The 56th International October Conference on Mining and Metallurgy
22-25 October 2025, Bor Lake, Bor, Serbia
www.ioc.tfbor.bg.ac.rs

DOI: 10.5937/IOC25360R *Original scientific paper*

STATISTICAL EVOLUTION OF NON-METALLIC INCLUSIONS IN CONTINUOUS CAST Al-KILLED STEEL

Karlo Raić[1], Mile Djurdjević[2], Srećko Manasijević[3], Aleksandra Patarić[4a], Marija Mihailović[4b]

[1] Faculty of Technology and Metallurgy, University of Belgrade, Karnegijeva 4, 11000 Belgrade, Serbia
[2] University of Applied Sciences, Roseggerstraße 15, 4600 Wels, Austria
[3] Lola Institute Ltd, Kneza Viseslava 70a, Belgrade, Serbia
[4] University of Belgrade - Institute of Chemistry, Technology and Metallurgy - National Institute of the Republic of Serbia, Njegoseva 12, 11000 Belgrade, Serbia
[1] karlo@tmf.bg.ac.rs, 0000-0002-1713-0130
[2] miledjurdjevic@yahoo.ca, 0009-0007-4561-3547
[3] srecko.manasijevic@li.rs, 0000-0002-4277-9783
[4a] aleksandra.pataric@ihtm.bg.ac.rs, 0000-0002-2734-0262
[4b] marija.mihailovic@ihtm.bg.ac.rs, 0000-0003-2451-4818

Abstract

The objective of this study is to develop statistical relationships that will enable the quantification of non-metallic inclusion content in continuously cast low-carbon, aluminum-killed deep-drawing steel in situations where standard techniques make metallographic control challenging or impossible. Further considerations can be focused on predicting the model of the size distribution curve after the quantitative characterization of non-metallic inclusions in steel is completed. So, the potential of reconstructing the entire content of non-metallic inclusions in steel will be estimated, and the influence of limiting factors can be assessed.

Key words: *non-metallic inclusions; Al-killed steel; log-normal distribution*

1. INTRODUCTION

Nonmetallic inclusions are a byproduct of deoxidization from the steelmaking process. Three spontaneous processes determine their final quantity and shape in the steel structure: (i) stable nuclei form from oxygen in steel and added deoxidizer, (ii) inclusions grow through various mechanisms, with collisions being the most effective, and (iii) non-metallic inclusions float and transition to slag or adhere to the refractory lining. The initial oxygen level in steel before deoxidation, as well as the available time between the start of deoxidation and steel solidification, are process parameters that influence the final number and size of inclusions following steel hardening [1].

Chemical analysis of oxygen, which, when combined with deoxidizers, forms non-metallic oxide inclusions, is used to calculate the bulk inclusion content in steel and to assess the cleanliness of the steel. Because oxygen solubility in the metal matrix is extremely low, the bulk oxygen concentration in steel can be estimated using the oxide inclusions content. The disparity between the oxygen content acquired by chemical analysis and the calculated one demonstrates that regular steel inspection does not allow for the determination of all parameters. The shape of the inclusions distribution curve is influenced by several factors, including the concentration of oxygen in the melt at the time of outflow (ΣO), the amount of residual oxygen after inclusions float (O), and the time (τ) available for inclusions to grow through collisions before the steel solidifies [2,3].

2. ELEMENTS OF ALGORITHM

The normal distribution law (Gaussian distribution) governs the distribution of several variables that can be used to verify statistical tests. It is recommended that the measurement findings be categorized into sets based on size, with each set encompassing 30–100 neighboring view fields, because the mean value distribution of non-metallic inclusions volume fractions (X) does not follow the normal law of distribution [x]. Calculating the four mean values of momentum (U_1, U_2, U_3, U_4) based on the mean values of each set (X_1, X_2,…, X_n) is the typical procedure to assess the normality of the data distribution. Zero momentum (A_1, A_2, A_3, A_4) must be established to compute them [4,5]. The calculation flow is given in Table 1.

