ACTA METALLURGICA SLOVACA
2024, VOL. 30, NO. 4, 167-170

RESEARCH PAPER

STUDY OF DEOXIDIZING PROPERTIES OF Fe-Si-Mn-Al COMPLEX ALLOY

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Received: 06.10.2024
Accepted: 17.11.2024

ABSTRACT

The article presents a study on the effectiveness of using the complex alloy Fe-Si-Mn-Al for steel deoxidation. The experiments conducted demonstrated the high deoxidizing capacity of this alloy, as evidenced by significant levels of extraction of alloying elements: silicon (75–85%), manganese (80–87%), and aluminum (60–70%). The study showed that steel deoxidized with the complex alloy has a 25–30% reduction in non-metallic inclusions compared to samples treated with traditional deoxidizers. This leads to improved metal purity and enhances mechanical properties, with an average hardness of the samples at 27 HRc, which is 1.5–2 units higher than that of traditionally deoxidized steels. The use of the complex alloy also reduces production costs by 10–15%, due to the efficient utilization of low-grade manganese ores and high-ash coals. The study results confirm the feasibility of using the complex alloy Fe-Si-Mn-Al as a promising deoxidizer for improving steel quality and optimizing production processes.

Keywords: Fe-Si-Mn-Al; Deoxidation of Steel; Non-Metallic Inclusions; Metallographic analysis; Microstructural analysis.

INTRODUCTION

Complex alloys in steel treatment offer significant potential for enhancing metallurgical processes' technological and economic efficiency. An auspicious approach involves the application of an alloy that simultaneously incorporates Fe, Si, Mn, and Al, effectively minimizing the presence of non-metallic inclusions in steel compared to conventional deoxidizers [1-3].

A key advantage of the complex alloy is its potential to be produced from off-grade manganese ores and high-ash coals, highlighting its appeal regarding resource efficiency and eco-economic sustainability. It is known that standard ferroalloys (FeSi, FeMn, FeSiMn) and aluminium and their alloys are typically used for deoxidizing steels of various grades. In recent years, Kazakhstan has seen active development and improvement of the technology for smelting complex alloys, driven by the availability of significant deposits of off-grade raw materials suitable for metallurgical use. Thus, combining alloying elements in a single alloy provides improved steel quality and reduced production costs [4-7].

Steel deoxidation is a vital technological process that directly impacts the quality of the final metal product. Utilizing the Fe-Si-Mn-Al complex alloy as a deoxidizer enhances the efficient assimilation of Si, Mn, and Al. The main objective of this process is to eliminate unwanted impurities from the melt by forming non-metallic inclusions, achieved by adding deoxidizers with a strong affinity for oxygen. Complex alloys used as deoxidizers have a significant advantage over traditional deoxidizers. This advantage lies in the formation of inclusions with minimal interfacial tension at the metal-inclusion boundary, facilitating their removal from the melt. One of these components is manganese, which, as part of the complex alloy, enhances the deoxidizing ability of other elements such as silicon and aluminum. This accelerates the deoxidation process and facilitates the removal of non-metallic inclusions, thereby improving the metal's overall purity [8-11].

Recent research has demonstrated that high-ash coals and off-grade manganese ores are valuable raw materials for producing the Fe-Si-Mn-Al complex alloy. Due to their high impurity content, these resources were previously not utilized in traditional metallurgy; however, thanks to advancements in melting technology, their incorporation into the smelting process of the complex alloy has become feasible.

The industrial production of FeSiAl (FSA) has been established in Kazakhstan, and technology was developed in 1985 based on high-ash coals. This experience was a foundation for developing the technology for producing the Fe-Si-Mn-Al complex alloy, enabling the processing of low-grade manganese ores and waste from coal beneficiation plants. The technology for producing the Fe-Si-Mn-Al complex alloy is characterized by high resource-saving efficiency, as it eliminates energy-intensive ore preparation and enrichment processes, significantly reducing the cost of the final product [12-13].

