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The Effect of CaSiAl Modification on the Non-metallic Inclusions and Mechanical Properties of Low-carbon Microalloyed Cast Steel

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Abstract

The effect of CaSiAl modification (43-49% Ca, 43-48% Si, 2% Al) on the non-metallic inclusions and mechanical properties of cast low-carbon steel is discussed. Tests were carried out on the cast steel with 0.2% C and micro-additives of V and Nb, used mainly for heavy steel castings (e.g. slag ladles). The modifier in an amount of 1.5 and 3 kg / Mg was introduced to the liquid steel before tapping the metal into a ladle. Test ingots of Y type and a weight of 10 kg were cast and then subjected to a normalizing heat treatment. Using light microscopy and scanning electron microscopy, qualitative and quantitative evaluation of the non-metallic inclusions present in as-cast samples was carried out. Additionally, tests of mechanical strength and impact strength were performed on cast steel with and without the different content of modifier. It was found that increasing the modifier addition affected impact strength but had no significant effect on tensile strength and yield strength. The material with high impact strength had the smallest area fraction of non-metallic inclusions in the microstructure (0.20%). The introduction of modifiers changed the morphology of non-metallic inclusions from dendritic to regular and nodular shapes.

Keywords: Low-carbon microalloyed cast steel, Microstructure, Mechanical property, Non-metallic inclusions

1. Introduction

One of the features that distinguish steel castings from steel products, is a significant increase in the content of non-metallic inclusions in castings. This effect is mainly related to the differences that occur in the technological process of liquid steel preparation. How important is the impact of these inclusions on the mechanical properties of steel and cast steel is evidenced by the large number of publications discussing various possibilities of increasing the purity of liquid metal, among others, by removing and/or modifying the non-metallic inclusions [1-4]. This mainly applies to castings working under low load conditions and those that require high impact strength. A lot of research carried out apply jointly the processes of the modification of non-metallic inclusions with calcium-based compounds and grain refinement through the use of micro-additives.

In steelmaking and casting processes, calcium treatment leads to modification of non-metallic Al_2O_3 inclusions and oxygen decrease. In generally, additions of Ca or REM provide to change the type non-metallic inclusions [4, 5]. As a consequence, the dendritic oxides assume a more rounded shape

Table 1.
Chemical composition of the low-carbon microalloyed cast steel investigated

Samples	C	Si	Mn	Cr	Ni	P	S	Al	Ca	other
	wt. %									
B	0.19	0.18	1.50	0.35	0.20	0.017	0.008	0.05	0.0005	0.04% Nb 0.07% V
M1	0.18	0.21	1.47	0.33	0.18	0.016	0.006	0.04	0.0010	0.04% Nb 0.06% V
M2	0.18	0.27	1.48	0.34	0.19	0.015	0.005	0.03	0.0040	0.04% Nb 0.07% V

An additional effect of this treatment is the decreasing content of sulphide inclusions, which improves toughness, ductility and fatigue strength [1-3]. The addition of micro-alloying elements (V, Nb, Ti) to cast carbon and low-alloy steel has an effect on both, tensile strength and impact strength [4, 6-8]. However, more and more often, the conducted research works are heading towards the development of new innovative materials that can be used in the foundry industry.
Current research is focused on various means to refine the microstructure and increase the mechanical properties of carbon steels due to the introduction of nanoparticles. As a result, a significant reduction in the size of grains and an increase in strength can be achieved. Typically, carbide particles, e.g. VC, NbC, TiC, and also carbonitrides, e.g. TiCN, VCN, NbCN, are introduced into the liquid steel. These particles are produced in separate processes and are mixed with powders of iron or nickel. Then they are introduced into the liquid steel in the form of a compressed mixture or in the form of powder placed in a container made of steel sheet / aluminium foil [9-11]. The disadvantage of this method is the tendency of the particles to agglomeration and uneven distribution in the volume of the alloy, which is important in the case of making massive castings.
Therefore, in this paper, an attempt was made to demonstrate the beneficial effect of different amounts of a complex CaSiAl modifier, introduced into molten steel in form of cored wire, on selected mechanical properties of cast low-carbon steel with V and Nb microadditions.
The effect of CaSiAl modification (43-49% Ca, 43-48% Si, 2% Al) on the microstructure and mechanical properties of low-carbon cast steel is discussed. Tests were carried out on the cast steel with 0.2% C and micro-additions of V and Nb. This grade of cast steel is used, among others, for heavy castings like slag ladles. Melting was carried out in an electric induction furnace under laboratory conditions. Armco iron, low-alloy steel scrap and ferro-alloys of Fe-Si and Fe-Mn were used as a charge.

