The Influence of Technological Parameters of X70 Stainless Steel Ladle Refining on the Residual Content of Non-Metallic Inclusions

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Abstract

It is demonstrated that during secondary refining at the ladle furnace the carbon content of steel and the residence time of the metal in the ladle exert a significant impact on the residual content of non-metallic inclusions (NMI) in steel. Mathematical calculations showed that the dynamic forces have minor effect on the motion of small sized NMI, making it difficult to penetrate deep into the slag.

Keywords: Non-metallic inclusions, Secondary refining, Ladle furnace, Tundish ladle

1. Introduction

The tendency to increase performance of gas transportation systems leads to steady rise in the rated operating pressure in the line (from 5.4-7.4 to 9.8-14.0 MPa currently) [1], necessitating to equip the gas transmission industry with larger diameter pipes made of higher quality steel grades [2]. The solution to this problem is largely determined by the metal purity in terms of the non-metallic inclusions (NMI) [3, 4].

2. The results of the industrial experiment

The investigations were carried out in the converter shop of PJSC Azovstal Iron & Steel Works. According to the existing technology X70 strength category steel always undergoes secondary refining with calcium at the ladle furnace (LF), where calcium exerts a final active influence on the non-metallic inclusions [5, 6]. The results of NMI analysis performed under the ASTME 45-97 indicate that inclusions are mainly present in the steel in the form of brittle (category B) and large (globular) non-deformable (category D) silicates, which are classified into the thin and thick series with particle diameter of 2-9 and 9-15 microns, respectively.

The resulting *Ca/Al* curves at different carbon contents are shown in Fig. 1, which indicate almost the same effect of the *Ca/Al* ratio on the rating of brittle and globular silicates.

However, while reducing the carbon content of the metal after tapping from 0.07 to 0.03%, the *Ca/Al* ratio makes a controversial impact on the NMI content in steel, which must be considered to ensure the given quality of metal.

a)

b)

Legend:

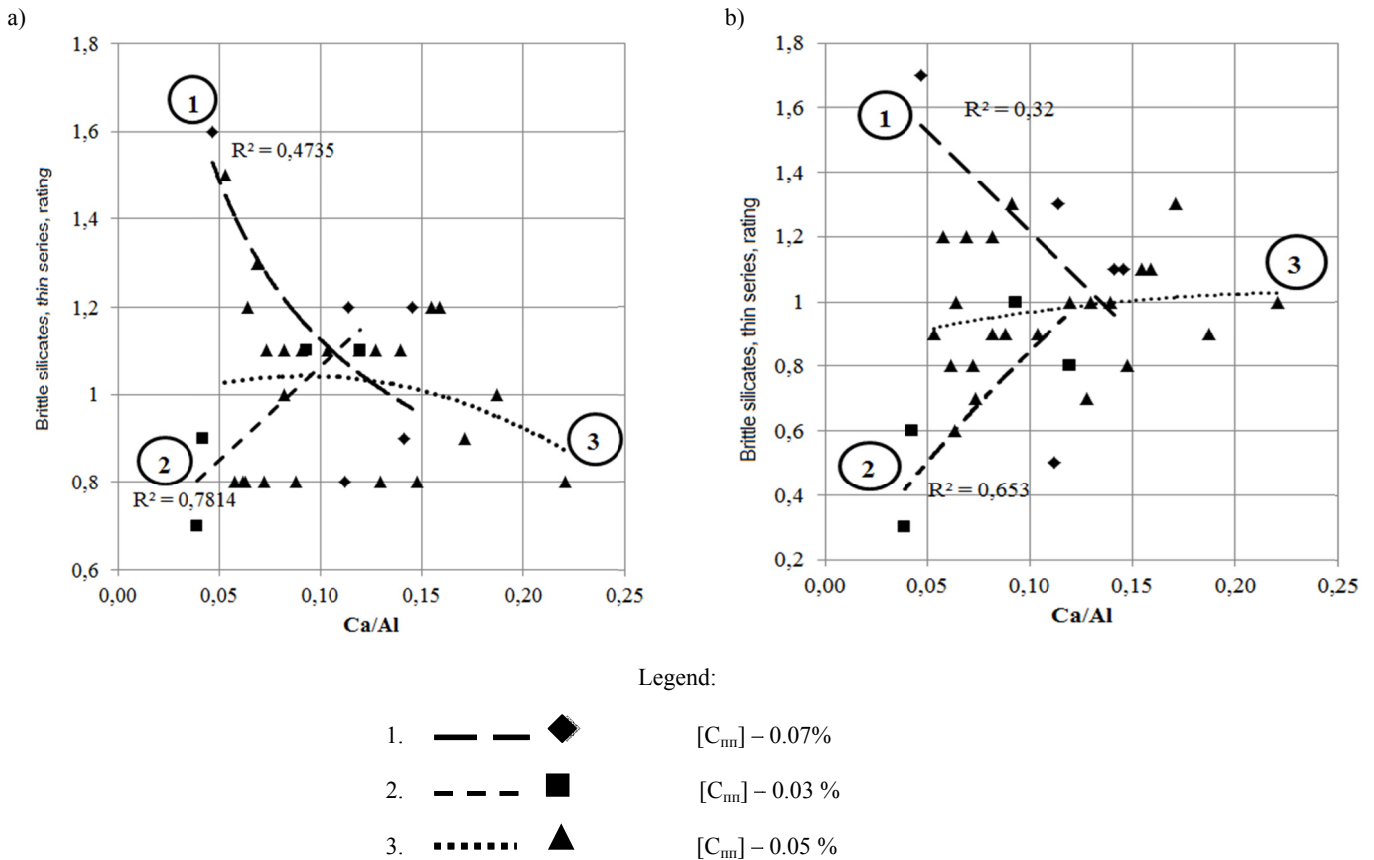|		
1.	▬ ▬ ◆	$[C_{nn}] - 0.07\%$
2.	─ ─ ─ ■	$[C_{nn}] - 0.03\%$
3.	•••••• ▲	$[C_{nn}] - 0.05\%$

