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ROOT CAUSE ANALYSIS OF THE DEFECTS IN GREY IRON CASTINGS

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Abstract

The sand casting process suffers from defects and imperfections in components or casted parts. In this paper, green sand process parameters and gating system is combined to analyse the root cause of the defects in green sand casting. The green sand process parameters considered are; moisture content, permeability, compressive strength, sieve analysis and clay content. For analysing the gating system through simulation route, Solidworks 2017 was used. The practiced gating system and proposed gating system were simulated and parameters considered during simulation were velocity and pressure of the melt. From green sand testing, moulding sand consisted of coarse particles, high moisture content and significant permeability. Moreover, the routinely practiced gating system showed turbulent flow with higher pressure. The proposed gating system exhibited an adequate reduction in pressure and turbulence in the grey cast iron melt flow. Therefore, such results are promising for stable mold cavity and optimum pressure necessary for sound quality castings.

Keywords: Casting defect, Green sand, Grey iron, Sand mould, Solidworks 2017.

1. Introduction

Sand casting is known to be one of the most economical and widely used techniques which can be opted to produce a variety of products with different shapes and sizes. In this process, material to be shaped is first liquefied and then decanted into a prepared mould cavity where it solidifies and ultimately, the product is removed. The pattern is a replica of the foundry, and it is used to make the mould cavity by Gabelchenko et al. [1]. Sand consists of various components like binders and water content by Stefana et al. [2]. An ordinary mixture by volume could be 89% sand, 7% clay and 4% water. Binders help to harden the sand. The pattern is intentionally more critical than casting to allow removal during cooling. Mould is a set of two or more metal blocks or joined refractory particles (sand) formed by a primary cavity [3, 4]. The mould cavity contains the liquid material and acts mainly as a negative of the desired product. Proper attention during the merger is essential Wan et al. [5]. Factors to consider when melting include gases in the metal, the selection and control of scrap, flow, furnace and temperature by Kmita et al. [6].

A good grid design guarantees distribution of metal in the mould cavity at an adequate speed without excessive loss of heat, turbulence and entrapment of gases and slag as discussed by Zawieja and Sawicki [7]. The main activities involved in preparing a mould are moulding, melting, decanting, solidification, cleaning, inspection and disposal of defective moulds to final production. It is normal to have certain imperfections on the casted product, but they also exit the solution to limit those deformities effectively, before arriving as the completed product [8, 9]. This research used the experimental design of the mixture, the response surface methodology (R.S.M) with several variables studied, which affect the casted product as discussed by Shekhar [10]. Sand, degree of ramming and melt composition are some of the most critical variables. Sand must be evaluated according to moisture and clay content, permeability and compressive strength. Each variable has its own sensitivity and shall be analysed over its behavior to process parameters [11, 12]. Accordingly, water content has the most substantial influence on ten bentonites. Similarly, the degree of ramming also plays a vital role in sand characteristics. The presence of SiO_2, fly ash and bentonite enhances the physical properties and binding strength of green sand [13-15].

During pouring operation, the entrapment of gases is a significant hurdle. The severity of gas entrapment depends on process parameters. Higher filling speed causes greater, more considerable turbulence and hence, increases gas absorption and permeability effect inversely[16-18]. Sources of gases can be the surrounding environment, moisture content and binders. Gases are emitted till solidification is completed and the duration of gas emittance increases with an increase in the moisture content as discussed by Alisir and Cevik [19]. Castings have surface porosity at the front side. In contrast, if the porosity is observed on the opposite side, it is primarily due to higher turbulence or higher metal penetration.

The blowhole is a filling related defect. It is one of the severe casting defects among all. They occur when the entrapped gas escapes out from molten metal during solidification, leaving behind a permanent hole in the casting which can either be found on the surface or in the subsurface. Another significant defect is a pinhole, which is caused by absorption of the gases (hydrogen, nitrogen and oxygen) in the melt, especially hydrogen by Zych et al. [20]. Mould shift or mismatch caused by improper alignment of cope and drag is also a reason behind rejection of casting. A mismatch is caused by several reasons like worn out or bent clamping pins during casting causes misalignment and improper support of core by chaplets [21, 22]. These defects reduce the efficiency of the foundry and increase the cost as discussed by Zych and Mocek [23]. Conventionally trial and error methods are used to detect defects which are time and cost consuming. Besides that this investigation focuses on analysing the green sand and simulating the gating system. As green sand is the material subjected to forces and eat from the melt, its properties are vital for successful casting. To configure the gating system simulation can help to optimize different aspects of it and provide optimum results.

