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Size of Non-Metallic Inclusions in High-Grade Medium Carbon Steel

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Abstract

Non-metallic inclusions found in steel can affect its performance characteristics. Their impact depends not only on their quality, but also, among others, on their size and distribution in the steel volume. The literature mainly describes the results of tests on hard steels, particularly bearing steels. The amount of non-metallic inclusions found in steel with a medium carbon content melted under industrial conditions is rarely presented in the literature. The tested steel was melted in an electric arc furnace and then desulfurized and argon-refined. Seven typical industrial melts were analyzed, in which ca. 75% secondary raw materials were used. The amount of non-metallic inclusions was determined by optical and extraction methods. The test results are presented using stereometric indices. Inclusions are characterized by measuring ranges. The chemical composition of steel and contents of inclusions in every melts are presented. The results are shown in graphical form. The presented analysis of the tests results on the amount and size of non-metallic inclusions can be used to assess them operational strength and durability of steel melted and refined in the desulfurization and argon refining processes.

Keywords: Quality management, Environment protection, High-grade steel, Steel, Non-metallic inclusions, Quantitative metallography

1. Introduction

Under industrial conditions, alloys of ferrous metals are produced from pig iron and industrial and re-usable scrap. A charge obtained from re-usable scrap may contain particles integrated with the material during operational processes. Different types of impurities from steelmaking furnaces and equipment, e.g. the furnace lining, the lining of tapping spouts etc., may also get into the melted steel during the metallurgical process. Compounds creating non-metallic inclusions may also form during the metallurgical process. Their occurrence in steel is natural. Metallurgical processes seek to remove the highest possible amount of impurities from steel using mechanical, metallurgical and chemical methods. Although complete elimination of inclusions in a material melted under industrial conditions is impossible, it is possible to reduce their occurrence. These measures entail costs which rise disproportionately to the achieved degree of steel purity. Despite existing technological possibilities of obtaining alloys of very high purity, it is not the main aim to achieve the maximum possible effect. Economic conditions, combined with the required steel purity, determine the degree of its purity which must be achieved [1-14].

The quantity and quality of non-metallic inclusions is determined mostly by the steel melting technology. Out-of-furnace treatment regime are also introduced to minimize the quantity of non-metallic inclusions. The quantity of non-metallic inclusions in steel is relatively low, nevertheless, they have a significant impact on the structure, technological and strength parameters of the resulting alloy [15-18].

The distribution of inclusions is an equally important factor. Single inclusions and clusters of inclusions exert different effects.

Large, individual inclusions can produce discontinuities that grow rapidly under variable load. During processing, the shape and distribution of micro particles change, and impurities undergo anisotropic deformation. Non-metallic inclusions play a special role in the process of steel hardening. Due to differences in the physical properties of steel and inclusion-forming phases, structural stresses are formed along inclusion boundaries [19-23].

To ensure an appropriately high reliability of machine parts, research has been conducted on the effect of impurities on the performance characteristics of a construction material and its durability. The effect of, among others, the amount, quality and distribution of impurities in the material volume has been analyzed. Models have been created describing the processes occurring in materials as a result of impurities. Criteria have been developed to predict the durability and performance characteristics of alloys based on the quality, size and distribution of impurities. Researchers are particularly interested in high-carbon or high-alloy steels. This interest results from the high sensitivity of hard materials, with low plasticity, to disturbances in the microstructure. Researchers have taken a special liking to bearing steels [24-26]. A literature analysis shows that, for these steels, the phenomena occurring during their use with respect to their microstructure and non-metallic inclusions have been analyzed most deeply. Fatigue tests are a particularly sensitive method for testing a material's durability. A comparison of fatigue properties and the size of impurities suggests that submicroscopic inclusions in high-plasticity steel inhibits dislocation motion. Inclusions absorb energy which contributes to the formation of discontinuities and slows down decohesion. Their results set strict criteria as to the allowable steel impurity. In hard steels, reduced mechanical properties at changing loads are unambiguously attributed to non-metallic inclusions [8,27-37].

Steels with a medium carbon content operating at changing loads are also widely used in industry. Mining chains are an example of their use. Despite the important role played by these steels, the number of conducted studies analyzing impurities found in them is much lower for bearing steels. This probably results from a more detailed analysis of this problem. Nevertheless, the acting mechanism of a non-metallic inclusion located in a plastic matrix differs from the analogous mechanism for a rigid matrix. This observation is also an inducement to take up this subject of research.

The developed models for analyzing the effect of non-metallic inclusions on the set mechanical parameters of analogous steels can be used to simulate these features on condition that data is available on the morphology of these inclusions [6,7,14,33,37,38]. This justifies the need to conduct research on this subject.

