INFLUENCE OF STEEL TREATMENT COURSE AT UNITS OF SECONDARY METALLURGY ON THE MICROCLEANNESS OF AL-KILLED STEELS

SOCHA Ladislav[1], HUCZALA Tomáš[2], MICHALEK Karel[1], KALETA Jaromír[2], ZWYRTEK Jaroslav[1]

[1]*VSB - Technical University of Ostrava, Faculty of Metallurgy and Materials Engineering, Department of Metallurgy and Foundry, Czech Republic, EU*
ladislav.socha@vsb.cz, karel.michalek@vsb.cz, jaroslav.zwyrtek@vsb.cz
[2]*TŘINECKÉ ŽELEZÁRNY, a.s., Třinec, Czech Republic, EU*
Tomas.Huczala@trz.cz, Jaromir.Kaleta@trz.cz

Abstract

The paper presents the results of operating experiments focused on the study of the formation and modification of non-metallic inclusions during treatment of aluminium-killed steels at units of secondary metallurgy. The process melts were focused on analysis of the influence of deoxidizing and slag-making agents and wear of the lining on the steel microcleanness. The experiments were aimed at studying the patterns of formation, origin and conditions of elimination of non-metallic inclusions during treatment of steels on the homogenization station and ladle furnace. The actual evaluation of microcleanness was executed by means of SEM microscope. The results present the number, ratio and analysis of chemical composition of non-metallic inclusions including their plotting in ternary diagrams. The evaluation indicated in the paper represents basic information on the achieved microcleanness, and thus also the produced steel quality.

Keywords: Steel, slag, secondary metallurgy, microcleanness, non-metallic inclusions

1. INTRODUCTION

In the present-day steel industry, there are ever-increasing demands for steel quality to achieve maximum production efficiency at the lowest possible costs. Fulfilment of the mentioned demands is primarily predetermined by provision of high-level metallurgical technology to obtain steel of high cleanness. Modern and progressive technologies enabling fulfilment of these demands can include secondary metallurgy, which provides for refining processing of a wide variety of types, which include [1, 2, 3]: controlled deoxidation and alloying of steel, homogenization of molten steel, desulphurization of steel, elimination of undesirable gases (hydrogen or nitrogen), modification of inclusions, improvement in microcleanness and temperature adaptation of liquid steel [4] to the needs of the equipment for continuous casting of steel [5, 6].

One of the basic functions of secondary metallurgy is steel refining aimed at the elimination or modification of non-metallic inclusions. Formation of non-metallic inclusions during steel production is unavoidable. The influence of non-metallic inclusions on the steel cleanness and quality can be characterized by many parameters, which, for instance, include their total number, morphology, composition, shape, size, manner of arrangement, etc. It is suitable to realize that it is the increased content of non-metallic inclusions that is the cause of possible problems occurring during treatment of steel, such as casting, forming or heat treatment, whereas the non-metallic inclusions have also a negative impact on the properties of final products. The non-metallic inclusions cannot be eliminated from steel totally; their negative influence, however, can be limited by minimization of their formation and improved conditions of their elimination or modification [7, 8, 9].

The paper indicates the results of operating experiments aimed at the study of formation and modification of non-metallic inclusions during treatment of aluminium-killed steels at units of secondary metallurgy. The process melts were focused on the analysis of the influence of deoxidizing and slag-making agents and lining wear on the steel microcleanness achieved. The experiments were aimed at studying the patterns of formation, origin and conditions of elimination of non-metallic inclusions or at least restriction of their harmful effects, which is of cardinal importance in order to achieve high cleanness and thus also quality of the steel produced.

2. EXPERIMENT CHARACTERISTICS

The operating experiments aimed at the study of formation of non-metallic inclusions were executed during steel treatment at units of secondary metallurgy within the following production scheme: homogenization station HS → ladle furnace LF. The actual operating experiments were executed during production of plain structural steel, the chemical composition of which is indicated in **Table 1**.

Table 1 Basic chemical composition of plain structural steel

Range	Chemical composition (wt. %)								
	C	Mn	Si	P	S	Cr	Mo	Ni	Al
Min.	0.4	0.50	×××	×××	×××	×××	×××	×××	0.02
Max	0.5	0.80	0.40	0.030	0.035	0.40	0.10	0.40	0.05

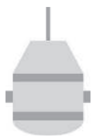
In the course of the experiments, steel was processed in the LD oxygen converter, with subsequent tapping in the foundry ladle. After the tap had been started, lime (*CaO*) and synthetic slag were added first; next, aluminium (Al_{granul}) was added in order to deoxidize the steel. During the tap, alloying additives were added, such as FeSi, FeSiMn, FeCr and a carburizing agent (*coke*). The tapping was concluded by the addition of the main portion of slag-making additives forming lime (*CaO*). After tapping, the ladle with steel and slag formed was transferred to the homogenization station HS, where the steel was homogenized; namely through the upper nozzle and ground tuyer by means of argon. Within treatment on the homogenization station HS, aluminium (Al_{granul}) or a carburizing agent (*coke*) was used to reduce the content of easily reducible oxides which represent the furnace slag which overflowed from the oxygen converter LD.

