Вісник Тернопільського національного технічного університету
Scientific Journal of the Ternopil National Technical University
2018, № 1 (89)
ISSN 2522-4433. Web: visnyk.tntu.edu.ua

UDC 669.18:519.876.3:621.43

PHYSICAL-CHEMICAL REGULARITIES OF STEEL REFINING FROM NON-METALLIC INCLUSIONS

Veronika Yefimova; Tatyana Pilipenko

National Technical University of Ukraine Igor Sikorsky Polytechnic Institute

Summary: *Using the thermodynamic analysis, the possibility of a colloid interaction of the dispersed phase with a dispersed medium, the possibility of coagulation of the non-metallic phase, has been determined. It is established, that on the surface of a particle of nonmetallic inclusions metal films (layers) are formed that "wet" them and prevent further coagulation and removal of the non-metallic phase. It has been determined, that in order to prevent the effect of "wetting" by these films (layers), it is necessary to create mixing in the tundish. Based on the theoretical principles of removing non-metallic inclusions, a physical modeling of the hydrodynamic processes occurring in the tundish, has been carried out. These studies have made it possible to establish, that the most effective structure of streams is a vortex, which is formed by the introduction of a reaction chamber. For confirmation of theoretical conclusions and results of physical modeling, industrial tests were conducted to determine the contamination of the metal by the non-metallic inclusions. The test results correspond well with the data of physical modeling and theoretical conclusions.*

Key words: *coagulation, non-metallic inclusions, hydrodynamic structure, thermodynamic analysis, tundish.*

Received 22.02.2018

Introduction. Nowadays the main directions of the metallurgical production development in our country are the improvements of the metal quality, being caused by the competition arose on both the internal and the world markets.

One of the main requirements for the high quality steel is low content of the non-metallic inclusions in the finished product, as well as their uniform distribution along the metal blank cross-section.

Since lately the manufacturing of the high quality metal has become possible because of its refining in the molten state at the last stage of casting in the tundish. Investigations in the casting device under the industrial conditions are limited, because of the physical conditions of the process being carried out, the size of the casting device and high temperature in particular. These limitations can be overcome, if the experiments are carried out not on the conventional device, but on the physical model with the further investigation of the metal quality, taking advantage of the metallographic methods [1 – 5].

Analysis of the available publications. The analysis of the latest publications testify, that to obtain high quality steel, that of the lowest content of the non-metallic inclusions, different structure rapids and partitions are formed additionally in the tundish in order to make the casting streams effective [1 – 5]. The non-metallic inclusions are known to transfer the phase interface melting-slag due to the inter-phase phenomena in the system steel melting-slag-non-metallic inclusion.

But the investigation carried out earlier [6 – 10] do not take into account the effect of the thermodynamic problems of the non-metallic inclusions removal in the tundish. That is why the hydrodynamic estimation of the situation being on the phase interface melting-slag-non-metallic inclusions while removing the non-metallic inclusions, is the pressing task now.

The Objective of the work. The main objective of our investigations was to improve the quality of the continuous casting blanks due to:

1) carrying out the thermodynamic analysis of the dispersion system strength the steel melting-slag-non-metallic inclusion, which facilitates the coagulation and surfacing of the non-metallic inclusions;

2) creation of the effective hydrodynamic situation in the melted steel volume being in the tundish facilitating the mass exchange;

3) investigation of the finished metal products taking advantage of the metallographic methods.

Statement of the task. Using the thermodynamic analysis to determine the most favorable thermodynamic conditions of coagulation and surfacing of the non-metallic inclusions. To determine the effective hydrodynamic conditions for the removing of non-metallic inclusions using physical modeling. To carry out metallographic investigations of the finished metal obtained from casting through the tundish of the improved design.

Presentation of the main ideas. The steel is known to be a heterogeneous system composed of the metal matrix (molten or solid solution) and non-metallic dispersed particles. The steel-casting ladle to the crystallizer results in the creation of the dispersed system composed of the solid products deoxidation suspension and silicate emulsion in the molten metal. That is why to determine such important process characteristics as the thermodynamic possibility of the colloid interaction of the dispersed phase and the dispersed medium, thermodynamic stability of the system being created the possibility to remove non-metallic inclusions, it is necessary to estimate taking into account the surface properties of the system – non-metallic inclusion – steel melt.

