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INDUSTRIAL TESTS OF STEEL FILTERING PROCESS

BADANIA PRZEMYSŁOWE PROCESU FILTRACJI STALI

The concerned paper presents results of wide scope of liquid steel filtering tests by means of ceramic filters, including laboratory, model and industrial testing in the conditions of conventional (ingot) and continuous steel casting. Multi- hole (sieve) ceramic filters made of mullite and corundum, of the structure adjusted to the type of conducted experiment were used for testing. Selection of ceramic material for filter construction accounted for the conditions of filter operations including: high temperature (liquid steel temperature), filtering duration determined by mass of the filtered steel, hydrodynamics of steel flow through filter holes an and wettablity of filter ceramics by non-metallic inclusions. In order to assess the effectiveness of liquid steel filtering in reference to unfiltered steel, the following criteria have been adopted:

– change in surface share of non-metallic inclusions,
– change in the quantity of non –metallic inclusions and dimensions thereof,
– change in total oxygen content (summary).

The obtained results of tests confirm high effectiveness of liquid steel filtering by means of ceramic filters and may constitute a basis for development of a new technology of steel refining by means of filtration.

Keywords: ceramic filter, casting, continuous casting, refining of steel, metallurgical purity of steel

W prezentowanej pracy przedstawiono wyniki szerokiego zakresu badań procesu filtracji ciekłej stali filtrami ceramicznymi, obejmującego badania laboratoryjne, modelowe i przemysłowe w warunkach konwencjonalnego (do wlewnic) i ciągłego odlewania stali. W badaniach stosowano filtry ceramiczne wielootworowe (sitkowe) wykonane z mulitu i korundu o konstrukcji dostosowanej do rodzaju prowadzonego eksperymentu. Wybór tworzywa ceramicznego do budowy filtrów uwzględniaływarunki pracy filtra do których zaliczano: wysoką temperaturę (temperaturę ciekłej stali), czas filtrowania określony masą filtrowanej stali, hydrodynamikę przepływu stali przez otwory filtra oraz zjawisko zwilżalności ceramiki filtra przez ciekłe wtrącenia niemetaliczne. Dla oceny skuteczności procesu filtrowania ciekłej stali w odniesieniu do stali niefiltrowanej, przyjęto następujące kryteria:

– zmianę udziału powierzchniowego wtrąceń niemetalicznych,
– zmianę liczby wtrąceń niemetalicznych i ich wymiar,
– zmianę zawartości tlenu całkowitego (sumarycznego).

Uzyskane wyniki badań świadczą o dużej skuteczności metody filtrowania ciekłej stali filtrami ceramicznymi i mogą stanowić podstawę do opracowania nowej technologii rafinacji stali metodą filtracji.

1. Introduction

The project was aimed at testing the new technology of steel refining by means of ceramic filters application. The present project included a range of basic (model) and technological tests, both laboratory scale tests and industrial tests.

The concept of steel filtering process tests assumed carrying out laboratory tests in the Institute for Ferrous Metallurgy in Gliwice as well as the Faculty of Metallurgy of the Silesian University of Technology.

Industrial tests were conducted in technological conditions of:

♦ Gonar – Stalownia Baildon Sp. z o.o. in Katowice, where heats with filtering of liquid steel during continuous casting were conducted; steel was filtered through ceramic baffles installed in tundish,

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- Magnesy Baildon Sp. z o.o. – Micro Steel Plant in Katowice, where liquid steel filtering was conducted in ceramic hot top with filter, installed over the mould, during conventional (downhill) casting.

Multi-hole channel (sieve) filters, the filtering component of which is the inner surface of filter channels were selected for steel filtering tests. Thus, in the said mechanism of liquid steel filtering a vital part is played by state of matter of non-metallic inclusions and surface phenomena of contacting phases: filter ceramics – non-metallic inclusions – liquid steel.

The following factors were taken into consideration during selection of filters' material: extreme conditions of filters' operations, in that temperature of cast steel, mechanical load and thermal shock occurring during each casting process.