The ladle was then transferred to the ladle furnace LF, where the slag was adapted by the addition of lime (*CaO*) and synthetic slag. During treatment in the ladle furnace LF, alloying additives were added, such as FeSi, FeSiMn, FeCr, aluminium (Al_{wire}, Al_{granul}) and the carburizing agent (*coke*). This addition of additives resulted in adapted chemical composition of the steel and slag, after which standard treatment was executed at the ladle furnace LF, consisting of heating-up, desulphurization, homogenization and refining of the steel. After the treatment on the ladle furnace was finished, casting was executed on the continuous casting machine.

In total, 6 relevant process melts were evaluated. During the operating experiments, steel samples were taken for evaluation from the selected units of secondary metallurgy. **Table 2** contains the sampling scheme. In the case of steel sampling, microcleanness was evaluated.

The obtained steel samples were analysed by means of an electronic microscope working in the mode of a scanning electron microscope (SEM) or energy dispersive spectrometry (EDS). Distribution of non-metallic inclusions was evaluated by means of the image analysis within the software in the SEM mode. The system scans the sample and localizes particles representing potential non-metallic inclusions. Subsequently, it measures their size and analyses their composition by means of the EDS mode. As soon as the sample analysis has been completed, particles other than non-metallic inclusions (such as scratches, abrasive paper particles, etc.) are filtered off. Subsequently, basic analysis of oxides and sulphides is executed. Thanks to this analysis, the location, size and chemical composition of the non-metallic inclusions are determined.

Table 2 Sampling scheme of the course of steel treatment at units of secondary metallurgy

<table>
<tr><th colspan="8">Scheme of the course of plant experiment</th></tr>
<tr><td colspan="2">
Basic Oxygen Converter
BOF</td><td colspan="2">
Homogenization Station
HS</td><td colspan="2">
Ladle Furnace
LF</td><td colspan="2">
Continuous Casting
Machine CCM</td></tr>
<tr><th colspan="8">Sampling of steel</th></tr>
<tr><td>×××</td><td>×××</td><td>HS start</td><td>HS end</td><td>×××</td><td>LF end</td><td>×××</td><td>×××</td></tr>
</table>

3. RESULTS AND DISCUSSION

The evaluation of microcleanness during treatment of steel on secondary metallurgy units was executed in several parts. Firstly, the density (number) of non-metallic inclusions per cm^2 was evaluated. Next, distribution of non-metallic inclusions was evaluated by their size. This evaluation was supplemented with plotting of the chemical composition of the non-metallic inclusions in ternary diagrams CaO-Al_2O_3-MgO.

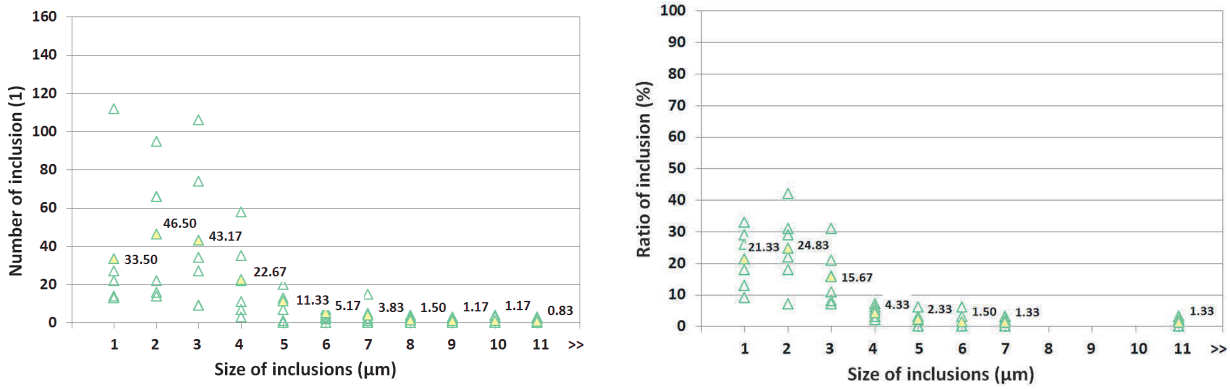
The resulting pattern of change in the density (number) of non-metallic inclusions is indicated in **Figure 1**. The results reveal that during treatment of steel on the homogenization station (*samples* $HS_{start} \rightarrow HS_{end}$), the steel contamination by non-metallic inclusions increased 1.8 times. This contamination is also characterized by the variance of results achieved within the individual melts. This phenomenon can be explained by gradual solution of the individual additives added during tapping of the steel as well as intensive homogenization of the bath on the homogenization station by means of the inert gas.

