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Recenzované výzkumné články

Physical modelling of liquid steel refining process with argon

Fyzikální modelování procesu rafinace tekuté oceli argonem

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The presence of gas bubbles and their movement in the steel bath as well as the appropriate intensity of the process forces a more or less intensive circulation movement of the liquid steel. This movement, in turn, is necessary to homogenize the temperature and to achieve a state close to chemical homogenization of the liquid steel after the introduction of the alloy addition and to support the flotation of non-metallic inclusions. Therefore, the intensity and configuration of argon injection are important technological parameters that can result in a significant reduction in production costs while maintaining identical or higher quality parameters. Many researchers have studied most of these parameters extensively (based on physical modelling), and in particular their impact on the process of blowing argon into the steel in the ladle, which made it possible to understand the phenomena occurring during the process to a relatively good extent. Still, many aspects of the process remain experimental. The paper presents an overview of the conducted model tests.

***Key words**: steel, refining, argon blowing, physical modelling*

Přítomnost bublin inertního plynu a jejich pohyb v ocelové lázni, jakož i vhodná intenzita procesu dmýchání plynu během zpracování taveniny v licí pánvi, vynucují více či méně intenzivní cirkulační pohyb tekuté oceli. Tento pohyb je nezbytný pro homogenizaci teploty a pro dosažení stavu blízkého chemické homogenitě tekuté oceli po zavedení přídavku legury a pro podporu flotace nekovových vměstků. Intenzita dmýchání argonu a konfigurace dmyšných elementů ve dně licí pánve představují proto důležité technologické parametry, které mohou vést k výraznému snížení výrobních nákladů při zachování stejných nebo vyšších kvalitativních parametrů finální oceli. Vhodným nástrojem, který umožňuje porozumět probíhajícím jevům během uvedeného procesu, je fyzikální a numerické modelování. Optimalizaci procesu rafinace taveniny oceli v licí pánvi dmýcháním inertního plynu pomocí metod modelování byla již věnována řadou autorů poměrně velká pozornost. Cílem příspěvku je proto stručná rekapitulace stávajících poznatků v dané oblasti včetně odkazů na nejdůležitější práce mezinárodních výzkumných týmů.

***Klíčová slova**: ocel; rafinace; foukání argonu; fyzikální modelování*

1. Introduction

Currently, steel is produced using two steelmaking units: an oxygen converter or an electric arc furnace. Regardless of the process used, the steelmaking furnace is used to produce a liquid metal bath, which is a semi-finished product, which, after tapping into the ladle, is subjected to refinement operations and obtaining finished steel in secondary metallurgy (ladle metallurgy) devices. The refining of the steel metal bath is carried out in a ladle with the use of technological solutions designed and matched to the range of steel grades produced, with the use of an aggregate available in the steelworks. Irrespective of the type of ladle metal refining operations used in a particular case, argon refining is always used. The main task of this refining is to homogenize the chemical composition and temperature in the entire volume of liquid metal as a result of introducing mechanical energy of mixing with inert gas blown in. It should be noted that the injection of argon is carried out throughout the refining process, because chemical processes in the liquid metal are still taking place. For this reason, this element of refining plays an important technological role and requires optimization activities in the conditions of each steelworks, and model tests and simulation results are very useful for this purpose.

2. Physical Modelling of the Argon Steel Refining Process

Physical models, e.g. water or mathematical models with the use of computer software, are commonly used in understanding the phenomena occurring during various metallurgical processes, especially to determine the mixing conditions and distribution of gas bubbles in liquid steel in the process of inert gas injection. In the refining of ferrous alloys, physical and numerical modelling have been popularly used for several decades.

Research using physical models requires compliance with the rules resulting from the principles of similarity, which refer to the characteristic features of the real object, and which have a significant impact on the phenomena occurring in the investigated process. Similarity conditions are geometric, mechanical, kinematic, thermal or chemical. In order to ensure the similarity of the studied phenomena, full similarity should be sought, which in real conditions is often difficult to achieve, which is why the value that dominates in the examined process is usually selected. In order to maintain the aforementioned rules of similarity, it is enough to fulfil the rule on the equality of the relevant criterial numbers for the model and the tested object; then the results obtained as a result of experiments conducted on physical models can be transferred to real conditions.

