

# Simulation for grinding balls production using sand mold-gravity casting

F Nurjaman, A Shofi, U Herlina, N M Prilitasari, and Y Triapriani

Research Unit for Mineral Technology, Indonesian Institute of Sciences, Lampung-Indonesia

E-mail: fajar.nurjaman@lipi.go.id

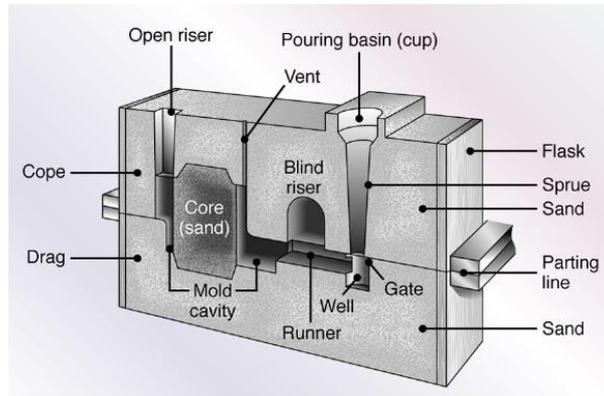
**Abstract.** In this present work, the grinding balls from high chromium white cast iron (ASTM A-532) were produced by using sand mold-gravity casting. The simulation casting process was conducted before making these grinding balls by using SOLIDCast™ version 8.2.0. The gating system design and the pouring temperature of hot metal were investigated clearly to obtain grinding balls with no-defect. The sound casting of grinding balls was resulted by using the proper gating system with the addition of vent air on the top of each grinding ball's mold. The dimension of vent air was reduced by the increasing of pouring temperature, thus it resulted on the increasing of the yield production of grinding balls.

## 1. Introduction

Grinding ball is a spherical component that was rotated in ball mill unit. It is generally used in mining industries for grinding raw materials, such as coal, iron ore, quartz, etc [1-2]. High chromium white cast iron is one of material that commonly used as grinding ball, because it has high hardness and wear resistance, especially after being heat treated [3-5]. Grinding ball that was made from high chromium white cast iron, commonly produced by sand mold-gravity casting method [6-7]. Porosity is one of the casting defects that mostly found in this method [8]. This porosity will be the source of crack inside the grinding ball. It will rupture due to its crack propagation that has rapidly occurred with a high density of impact load on grinding ball movement in ball mill unit. Thus, gating system design should be calculated approximately to produce sound casting or grinding ball with no-defect. Furthermore, casting simulation is the best tool to help engineers to produce sound casting product by visualizing the mold filling, solidification, and cooling. It also can predict the location of internal defects, such as shrinkage and porosity [9]. *Gating system* is the inlet where the hot metal will flow and fill the mold. The appropriate gating system will contribute in preventing the casting defect, such as shrinkage, porosity, miss-run, cold-shut, etc. The outline of gating system in gravity casting is shown in Figure 1. The gating system design for grinding balls production in this experiment was investigated clearly. Pouring basin and sprue are the first entrance of hot metal into the mold. In Figure 2, there is some of the important dimension for pouring basin and sprue, they are  $A_1$ ,  $A_2$ ,  $H_1$ , dan  $A_2$ . The dimension of choked area ( $A_2$ ) can be obtained from equation (1).

$$A_2 = \frac{w}{d.t.c.\sqrt{2.g.h}} \quad (1)$$





**Figure 1.** Gating system of sand mold casting [10]

where,  $w$  = weight of product (lb);  $d$  = density of hot metal (lb/in<sup>3</sup>);  $C$  = efficiency process;  $H$  = height of product (in);  $t$  = pouring time (s);  $g$  = gravity acceleration (386.4 in/s<sup>2</sup>).

The carbon content of high chromium white cast iron, that is 2.2% C, is similar to high carbon steel. Thus, the pouring time ( $t$ ) is expressed by equation (2) [11].

