Wiley
Advances in Materials Science and Engineering
Volume 2026, Article ID 1047641, 11 pages
https://doi.org/10.1155/amse/1047641

Research Article

Improving the Cleanness of Low-Carbon Tube Steel Under Steel Plant Conditions

Dmytro Zotov,[1] **Kostiantyn Niziaiev**,[1] **Oleg Uzlov**,[2] **and Oleksandr Puchykov**[2]

[1]*Department of Iron and Steel Metallurgy, Ukrainian State University of Science and Technologies, Nauki Av. 4, Dnipro 49005, Ukraine*
[2]*Department of Problems of Deformation and Heat Treatment of Structural Steels, Iron and Steel Institute of Z. I. Nekrasov of National Academy of Sciences of Ukraine, Academican Starodubova Sq. 1, Dnipro 49107, Ukraine*

Correspondence should be addressed to Dmytro Zotov; dmitry.zotov@gmail.com

Received 21 August 2025; Revised 13 November 2025; Accepted 12 December 2025

Academic Editor: Mohammad Rezwan Habib

Reducing the number of nonmetallic inclusions in high-quality steel rolled products is of great importance for all steel plants. One of the ways to decrease the size and quantity of alumina and silicate nonmetallic inclusions could be suppressing their formation during steel tapping from the BOF converter to the ladle. This could be achieved by changing part of the aluminum for alternative deoxidizers which do not remain in crude steel. Steel deoxidation with the help of calcium and carbon compounds may allow for a drastic decrease in the quantity of alumina nonmetallic inclusions because of the positive effect on their solubility in liquid steel as well as redundant oxygen removal as a gas in CO and CO_2 compounds. Another way to eliminate endogenous Al and Si inclusions is to create favorable thermodynamic conditions to maximize the transfer of nonmetallic inclusions into slag during subsequent ladle furnace treatment. Establishing an optimum range of slag basicity may allow to suppress the harmful spinel inclusions. The effect of calcium carbide preliminary deoxidation during pouring of the semifinished product from BOF converter on the content of nonmetallic inclusions in flat-rolled product has been analyzed. It has been shown that partial replacement of aluminum with calcium carbide during deoxidation of crude steel by BOF tapping together with liquid slag basicity control during ladle furnace treatment allows to reduce content of nonmetallic inclusions in low-carbon steel.

Keywords: calcium carbide; low-carbon steel; nonmetallic inclusions; plate tube steel

1. Introduction

Cleanness by nonmetallic inclusions, gas, and impurities is the main condition for high-quality BOF steel production. Morphology and character of primary nonmetallic inclusion distribution in BOF crude steel are mostly formed during the deoxidation of crude steel at converter tapping. It is determined by the deoxidizer type and its introduction sequence into crude steel [1–3]. One should provide coagulation of primary nonmetallic inclusions into slag during further ladle furnace treatment to produce clean steel. Liquid slag control for better assimilation of nonmetallic inclusions during ladle furnace treatment is an important technological way of nonmetallic inclusion elimination [4–8].

Addition of aluminum into unkilled metal during BOF tapping leads to the formation of a wide variety of oxides. This leads to corundum formation. Dissolved in steel, aluminum [Al] also interacts with ladle refractory lining and slag with subsequent magnesia spinel $MgO·Al_2O_3$ formation [5, 6, 9, 10]. This is determined by the fact that MgO is less stable than CaO, and thus, oxygen from MgO lining and slag reacts with Al_2O_3. Complex particles of $MgO\text{-}Al_2O_3$ are formed as a result [11, 12].

Corundum, magnesium oxides, and silicates are not desired in the plate tube product from the steel cleanness point of view. To decrease their quantity and size in the production of plate tube steel, one should suppress the formation of these nonmetallic inclusions during steel deoxidation at the BOF converter tapping.

This could be fulfilled by creating conditions for the transit of these nonmetallic inclusions into slag by their reduction.

The common chemical reaction of the reduction of calcium and magnesium oxides is as follows:

$$3\,<\mathrm{MeO}> + 2\,(\mathrm{Al}) = <\mathrm{Al_2O_3}> + 3\{\mathrm{Me}\} \tag{1}$$

Gibbs energy for CaO and MgO reduction could be determined from the following equations:

$$\begin{aligned}\Delta G_{\mathrm{CaO-Al}} &= 687780 - 15.675 \cdot T \cdot \lg(T) \\ &\quad - 199.16 \cdot T,\ \mathrm{J/mole}\,(T = 1760 - 2500\,\mathrm{K}),\end{aligned} \tag{2}$$

$$\begin{aligned}\Delta G_{\mathrm{MgO-Al}} &= 581190 + 76.75 \cdot T \cdot \lg(T) \\ &\quad -563.8 \cdot T,\ \mathrm{J/mole}\,(T = 1700 - 2500\,\mathrm{K}).\end{aligned} \tag{3}$$

Reactions start at temperatures of 2720 K and 1850 K, respectively, under the condition that $\Delta G < 0$ [13]. However, aluminum oxide which is formed during reaction (2) should interact with CaO actively, thus preventing CaO reduction.

It is impossible to conduct a complete transit of aluminum, calcium, and magnesium oxides into slag with full coalescence in BOF serial production. Simultaneous addition of aluminum and silicon into unkilled crude steel during tapping leads to the formation of a certain amount of mullite $2Al_2O_3{\cdot}SiO_2$ [11].

Heating temperatures of mullite and magnesia spinel are higher than those of liquid steel. Heating temperature of mullite ($2Al_2O_3{\cdot}SiO_2$) is Tm. = 1850°C, while that of magnesia spinel ($MgO{\cdot}Al_2O_3$) is Tm. = 2105°C [14].

Bigger particles coagulate and assimilate into slag, whereas smaller particles of mullite and magnesia spinel remain in the crude steel. Complete elimination of these particles during ladle treatment of steel could be very difficult.

These particles at slab casting always solidify on the surface of the shroud nozzle during flowing from tundish into the mold. When their quantity in a ladle is critical, this will lead to shroud nozzle clogging. Clogging leads to significant technological problems during continuous casting. Uncontrolled casting speed oscillations of crude steel take place. This leads to the takeover of slag-forming mixture under the surface of cast slab and thus to the entry of additional undesirable quantities of aluminum oxides into the cast metal [12, 15–18].

