Journal
of Achievements in Materials
and Manufacturing Engineering

VOLUME 55
ISSUE 2
December
2012

The influence of slenderness ratios of multi- hole ceramic filters from λ = 1.67 to λ = 8.36 of filter surface on efficiency of liquid steel refining from solid non metallic inclusions

K. Janiszewski*
Department of Metallurgy, Silesian University of Technology,
ul. Karsińskiego 8, 40-019 Katowice, Poland
* Corresponding e-mail address: krystian.janiszewski@polsl.pl

Received 10.10.2012; published in revised form 01.12.2012

Methodology of research

ABSTRACT

Purpose: I propose in this publication to introduce the additional, standardized conception, characterizing the filters used in research works (already known in metallurgy in definitions of forms of the ingot moulds) - *the filter slenderness ratio*.
Design/methodology/approach: In order to confirm the theoretical assumptions we have performed a series of the laboratory scale experiments (for the filter slenderness ratio SF1 λ = 1.67 and SF2 λ = 8.36).
Findings: The influence of the filter slenderness on the filtration process efficiency has been determined through variations in quantities and surface shares of the non-metallic inclusions in the filtrated steel in relation to the non-filtered steel. We present also the results of researches on the separating surfaces between the liquid steel and the ceramic filter material, which in form of photos and scanning microscope microanalyses are put together in the publication.
Research limitations/implications: The aim of the research carried out has been to prove that the liquid steel filtration is a cheap and efficient additional processing stage, separating the non-metallic inclusions, which in case of the conventional casting technology could remain in the cast steel bodies.
Practical implications: The research results presented in the paper can be used for steel production of high purity steels.
Originality/value: The goal of the research carried out, the results of which are presented here, has been to prove the possible extent of the solid non-metallic inclusion removal from liquid steel through the steel filtration by means of multiple-orifice ceramic filters. These inclusions most frequently throw into confusion the process of continuous casting d inclusion deposits formed on the walls of the submersion-type nozzles, which gradually reduce the nozzle cross-section (which cause nozzle accretion).
Keywords: Quantitative metallography; Refining; Ceramic filter; Solid non-metallic inclusions; Filter slenderness ratios

Reference to this paper should be given in the following way:
K. Janiszewski, The influence of slenderness ratios of multi- hole ceramic filters from λ = 1.67 to λ = 8.36 of filter surface on efficiency of liquid steel refining from solid non metallic inclusions, Journal of Achievements in Materials and Manufacturing Engineering 55/2 (2012) 410-415.

1. Introduction

It can be concluded from the hitherto existing experience [4,8] that the traditional post-furnace steel processing (especially of steel deoxidized with use of a depositing method, e.g. by means of aluminium) does not guarantee high metallurgical purity of the steel. Additionally the presence of non-metallic inclusions in steel, namely Al_2O_3 oxides, disturbs the continuous casting process due to the phenomenon of covering the ladle discharge nozzles by a layer of such inclusions. According to opinions of many research centres [1-7, 8] the filtration of liquid steel by means of multi-hole ceramic filters can be the effective and economical method of removing the non-metallic inclusions from liquid steel. The results of the laboratory and field research works carried out hitherto give the evidence of essential decrease in contents of non-metallic inclusions and damaging impurities in the filtrated steel [5,6,9,13,14]. However the effectiveness of this method of steel refining varies greatly depending on local refining conditions. The reason for these variations is probably in a phenomenon of secondary oxidation of filtrated steel by oxygen contained in the air [3,5]. The aim of the developed and performed laboratory research works has been to verify the influence of slenderness ratios of multi-hole ceramic filters (filtrating surfaces) at the effectiveness of filtration of solid non-metallic inclusions from liquid steel.

2. The filter slenderness ratio

However when one knows only the filtration surface parameter (and does not see the filter drawing) he-she is not able to have imagination about its geometric form.