$$t = k\sqrt{w} \tag{2}$$

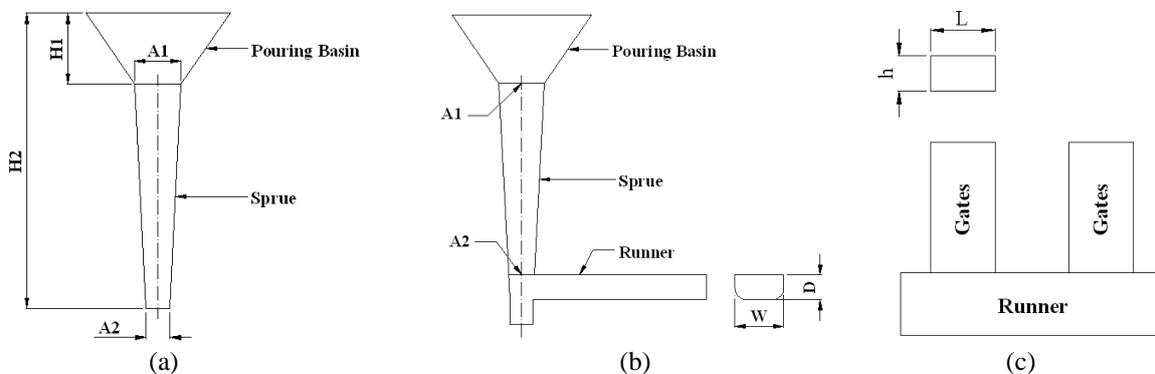
For high chromium white cast iron with 2.2% C and less than 100 lb weight of a product, the value of  $k$  is 1.2.

The total height of sprue and pouring basin ( $H_2$ ) is greatly determined by the flow type of hot metal when it is poured into the mold. The flow of hot metal must be in the mixed of laminar-turbulent with *Reynold Number* ( $Re$ ) about 2000-20.000. The Reynolds number is expressed in equation (3).

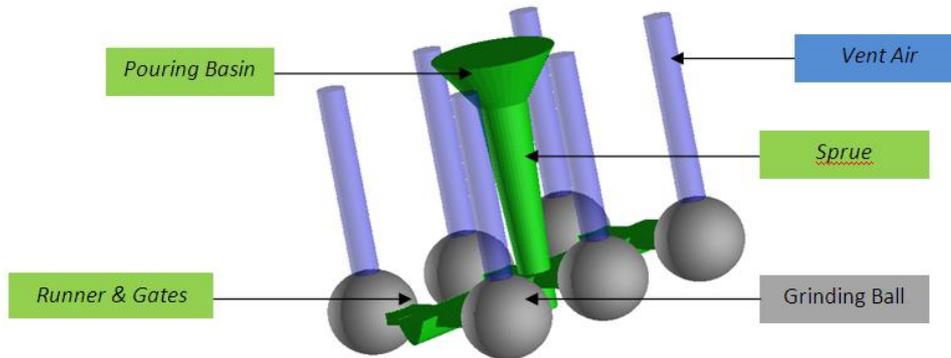
$$v = \frac{Re \cdot \mu}{\rho \cdot D_2} \tag{3}$$

where,  $v$  = velocity of hot metal in  $A_2$  (in/s);  $\mu$  = dynamic viscosity (lb. in<sup>-1</sup>. s<sup>-1</sup>);  $D_2$  = diameter of  $A_2$  (in). By using the Bernouli's equation, thus  $H_2$  can be obtained from equation (4).

$$V = \sqrt{2 \cdot g \cdot H_2} \tag{4}$$



**Figure 2.** Dimension of gating system : (a) pouring basin and sprue, (b) runner, (c) gates



**Figure 3.** Gating system design for grinding ball casting simulation

**Table 1.** Parameters and constants for gating system design

Parameter/Constants	Index	Units	Value	Remark
weight of grinding balls	W	Kg	3.8705	6 pcs of <i>grinding ball</i>
<i>density hot metal</i>	$\rho_{(1450^{\circ}C)}$	Kg/m <sup>3</sup>	6840.76	cast iron
efficiency process	C	-	0.8	assumption
total height	H	m	0.16	-
gravity acceleration	g	m/s <sup>2</sup>	9.8	-
<i>reynold number</i>	Re	-	7500	laminar-turbulent flow
dynamic viscosity	$\mu$	m <sup>2</sup> /s	5.5 x 10 <sup>-7</sup>	cast iron

**Table 2.** Dimension of gating system design

Gating System	Index	Units	Value
pouring time	t	second	5
pouring basin and sprue	A <sub>1</sub>	m <sup>2</sup>	0.00068
	A <sub>2</sub>	m <sup>2</sup>	0.00014
	H <sub>1</sub>	mm	30.226
runner	H <sub>2</sub>	mm	120.9
	w	mm	9.82
gates	D	mm	11.18
	h	mm	8.31
	l	mm	25.4

The dimension of A<sub>1</sub> and H<sub>1</sub> can be obtained from the ratio of a total height of sand mold and diameter of sprue that was expressed in equation (5) [10].