Decreasing of temperature of aluminates and silicates heating in liquid steel could be possible by means of calcium addition. $MgO{\cdot}Al_2O_3$ spinels become unstable after steel deoxidation by calcium and modify into $CaO–MgO–Al_2O_3$ complex particles. The following complex particles may form because of this modification (heating temperature is in brackets): $CaAl_2O_4$ (1600°C), $Ca_3Al_2O_6$ (1535°C), $Ca_{12}Al_{14}O_{33}$ (1455°C), $Ca_5Al_6O_{14}$ (1455°C), $CaMgSi_2O_6$ (1382°C), $CaAl_2Si_2O_8$ (1553°C), $Ca_2Al_2SiO_7$ (1590°C). The heating point of these inclusions decreases. This may promote their transition into the liquid state in crude steel with subsequent coalescence and coagulation into cover slag.

Aluminum oxide quantity reduction in crude steel is also possible by means of aluminum shifting for alternative deoxidizers which will not bring into steel undesirable corundum and complex aluminum-based oxide particles.

Pure Ca has good deoxidation ability. However, it is rather expensive to apply pure Ca as deoxidizer of unkilled steel due to its low solubility. Ca alloy addition provides satisfactory deoxidizing ability due to its solubility increase in crude steel. One should consider that complex steel deoxidation by means of Ca together with Al and Si increases the common potential of steel deoxidation [19].

Ca is more expensive than Al. That's why FeCa and SiCa wires are commonly used at the end of ladle furnace treatment or after vacuum degassing to modify nonmetallic inclusions.

Deoxidation with carbon is another way to satisfy steel cleanness by nonmetallic inclusions. This is because carbon unlike all other deoxidizing agents forms CO and CO_2 gas. These compounds evacuate easily from crude steel and do not interact with solid nonmetallic inclusions [19]. However, it is not correct to put coal into the ladle during converter steel tapping from the technological point of view.

Disadvantages of separate applications of Ca and carbon could be completely removed when they are complexly added to unkilled steel in one compound—calcium carbide CaC_2.

Calcium carbide has found limited application in metallurgy, mainly for cast iron desulfuration or steel desulfuration during ladle furnace treatment [1, 20]. Technology of aluminum shift with calcium carbide did not find vast application in steelworks due to technical difficulties of calcium carbide storage and transportation (CaC_2 should be stored in an insulated container from the atmosphere container with inert gas, usually N_2, and be given into the ladle from a special device with a vacuum valve through a separate path). However, calcium carbide application partly instead of aluminum for BOF converter steel deoxidation during tapping may allow for decreasing aluminum consumption and saving expenses when the steel shop is equipped with this installation. CaC_2 has been applied for a long period of time in the industrial practice of an oxygen converter shop at a Ukrainian steelworks as a deoxidant of medium-carbon steel grades. And it has been experimentally proved that calcium carbide application for preliminary deoxidation of steel may allow to decrease total aluminum consumption. The results have been highlighted in a paper [21]. CaC_2 application has been found economically effective during preliminary deoxidation in comparison with secondary aluminum with 87% of Al content. Deoxidation expenses have decreased on at least 20% or 0.41 kg/t of crude steel due to the decrease in total aluminum content. However, the issue of steel cleanness by nonmetallic inclusions has not been investigated in this paper.

Sjöqvist et al. have investigated the cleanness of CaC_2-treated steel. They found that inclusion content in

CaC_2-treated steel was lower than that of the standard medium-carbon steel for railway wheel application [22]. Other open sources describing various aspects of nonmetallic inclusions refining during LF treatment such as [1–5, 12, 23] do not contain information about aspects of calcium carbide deoxidation influence on steel cleanness by nonmetallic inclusions. Thus, investigation of influence of technological aspects of preliminary calcium carbide deoxidation during tapping on cleanness of low-carbon plate tube steel by nonmetallic inclusions is actual to study.

The objective of the study is the development of adjusted deoxidation and refining treatment of low-carbon tube plate steel grades (C = 0.07%–0.20%) for the production route "BOF steelmaking ⟶ LF treatment ⟶ VD ⟶ continuous slab casting" aimed to decrease the severity level by nonmetallic inclusions.

2. Experimental Methods

Study of actual steelmaking technology has been made on one of Ukrainian oxygen converter steelworks with respect to cleanness of low-carbon plate tube steel by nonmetallic inclusions. This was caused by the increasing quality demands of a few customers of this plate tube steel.

On the first stage two heats of industrial trials were performed on the low-carbon low-alloyed tube steel. On the second stage, eight heats of industrial trials were performed on the steel grade L290NE/X42NEPSL2. The production process consisted of 350 t BOF steelmaking ⟶ LF treatment ⟶ VD ⟶ 220-mm-thick slab continuous casting ⟶ 8–80 mm heavy plates rolling.

During the tapping of BOF on both stages, most alloys, Al, and calcium carbide were added into the ladle for composition adjustment, deoxidation, and early slag formation. During LF treatment, argon was used for metal stirring with the flow rate of 300–600 L/min. Vacuum degassing of heats has been made for 10 min with vacuum pressure < 3.0 mbar. Steel samples were taken before and after BOF tapping, after LF treatment and after VD. Cover slag samples were taken before LF treatment on both stages. Cover slag samples were taken after LF treatment in addition to the second stage. The content of carbon, oxidation, and liquid steel temperature was measured by Heraeus Multilab. Steel and slag samples were prepared for chemical analysis. Steel samples for inclusions were taken from the rolled heavy plates at one-quarter thickness. Steel samples were grinded and polished by an automatic grinding and polishing machine with diamond grinding discs and diamond suspensions. The morphology and element mapping of inclusions were detected by Karl Zeiss Supra 40 FE SEM equipped with an Oxford INCA EDX spectrometer. Quantitative analysis of nonmetallic inclusions severity was made manually by light microscope.

Rolled plate tube steel cleanness evaluation by nonmetallic inclusions is made by the procedure of comparison with model scales according to Ukrainian standard DSTU 8966:2019 "STEEL.Metallographic Method for the Determination of Non-metallic Inclusions" [24]. Evaluation of thin section cleanness is made under magnification × 90–110 in the field with 1.10–1.30 mm diameter by the most severe spot of the thin section. This spot is compared with a standard photo model with severity level numbers from 1–5, where 1 is the cleanest and 5 is the most severe model for each type of nonmetallic inclusion.

Oxides, silicates, and aluminates have been determined as the most critical for plate tube steel from the cleanness by nonmetallic inclusion point of view. Comparison of the rolled metal specimens has been made according to specific scale of the Ukrainian standard.

