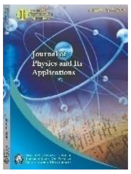
Journal of Physics and Its Applications

Journal homepage : https://ejournal2.undip.ac.id/index.php/jpa/index



Stokes' Law Approach to Slag Formation Process to Increase the Effectiveness of Cleaning Metal Liquids in Cast Iron Smelting Process

Muhammad Rizki Gorbyandi Nadi*, Cecep Ruskandi, Ari Siswanto, and Gita Novian Hermana

Foundry Engineering, Bandung Polytechnic of Manufacturing, Bandung, Indonesia

*)*Corresponding author: rizkigorby@gmail.com*

ARTICLE INFO

Article history:
Received: 8 June 2022
Accepted: 30 September 2022
Available online: 30 November 2022

Keywords:
Slag
Cast iron
Slag characterization
Terminal velocity of slag

ABSTRACT

The purpose of this study was to increase the effectiveness of slag cleaning in the cast iron smelting process using an induction furnace. This study resulted in the calculation of the terminal velocity of the slag emerging to the surface of the induction furnace based on Stokes' Law approach for each slag that appears during the cast iron smelting process. For each cast iron casting, three samples were taken based on the fastest time on the very light slag, the slag's time for the heaviest slag, and the extreme time for comparison. The results of each sample are tested for characterization such as shape, size, and chemical composition of each sample which are then adjusted to the calculations that have been made. The characterization was analyzed using X-ray diffraction, scanning electroscope, and energy dispersive spectroscopy microanalysis. The results show that the Stokes law approach to predict the slag reaching the surface gets the appropriate result that all the slag reaches the surface at time t = 230 s. The slag that appears at time t = 300 s is the slag formed due to the interaction of the liquid with the surface which is not the slag that occurs from the raw material used. This study succeeded in minimizing the formation of slag in each casting of cast iron using an induction furnace.

1. Introduction

The production of iron and steel in the world is very large because of the need for iron and steel used by the whole world today. With this very large production, the slag produced is also very large. Every ton of steel will produce slag of 8-15%. Until 2019, the production of slag has increased by up to 20%. Indonesia itself can produce up to 540.000 tons of slag per year. Until now, the use of slag has been widely carried out including making concrete [1], agriculture [2], cement raw materials [3-4], slag remover [5-7], water treatment [8], etc. Several studies have investigated the utilization of the slag produced by casting and only a few studies about increasing the efficiency of iron and steel production and reducing the slag produced in the process.

In the iron and steel-making process, slag becomes one of the most important aspects, especially in smelting. Smelting is the process of reducing ore or scrap so that it becomes elemental metal that can be used by various substances such as carbide, hydrogen, active metal, or by electrolysis. The selection of this reducing agent depends on the reactivity of each substance. The more active the metal, the more difficult it is to reduce, so a stronger reduction material is needed.

Slag is a by-product formed in smelting, welding, and other metallurgical and combustion processes from impurities in the metal or ore being processed. Slag is mostly composed of mixed oxides of elements such as silicon, sulfur, phosphorus, and aluminum; Ash; and the products formed in reaction with the furnace lining and flux substances such as limestone. Slag on the surface of the molten metal protects it from oxidation by the atmosphere and keeps it clean. Slag forms the coarse aggregate used in certain concretes; used as road material and ballast and as a readily available source of phosphate fertilizer [4].

The occurrence of slag in the smelting process occurs when there is a reaction between the metal being processed interacting with the air, the lining of the induction furnace as well as the interaction between the elements present during the smelting process. The slag formed will immediately appear on the surface of the furnace as a result of the difference in the density of the slag with the density of the raw material for smelting [4]. If the smelting process is carried out for too long, the surface of the liquid will always interact with the air which results in the formation of more slag. If the smelting is carried out too short, the slag that appears in the smelting process has not yet reached the surface. Based on this, if you know the time required for the slag to reach the surface in the smelting process, the slag formed during the smelting process will produce sufficient and not excessive slag, thereby reducing slag production in each smelting process.