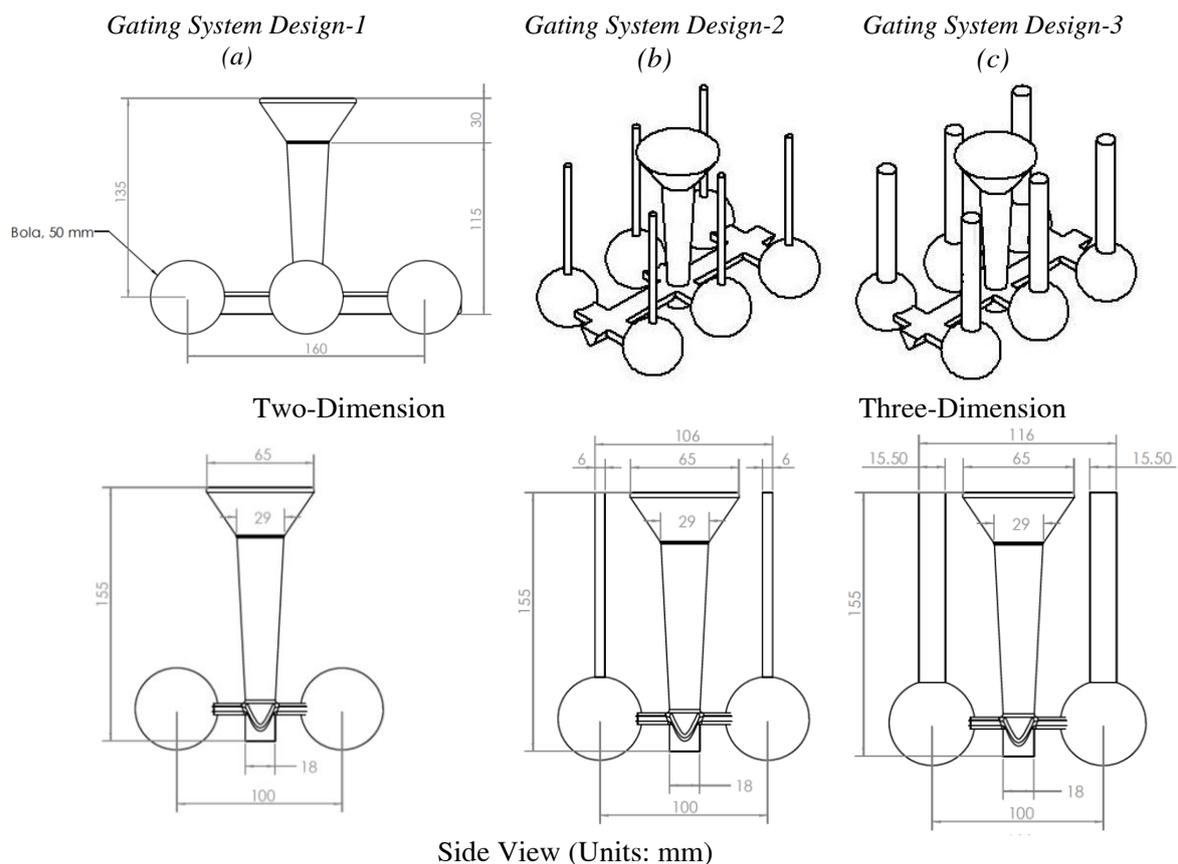
$$\frac{A_1}{A_2} = \sqrt{\frac{H_2}{H_1}} = 2 \tag{5}$$

Runner and gates were shown in Figure. 2b. The hot metal that flowing from sprue will enter the runner and distributed into several gates, then it flows into grinding ball’s mold. For high carbon steel, the ratio of *choke area* (A<sub>2</sub>), *runner* (A<sub>runner</sub>), and *gates* (A<sub>gates</sub>) is 1: 2: 1.5 [11], where W (width) > D (diameter) for a *runner*, and L > h for *gates*. Air vent, as shown in Figure 1 was used for preventing

the porosity that caused by gas entrapment in the sand mold after pouring process. In this study, the effect of a various dimension of an air vent in gating system on grinding ball's defect casting was investigated clearly. The influence of pouring temperature and yield production on grinding balls was also investigated to produce the sound casting product. In this study, the casting simulation of grinding balls production that was made from high chromium white cast iron was conducted by using SOLIDCast™ verion 8.2.0 [12].