2. Laboratory tests of steel filtering process

During laboratory tests, filtering was effected in the conditions of vacuum induction furnace VSG 50 – of the capacity 25 kg, where steel during casting flew through ceramic filter installed in a hot top.

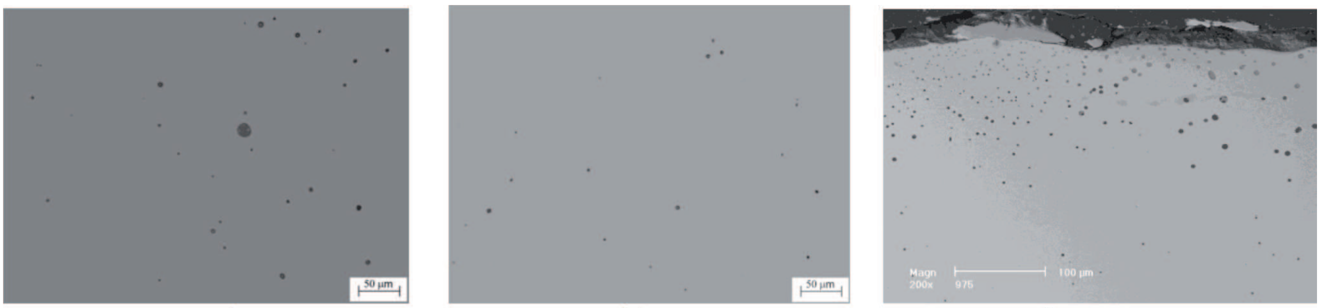
Channel filters of hole (channel) diameters 4,6 and 9 mm were used in tests. Filter materials included ceramic corundum and mullite. The constructed hot top prepared for filtering process is depicted in Fig. 1. Prior to casting filters were preheated to the temperatures of 635÷815°C. Casting (filtering) was conducted at such rate so that to achieve a complete submergence of the filter, i.e. so that the liquid steel covers totally the area of ceramic filter in hot top.

Fig. 1. Hot top with installed filter. Channel diam. 4 mm

In order to assess the effectiveness of filtering process, chemical and metallographic analyses of steel were carried out on samples cut out from ingot frame – from the filtered part and from the riser head reflecting the non-filtered steel, which solidified over the filter.

The surface where metal contacts the ceramic material of filter was also subject to analyses. The manner of samples drawing is presented in Fig. 2.

Fig. 2. The point of sample cutting from ingot top – filter poured with steel, for metallographic tests



a) b) c)

Fig. 3. Non-metallic inclusions in sample of non-filtered steel (a), steel filtered through corundum filter (b), and steel solidified in filter channel, close to the metal – ceramic material interphase boundary (c)

The conducted quantitative tests of non-metallic inclusions as well as microanalysis of selected inclusions have indicated that a positive effect of filtration may be achieved both owing to application of mullite and corundum filters. Surface share of all inclusions in filtered steel as compared to steel prior to filtration was reduced in consecutive melts by 48÷50%, while the number of inclusions decreased by ca. 38%, with simultaneous reduction in the size of inclusions that remained in steel. At the same time total oxygen reduced to 58%.

Tests of the surface where metal contacts the ceramic material of filter have revealed the presence of the "layer" concentrated in the inclusion, close to the channels of filter ceramic material, which is depicted in Fig. 3.

3. Industrial tests

Industrial tests were preceded with detailed model tests – simulations of liquid steel flow in tundish. The said tests were aimed at comparison of hydrodynamic conditions of model liquid flow through tundish equipped with conventional dams and through baffles with flow conditions with application of multi hole filters instead of the former. Filter models were constructed in two options: as baffle, located in the channel part of tundish, before outlet nozzles – option I and as a dam located between the tundish inlet and its channel part (option II).

Model tests along with visualization of steel flow through CCM tundish, covering the optional construction of the tundish included physical tests on the constructed water model of tundish as well as numerical simulations.

