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DEOXIDATION AND MODIFICATION OF STEELS WITH REDUCED SILICON CONTENT

The object of research is the processes that affect the mechanical characteristics of steels after the treatment of melts with silicon-free complex master alloys according to existing technologies. One of the most problematic places is the negative effect of silicon on the weldability of low-alloy steel, sharply increasing the heterogeneity of welds in sulfur and phosphorus and increasing their susceptibility to hot cracks. The cyclic strength of welded joints decreases markedly with an increase in the silicon concentration of steel. Also in this case, there is a threat of the formation of silicon monoxide, which significantly increases the fragility of the finished steel products. Also, steels processed with alloys containing silicon are prone to decarburization, the formation of surface defects during hot working and graphite formation, which reduces their endurance limit.

In the research it was possible to prove that the use of silicon-free complex ligatures (SFCL) in smelting made it possible to obtain an increase (2–3 times) in the entire complex of mechanical and operational properties, especially ductility, impact strength at normal and negative test temperatures (cold resistance), fatigue strength. In some cases, the level of properties of cast metal reaches the deformed version of its manufacture, for example, rolled products and even metal obtained by electroslag remelting. Processing of the melt of various BKL steels when tapping from the furnace into a pouring ladle instead of aluminum master alloys, silicocalcium and ferrocerium (according to the current technology) provided the required level and high stability of the mechanical properties of 20GML steel. Also, thanks to the use of BCL, it was possible to reduce the consumption of ligatures and deoxidizers by 4.2 kg per ton of liquid metal and increase the yield of rejection of casting defects by 6–10 %. It has been established in the work that BCL treatment leads to stabilization of the chemical composition, refinement of the grain structure of steels, as well as an increase in its dispersion and the level of mechanical characteristics.

Keywords: *silicon-free complex ligatures, chemical composition, mechanical characteristics, alloyed steels.*

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1. Introduction

There is a need to reduce the concentration of silicon in low-alloy and alloy steels to increase the homogeneity, weldability and performance of metal products [1–3]. It has been established that it is advisable to use carbon calm steels with reduced silicon content instead of standard calm steels of the corresponding grades for applications where high ductility, reduced metal contamination with silicates and improved weldability are required. They are also promising instead of a boiling and semi-calm flock for structures, products and machines, the manufacture and operation of which require increased uniformity of composition and mechanical properties, improved macrostructure and surface of rolled products. Taking this into account, as well as foreign experience, it was concluded that it is necessary to create and develop economical low-silicon and low-silicon calm steels instead of standard ones. At the same time, a reduction in the consumption of siliceous ferroalloys by 2–12 kg per ton was achieved, and the cost of production was significantly (by 0.3–3 %) reduced.

Low-silicon and low-silicon calm steels should be mastered on a mass scale instead of boiling and semi-quiet steels when steel-smelting shops are transferred to continuous casting.

2. The object of research and its technological audit

The object of research is the processes that affect the mechanical characteristics of steels after the treatment of melts with silicon-free complex ligatures according to existing technologies. Analysis of the chemical composition of serial low-silicon and alloy steels by statistical processing showed the following:

– low degree of reduction in the number of non-metallic inclusions of the above steels;
– unstable chemical composition and mechanical characteristics of low-silicon and alloy steels processed in the traditional way.

When using new silicon-free complex master alloys, it was proved that the optimal level of mechanical characteristics of the studied steels was achieved. It has been determined that in ferroalloys there are two significant drawbacks associated with the presence of silicon in their composition and a rather low content of such elements as calcium, rare earth metals, vanadium, niobium and others. An even greater disadvantage is the lack of complexity of traditional materials. The development of new silicon-free complex ligatures (SFCL) solves this problem in metallurgy.

3. The aim and objectives of research

The aim of this research is to determine influence modifications silicon-free complex master alloys to improve the mechanical characteristics of alloyed steels.

In order to reach the target goals were delivered the following tasks:

1. Determine the assimilation of elements in steels with reduced silicon content under the action of modification.
2. Give methods for modifying alloy steels
3. Describe the mechanical characteristics of alloy steels.

