INFLUENCE OF OUTSIDE FURNACE TREATMENT ON PURITY MEDIUM CARBON STEEL

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Abstract

The physical and chemical reactions that occur in the process of steel melting and solidification produce non-metallic compounds and phases, referred to as inclusions. The quantity of non-metallic inclusions is correlated with the content of tramp elements in the alloy, while their phase composition and structure, in particular shape, dimensions and dispersion, are determined by the course of metallurgical processes.

Aim of this study was to determine the effect of the outside furnace treatment on purity high-grade medium carbon steel melted in a converter and deoxidized by vacuum as well as steel melted in an electric furnace and subjected to desulfurization as well as desulfurization and refining with argon.

Data were processed using mathematical statistics. It was assumed that the structure of inclusions within dimensional intervals will be characterized by the dimension structure coefficient (stereometry parameter) which indicates the share of the relative volume of inclusions within a given size range.

The results of the analysis indicated the highest dimension structure coefficients in heats from an electric furnace with desulfurization, while the distribution and the share (quantity) of inclusions in heats from an electric furnace with argon refining and a converter were found to be similar.

Keywords: metallurgy, high-grade steel, steel, non-metallic inclusions, stereometry

1. INTRODUCTION

The parameters of high-grade steel are influenced by a combination of factors, including chemical composition and production technology. The impurity content is also a key determinant of the quality of high-grade steel. Inclusions may also play an important role, subject to their type and shape.

Yet as regards steel, non-metallic inclusions have mostly a negative effect which is dependent on their content, size, shape and distribution [1, 2].

The effect of impurities is closely related to the processes taking place in micro-areas, which is why the size of inclusion particles significantly influences the properties of constructional materials [3, 4].

Distribution of non-metallic inclusions in steel and their quality is determined by various factors, including charge quality, process regime, furnace type and out-of-furnace processing. Alloy additives introduced during out-of-furnace processing have a more supportive reaction environment than inside the furnace, and the above improves charge yield [5-8].

2. AIM OF THE STUDY AND METHODS

Aim of this study was to determine the effect of the outside furnace treatment on purity high-grade medium carbon steel.

The experiment was carried out in a comparable research conditions with constant wire rod dimensions in all three experimental series and similar quantities of melted steel. The test involved semi-finished products of high-grade, medium-carbon structural steel 23GHNMA (PN-92/H-93028) with boron. It was produced in industrial conditions.The impurity content of steel was low as phosphorus and sulphur levels did not exceed 0.025 %.

In the first process, steel was melted in a 140-ton basic arc furnace (E). The metal was tapped into a ladle, it was desulfurized and 7-ton ingots were uphill teemed. Ingots heated to temperatures 1200 °C in furnaces pits. Billets with a square section of 100x100 mm were rolled with the use of conventional methods in continuous rolling mill. As part of the second procedure, steel was also melted in a 140-ton basic arc furnace. After tapping into a ladle and desulphurization, steel was additionally refined with argon (EA). Gas was introduced through a porous brick, and the procedure was completed in 8-10 minutes. Steel was poured into moulds, and billets were rolled similarly as in the first method. In the third process, steel was melted in a 100-ton oxygen converter and deoxidized by vacuum (K). Steel was cast continuously and square 100x100 mm billets were rolled. Desulfurization was carried out in a mixer. In order to evaluation effect of outside furnace treatment on purity high-grade medium carbon steel evaluated the relative volume of inclusions and their dimensional structure. Billet samples were collected to determine:

- chemical composition. The content of alloy constituents was estimated with the use of LECO analyzers, an AFL FICA quantometer and conventional analytical methods;
- relative volume of non-metallic inclusions with the use of the extraction method;
- dimensions of impurities by inspecting metallographic specimens with the use of a Quantimet video inspection microscope.

Metallographic specimens were examined under 400x magnification. Sample fragments corresponding to the area of 500 vision fields were analyzed. The relative volume of impurities was determined selectively by modifying the lower limit of the range determining the dimensions of the investigated inclusions to form seven fractions.

The values of the investigated parameters were determined for each sample. The dimensions of non-metallic inclusions were equal to or higher than the adopted boundary values (minimum dimensions of the measured particle). The measuring range was identical for all heats, and it was set based on theoretical assumptions and the results of preliminary tests. The applied measuring ranges were 2, 5, 10, 15, 25, 35 and 45 μm, respectively. The above approach enabled to determine the share of non-metallic particles at a level higher than and equal to the boundary value, e.g. the share of particles measuring $d \geq 5$ μm was determined for a boundary value of 5 μm.

