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INTEGRATED LADLE TREATMENT OF 40HN3MF STEEL USING FESIAL AND FEMN FOR METALLURGICAL ROLLERS

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ABSTRACT
This paper is a review and deals with the study of manufacturing rollers for met-allurgical furnaces with improved performance characteristics. The main attention is paid to complex extra-furnace treatment aimed at improving the mechanical and thermal properties of materials. The study includes the analysis of existing steels and technological approaches. Steel 40HN3MF was selected as the main ob-ject of study.
The chemical composition was optimized using the ThermoCalc software pack-age, where the silicon and aluminum content was varied. The effect of FeSiAl and FeMn deoxidizers was studied to increase strength and heat resistance of materi-als. The work uses literature data that reflect modern trends in the development of steels for metallurgical equipment.
The results obtained allowed formulating recommendations for improving the structure and performance characteristics of metallurgical furnace rollers.

INTRODUCTION

Metallurgical furnaces used in various metallurgical processes such as smelting, rolling and heat treatment operate under extreme temperatures and are ex-posed to mechanical and chemical stress. Stability and durability of these fur-naces directly depend on the quality of the materials they are made of, as well as on the technologies used to treat them. In recent decades, special attention has been paid to the development of methods of improving the performance of furnace components. One of the most promising areas is complex out-of-furnace treatment that can significantly improve the strength, heat-resistant and corrosion properties of materials, thereby increasing the service life of furnaces and improving the efficiency of metallurgical processes. According to the existing research, adding manganese to steel can improve its performance.

Adding manganese to steel has a significant effect on its mechanical and performance properties. Manganese is an important alloying element that im-proves various characteristics of steel, including strength, wear resistance and machinability. Depending on the manganese content, various effects can be achieved, which allows using the steel in various industries and for different types of applications.

The use of manganese steels:

– High-manganese steels (with the manganese content of 10 to 14 %) are used in conditions of intense wear, for example, for the production of crushers, jaw and cone crushers, excavator parts and mining equipment.

– Manganese steels with a lower manganese content (up to 1-2 %) are used in various areas of mechanical engineering, including the manufacturing of such structural components as shafts, gears and axles operating under normal or increased loads.

Thus, adding manganese to steel significantly improves its mechanical properties and expands the areas of application of the material.

High-manganese steels that contain 8.5–15 % manganese, due to their high wear resistance under impact loads, for many years have remained an indispensable structural material for manufacturing replaceable parts of machines and equipment in mechanical engineering, mining, metallurgy, railway and the other industries. Linings of vortex and ball mills, tram and railway frogs and turnouts, track links, sprockets, excavator bucket teeth and other parts are made of these steels (Likholobov, 2012). Such steels can also be used to manufacture various parts of metallurgical furnaces with increased performance properties. Some of them include: furnace fireboxes, masonry furnace and crucible components, grates, components for cooling systems, screw elements and ladles, burning elements. The use of high-manganese steels in these components improves their performance characteristics, reduces the frequency of maintenance and improves the overall efficiency of metallurgical processes.

High-manganese steel can also be used to make furnace rollers, especially for furnaces that are subject to high temperatures and mechanical stress.

Metallurgical furnace rollers play an important role in the metalworking process. They are an integral part of many types of furnaces, such as smelting, annealing, roasting, and rolling furnaces. These devices help to ensure stability of the furnace and also contribute to the improvement of technological processes.

Metallurgical furnace rollers perform several main functions:

– Supporting and moving materials. They ensure the movement of metal blanks, ingots, products, and other materials inside the furnace, which is necessary for uniform heating or melting. In some cases, rollers can be part of a system for automatic feeding or extraction of materials;

– Minimizing friction. Rollers reduce friction between the workpiece and the furnace walls, which is important for increasing the service life of both the workpiece and the equipment, as well as improving furnace efficiency;

– Providing high temperature resistance. Rollers are used to move materials through areas with extreme temperatures. This is a very important function, as metallurgical furnaces can operate at temperatures reaching 1000-2000°C, de-pending on the type of metal and the process. Rollers must be made of high-strength materials that can withstand such conditions;

– Reducing mechanical stress. They also help to distribute the load and to reduce wear of the other furnace components, such as screws, conveyor belts or other mechanisms.

Rollers for metallurgical furnaces can be solid-cast, composite (with a steel core and heat-resistant shell), water-cooled and floating to compensate for thermal expansion. Depending on the material, they are made of heat-resistant steel, ceramics, cast iron or have a protective coating to increase wear resistance. According to the area of application, rollers are used for heating and annealing furnaces, cooling sections and continuous casting furnaces where high heat resistance and resistance to mechanical loads are required. They are also divided into driven that actively move the blanks, and non-driven (support) that perform a supporting function.

EXPERIMENTAL PART

The study of manufacturing rollers for metallurgical furnaces with improved performance through com-plex out-of-furnace treatment is key to enhancing their durability and efficiency under high temperatures and mechanical loads. Such treatment methods significantly boost wear resistance, heat resistance, and resistance to mechanical damage. To achieve increased performance characteristics of rollers, various methods of material treatment are used, which can significantly improve their wear resistance, heat resistance, and resistance to mechanical damage. Let's consider the main aspects of this approach.