Model values of the DSTU 8966 could not be directly compared with criteria stated in ASTM E45-18a, ISO 4967, and SAE J422. Nevertheless, this procedure of evaluation could be compared with the A and C methods of ASTM E45-18a, where aluminates could be referred to the B category, silicates to the C category, and oxides to the D category [25]. Evaluation of severity level is made in the range from 0.5–5.0 numbers with a step of 0.5 number. The search is made at × 100 magnification. Maximum length or the quantity of nonmetallic inclusions is defined in the field of 0.50 mm^2. ASTM E45-18a Method A is close to the determination of the average severity level number in DSTU 8966. ASTM E45-18a Method C is close to the determination of the maximum severity level number in DSTU 8966 with the only difference. ASTM E45-18a Method C determines maximum severity level by the longest nonmetallic inclusion, whereas the maximum severity level in DSTU 8966 is determined by the common quantity of nonmetallic inclusions.

To simplify results interpretation in further description, the evaluation will be shown according to ASTM E45-18a.

3. Results and Discussion

A study of actual steelmaking technology has been made on one of the Ukrainian oxygen converter steelworks with respect to cleanness of low-carbon plate tube steel (C = 0.07%–0.20%) by nonmetallic inclusions. This was caused by the increasing quality demands of a few customers of this plate tube steel.

A comparison has been made of the present "as is" common nonmetallic inclusions' severity level in plate tube steel with the customer's desired one "to be," as shown in Table 1.

Some of the typical nonmetallic inclusions in low-carbon plate tube steel are presented on Figures 1, 2, and 3.

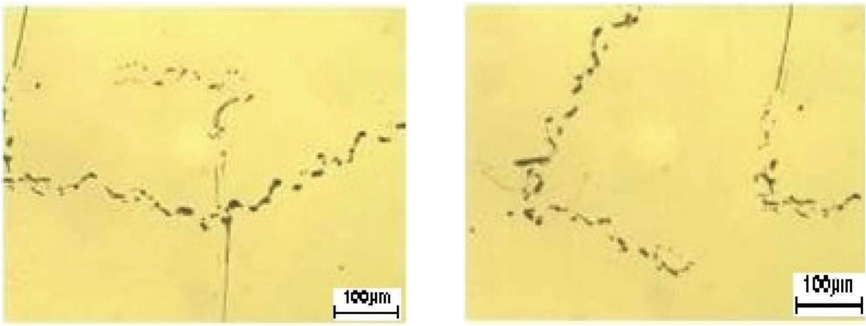
Distribution of nonmetallic inclusions in ladle volume during continuous casting has been analyzed. It has been found that nonmetallic inclusions distribute almost homogeneously in the volume of the ladle.

Scanning electron microscopic analysis has been made to identify the origin of some typical nonmetallic inclusions of serial heavy plate rolled tube steels. An investigation has been carried out into SEM Karl Zeiss Supra 40 with EDX. Some typical nonmetallic inclusions are presented on Figures 4, 5, and 6.

SEM EDX analysis has shown that nonmetallic inclusions are mostly aluminum oxides and silicon oxides with some content of calcium or magnesium.

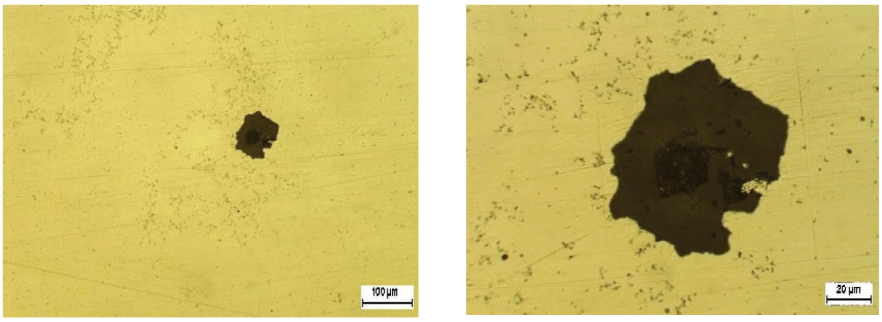
Table 1: Comparison of demands for severity level number of nonmetallic inclusions.

Name	Severity level number of inclusions of B, C, and D types according to ASTM E45-18a	
	Average (ASTM E45-18a Method A)	Maximal (ASTM E45-18a Method C)
Customer's demand	2.0	3.5
Serial production	3.0	5.0



(a) (b)

Figure 1: Nonmetallic inclusions of aluminates Al_2O_3—Type B according to ASTM E45-18a. (a, b) Aluminates.



(a) (b)

Figure 2: Nonmetallic inclusions of oxides—Type D according to ASTM E45-18a. (a, b) Oxide.

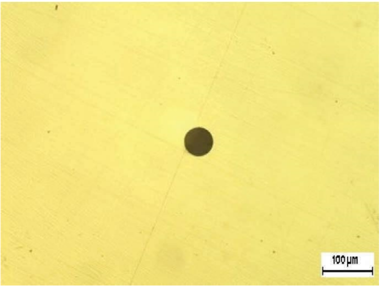


Figure 3: Silicate nonmetallic inclusion—Type C according to ASTM E45-18a.

A suggestion has been made that calcium carbide could be an effective alternative deoxidant with respect to the objective of nonmetallic inclusion severity level decrease in flat-rolled product. This suggestion was based on the previous successful practical experience of CaC_2 application as a partial shift of aluminum for medium-carbon steel production during BOF tapping [21, 22].

However, CaC_2 has never been applied for deoxidation of low-carbon steel grades ($C = 0.07\%–0.20\%$) in oxygen converter shop of this steelwork before. In terms of industrial experiment, a technology of preliminary deoxidation has been changed for two low-carbon tube steel heat production to evaluate effectiveness of CaC_2 instead of part of aluminum with respect to nonmetallic inclusions'