To reduce slag production in the cast iron casting process, it is important to know the characteristics of the slag itself, such as the chemical and mechanical composition of the slag formed. The information on the chemical, morphological, and mineralogical properties of slags is playing a key role to understand slag formation and their utilization [9]. This information is useful for determining the effect of chemical elements or the density or shape of the slag during the cast iron smelting process. Several studies have been conducted on the formation of slag having a round and flat shape which is mostly oxides such as FeO and MnO [10].

Many studies have been conducted to find the slag phenomena in the casting process by using numerical simulation. The model successfully predicted the slag phenomena in the casting process. In this study, the investigation of slag phenomena in the casting process has been carried out by using Stokes' law to determine the velocity at which the slag appeared on the surface of the molten metal. This study aims to provide a new perspective on the slag phenomena generated during the casting process.

Slag Characterization

Several studies have discussed the amount and chemical composition of slag even though some information regarding the phase is not fully reported. The amount of slag formed in the smelting process using iron ore with high purity will have the lowest guess and the slag content using steel scrap will be higher [11]. It was also concluded that the chemical content of iron slag waste usually varies depending on the basic materials and steel-making processes, including CaO, SiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, and P_2O_5. The general mineral content of iron slag consists of olivine, merwinite C_3S, C_2S, C_4AF, C_2F, and RO (free of CaO) [12-13]. With differences in raw materials, smelting technology, and steel types, the composition of steel slag may also change.

Terminal Velocity of Slag

The equation for calculating the terminal velocity of the slag can be measured using the Stokes Law equation approach regarding viscosity.

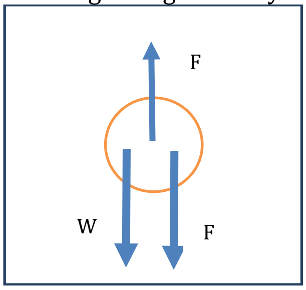


Fig.1: The force received by the slag in the molten metal.

With the slag formed tends to be spherical [5] and the slag appears after the reaction in the aluminum liquid occurs, the slag will receive 3 forces in Figure 1, namely the Archimedes Lifting Force then the gravity of the slag itself and the viscosity force so that the terminal velocity equation is obtained as follows :

$$v = \frac{2gr^2}{9\eta}(\rho_f - \rho_b) \qquad (1)$$

Where v is the terminal velocity of the slag (m/s), g is Earth's gravity, r is the radius of the slag (m) and the density of the liquid metal and the density of the slag.

By knowing the height of the furnace used during the smelting process, an estimate of the terminal velocity of each slag is obtained with the smallest slag radius of slag which is 0.075 mm [14] and the viscosity value of iron is 0.0049 kg/ms [10] and using the velocity equation that The time taken for the slag to reach the surface of the kiln can be seen in Table 1.

Table 1. Type, characterization, and velocity terminal of slag.

No	Slag Type	The density of slag (kg/m³)	Terminal Velocity (cm/S)	Time It Takes Slag To Reach The Surface (s)
1	Fe_2O_3	5.25	0.445	112
2	Al_2O_3	3.95	0.75	66
3	MgO	3.59	0.85	58
4	CaO	3.34	0.9	54
5	SiO_2	2.65	1	70
6	MnO	5.37	0.4025	174
7	FeO	5.74	0.31	226

2. Methods

This research can be seen in the following diagram Fig. 2. The research was carried out in the production of cast iron by using a 100 kg medium frequency induction furnace (Inductotherm, USA). The casting process is carried out using scrap metal and recycling cast iron as the basic material. The material is melted gradually until all the base metals are melted. Based on the results in Table 1, immediately after all the iron was melted, the time calculation began, and sampling was carried out at 65, 230, and 300 seconds in time intervals. This time interval is determined based on the slag terminal speed data from the slowest and the highest and extreme time. Sampling was carried out using special dies on the surface of the molten metal in the induction furnace.

