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RESEARCH PAPER

METALLOGRAPHIC ANALYSIS OF NON-METALLIC INCLUSIONS IN SEMI-KILLED STEEL (GRADE 25G2S) DEOXIDIZED WITH A COMPLEX ALLOY Fe-Si-Mn-Al

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ABSTRACT

This study presents a metallographic analysis of non-metallic inclusions in steel samples obtained from six different heats of the oxygen converter shop at JSC Qarmet and under laboratory conditions at the Karaganda Industrial University. The investigation focused on semi-killed steel samples deoxidized using traditional technology under industrial conditions and with a complex alloy containing Fe-Si-Mn-Al under laboratory conditions, aiming to identify the types and assess the level of contamination by non-metallic inclusions. The results revealed the presence of various types of non-metallic inclusions, such as corundum, chromite spinel, chromium oxides, titanium nitrides and carbonitrides. The degree of contamination by non-metallic inclusions ranged from 2 to 3 points. The analysis showed that using a complex Fe-Si-Mn-Al alloy instead of traditional deoxidizers can affect non-metallic inclusions' quantitative and qualitative composition. It was established that the complex alloy promotes the formation of more stable inclusion phases, which can positively impact the mechanical properties of the steel. It was also found that different production technologies and deoxidizers can significantly influence the quantity and types of non-metallic inclusions, requiring further study and optimization of technological processes. Therefore, the results of this study can be valuable for metallurgical enterprises in selecting optimal steel deoxidation methods and improving steel quality, as well as for further scientific research in the fields of metallurgy and materials science.

Keywords: Metallographic analysis, Microstructural analysis, Semi-killed steel, Non-metallic inclusions, Complex alloy Fe-Si-Mn-Al.

INTRODUCTION

Global steel quality standards are rising annually. In this context, manufacturers are striving to reduce the cost of metal products by conserving energy resources and materials used without compromising quality. Various steel production technologies and the use of different deoxidizers can significantly affect the quantity and types of non-metallic inclusions. Traditional deoxidizers such as ferromanganese, ferrosilicon, ferrosilicomanganese, and pig aluminum have long been used in the metallurgical industry to remove oxygen and non-metallic inclusions from steel. These materials effectively bind oxygen, forming non-metallic inclusions that can then be removed from the melt. However, traditional methods may leave various types of non-metallic inclusions in the steel, which can negatively impact its mechanical properties. Therefore, it is necessary to increase the amount of deoxidizers [1-3].

Since increasing the consumption of ferroalloy deoxidizers significantly affects the cost of steel, to reduce the activity of deoxidation products, it is necessary to add a complex deoxidizer - a complex alloy - to the steel. The activity decreases if the components of the composite alloy form metal oxides that interact with each other during the reaction with oxygen. The resulting complex compounds have a lower melting point, their growth rate increases, and the conditions for their removal from the metal improve [4,5].

Silicomanganese (an alloy of silicon and manganese), AMS (an alloy of aluminum, manganese, and silicon), KMC (an alloy of silicon, manganese, and calcium), and silicocalcium (an alloy of silicon and calcium) are most commonly used as complex alloys for deoxidation. The use of complex alloys, such as AMS alloys containing Fe-Si-Mn-Al, represents a more modern approach to steel deoxidation. These alloys facilitate more effective removal of oxygen and other impurities, leading to a significant reduction