The production technology of the Fe-Si-Mn-Al complex alloy leverages high-ash coals with low sulfur and phosphorus content, making them highly suitable for metallurgical applications. Additionally, processing off-grade manganese ores into this complex alloy offers a more cost-effective alternative to traditional manganese ferroalloy production by eliminating the need for beneficiation. The application of the Fe-Si-Mn-Al complex alloy in metallurgy allows for the replacement of expensive traditional ferroalloys such as FeMn, FeSiMn, and FeSi, as well as the scarce and costly FeAl [14-17].

This research aims to produce the Fe-Si-Mn-Al complex alloy using off-grade manganese ores and high-ash coals, and to evaluate its effectiveness in steel deoxidation compared to traditional deoxidizers such as FeMn, FeSiMn, FeSi, and aluminum ingots. The study will also involve analyzing the microstructure of deoxidized steels and identifying the resulting types of steel microstructures.

MATERIAL AND METHODS

The production of the Fe-Si-Mn-Al complex alloy using off-grade manganese-containing ore and high-ash coal was conducted in a two-electrode ore-thermal electric furnace with a conductive bottom, where one electrode is coked in the bottom mass, meaning the electric furnace has a structure similar to that of a ‘Mige’ type electric furnace. [18-19].

The main advantage of the laboratory ore-thermal electric furnace is its lower energy and material consumption compared to a semi-industrial furnace with a 200-250 kVA capacity, while still capable of solving the same technological tasks.

The main characteristics of the furnace bath are diameter 300 mm, depth 300 mm, and the graphite electrode used has a diameter of 100 mm. The power transformer is the OSZ-250/0.5 UHL4 type. Cooling is natural air cooling. PBV (no-load switching). Frequency – 50 Hz. Insulation heat resistance class – F. Phases – 1. Connection scheme and winding group – 1/1-0. The transformer has seven voltage steps on the secondary side ranging from 27.5 V to 71.3 V. In the laboratory ore-thermal furnace, based on the geometry of the bath and the diameter of the furnace electrodes, the following voltage step on the secondary side is used: 27.5 V. The furnace bath is lined with chamotte bricks. The bottom of the furnace is packed with electrode mass, preheated to 100-120°C. The surface of the bottom has a slope of 5-7° towards the tapping hole to facilitate the removal of the melt.

DOI: 10.36547/ams.30.4.2082

High-ash coal, off-grade manganese-containing briquettes, and quartzite were used as charge materials. Quartzite was used in the charge mixture to adjust the chemical composition and neutralize residual carbon. The technical and chemical composition of the charge materials is presented in **Tables 1** and **2**.

Table 1 Technical Composition of Charge Materials

Material	A^c	V^r	W^r	C
Saryadyr Coal	50.04	19.28	1.98	31.86

Table 2 Technical Composition of Charge Materials

Material	Fe_2O_3	SiO_2	Al_2O_3	MnO_2	CaO	MgO	TiO_2	P_2O_5	S	LOI
Saryadyr Coal	5,79	66,36	20,7		2,64	3,46	1,01	0,035	0,005	
Manganese ore deposit «Bogach»	5,72	6,27	0,72	49,94	15,05	0,83		0,02	0,01	21,44
Quartzite	0,52	95,57			0,24	0,12			0,01	3,54

Steel deoxidation was carried out in a Tamman furnace, using the Fe-Si-Mn-Al complex alloy obtained in a laboratory furnace with a capacity of 150 kVA, along with traditional deoxidizers, as presented in **Table 3**.

Table 3 Chemical Composition of Deoxidizers

Name of Deoxidizers	Mass Fraction of Chemical Elements, %					
	Al	C	Mn	S	P	Si
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

The phase composition of the Fe-Si-Mn-Al complex alloy sample was analysed using X-ray diffraction (XRD) with a D8 ADVANCE diffractometer (Bruker AXS, Germany). This equipment is equipped with an X-ray tube with a copper anode (Cu Kα, λ = 1.5406 Å) and utilizes Kβ line filtration with a graphite monochromator. The operating voltage and current were set at 40 kV and 40 mA, respectively. Scanning was performed over an angular range of 2θ from 10° to 90° with a step size of 0.02° and a scanning speed of 0.5°/min. The obtained data were processed, and phase identification was carried out using the DIFFRAC.SUITE EVA software and the PDF-2 database (ICDD) [20-22]. The selection of scanning parameters and phase identification aimed to minimize possible measurement errors and enhance result accuracy. Special attention was given to determining crystalline phases and analyzing their quantitative content.