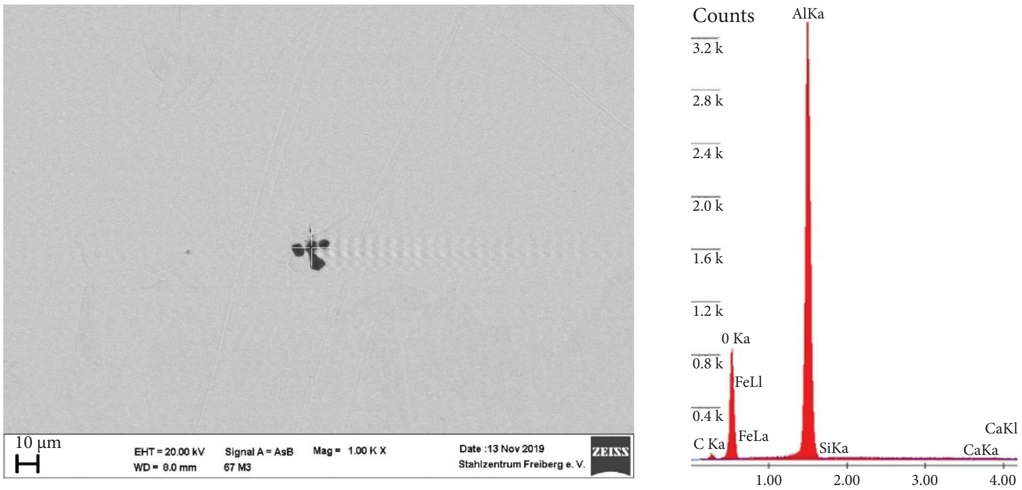


Figure 4: Al_2O_3 cluster. Mostly aluminum oxide according to the EDX analysis (Al [mass %] = 53%, O [mass %] = 31%, Fe [mass %] = 12%).

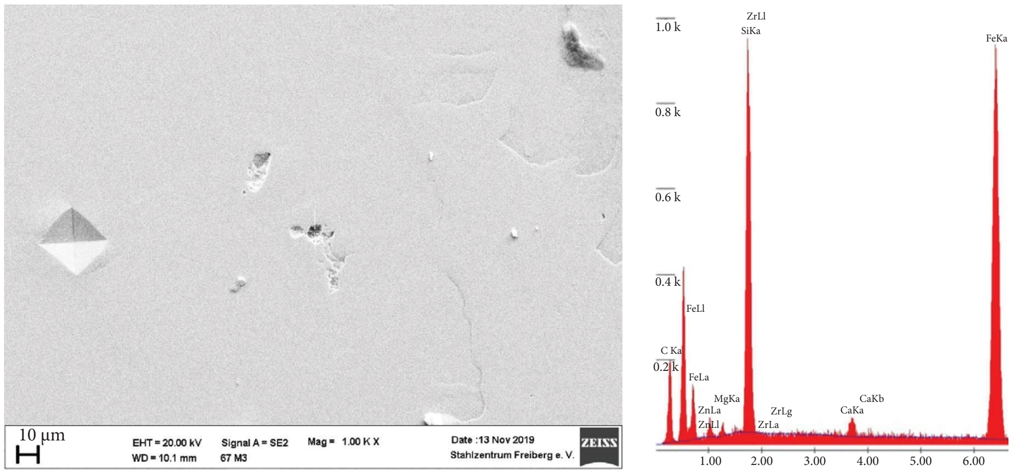


Figure 5: Agglomeration of oxides. Aluminum oxides according to EDX analysis (Al [mass %] = 58%, Fe [mass %] = 2%, Ca [mass %] = 0.5%).

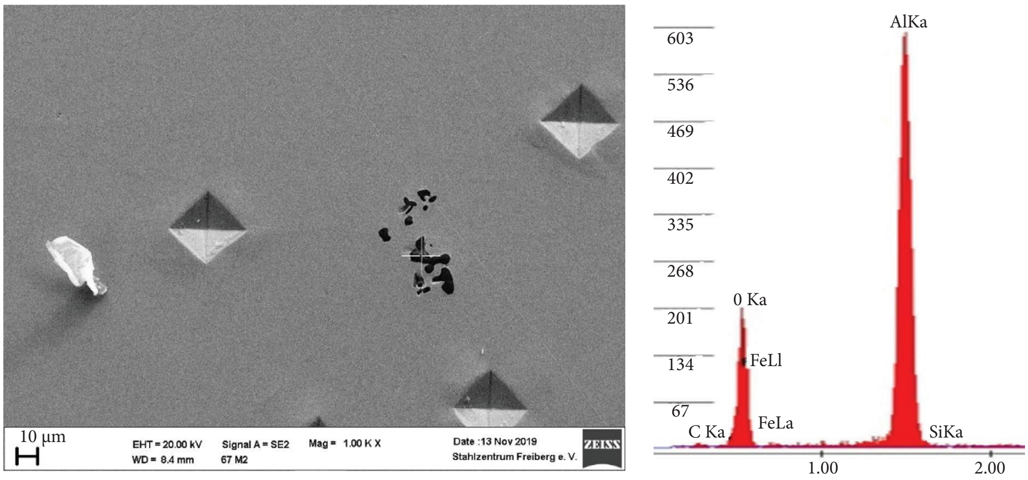


Figure 6: Agglomeration of oxides. Silicon oxides in iron matrix according to EDX analysis (Si [mass %] = 16%, O [mass %] = 10%, Fe [mass %] = 56%, C [mass %] = 14%, Ca [mass %] = 2%).

severity level. Chemical composition of this low-carbon, low-S, and low-P tube steel grade is presented in Table 2.

The following technological operations have been implemented for preliminary deoxidation of steel during tapping from the BOF converter into a ladle.

1. Partial deoxidation with CaC_2 instead of aluminum has been made. Required CaC_2 consumption has been calculated with respect to the defined carbon content in finished steel. CaC_2 addition has been made after a ladle filling with crude steel for a 1/4 of its height.
2. Metallic manganese (C content not more than 0.2%) and ferrosilicon (FeSi 65) were added after a ladle was filled 1/3 of its height with crude steel, followed by a 30-s pause.
3. Granulated secondary aluminum with 87% content of aluminum has been added through a supply path after Mn and FeSi 65 addition.

Main parameters of steel heats after BOF tapping and before ladle furnace treatment are presented in Table 3.

No carbon pickup was detected in the first steel sample compared with the first sample taken during ladle furnace treatment. This could be explained by changes in the technology of preliminary deoxidation together with favorable conditions for active mixing of metal in a ladle made by falling metal jet energy.

Cover slag amount for both heats before ladle treatment was 16 kg/t. CaO content was 49.19%, Al_2O_3 content in slag was 16.8%, $SiO_2 = 17.55\%$, $MgO = 9.76\%$, and $F = 2.24\%$.

Assimilating slag control has been made during ladle furnace treatment. Heating of heat has been made up to 1620°C–1640°C with subsequent addition of aluminum and calcium–silicon wire rods to modify endogenous nonmetallic inclusions.

Subsequently, vacuum degassing of heats has been made. Slag tapping from a ladle has been made before VD to eliminate assimilated endogenous inclusions into slag. Aluminum and calcium–silicon wire rods have been added after vacuum degassing to obtain the final chemical composition of steel and to modify tertiary endogenous nonmetallic inclusions.