2. Materials and methods

The cast steel used for the tests was melted in laboratory induction furnace with crucible made of Calderys MIX SC85 M17 lining material. The weight of charging scrap was 30 kg. The starting chemical composition of the tested cast steel is shown in Table 1. The powdered modifying mixture was introduced in the form of a cored wire into the metal bath previously deoxidized with aluminium. Three Y-shape ingots were cast from the tested steel, i.e. a reference sample and two samples after modification with a mixture of CaSiAl added in an amount of 1.5 and 3 kg/Mg. Then the samples were heat treated, i.e. normalized at 920°C which is the type of heat treatment used for massive (large-size) castings made of this steel.
Examinations of fractures and non-metallic inclusions were carried out using a Neophot 32 light microscope and JEOL 5500 LV scanning electron microscope. Determination of the oxygen content in as-cast steel and after modification was carried out on a LECO RO16 device. For mechanical tests, the testing machine provided by INSTRON 5982 Company was used. Impact tests were carried out on a Charpy pendulum machine with an energy of 150J using standard 55x10x10 mm samples with a U notch. The content of non-metallic inclusions in the microstructure of the examined materials was determined by ImageJ software on images obtained by light microscopy at a magnification of 500x. Twelve measurements were made for each material.

3. Results and discussion

3.1. Non-metallic inclusions

The metallographic examinations by light microscopy and scanning microscopy as well as the mechanical tests have confirmed that the use of CaSiAl mixture during steel melting changes not only the shape and chemical composition of non-metallic inclusions, but also the mechanical properties, mainly impact strength.
In figure 1 are shown the typical non-metallic particles morphology obtained in cast steel made in laboratory condition before modification with CaSiAl. This optical microscope observation shown that inclusions are irregular and globular (type I to III) [12-13]. The fraction area of inclusions in unmodified cast steel (designated as B) is 0.44%. Standard deviation in metallographic examination is 0.21 and it is indicate that inclusion particles arrangement is not uniform.

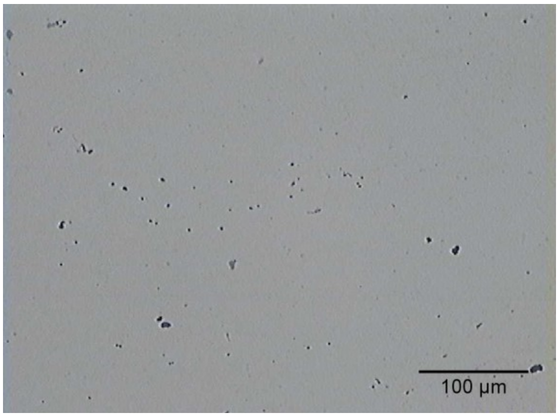
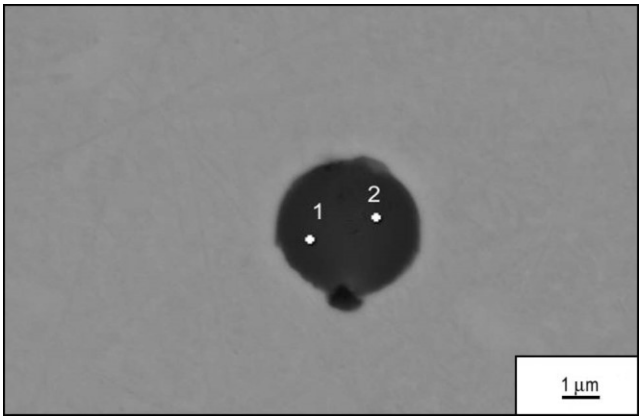


Fig. 1. Optical image of inclusions in cast steel before modification

The examinations by scanning microscopy have revealed that the unmodified cast steel contained non-metallic inclusions such as MnS sulphides, oxides and oxide sulphides of various shapes. The use of the CaSiAl mixture changed the shape (the predominance of globular inclusions) and the chemical composition of inclusions, especially of oxide sulphides due to their enrichment with calcium (Fig. 2).