Analytical calculations were performed on the assumption that the particles had a spherical shape. It was also assumed that the quotient of the number of particles on the surface divided by the area of that surface was equal to the quotient of the number of particles in volume divided by that volume.

The resolution of the applied microscope did not permit to include impurities smaller than 2 μm in the analysis. The number of particles for the microscopically undetectable range was determined by chemical extraction where the content of all non-metallic particles was identified in the investigated steel. The particle content was the difference between the number of all inclusions and the number of inclusions measured at the lowest boundary value of 2 μm.

In view of the segregation of technical iron alloys and the methods of determining the relative volume of impurities, the properties representing the structure of inclusions should be regarded as random variables. For this reason, data were processed using mathematical statistics. It was assumed that the structure of inclusions within dimensional intervals will be characterized by the dimension structure coefficient (1) which indicates the share of the relative volume of inclusions within a given size range. Dimensional non-metallic inclusions structure coefficient is a stereometry parameter.

$$\upsilon = V_i / V_v \quad (1)$$

where:

V_i - relative volume of inclusions defined by metallography method, %,

V_v - relative volume of inclusions defined by chemical method, %.

The relative volume was replaced with dimension structure coefficients to produce sets of values independent of the impurities content of each heat.

3. RESULTS AND DISCUSSION

The chemical composition and the relative volume of inclusions in the analyzed steel are presented in **Table 1**.

Table 1 Chemical composition and relative volume of steel inclusions

Process	Contents, %											
	C	Mn	Si	P	S	Cr	Ni	Cu	Mo	B	O	V_v
E	0.26	0.94	0.14	0.021	0.018	0.54	0.44	0.22	0.26	0.002	0.0052	0.192
EA	0.23	1.12	0.22	0.023	0.019	0.53	0.46	0.15	0.23	0.002	0.0054	0.197
K	0.24	1.13	0.27	0.018	0.018	0.56	0.5	0.02	0.26	0.003	0.0025	0.091

where: V_v - relative volume of inclusions, %.

Contents of chemical components in the present melts do not show significant differences.

Refining argon had no influence on the relative volume of inclusions (O i V_v - **Table 1**) found in the melted steel in an electric furnace. Degassing in a vacuum has introduced a significant increase in the purity of steel (O i V_v there are about 50 % lower than in the steels melted in an electric furnace-**Table 1**).

The share of non-metallic inclusions in each size range is presented in **Fig. 1**. Steel melted in an electric furnace (E - **Table 1**) had 0.192 % non-metallic inclusions. Inclusions with a diameter of 2-5 μm had the highest share of the analyzed fractions ($14*10^{-3}$ %). Inclusions with a diameter under 2 μm had the highest share of steel melted in an electric furnace (E).

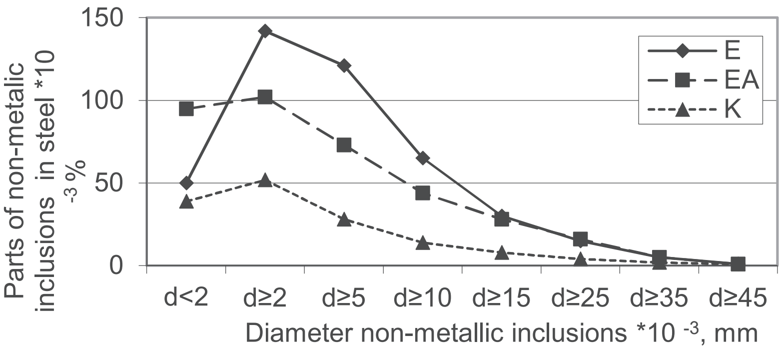

Fig. 1 Relative volume of non-metallic inclusions in dimensional intervals

Dimension structure coefficients in the dimensional intervals of the analyzed inclusions are presented in **Fig. 2**. The highest structure coefficient was noted in respect of steel melted in an electric furnace (E) at d≥2 μm. Similar dimension structure coeficient were reported for steel heats from an electric furnace with argon refining and steel heats from a converter. A smaller number of inclusions were observed in converter heats (**Fig. 2**). Dimension structure coefficients in stemplots are presented in **Fig. 3**.