in the content of non-metallic inclusions in the final product. Complex alloys ensure the formation of more stable phases of inclusions, improving the uniformity and quality of steel. Thus, complex alloys can produce steel with enhanced mechanical properties and performance characteristics [6-8].
Many authors have written about the use of complex deoxidizers in their works. They all agree that using complex alloys enhances the deoxidizing capability of the elements, accelerates the deoxidation process, and facilitates the removal of non-metallic inclusions from the metal.
As mentioned above, improving steel quality can be achieved by using complex alloys or ligatures containing silicon, manganese, and aluminum, which, during the deoxidation stage, contribute to the deep purification of steel from oxygen and non-metallic inclusions. The use of complex alloys in steel deoxidation is becoming increasingly relevant, as they provide more stable and uniform properties of the final product. Such alloys can improve the microstructure of the steel, reduce the amount of harmful impurities, and decrease the number of non-metallic inclusions, which, in turn, contributes to improved mechanical and performance characteristics of the steel. This makes the use of complex ligatures an important step in optimizing production and enhancing the quality of metal products.
Metallographic analysis of non-metallic inclusions plays a key role in assessing steel quality, as these inclusions can significantly affect the mechanical properties and performance characteristics of the material. Inclusions can serve as stress concentration sites and cause defects during metal processing. Different steel production technologies and the use of various deoxidizers can significantly influence the quantity and types of non-metallic inclusions [9, 10].
This study examines non-metallic inclusions in samples of semi-killed steel produced in the oxygen converter shop of JSC Qarmet and under laboratory conditions at Karaganda Industrial University. Particular attention is given to comparing traditional steelmaking technology with the use of the complex alloy Fe-Si-Mn-Al. The work aims to identify the types of non-metallic inclusions and assess the level of steel contamination depending on the production technology used.

MATERIAL AND METHODS

To study non-metallic inclusions, metal samples were taken from the oxygen converter shop (OCS) of JSC Qarmet using traditional deoxidation technology and under laboratory conditions at Karaganda Industrial University using a complex deoxidizer. From each sample, specimens were prepared for microstructural analysis. The specimens were prepared using a standard method with an EcoMet 250/300 automatic grinding and polishing machine.
The analysis of non-metallic inclusions was conducted using a metallographic method with an Olympus BX51 TRF microscope at a magnification of ×500. The types of non-metallic inclusions were determined according to GOST 1778-70 Steel - metallographic Methods for Determining Non-Metallic Inclusions, with the assessment performed on the most contaminated area.
Samples of semi-killed steels used to produce merchant weldable rolls were studied. The chemical composition of the investigated steels is presented in **Table 1**. Samples No. 1 and No. 2 were provided by the oxygen converter shop of JSC Qarmet before and after deoxidation, respectively, using the traditional method. Sample No. 3 is remelted steel of merchant roll grade. Sample No. 4 is deoxidized steel using standard deoxidizers in laboratory conditions: FeSiMn, FeSi, metallic Mn, and AB91. Samples No. 5 and No. 6 are deoxidised by adding complex alloys of various compositions, partially and/or completely replacing the standard deoxidizers. The chemical composition of the standard deoxidizers and the complex alloy Fe-Si-Mn-Al is provided in **Table 2**.

Table 1 Chemical Composition of Steels

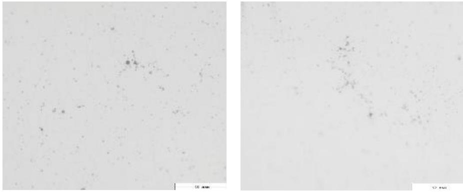
№	Steel Samples	Mass Fraction of Chemical Elements, %								
		Al	C	Mn	S	P	Si	Cr	Ni	Cu
1	Before Deoxidation	-	0,05	0,05	0,018	0,007	-	0,01	0,02	0,03
2	After Deoxidation	0,35	0,05	0,38	0,018	0,014	0,069	-	-	-
3	Ст0	-	0,245	1,4	0,045	0,04	0,75	0,3	0,3	0,3
4	Ст1	-	0,245	1,4	0,045	0,04	0,75	0,3	0,3	0,3
5	Ст2 (AMS 1-1) experimental	-	0,245	1,4	0,045	0,04	0,75	0,3	0,3	0,3
6	Ст3 (AMS 1-2) experimental	-	0,245	1,4	0,045	0,04	0,75	0,3	0,3	0,3