Another aspect of conducting tests on physical model of CCM was verification of the obtained results with numerical modelling methods. Fluent calculation code was used in the study. As a result of calculations, three dimensional distributions were obtained of velocity vectors and turbulence kinetic energy fields for the assigned conditions in the predetermined state. Analysis of tests' results allowed to formulate the following conclusions:

- location of filters in working area of tundish results in expected reduction in model liquid flow kinetics. The said is caused by resistance of flow occurring in filtration holes,
- impact of filters on flow character is significant; positive impact on medium movement structure thus causing homogenization of flow character in channel zone,
- application of filters does not pose a risk for the process and does not imply introduction of significant changes in process control system,
- location of the filter in working space of the tundish and its geometry influences model liquid flow structure and thus formation of transitional zone and the possibility of non metallic inclusions removal
- should the filter be placed as a baffle in channel zone of tundish, even piston flow is obtained behind the filter and by adjustment of filtration hole placement full utilization of tundish working space is obtained.

3.1. Industrial tests of steel filtering in CCM tundish

Steel grades included in production portfolio of the steel plant. All test melts prior to casting, were subject to vacuum ladle treatment in VAD device as well as to lime treatment, in order to modify non-metallic inclusions.

For the purpose of filtering process, filters construction was developed in form of baffles installed in CCM tundish. The said filters had filtering channels of 25mm diam. and 80mm length, the number of channel was, 28 and 30 respectively.

The developed filtration technology assumed optional location of filters in CCM tundish; the best results were achieved in option I, where the filter was placed in the preliminary chamber of tundish, where steel is poured from casting ladle, and the concerned option was selected for further filtration tests. In the above option a TURBOSTOP was installed in the preliminary chamber, under steel stream casing pipe.

In order to design the structure of multi-hole ceramic filters, the following calculation methodology was adopted:

Data for calculation:

H_m – height of liquid steel column in the main ladle = 1.3 – 1.5 m,
$H_{\dot{Z}}$ – height (thickness) of slag layer in the main ladle = max 0.1 m,
ρ_s – liquid steel density = 6900 kg/m^3,
$\rho_{\dot{Z}}$ – slag density = 2800 kg/m^3,
D_w – diameter of main ladle nozzle outlet = 0.05 m,
d_w – diameter of tundish nozzle outlet = 0.032 m,
ϕ – coefficient of steel flow resistance in the main ladle nozzle outlet = 0.90 [1],
g – acceleration of gravity, m/s^2

- *determining the maximum linear velocity of steel outflow (ϑ_L) from the main ladle, defined by the formula:*

$$\vartheta_L = \phi \cdot \sqrt{2 \cdot g \cdot \left(H_m + H \cdot \frac{\rho}{\rho_S}\right)}, \quad m/s \qquad (1)$$

- *determining the maximum intensity of steel outflow from the main ladle S_C, defined by the formula:*

$$S_C = \vartheta_L \cdot \rho_S \cdot \frac{\pi \cdot D_W^2}{4}, \quad kg/s \tag{2}$$

– *determining the minimum number of filtering holes in the filter*

It was assumed that the totality of steel shall flowing out of the main ladle shall flow through the filter constituting baffle located before outlet nozzle of tundish. Based on the above assumption, the minimum number of holes was determined by the following formula:

$$n_F' = \frac{4 \cdot S_c}{\phi_F' \cdot \vartheta_{LF}' \cdot \rho_S \cdot \pi \cdot d_F'^2}, \quad pcs. \tag{3}$$

where:

n_F – the minimum number of filtering holes

d_F – filter hole diameter

ϑ_{LF} – linear velocity of steel flow through filtering holes

– *determining the filtration area P_F with the following formula:*

$$P_F = n_F \cdot \pi \cdot d_F \cdot g_F, \quad m^2 \tag{4}$$

where: g_F – filter thickness

– *determining the ratio of filtration area per unit of filtered steel mass will be as follows:*

$$W_F = \frac{P_F}{M_S} \tag{5}$$

where: M_S – mass of the filtered steel

The above equations have also been applied in designing of the ceramic container with ground filter, at steel pouring into mould.