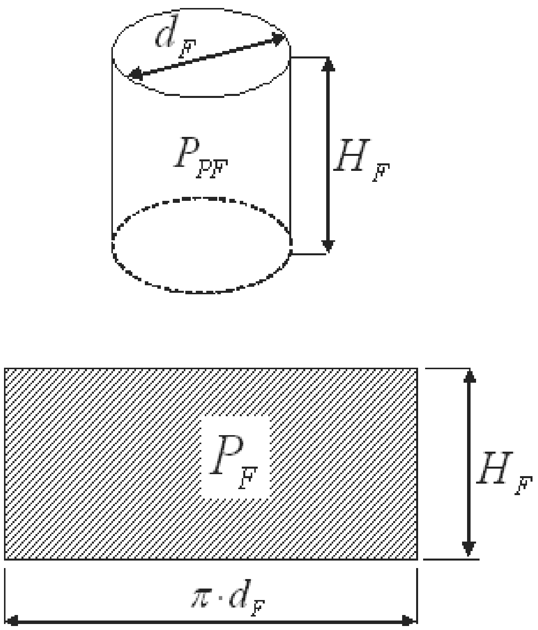

Fig. 1. The scheme of the filter channel and the filtrating surface

This is why we propose in this publication to introduce the additional, standardized conception, characterizing filters used in research works (already known in metallurgy in definitions of forms of the ingot moulds) - ***the filter slenderness ratio***. As the base for the definition of this we use the assumptions presented in Fig. 1 and in the equations (1-4).

After introduction of the filter slenderness concept - the equation (4) one can easily imagine, when seeing the presentation of the research results, the geometric configuration of the ceramic filters under consideration (the filter's channel, its length and filtrating surface). We propose the filter slenderness $\mathbf{S_F}$, as the additional definition describing the employed ceramic filter, to be denoted with use of the symbol $\boldsymbol{\lambda}$ - as the nondimensional unit. Using this coefficient we obtain the possibility to compare the filtration effectiveness of different types of ceramic filters, not only for filters with cylindrical filtrating orifices, but also for other types, e.g. with orifices of rectangular section.

$$S_F = \frac{H_F}{\sqrt{\frac{\pi \cdot d^2}{4}}} \tag{1}$$

$$P_F = \pi \cdot d_F \cdot H_F \tag{2}$$

$$S_F = \frac{\frac{P_F}{\pi \cdot d_F}}{\sqrt{\frac{\pi \cdot d_F^{\,2}}{4}}} = \frac{\frac{P_F}{\pi \cdot d_F}}{\frac{d_F}{2} \cdot \sqrt{\pi}} = \frac{\frac{P_F}{\pi \cdot d_F}}{\frac{d_F \cdot \sqrt{\pi}}{2}} \tag{3}$$

$$S_F = \frac{\frac{2 \cdot P_F}{4}}{\frac{\pi \cdot d_F^2}{4} \cdot \sqrt{\pi}} = \frac{\frac{2 \cdot P_F}{4}}{P_{PF} \cdot \sqrt{\pi}} \tag{4}$$

$$S_F = \frac{P_F}{2 \cdot P_{PF} \cdot \sqrt{\pi}} = \frac{P_F}{3{,}544 \cdot P_{PF}} \tag{5}$$

where:

P_F - the filtrating surface of the filter channel, m^2,

P_{PF} - the surface area of the filter channel cross-section, m^2,

S_F - the filter slenderness ratios.

3. Results of the laboratory research of steel filtration

The laboratory research works have been carried out in the laboratory of Metallurgy Department of the Silesian Technical University. Five steel melts, 11 kilogram in weight (five melts for S_F1 filter slenderness ratio (λ_1 = 1.67) and five ones for S_F2 filter slenderness ratio (λ_2 = 8.36), have been heated to temperature of about 1853 K, deoxidized subsequently with use of the singular deoxidizing agent in form of metallic aluminium, The argon protective atmosphere has been generated in a special caisson, where the mould, "receiving" the filtrated steel, has been placed together with the whole filtration system. The multi-hole ceramic filter used for steel filtration, manufactured by the company of Keramtech s.r.o. Žacleř (Czech Republic), has been made on the base of mullite ($3Al_2O_3 \cdot 2SiO_2$). The filters used have had equal orifice numbers 19, diameters of $8.1 \cdot 10^{-6}$ m and the total filtrating surface of $5802 \cdot 10^{-6}$ m^2 (Fig. 2 a) for S_F1 filter slenderness ratio and $11604 \cdot 10^{-6}$ m^2 (Fig. 2 b) for S_F2 correspondingly. Measurements of the liquid steel temperature and the oxygen activity therein have been made with use of Heraus Elektro-Nite equipment, specifically prepared for this purpose.