Table 2 Chemical Composition of Deoxidizers

Name of Deoxidizers	Mass Fraction of Chemical Elements, %							
	Al	C	Mn	S	P	Si	CaO	MgO
(AMS) 1-1	10.3	0.109	48.8	0.0047	0.035	31.15	1.2	0.35
(AMS) 1-2	12.85	1.18	20.3	0.0066	0.056	37.79	3	0.2
FeSiMn		1.32	66.078	0,02	0,099	15.627		
FeSi	1,145	0.099	0.164	0.001	0.027	74,495		
Mn		0.0178	97.18	0.0343	0.0008	0.333		
AB91	93.46		0.47			2.63		

RESULTS

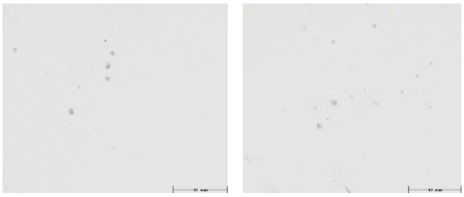
In this study, a metallographic analysis of non-metallic inclusions in semi-killed steel (grade 25G2C) was conducted using both traditional deoxidation methods and the complex alloy Fe-Si-Mn-Al. The primary objective was to investigate how the complex alloy affects the steel's purity, specifically the type and distribution of non-metallic inclusions.
The results show that the use of the complex alloy Fe-Si-Mn-Al affects the type and quantity of non-metallic inclusions. Traditional deoxidation methods, as observed in industrial production samples (samples 1 and 2), typically led to the formation of inclusions such as corundum (Al_2O_3) and various spinels (based on chromium and titanium). These inclusions were often dispersed throughout the metal, ranging from crystal forms with sharp edges to agglomerates of irregular shapes. The overall level of contamination in these samples was rated as 3 on a standard scale. **Fig. 1** (sample 1) shows the results of the study of non-metallic inclusions in the metal sample before the converter. **Fig. 1(a)** and **Fig. 1(b)** show different areas of the same sample, allowing a more detailed observation of the nature and size of the inclusions in this and subsequent figures.



a *b*

Fig. 1 Non-Metallic Inclusions in the Metal Sample Before the Converter, ×500

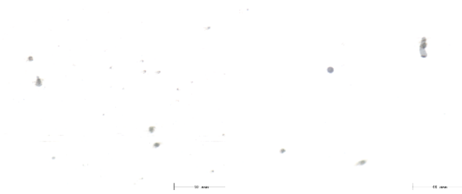
In **Fig. 2** (Sample 2), the results of the study of non-metallic inclusions in the metal sample from the ladle furnace (LF) installation are presented.



a *b*

Fig. 2 Non-metallic inclusions in the metal sample from the ladle furnace installation, x500.

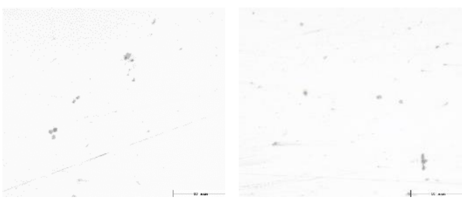
Fig. 3 shows the results of the study of non-metallic inclusions in steel grade (25G2C) produced by traditional technology.



a *b*

Fig. 3 Non-Metallic Inclusions in Steel Grade 25G2C, ×500

In the cast sample of steel grade 25G2C, non-metallic inclusions were identified as crystals of chromium oxide (Cr_2O_3) in irregular and prismatic shapes. Inclusions of chromospinelids (Fe, MgO)·$(Cr,Al)_2O_3$ were observed as isolated particles in triangular and irregular shapes. Single small inclusions of corundum (Al_2O_3) were also noted. The level of contamination with non-metallic inclusions was rated as 2.5 on the scale, **Fig. 4**.