Thermodynamic possibility of the process of the non-metallic inclusions transition from the steel volume to the melt surface can be estimated using the general conditions of the process directions obtained, basing on the second law of thermodynamics and the Gibbs general equilibrium criterion [11].

The removal of the non-metallic inclusion particle on the steel surface, when the chemical processes and dissolution are not available and without taking into account the effect of the aggregate walls, can be presented as follows [11]:

$$\Delta G = \sigma^{(i-a)} - \sigma^{(i-m)} \frac{1+\cos\theta^{i-m}}{2} - 0{,}3\sigma^{(i-m)}. \qquad (1)$$

where $\sigma^{(i-a)}$ – surface tension at the phase interface of non-metallic inclusion – gas; $J \cdot m^{-2}$; $\sigma^{(i-m)}$ – surface tension at the phase interface of inclusion-metal; $J \cdot m^{-2}$; θ^{i-m} – contact angle of inclusion welting by the steel melt.

The calculations performed due to the equation (1) showed, that all metallurgic suspensions and emulsions while surfacing to the phase interface metal-gas are unstable dispersed systems.

Taking into account the capillary pressure the rate of the spherical-shape inclusions surfacing can be presented by the equation, which takes into account the fact, that the surfacing inclusion is affected by three forces: motion resistance caused by the melt viscosity, buoyant force and the stress caused by the capillary pressure. The rate of the inclusion surfacing from the steel is described by the following equation:

$$U_A = \frac{2}{9} r^2 g \frac{\rho_m - \rho_i}{\eta} + \frac{1}{3} \frac{\Delta\sigma}{\pi r^2} \, . \qquad (2)$$

where $\Delta\sigma$ – the change of the surface tension on the inclusion semi-spheres; $m \cdot s^{-2}$; $J \cdot m^{-2}$; g – gravitational force acceleration $m \cdot s^{-2}$; ρ_m and ρ_i – the metal melt density and of the non-metallic inclusion correspondingly, $kg \cdot m^{-3}$; r – non-metallic inclusion radius, *m*.

Taking into account the mentioned above, the rate of the inclusions surfacing in steel exceeds that, calculated due to the Stock's equation [11].

Using the Stock's equation to specify the characteristics of the inter-wetting phases separation rate, it should be taken into account, that there is the medium film on the internal friction in the viscous liquids, which takes into account the interrelation of the displacement rates of the medium and the particle moving in this medium.

Thus, in the steel melt not the inclusion in the metal shell. The latter increases the efficient weight of the inclusion. As the result, the value $\rho_m - \rho_i$, in the equation (2) decreases and, correspondingly, the inclusion surfacing rate decreases.

The change of the interphase tension affects the inclusions coagulation processes and, thus, the steel melt refining.

If thin shells are formed on the inclusion, its particle can press out the shell to some boundary, creating the wetting contact angle on the phase interface metal-gas about 90^0. In this case, according to the data [11], the possibility of the inclusion exit on the phase interface steel melt-gas is assessed by the approximation criterion:

$$K = 0{,}5\sigma^{m-a} + \Pi \cdot l\,, \tag{3}$$

where *P* – the disjoining pressure, *Pa*; l – the metal film thickness, *м*; σ^{m-a} – the surface tension on the phase interface of metal melt-gas, $J \cdot m^{-2}$.

The analysis of this equation makes us conclude, that at $K < 0$, the value of the disjoining pressure is of minus value $\left(P \le -\frac{0,5\sigma^{m-a}}{l}\right)$, the inclusion will go out of the metal shell unwarrantly, coagulate and be removed. The available metal film wetting the inclusion can make easier the reverse attraction of the non-metallic inclusions in the melt volume from the phase interface metal-slag and, in its turn, to facilitate the increase of the dispersed system stability.

To overcome the barrier effect of the films wetting the inclusions requires the intensive mixing, under which the increase of the convection flows rates results in the films break, further inclusions coagulation and their removing.

Being based on the mentioned above theoretical principles, with the purpose to create the most favorable hydrodynamic conditions for the non-metallic inclusions coagulation, the physical modeling of the hydrodynamic streams in the tundish, was carried out.