Fig. 1. The effect of the Ca/Al ratio with different carbon contents
in the tapped-out metal on the brittle (a) and non-deformable silicates (b)

At the low carbon content in the tapped-out metal being equal to 0.03-0.04% and while increasing the *Ca/Al* ratio, the NMI rating increase is observed. It is required to provide the *Ca/Al* ratio at the lower level making approximately 0.05-0.10 units for its reduction, i.e. in this case the calcium content in the metal should be reduced and the aluminum content should be increased, bringing it closer to the upper limit by the steel grade composition.

This need is explained by the fact that while reducing the carbon content in the metal, the oxygen content is increased and, therefore, a significantly larger amount of aluminum is required to remove it and the formed solid aluminates are well removed from the metal.

When the carbon content in the tapped-out metal makes 0.05-0.06%, the *Ca/Al* ratio exerts less influence on the formed NMI rating, which is about at the same level.

When the carbon content makes 0.07% and the *Ca/Al* ratio increases from 0.05 to 0.15, the decrease of the NMI rating is observed in steel. The *Ca/Al* ratios exceeding 0.10 ensure a minimum NMI rating. This is explained by the fact that at the

higher carbon content it is necessary to use larger amounts of calcium for the NMI globularization and removal.

Full duration of steel residence in the ladle is the time from the tapping ending until the start of casting in the continuous casting machine (CCM), which is composed of the time of metal impact by technological operations (processing time) and the metal residence time spent without technological operations (holding time), which affect the NMI content. In the process of steel making the time to be fixed is T_1, being the time from the completion of heat tapping in the casting ladle until the end of secondary refining at the LF, and T_2, being the time from the end of secondary refining at the LF until the start of steel casting in the CCM.

Behavior curves of the T_1 process time depending on the rating variation of brittle and large non-deformable silicates with the different carbon content after heat tapping $[C]_{nn}$ are shown in Fig. 2 (a and b), respectively. Both these graphs indicate the typical impact of the carbon content in steel on the average rating of brittle and non-deformable silicates after the heat tapping.