Table 1. Procedure of the algorithm [6]

$A_1 = \sum(X_1 + X_2 + X_3 + \cdots + X_n)$ (1) $A_2 = \sum(X_1^2 + X_2^2 + X_3^2 + \cdots + X_n^2)$ (2) $A_3 = \sum(X_1^3 + X_2^3 + X_3^3 + \cdots + X_n^3)$ (3) $A_4 = \sum(X_1^4 + X_2^4 + X_3^4 + \cdots + X_n^4)$ (4) $V_i = A_i / n$ (5)	$U_2 = V_2 - V_1^2$ (6) $U_3 = V_3 - 3V_1V_2 + 2V_1^3$ (7) $U_4 = V_4 - 4V_1V_3 + 6V_1^2V_2 - 3V_1^4$ (8) $\beta_1 = \frac{U_3 \cdot \lvert U_3 \rvert}{(U_2)^3}$ (9a) $\beta_2 = \frac{U_4}{(U_2)^2}$ (9b)
$[\%\,O] = NI(\%)\ \frac{\rho_{NI} \cdot 3M(O)}{\rho_{steel} \cdot (2M(Al) + 3M(O))} [ppm]$ (10)	$NI = (A_{theor} / A_{exp}) * 100\ (\%)$ (11)

The arithmetic mean value of each measurement set is determined by Eq. 5, where n is the number of measured values. These mean values of the measuring sets are used to determine the moments of the mean values (U) of the third and fourth orders, as shown in Eqs. 6 to 8. The coefficient of asymmetry β_1 and the coefficient of excess β_2 are calculated according to the Eqs. 9a and 9b.

Based on Eqs. 1 to 9, the algorithm for predicting possible distribution in the case of very clean steels can be evaluated. In the case of Al killed steel, non-metallic inclusions are of the Al_2O_3 type. The further calculation is as follows in Eq. 10. Non-metallic inclusions surface share, NI (%), can be expressed in Eq. 11, where: A_{exp} is the examined surface area, and A_{theor} is the total surface with inclusions on the examined surface. $A_{exp} = (a \cdot b) \cdot N_{fields} = (205 \times 140) \times 100 = 2{,}870{,}000\ m^2$; a and b are the dimensions of a view field, and N_{fields} is the number of examined fields. For the sake of comparison between different arrays, the number of fields is normalized to 100 [6].

The total surface occupied by inclusions on the examined surface may be calculated according to: $A_{theor} = (d^2 \cdot \pi/4) \cdot N$, where: N is the number of inclusions for each size class, and d is the mean diameter of the inclusions of a given size class. So, the mean diameter of the inclusions can be expressed as Eq. 12.

$$d = \sqrt{\frac{4 \cdot [\%O] \cdot A_{exp}}{\pi n \cdot const \cdot 100}} \qquad \text{(Eq. 12)}$$

For the aluminate type of non-metallic inclusions, the constant can be calculated based on atomic mass and density, as follows: const = 0.233795 [6–8].

3. EXPERIMENTAL

The chemical composition of the steel is given in Table 2, and the industrial casting conditions are shown as follows: slab thickness 1040x200 mm, cast speed was 0.55 m/min, number of oscillations 50–70 o/min, working rollers pressure 1.12 MPa, and cast temperature 1570 °C. The amount of Al after deoxidation, in addition to the steel composition, is shown in Table 2.

Table 2. Chemical composition of the steel in mass percent (%)

C	Si	Mn	P	S	Al	Cu	[O]
0.07–0.06	0.03–0.02	0.37–0.35	0.02–0.018	0.026–0.025	0.06–0.043	0.07	0.0054

A sample is taken from a slab with a cross-section of 200 x 1400 mm, encompassing its half-thickness. The non-metallic inclusions are examined on the surface oriented perpendicularly to the casting direction, sized 3x3 mm, with a center distance of 63.5 mm from the slab surface.
For final polishing, both 1 µm and 1/4 µm diamond polish pastes are used. The same sample surface was examined for each polish variation at x400 and x1024 magnification. At a magnification of x400, the entire sample surface of 9 mm² was examined, paying attention not to overlap adjacent view fields. The sum of 320 view fields was observed. At the magnification of x1024, the equidistantly distributed view fields over the sample surface were examined, and the sum of 100 view fields amounted to 0.4736 mm^2 [6–8].

4. RESULTS AND DISCUSSION

According to Table 3, it is obvious that for the same oxygen content, the coefficient of excess (β_2) increases with the increase of the time that the inclusions had at their disposal. The asymmetry coefficient (β_1) within lot 4, with O = 67 ppm, decreases with increasing time, whereas for lot 11, with O = 54 ppm, it remains constant. **Note:** Samples from position A are in the surface zone of the ingot, where the time for growth is shortest, while samples at position D had an additional 15–20 minutes for growth [6-8].