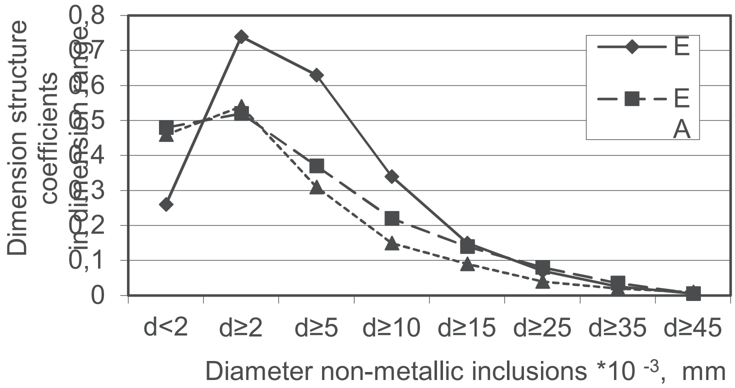

Fig. 2 Dimension non-metallic inclusions structure coefficients in the dimensional range of the analyzed inclusions

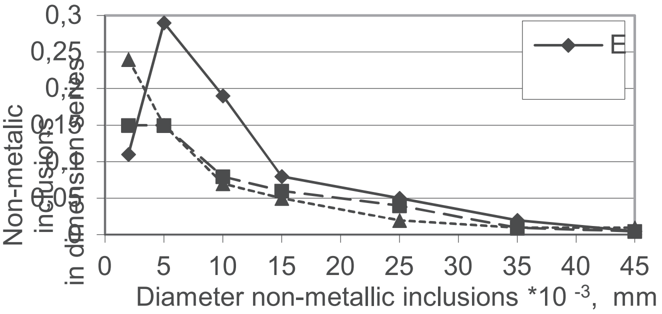

Fig. 3 Dimension non-metallic inclusions structure coefficients in stemplots.

The similarities between parameters in each population were evaluated by a correlation analysis. Variate transformation was applied and regression equations were derived by the least squares method. Correlation coefficients were calculated and their significance was evaluated by the Student's t-test. The results are shown in **Tables 2 and 3**, and they are presented graphically in **Figs. 4 and 5**.

Table 2 Distribution of properties in stemplots

Process	Regression equation	R	t	$t_{\alpha=0.05}$
E	$\overline{\upsilon}_{Ei} = 2.36 \cdot \frac{1}{\overline{d}} - 0.03$	0.889	3.882	2.776
EA	$\overline{\upsilon}_{EAi} = 0,96 \cdot \frac{1}{\overline{d}} + 0.01$	0.821	2.876	2.776
K	$\overline{\upsilon}_{KPi} = 0,83 \cdot \frac{1}{\overline{d}} - 0.001$	0.845	3.533	2.571
$\overline{\upsilon}$ - dimension inclusions structure coefficient, $\overline{d}$ - mean value in class interval				

Table 3 Distribution of impurities in dimensional non-metallic inclusions structure

Process	Regression equation	r	t	$t_{\alpha=0.05}$
E	$\upsilon_{Ei} = 0,865 - 0,225 \ln d$	-0.838	3.434	2.571
EA	$\upsilon_{EAi} = 0,567 - 0,149 \ln d$	-0.878	4.101	2.571
K	$\upsilon_{KPi} = 0,585 - 0,152 \ln d$	-0.835	3.393	2.571
$\overline{\upsilon}$ - dimension inclusions structure coefficient, d - lower threshold of inclusion size in μm				

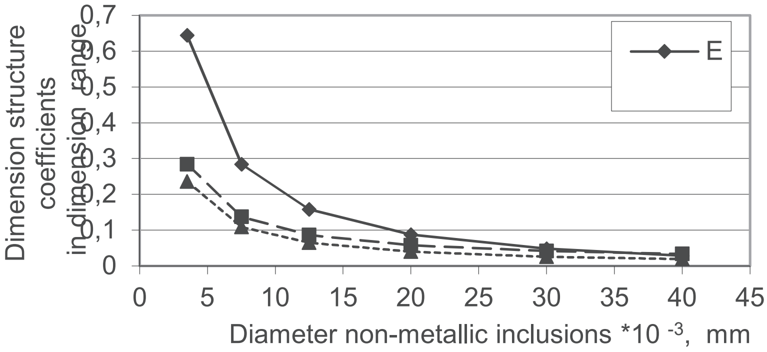

Fig. 4 Dimension non-metallic inclusions structure coefficients for each heat variant