a)

b)
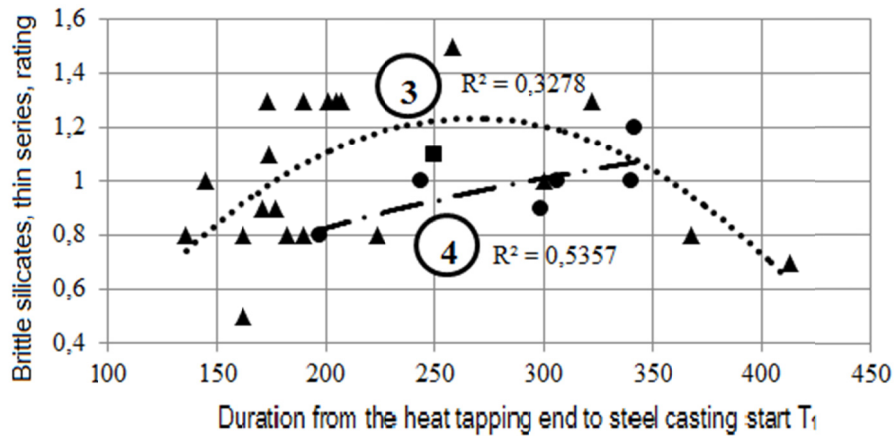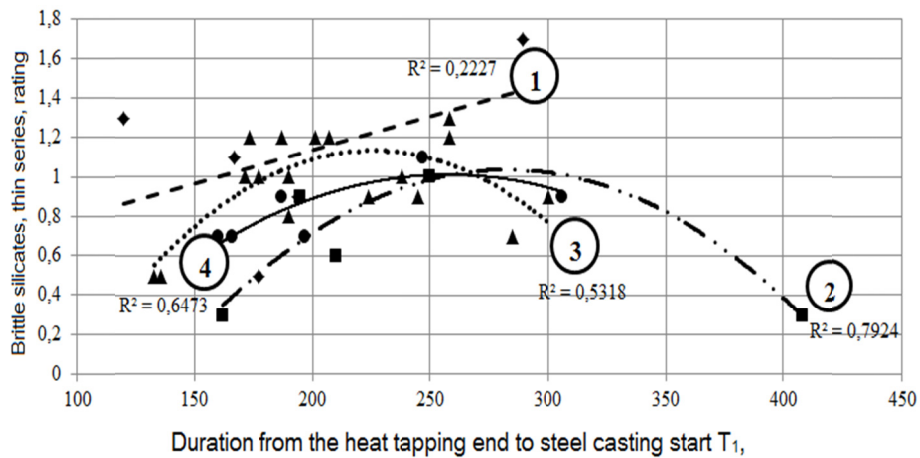
Legend:

1	– – – –	◆	- $[C]_{nn}$ - 0.07%
2	– · · –	■	- $[C]_{nn}$ - 0.03%
3	··········	▲	- $[C]_{nn}$ - 0.04%
4	————	●	- $[C]_{nn}$ - 0.06%

Fig. 2. NMI rating behavior in steel, respectively: a) of brittle silicates and b) non-deformable silicates depending on the duration from the heat tapping end to steel casting start at the different content of $[C]_{nn}$

Behavior curves of the T_2 holding time depending on the rating variation of brittle and large non-deformable silicates with the different carbon content after heat tapping $[C]_{nn}$ are shown in Fig. 3 (a and b), respectively.

It follows from the obtained curves (Fig. 3) that the ladle residence time of the metal from the LF secondary refining end until the start of the CCM casting has a significant impact on the average rating of brittle and non-deformable silicates in steel. In particular, the average rating of brittle silicates increases with the increase of the holding time, and the average rating of the large globular non-deformable NMI has an extremum, which is greatly influenced by the carbon content of the steel after tapping. When the carbon content is 0.03%, the non-deformable NMI rating is higher than at 0.05%.

a)

b)

Legend:

1. ▬ ▬ ■ $[C]_{пп}$ - 0.03%;