Scheme of optional installation of filter in tundish is presented in Fig. 4.

Figure 5 depicts filter installation in tundish in industrial conditions.

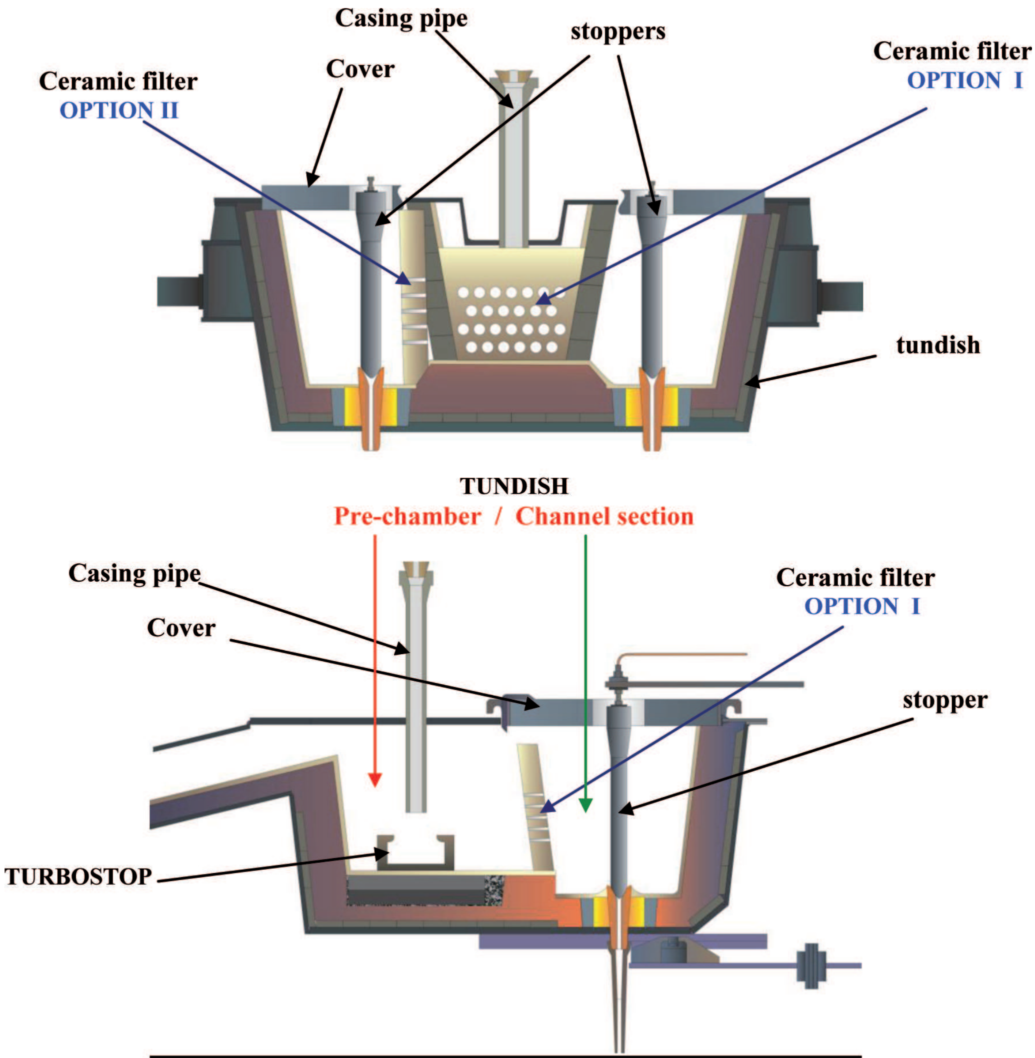


Fig. 4. Front and side view of the tundish with installed filters