The objective of this investigation is to determine the root cause for the generation of blowholes in the casting and necessary arrangements which could be made to overcome this problem. Different constitutes of sand have been analysed; melt flow was simulated in the current gating system used in industry and proposed gating system. The result of the study can be beneficial for the sector performing sand casting. Another major factor that plays a vital role in describing the authenticity of the melt is the gating system, which is also taken into consideration under this study along with following important casting parameters.

2. Moisture Content

The experiment was conducted by taking 2 grams of green sand and heating it in the furnace for about 4 hours at 105 °C removing the moisture content, which was calculated by dividing difference in weight with the original weight. This procedure is also known as weighing method for calculating the moisture content as explained with Eq. (1).

$$Moisture = \frac{w_2 - w_3}{w_2 - w_1} \quad (1)$$

Quantity of water present in the material (greensand in this scenario). The green strength of the moulding mixture increases with the amount of water up to optimum value under the quantity of clay, after which it starts to diminish. An additional amount of free water causes the green strength to decrease however the dry strength tends to increase to obtain the correct value of moisture content shall be achieved with minimum use of clay.

2.1. Permeability

It is a physical property that allows gas to pass through the moulding sand. The rate of flow of air is determined through metric standard rammed specimens under standard conditions. This is carried out by preparing sample in the standard cylindrical tubes in which the sand is packed. The permeability meter constitutes a graduated bell of 2000ml, a tube carrying air and a scale measuring water height is mentioned in Eq. (2).

$$P = \frac{V.H}{p.A.t} \quad (2)$$

2.2. Compressive strength

The mould is subjected to high compressive stress when the melt is decanted on it from the ladle and a weak compressive strength result in crushing of the mould.

2.3. Sieve analysis

To analyse the distribution of sand particle size, Grain distribution is an essential factor affecting permeability and strength both. Grading is conducted with the help of standard sieves, which separate a fraction of sand [21, 24].

2.4. Gating system

The gating system is the most vital element of the casting process. About 80 percent defects are caused due to an improper gating system, which in result causes turbulence [25, 26]. The height from which the melt is falling is essential. The greater the height, the more considerable energies are involved by Choudhari et al. [27]. Entering velocity of the melt is crucial as altering it can achieve either complete success or failure. Therefore, velocity above critical velocity (which is about 0.45 m/s) should be achieved. Furthermore, a critical height of 10.4 mm should also be maintained during the poring process. The critical velocity (V_{crit}) and height (h) are influenced by surface tension (critical velocity shall be accomper compl). Hence calculated from the following Eqs. (3) and (4) [24, 28, 29].

$$h = 2\sqrt{\frac{\gamma}{\rho g}} \tag{3}$$

$$V_{crit} = 2\sqrt[4]{\frac{\gamma g}{\rho}} \tag{4}$$

Each molten product was checked very carefully based on numerous product defects. Among variety of errors, defects such as blowholes, small holes, sand spots were the most worrisome in our data analysis. The physical properties of the sand assist in determining the effects on the properties of casted product such as moisture content, permeability, compressive strength and mesh size. The features required for casting are determined by the moulding and casting methods and conditions. Principle requirements of sand are its strength and moisture content, which varies according to the type of casting practice conducted. Higher strength is required when the mould is needed to withstand deeper cores, whereas lower strength is necessary in the case of shallow cores. To produce heavy casting, an appropriate combination of properties at high temperatures is required as discussed by Li et al. [30].

2.5. Clay content

Reusing of clay is permissible depending upon the shelf life of the green sand and its overuse can adversely affect compressive strength, permeability and flow ability as clay content has a high effect on these properties by Kim et al. [31]. Excessive reusing alters the standard clay content. However, in this study, simulation is also used to understand the gating system in place & to determine whether the pouring system itself works fluently. Besides, some testing was also carried to assess the material parameters, i.e., green sand testing.

3. Materials and Method

In this present work, grey cast iron containing blowholes and green sand were received from local industry. For analysing the root cause of the defect, green sand process parameters and gating system were considered. Green sand process parameters were considered to identify the role of the green sand in the generation of blowhole defects in the grey cast iron casting. The process parameters considered were moisture content, permeability, compressive strength, sieve analysis and clay content. These are the most significant parameters that affect the quality of the casting. Moreover, they were identified using the procedure mentioned in sections 3.1.1. to 3.1.5.

For analysing gating system simulation was carried out using Solidworks 2017. During the simulation, the practiced gating system was constructed in Solidworks 2017, and parameters of velocity and pressure of the melt (melted grey cast iron) were observed. The proposed gating system was also simulated considering the velocity and pressure of the melt. Changes in velocity and pressure were studied in the melt flow during the melt entering the gating system, then reaching the mould cavity through the gating system and finally filling the mould cavity.

3.1. Characterization techniques

Several tests were carried out on different samples of moulding sand as well as the casted product since the molten metal plays a crucial role while pouring in the mould. These tests include moisture content, permeability, compressive strength, clay content, sieve analysis and chemical composition.