Table 3. Summary of the coefficients that define the distribution curve's shape [7,8]

Field position /lot	Coefficient of asymmetry (β_1)		Coefficient of excess (β_2)	
	Experimental	Theoretical	Experimental	Theoretical
A-4	2.87	0.07	8.32	2.60
B-4	0.19	0.008	2.70	2.75
C-4	0.001	0.05	3.29	3.02
D-4	0.73	0.02	4.39	3.50
A-11	0.01	0.007	2.25	2.35
B-11	0.4	0.007	2.45	2.50
C-11	0.04	0.007	6.87	2.50

The asymmetry coefficient of 0.0619. The average curve computed for Lot 11 has an excess coefficient of 2.45 and an asymmetry coefficient of 0.0417.
The typical characteristics of the oxide non-metallic inclusion distribution in the aluminum-killed, continuously cast steel should be included in the average distribution. The distribution of [O] ppm by size classes can be derived from the previously reported percentage distribution of oxygen by classes, assuming that the steel with 6 ppm [O] is examined. Eq. 12 can be used to determine the diameter of the greatest inclusion in class I, assuming that there is only one (which is typically the case). It becomes feasible to compute diameters in every other class based on the step between the size classes.
The method indicates that the newly obtained distribution for Lot 4 is also log-normal, with an asymmetry coefficient of 0.0535 and an excess coefficient of 2.36. The newly obtained distribution in Lot 11 has an asymmetry coefficient of 0.0493 and an excess coefficient of 2.16. Table 4 provides a summary of all these coefficients.
Based on the newly acquired inclusions diameter data, the amount of oxygen they would represent, expressed in parts per million (ppm), is calculated to be 5.74 ppm, fully satisfying the original assumption regarding steel with 6 ppm of oxygen.

Table 4. Asymmetry and excess coefficient: average and using algorithm calculated [7,8]

Non-metallic inclusions distribution	Coefficient of asymmetry (β_1)	Coefficient of excess (β_2)
Average distribution Lot 4	0.0619	2.65
Average distribution Lot 11	0.00417	2.45
Distribution L4 per algorithm, N_I=1	0.0535	2.36
Distribution L11 per algorithm, N_I=1	0.0493	2.16
Distribution L4 per algorithm, N_I=2	0.0527	2.31
Distribution L11 per algorithm, N_I=2	0.0493	2.16

5. CONCLUSIONS

This approach is suitable for continuously cast steel that has been deoxidized with aluminum, for which the oxygen concentration at pouring time and the hydrodynamic regime of ladle processing are not well understood [9-11]. Therefore, based on the established relations, a potential model algorithm based on mapping the distribution for higher oxygen contents determined by metallographic counting techniques and graphical reconstruction can be provided to describe the formation of the distribution of deoxidation products by size when metallographic control is difficult or not feasible by usual performance.

ACKNOWLEDGEMENTS

The authors are grateful for financial support within the framework of institutional funding by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (contract numbers: 451-03-136/2025-03/200066 and 451-03-136/2025-03/200026).

REFERENCES

[1] A. Costa e Silva, J. Mater. Res. Technol., 7 (3) (2018)283–99.
[2] P. Kaushik, J. Lehmann, M. Nadif., Metall. Mater. Trans. B, 43 (4) (2012) 710–25.
[3] D. You, SK Michelic, P. Presoly, J. Liu, C. Bernhard, Metals, 7 (11) (2017) 460.
[4] R. Kiessling, Non-metallic Inclusions in Steel, Part V, The Institute of Metals, London (1989)142-165.
[5] G.F. Vander Voort, Inclusion Measurement, Metallography as a Quality Control Tool, ed. J.L. McCall &P.M. French, Plenum Press, N.Y. (1980).
[6] M.D. Mihailović, MS Thesis, Faculty of Technology and Metallurgy, Belgrade (2000), pp. 106.
[7] M. Mihailović, K. Raić, Metall. and Mater. Eng., 27 (4) (2021) 437–447.
[8] M. Mihailović, Particle Size Distribution in Metals, Chapter 2, in Advances in Chemistry Research Vol. 78, Edited by James C. Taylor, Nova Science Publishers, (2023). 27–49.
[9] L. Zhang, Q. Ren, H. Duan, Y. Ren, W. Chen, G. Cheng: Miner. Process. Extr. Metall., 129 (2020) 184–206.
[10] Y. Wu, H. Zhang, L. Jian, Z. Lv, Adv. Eng. Inform., 62 (A) (2024) 102629.
[11] S. Gao, Y. Jiang, T. Xia, Y. Li, Y. Zhu, L. Xi, Adv. Eng. Inform., 64 (2025) 103080.