4. Research of existing solutions of the problem

Modern steels are multicomponent systems, but they are widely used in various fields of human activity. They are used in reinforced concrete structures, reinforced concrete wheels and others. At the same time, improving the quality of structural products is one of the priority areas of research [4]. However, these works do not consider such problems as improving the morphology of non-metallic inclusions, reducing the content of sulfur and phosphorus with simultaneous stabilization of the chemical composition and increasing the level of mechanical characteristics.

Among the main directions for solving this problem of using steel products found in the resources of world scientific periodicals, one can single out [5, 6], but they do not consider the effect of modification with a reduced silicon content. Works [7, 8] are devoted to the study of methods for processing steels by using silicon-containing master alloys, however, the problem of the occurrence of silicon monoxide, which significantly embrittles steel products, remains unresolved. In [9], it was noted that research on the treatment of steel in a liquid state with silicon-containing modifiers is topical. However, this work has not fully disclosed the mechanisms by which there is a decrease in non-metallic inclusions that affect the mechanical characteristics of steel.

The authors of [10] showed that when using a complex additive with low silicon content, the characteristics of the alloys increase. But the question remains about the effect of rare earth elements on the quality of the finished metal. A similar situation is described in [11], but it also assumes the absence of REM in the composition of the modifier, which makes it impossible to form a sufficient level of characteristics after out-of-furnace processing of materials.

It was shown in [12] that the content of such elements as Ca, rare earth metals, Ni does not provide a sufficient level of mechanical characteristics. Therefore, it is very important to use methods that will help ensure sufficient quality of the finished product.

It was considered in [13, 14], which emphasizes the inaccuracy of using silicon for processing steel melts. This suggests that it is necessary to carry out research in this direction in more detail, since it is precisely the optimal composition of this important element that will make it possible to avoid the appearance of an excess of silicates in iron-carbon alloys for various purposes.

The author of [15] emphasizes the importance of using modification to improve the quality of finished products from iron-carbon alloys. Although this statement can be considered as an argument for the use of steels with a reduced silicon content, at the same time, such materials do not have the complexity of using traditional materials. The development of new silicon-free complex ligatures (SFCL) solves this problem in metallurgy. Table 1 shows the compositions of some SFCLs [8].

Table 1

Compositions of various grades of SFCL

Brand SFCL	Mass fraction of elements, %			
	Aluminium	Calcium	REM (rare earth metals)	Other elements
AKCe	5–25	5–15	10–30	–
ACCET	10–30	10–15	5–30	Titanium 10–20
AKCEF	5–30	10–15	10–30	Vanadium 5–30
AKTseB	10–30	10–15	10–30	Niobium 5–20
AKCER	5–15	10–15	20–30	Bor 1–5
AKCeTF	15–25	5–15	10–30	Titanium 0.5–9, vanadium 0.5–3
FCTSED	5–90	5–15	5–30	Copper 5–15

Therefore, the results of the analysis make it possible to conclude that a very important point is the possibility of using modifiers with low silicon content in the form of briquettes, since they are completely dissolved in the steel melt. This will improve the level of mechanical characteristics of alloyed steels and the quality of the finished metal.

5. Methods of research

In order to determine which SFCLs are used to process alloyed steels, analytical review was applied.

Analysis the chemical composition of alloy steels of various grades showed, that this article besides dial with next alloyed steels were used: 20L, 45L, 40KhL, 30KhNML, 5KhNML, 5KhNVL, 10Kh18N9TL and 10Kh18N12M3TL. To receive accurate and reliable results used a complex of modern methods definitions properties studied materials. The chemical composition of steel was determined on high-precision instruments: Polivak E-600 and LECO (England). Mechanical properties determined on standard discontinuous samples at discontinuity machine MUP-20 and pendulum pile driver MK-30 (Russia). Treatment experimental data performed using contemporary computer Microsoft Office 2021 programs.

6. Research results

Calm low-silicon steel 15G2AF(D), an analogue of semi-quiet steel 15G2AFDps, has been developed and mastered under the conditions of pouring metal on continuous casting machines (CCM).