3.1.1. Moisture content

As per casting conditions, hot cast iron is decanted over the sand which is above 1000oC. At this temperature, the mould goes under changes cryptographically and loses moisture content, exhibiting shrinkage and loss of bonding capacity; thus, the mould must contain additives with higher water absorption capabilities providing better results at a higher temperature.

3.1.2. Permeability

Taking standard volume, area and height and substituting them in the formula shows that it is necessary to determine the time taken for 2000ml air to pass through the specimen and known pressure.

3.1.3. Compressive strength

It is a measure of the compressive stress at which the material fails. The test utilizes a 50 mm X 50 mm cylinder prepared by ramming of sand, which is then carried to the compressive testing machine over which sand is subjected to an increasing weight under standard condition until it calibrates the cracks and the mould breaks. The Sand Testing Compressive Strength Machine calculated it. A specimen of 50mm was prepared with the help of a prepared cavity.

3.1.4. Clay content

Clay provides strength to the mould. Therefore, it is necessary to identify its percentage 100 g of sand was taken and decanted in a measuring cylinder, then 475 ml of distilled water and 25ml of NaOH (5%) solution was taken. This mixture was stirred with a mechanical stirrer for about 5 to 7 minutes and then the mixture can settle for 5 minutes. Then siphon out the water and then add distilled water again. This procedure was repeated three times until water cleaned up and finally, wet sand was transferred for drying in an oven at 110°C to remove the moisture.

3.1.5. Sieve analysis

The sand was dried with the help of a furnace at 105°C and weighed as transferred to the sieve. It weighed 9.15 grams and was mechanically shaken in sieves until constant weights were achieved.

3.1.6. Chemical composition

The spectrometric analysis of the given sample was conducted using Spectro MAXx instrument and Spark Analyzer Pro Maxx (2.0) system was used to measure and perform quantitative analysis on instrument. The instrument functions on the principle of Optical Emission Spectroscopy.

3.1.7. Gating system

Gravity pouring is practiced in the industry. In this, a running system guides the melt to the mould. Improper running system results in higher melt velocities causing defected products. Surface Turbulence leads to porosity and loss of mechanical properties. A sound system comprises of the following elements. The casting shall be economical in terms of size, ratio of the cast to weight and the finished product should be less, resulting in higher yield. Secondly, the running system should keep the melt velocity below the critical value. Finally, delivery of the melt in the mould should not be accompanied by other phases like air. These aspects were considered during construction of proposed gating system,

4. Results and Discussion

4.1. Moisture content

Moisture content was calculated with multiple weights, as discussed earlier. The calculated moisture content yielded 5.17% as an increase in the moisture content reduces the bulk density until the saturation point. Simultaneously, standardized moisture content for cast iron is 3-4%. It would cross the saturation point and hence, disturbed casting properties as shown in Fig. 1.

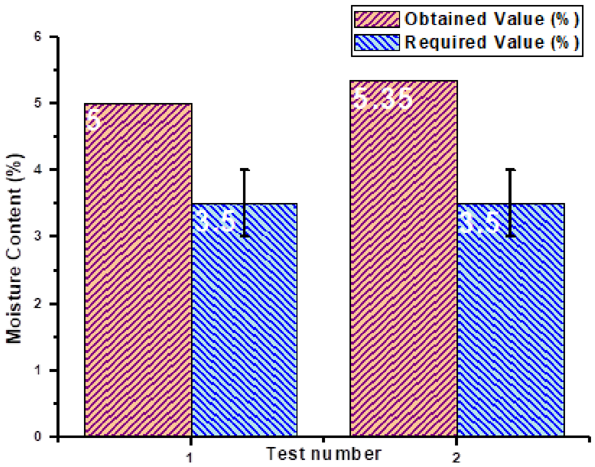

Fig. 1. Moisture content of commercially used sand vs. AFS standards.

4.2. Permeability

The results indicate that the sand has enough permeability for gases to escape, but it is slightly more than our requirement. It must be around 320 AFS per unit, corresponding to the moisture content of 5 %. Permeability is dependent on the size and shape of the grain. Moisture content also affects the permeability as excess moisture content traps in the cavities between the sand particles decreasing the permeability and hence, excessive permeability results in metal flooding in the sand mould. The obtained values are shown in Fig. 2.