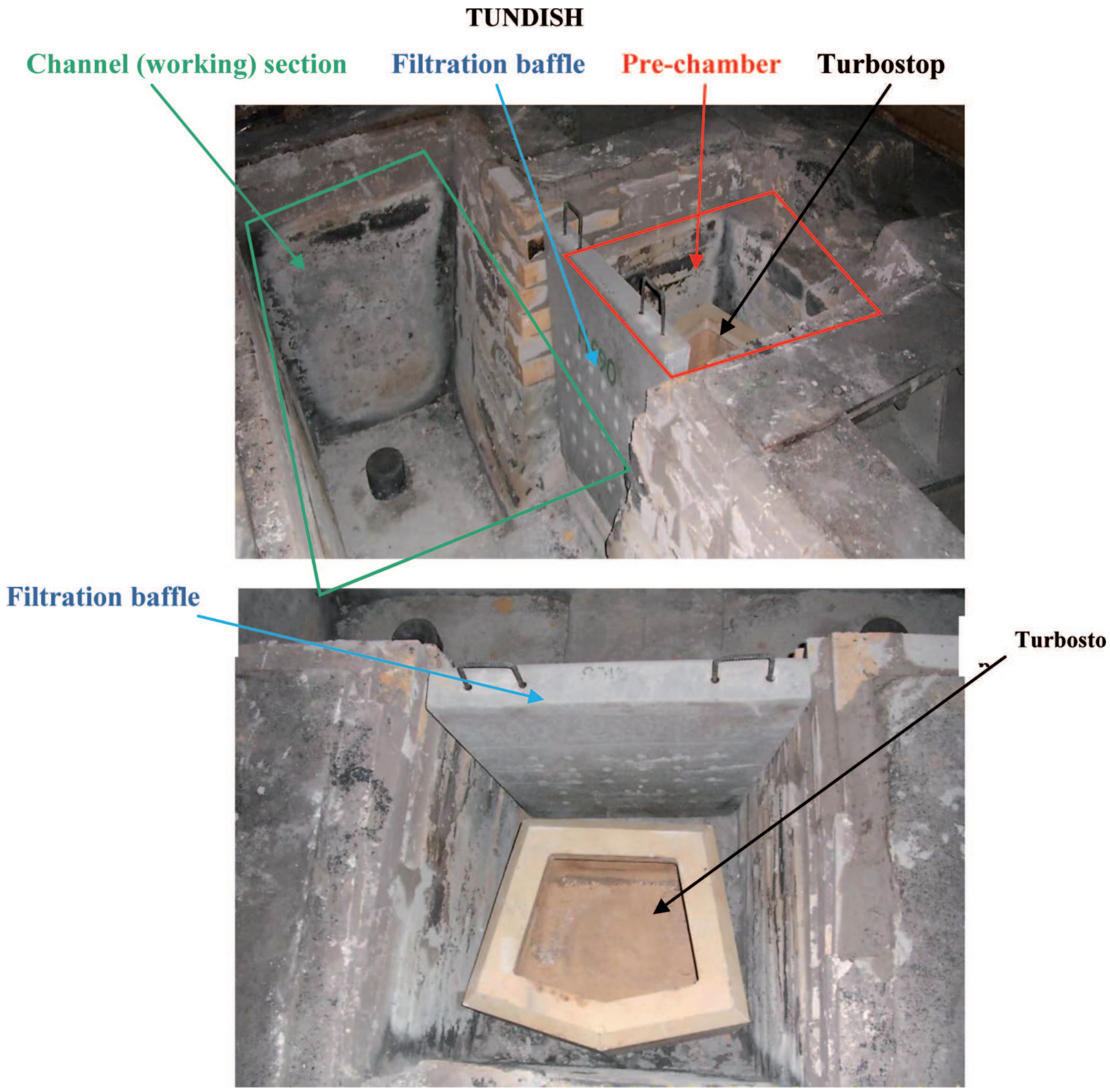


Fig. 5. Tundish filter – option II

Tundish with installed filters was heated up to the temperature of ca. 1100°C with gas burners. Four trial 1, 2 and 3 – melt sequence castings were conducted in the industrial conditions.