Low-silicon ageless steels 08Yu (for automobile cold-rolled sheet) and 07T (for hay-binding wire) were created. However, the areas of use of these steels are limited, and the technological principles of their production are unacceptable in the smelting of low-silicon steels for mass use due to the high consumption of high-quality and scarce

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deoxidizers, and increased requirements for the purity of metal products.

According to the results of research by PJSC «Arcelor-Mittal Kryvyi Rih» (Ukraine), the quality level of large forging ingots made of alloyed steels, which is necessary for the effective implementation of high and mobile technologies in mechanical engineering, is achieved only when using silicon-free calm steel. Standards for the chemical composition of small- and low-silicon calm steels for mass use have been developed [14].

Modification is one of the ways to influence the structure and, as a result, the properties of the metal.

The modification technology should provide a solution to two main tasks:

– maximum and stable assimilation of active elements by liquid melt;

– identification of optimal concentrations of active elements (calcium, REM, magnesium, titanium, etc.), that is, optimization of the modifier specific consumption.

The development of the modification technology includes a reasonable choice of the composition of the ligature, which can provide a solution to the problem. These most frequently occurring problems include the elimination of gas-shrinkage defects, the reduction of contamination of castings with non-metallic inclusions, the improvement of their mechanical properties, the increase in cold and heat resistance of castings, etc.

The introduction of calcium into steel increases its fluidity, modifies oxide and sulfide inclusions, improves the plastic properties of castings, etc.

Supplementation of the ligature with barium leads to an increase in the absorption of calcium and, accordingly, to an increase in its positive effect [15].

Rare-earth metals do not impair the fluidity of steel, reduce the sulfur content in it, effectively modify non-metallic inclusions, refine the cast structure of castings, weaken segregation processes and sensitivity to hydrogen, etc.

Active nitride-forming elements (titanium, vanadium, etc.) weaken the negative effect of elevated nitrogen concentrations, refine grain, increase the strength characteristics of castings, etc.

The modifiers should be added to the preliminarily deoxidized metal in order to exclude the direct interaction of active elements (calcium, rare earth metals, etc.) with the oxygen of the melt and preserve them for modifying non-metallic inclusions and forming the necessary structure of the metal matrix.

Silicon calm steel is deoxidized sequentially with ferromanganese (from 2 to 4 kg/t) and secondary aluminum ingot (from 0.5 to 2.4 kg/t), and low-silicon calm steel is deoxidized with silicomanganese (from 3.0 to 9.1 kg/t) and ingots of secondary aluminum (from 0.25 to 1.3 kg/t) in the ladle during the taping of the melt from the unit. Deoxidizers and modifiers for some grades of low silicon and small siliconsteels are shown in Table 2.

To obtain a completely calmed metal in low-silicon (up to 0.1 silicon) calm steels, it is necessary to have at least 0.005 % acid-soluble aluminum [16].

The content of silicon and aluminum during casting in low-silicon steels was, respectively, from 0.02 to 0.04 % and from 0.005 to 0.06, and in low-silicon steels – from 0.05 to 0.15 % and from 0.005 to 0.03 %.

The assimilation of elements during deoxidation and alloying of quiet steels with low silicon content is shown in Table 2.

Table 2

Assimilation of elements in steels with a reduced silicon content

Steel type	Assimilation of elements, %		
	Manganese	Silicon	Aluminium
low silicon	54–79	–	11–33
small silicon	71–88	75–87	20–34

New SFCL simultaneously with deep deoxidation, refining and modification of the structure provide microalloying of processed alloys. It ultimately leads to a sharp increase (2–3 times) of the entire complex of mechanical and operational characteristics. In some cases, the level of properties of cast metal reaches the deformed version of its manufacture, for example, rolled metal and even metal obtained by electroslag remelting.