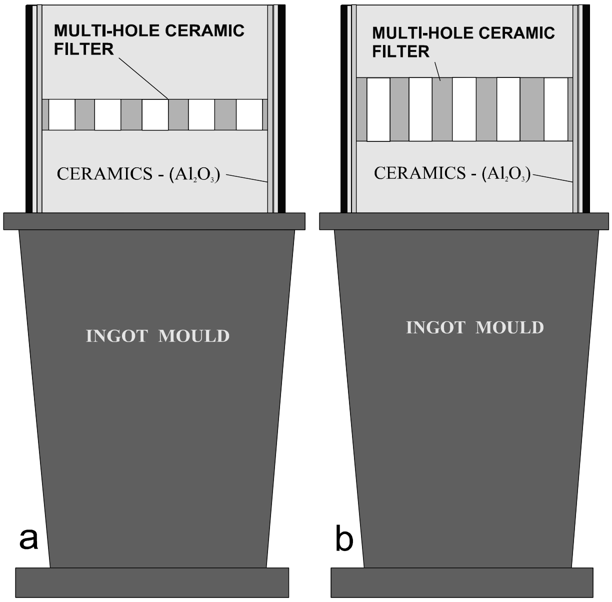

Fig. 2. The scheme of the pouring gate with the built-in multiple orifice ceramic filter: a) for the filter slenderness ratio $\lambda = 1.67$, b) for the filter slenderness ratio $\lambda = 8.36$

After having the steel solidified in the mould and pouring system the two samples in form of slices of filtered and non-filtered steel have been collected from each melt for examination of steel pollution with the non-metallic inclusions and variations in the steel chemical composition. A percentage of a surface share of metallic inclusions has been used for analyses of steel pollution according to formula:

$$\eta_{NMI} = \frac{x_p - x_k}{x_p} \cdot 100\,\% \qquad (6)$$

where:
x_p - inclusion surface share (or inclusion number) before filtration,
x_k - inclusion surface share (or inclusion number) after filtration,

with use of the following intervals of inclusion diameters according to Ferret: 0.5-2.5 μm, 2.6-6.5 μm, 6.6-15 μm, 15.6-30 μm.

The results of examination of pollution with non-metallic inclusions are presented in tables 1 and 2. The inclusions observed have shown differences in form and size. In melts deoxidized with aluminium the inclusions occur as individual ones and as clusters of irregular form and varying configuration. They are built of non-metallic phase (Al_2O_3) produced during the deoxidizing process.

4. Comparing the effectiveness of liquid steel filtration depending on the filter slenderness ratio

The influence of argon protective atmosphere has not caused substantial variations in the chemical composition of filtrated and non-filtrated steel. For S_F1 slenderness (λ=1.67) the increase has been observed in carbon contents of about η_C = -2.13% in the melt no. 2 and in sulphur contents in melts no. 1, 2 and 4. Instead, in three experimental melts, the decrease in phosphorus contents in the steel has been observed - especially in the melt no. 4 (η_P =9.09%). For S_F1 slenderness ratio (λ=8.36) the increase in sulphur contents has been observed in the steel after filtration for the melt no. 6 (η_S = -4.65%) and insignificant increase in carbon contents for melt no. 8 (η_C = -1.32%). Instead, in two experimental melts, similarly to the previous case, the decrease in phosphorus contents has been observed - especially in the melt no. 6 (η_P = 7.48%). Results of examinations of the degree of steel pollution with atmosphere for the eight experimental melt, are presented in Figs. 3-6. The numbers of non-metallic inclusions in the steel, in accordance with Feret diameters, are shown in Fig. 3. Instead, the surface share of non-metallic inclusions in each diameter interval presents Fig. 4. For S_F1 slenderness ratio (λ=1.67) only in one experimental melt (no. 5) the decrease in total number of non-metallic inclusions (η_{WN} = 18.63%) has been found, as well as decrease in all interval of Feret diameters. For S_F2 slenderness ratio (λ=8.36) in three melts (no. 6, 7 and 8) the decrease in total number of non-metallic inclusions has been found (η_{WN} = 73.34%, η_{WN} = 21.05 % and η_{WN}= 45.09%), as well as in all intervals of Feret diameters. For S_F1 slenderness ratio (λ=1.67) the largest number of non-metallic inclusions eliminated has been for F_x diameter interval of 15.5-30.0 μm in melt no. 3 (η_{WN} = 82.86%). In the remaining experimental melts the decrease has been found only in number of inclusions larger than 6,5 μm in diameter. For S_F2 slenderness ratio (λ=8.36) the largest number of non-metallic inclusions eliminated has been for F_x diameter interval of 15.5-30.0 μm in melt no. 8 (η_{WN} = 100.00%). The number of non-metallic inclusions in lesser diameter intervals (below 6.5 μm) has not increased to different degree depending on the melt number and Feret's diameter interval. As final result the total number of non-metallic inclusions in filtered steel has decreased to η_{WN} = 8.31% for S_F1 filter slenderness (λ=1.67) and to η_{WN} = 46.49% for S_F2 filter slenderness (λ=8.36) (Fig. 4).