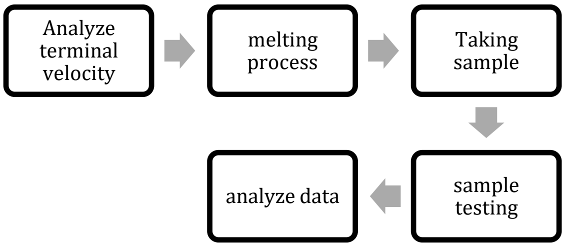


Fig.2: Research method.

To analyze the phenomena, each sample has been cut into several pieces. Each sample was observed under a scanning electron microscope with energy dispersive spectrometry (SEM-EDS, Hitachi SU 3500, Japan) to obtain morphology and chemical element. To study phase formation, the sample was crushed into powder for x-ray diffraction analysis (XRD;

Bruker D8, Germany). The morphology, elements, and phase formation were analyzed and adjusted to the results of the hypotheses.

3. Results and Discussion

Samples were taken with a total of 9 samples with a size of 30 x 40 mm from 3 smelting processes. Each sample can be seen in Figure 3. Based on the picture, it can be seen from the shape and color produced that the longer the time for taking the liquid, the more slag formed. Over time, many holes were formed, and also different colors from the cast iron base indicated that a lot of slags were formed between t = 230 s and 300 s.

Fig.3: Samples that have been taken from the smelting process with t = 65 s, 230 s, and 300 s

The next test uses a Scanning Electron Microscopy (SEM) tool to see the size and shape of the slag in each sample. The test results can be seen in several test samples in Figure 4.

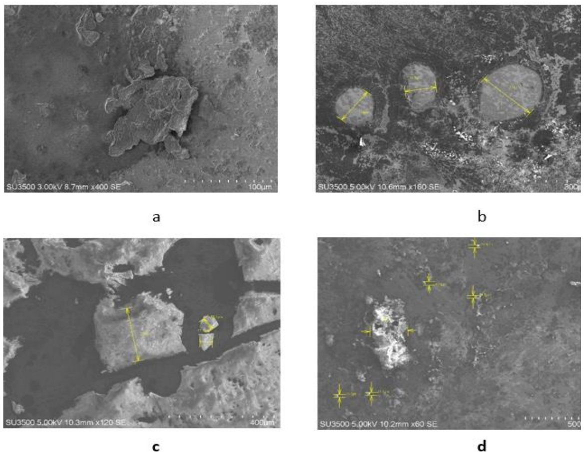


Fig.4: Slag in each sample (a) t = 65 s, (b) t = 230 s, (c) and (d) t = 300 s

Based on these results, it can be seen that at sample t = 65 s, the shape of the slag has various irregular shapes, although some have a slightly circular shape. The radius of the slag produced varies from the smallest size of 6.75 µm to 80 µm. This shows that the slag with the smallest radius that moves the slowest has reached the surface in 65 seconds. At sample t = 230 s, various slags are produced, and the slags that appear tend to have a spherical shape with radii varying from 2-169 µm. Based on several studies [6, 10] that have been carried out these results support that the form of slag comes from smelted scrap. At sample t = 300 s, many slag shapes vary, from spherical with a radius of 21-285 µm, then there are also crystalline forms that are formed. This crystalline slag indicates that the slag formed is the result of liquid interaction with the environment. because the form of slag that occurs that does not occur in the liquid will not experience pressure in all directions from the liquid so the slag tends to be crystalline or coarse. So that the slag at t = 300 s is a slag which is a combination of slag that occurs in the smelting process and the interaction of the liquid with the environment.

After knowing the shape and size of the slag that occurs, then to find out the elements contained in each slag, a test is carried out using Energy Dispersive Spectrometry. This EDS test is carried out on each part of the slag that appears in Figure 4. Each slag is then scanned for the elements contained therein. Next, the average calculation is performed which appears in Table 2.

Table 2. The average result of EDS test.