Point	O	Al	Si	S	Ca	Mn	Fe	Total
	wt. %							
1	15.6	47.0	0.3	1.7	18.7	1.8	14.9	100.00
2	14.2	45.3	0.3	2.0	14.7	2.2	21.3	100.00

Fig. 2. Globular oxide inclusion with an EDS analysis of the chemical composition at points 1 and 2; scanning microscope

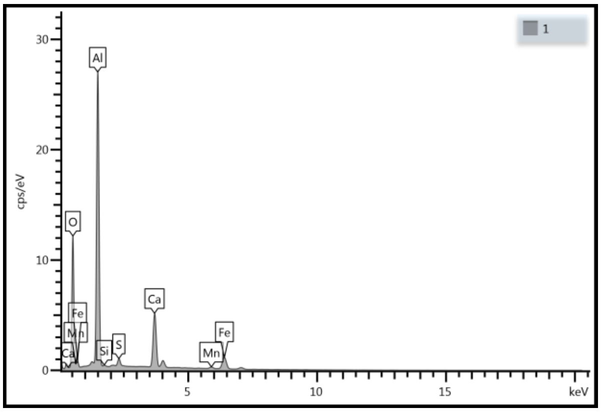
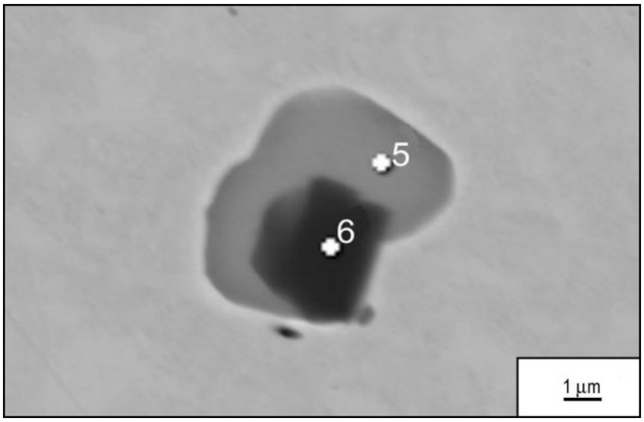


Fig. 3. Example of the X-ray spectrum of a oxides inclusion (from Fig. 2 point 1) - cast steel after modification with CaSiAl mixture

In globular non-metallic inclusions typical for oxides the EDS analysis showed, apart from the presence of Al, also the enrichment in Ca (Figs. 2 and 3).

In complex oxide-sulphide inclusions in the CaSiAl modified cast steel, where oxides served as a substrate for the MnS nucleation, in the dark oxide area, like in oxide precipitates, Ca was also identified (Fig. 4) [5]. In contrast, the brighter areas of inclusions were pure MnS sulphides (Figs. 4 and 5).



Point	O	Al	S	Ca	Mn	Fe	Total
	wt. %						
5	-	-	32.8	-	59.4	7.8	100.0
6	15.4	54.9	7.8	6.8	8.5	6.6	100.0

Fig. 4. Example of a complex inclusion with EDS analysis of the chemical composition in points 5 and 6

In both of the tested cast steels modified with 1.5 and 3.0 kg of CaSiAl, were observed the similar inclusions shape. However the content of non-metallic inclusions were different. Additionally area fraction of nonmetallic inclusions in material M2 is smaller than in M1.

a)

b)

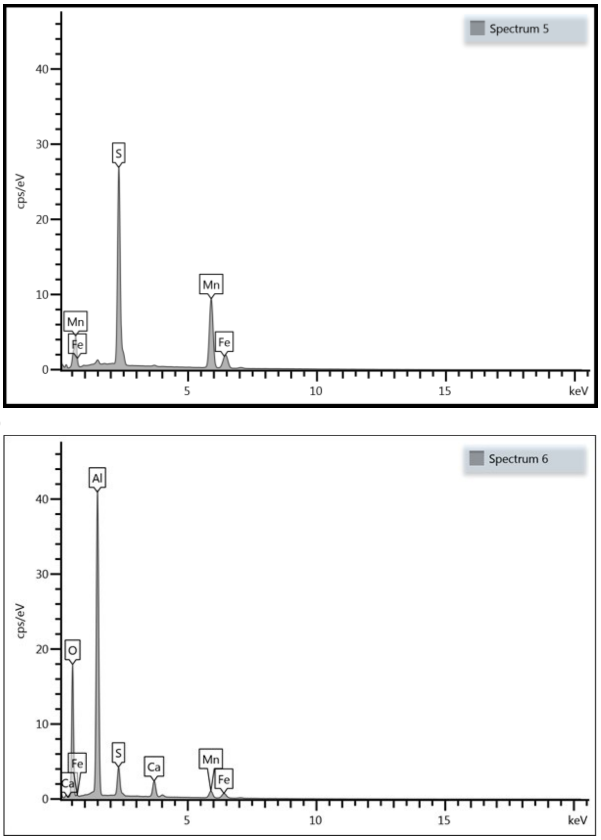


Fig. 5. Example of the X-ray spectrum of cast steel investigated after modification with CaSiAl mixture from Fig.4 point 5 - (a) and point 6 - (b)