The effectiveness of liquid steel filtration in the protective argon atmosphere, measured as an average rate of variations of the non-metallic inclusion surface share in filtrated steel, as compared with the non-filtrated steel, has been also compared for both filter slenderness ratios. For S_F1 filter slenderness ratio (λ=1.67) only in one melt (no. 4) a decrease in total surface share of non-metallic inclusions has been discovered (η_{WN} = 56.22%), as well as inclusions in all Feret's diameter intervals.

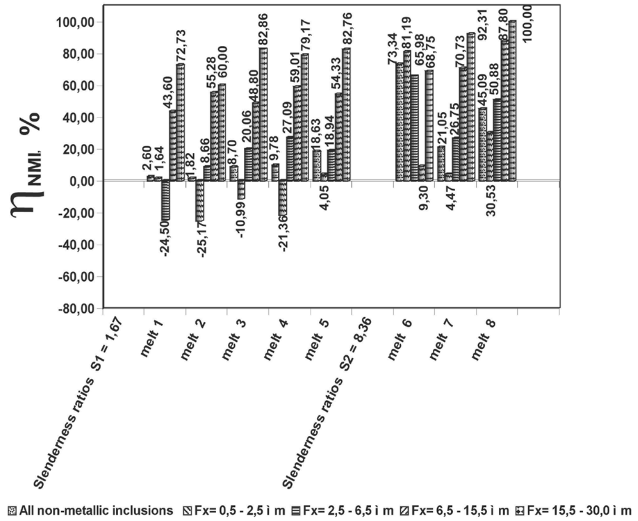

Fig. 3. The effectiveness of removing non-metallic inclusions as measured with the average rate of non-metallic inclusion number variation η_{NMI} , with division into inclusion size intervals according to F_x Feret diameters

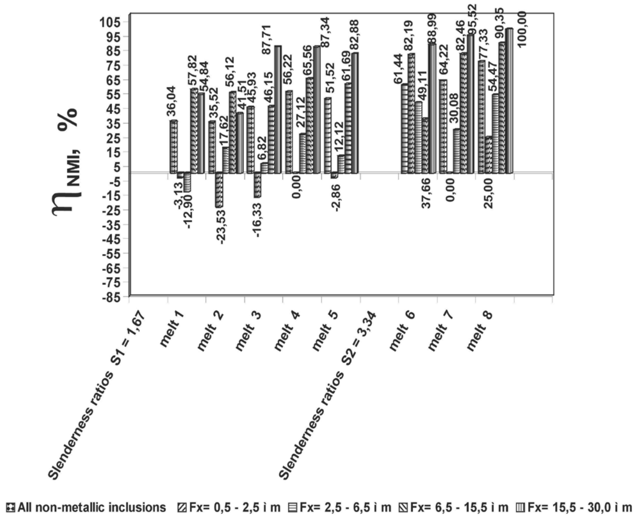

Fig. 4. The effectiveness of removing non-metallic inclusions as measured with the average rate of non-metallic inclusion superficial share η_{NMI} , with division into inclusion size intervals according to F_x Feret diameters