Modification of steel grades 20KhL and 08GDNFL with a new ligature leads to an increase in impact strength at negative test temperatures (cold resistance) by 2–3 times compared to steel smelted by serial technology. The processing of the SFCL melt when tapping from the furnace into the pouring ladle instead of aluminum, silicocalcium and ferrocerium (according to the current technology) provided the required level and high stability of the mechanical properties of steel 20GML, reduced the consumption of ligatures and deoxidizers by 4.2 kg per ton of liquid metal, increased the yield of good and reduction of rejects due to casting defects by 6–10 %. SFCL treatment leads to grain refinement and increased structure homogeneity. Comparative mechanical properties of steel of different grades after SFCL processing and according to existing technologies are given in Table 3.

Table 3

Mechanical characteristics of steel after SFCL processing and according to existing technologies

Steel	Mechanical characteristics				
	Ultimate strength, MPa	Yield strength, MPa	δ, %	Ψ, %	KCU, MJ/m^2
Carbonaceous					
20L	540/550	280/305	24/33	40/59	8/9
45L	1280/1370	750/800	3/6	9/14	0.5/1.3
Alloyed					
40KhL	853/866	684/703	11/16	26/38	3.3/5.8
30KhNML	863/882	723/735	14/22	34/59	7.5/13
5KhNML	1180/1270	972/1014	13/25	41/50	5/7.8
5KhNVL	1130/1157	945/990	8/14	30/44	3.3/5.3
Highly alloyed					
10Kh18N9TL	505/512	264/275	30/68	40/72	18/42
10Kh18N12M3TL	516/553	235/384	33/50	34/58	10.5/22.5

According to the data given in Table 3, the numerator shows the properties of steel smelted using the current technology, the denominator – after processing 0.2–0.3 % of SFCL.

As follows from Table 3, the use of SFCL significantly increased the plastic characteristics and impact strength with some increase in strength.

7. SWOT analysis of research results

Strengths. SFCL modification has a positive effect on structure formation. This results in a higher level of mechanical performance and improved quality of the finished metal.

The positive aspects of the study also include the fact that:

– there is a decrease in the melting time, since the SFCL is produced by a non-melting method for several tens of minutes per briquette. While serial deoxidizers are made in a fused way, as a result of which a minimum of 2 hours is required for 1 ligature;

– increases the efficiency of work on the production of steel products in general;

– the rate of production of finished wheels increases without loss of quality;

– the production of SFCL is more environmentally friendly than the use of ligatures smelted in the traditional way.

Weaknesses. A slight increase in the cost of production for 1 modifier briquette, which is offset by the need for a smaller amount of them during steel smelting in comparison with serial counterparts, which require more, and they are also more expensive.

Despite the fact that 1 SFCL briquette is more expensive than 1 ingot of master alloy made in the traditional way, SFCL is needed 4–5 times less in quantity and weight, as a result of which they are still lower in cost than traditional counterparts.

Opportunities. The use of SFCL in the smelting of alloyed steels contributes to the fact that when they are used, there is a significant reduction in energy consumption and an increase in the level of mechanical characteristics with a simultaneous decrease in the cost of production of the finished metal. The estimated economic effect of the introduction of multifunctional modifiers is approximately 0.25 USD/1 ton of steel.

Threats. For the manufacture of SFCL, it is necessary to buy shavings of titanium and aluminum alloys, as well as anthracite powder. But at the same time, when using them, there is no need to look for and provide places that are needed for the disposal of industrial waste.

To date, there are analogues of SFCL, but most of them are still manufactured by the fused method, where not only significant energy costs are important, but also places where it is necessary to dispose of industrial waste generated during their use [17, 18].

8. Conclusions

1. As a result of the work carried out, it was determined that all components of the modifier with low silicon content were assimilated by steel melts.

2. The methods of modification of alloyed steels given in the work showed that new BCL, simultaneously with deep deoxidation, refining and modification of alloyed steels, provide a sharp increase in the mechanical characteristics of steels (by 2–3 times).

3. The paper shows that the processing of the BCL melt when tapping from the furnace into the pouring ladle instead of aluminum, silicocalcium and ferrocerium (according to the current technology) provided an increase in the quality of the finished steel product.

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