validation studies	
1	Exp run order 2	4.381	4.35	0.7

Table 8 – Volume deficit for experimental run order 2.

Parameter	Exp run order 4
Vshrink	37.44
Total volume deficit	0.06522
%Total volume deficit	6.522
$\%V_{macro}$	29.17
V_{int}	5.361
$\%V_{int}$	14.31
$\%V_{sink}$	10.109
$\%V_{conc}$	46.398

4.3. *Analysis of results*

US A356 is promoting more amount of volume deficit compared to US 413 cast aluminium alloy as shown in Tables 5 and 8.

For long freezing alloys the liquid metal flow comes to an end at the leading tip of the flowing metal stream. When the solute concentration is increased, the solidification mode changes from growth of columnar grains with more or less planar front to the formation of equiaxed dendrites. These columnar grains flow downstream with the liquid metal till a critical fraction solid is reached and the metal flow ceases by choking at the tip of the solidifying metal as shown in the Fig. 7. These alloys solidify in mushy mode (solidified when nets of highly developed dendrites appear), which are spread over large part of the mould.

In short freezing range alloys, liquid metal enters in a mould (sand mould) and solidification initiates at mould wall. Solidification continues by the formation of columnar grains with a planar boundary as metal flows through the mould. Liquid metal flow comes to an end when columnar grains meet and the pinching by the grains from the mould wall ceases the flow as shown in the Fig. 8. So the solidification process does not prevent the flow of molten metal through the cross section of the mould. The molten metal flows through the mould until practically the whole alloy becomes solid.

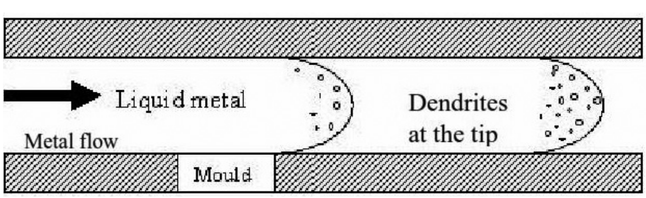


Fig. 7 – Liquid metal flow ceasing in long freezing range alloys.

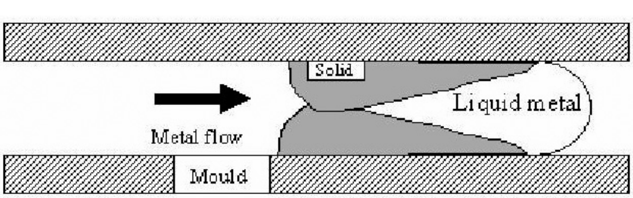


Fig. 8 – Liquid metal flow ceasing in short freezing range alloys.

4.3.1. *Influence of bottom chill*

To control the solidification of the liquid metal, it is possible to place the metal plates and chills in the mould. The associated rapid local cooling results a finer-grained structure and may form a somewhat harder metal at these locations. In ferrous alloy foundry, the effect is similar to quenching metals. In general, metals chills are used to promote directional solidification of the casting. By controlling the way a casting freezes, it is possible to prevent internal voids or porosity in the castings. Usage of chills can reduce the number of risers, there by the scrap rate. This result increased yield and reduced finishing as well as operation cost. Chills influence the shrinkage behavior of the molten metal. The bottom chill reduces the total volume deficit is shown at Fig. 9.

The interface becomes significant when the metal and chill have reasonably good rate of thermal conductance. Bottom chill extracts heat transfers and dissipates it to the surroundings from the casting. The efficiency of the chill depends on the amount of heat it extracts from the casting. However, there is an increased rate of heat extraction from the metal due to compensation of solidification shrinkage during the pouring time of molten metal. Presence of bottom chill

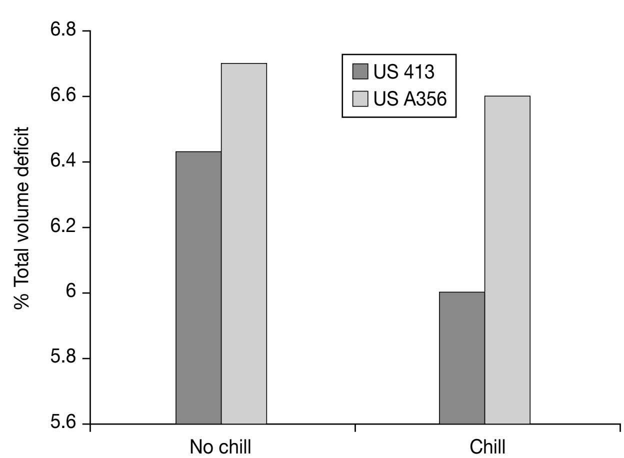


Fig. 9 – Influence of bottom chill on volume deficit.

change temperature and pressure gradient, which reduce the driving force for shrinkage formation. Bottom chill reduces the formation of hydrostatic tensions in the interior of the casting, which in turn minimizes the nucleation and growth of shrinkage. So this results in reduction in total volume deficit for US 413 and US A356.

5. Conclusions

The following conclusions can be drawn from the present investigation.

- Volume deficit was categorized as macro cavities, internal porosity, surface sinking and volumetric contraction.
- Macro cavities, volumetric contraction, internal porosity and surface sinking values were quantified using appropriate mathematical formulae.
- US A356 cast aluminium alloy is promoting more amount of volume deficit. Internal closed porosity of US 413 casting was calculated using the X-ray computer tomography and it is successfully validated through sectioning of the casting.
- The bottom chill reduces the total volume deficit for both alloys by extracting heat locally.

Acknowledgements

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

REFERENCES

[1] Stefanescu DM, ASM. ASM Metals Handbook. vol. 15. Casting. Novelty: ASM International, 2008.
[2] Li Y, Jolly MR, Campbell J. Internal and external porosity in short, medium and long freezing range aluminium alloy castings. In: Thomas BC, Beckermann C, editors. Modelling of casting, welding and advanced solidification processes VIII. The Minerals, Metals & Materials Society; 1998. p. 1241-53.
[3] Sundarrajan S. Roshan HMd, Ramachandran EG. Studies on shrinkage characteristics of binary Mg-Al alloys. Trans Indian Inst Met. 1984;37:4.
[4] Reis A, Xu Z, Van Tol R, Santos AD, Barbedo Magalhães A. Modelling of the underpressure occurring during the shrink porosity formation. In: Oñate E, Owen DRJ, editors. VIII International Conference on Computational Plasticity, COMPLAS VIII, Ó Cimne, Barcelona, 2005.
[5] Heine RW, Loper Jr CR, Rosenthal PC. Principles of metal casting. New Delhi: Tata McGraw-Hill, 1981.
[6] Eady JA, Smith DM. The effect of porosity on the tensile properties of al-alloy castings. Mat Forum. 1986;9:217-23.
[7] Brown JR. Foseco non-ferrous Foundry man's handbook. 11th ed. Boston: Butterworth Heinemann; 2008.
[8] ASTM E155. Standard reference radiographs for inspection of aluminum and magnesium castings; 2007.
[9] Muralidhar C, Siva Rao GV, Kumaran K, et al. Industrial Computed Tomography (ICT) system – An indigenous development, proceedings of national workshop on applications of Computer-Aided Tomography (CAT2004), DRDL Hyderabad, India.
[10] ASTM E1814-96. Standard practice for Computed Tomographic (CT) examination of castings; 2007.
[11] Losano F, Marinsek G, Merlo AM, Ricci M. Computer tomography in the automotive field. Development of new engine head case study. DGZfP Proceedings BB 67-CD 1999 paper 10; p. 65-73.