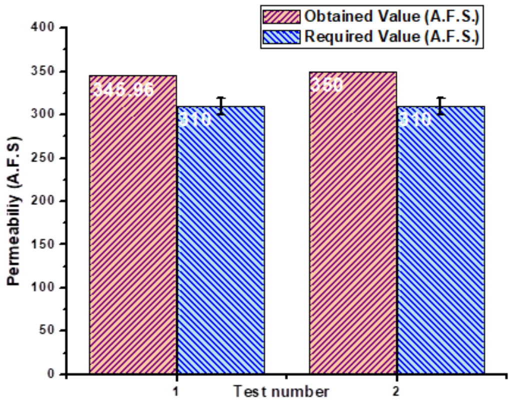

Fig. 2. Permeability of commercially used sand vs. AFS standards.

4.3. Compressive strength

The experiment was carried out three times, yielding an average compressive strength of 91.6 kN/m^2. It was found that compressive strength shall be 90 kN/m^2 as shown in Fig. 3. The specimen satisfies the condition but with a slight margin, which might generate problems in foundry operation.

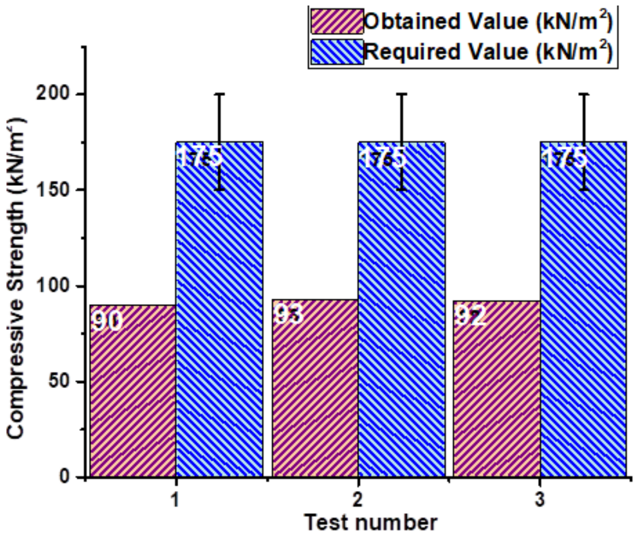

Fig. 3. Compressive strength of commercially used sand vs. AFS standards.

4.4. Clay content

The procedure was carried out three times and yielded an average clay content of 10.31%, as shown in Fig. 4, which proves that the clay content of the sand is within the accessible limit.

4.5. Sieve analysis

For proper compaction of the mould, it is vital for the weight of the sand to be distributed in a proportion of 95% in 4 to 5 sieves, which comply in this case. The Sand with wide particle range has higher compatibility then the sand with smaller particle sizes as more extensive range provides greater strength and exhibit lesser permeability as shown in Fig. 5.

4.6. Chemical composition

Some content did not match with the casting, which was supposed to be performed with the discussed green sand. Some irregular quantities were recorded as shown in Fig. 6.

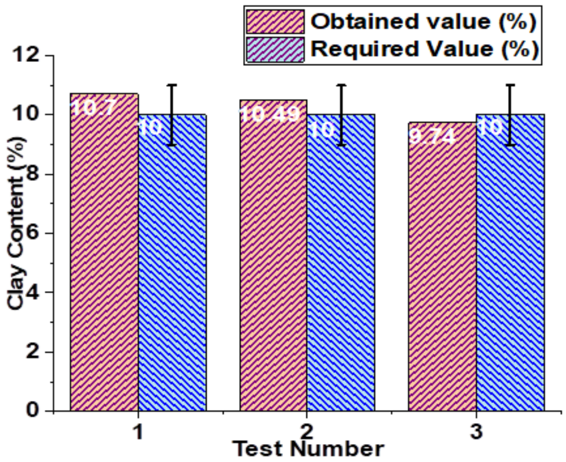

Fig. 4. Clay content of commercially used sand vs. AFS standards.

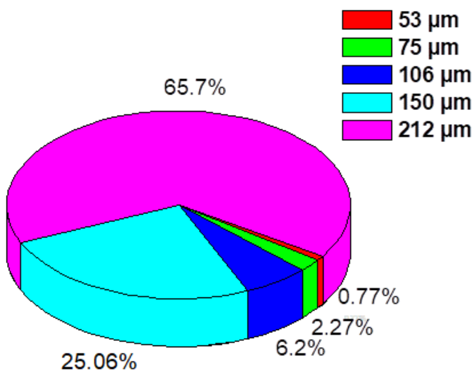

Fig. 5. Clay content of commercially used sand.

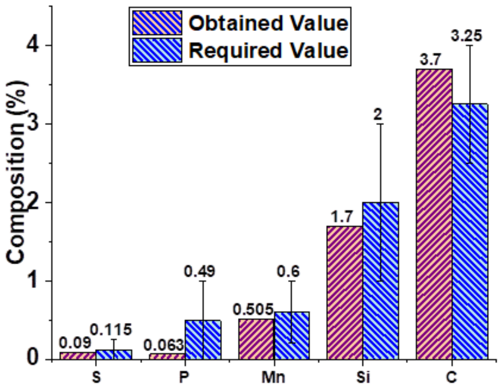

Fig. 6. Chemical composition of the molten metal which is casted in the sand.