The presence and movement of gas bubbles in the steel supports the movement of liquids to where the desired chemical reactions take place. A low proportion of the gas phase results in bubbling flow characterized by small, individual bubbles whose rising speed depends on their size, but does not depend on the diameter of the tank. An increase in the share of gas generates a greater number of bubbles, which, as a result of collisions and coalescence, take the form of a spherical bowl. Therefore, the intensity and configuration of argon purging are important technological parameters that can result in a significant reduction in production costs while maintaining identical or higher quality parameters [1-3]. From the technological point of view, it is important to obtain the optimal diameter of gas bubbles, their number and flow rate. These parameters are of decisive importance from the point of view of the efficiency of the process of purging argon into the steel bath. The gas flow rate, position of the porous body, bath height and slag layer are also important. Many researchers [1-40] have extensively studied most of these parameters (based on physical modelling), and in particular their impact on the process of purging argon into the steel in the ladle, which allowed for a relatively good understanding of the phenomena occurring during the process. Still, many aspects of the process remain experimental. Table 1 presents a summary of the conducted model tests and the studied issues.

Tab. 1 Summary of the results of model tests conducted for the argon steel refining process
Tab. 1 Přehled modelovaných variant rafinace taveniny oceli v licí pánvi dmýcháním argonu dle různých autorů

The studied phenomenon	Model liquid/gas/slag	Model height/scale	Literature
mixing and homogenization in the ladle			
mixing mechanism	water/air/-	787 mm/0.33	Joo and Guthrie [4]
mixing time	water/air/-	270 mm/0.2	Krisnapisharody et al. [5]
plug location	water/air/-	456 mm/0.14	Gonzalez-Bernal et al. [6]
place of Ca-Si introduction	water/air/-	800 mm/0.25	Fan and Hwang [7]
determination of dynamic similarity	water/air/-	930 mm/1 490 mm/0.53 410 mm/0.44 250 mm/0.27	Mazumdar et at. [8]
mixing time	water/air/-	450 mm/0.2	Mandal et al. [9]
mixing time	water/air/-	600 mm/0.17	Mazumdar et al. [10]
influence of slag properties on mixing time	water/air/-	410 mm/0.17	Amaro-Villeda et al. [11]
influence of plug location on mixing time	water/N_2/-	933 mm/0.33	Tang et al. [12]
liquid flow and bubble dispersion	water/nitrogen/-	200 mm	Taniguchi et al. [13]
influence of plug location on mixing time	water/N_2/-	700 mm/0.33	Liu et al. [14]
influence of plug location and slag height on mixing time	water/air/-	391 mm/ 0.125	Gomez et al. [15]
gas-liquid cone structure	water/air/-	450 mm	Sahai and Guthrie [16]
single bubble movement	water/air/-	80 mm	Wang et al. [17]
degree of homogenization	water/argon/-	950 mm/0.1	Michalek et al. [18]
frequency distribution of generated gas bubbles and their diameter	water/air/-	1080 mm/ 0.33	Owusu et al. [3]

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The studied phenomenon	Model liquid/gas/slag	Model height/scale	Literature
degree of homogenization and mixing time as a function of gas flow rate and number of plugs	water/air/-	120 mm/0.2	Merder and Pieprzyca [19]
behavior of gas bubbles			
single bubble movement	water/air/-	80 mm	Wang et al. [20]
influence of wettability on bubble formation	water/air/-	75 mmm	Xu et al. [21]
bubble size distribution in the gas-liquid cone zones	water/nitrogen/-	700 mm	Li et al. [22]
velocity of bubbles in a gas-liquid cone	water/air/-	400 mm	Castillejos and Brimacombe [23, 24]
arrangement of a gas-liquid cone above the plug	water/air/-	400 mm	Anagbo and Brimacombe [25]
the size of the bubbles in the gas-liquid cone	water/air/-	420 mm	Sheng and Irons [26, 27]
zones in a liquid-gas cone	water/air/-	233 mm	Iguchi et al. [28]
behavior of inclusions at the steel-slag interface and in liquid steel			
removal of inclusions in the area of the slag eye	water/air/silicone oil	590 mm	Kang et al. [29]
slag eye formation			
influence of slag properties on formation of slag eye	water/air/-	410 mm/0.17	Amaro-Villeda et al. [11]
slag eye size as a function of the Froude number	water/air/paraffin oil	500 mm / 0.1	Krishnapisharody and Irons [30]
the height of the gas-liquid cone	water/air/-	400 mm	Guo and Irons [31]
dragging slag in the slag eye	water/nitrogen/mixed oil	1252 mm	Huang et al. [32]
dependencies describing the slag eye	water/air/silicone oil	300 mm 750 mm	Iguchi et al. [33]
modified relationships describing the slag eye	water/air/soybean oil	300 mm/0.1	Peranandhanthan and Mazumdar [34]
Slag eye formation	water/air/silicone oil	500 mm/0.2	Wu et al. [35]
slag eye size	water/air/silicone oil	172 mm	Lv et al. [36]
mixing time and slag eye area	water/air/coconut oil	705 mm/0.28	Mazumdar et al. [37]
influence of the type of flow on the formation of a slag eye	water/air/-	410 mm/0.17	Perez et al. [38]