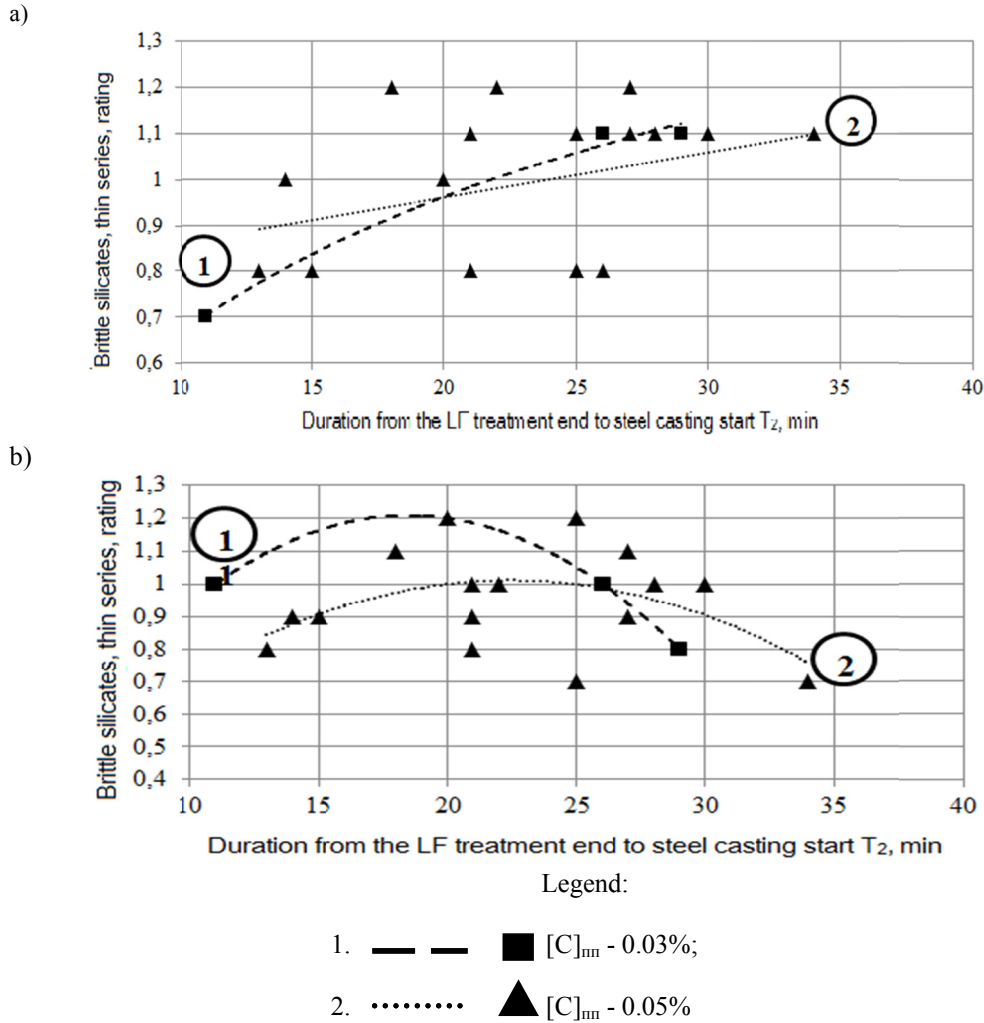2. •••••••• ▲ $[C]_{пп}$ - 0.05%

Fig. 3. NMI rating behavior in steel, respectively: a) of brittle silicates and b) non-deformable silicates depending on the steel holding time in the ladle at different content of $[C]_{пп}$

3. The results of mathematical simulation

Since the residual NMI are small, sizing, as indicated above, approximately 2-15 microns, their behavior in steel circulating flows in the tundish ladle (TL) of CCM was investigated by means of mathematical simulation.

When studying the dynamics of nonmetallic inclusions, it was considered that the thermal changes in the inclusions could be disregarded.

Also, the model was based on the following assumptions:
1. Hydrodynamic effects of non-metallic inclusions are not considered.
2. Collective component of NMI diffusion velocity relative to the melt motion is not considered.

3. Period of NMI heating to the phase transformation temperature is insignificant, so the thermal change in the inclusions can be neglected.

The first assumption is based on the fact that the NMI volume is much smaller than the gas phase volume. The second assumption is a purely phenomenological statement. The third assumption is based on the fact that NMI melting temperature is higher than the melt temperature.

To evaluate the NMI motion in the circulation flows it is required to use the Richardson criterion (Ri), which is equal to the ratio of the potential energy of the body immersed in a fluid to its kinetic energy:

$$Ri = \frac{(\rho_0 - \rho_\beta)\vec{g}x}{\rho_{_M} v^2} \quad \text{or} \quad Ri = \frac{Ar}{Re^2}, \tag{1}$$

where:
ρ_0 – fluid density; ρ_β – NMI density; g – gravity acceleration; x – NMI radius; v – flow velocity, ν - the kinematic viscosity factor.