4.7. Gating system

A comparison between turbulence and proposed flow was made using the software SolidWorks by Dassault Systems. As shown in Figs. 7 to 9, there exists a practiced gating system in which the melt enters the mould and hits the walls with much greater force and a high probability of causing defects. Another remedial measure was designed in a manner so that the melt coherently enters the mould reducing turbulence and velocity as illustrated in Figs. 10 to 12. The recommended gating system contains Offset basin from which the melt flows down to the tapper runner and finally enters the cavity for solidification as shown in Figs. 10 to 12. The impact of the melt on the mould walls is nullified with its bottom to up approach.

These images represent simulation, which ran several times, indicating at least ten-fold reduced entry velocity and doubled secondary pressure on the mould walls when the gating system it was changed to the bottom gating system, which also terminated the formation of bubbles due to proper offset basin. The offset basin in the above images avoids melt agglomeration and thereby, reduces the possibility of bubbles entrainment.

Practiced Flow

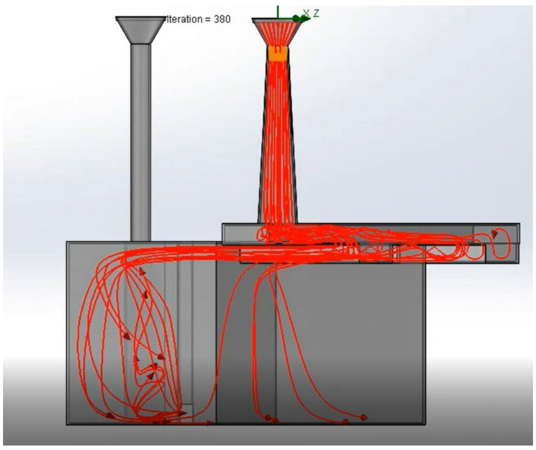

Fig. 7. Initial stage of practiced flow.

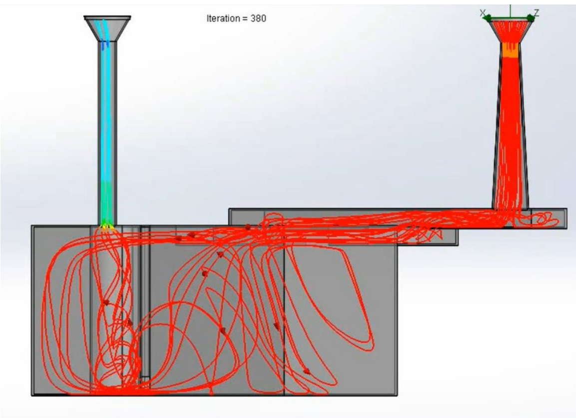

Fig. 8. Intermediate stage of practiced flow.

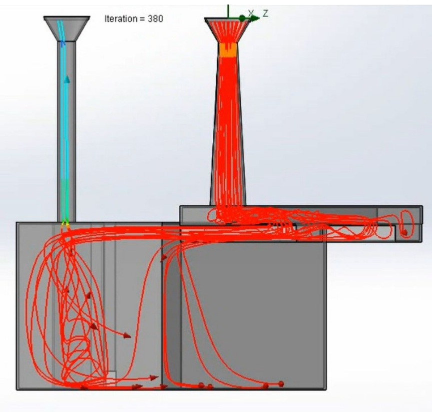

Fig. 9. Final stage of practiced flow.

Proposed Flow

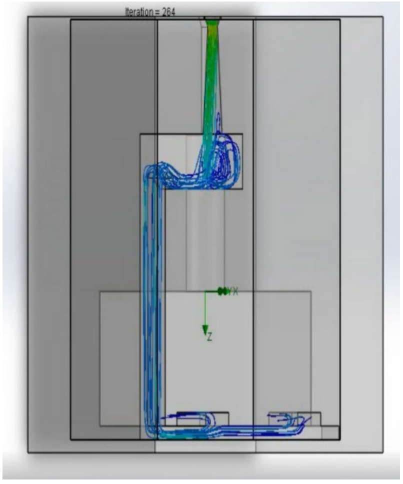

Fig. 10. Initial stage of proposed flow.