Figure 1 Change in the density (number) of non-metallic inclusions

This trend can be explained by improved conditions of floating and absorption of non-metallic inclusions by application of the following technologies: steel clarification by inert gas, adaptation of the slag chemical composition, and reduction in the slag viscosity by means of electric arc heating.

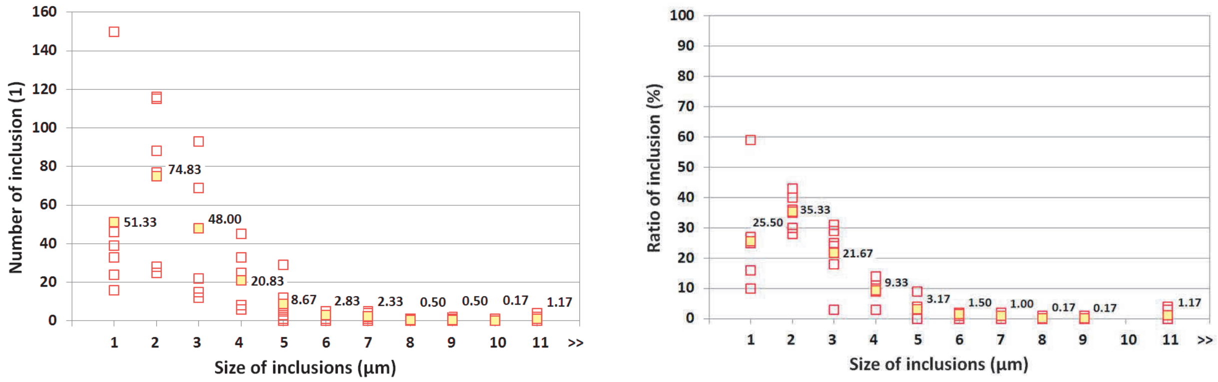
Subsequently, the contamination results were analysed by the number and ratio of non-metallic inclusions in the steel, as apparent from **Figure 2** to **Figure 4**. The average results reveal that at the beginning of steel treatment on the homogenization station (*sample* HS_{start}), the highest ratio is represented by non-metallic inclusions sized 1 to

3 µm, the ratio of which in the steel falls within the range of 15 to 24 %. The other non-metallic inclusions, sized 4 to 10 µm, occur in the steel; their ratio, however, is lower than 5 %.



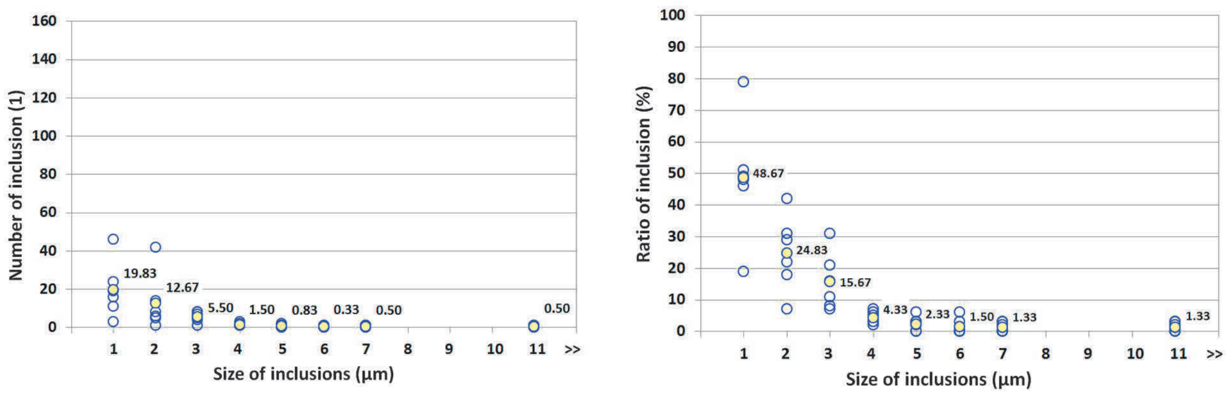
a) distribution of non-metallic inclusions by number *b) distribution of non-metallic inclusions by ratio*