2. Aim of the study

The literature gives very little information on the amount and size range of non-metallic inclusions found in high-quality steel with a medium carbon content. Because of this, it was decided to conduct tests on medium-carbonsteel melted in an electric furnace and subjected to post-furnace purification processes.

The aim of this study was to determine the outside furnace treatment as an analyze dimensional structure of non-metallic inclusions in high-grade medium carbon steel melted in an electric furnace and subjected to desulfurization and argon refining.

3. Materials and experimental procedures

The tests were conducted on alloy steel with a medium carbon content. It was melted in an electric arc furnace with a capacity of 140 tons. Pig iron was ca. 25% of the charge and the rest came from scrap. Desulfurization with a Desulfex mixture was conducted during steel tapping into the ladle. The steel was then argon-refined. The process time was set at 10 minutes. After the refining process, the steel was poured into even-ton ingot molds. After solidification, the steel was heated to a temperature of 1200^{o}C. Billets with a 100x100 mm square cross-section were then rolled.

In view of the applied metallurgical processes, the quality, quantity and distribution of non-metallic inclusions were regarded as random variables. They were evaluated by quantitative metallography. Billet samples were collected and analyzed to determine their chemical composition, the relative volume of non-metallic inclusions and the dimensions of impurities.

The chemical composition of heats was investigated with the use of the Leco analyzer, the ARL FICA quantometer and conventional analytical methods. The relative volume of non-metallic inclusions was determined by the extraction method, and the dimensions of impurities were described in an image analyzing station with the use of a video inspection microscope under 400x magnification. The percentage of inclusions equal to and larger than 2, 5, 10, 15, 25, 35 and 45 mm was determined. The above size ranges were adopted based on theoretical assumptions and an analysis of the relevant literature. The resolution of the applied microscope did not support the evaluation of impurities smaller than 2 μm. The above approach supported the determination of the percentage of non-metallic inclusions within specific measuring ranges. The percentage of inclusions in every size interval was calculated by subtracting the measuring range for a larger inclusion from the measuring range for a smaller inclusion. The share of non-metallic inclusions in the $0<w<2$ [μm] interval was determined by subtracting the percentage of impurities equal to and larger than 2 μm from the percentage of non-metallic inclusions determined by chemical extraction. The calculations were performed on the assumption that the quotient of the number of surface particles divided by the area of that surface was equal to the quotient of the number of particles in volume divided by that volume [17,20].

The dimensions of non-metallic inclusions were described by stereometric parameters. The analysis focused on oxygen due to the predominance of oxygen inclusions. The diffusion of non-metallic inclusions in steel volume was described by diffusion coefficient β (1) that illustrates the correlations between the volume of oxide inclusions and oxygen content.

$$B=O/V_i \quad (1)$$

where:
O – oxygen content of steel [vol. %],
V_i – relative volume of non-metallic inclusions evaluated in a metallographic analysis in the i^{th} size interval or measuring range [vol. %].

The calculated number of inclusions in each size interval per surface area is presented by the coefficient of non-metallic inclusions (2).

$$n_i= 4V_i /\pi d_{is}^2 \quad (2)$$

where:
d_{is} – average size of inclusion from the i^{th} size interval [µm].

Steel coming from seven industrial melts was selected for the tests. The chemical composition of individual melts is compiled in Table 1.

Assuming a random occurrence of non-metallic inclusions in the steel microstructure, it was decided to treat them as random variables and use statistical and stereometric methods to analyze their size and distribution.

Samples were taken from the billets to evaluate the chemical composition of non-metallic inclusions and analyze them stereometrically.

4. Results and discussion

The chemical composition of heats is presented in Table 1.Sample particleSiO_2·MnO-FeOdeformed by plastic working produced by the SEM analysis are presented in Fig. 1.

The content of sulfur and oxygen in steel from the examined heats is presented in Fig. 2. The impurity content of steel was low phosphorus levels did not exceed 0.025%and sulphur levels did not exceed 0.02%. The highest sulfur content of 0.16% was reported in melt number 7. Excluding heats 2, 6 and 7 sulfur content was estimated at 0.01%. The highest oxygen content of 0.0074% was noted in heat 6. At heats 2, 3 and 7, oxygen content did not exceed 0.004%

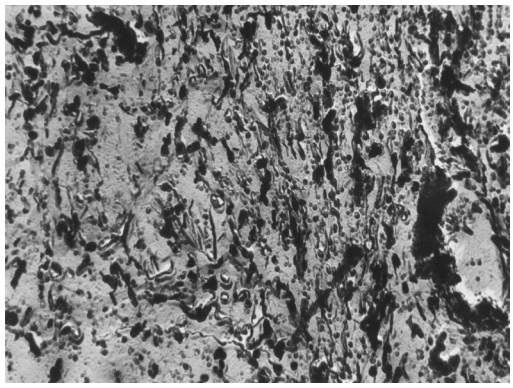

Fig. 1.The steel structure with SiO_2·MnO-FeOdeformed by plastic working, mag. 10 000 x