The conducted analysis of the oxygen content in the tested materials indicates that the expected values recommended for steel castings have been slightly exceeded (Table 2). Therefore, it is necessary to verify and correlate the amount of the introduced process steel scrap with the amount of the introduced deoxidizer. Probably reducing the oxygen content by approx. 20ppm will reduce the number of non-metallic oxide inclusions. The results of measurements of the surface fraction of non-metallic inclusions (oxides, sulphides and oxide sulphides) in the tested materials are presented in Table 2.

Table 2.
Oxygen content (ppm) and content of non-metallic inclusions (area fraction, %) in the tested cast steel

Material/ parameter	B	M1	M2
oxygen (std. dev.)	90.7 (5.1)	100.3 (17.6)	100.3 (3.1)
non-metallic inclusions (std. dev.)	0.44 (0.21)	0.29 (0.12)	0.20 (0.04)

3.2. Mechanical properties

Compared with the references melt, the change in the morphology of non-metallic inclusions, due to the use of the CaSiAl modifying mixture has increased, above all, the impact strength of the tested cast steel (Fig. 6).
It should be emphasized that the impact strength is closely related to the area fraction of non-metallic inclusions occurring in the microstructure of cast steel. Among various mechanical properties, the impact strength is the parameter most sensitive to the changing quantity and morphology of non-metallic inclusions. The impact strength assumes the lowest value in the starting material (designated as B) and this is accompanied by the largest surface area of non-metallic inclusions. On the other hand, in samples after modification (designated as M1 and M2), a significant increase in impact strength and, at the same time, a significant reduction in the surface fraction of non-metallic inclusions can be observed. Actually, the surface fraction decreases from 0.44 in the starting cast steel (designated as B) to 0.29 and 0.2 in the cast steel designated as M1 and M2, respectively.
On the other hand, modification was found to have no significant effect on the values of UTS, YS (for sample M2: UTS = 710÷720 MPa, YS = 415÷440 MPa). Similar results were reported for the elongation, for which a slight 2% increase was observed in the cast steel designated as M2 compared to the starting alloy (designated as B). This can be due to a lower content of non-metallic inclusions obtained in the cast steel designated as M2.

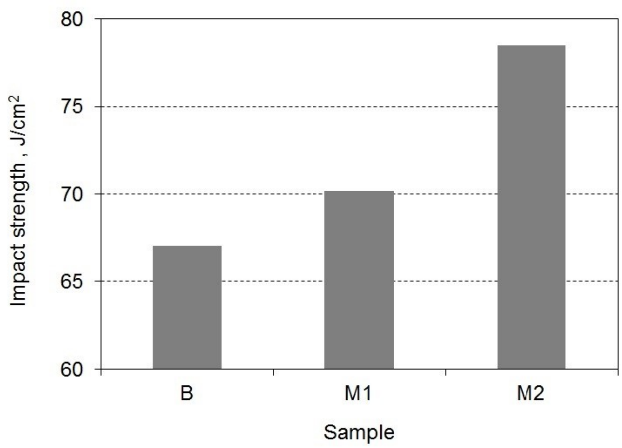


Fig. 6. Impact strength: B - starting chemical composition of the tested cast steel; M1- with 1.5 kg/Mg CaSiAl; M2 - with 3 kg/Mg CaSiAl

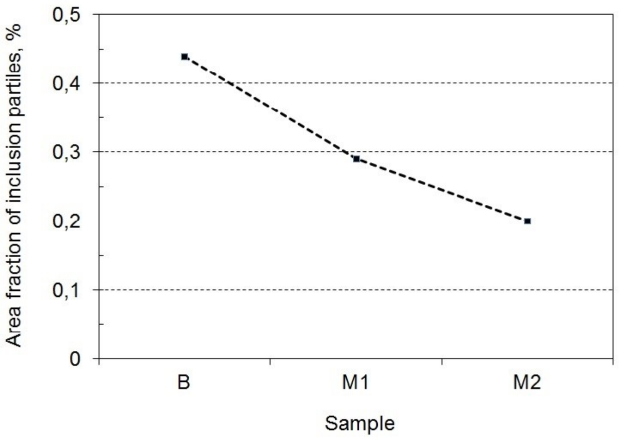


Fig. 7. Area fraction of non-metallic inclusions: B - starting chemical composition of the tested cast steel; M1- with 1.5 kg/Mg CaSiAl; M2 - with 3 kg/Mg CaSiAl