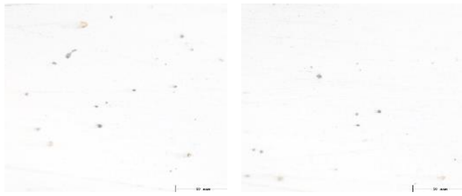


a *b*

Fig. 4 Non-Metallic Inclusions in Steel Grade 25G2C, ×500

In the cast sample of steel grade 25G2C, the non-metallic phase primarily consists of titanium nitrides and carbonitrides (TiN, TiNC) in regular cubic shapes, as well as chromium spinel ($FeO·Cr_2O_3$) inclusions and small particles of chromium oxides (Cr_2O_3) in irregular and prismatic shapes. The contamination of the metal with non-metallic inclusions was rated as 2.5 on the scale.

In contrast, the samples deoxidized using the complex alloy (samples 5 and 6) exhibited a different pattern. Here, the inclusions were primarily chromium spinels (FeO Cr_2O_3) and titanium carbonitrides (TiN, TiCN), often forming more regular cubic crystals. The level of contamination in these samples consistently remained at 2.5, indicating a slight improvement in steel purity when using the complex alloy. **Fig. 5** (sample 5) shows the results of the study of non-metallic inclusions in the experimental steel grade 25G2C deoxidized with the complex alloy (AMS 1-1).



a *b*

Fig. 5 Non-Metallic Inclusions in Experimental Steel Grade 25G2C, ×500

Fig. 6 (sample 6) shows the results of the study of non-metallic inclusions in the experimental steel grade 25G2C deoxidized with the complex alloy (AMS 1-2).

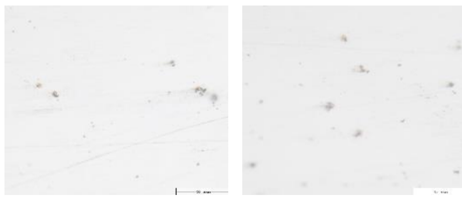


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Fig. 6 Non-Metallic Inclusions in Experimental Steel Grade 25G2C, ×500

The results obtained from processing samples under laboratory conditions with the use of complex alloys showed a more uniform distribution of non-metallic inclusions. This finding supports the hypothesis that complex alloys may promote the formation of more stable inclusion phases, potentially improving the mechanical properties of the final steel product. However, the overall reduction in contamination was modest, indicating that while the complex alloy affects the type of inclusions, it cannot significantly reduce their quantity.

It is also important to note that the morphology of the inclusions varied significantly depending on the deoxidation method used. For example, traditional methods resulted in inclusions with broader size distribution and more irregular shapes, which could negatively impact the mechanical properties of the steel. In contrast, the use of complex alloys generally led to the formation of smaller and more regular inclusions, which are less likely to act as stress concentrators in the steel matrix.

The results indicate that the use of complex deoxidizers, such as the Fe-Si-Mn-Al alloy, can positively influence the type of non-metallic inclusions formed in steel, thereby potentially

improving its mechanical properties. However, this technology does not allow for a significant reduction in the overall level of non-metallic inclusions, which suggests the need for further refinement of the process. This may involve optimizing the composition of the complex alloy or adjusting other process parameters to achieve better results.
These results are of great significance for steel producers aiming to improve product quality while maintaining economic efficiency. The ability to influence the type and morphology of non-metallic inclusions using complex alloys paves the way for enhancing the performance characteristics of steel, particularly in applications where material toughness and plasticity are critical.