Element	t = 65 s	t = 230 s	t = 300 s	After Being Given Slag Remover
	Mass (%)	Mass (%)	Mass (%)	Mass (%)
C	17.21	13.94	63.07	3.59
O	16.19	17.36	24.07	-
Fe	61.58	60.20	2.61	94
Al	1.36		3.25	-
Si	1.06	5.35	4.87	1.9
Mn	-	3.15	1.2	0.2
Mg	-	-	2.2	-

In the sample at t = 65 s, it was found that the slag that appears has elements that can become slag in the form of Al and Si with a composition > 1%. The element Si is one element that must exist because it is the main constituent of cast iron and the possibility of becoming slag is very high, it can be seen that every smelting has a Si value. The Al content that appears can also be obtained from the scrap used or other possibilities resulting from the interaction of the liquid with the lining of the furnace. At t = 230 s, another element was obtained, namely Mn with a composition >3% and an increase in the value of Si. At t = 300 s, the other element is mg by 2%. Based on these results, it shows that the slag-forming elements increase with time from 60-300 seconds according to the terminal velocity of each existing slag. Then the test data on the samples that have been cleaned can be concluded that the slag formed is very small so it can be said that the liquid is clean of slag.

Furthermore, XRD testing was carried out to see what compounds were formed from the slag. Based on the XRD test results in Figure 5 on the top, it can be seen that the slag produced in each sample contained slag in the form of SiO_2 and also slag in the form of graphite. While Figure 5 on the bottom is the result of XRD testing on the liquid sample t = 240s which produces several slags that appear including MnO, MgO, and SiO_2 which usually appear in the cast iron smelting process, especially those made from scrap. The XRD results show that the slag formed at any given time is predictable by the calculation results.

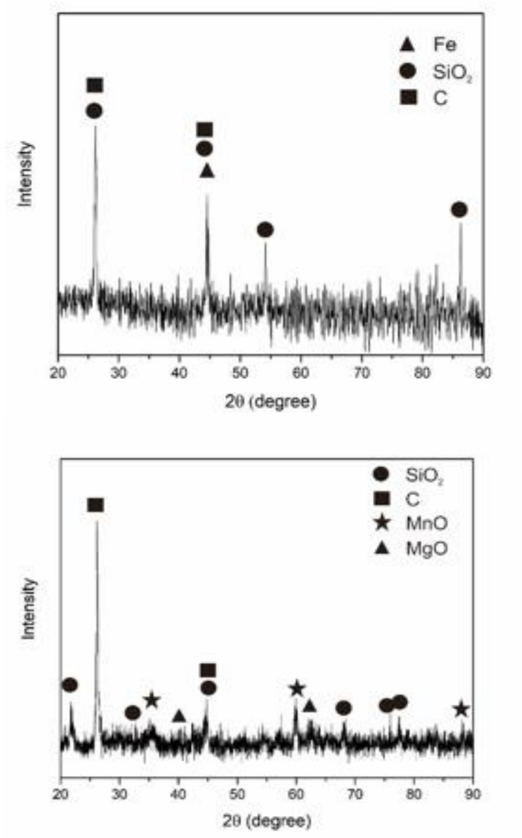


Fig.5: The results of the XRD test on the formed slag, the top of the slag test at t = 65 s, and the bottom of the slag test at t = 240 s.

Based on the results that have been obtained from this experiment, it is found that the Stokes Law approach to predicting the terminal velocity of the slag gets the appropriate results. By using the highest velocity, namely SiO_2 slag, the lowest velocity is FeO, although the slowest detected is MnO, it is found that the slag formed at t = 65s contains slags that are dominantly small or large and have a tendency to be spherical with the smallest radius. up to 6.75 μm. Furthermore, at t = 240 s slags are ranging from small to large radii at t = 300 s, the slags formed are not only spherical but also crystalline with a radius of 21-285 m which is a mixed slag between slags that appear in the liquid and also the slag that arises as a result of interaction with the environment. After time t = 300 s the liquid is given slag remover until the slag surface is clean. Then the liquid was tested again and it was found that no slag was formed in the liquid.