In the conducted filtering tests, the course of casting process was correct and assured maintaining of the proper, constant level of liquid steel in tundish. The process of steel filtering had a positive impact on stable operations of stoppers and maintaining stable level of steel in mould. In all experimental sequences, following casting, no defects of refractory material in baffles were found, including defects within the area of filtration channels, which proves high resistance of the applied refractory material to erosion and corrosive impact of liquid steel and ladle slag.

In order to determine the effectiveness of filtering process, tests were conducted of metallurgical purity of both steel subject to filtering, and the non filtered steel. Samples for chemical examinations and metallographic tests were drawn from disks cut from concast strands.

As a result of filtering, metallurgical purity of steel was improved, reflected in reduction of inclusions surface share as well as the number of inclusions. In case of steel melts subject to filtration, reduction was achieved in the surface share of inclusions at the level of 43÷50% – for mullite filter and 53% – for corundum filter respectively. Reduction in the number of non-metallic inclusions of filtered steel as compared to steel prior filtration was comparable to melts with application of both types of filters and reached ca. 50%. The content of total oxygen in strands of filtered steel was on average lower by 22% than in non filtered steel strands.

In some melts of steel subject to filtration, presence of larger non-metallic inclusions was observed simultaneously with reduction in the number of inclusions. This particularly concerned the melt cast as third in sequence with use of corundum filter.

The conducted microanalysis of non-metallic inclusions in strands of filtered steel from experimental melts has revealed presence of mainly complex inclusions such as calcium aluminates or calcium aluminosilicates.

Examinations of the interior surface of filtration channels, in the point of contact with steel slow, have shown the presence of particles of the composition varying from filter material in the surface layer of ceramic material. The conducted examinations of morphology and chemical composition of the said particles imply that these are clusters of non-metallic inclusions of composite structure and various chemical composition. The conducted microanalysis of these clusters shows that during steel flow through ceramic filter non-metallic inclusions present in steel, constituting a complex products of liquid steel deoxidation, combined in large agglomerates and settled on filtration surface of the filter. The said process resulted in high purity of cast steel.

3.2. Industrial tests of filtering steel cast by means of conventional downhill casting into moulds

Filtering process was conducted in Mikrostalownia – Magnesy Baildon; filtering was effected during casting of steel into vb11 mould, ingot weight ca. 1 tonne.

Filtration technology was developed based on experiences gained during filtering experiments in laboratory conditions of the Institute for Ferrous Metallurgy (IMŻ). Similarly to laboratory experiments, set for steel casting constituted also the filtering set, composed of: mould with ceramic top (container) where ceramic filter was installed. (Fig. 6).

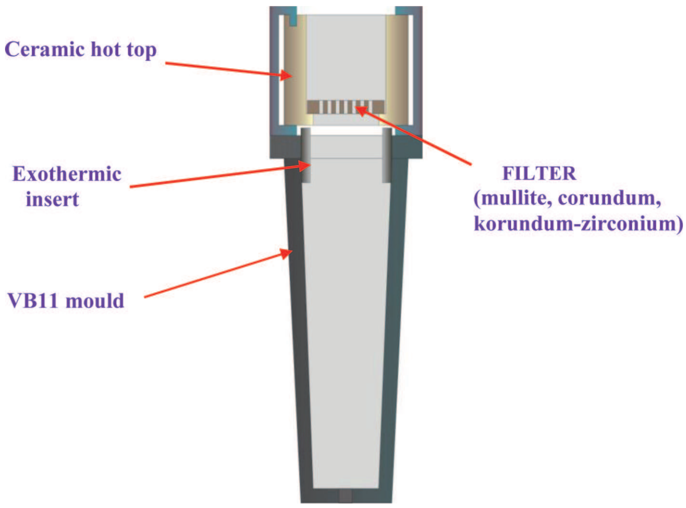


Fig. 6. Filtration set for industrial-scale experiments at the company Magnesy Baildon

Low and medium alloy steel grades included in production range of the steel melt plant were selected for filtration experiments; the said grades were cast in an open induction furnace of the capacity 1.5 tonne. Filtration set, prior to installation on mould flange, was heated up to the temperature of filter surface, i.e. 600-800°C. Following preheating, the filtering set was installed on mould flange.