Parameters of heats before and after vacuum degassing are presented in Table 4.

Steel cleanness by nonmetallic inclusions has been determined in rolled heavy plates made from these two heats continuously cast 220 mm slabs.

Data with severity level by nonmetallic inclusions of experimental heats are presented in Tables 5 and 6.

Graphic distribution of average and maximum severity level by nonmetallic inclusions in these heats is presented in Figures 7 and 8.

Improvement of cleanness by nonmetallic inclusions has been observed on both experimental heats compared to serial production. Analysis of severity level numbers in Figures 7 and 8 has shown that quantity of nondeformed nonmetallic inclusions decreases as a function of increase of slab reduction ratio during rolling and metal thickness. Nonconformities have been observed on plates with thickness more than 50 mm (and correspondingly lower reduction ratio).

Modification of technology of low-carbon steel deoxidation with calcium carbide during tapping has resulted in improvement of steel cleanness by nonmetallic inclusions in two experimental heats in comparison with basic technology. However, these changes did not correspond completely to the demands of a customer.

Therefore, on the second stage of industrial experiment, another effort was made to improve steel heating technology regarding nonmetallic inclusion cleanness. On the second stage, deeper analysis of serial technology of cover slag during ladle furnace treatment has been made. During this stage, cover slag samples after LF treatment have been analyzed. Chemical composition of the cover slag of serial heats in a slag sample 2-2 is presented in Table 7.

Zimmerman and Gunter have found that system Al_2O_3 may form both hard melting nonmetallic inclusions such as $CaO * 2Al_2O_3$ and $CaO * 6Al_2O_3$, as well as fusible nonmetallic inclusions such as $CaO * Al_2O_3$, $5CaO * 3Al_2O_3$, and $12CaO * 7Al_2O_3$, by $CaO * 2Al_2O_3$ and $CaO * 6Al_2O_3$. The formation of fusible, easily coalescing inclusions that separate from the steel is possible when a CaO/Al_2O_3 ratio of 1.0–1.7 is achieved in the ladle cover slag [26].

Shin and Park have investigated multiphase reactions among the Mn-V-alloyed steel melt, the $CaO–Al_2O_3–SiO_2–MgO–CaF_2$ slag, and the MgO refractory to understand the evolution mechanism of the inclusions. The CaO/Al_2O_3 (= C/A) ratio of the ladle slag varied in interval 0.9–3.3. As a result, they have proposed the optimum range of ladle slag CaO/Al_2O_3 ratio of 1.5–2.5 in order to suppress the harmful solid inclusions such as spinel during secondary refining processes [5].

However, every steel plant has its unique ratio of CaO/Al_2O_3 adopted to its technological process with respect to the local raw material base.

The issue of CaO/Al_2O_3 ratio has never been previously considered for low-carbon low-alloyed tube steel production on this steelworks. Therefore, analysis of CaO/Al_2O_3 ratio distribution in cover slag during ladle furnace treatment of serial heats has been made. 459 serial heats of low-carbon steel have been subjected to this analysis. CaO/Al_2O_3 ratio distribution in cover slag of these heats is presented in Figure 9.

Study of the diagram has shown that only 70 out of 459 heats (13%) had the CaO/Al_2O_3 ratio less than 2.17. More than 50% heats out of the array had the CaO/Al_2O_3 ratio from 2.18–3.04. Other heats had even less quantity of Al_2O_3 in cover slag. Shortage of Al_2O_3 influences drastically on slag fluidity. Slag fluidity is thus not achieved. Such slag does not provide sufficient assimilating degree for nonmetallic inclusions in crude steel.

In our opinion, this could cause problems with effective elimination and assimilation of nonmetallic inclusions during ladle furnace treatment. Therefore, correspondence

Table 2: Chemical composition of low-carbon heavy plate steel for linepipe applications, mass (%).

Mass (%)														
C	Mn	Si	Al	Nb	Ni	S	P	Ti	Cr	Cu	N	V	Mo	Ca
						Not more than								
0.08–0.12	1.60–1.70	0.50–0.70	0.020–0.050	0.020–0.040	0.20–0.30	0.003	0.012	0.005	0.15	0.15	0.008	0.080	0.08	0.020

Table 3: Parameters of steel heats after tapping but before ladle treatment beginning (data obtained by Heraeus Multilab).

Heat no	Parameters at converter turndown before tapping			Consumption for deoxidation (kg/t)		Parameters after tapping and deoxidation but before ladle treatment			
	T of metal (°C)	C (%)	Oxidation (ppm)	CaC_2	Al	T of metal (°C)	Mass (%)		
							C	Al	Ca
9150	1643	0.063	648	0.99	1.176	1569	0.07	0.0494	0.0006
9151	1615	0.084	407	0.735	0.88	1575	0.09	0.0181	0.0005

Table 4: Parameters of heats before and after vacuum degassing.

Heat no	Parameters before VD				Parameters after VD and Al + SiCa wire rods addition				
	T of metal (°C)	Content (%)			T of metal (°C)	Content (%)			H_2 (ppm)
		C	Al	Ca		C	Al	Ca	
9150	1633	0.11	0.0375	0.0068	1560	0.11	0.0324	0.0022	2.0
9151	1626	0.12	0.0181	0.0060	1558	0.11	0.0350	0.0042	1.8

Table 5: Severity level by nonmetallic inclusions of heavy plates made of heat No. 9150.

No	Slab number	Heavy plate thickness (mm)	Severity level number by inclusions of B, C, and D types according to ASTM E45-18a	
			Average (ASTM Method A)	Maximum (ASTM Method C)
1	5–3	80	0.2–1.9	0.5–3.0
2	4–1	70	0.60–2.3	1.0–4.0
3	2–1	11	1.1–2.1	1.5–2.5
4	3–6	10	1.5–2.3	2.0–3.0

Table 6: Severity level by nonmetallic inclusions of heavy plates of heat No. 9151.

No	Slab number	Heavy plate thickness (mm)	Severity level number by inclusions of B, C, and D types according to ASTM E45-18a	
			Average (ASTM Method A)	Maximum (ASTM Method C)
1	6–1	70	1.3–4.0	2.0–5.0
2	4–5	50	0.8–2.3	1.0–3.0
3	4–6	30	1.6–2.4	2.5–4.0
4	4–1	10	1.2–2.6	3.0–4.0
5	2–1	8	1.5–2.6	2.5–3.0

to strict demands of clients could not be achieved by nonmetallic inclusions' severity level not higher than 2.0 average number (ASTM E45-18a Method A) and 3.5 maximum number (ASTM E45-18a Method C).