Based on the above list of studies, it can be concluded that currently modelling research of the liquid steel refining process with argon focus on four fundamental problems:

- mixing and homogenization in the ladle - the influence of the number of plugs in the ladle and their arrangement on the mixing time as well as the type and flow pattern of gas bubbles was tested, the method of introducing the tracer into the liquid was analysed and mathematical correlations were derived for the mixing time depending on the gas flow rate, mixing power or height liquid,
- behavior of gas bubbles from the moment of detachment from the hole of the plug to the gas-liquid cone - mainly the analysis of the frequency of detachment of gas bubbles from the hole of the plug, the speed of bubbles rising, behavior of gas bubbles in the gas-liquid cone,
- behavior of inclusions at the steel-slag interface and in liquid steel - the influence of various parameters (size of gas bubbles, concentration of solid particles, size of inclusions) on the rate of removal of inclusions and the mechanism of their removal was studied,
- slag eye formation.

Examples of results obtained in the above-mentioned issues are shown in Fig. 1.

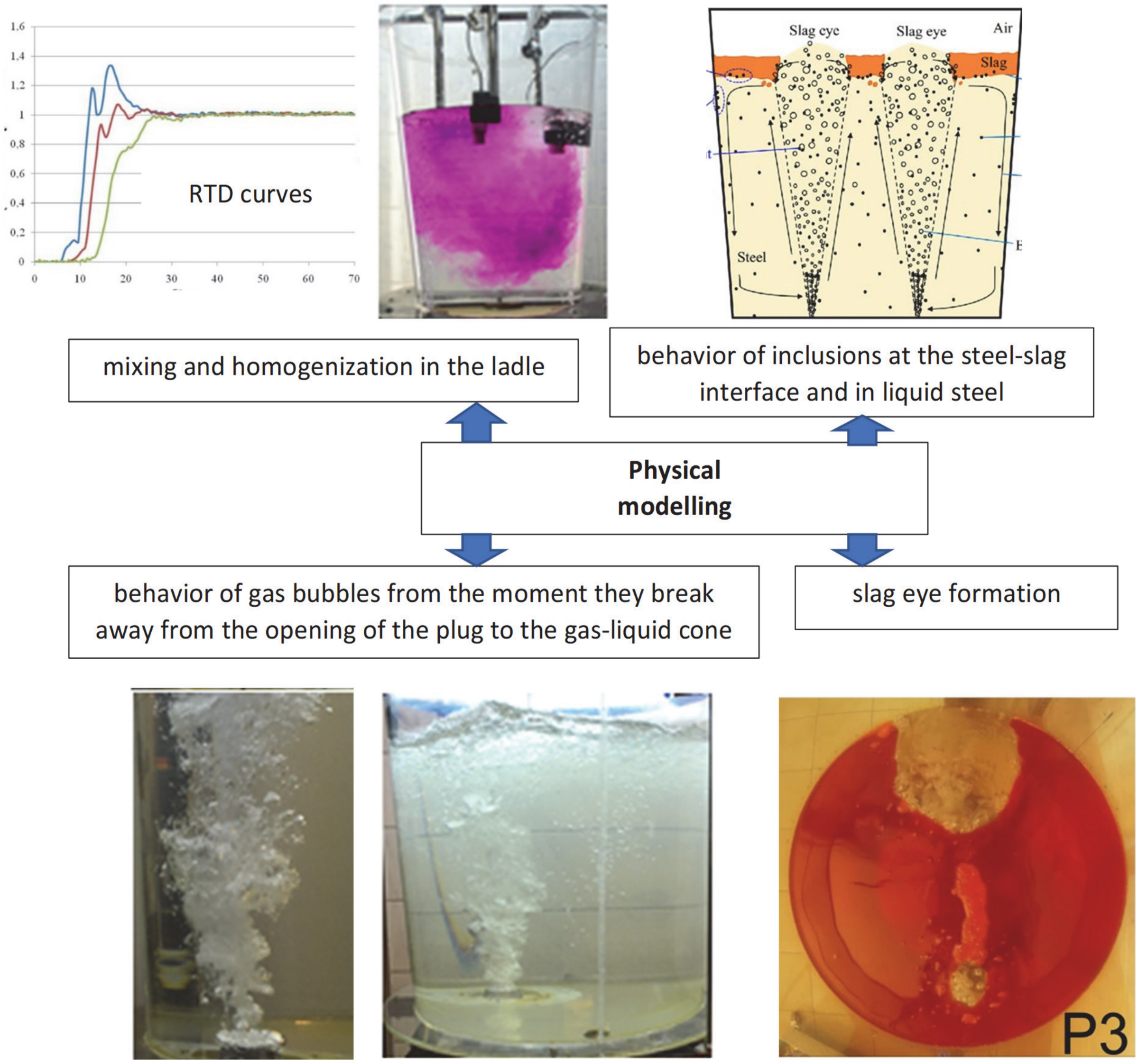

Fig. 1 Exemplary results of tests of the argon blowing process of steel obtained as a result of physical modelling [19, 39-40]
Obr. 1 Příklady výsledků fyzikálního modelování procesu dmýchání argonu do oceli během zpracování v licí pánvi [19, 39-40]

3. Summary

In the process of refining a metal bath in a ladle, one of the most important technological tasks is to obtain the highest degree of temperature homogenization and chemical composition in the entire volume of the bath. In addition, there is an intensification of the outflow of non-metallic inclusions (mainly solid particles, but also liquid), intensification of the release and outflow of gases (mainly hydrogen, but also nitrogen). Typically, mixing is considered sufficient when 95% homogenization of the bath is achieved. Therefore, the concept of mixing time was introduced, which should be understood as the time necessary to obtain a specific (assumed) degree of homogenization of the metal bath in the ladle. Determining the mixing time in industrial conditions is not easy. Changes in chemical composition and temperature in the metal bath volume occur continuously during refining processes. Chemical reactions of oxidation, deoxidation, dissolution of added ingredients, flow of non-metallic inclusions take place continuously. At the same time, temperature changes occur continuously as a result of heating from above with an electric arc and the radiation of thermal energy through the surface of the metal and slag, as well as from the external surfaces of the ladle. For this reason, attempts to estimate the actual mixing time occurring in industrial conditions are carried out using experimental methods performed on physical models.

The most optimal conditions for the process of refining liquid steel with argon are therefore conditions that ensure shorter mixing times, as well as the smallest possible area of the slag eye. Therefore, the process of optimizing the liquid steel refining process by blowing argon is multi-tasking and multi-dimensional. The consequence of this is a set of values or solutions, not a single, optimal value or optimal solution. Therefore, each process taking place under given process conditions for a specific ladle is treated separately, although the model assumptions are the same.

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References

[1] SAHAI, Y. and GUTRIE R.I.L. The formation and role of bubbles in steelmaking operations. In *Proceedings of the International Symposium on Modern Developments in Steelmaking*. Jamshedpur, India, 1981.

[2] ENGH, T.A. *Principles of metal refining*. London: Oxford University Press, 1992.

[3] OWUSU, K.B., HAAS, T., GAJJAR, P., EICKHOFF, M., KOWITWARANGKUL, P. and PFEIFER, H. Interaction of injector design, bubble size, flow structure, and turbulence in ladle metallurgy. *Steel Research International*, 1800346, (2018), 1-10.

[4] JOO, S. and GUTHRIE, R.I.L. Modeling flows and mixing in steelmaking ladles designed for single – and dual-plug bubbling operations. *Metallurgical Transaction B*, 23 (1992), 765-778.