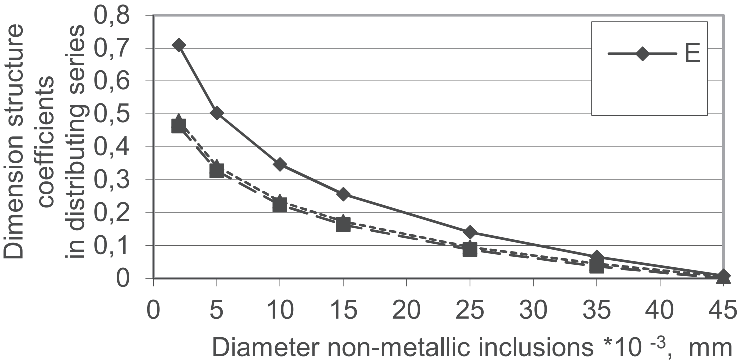

Fig. 5 Distribution of impurities in dimensional non-metallic inclusions structures

Fig. 4 shows the relative share of the volume of the inclusions in different dimensional spaces (the average particle size of the interval dimension). **Fig. 5** shows the relative share of the volume of the inclusions in distributing series (for all inclusions larger than the size of certain range).

A parallel regression test was performed to indicate that regression equations representing various heats belong to a single family therefore, the distribution of the analyzed properties was marked by similarities.

The above hypothesis was validated by comparing correlation coefficients. The results of this study indicate that the functions representing the dimensional structure of impurities are determined mainly by the relative volume of submicroscopic particles, while the distribution of inclusions larger than 10 μm is of secondary importance (**Table 4**).

Table 4 Evaluation of differences in the distribution of dimension non-metallic inclusions structure coefficients by the parallel regression test

Parameters	**t-test values**			$t_{\alpha=0.05}$
	Compared process			
	E-EA	E-K	EA-K	
Impurity parameters	0.136	0.361	0.230	2.228
Stemplots	1.921	1.800	0.930	2.228

Although the dimensional structure of heats was most affected by impurities smaller than 10 μm, inclusions with a larger diameter could also determine the properties of steel, in particular its fatigue strength. The results of the analysis indicated the highest dimension structure coefficients in heats from an electric furnace with desulfurization (E), while the distribution and the share (quantity) of inclusions in heats from an electric furnace with argon refining (EA) and a converter (K) were found to be similar. The above similarities were observed in respect of dimensional structure (**Fig. 4**) as well as stemplots (**Fig. 5**).

Comparing the relative volume of inclusions (Vv - **Table 1**) with dimension non-metallic inclusions structure coefficients for each heat variant (**Fig. 4**) and distribution of impurities in dimensional non-metallic inclusions structures (**Fig. 5**) can be assumed that the melting of steel in a converter of degassing in a vacuum (KP) increases the purity of steel, while the process of smelting in an electric furnace with argon gas refining (EA) causes fragmentation of the dimensional structure of the inclusions.

CONCLUSIONS

The results of the analysis lead to the following conclusions:

- The results of this study suggest that material purity and the dimensional structure of inclusions are determined by the steel melting process and outside furnace treatment.
- The development of characteristics supports a statistical presentation of dimensional non-metallic inclusions structures.
- The dimension structure coefficient indicates the share of inclusions in each size interval, and the obtained results are independent of the number of non-metallic inclusions.
- The character and the value of distribution functions for heats from a converter (K) and an electric furnace with argon refining (EA) are similar.
- Steel melted in an electric furnace with desulfurization contains more non-metallic inclusions in all size intervals.
- Distributions of non-metallic inclusions in the structure suggest that both argon refining and degassing in a vacuum cause the fragmentation of the inclusions and the increase in their dispersion. As a consequence, the volume fraction of submicroscopic precipitates in alloys refined outside furnace treatment is bigger.
- The results of this study suggest that material purity and the dimensional structure of inclusions are determined by the steel melting process.
- The number of inclusions produced by various melting methods differs at each size interval.
- Converter melting with vacuum degassing (KP) is the most effective method of eliminating inclusions larger than 2 µm. The above process is more effective in capturing oxide impurities than the remaining melting methods (E and EA) examined in this study.

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