4. Conclusion

Stokes's Law approach predicts the terminal velocity of each slag to reach the surface to get results that are by the experimental results. By knowing the velocity of each slag, the smelting process will have a higher efficiency because the slag produced can be known so that there is no more slag that appears due to too long smelting process which causes unexpected slag to appear. The time t = 240 s after all the molten material has melted is the time when all the slag appears on the surface. The characterization of the slag produced in this study also resulted in several shapes such as spheres and crystal shapes due to the interaction of slag in the liquid or with the lining induction furnace. Furthermore, the phase formed in the slag is also by the reference and calculation results, the phase formed is MnO, MgO, and SiO_2.

5. Conflict of Interest

The authors declare that they have no conflict of interest.

References

[1] L. Bing, T. Biao, M. Zhen, C. Hanchi, and L. Hongbo, “Physical and Chemical Properties of Steel Slag and Utilization Technology of Steel Slag at Home and Abroad,” IOP Conf Ser Earth Environ Sci, 242, 3, 3–8, (2019).

[2] S. Suwarno, “Pemanfaatan Steel Slag Indonesia Di BidangPertanian,” JurnalIlmu Tanah dan Lingkungan, 12, 1, 36, (2010).

[3] S. Zhuang and Q. Wang, “Inhibition mechanisms of steel slag on the early-age hydration of cement,” Cem. Concr. Res., 140, 106283, (2021).

[4] J. Liu, B. Yu, and Q. Wang, “Application of steel slag in cement treated aggregate base course,” J. Clean. Prod., 269, 121733, (2020).

[5] A. Mehdilo and M. Irannajad, “Iron removing from titanium slag for synthetic rutile production,” Physicochemical Problems of Mineral Processing, 48, 2, 425–439, (2012).

[6] G. Wang, L. Qiu, S. Zhang, X. Zhai, and J. Ma, “Notice of Retraction: Hydrothermal modification of granular steel slag for phosphate removal,” 5th International Conference on Bioinformatics and Biomedical Engineering, iCBBE 2011, (2011).

[7] Q. Song, M. Z. Guo, L. Wang, and T. C. Ling, “Use of steel slag as sustainable construction materials: A review of accelerated carbonation treatment,” Resour. Conserv. Recycl., 173, 105740, (2021).

[8] C. Yu, W. Zhang, F. Gao, H. Huang, and L. Zhao, “An overview of resource utilization of steel slag as absorbent material for wastewater treatment,” E3S Web of Conferences, 199, (2020).

[9] I. Z. Yildirim and M. Prezzi, “Chemical, mineralogical, and morphological properties of steel slag,” Advances in Civil Engineering, (2011).

[10] C. Labrecque, M. Gagne, and E. Planque, “Effect of Charge Materials on Slag Formation in Ductile Iron Melts,” Keith Millis Symposium on Ductile Cast Iron, (2003).

[11] A. Regordosa and N. Llorca-Isern, “Chemical and structural characterization of slag compounds formed in the melting processes to produce

spheroidal graphite cast irons," International Journal of Metalcasting, 10, 4, 421–434, (2016).

[12] M. Tüfekçi, A. Demirbaş, and H. Genç, "Evaluation of steel furnace slags as cement additives," Cem. Concr. Res., 27, 11, 1713–1717, (1997).

[13] U. Reuter, M., Xiao, Y., and Boin, "Recycling and Environmental Issues of Metallurgical Slags and Salt Fluxes," Molten Slags, Fluxes, and Salts 2004: Proceedings of the 7th International Conference, 349–356, (2004).

[14] I. I. Baharuddin, A. M. Imran, A. Maulana, and A. Hamzah, "Karakterisasi Fisik dan Kimia Slag Feronikel Kecamatan Pomalaa Sulawesi Tenggara," Ilmu Alam dan Lingkungan, 12, 1, 7–16, (2021).