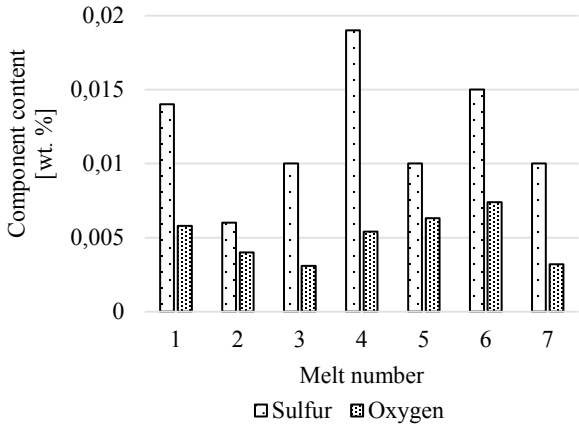

Fig.2. Content of sulfur and oxygen on melt numbers of steel

Table 1.
Chemical composition of high-grade medium carbon steel

Melt number	Chemical composition [wt. %]									
	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	B
1	0.20	1.17	0.27	0.025	0.010	0.43	0.46	0.20	0.15	0.002
2	0.22	1.12	0.27	0.019	0.014	0.49	0.44	0.24	0.13	0.004
3	0.22	1.40	0.22	0.020	0.006	0.40	0.50	0.22	0.15	0.004
4	0.23	1.29	0.30	0.023	0.010	0.53	0.40	0.23	0.15	0.002
5	0.24	1.05	0.32	0.024	0.010	0.42	0.51	0.22	0.13	0.003
6	0.24	1.30	0.34	0.024	0.015	0.55	0.46	0.25	0.17	0.002
7	0.25	1.14	0.22	0.014	0.016	0.50	0.42	0.23	0.15	0.002

The total relative volume of non-metallic inclusions in steel volume is presented in Fig. 3. Excluding heat 5 (0.214%) and 6 (0.236%), the total relative volume of inclusions did not exceed 0.2%.

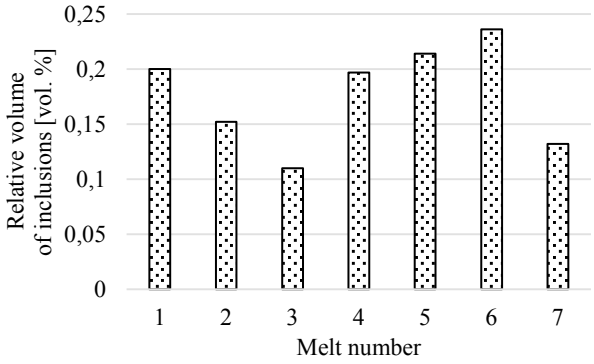

Fig. 3. Relative volume of inclusions per steel melt numbers

The values of the quantity coefficient of non-metallic inclusions in every size interval for every heat are presented in Fig. 4.

The highest number of inclusions was reported in the fraction smaller than 2 µm, and was more than 20-, 50- and 70-fold higher in successive intervals than first fraction (smaller than 2 µm). Larger inclusions occupied greater volume in the alloy, but their number was lower. The increase in the size of impurities was generally accompanied by a decrease in their number.

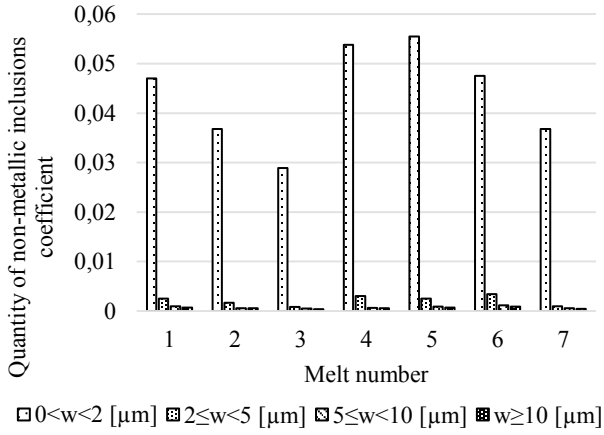

Fig. 4. Quantity coefficient of non-metallic inclusions in every size interval

The relative volume of non-metallic inclusions in measuring range is presented in Fig. 5, and in every size interval – in Fig. 6. The volumetric share of large inclusions measuring over 10 µm was smaller than that of the remaining inclusions. Because the percentage of non-metallic inclusions in the remaining measuring ranges indicates their volume for size w and greater (Fig. 5) therefore the volume of inclusions decreased with an increase in their size. This way approach is purposeful in analyses aiming to determine the effect of impurities of a given size or larger on steel properties.