[5] KRISHNAKUMAR, K., BALLAL, N.B., SINHA, P.K., SARDAR, M.K. and JHA, K.N. Water model experiments on mixing phenomena in a VOD ladle. *ISIJ Int*., 39 (1999), 419-25.

[6] GONZALEZ-BERNAL, R., SOLORIO-DIAZ, G., RAMOS-BANDERAS, A., TORRES-ALONSO, E., HERNANDEZ-BOCANEGRA, C.A. and ZENIT, R. Effect of the fluid-dynamic structure on the mixing time of a ladle furnace. *Steel Res. Int.,* 89 (2017), 1700281.

[7] FAN, C.M. and HWANG, W.S. Study of optimal Ca-Si injection position in gas stirred ladle based on water model experiment and flow simulation. *Ironmak. Steelmak*., 29 (2002), 415-26.

[8] MAZUMDAR, D., KIM, H.B. and GUTHRIE, R.I.L. Modelling criteria for flow simulation in gas stirred ladles: experimental study. *Ironmak. Steelmak*., 27 (2000), 302-09.

[9] MANDAL, J., PATIL, S., MADAN, M. and MAZUMDAR, D. Mixing time and correlation for ladles stirred with dual porous plugs. *Metall. Mater. Trans. B*, 36B, (2005), 479-87.

[10] MAZUMDAR, N., MAHADEVAN, A., MADAN, M. and MAZUMDAR, D. Impact of ladle design on bath mixing. *ISIJ Int.,* 45 (2005), 1940-42.

[11] AMARO-VILLEDA, A.M., RAMIREZ-ARGAEZ, M.A. and CONEJO, A.N. Effect of slag properties on mixing phenomena in gas-stirred ladles by physical modeling. *ISIJ Int.,* 54 (2014), 1-8.

[12] HAIYAN, T., CHIAOCHEN, G., GUANGHUI, W. and YONG, W. Effect of gas blown modes on mixing phenomena in a bottom stirring ladle with dual plugs. *ISIJ Int*., 56 (2016), 2161-70.

[13] TANIGUCHI, S., KAWAGUCHI, S. and KIKUCHI, A. Fluid flow and gas–liquid mass transfer in gas-injected vessels. *Appl. Math. Modell*., 26 (2002), 249-62.

[14] LIU, Z.Q., LI L.M. and LI B.K. Modeling of gas-steel-slag three-phase flow in ladle metallurgy: Part I. Physical modeling. ISIJ Int., 57 (2017), 1971-1979.

[15] GOMEZ, A.S., CONEJO, A.N. and ZENIT, R. Effect of separation angle and nozzle radial position on mixing time in ladles with two nozzles. *J. Appl. Fluid Mech*., 11 (2018), 11-20.

[16] SAHAI, Y. and GUTHRIE, R.I.L. Hydrodynamics of gas stirred melts: Part I. Gas/liquid coupling. *Metall. Trans. B*, 13B, (1982), 193-202.

[17] WANG, G.C., ZHOU, H.C., TIAN, Q.R., AI, X.G. and ZHANG, L.F. The motion of single bubble and interactions between two bubbles in liquid steel. *ISIJ Int*., 57 (2017), p. 805-13.

[18] MICHALEK, K., GRYC, K. and MORAVKA, J. Physical modeling of bath homogenization in argon stirred ladle. *Metalurgija,* 48 (2009) 4, 215-218.

[19] MERDER, T. and PIEPRZYCA, J. Physical modelling of mixing in occurring steelmaking ladle designed for single- and dual-plug blowing process. In *METAL 2018*: 27rd International Conference on Metallurgy and Materials. Ostrava: TANGER, 2018, p. 163-169.

[20] WANG, G.C., ZHOU, H.C., TIAN, Q.R., AI, X.G. and ZHANG, L.F. The Motion Of Single Bubble And Interactions Between Two bubbles in liquid steel. *ISIJ Int.,* 57 (2017), 805-813.

[21] XU, Y.G., ERSSON, M. and JONSSON, P.G. A mathematical modeling study of bubble formations in a molten steel bath. *Metall. Mater. Trans.* B, 46B (2015), 2628-3268.