## 2. Material and Method

The gating system was designed for six grinding balls with 50 mm diameter for each grinding ball, as shown in Figure 3. The dimension of gating system design was obtained by input some parameters in table 1 into equation (1) to (5). Thus, the dimension of the grinding balls gating system was listed in table 2. Three kinds of gating system design were made, as shown in Figure 4. The influence of vent air will be investigated in this simulation and production of grinding balls. Gating system design-1 was without vent air. Gating system design-2 had diameter 6 mm of vent air, while gating system design-3 had a larger diameter of vent air that is 15.5 mm. The simulation for grinding ball casting process was conducted by using SOLIDCast™ version 8.2.0 [12]. The casting simulation was started by selecting the parameter from the SOLIDCast™, as shown in Figure 5, such as grinding balls material, that was ASTM A-532, and the material for mold, that was silica sand.



**Figure 4.** Gating system design for casting simulation of grinding balls

After the simulation data was obtained, the grinding ball casting process was conducted. Induction furnace, with capacity 500 Kg/heat, was used to melt scrap steel and ferroalloys, such as ferrochromium and ferromolybdenum. The hot metal then poured into sand molds. The composition of grinding balls was 2.18C - 0.72Si - 13Cr - 1.38Mo. The casting defects either on the surface or inside the grinding balls were examined carefully.

	CI A532 IIA	
Thermal Conductivity	14.454	BTU/HR-FT-F
Specific Heat	0.12	BTU/LBM-F
Density	474.466	LBM/CU FT
Initial Temperature	2642	F
Solidification Temperature	2165	F
Freezing Range	225	F
Latent Heat of Fusion	120.461	BTU/LBM

(a)

Material Name	Material Type
Silica Sand	Normal Mold
InitialTemp	80 F
Thrm Cond	0.341 BTU/HR-FT-F
Spc Ht	0.257 BTU/LBM-F
Density	95 LBM/CU FT

(b)

**Figure 5.** Parameters for casting simulation: (a) material selection, (b) mold selection

### 3. Result and Discussion

The casting simulation of three kinds grinding ball's gating system would be emphasized on solidification time, gradient temperature, and niyama criterion. Solidification time would provide an overview of solidification stages for a specific time, while temperature gradient and niyama criterion were related to the formation of casting defects, such as shrinkage and porosity [13]. The simulation of casting process was shown in Figure 6 to 8. The simulation was conducted by using initial pouring temperature 2642 °F (1450 °C), as shown in Figure 4a. All of the gating system design in Figure 4 had a similar tendency of solidification stages, as shown in Figure 6. The solidification was started from the smallest volume of gating system part that was sprue and runner. The last solidification area was pouring basin. The addition of vent air on gating system (Figure 4b), and also the addition of larger volume vent air (Figure 4c) did not result in solidification time difference significantly. The solidification time of all design system was about 5-7 seconds.