With this purpose the hydrodynamic model of the tundish was created with the scale 1:3 following the Frood equation of the similarity criterion and due to the Reynolds criterion (Fig. 1).

The method of modeling comprised the introduction of the stream indicators, recording of time the granules portion has been staying in the tundish, recording of the vortex-like structures sizes and the stream rates in them. The polystyrene granules of 0,7-0,9 $g{\cdot}cm^{-3}$, density and particles of 1-2 *mm* size were the stream indicators. Changing the reaction chambers construction, the possibility to vary the hydrodynamic structures, the streams rates and the duration of the granules portion staying in the tundish, was provided.

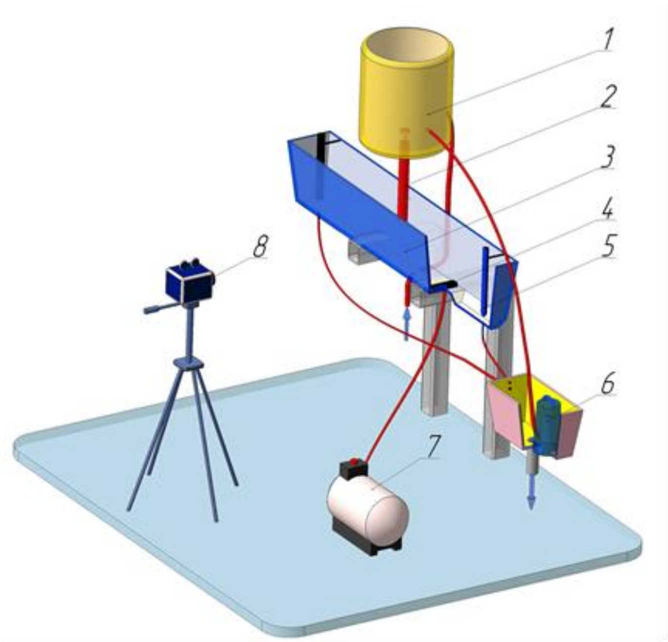

Figure 1. Scheme of the model stand of the tundish: 1 – tank simulating the ladle; 2 – protective pipe; 3 – tundish; 4 – blowing device; 5 – stop; 6 – tank for the collection of water coming from tundish; 7 – compressor; 8 – digital camera

While modeling it has been determined, that from the point of view of removing the non-metallic inclusions from the melted steel in the tundish, the most efficient hydrodynamic streams structure is that of the vortex-like one, which provides the creation of the most favorable conditions for the coagulation and the removal of the non-metallic phase. Creation of this hydrodynamic structure is possible, if the tundish is equipped with the additional reaction chamber, which is formed owing to the setting of the additional partition, Fig. 2.

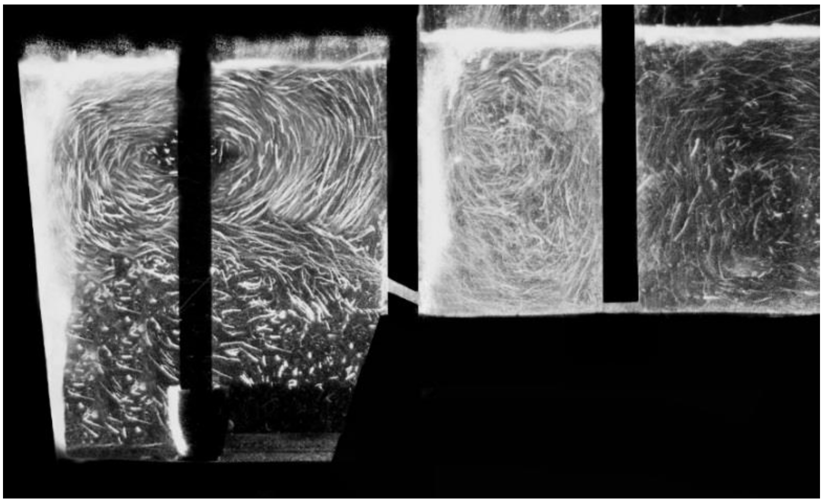

Figure 2. Reaction chamber for the streams vortex-like structure firming

While modeling the constructions of the reaction chambers, which consists of two solid partitions having canals in the tundish bottom, have demonstrated the best results. The partition from the input chamber had a slot under the 20-25^0 inclination to the tundish face plane wall. The slot width was 45-60 *mm*. The modeling experiments testified, that this construction of the tundish provides the increase of the non-metallic inclusion imitators duration in 4 – 6 times, than those being in the available construction of the tundish.