While studying the microstructure of steel 08PS, methods compliant with GOST 1778-70 [23] were employed. According to this standard, samples were prepared for metallographic analysis, which included determining the microstructure and chemical composition of the material. The composition of non-metallic inclusions was determined using energy dispersive X-ray analysis (EDX) in the metal science and non-destructive testing laboratory of the Analytical Control Center, JSC «Qarmet».

This method allows for analysing the material's elemental composition by determining the energy and intensity of the scattered X-rays when interacting with the sample. EDX analysis identifies and quantitatively assesses present elements in non-metallic inclusions, such as oxides, sulfides, carbides, and other compounds [24]. Thus, the energy dispersive X-ray analysis (EDX) method represents an effective tool for determining the composition of non-metallic inclusions in steel and provides additional information for studying their impact on the microstructure and properties of the material.

RESULTS

Laboratory tests to produce the complex alloy were conditionally divided into the following periods: heating of the electric furnace and bringing it to operational mode, and the smelting of the Fe-Si-Mn-Al complex alloy using high-ash coal from the «Saryadyr» cut and manganese ore from the «Bogach» deposit (**Tables 1** and **2**). Quartzite was used in the charge mixture to adjust the chemical composition and neutralize residual carbon.

The furnace was heated for 5 hours on a coke bed at the first step with a voltage of 27.4 V and a low-side current of 100 A - 500 A. After the heating period, the electric furnace bottom was completely cleaned of coke and ash residues. Following the five-hour heating of the lining, the bottom was preheated with the charge supplied around the electrode. This reduced heat losses due to radiation by redirecting them to heat the bottom. During the slag formation in the furnace bath and before the first alloy tapping, 15 kg of coal, 12 kg of ore, and 4.2 kg of quartzite were consumed.

When loading the main charge, the electrical parameters of the smelting were characterized by the following indicators: nominal secondary voltage – 27.4 V, low-side current – from 1,600 A to 2,200 A. During the smelting of the Fe-Si-Mn-Al complex alloy using high-ash coal from the «Saryadyr» cut and manganese ore from the «Bogach» deposit, the following composition was accepted: coal – 5 kg, manganese ore – 5 kg, and quartzite – 0.55 kg. This period lasted 12 hours, and the first two taps were considered transitional in the calculations and were not included in the chemical analysis. The total quantity of charge materials consumed in the first period was coal – 60 kg, manganese ore – 60 kg, and quartzite – 6.6 kg. Four metal taps were accounted for, with an average mass of approximately 2.9 kg. The recovery of the main elements was (in % by mass): Si – 75-85, Al – 60-70, and Mn – 80-87. The metal from each tap was weighed, after which samples were taken according to GOST 17260-87 to determine the chemical composition. The chemical analysis of the samples was performed following GOST 22772.4-77, GOST 22772.6-77, and GOST 22772.7-96. The weighted average chemical composition of the complex alloy is presented in **Table 4**.

Table 4 Chemical Composition of Fe-Si-Mn-Al Containing Complex Alloy, %

Fe	Si	Mn	Al	C
12.95	30.23	51.27	3.73	1.82

Thus, the conducted experimental tests indicate the fundamental possibility of smelting complex alloys based on Fe-Si-Mn-Al using the charge above materials. The charge in the furnace bottom did not sinter, and its processing was carried out without difficulties. Tapping the furnace at the end of the period was significantly easier. The yield of the complex alloy was active.

X-ray structural analysis was performed using a D8 ADVANCE diffractometer (Bruker AXS, Germany) to determine the phase composition of the obtained complex alloy. The results of the X-ray structural analysis of the obtained alloy are presented in Figure 1. The study showed that the alloy consists of the following phases: MnSi, $Fe_{0.75}Mn_{0.25}$, $Al_{9.88}Fe_{0.806}Mn_{2.314}$, Si, $Al_{0.47}Fe_{0.53}$.