Also for S_F2 filter slenderness ratio (λ=8.36) in four melts (no. 6, 7, 8) a decrease in total surface share of non-metallic inclusions the largest in melt no. 8 (η_{WN} = 77.33%) and inclusions in all Feret's diameter intervals has been found. For S_F1 filter slenderness (λ=1.67) the largest number of eliminated non-metallic inclusions in F_x interval of 15.5-30.0 μm has been obtained in melt no. 3 (η_{WN} = 87.71%), no. 4 (η_{WN} = 87.34%) and no.5 (η_{WN} = 82.88 %). For S_F2 filter slenderness (λ=8.36) the largest number of eliminated non-metallic inclusions in F_x interval of 15.5- 30.0 μm has been obtained in melt no. 7 (η_{WN} = 95.52%) and no. 8 (η_{WN} = 100.00%).

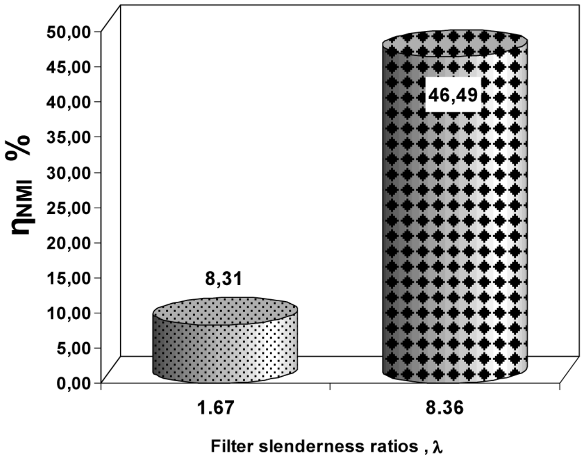

Fig. 5. The average rate of η_{NMI} non-metallic inclusion number variation for filter slenderness ratios of S_F1 (λ=1.67) and S_F2 (λ=8.36)

In the remaining experimental melts a decrease, in all melts, has been found in the surface share of non-metallic inclusions only in diameters above 6.5 μm. Finally the total surface share of non-metallic inclusions in steel after filtration has been decreased to the value of η_{WN} = 45.05% for S_F1 filter slenderness ((λ=1.67) and η_{WN} = 67.66% for S_F2 (λ=8.36) correspondingly (Fig. 6). The estimation of effectiveness of liquid steel filtration has been also carried out in relation to oxide- and sulphide-inclusions (Fig. 7). The degree of surface share variation of the oxide non-metallic inclusions, as well as the sulphide ones, shows that the process of steel filtration with use of multi-hole ceramic filters is justified and effective, as much as possible. The highest degree of decrease (η_{MeO} = 58.72%) in the surface share of oxide non-metallic inclusions for S_F1 slenderness ratio (λ=1.67) has been obtained during filtration of melt no. 4, while the lowest one (η_{MeO} = 32.40%) during filtration of the melt no. 1. For S_F2 slenderness ratio (λ=8.36) the highest degree of decrease (η_{MeO} = 76.46%) in the surface share of oxide non-metallic oxide inclusions has been obtained during filtration of the melt no. 8, while the lowest one (η_{MeO} = 66.20%) during filtration of melt no. 7. For the sulphide non-metallic inclusions the highest degree of decrease in the surface shar in relation to S_F1 slenderness filter (λ=1.67) has been noted in the melt no. 1 (η_{MeS} = 60.56%), while the lowest one (η_{MeS} = 43.23%) has been observed during filtration of melt no.2.

For S_F2 filter slenderness (λ=8.36) the highest degree of decrease in surface share of sulphide non-metallic inclusions (η_{MeS} = 95.24%) has been found in melt no. 8, while the lowest one (η_{MeS} = -93.10%) has been obtained during filtration of melt 6.