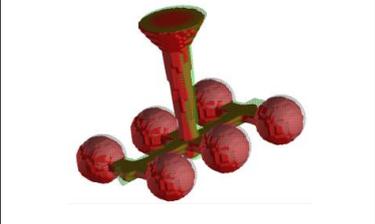
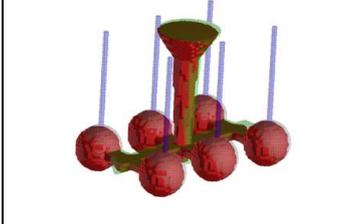
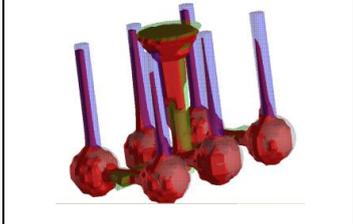
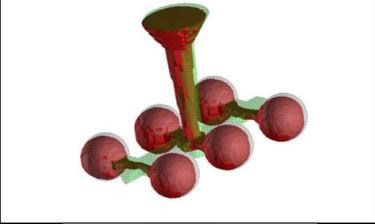
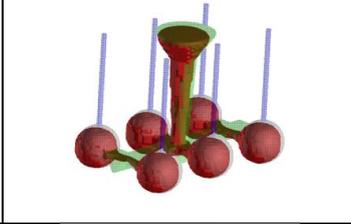
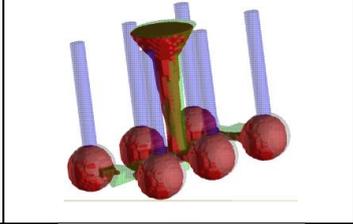
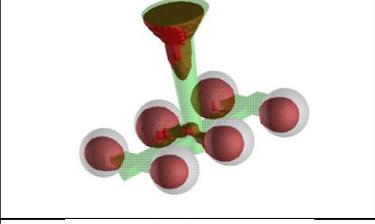
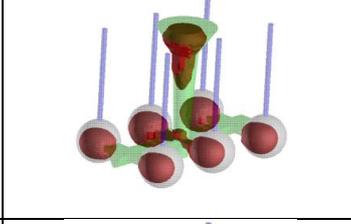
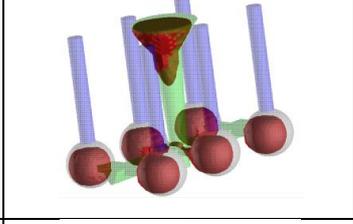
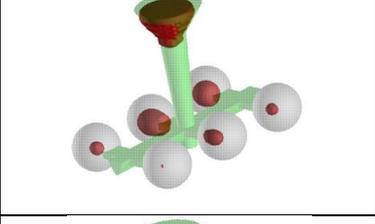
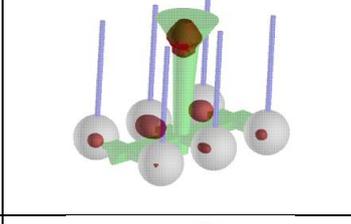
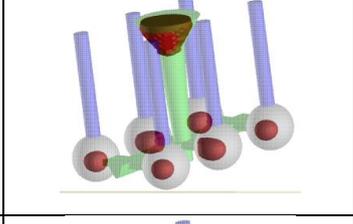
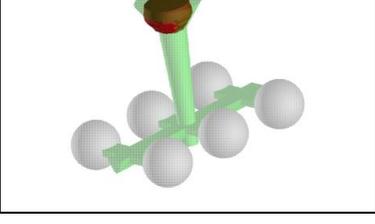
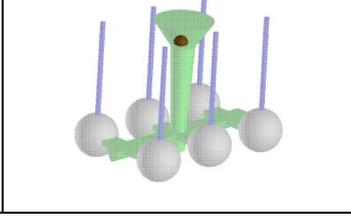
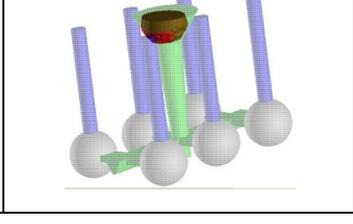
The gating system area with high-temperature gradient was very susceptible to the formation of casting defects, such as shrinkage and porosity. From Figure 7, it was shown that the addition of vent air on gating system (Figure 4b) and larger volume of *vent air* (Figure 4c) had resulted in a positive impact on the reduction of high-temperature gradient area in gating system, which was indicated by blue and yellow color. The casting defects, such as shrinkage and porosity, were identified by using niyama criterion in this simulation casting process, as shown in Figure 8, where it was indicated by the blue color in the last row.

From this casting simulation, it was resulted that vent air would contribute in the sound casting of grinding balls production. Vent air volume as  $1.89 \times 10^{-5} \text{ m}^3$  (cross-sectional area of *vent air* with diameter 15.5 mm) in gating system design-3 resulted in grinding ball with no-defect.