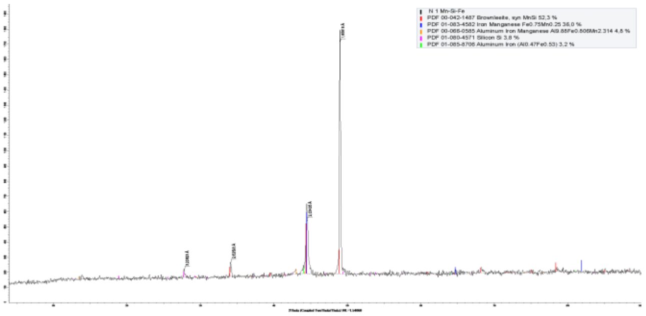


Fig. 1 X-ray Diffraction Pattern of the Alloy

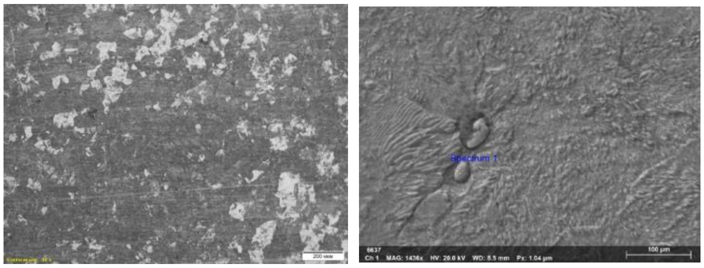
Three steel samples with different chemical compositions and microstructures were analyzed during the study. The main focus was on microstructural features, the presence and type of non-metallic inclusions, and hardness determination according to GOST 9013-59. The obtained results allow for identifying the influence of composition and structure on the mechanical properties of steel, which is crucial for optimizing the production process and improving performance characteristics.

The microstructure of sample No. 1 **(Fig. 2a**), considered the baseline version of the samples in the study, consists of ferrite and pearlite with rounded grains, typical for carbon steel with minimal amounts of alloying elements. The structure is heterogeneous, which may be related to the specifics of the crystallization and cooling technology. The primary type of non-metallic inclusions are manganese sulfides, which typically form due to insufficient sulfur removal from the metal. Sulfide inclusions can lead to localized brittleness, reducing the mechanical properties of the steel. The average hardness of the sample was 25.5 HRc, indicating a soft state of the material. The low hardness is attributed to the lack of significant amounts of alloying elements and the formation of relatively large grains of ferrite and pearlite.

It should be noted that this sample represents steel without any additions of deoxidizers. This resulted in the formation of manganese and sulfur-based sulfide inclusions. An important feature is the significant content of manganese (up to 60 wt.%) and sulfur (around 40 wt.%) in several spectra, indicating the presence of phases such as MnS (**Fig. 2b**). Such inclusions likely contribute to increased brittleness of the material.

In particular, Spectrum 1 and Spectrum 3 (Google Drive) demonstrate high levels of manganese and sulfur (Mn up to 60 wt.%, S around 40 wt.%). These are typical parameters for the formation of MnS, often found in non-deoxidized steel. In some areas, iron is present in combination with sulfur, as in Spectrum 2, where iron constitutes about 66 wt.% and sulfur 16 wt.%. Such inclusions may indicate complex sulfide compounds of Fe-Mn-S.

Thus, sample No. 1's microstructure is characterized by a predominance of sulfide inclusions, indicating low steel purity and a high likelihood of forming brittle phases that may negatively impact the material's mechanical properties.



a *b*

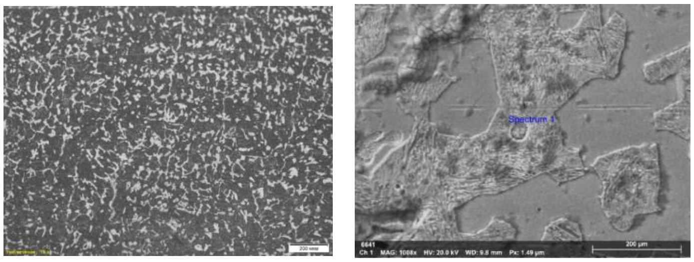
Fig. 2 Figure 3 - Sample 1

The microstructure of Sample No. 2 (**Fig. 3a**) is represented by ferrite and pearlite with a dendritic structure, which shows signs of porosity. This sample was deoxidized using standard deoxidizers from **Table 3**. The dendritic structure may result from uneven cooling during crystallization, leading to areas with heterogeneous density. The inclusions identified in the sample vary in composition: iron oxides, titanium carbides, manganese sulfides, and corundum (aluminum oxide). These inclusions significantly impact the mechanical properties of steel. Oxides and sulfides typically reduce ductility and impact toughness, while titanium carbides and corundum enhance hardness but increase the risk of brittleness in localized areas. The average hardness of the material is 32.5 HRc, which is significantly higher than that of Sample No. 1, explained by the presence of alloying elements such as silicon, manganese, and aluminum, which contribute to strengthening the steel.