CaO/Al_2O_3 ratio less than 1.5 is not desirable from economical point of view because it may lead to bigger consumption of aluminum and aluminoflux during ladle furnace treatment. On the other hand, the analyzed array of low-carbon steel melts with a CaO/Al_2O_3 ratio more than 2.17 did not meet the desired demands of nonmetallic inclusion severity level. Coming out of these data, an assumption was made that CaO/Al_2O_3 ratio of 2.0 could be satisfactory to achieve desired demands of nonmetallic inclusions severity level together with permissible cost increase. Another industrial trial has been planned in order to confirm this assumption.

New deoxidation and treatment procedures have been developed for low-carbon tube steel on the second stage of industrial experiment. Demand to control deoxidation of cover slag in the beginning of ladle treatment has been

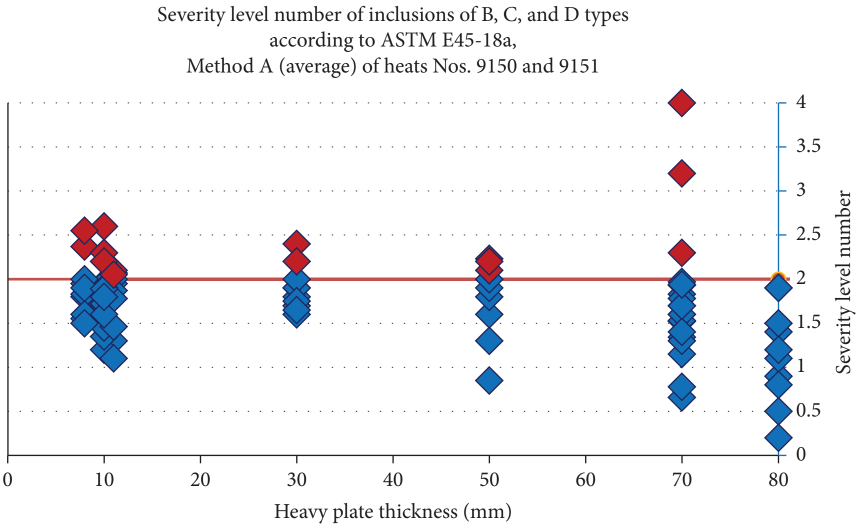


Figure 7: Average severity level by nonmetallic inclusions of heats No. 9150 and 9151 heavy plates.

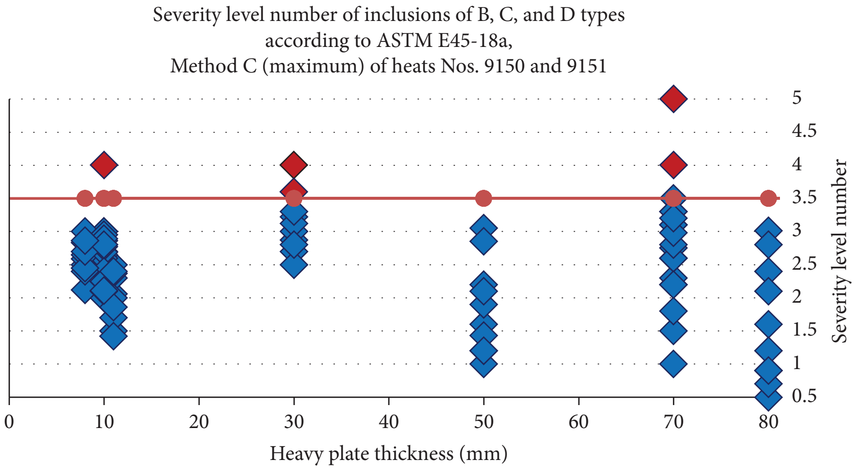


Figure 8: Maximum severity level of heats No. 9150 and 9151 heavy plates by nonmetallic inclusions.

Table 7: Chemical composition of the cover slag of serial heats in slag samples 2-2 during ladle treatment, mass (%).

SiO_2	CaO	MgO	MnO	Al_2O_3	P_2O_5	S	F	FeO
17–18	48–49	9.3–9.9	0.5–0.6	16–17.0	0.02–0.04	0.8–0.9	2.2–2.34	0.75–0.85

included along with controlled deoxidation of unkilled steel during BOF tapping to a ladle and application of calcium carbide during tapping. The quantity and ratio of the complex deoxidating aluminoflux were regulated to maintain a CaO/Al_2O_3 ratio of no more than 2.0 in 2-2 and 2-3 ladle samples. Quantity of aluminum for cover slag deoxidation has not been changed.

On the second stage, series of heats L290NE/X42NEPSL2 has been produced. Chemical composition of these heats is presented in Table 8.

In these heats, on the second stage of industrial experiment, application of CaC_2 during BOF tapping along with cover slag CaO/Al_2O_3 ratio control has been made. Preliminary deoxidation with CaC_2 during BOF tapping was set corresponding to the values of the first stage of industrial experiment: 0.9 kg/t —1.1 kg/t Al. During the following LF treatment, $CaO/Al_2O_3 \leq 2.0$ ratio in cover slag was achieved by adding a fixed amount of lime (4.5 kg/t of crude steel) and by controlling the addition of aluminum flux from 3.0–3.5 kg/t of crude steel to increase the Al_2O_3 in the cover slag. Summary by final CaO/Al_2O_3 ratio in cover slag during LF treatment and results of cleanness by nonmetallic inclusions are presented in Table 9.

Obtained results have been found satisfactory with respect to cleanness of steel by nonmetallic inclusions. Samples of all heats were satisfactory by maximum severity level number. Average severity level results are shown in Figure 10. By average severity number, only one sample value of all has shown non satisfactory result (2.2 number with demand not higher than 2.0).