DISCUSSION

The metallographic analysis of non-metallic inclusions in semi-killed steel (grade 25G2C), deoxidized using both traditional methods and the complex alloy Fe-Si-Mn-Al, revealed several important findings. These results highlight the potential advantages and limitations of using complex alloys for steel deoxidation, with a focus on the type, morphology, and distribution of non-metallic inclusions.
In the samples deoxidized using traditional methods (samples 1 and 2), non-metallic inclusions primarily consisted of corundum (Al_2O_3) and spinels, such as chromium spinel (FeO - Cr_2O_3) and titanium carbonitrides (TiN, TiCN). These inclusions exhibited various morphologies, ranging from crystals with sharp edges to irregular agglomerates. The overall level of contamination in these samples was rated as 3.0 on the contamination scale.
In the samples treated with the complex alloy Fe-Si-Mn-Al (samples 5 and 6), the inclusions were predominantly small, more regular cubic crystals of chromium spinel and titanium carbonitrides. The contamination level of these samples was somewhat lower, at 2.5 on the scale.
The introduction of the complex alloy resulted in a slight reduction in the overall content of inclusions, improving the purity of the steel. While traditional deoxidation methods resulted in a contamination level of 3.0, the complex alloy improved this to 2.5. This indicates a reduction in the content of non-metallic inclusions by 16.7%, which, although modest, points to a trend toward increased steel purity.
The use of the complex alloy Fe-Si-Mn-Al facilitated the formation of more stable and uniformly distributed non-metallic inclusions. The more regular morphology and reduced size of these inclusions could potentially lead to improved mechanical properties of the final steel product, such as increased toughness and plasticity.
When comparing the two deoxidation methods, it became evident that the complex alloy has a more significant impact on the morphology of inclusions than on the overall quantity of inclusions. The use of the complex alloy resulted in a more uniform and controlled size and shape of inclusions, which are less likely to act as stress concentrators in the steel matrix. This may lead to improved performance in applications where mechanical strength and reliability are critical.
Implications for Industrial Application: The results indicate that the Fe-Si-Mn-Al complex alloy can be effectively used to improve the purity and quality of semi-finished steel, particularly in terms of controlling the type and morphology of non-metallic inclusions. However, the modest reduction in the overall content of inclusions suggests that further optimization of the alloy composition or process parameters is needed to achieve more significant improvements.
For industrial applications, especially in sectors where high-strength steel is required, these results highlight the potential of the complex alloy for producing steel with superior mechanical properties. The 16.7% reduction in inclusion content, while modest, represents a step forward in the pursuit of higher-quality steel products.
The study concludes that the use of complex deoxidizers, such as Fe-Si-Mn-Al, can positively influence the nature of non-metallic inclusions. However, achieving significant reductions in inclusion content requires further optimization. The results provide a foundation for future research aimed at improving steelmaking processes and enhancing the quality of semi-killed steels. These findings may be precious in the development of new steel grades with superior mechanical properties, intended for demanding industrial applications.

CONCLUSION

The following conclusions can be drawn on the basis of the conducted research: the use of Fe-Si-Mn-Al complex alloy as a deoxidizer for semi-quiet steel allows to achieve improvements in the morphology of non-metallic inclusions, despite a slight decrease in their total amount. In particular, when using traditional deoxidizers, the level of steel contamination with non-metallic inclusions is estimated at 3.0 points, whereas when using the complex alloy it is reduced to 2.5 points, which corresponds to a 16.7% reduction in the content of inclusions. However, not only the quantitative reduction of inclusions is important, but also their qualitative transformation.
The steel treated with Fe-Si-Mn-Al alloy exhibits more homogeneous and predictable inclusions in terms of shape and size. The inclusions acquire a regular cubic shape, which helps to reduce their negative influence on the mechanical properties of the steel. A more regular inclusion morphology reduces stress concentration, which can have a positive effect on the strength and ductility of the steel, especially in critical applications where material reliability and durability are critical.
Thus, although the reduction in overall inclusion contamination with Fe-Si-Mn-Al alloy is not significant, its effect on inclusion morphology can significantly improve the mechanical properties of the steel. This opens up opportunities for further optimization of alloy composition and process parameters to further reduce contamination levels and improve steel quality. For steel producers focused on improving the strength and durability of their products, the use of this complex alloy represents a promising way to improve steel performance.

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