Figure 2 Distribution of non-metallic inclusions at the beginning of treatment on the homogenization station *(sample HS_{start})*



a) distribution of non-metallic inclusions by number *b) distribution of non-metallic inclusions by ratio*

Figure 3 Distribution of non-metallic inclusions at the end of treatment on the homogenization station *(sample HS_{end})*



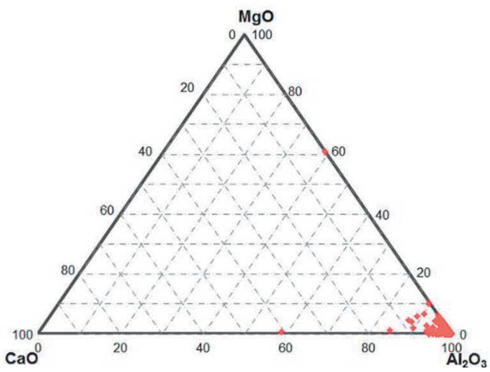
a) distribution of non-metallic inclusions by number *b) distribution of non-metallic inclusions by ratio*

Figure 4 Distribution of non-metallic inclusions at the end of treatment on the ladle furnace *(sample LF_{end})*

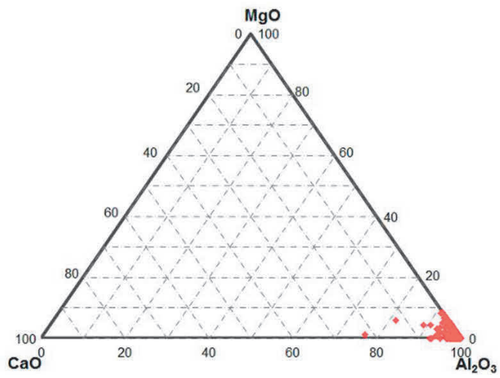
Further, the results reveal that at the end of steel treatment on the homogenization station (*sample* HS_{end}), there is increased steel contamination. This was evident from an increased number of non-metallic inclusions in the size category of 1 to 3 µm, the ratio of which increased in the steel to the range of 21 to 35 %. Non-metallic inclusions sized 4 to 10 µm also occur in the steel. Their ratio in the steel rose slightly, being still below 10 %, however.

The last step involves steel treatment on the ladle furnace (*sample* LF_{end}). In this case, it can be stated that conditions have been created for substantial reduction in the content of non-metallic inclusions. As apparent from **Figure 4**, this resulted in substantial reduction in the number of non-metallic inclusions in all of the size groups. The highest number of non-metallic inclusions is represented by the size category of 1 to 2 µm, the ratio of which increased in the steel to the range of 24 to 48 %. As for the other size categories of 4 to 10 µm, their number was reduced, whereas their ratio is lower than 5 %.

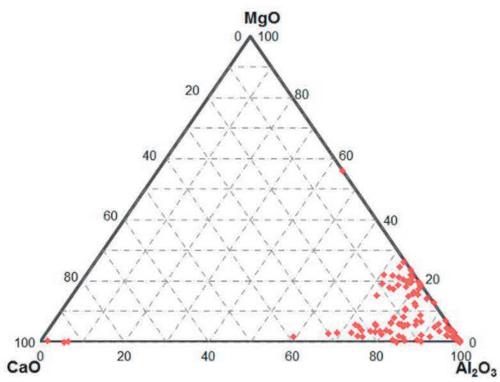
Evaluation of the distribution of non-metallic inclusions by size was supplemented with the results of the chemical composition of the non-metallic inclusions. These results, represented by ternary diagrams CaO-Al_2O_3-MgO, are indicated in **Figure 5**. The results reveal that at the beginning and end of steel treatment on the homogenization station (*samples* $HS_{start} \rightarrow HS_{end}$), the chemical composition of non-metallic inclusions fall within the range of 90 to 100 % of Al_2O_3, 0 to 10 % of MgO and 0 to 10 % of CaO. It can be stated that these are non-metallic inclusions formed within the steel deoxidation by aluminium (Al_{granul}). The results further reveal that the steel is partly contaminated by erosion, specifically, of the lining on the MgO basis. In addition, the non-metallic inclusions react with lime (*CaO*) from the slag.



a) melt at the beginning of treatment on HS start



b) melt at the end of treatment on HS end



c) melt at the end of treatment on LF_{end}

Figure 5 Ternary diagrams of CaO-Al_2O_3-MgO with non-metallic inclusions for various stages of steel treatment

Treatment of steel on the ladle furnace (*sample LF_{end}*) results in the change in the chemical composition of the non-metallic inclusions. The results reveal that the chemical composition of non-metallic inclusions fall mainly within the range of 70 to 100 % of Al_2O_3, 0 to 30 % of MgO and 0 to 30 % of CaO. This phenomenon can be explained on the basis of the mechanism described by the authors [10], illustrated in **Figure 6**.