Taking into account the theoretical principles and the experiments performed on the model, the industrial testings with the purpose to improve the quality of the metal being casted owing to the decrease of the non-metallic inclusions content, have been carried out.

The estimation of the steel contamination was performed on the polished specimens of the steel samples taking advantage of the microscope "Axiovert-200" in the light, dark and DIC fields being scaled up in 100 times due to ГОСТ1778-70 and ASTM E45-97 (the method of the worst fields).

As the qualitative estimations in the samples of metal being casted through the reaction chamber testified, the number of non-metallic inclusions decreases in average by 40 – 80% as compared with that, for which the reaction chamber was not applied.

The main types of non-metallic inclusions in the tested metal samples are presented in Fig. 3.

It was determined, that, in fact, thin sulphine inclusions up to 0,5 points, oxide inclusions up to 0,5 points and silicate inclusions up to 4 points happen to be in the tested and compared metals.

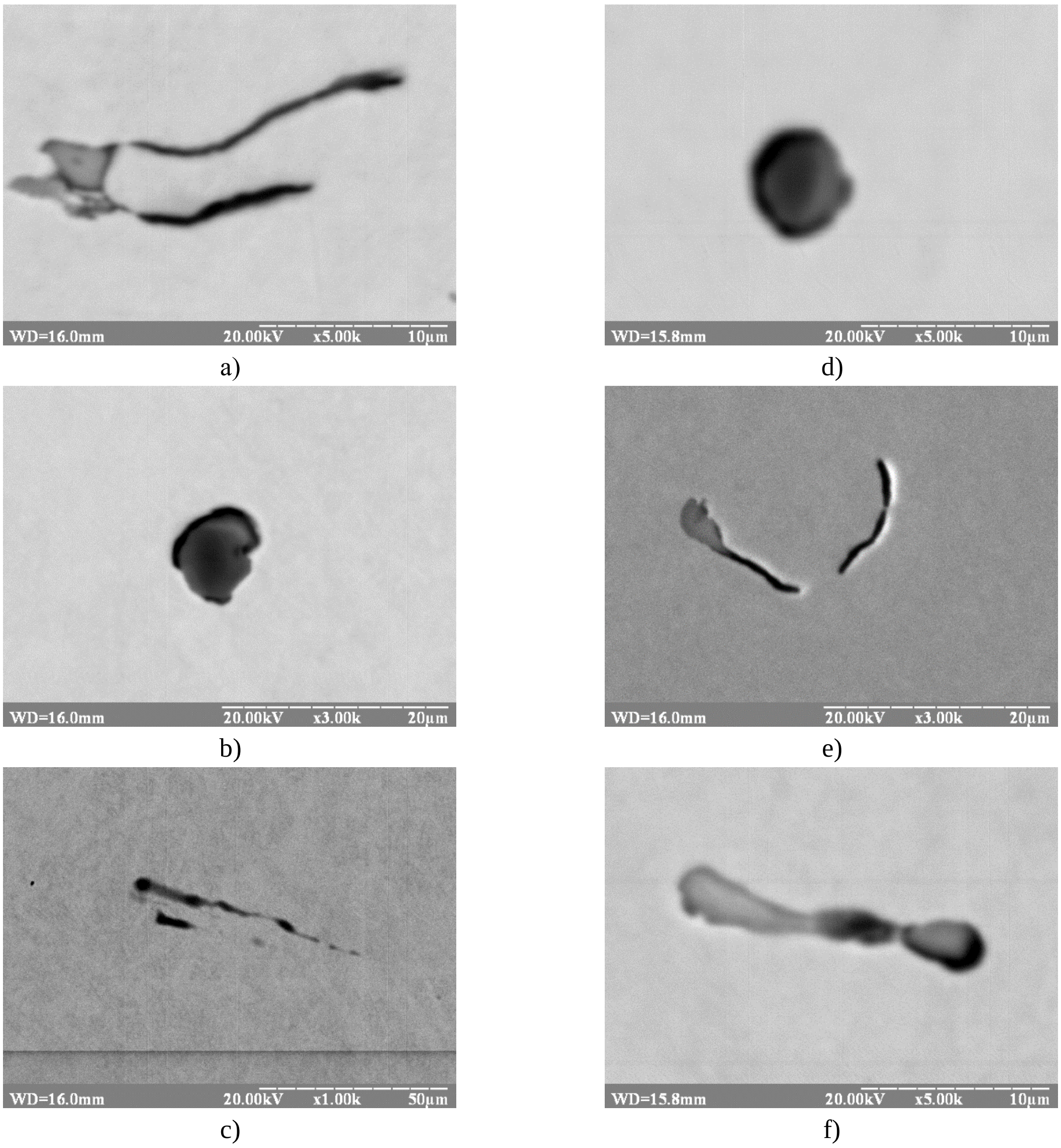

Figure 3. The main types of non-metal inclusions in the compared (a, b, c) and experimental (d, e, f) metal samples

Conclusions.

1) The analysis of the thermodynamic stability of the dispersed steel melting system – the non-metallic inclusions has shown, that the stable metallic films (layers) are formed on particles of non-metallic inclusions, that interfere with the coagulation process. In order to overcome the action of these films, that “wet” the non-metallic inclusions, intensive mixing is required.

2) Physical modeling has made it possible to establish, that the most effective structure of hydrodynamic flows is a vortex, which facilitates the coagulation of non-metallic inclusions and further removes them.

3) Estimation of the steel contamination by non-metal inclusions testified, that in samples of steel, which was casted through the reaction chamber, the amount of non-metallic inclusions decreased by 40-80%.

References