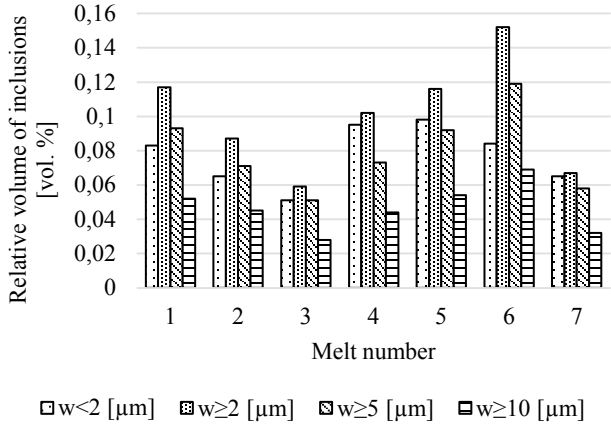

Fig. 5. Relative volume of inclusions per steel melt numbers in measuring ranges

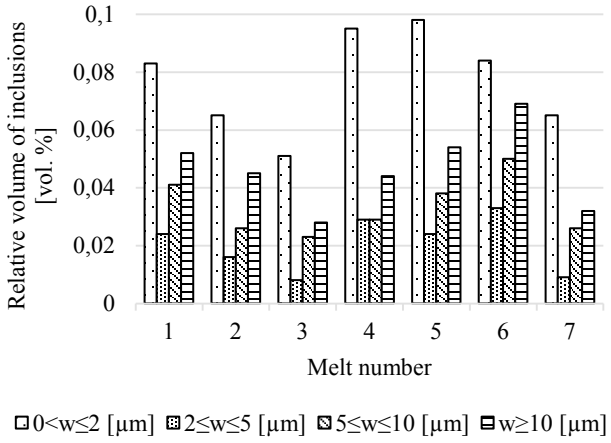

Fig. 6. Size range relative volume of inclusions per steel melt numbers in size intervals

The values of the diffusion coefficient for inclusions from 7 heats in every size interval are presented in Fig. 7and in measuring ranges in Fig. 8.The oxygen content of steel was correlated with the share of non-metallic inclusions. The diffusion coefficient was highest for large inclusions of over than 10 µm. The broad size interval accounted for inclusions equal to and smaller than 2 µm. Minor changes in the diffusion coefficient were noted in the 2≤w<5 um interval for all 7 heats. The above results point to stable correlations between oxygen content and the share of inclusions.

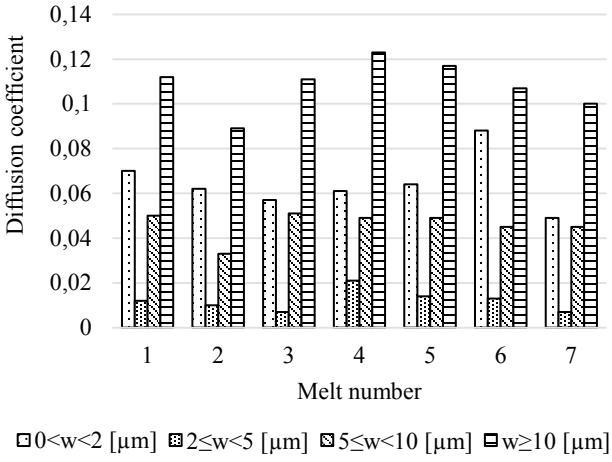

Fig. 7. Diffusion coefficient for inclusions from 7 heats in size interval

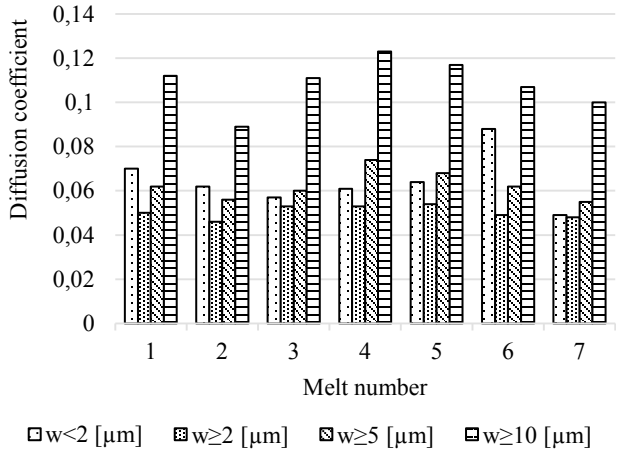

Fig. 8. Diffusion coefficient for inclusions from 7 heats in measuring ranges

5. Conclusions

An analysis of the test results showed that:

- inclusions up to 2 µm occupied the largest volume among individual size intervals for all melts,
- the distribution of non-metallic inclusions in both size intervals and series was analogous for all melts, which confirms the correctness of the performed analysis,
- the size of scatter coefficients within size intervals had a similar character for all analyzed melts.

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