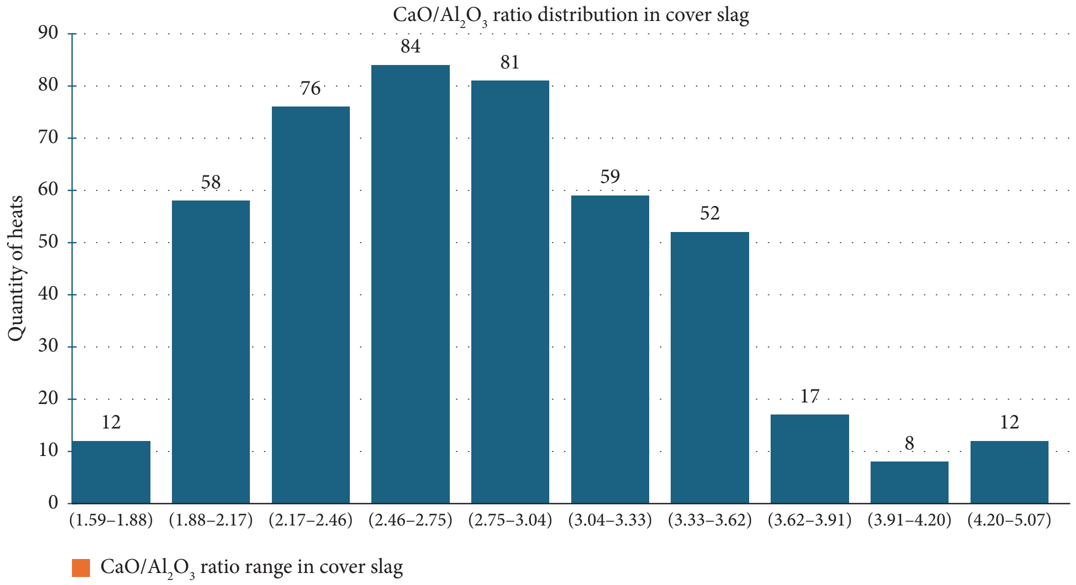


Figure 9: Diagram of CaO/Al$_2$O$_3$ ratio distribution in cover slag during ladle furnace treatment of serial heats.

Table 8: Chemical composition of low-carbon heavy plate steel for linepipe applications L290NE/X42NEPSL2, mass (%).

Mass (%)													
C	Mn	Si	Al	Nb	S	P	Ti	Ni	Cr	Cu	N	V	Mo
				Not more than									
0.14–0.16	1.00–1.20	0.15–0.25	0.020–0.050	0.050	0.005	0.020	0.040	0.30	0.30	0.25	0.008	0.060	0.10

Table 9: Severity level results by nonmetallic inclusions in a series of experimental heats with CaC$_2$ deoxidation instead of a part of aluminum during BOF tapping and controlled CaO/Al$_2$O$_3$ ratio in cover slag during LF treatment.

No. of heat	CaO/Al$_2$O$_3$ ratio in cover slag samples			Severity level number of inclusions of B, C, and D types according to ASTM E45-18a		Flat product thickness (mm)
	2-1	2-2	2-3	Average (ASTM Method A)	Maximum (ASTM Method C)	
1284	2.00	1.81	1.74	0.17–1.25	2	10
1285	2.75	2.04	1.82	0.75–1.83	2.5	9
1287	2.33	2.18	1.93	0.6–2.2	3.5	8
1289	1.79	1.81	1.86	1.0–1.9	3.5	20
1290	2.06	2.31	2.37	0.5–1.8	2.5	8
1292	1.37	1.69	2.00	0.8–1.5	2.0	8
1294	1.30	1.63	1.64	0.25–1.33	2.5	8
1296	1.49	1.93	1.94	0–2.0	2.5	8

Adjusted technology of low-carbon steel (C = 0.07%–0.20%, grade L290NE/X42NEPSL2) production with CaC$_2$ deoxidation during BOF tapping and conduction of favorable assimilation of nonmetallic inclusions during ladle furnace treatment with controlled CaO/Al$_2$O$_3$ ratio proved to be effective. On the second stage of industrial experiment, this allowed to achieve correspondence of low-carbon heavy plate tube steel to the demand of ASTM E45-18a for severity

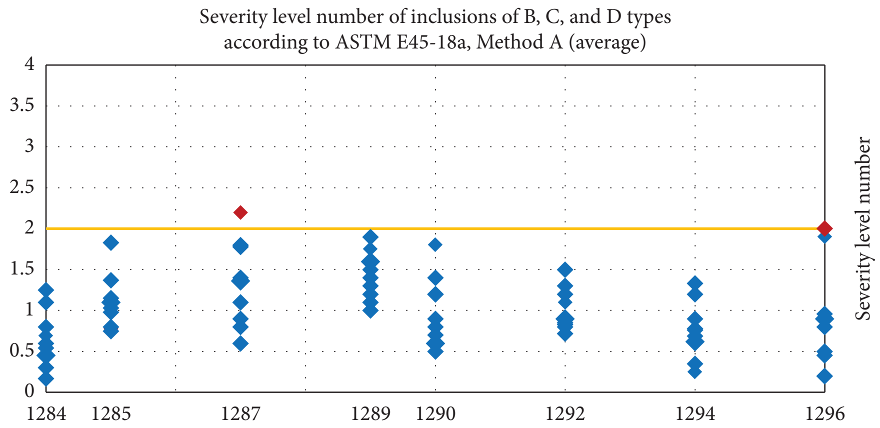


Figure 10: Average severity level by nonmetallic inclusions of heats with CaC_2 deoxidation instead of a part of aluminum during BOF tapping and controlled CaO/Al_2O_3 ratio in cover slag during LF treatment.

level number 2.0 by average number and 3.5 by maximum number for inclusions of B, C, and D types.

4. Summary and Conclusions

The objective of this study was to develop adjusted deoxidation and refining treatment of low-carbon tube plate steel grades ($C = 0.07\%–0.20\%$) at BOF production aimed to decrease severity level by nonmetallic inclusions. CaC_2 as a slag reducer has been successfully applied during BOF tapping instead of part of the aluminum for low-carbon steel grades ($C = 0.07\%–0.20\%$). Analysis of CaO/Al_2O_3 ratio distribution in cover slag during ladle furnace treatment of 459 serial low-carbon steel grade heats has been made. CaO/Al_2O_3 ratio 2.0 has been experimentally defined for cover slag control during ladle furnace treatment.

The new deoxidation and treatment procedure has been developed for low-carbon tube steel grades. This procedure combines new aspects of slag reducing with CaC_2 instead of part of aluminum during BOF tapping together with adjustment of CaO/Al_2O_3 ratio control in cover slag during LF treatment. This allowed to suppress nonmetallic aluminum inclusion formation during tapping as well as to provide effective elimination of aluminum inclusions during ladle furnace treatment.

The results show that calcium carbide CaC_2 application for deoxidation instead of part of aluminum during BOF tapping along with controlled CaO/Al_2O_3 ratio in cover slag during ladle treatment allows to improve cleanness of low-carbon heavy plate tube steel by nonmetallic inclusions such as oxides, corundum, and silicates according to requirements of ASTM E45-18a for severity level number 2.0 by average number and 3.5 by maximum number for inclusions of B, C, and D types, Methods A and C.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Funding

No funding was received for this manuscript.