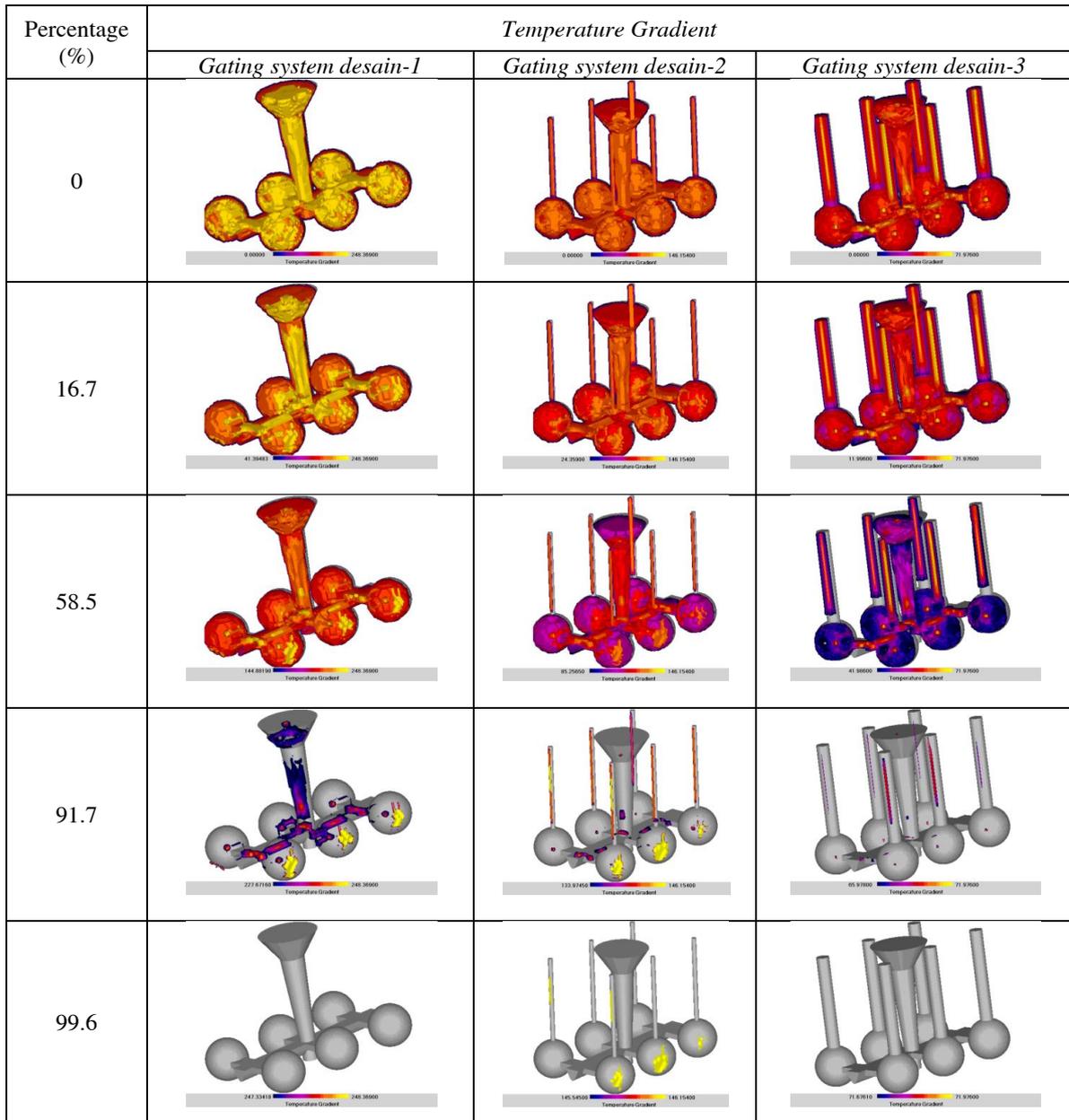
The yield production for each gating system, as listed in table 3, was calculated by the ratio of the total weight of grinding ball (GB) product to the total weight of grinding balls (GB) and gating system (GS), as expressed in equation (6).

$$\% \text{ Yield} = \frac{\text{weight of GB}}{\text{weight of (GB+GS)}} \cdot 100\% \quad (6)$$

From table 3, the higher volume of vent air, the lower yield would obtain. Though gating system design-3 had no defect and it also had the lowest percentage of yield production. Thus, the optimization casting simulation of grinding balls should be enhanced by changing the casting simulation parameter, such as pouring temperature.

Time (s)	Solidification Time		
	<i>Gating system design-1</i>	<i>Gating system design-2</i>	<i>Gating system design-3</i>
1			
2			
3			
4			
5			