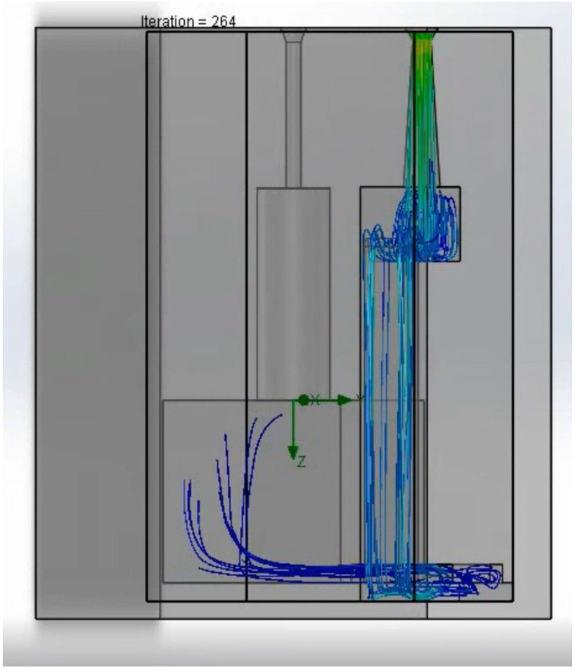

Fig. 11. Intermediate stage of proposed flow.

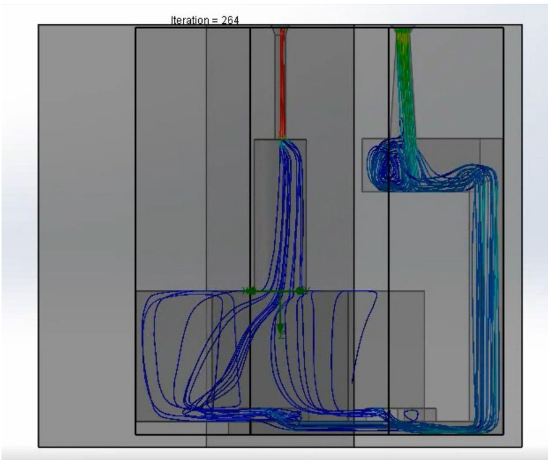

Fig. 12. Final stage of proposed flow.

Combined factors of practiced and proposed flows are discussed below with their respective charts obtained from the results of simulation.

Figures 13 and 14 show point velocity in proposed and practiced flows, when the melt first enters the mould. Practiced flow has a higher entry point velocity (as shown in Fig. 13) which then decreases as the melt hits the runner in the cope, then again increases as it flows in the runner section to the casting and drops in the casting cavity. This drastic change in a limited amount of time generates turbulence in the melt velocity leading to non-uniform filling of the mould. Comparatively, in proposed gating system as shown in Fig. 14, the velocity is lesser at the entry point and increases as the melt leaves the offset basin and eventually, increases in the taper sprue. Then again, velocity increases gradually as the melt enters and exists the taper runner. In proposed gating system, as the melt enters the main cavity there is much lesser variation in velocity and melts fills flows homogenously whereas, in practiced flow there exist variation in the velocity which effects the melts ability to flow homogenously.

Figure 15 shows the difference in pressure levels of proposed and practiced gating system. In practiced gating system pressure levels are higher and fluctuate whereas in proposed the pressure levels are lower and steadier. High pressure level in practiced gating system effects the integrating of the sand mould system as strength of the mould is affected. Furthermore, fluctuation in pressure hinders homogenous filling as shown in Figs. 7 to 9. Lower pressure in proposed gating system possesses minimal effect to the strength of sand mould and pressure is observed to increases proportionally with change in the geometry which promotes homogenous filling.

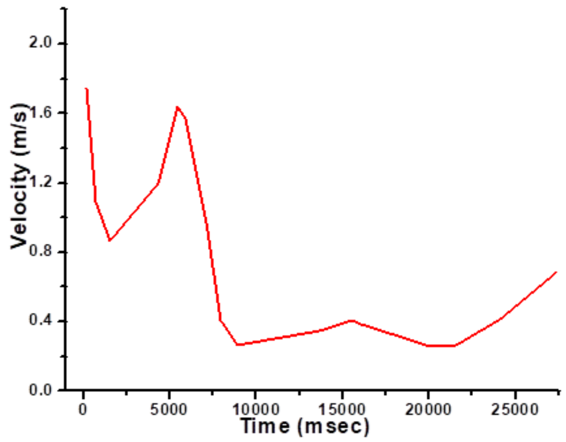

Fig. 13. Velocity detected in practiced flow with respect to the gating system.