1. Gushchin V.N., Ul’yanov V.A. Improved tundish refining of steel in continuous-casting machines, Steel in Translation, 2017, vol 47, no. 5, pp. 320 – 324. [In English].
2. Yang G., Yang, Wang X., Huang F., Wang W., Yin Y., Tang C. Influence of Reoxidation in Tundish on Inclusion for Ca-Treated Al-Killed Steel, Steel research international 2013, vol. 85, no. 5. Pp. 784 – 792. [In English].
3. Holappa L.E., Louhenkilpi S., Nurmi S. Role of slags in steel refining: Is it really understood and fully exploited?, Revue de Métallurgie, 2009, vol. 106, no. 1. Pp. 9 – 20. [In English].
4. Janiszewski K. Refining of Liquid Steel in a Tundish Using the Method of Filtration During its Casting in the CC Machine. Metalurgija, 2013, vol. 52, no. 1. Pp. 71 – 74. [In English].
5. Mabentsela A. Numerical and physical modelling of tundish slag entrainment in the steelmaking process. Journal of Mining and Metallurgy, Section B: Metallurgy, 2017, vol.117, no. 5. Pp.469 – 483. [In English].
6. Mishra R. Physical and Mathematical Modeling of Slag Entrainment During Drainage of Steelmaking Ladles. Journal of the Southern African Institute of Mining and Metallurgy, 2017, vol. 117, no. 5. Pp. 469 – 486. [In English].
7. Yin X., Sun Y.H., Yang Y.D., Bai X.F., Deng X.X., Barati M. Inclusion evolution during refining and continuous casting of 316L stainless steel. Ironmaking & Steelmaking, 2016, vol. 43, no. 7. Pp. 533 –540. [In English].
8. Warzecha M., Hutny A.M., Warzecha P., Merder T., Jedrysiak B. Methodology of inclusions removing from steel flowing through the tundish. Metalurgia, 2017, vol.56, no.3. Pp. 291 – 293. [In English].
9. Yan P., Ende M.V., Zinngrebe E., Laan S., Blanpain B., Guo M. Interaction between Steel and Distinct Gunning Materials in the Tundish. ISIJ International, 2014, vol. 54, no. 11, pp. 2551 – 2558. [In English].
10. Chang S., Zhong L., Zou Z. Simulation of Flow and Heat Fields in a Seven-strand Tundish with Gas Curtain for Molten Steel Continuous-Casting. ISIJ International, 2015, vol. 55, no. 4, pp. 837 – 844. [In English].
11. Minaev Y.A. Physical chemistry in the metallurgy, M.: MSUFP, 2001, 320 p. [In Russian].