As mentioned above, traditional deoxidizers such as ferromanganese, ferrosilicon, and aluminum were used in Sample No. 2. Due to deoxidation, the microstructure shows various phases, including oxides, sulfides, and carbides.

Spectrum 1 (**Fig. 3b**) shows a predominance of iron (Fe, 73.39 wt.%) with added sulfur (S, 26.61 wt.%). This indicates the presence of sulfide inclusions, likely based on FeS or FeMnS, which, despite deoxidation, continue to be present in the steel matrix. Spectrum 2 demonstrates a high titanium content (77.27 wt.%), suggesting the possible formation of titanium-containing phases such as TiC or TiN, characteristic of titanium alloys. In Spectrum 6, there is a high proportion of aluminum (Al, 53.83 wt.%) and oxygen (O, 46.17 wt.%), confirming the formation of oxide inclusions, likely based on Al_2O_3, which are desirable products of deoxidation and contribute to improving the cleanliness of the steel (Google Drive).

Thus, in Sample No. 2, traditional deoxidation led to more complex oxide and sulfide inclusions, which should contribute to better metal cleanliness than un-deoxidized steel. However, the presence of FeS and MnS sulfides indicates that not all sulfur was removed from the system, which may continue to affect the properties of the steel negatively



a *b*

Fig. 3 Sample 2 FeSi, Fe-Mn, Al

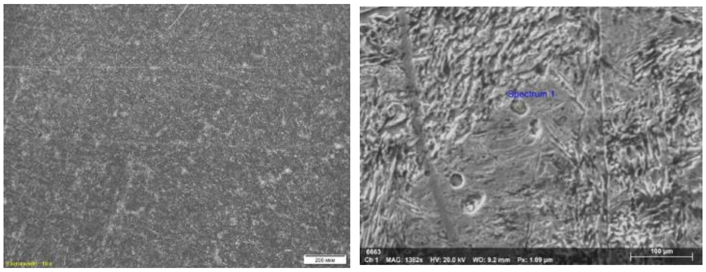
The most complex microstructure is observed in Sample No. 3 (**Fig. 4**), where a bainitic structure has been identified. This sample was deoxidized using the complex alloy Fe-Si-Mn-Al from **Table 4**. Bainite forms at intermediate cooling rates and consists of a mixture of ferrite and carbides, providing higher strength and ductility than pearlitic and ferritic structures. Additionally, this sample contains complex non-metallic inclusions of manganese, aluminum, and calcium, as well as titanium nitrides and manganese sulfides. The complex inclusions are generally fine-grained and evenly distributed, which enhances the mechanical properties; however, their presence may lead to brittleness in certain areas. The average hardness of the sample is 37.0 HRc, which is significantly higher than in the previous samples. The high hardness is attributed to the bainitic structure and alloying elements, making this material promising for use in applications requiring increased strength and wear resistance.

Sample No. 3 represents steel deoxidized using a new complex alloy based on Fe-Si-Mn-Al. The microstructure of this steel exhibits significant changes compared to Samples No. 1 and No. 2, which is confirmed by the presence of more complex phases that can be easily removed.

Spectrum 1 (**Fig. 4b**) shows that the composition includes manganese (Mn, 51.33 wt.%), sulfur (S, 33.36 wt.%), aluminum (Al, 10.20 wt.%), and calcium (Ca, 5.10 wt.%). This indicates the formation of complex sulfides and aluminates, possibly containing calcium, suggesting more effective deoxidation than traditional methods.