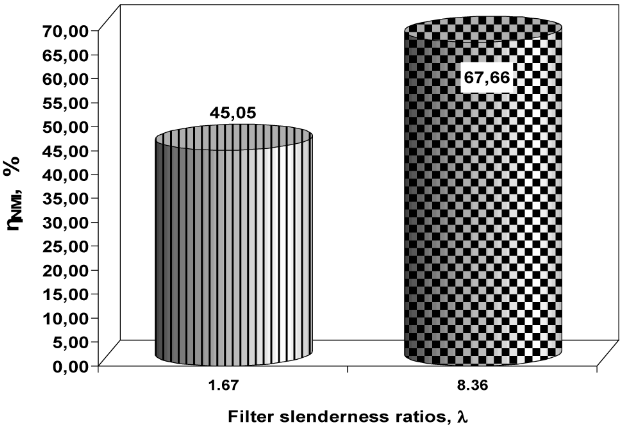

Fig. 6. The average rate of η_{NMI} non-metallic inclusion superficial share for filter slenderness ratios of S_F1 (λ=1.67) and S_F2 (λ=8.36)

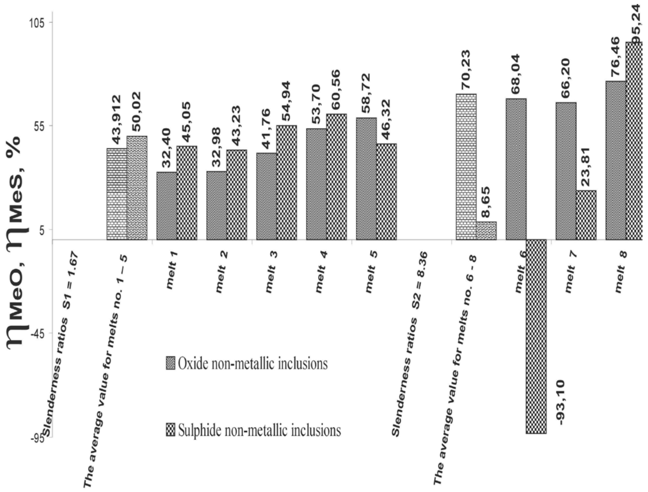

Fig. 7. The effectiveness of removing non-metallic inclusions, with the division into sulfide and oxide inclusions for ten experimental melts founded in the atmosphere of argon

The microscopic image analyses of the samples investigated shows the oxide non-metallic inclusions, as well as sulphide ones, that in most cases are of globular or similar shape, occur in clusters, which are mutually connected to the lower or higher degree. The results of investigations of the division lines between the steel and the filter ceramics, as well as of border-line areas after filtration tests of melts no. 4 and 8 (deoxidized with use of aluminium) are presented, as exemplary data, in form of scanning images in Figs. 8 and 9.

Solid products of the steel being deoxidized with aluminium, in form of Al_2O_3, have been identified on the surface of ceramic filter and in the border line area. Type of contact of the Al_2O_3 particle inclusion, as well as of particle cluster with the ceramic filter surface excludes chemical bonding and agglomeration of the contacting phases. The chemical composition of the identified products of process of steel deoxidizing with aluminium is proved by X-ray photos presented in Figs. 10 and 11.

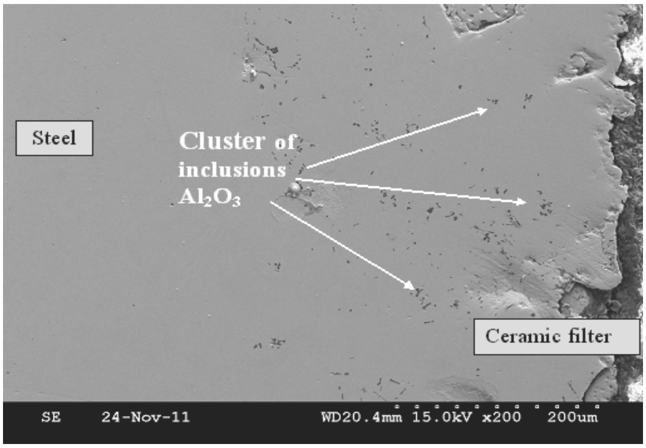

Fig. 8. Scanning pictures of interface partition filters ceramic-filtration steel of head no 4