**Figure 6.** Casting simulation for solidification time



**Figure 7.** Casting simulation for temperature gradient

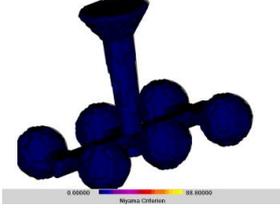
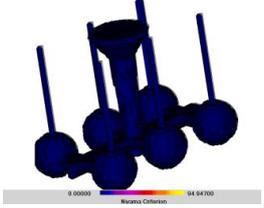
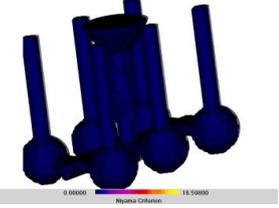
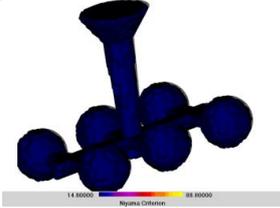
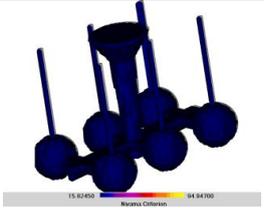
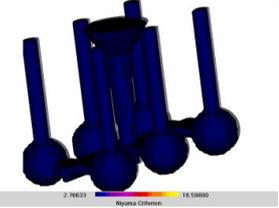
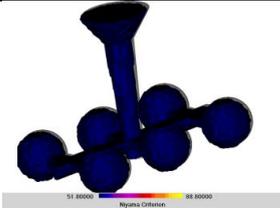
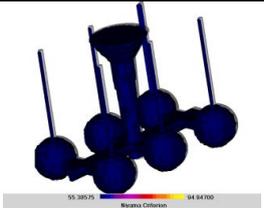
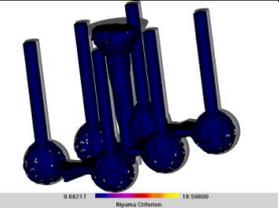
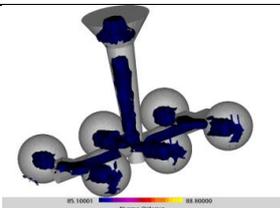
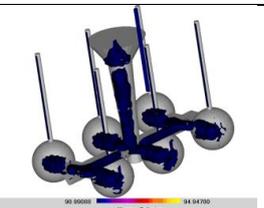
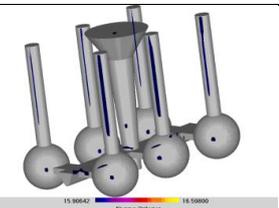
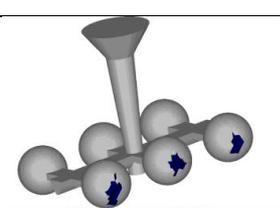
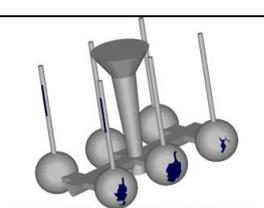
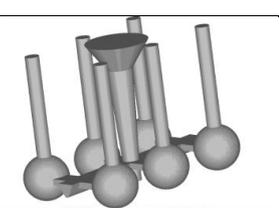
Percentage (%)	Niyama Criterion		
	<i>Gating system desain-1</i>	<i>Gating system desain-2</i>	<i>Gating system desain-3</i>
0			
6.7			
58.3			
95.8			
99.6			

Figure 8. Casting simulation for niyama criterion

s / (%)	Gating system design-2		
	<i>Solidification Time</i>	<i>Temperature Gradient</i>	<i>Niyama Criterion</i>
1/0			
2/16.7			
3/58.3			
4/91.7			
5/99.6			

**Figure 9.** Optimization casting simulation for gating system design-2 with pouring temperature of hot metal at 2696 F (1480 °C)

**Table 3.** Percentage of yield production of grinding balls

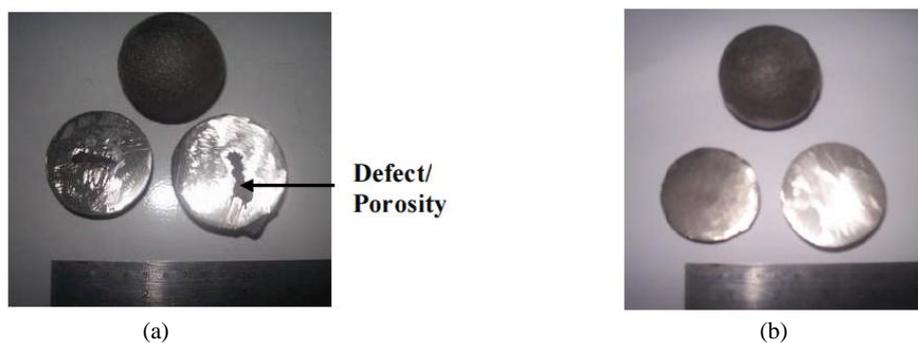
Gating System Design	Weight of GB (Kg)	Weight of GS (Kg)	Total Weight (GB+GS) (Kg)	Yield Production (%)
1	2.97	1.31	4.28	69.39
2	2.97	1.425	4.395	67.58
3	2.97	2.37	5.34	55.65

High chromium white cast iron (ASTM A532) is one of cast iron that could solidify rapidly from a liquid phase. Thus, the pouring temperature will be a very important parameter in this casting process. Thus for the next simulation, the pouring temperature was changed to 2696 F (1480 °C).