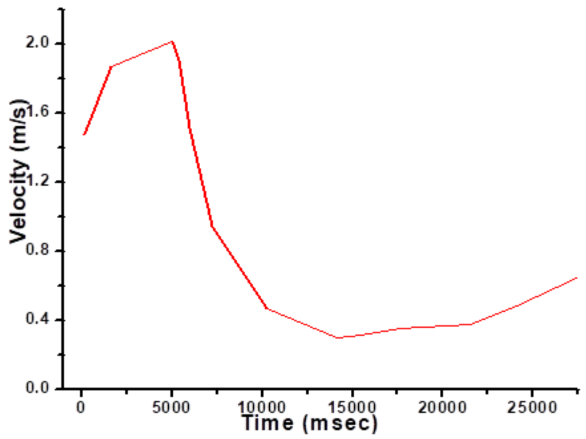

Fig. 14. Velocity change in proposed flow with respect to the gating system.

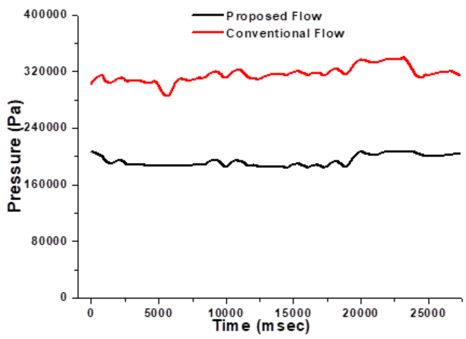

Fig. 15. Pressure change in proposed and practiced flow with change in gating system.

5. Conclusion

To conclude the above discussion, it was found that moisture content is very high compared to that prescribed by the American Foundry System (AFS). This adversely affected the green compressive strength and shrinkage allowance of the mould whereas, it promotes the gas entrapment. Also, it is shown that the sand particles used in the mould were coarse beside the recommended value of AFS. Furthermore, higher carbon content in the composition of defected region was also observed. Simulation highlights the turbulent flow with high pressure in the practiced gating system. Besides that, proposed gating system is observed to be laminar with lower pressure which is vital for reducing the casting defects.

Nomenclatures

A	Area of the cross-section, cm^2
g	Gravity acceleration, m/s^2
H	Height of specimen, cm
h	Height, cm
P	Permeability number
p	Pressure of air, cm H_2O, Pa
t	Time, s
V	volume of air flowing through the specimen, ml
W_1	Weight of Empty Dish, gr
W_2	Weight of dish + sample, gr
W_3	weight of dish + sample after drying, gr

Greek Symbols

γ	Surface tension, N/m
ρ	Density of metal, g/cm^3

Abbreviations

AFS	American Foundry System

References

1. Gabelchenko, N.; Belov, A.; and Meshcheryakova, O.N. (2019). Production of high-quality castings from gray iron by differentiated cooling in iron mould. *Materials Science Forum*, 973: 15-20.

2. Stefana, E.; Cocca, P.; Marciano, F.; Rossi, D.; and Tomasoni, G. (2019). A review of energy and environmental management practices in cast iron foundries to increase sustainability. *Sustainability*, 11(24): 7245.
3. Mitra, S.; de Castro, A.R.; and El Mansori, M. (2019). On the rapid manufacturing process of functional 3D printed sand molds. *Journal of Manufacturing Processes*, 42, 202-212.
4. Al-Saraireh, F.M. and Svinoroev, Y. (2020). Assessment of casting binding materials based on modified technical lignosulfonates. *International Journal of Mechanical and Production Engineering Research and Development* (*IJMPERD*), 10(2), 335-346.
5. Wan, P.; Zhou, J.; Li, Y. et al. (2019). Experimental study on gas evolution process of binders in foundry industry based on TG-MS. *Procedia Manufacturing*, 37, 311-318.
6. Kmita, A.; Fischer, C.; Hodor, K.; Holtzer, M.; and Roczniak, A. (2018). Thermal decomposition of foundry resins: a determination of organic products by thermogravimetry–gas chromatography–mass spectrometry (TG–GC–MS). *Arabian journal of chemistry*, 11(3), 380-387.
7. Zawieja, Z.; and Sawicki, J. (2022). The gas evolution of a modified cellulose mixture used for gating systems in the no-bake mould process. *Journal of Thermal Analysis and Calorimetry*, 147(3), 2027-2034.
8. Sandeep, M.J.; Manjunath, G.C; Chate, G.R.; Parappagoudar, M.B.; and Daivagna, U.M. (2019). Multi response optimization of green sand moulding parameters using Taguchi-DEAR method. *Applied Mechanics and Materials*. Trans Tech Publ. 895: 1-7.
9. Kumari, A.; Murari, A.; Ohdar, R.; and Prasad, U. (2020). *Multi Response Optimization of the Green Sand Moulding Process using Grey Taguchi Method*.Proceedings of the 2020 *International Conference on Computer Science*, *Engineering and Applications* (*ICCSEA*), Gunupur, India, 1-6.
10. Shekhar, C. (2019). *Reducing the defects in casting of piston using six sigma* (*DMAIC Approach*. MSc. Disertation. University Of Science & Technology.
11. Shilpa, M.; Prakash, G.; and Shivakumar, M. (2021). A combinatorial approach to optimize the properties of green sand used in casting mould. *Materials Today: Proceedings*, 39: 1509-1514.
12. Ganganallimath, M.M.; Patil, S.D.; Gijo, E.; Math, R.B.; and Hiremath, V. (2019). Application of Taguchi-based Six Sigma method to reduce defects in green sand casting process: a case study. *International Journal of Business and Systems Research*, 13(2), 226-246.
13. Pulivarti, S.R. and Birru, A.K. (2018). Optimization of green sand mould system using Taguchi based grey relational analysis. *China Foundry*, 15(2), 152-159.
14. Chelladurai, C.; Mohan, N.; Hariharashayee, D.; Manikandan, S.; and Sivaperumal, P. (2021). Analyzing the casting defects in small scale casting industry. *Materials Today: Proceedings*, 37, 386-394.
15. Ranade, P.B.; Reddy, G.; Koppal, P.; Paithankar, A.; and Shevale, S. (2021). Implementation of DMAIC methodology in green sand-casting process. *Materials Today*: *Proceedings*, 42 (Part 2), 500-507.
16. Sama, S.R.; MacDonald, E.; Voigt, R.C.; and Manogharan, G.P. (2019). Measurement of metal velocity in sand casting during mold filling. *Metals*, 9(10): 1079.