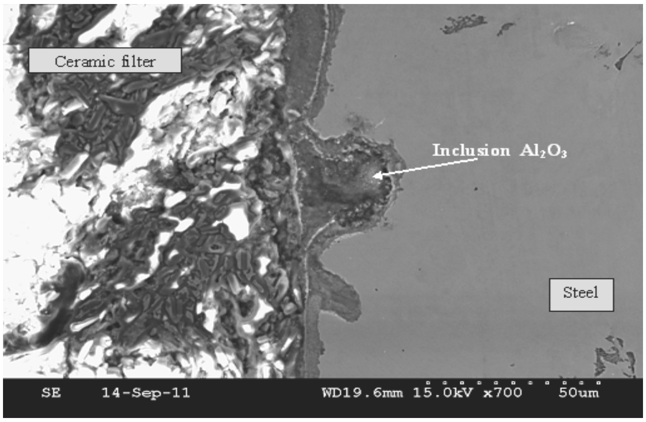

Fig. 9. Scanning pictures of interface partition filters ceramic-filtration steel of head no 8

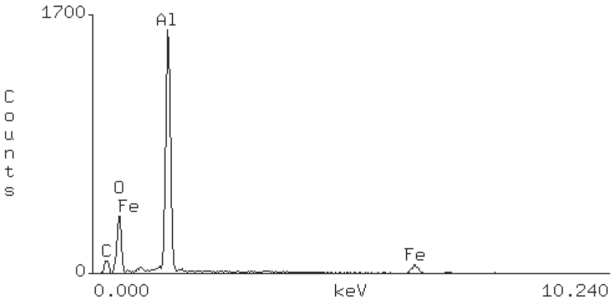

Fig. 10. X-ray photograph of non metallic inclusions chemical composition identified on the surface of a ceramic filter and in steel volume from melt 4

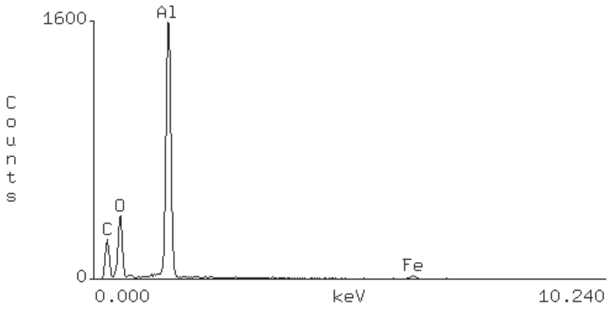

Fig. 11. X-ray photograph of non metallic inclusions chemical composition identified on the surface of a ceramic filter and in steel volume from melt 8

5. Conclusions

The researches carried out constitute the fourth phase of planned research cycle concerning the process of liquid steel filtration with use of multi-hole ceramic filters in protective atmosphere and with variable filter slenderness (filtrating surface), carried out in the Metallurgy Department of the Silesian University of Technology, and prove suggestions of authors of papers [3-11] about negative influence of the oxidizing air atmosphere at the effectiveness of steel filtration through ceramic filters. The results of researches carried, measured in form of η_{WN} index, prove that the use of protective atmosphere during the process of liquid steel filtration decidedly increase the process effectiveness.

Its use during experiments carried out in laboratory condition has the aim to imitate as much as possible the condition of industrial refining in processing line of CC machine. The research results obtained evidence the substantial influence of the multi-hole ceramic filter slenderness at the results obtained. The steel cleaning effectiveness, as measured with average degree of the surface share variation, in relation to the whole range of inclusions, has decidedly increased and amounted respectively: η_{WN} = 45.05% for S_F1 filter slenderness (λ=1.67) and η_{WN} = 67.66% for S_F2 filter slenderness (λ=8.36). The total variation degree of inclusion number has also increased and amounted respectively η_{WN} = 8.31% for S_F1 filter slenderness (λ=1.67) and η_{WN} = 46.49% for S_F2 filter slenderness (λ=8.36). In case of filtration of steel out of the non-metallic inclusions of larger size the results prove the earlier suggestions of authors of papers [3,5,6] about the highest effectiveness of this method of liquid steel refining in relation to the non-metallic inclusions of dimension above 6.5 µm.

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