Список використаної літератури

1. Gushchin, V.N. Improved tundish refining of steel in continuous-casting machines [Text] / V.N. Gushchin, V.A. Ul’yanov // Steel in Translation. – 2017. – Vol. 47, no. 5. – P. 320 – 324.
2. Yang, G. Influence of Reoxidation in Tundish on Inclusion for Ca-Treated Al-Killed Steel [Text] / G. Yang, X. Wang, F. Huang, W. Wang, Y. Yin, C. Tang // Steel research international. – 2013. – Vol. 85, no. 5. – P. 784 – 792.
3. Holappa, L.E. Role of slags in steel refining: Is it really understood and fully exploited? [Text] / L.E. Holappa, S. Louhenkilpi, S. Nurmi // Revue de Métallurgie. – 2009. – Vol. 106, no. 1. – P. 9 – 20.
4. Janiszewski, K. Refining of Liquid Steel in a Tundish Using the Method of Filtration During its Casting in the CC Machine [Text] / K. Janiszewski // Metalurgija. – 2013. – Vol. 52, no. 1. – P. 71 – 74.
5. Mabentsela, A. Numerical and physical modelling of tundish slag entrainment in the steelmaking process [Text] / A. Mabentsela // Journal of Mining and Metallurgy, Section B: Metallurg. – 2017. – Vol. 117, no. 5. – P. 469 – 483.
6. Mishra, R. Physical and Mathematical Modeling of Slag Entrainment During Drainage of Steelmaking Ladles [Text] / R. Mishra // Journal of the Southern African Institute of Mining and Metallurgy. – 2017.– Vol. 117, no. 5. – P. 469 – 486.

7. Yin, X. Inclusion evolution during refining and continuous casting of 316L stainless steel [Text] / X. Yin, Y. H. Sun, Y.D. Yang, X.F. Bai, X.X. Deng, M. Barati // Ironmaking & Steelmaking. –2016. – Vol. 43, no. 7. – P. 533 – 540.
8. Warzecha, M. Methodology of inclusions removing from steel flowing through the tundish [Text] / M. Warzecha, A.M. Hutny, P. Warzecha, T. Merder, B. Jedrysiak // Metalurgia. – 2017. – Vol. 56, no.3. – P. 291 – 293.
9. Yan, P. Interaction between Steel and Distinct Gunning Materials in the Tundish [Text] / P. Yan, M.V. Ende, E. Zinngrebe, S. Laan, B. Blanpain, M. Guo // ISIJ International. – 2014. – Vol. 54, no. 11. – P. 2551 – 2558.
10. Chang, S. Simulation of Flow and Heat Fields in a Seven-strand Tundish with Gas Curtain for Molten Steel Continuous-Casting [Text] / S. Chang, L. Zhong, Z. Zou // ISIJ International. – 2015.– Vol. 55. – Iss 4. – P. 837 – 844.
11. Минаев, Ю.А. Физико-химия в металлургии [Текст] / Ю.А. Минаев, В.В. Яковлев – М.: МИСИС, 2001. – 320 с.

УДК 669.18:519.876.3:621.43

ФІЗИКО-ХІМІЧНІ ЗАКОНОМІРНОСТІ ОЧИЩЕННЯ СТАЛІ ВІД НЕМЕТАЛЕВИХ ВКЛЮЧЕНЬ

Вероніка Єфімова; Тетяна Пилипенко

Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», Київ, Україна

Резюме. *На основі термодинамічного аналізу встановлено, що на поверхні частинки неметалевих включень утворюються плівки металу, що змочують їх та перешкоджають подальшій коагуляції та видаленню неметалевої фази. Визначено, що для запобігання дії плівок, що змочують, необхідно створювати перемішування у проміжному ковші. Проведене фізичне моделювання гідродинамічних процесів у проміжному ковші дозволило встановити, що найефективнішою структурою потоків є вихороподібна, яка утворюється за рахунок встановлення реакційної камери. Результати промислових випробувань добре узгоджуються з даними фізичного моделювання та теоретичних висновків.*

Ключові слова: *коагуляція, неметалеві включення, гідродинамічна структура, термодинамічний аналіз, проміжний ківш.*

Отримано 22.02.2018