17. Maruyama, T.; Tamaki, M.; Nakamura, G.; and Nakamura, K. (2019). Effect of molten metal temperature on mold filling in evaporative pattern casting. *International Journal of Metalcasting*, 13(3), 611-617.
18. Koroyasu, S. (2020). Effects of reduced pressure, casting design and heat transfer resistance of liquid resin on mold filling in expendable pattern casting process of aluminum alloy. *Materials Transactions*, 61(3), 528-533.
19. Alisir, S. and Cevik, S. (2020). The effects of foundry sand components on the cast iron. Research on Engineering Structure & Material, 6(2), 127-140.
20. Zych, J.; Mocek, J.; and Kaźnica, N. (2018). Kinetics of gases emission from surface layers of sand moulds. *Archives of Foundry Engineering*, 18(1), 222-226.
21. Jezierski, J.; Dojka, R.; and Janerka, K. (2018). Optimizing the gating system for steel castings. *Metals*, 8(4), 266.
22. Aloni, S.N.; Chaudhari, S.S.; and Shrivastava, R.L. (2020). Optimisation and predictive modelling of green sand casting process to minimise persisting defects in GI components. *International Journal of Productivity and Quality Management*, 30(3), 394-427.
23. Zych, J. and Mocek, J. (2016). Gas generation the top layer of sand mould. *Nauka i technika w inżynierii procesów odlewniczych. Seria Monografie*, 8, 65-78.
24. Dojka, R.; Jezierski, J.; and Campbell, J. (2018). Optimized gating system for steel castings. *Journal of Materials Engineering and Performance*, 27(10), 5152-5163.
25. Shaikh, M.B.N.; Ahmad, S.; Khan, A.; and Ali, M. (2018). Optimization of multi-gate systems in casting process: Experimental and simulation studies. *IOP Conference Series: Materials Science and Engineering*, 404: 012040.
26. Sultana, N.; Rafiquzzaman, M.; Rahman, Y.; and Das, A. (2018). Solidification and filling related defects analysis using casting simulation technique with experimental validation. *International Journal of Mechanical Engineering and Applications*, 6(6), 150-160.
27. Choudhari, C.M.; Narkhede, B.E.; and Mahajan, S.K. (2013). Optimum design and analysis of riser for sand casting. *Proceedings of the* 2013 *IEEE International Conference on Industrial Engineering and Engineering Management*. Bangkok, Thailand, 1151-1155.
28. Malinovsky, D.A.; Safronov, N.N.; and Kharisov, L.R. (2019). Improvement of gating systems with the purpose of reducing defects in large-size castings from gray iron. *Helix - The Scientific Explore*, 9(4), 5197-5208.
29. Persson, P.; Ignaszak, Z.; Fransson, H. et al. (2019). Increasing precision and yield in casting production by simulation of the solidification process based on realistic material data evaluated from thermal analysis (Using the ATAS MetStar System). *Archives of Foundry Engineering*, 19(1), 117-126.
30. Li, F.; Zhao, H.; Ren, F. et al. (2020). Simulations and experiments of mould filling in lost foam casting. *International Journal of Cast Metals Research*, 33(4-5): 194-200.
31. Kim, D.; Nam, B.H.; and Youn, H. (2018). Effect of clay content on the shear strength of clay–sand mixture. *International Journal of Geo-Engineering*, 9:19, 1-12.