If the Richardson number is less than unity, then the Archimedes number (Ar) is not important for the flow. If it is greater than unity, the buoyancy force is dominant (in the sense that the convection may not mix effectively the medium segregated in density).

Studies were carried out for the non-metallic inclusions with a density ρ_β=3,032 kg/ m^3 and the inclusion radii: 5, 10, 15 and 20 microns. These parameters are needed to determine the Archimedes number (Ar), which characterizes the motion of bodies in the environment (liquid or gas) that occurs as a result of density inhomogeneity in the "body - environment" system [8]:

$$Ar = \frac{\vec{g}x^3\left(\rho_0 - \rho_\beta\right)}{\rho_0\nu^2}. \qquad (2)$$

To determine the Reynolds criterion (Re), characterizing the ratio of the dynamic forces to viscous ones:

$$Re = \frac{vx}{\nu}, \qquad (3)$$

it is necessary to know the NMI velocity. For this purpose the NMI diffusion velocity is determined according to Stokes' law, which characterizes the NMI movement in a stationary medium:

$$\vec{w} = \frac{2x^2\vec{g}(\rho_0 - \rho_\beta)}{9\mu}, \qquad (4)$$

where μ is dynamic viscosity of the medium. Then NMI collective velocity relative of the melt is given by the formula:

$$\vec{v} = (1-k\alpha)\vec{w} + k\alpha\vec{V}, \qquad (5)$$

where:
v and V denote the NMI relative speed and the melt speed, respectively, $k \in [0, 1]$ is an empirical capture coefficient which determines the fraction of particle captured by the gas phase. Obviously, the larger it is, the smaller is the particle, α is the gas phase, the distribution of which was described in [9]. The maximum speed of the flow motion in the TL, according to calculations carried out in [10] is 0.44 m/s (calculations were performed for 44 ton TL of Azovstal Iron & Steel Works).

In contrast to the the buoyancy forces the hydrodynamic resistance acts on the NMI, which depends on the shape of the body, flow rate and similarity numbers:

$$\chi = c_v \frac{\rho_0 v^2}{2} S \qquad (6)$$

where:
c_v – dimensionless coefficient of resistance, which depends on the similarity of Reynolds criteria [8], S – an area, typical for this body.

The results of calculations of the specified values are tabulated.

Table 1.
The results of calculations of the specified values

NMI radius, m	Ar	χ, N/m^2	$\vec{w}$, m/s	$\vec{V}$, m/s	Re	Ri
0.000005	0.0007075	0.017584	3.14 10^{-06}	0.3998	2.00	0.00018
0.000010	0.00566	0.035168	1.26 10^{-05}	0.3996	4.00	0.00035
0.000015	0.0191025	0.052752	2.83 10^{-05}	0.3994	5.99	0.00053
0.000020	0.04528	0.070336	5.03 10^{-05}	0.3992	7.98	0.00071

As can be seen, the smaller hydrodynamic resistance coefficient (χ) is, the more the inclusion is structured in the hydrodynamic flow. With the NMI radius growth, the criterion of buoyancy (Ar) grows in the parabolic dependence, hydrodynamic resistance is almost linear. In addition, the buoyancy forces (Ar) affect scarcely the NMI movement to the area of slag. However, the influence of convection (kinetic energy that characterizes the Re^2 criterion) is not essential for the NMI with a small radius.

4. Conclusion

The undertaken studies found that under the similar technological operations of LF steel secondary refining the carbon content of the tapped-out steel and the process time of metal residence in the steel-casting ladle exert a significant impact on the residual content of NMI, in particular brittle and non-deformable silicates. The following optimal parameters were determined:
- the carbon content in the metal after a tapping making 0.05-0.07%;
- time from the end of steel tapping out of the converter until the start of casting being 100-200 min.;
- time from the end of LF secondary refining until the CCM casting making 10-15 min.

Mathematical calculations showed that the small sized NMI exhibited little resistance to flow and may be brought out to the slag area and to the TL bottom. The dynamic forces exert a slight impact on the NMI motion. This hampers the penetration of such inclusions deep into slag, which in its turn makes it difficult to clean the metal from inclusions and, therefore, to bring out such particles in the slag area it is

required to substantially turbulize the flow, for example by intensifying TL bath blowing.

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