Therefore, it is possible to state that during the steel treatment on the homogenization station, the steel contamination is represented by aluminate inclusions (Al_2O_3) forming networks or clusters. Thanks to the steel reactions with the lining and ladle slag, the following treatment on the ladle furnace results in the change in the chemical composition of non-metallic inclusions. These inclusions are represented by pure aluminates (Al_2O_3), spinels ($MgO \cdot Al_2O_3$) or aluminates modified by the calcium from slag ($CaO \cdot 6Al_2O_3$).

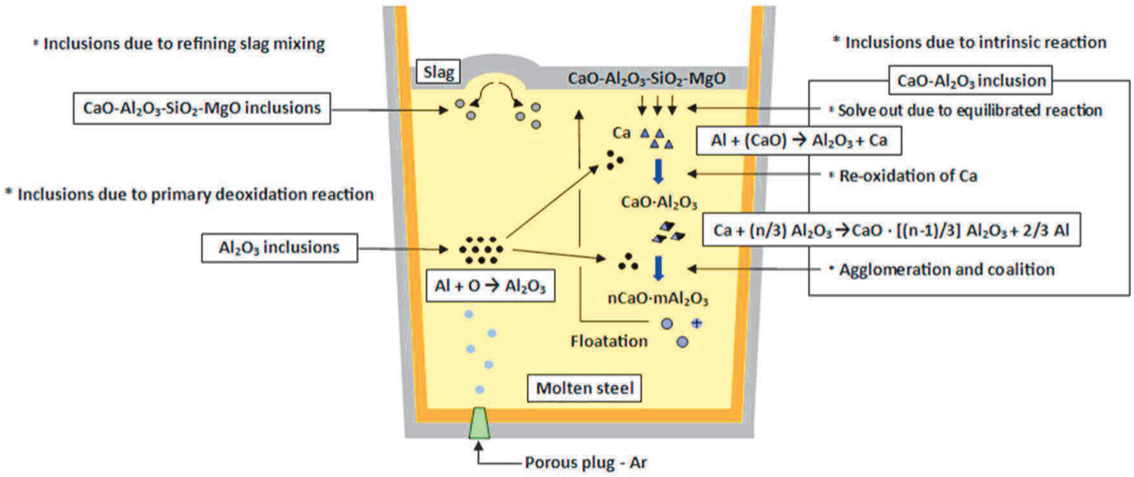


Figure 6 New generation mechanism of inclusions during LF refining [10]

4. CONCLUSIONS

In operating conditions, experiments were executed to obtain information on the formation, origin and conditions of elimination of non-metallic inclusions during treatment of steel within secondary metallurgy. From the achieved results of the operating experiments, the following findings can be defined:

- *steel treatment on the homogenization station results in a 1.8fold increase in the steel contamination with non-metallic inclusions. This contamination can be explained by the gradual solution of the additives added during the steel tapping and intensive homogenization of the bath on the homogenization station;*
- *the steel contains the largest number of non-metallic inclusions before steel treatment on the ladle furnace;*
- *the following steel treatment on the ladle furnace results in a 4.7fold decrease in the steel contamination with non-metallic inclusions. This trend can be explained by improved conditions of floating and absorption of non-metallic inclusions;*
- *the largest ratio of non-metallic inclusions at the beginning of steel treatment on the homogenization station is made of non-metallic inclusions sized 1 to 3 μm, the ratio of which in the steel is within the range of 15 to 24 %;*
- *at the end of steel treatment on the homogenization station, there is an increase in the steel contamination with non-metallic inclusions sized 1 to 3 μm, the ratio of which in the steel has risen to the range of 21 to 35 %;*
- *steel treatment on the ladle furnace created conditions for a substantial reduction in the content of non-metallic inclusions. The highest number of non-metallic inclusions is represented by the size category of 1 to 2 μm, the ratio of which in the steel has risen to the range of 24 to 48 %;*

- *chemical composition of the non-metallic inclusions reveals that after steel treatment on the homogenization station the non-metallic inclusions are represented by aluminates (Al_2O_3) forming networks or clusters;*
- *subsequent treatment on the ladle furnace involves reactions of the steel with lining and the ladle slag. These inclusions are represented by pure aluminates (Al_2O_3), spinels ($MgO{\cdot}Al_2O_3$) or aluminates modified by the calcium from slag ($CaO{\cdot}6Al_2O_3$).*

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