3.3. Fractures

In all fractures after strength and impact tests, the predominance of ductile fracture mode was observed. Studies of the fracture surface revealed the presence of micro-shrinkage and clusters of non-metallic inclusions, especially in the starting material, and besides the high surface fraction of non-metallic inclusions, this micro-shrinkage was the cause of the low impact strength (Figs. 8 and 9).

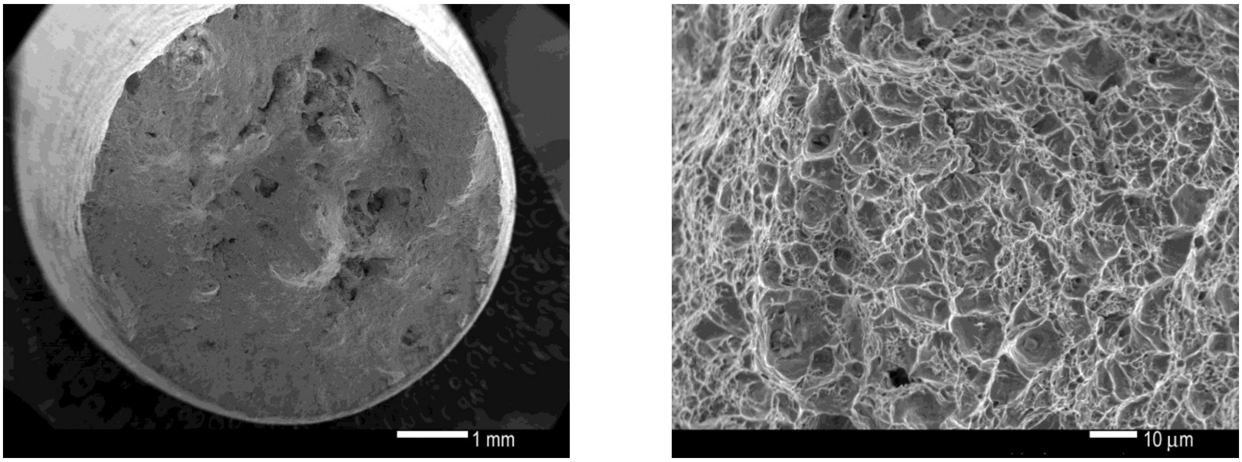


Fig. 8. Example of fracture after strength testing of the starting cast steel

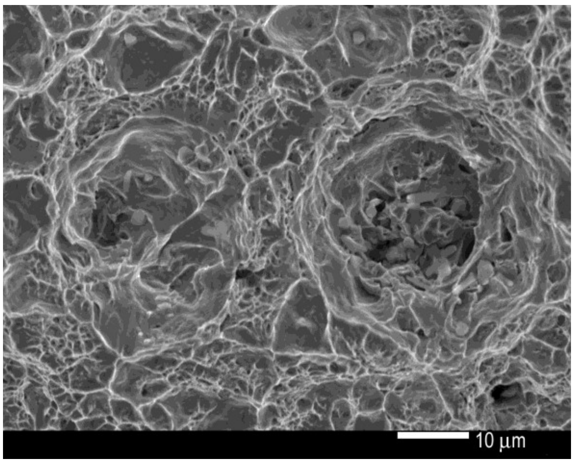


Fig. 9. A cluster of non-metallic inclusions on the fracture of the tested material - cast steel B

4. Conclusions

Based on the results obtained in the conducted tests, it was found that introducing a CaSiAl mixture during melting of cast low-carbon steel after melt deoxidation reduced the area fraction of non-metallic inclusions and modified them (changes in the shape and composition of inclusions). It increased the impact strength by max. 20%, but no significant changes were noticed in other mechanical properties, i.e. UTS, YS and EL. It was also found that in the tested cast steel modified with CaSiAl, typical globular oxide inclusions were enriched in Al and Ca.

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