[22] LI, L.M., LIU, Z.Q., LI, B.K., MATSUURA, H. and TSUKIHASHI, F. Water model and CFD-PBM coupled model of gas-liquid-slag three-phase flow in ladle metallurgy. *ISIJ Int.,* 55 (2015), 1337-1346.

[23] CASTILLEJOS, A.H. and BRIMACOMBE, J.K. Measurement of physical characteristics of bubbles in gas-liquid plumes: Part I. An improved electroresistivity probe technique. *Metall. Trans. B*, 18B (1987), 649-58.

[24] CASTILLEJOS, A.H. and BRIMACOMBE, J.K. Measurement of physical characteristics of bubbles in gas-liquid plumes: Part II. Local properties of turbulent air-water plumes in vertically injected jets. *Metall. Trans. B*, 18B (1987), 659-71.

[25] ANAGBO, P.E. and BRIMACOMBE, J.K. Plume characteristics and liquid circulation in gas injection through a porous plug. *Metall. Trans. B*, 21B, (1990), 637-48.

[26] SHENG, Y.Y. and IRONS, G.A. A combined laser Doppler anemometry and electrical probe diagnostic for bubbly two-phase flow. *Int. J. Multiphase Flow*, 17 (1991), 585-598.

[27] SHENG, Y.Y. and IRONS, G.A. The impact of bubble dynamics on the flow in plumes of ladle water models. *Metall. Mater. Trans*. *B*, 26B, (1995), 625-635.

[28] IGUCHI, M., TAKEUCHI, H. and MORITA, Z. The flow field in air-water vertical bubbling jets in a cylindrical vessel. *ISIJ Int*., 31(1991), 246-253.

[29] KANG, Y.J., YU, L. and SICHEN, D. Study of inclusion removal mechanism around open eye in ladle treatment. *Ironmak. Steelmak*., 34 (2007), 253-261.

[30] KRISHNAPISHARODY, K. and IRONS, G.A. Modeling of slag eye formation over a metal bath due to gas bubbling, *Metall. Mater. Trans*. *B*, 37B (2006), 763-772.

[31] GUO, D. and IRONS, G.A. A water model and numerical study of the spout height in a gas-stirred vessel, *Metall. Mater. Trans. B*, 33B (2002), 377-384.

[32] HUANG, A., HARMUTH, H., DOLETSCHEK, M., VOLLMANN, S. and FENG, X.Z. Toward CFD modeling of slag entrainment in gas stirred ladles, *Steel Res. Int*., 86 (2015), 1447-1454.

[33] IGUCHI, M., MIYAMOTO, K., YAMASHITA, S., IGUCHI D. and ZEZE M. Spout eye area in ladle refining process, *ISIJ Int*., 44 (2004), 636-638.

[34] PERANANDHANTHAN, M. and MAZUMDAR, D. Modeling of slag eye area in argon stirred ladles, *ISIJ Int*., 50 (2010), 1622-1631.

[35] WU, L., VALENTIN, P. and SICHEN, D. Study of open eye formation in an argon stirred ladle, *Steel Res. Int*., 81 (2010), 508-515.

[36] LV, N., WU, L., WANG, H., DONG, Y. and SU, C. Size analysis of slag eye formed by gas blowing in ladle refining*, Int. J. Iron Steel Res*., 24, 2017, 243-250.

[37] MAZUMDAR, D., DHANDAPANI, P. and SARVANAKUMAR, R. Modeling and optimization of gas stirred ladle systems, *ISIJ Int*., 57 (2017), 286-295.

[38] JARDON-PEREZ, L.E., VILLEDA, A.A., CONEJO, A.N., GONZALEZ-RIVERA, C. and RAMIREZ-ARGAEZ, M.A. Optimizing gas stirred ladles by physical modeling and PIV measurements, Materials and Manufacturing Processes, 33 (8), 2018, 882-890.

[39] CAO, Q. and NASTAC, L. Numerical modelling of the transport and removal of inclusions in an industrial gas-stirred ladle. *Ironmaking & Steelmaking*. 45(2018), 1-8, 10.1080/03019233.2018.1426697.

[40] MERDER, T. and PIEPRZYCA, J. The influence of porous plug type on argon blowing process. In *METAL 2017*: 26th Intern. Conference on Metallurgy and Materials. Ostrava: TANGER, 2017, p. 188-193.