As previously described that vent air would prevent the formation of casting defects. Therefore, the optimization of gating system design-2, that had a better in yield production than gating system design-3, had been conducted. The new pouring temperature (1480 °C) had been applied on gating system design-2. The casting simulation was included solidification time, temperature gradient, and niyama criterion, as shown in Figure 9.

From the result, it was shown that there was no defect (no-blue color) on simulation of niyama criterion for the gating system design-2. It was found that by changing the pouring temperature from 2642 F (1450 °C) to 2696 F (1480 °C) had improved the quality of grinding ball product significantly.

By using all parameters of previous casting simulation, the grinding balls were produced by smelting a scrap of cast iron and steel, and ferroalloys in an induction furnace. The hot metal was poured into a sand mold in two difference of pouring temperature that was 1450 °C to 1480 °C. The grinding ball casting product was shown in Figure 10. The hot metal that was poured into grinding ball's mold with gating system design-1 at 1450 °C showed defect/porosity inside the grinding ball, as shown in Figure 10a. Meanwhile, the hot metal that was poured into grinding ball's mold with gating system design-2 at 1480 °C showed no-porosity inside the grinding ball, as shown in Figure 10b. Therefore, the casting simulation of grinding balls was agreed with the actual casting process in this experiment.



**Figure 10.** Grinding ball casting product, (a) Gating system design-1 at pouring temperature 1450 °C, (b) Gating system design-2 at pouring temperature 1480 °C

#### 4. Conclusion

Grinding balls with 50 mm diameter, that had 2.18C - 0.72Si - 13Cr - 1.38Mo, were made with no-defect using the sand mold-gravity casting process. From the casting simulation using SOLIDCast™ version 8.2.0, the vent air in gating system could prevent the internal defect on grinding balls. The vent air with 6 mm diameter resulted in the sound casting of grinding ball by applying pouring temperature at 1480 °C. Thus it was resulted in better yield production rather than by using pouring temperature at 1450 °C.

#### Acknowledgments

We would like thanks to Mr. Jeff Meredith as Trainee Staff from SOLIDCast™ version 8.2.0 who gave this software license for a month to authors for completing this study.

#### References

- [1] Gundewar C S, Natarajan K A, Nayak U B and Satyanarayana K 1990 *Minerals Engineering* **3** 207
- [2] Albertin E and Moraes S L 2007 *Wear* **263** 43
- [3] Albertin E and Sinatora A 2001 *Wear* **250** 492
- [4] Reda R, Nofal A, Ibrahim K H and Hussien A 2010 *China Foundry* **7** 438.
- [5] Wang J, Xiong J, Fan H, Yang, H S and Liu H H 2009 *Journal of Materials Processing Technology* **209** 3236.
- [6] Chenje T W, Simbi D J and Navara E 2004 *Materials and Design* **25** 11.
- [7] Amland H, Barnard L, Bates C, Birkey H, Dunbar D, Duncan R, Dutcher D, Ferguson G, Heger J, Hollander D, Houghton K, Kerwin T, Monroe R, Nariman R, Nelson R, Rudd P, Sailors D, Scott D, Schleg F, Steel C, Stevens T and Voigt R 1995 *Steel Casting Handbook-Sixth Edition* ed Blair M and Stevens T L (United States of America: Steel Founders' Society of America and ASM International) chapter 13 4-6.
- [8] Naro R L 1999 *AFS Transactions* **839**
- [9] Ravi B 2008 Casting Simulation: Benefits, Bottlenecks, and Best Practices. *Indian Foundry Journal* 1
- [10] Kalpakjian S and Schmid S R 2006 *Manufacturing, Engineering, and Technology-Fifth Edition* (Singapore: Prentice Hall, Pearson Education South Asia Pte Ltd) 285-321.
- [11] Heine R W, Loper C R and Rosenthal P C 1967 *Principle of Metal Casting-Second Edition* (Newyork: Mc. Graw Hill Book Company)
- [12] SOLIDCast™ version 8.2.0 (June 20) 2012 Finite Solution Incorporated
- [13] Carlson K D and Beckerman C 2008 *Proc. Int. Conf. on the 62<sup>nd</sup> SFSA Technical and Operating Conference (Chicago: Steel Founders' Society of America)* 1