Spectrum 2 contains high concentrations of manganese (Mn, 60.64 wt.%) and sulfur (S, 39.36 wt.%), which continues to indicate the presence of MnS sulfides; however, their quantity and distribution may be more uniform. It is important to note the presence of aluminum in significant amounts, as seen in Spectrum 1 and Spectrum 6, which indicates the formation of aluminum oxides (Al_2O_3) that can enhance the purity of the metal and improve its mechanical properties.

Thus, deoxidation using the complex alloy Fe-Si-Mn-Al leads to the formation of more complex phases, such as MnS sulfides with aluminates and aluminium oxides, which may contribute to improved purity and reduced brittleness of the steel compared to samples No. 1 and No. 2. Complex deoxidation also ensures complete binding of sulfur and oxygen.



a *b*

Fig. 4 Sample 3, Deoxidized with the complex alloy Fe-Si-Mn-Al

DISCUSSION

The studies' results confirm the promise of using the complex alloy Fe-Si-Mn-Al for deoxidizing steel. Experimental data show that the application of this alloy positively influences the reduction of non-metallic inclusions in steel, improving its microstructure and mechanical properties.

A comparative analysis of steel samples subjected to deoxidation with traditional ferroalloys and the complex alloy Fe-Si-Mn-Al revealed several significant differences. In the steel sample treated with the complex alloy, the number of large non-metallic inclusions, such as manganese sulfides and aluminum oxides, was significantly reduced, directly reflecting the metal's purity. This is confirmed by the results of energy-dispersive X-ray analysis (EDX), which showed that in the steel deoxidized with the complex alloy, the content of silicon and aluminum oxides was 25-30% lower compared to samples treated with traditional deoxidizers. It is important to note that deoxidizing steel using Fe-Si-Mn-Al allows for more effective absorption of alloying elements (Si, Mn, Al), as evidenced by their high extraction levels: 75-85% for silicon, 60-70% for aluminum, and 80-87% for manganese.

An additional advantage of using the complex alloy is the improved deoxidizing ability of aluminum due to the presence of manganese and silicon. These elements facilitate the accelerated deoxidation process and the formation of inclusions with low interfacial tension at the metal-inclusion boundary. This makes their separation from the melt easier, as confirmed by metallographic analysis: the structure of the steel treated with the complex alloy revealed smaller inclusions of oxides and sulfides, indicating a cleaner microstructure.

Thus, using the complex alloy Fe-Si-Mn-Al has demonstrated advantages over traditional deoxidizers from both technological and economic perspectives. First, reducing the number of non-metallic inclusions leads to improved steel quality and enhanced mechanical properties manifested in increased strength and ductility. Second, due to the effective absorption of elements, the costs associated with adding alloying components are reduced, which helps to lower overall production expenses.

CONCLUSION

Based on the results of the research conducted, the following conclusions can be drawn:

1. Effectiveness of the complex alloy Fe-Si-Mn-Al in steel deoxidation. The application of this alloy allowed achieving high levels of extraction of alloying elements: 75–85% for silicon, 80–87% for manganese, and 60–70% for aluminum. These indicators significantly exceed the results obtained with traditional deoxidizers (FeSi, FeMn, FeSiMn, and Al).
2. Reduction in the quantity of non-metallic inclusions: Steel deoxidized with the Fe-Si-Mn-Al complex alloy demonstrated a 25–30% decrease in the content of large non-metallic inclusions compared to samples treated with conventional deoxidizers. This reduction contributed to enhanced steel purity and improved microstructural characteristics.
3. Improve steel's mechanical properties: Using the Fe-Si-Mn-Al complex alloy as a deoxidizer enhanced steel's strength and hardness. The average hardness of the samples deoxidized with the complex alloy reached 27 HRc, 1.5–2 units higher than samples treated with conventional ferroalloys.
4. Economic benefits: The application of the Fe-Si-Mn-Al complex alloy enables a substantial reduction in steel production costs through the efficient utilization of low-grade manganese ores and high-ash coals. This approach enhances production profitability, reducing the cost of the final product by 10–15% compared to traditional deoxidation methods.

Thus, the complex alloy Fe-Si-Mn-Al demonstrates high potential as an effective deoxidizer for steel production, improving the properties of the end product and significantly reducing production costs.

Acknowledgements: This work was carried out as part of a study funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant No. AP 13268863)

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