Channel filters of two various channel diameters were used in tests: 18 channels of 15 mm diameter and 22 channels of 12 mm diameter. Filtration was effected with use of ceramic filters made of 3 types of material, i.e.: mullite, corundum and corundum – zirconium material.

During casting, liquid steel covered the entire surface of ceramic filter in hot top. Following completion of casting, the filtering set was removed from mould frame and ingot head was covered up with insulation powder.

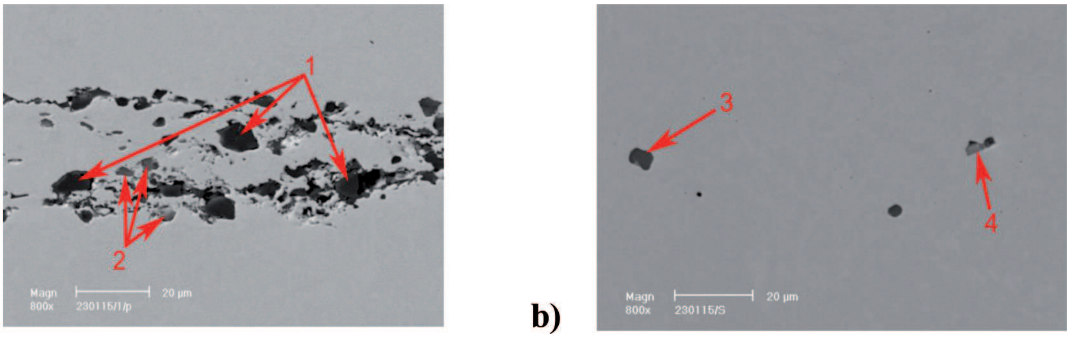
Following filtration, filtering channels were not filled with steel and no defect or deformation thereof was ascertained, which proves proper selection of refractory materials for filtration set (Fig. 7).

Fig. 7. Hot top with filter following completed casting process

In order to determine the effectiveness of filtering process, metallurgical purity of steel subject to filtering was examined. The above examinations have shown that the best result of filtering, in scope of steel metallurgical purity improvement was achieved in those melts where mullite filter was used. In those melts, the maximum reduction of inclusions' surface share was 33% while the number of inclusions was 13%. The number of inclusions of maximum dimensions also went down by 36%. Improvement of steel purity was reflected in overall oxygen content reduction, which at its maximum was 75%.

Conducting tests using the same filter three times for steel filtering had a negative effect. In the third melt executed with use of one filter, purity of steel deteriorated significantly.

Figure. 8 presents examples of non-metallic inclusions in samples of non filtered steel and steel subject to filtration.



a) b)

Fig. 8. Non-metallic inclusions in samples of non-filtered steel (a) and steel filtered through mullite filter (b)

Inclusions in steel following filtration are smaller and are of globular nature, evenly distributed in steel. Clusters and elongated chains have not been observed. Analysis of single inclusions has shown in most cases presence of composite oxygen inclusions.

Microscopic analyses of filters have shown the presence of clusters of non-metallic inclusions of composite structure and diversified chemical composition (coming from the filtered steel) in the surface layer of ceramic material.

4. Summary

The achieved results of liquid steel filtering tests in laboratory and industrial conditions have proven high efficiency of the method of liquid steel purification – removal of non-metallic inclusions. The ascertained improvement in metallurgical purity of steel is reflected in reduction of :

– the surface share of non-metallic inclusions,
– the number of non-metallic inclusions,
– the content of total oxygen.

The revealed metallurgical effects justify making attempts to develop a new technology of liquid steel refinement by means of ceramic filters.

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