References

[1] A. Ghosh and A. Chatterjee, *Ironmaking and Steelmaking. Theory and Practice* (PHI Learning, 2008).

[2] K. Wünnenberg and J. Cappel, “Cost-Saving Operation and Optimisation on Metallurgical Reactions in BOF Practice,” *Stahl und Eisen* 5 (2008).

[3] B. H. Reis, W. V. Bielefeldt, and A. C. Faria Vilela, “Absorption of Non-Metallic Inclusions by Steelmaking Slags—A Review,” *Journal of Materials Research and Technology* 3, no. 2 (2014): 179–185.

[4] Z. Deng and M. Zhu, “Evolution Mechanism of Non-Metallic Inclusions in Al-Killed Alloyed Steel During Secondary Refining Process,” *ISIJ International* 53, no. 3 (2013): 450–458, https://doi.org/10.2355/isijinternational.53.450.

[5] J. H. Shin and J. H. Park, “Effect of CaO/Al_2O_3 Ratio of Ladle Slag on Formation Behavior of Inclusions in Mn and V Alloyed Steel,” *ISIJ International* 58, no. 1 (2018): 88–97, https://doi.org/10.2355/isijinternational.isijint-2017-456.

[6] N. Verma, P. C. Pistorius, R. J. Fruehan, M. S. Potter, H. G. Oltmann, and E. B. Pretorius, “Calcium Modification of Spinel Inclusions in Aluminum-Killed Steel: Reaction Steps,” *Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science* 43, no. 4 (2012): 830–840, https://doi.org/10.1007/s11663-012-9660-4.

[7] N. Verma, P. C. Pistorius, R. J. Fruehan, M. S. Potter, M. Lind, and S. R. Story, “Transient Inclusion Evolution During Modification of Alumina Inclusions by Calcium in Liquid Steel: Part II. Results and Discussion,” *Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science* 42, no. 4 (2011): 720–729, https://doi.org/10.1007/s11663-011-9517-2.

[8] L. Holappa and A. C. Nava, “Secondary Steelmaking,” *Treatise on Process Metallurgy* (Amsterdam, the Netherlands: Elsevier, 2024), 267–301.

[9] L. Wang, H. Zhu, J. Zhao, M. Song, and Z. Xue, "Steel/Refractory/Slag Interfacial Reaction and Its Effect on Inclusions in High-Mn High-Al Steel," *Ceramics International* 48, no. 1 (2022): 1090–1097, https://doi.org/10.1016/j.ceramint.2021.09.194.

[10] J. H. Shin and J. H. Park, "Modification of Inclusions in Molten Steel by Mg-Ca Transfer From Top Slag: Experimental Confirmation of the 'Refractory-Slag-Metal-Inclusion (Resmi)' Multiphase Reaction Model," *Metallurgical and Materials Transactions B, Process Metallurgy and Materials Processing Science* 48, no. 6 (2017): 2820–2825, https://doi.org/10.1007/s11663-017-1080-z.

[11] A. B. Milejkovskpj, N. V. Malahov, A. A. Kazakov, P. V. Kovalev, and S. V. Rjaboshuk, "Nemetallicheskie Vkljuchenija V Vysokoprochnyh Trubnyh Staljah," *Chernye Metally* 5 (2009): 5–11.

[12] C. Liu, X. Gao, S. Ueda, M. Guo, and S. Kitamura, "Composition Changes of Inclusions by Reaction With Slag and Refractory: A Review," *ISIJ International* 60, no. 9 (2020): 1835–1848, https://doi.org/10.2355/isijinternational.isijint-2019-695.

[13] O. Kubashevskij and K. B. Olkokk, *Metallurgicheskaja Termohimija* (Metallurgija, 1982).

[14] A. Berezhnoj, *Bagatokomponentni Sistemi Okisliv* (Naukova Dumka, 1970).

[15] M. Nadif, J. Lehmann, M. Burty, and J.-F. Domgin, "Control of Steel Reoxidation and CC Nozzle Clogging: An Overview," *Metallurgical Research & Technology* 104, no. 10 (2007): 493–500, https://doi.org/10.1051/metal:2007209.

[16] B. Harcsik, P. Tardy, and G. Karoly, "Examination of Nozzle Clogging in Continuous Casting," *Metallurgical Research & Technology* 109, no. 3 (2012): 177–186, https://doi.org/10.1051/metal/2012046.

[17] L. A. Frank, "Castability From Alumina to Spinels," *Iron and Steelmaker* 26 (April 1999): 33–39.

[18] S. Inada and H. Todoroki, *Textbook of the 182nd and 183rd Nishiyama Memorial Lectures* (ISIJ, 2004).

[19] H. Knuppel, *Reduction and Vacuum Treatment of Steel*, 1 (Metallurgiya, 1973).

[20] O. M. Grudnitsky, "The Experience of Using Calcium Carbide for the Deoxidation of Steel to Replace Aluminum in the Conditions of OJSC «BSW—Management Company of the Holding «BMC»," *Foundry Production and Metallurgy* no. 2 (2020): 53–58, https://doi.org/10.21122/1683-6065-2020-2-53-58.

[21] I. Kostyrya, M. Orlichenko, S. Frolov, and D. Zotov, "Experience in Application of Calcium Carbide in BOF Converter Shop of PJSC 'Azovstal Iron- and Steelworks'," *Metallurgisches Kolloquium Zu Ehren Von Prof. Dieter Janke. 67. Berg- und Huetmaennischer Tag* (Freiberg, Germany: Freiberger Forschungshefte, 2016), 120–123.

[22] T. Sjöqvist, S. Jung, P. Jönsson, and M. Andreasson, "Influence of Calcium Carbide Slag Additions on Inclusion Characteristics in Steel," *Ironmaking and Steelmaking* 27, no. 5 (2000): 373–380, https://doi.org/10.1179/030192300677688.

[23] H. V. Atkinson and G. Shi, "Characterization of Inclusions in Clean Steels: A Review Including the Statistics of Extremes Methods," *Progress in Materials Science* 48, no. 5 (2003): 457–520, https://doi.org/10.1016/s0079-6425(02)00014-2.

[24] "Steel. Metallographic Method for the Determination of Non-Metallic Inclusions," Ukrainian State Standard DSTU 8966: 2019.

[25] "Standard Test Methods for Determining the Inclusion Content of Steel," ASTM E45-18a.

[26] R. Zimmerman and K. Gunter, *Metallurgy and Materials Science* (Metallurgiya, 1982).