1. Selecting the material for manufacturing rollers

High-manganese steels with good wear resistance and resistance to high temperatures are often used to manufacture rollers for metallurgical furnaces. However, various methods of out-of-furnace treatment can be used to improve the performance characteristics of the material.

2. Complex out-of-furnace treatment

Complex out-of-furnace treatment includes several processes that can significantly improve the properties of the material and the rollers in particular. Here is a histogram comparing the properties of the material before and after different types of out-of-furnace treatment. It shows how each method affects the material hardness, wear resistance, corrosion resistance, heat resistance and viscosity.

The diagram (Figure 1) shows how different treatment methods affect such material properties as hardness, wear resistance, corrosion resistance, heat resistance and toughness. Heat treatment (quenching and tempering) in-creases hardness and wear resistance (up to level 7), improves toughness, which is critical for rollers operating under mechanical loads. Nitrocar-burizing/nitriding significantly increases wear resistance (up to 8) and corrosion resistance (up to 6) by developing a durable surface layer. Inert gas treatment increases heat resistance (up to 7) and reduces oxidation maintaining the chemical stability of the material. Plasma spraying significantly improves hard-ness, wear resistance and heat resistance (up to level 8) forming a protective layer. Plasma-activated spraying (PAS) provides maximum performance for most properties: wear resistance and heat resistance reach level 9, and hard-ness and corrosion resistance level 8. This makes PAS especially effective for rollers in metallurgical furnaces.

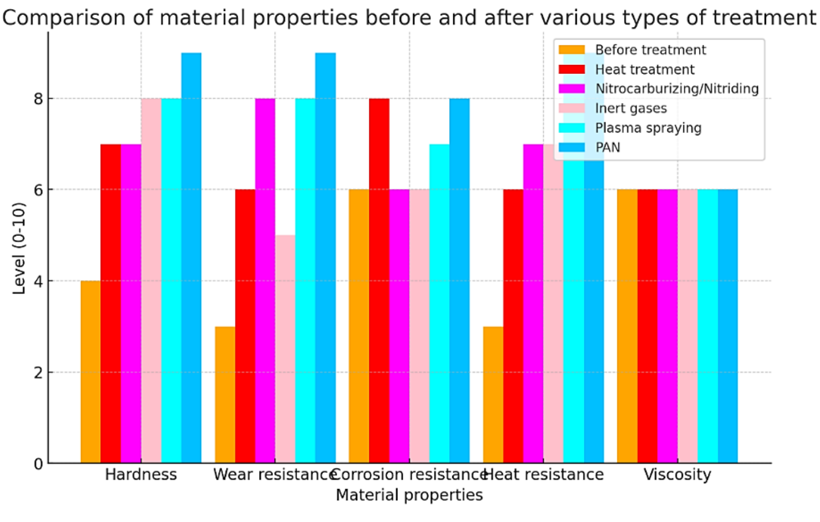


Figure 1. Different methods affecting the material properties
Note – compiled by the authors

High-manganese steels are commonly used for furnace rollers due to their good wear and heat resistance. However, out-of-furnace treatments can further enhance their properties.

This includes processes like heat treatment, nitriding, inert gas treatment, plasma spraying, and plasma activated spraying (PAS).

At the initial stage of this study, a literature review was conducted to analyze current approaches to improving furnace roller properties. Recent research emphasizes the use of inoculants to enhance the crystallization process in casting (Zatulovsky, 1989; Morton & Bryant, 1979; Grigorenko, Kostin, Golovko, et al., 2015; Petrova, 2006; Harvey & Noble, 2007; Scaland, 2001). Studies (Zatulovsky, 1989; Morton & Bryant, 1979) highlight the long-standing use of inoculants of various origins, while modern works focus on updated compositions, particle sizes, and innovative introduction methods. In (Petrova, 2006; Harvey & Noble, 2007), inoculants containing Ce, FeSi and Ca demonstrated positive effects on primary crystallization, acting as both modifiers and microcoolers.

Active development of this area is caused by the fact that traditional methods of improving the properties of materials, such as alloying, heat treatment and modification of ingots, have almost reached the limit of their effectiveness. It should be emphasized that high-alloy steels, including wear-resistant, heat-resistant and corrosion-resistant alloys, are most often selected as objects of research. This is due to the high cost of nanomodifiers, which significantly increases the cost of the final product. In addition, the process of adding nanomodifiers to molten steel is a complex technological task that requires introducing an additional production stage (Vladimirov & Golubev, 1999; Orlov, Malyshevsky, Khlusova, & Golosienko, 2014; Kovalev, Ryaboshuk, Issagulov, Sultamurat, & Jironkin, 2016).

Studies (Russian Federation, 2009a; Russian Federation, 2009b; USSR, 1971; Gulyaev, 2001; Issagulov, Kvon, & Kulikov, 2019; Goldstein, Grachev, & Veksler, 1989; Perelygin, 2008; New high-strength weldable wear-resistant steel, 2005; Duzcukohfu, 2015) are focused on the analysis of the effect of nanomodifiers on increasing the material wear resistance. Structured composite materials and chemical compounds such as SiC, TiO_2 and others were used as nanomodifiers. All the studies showed an increase in wear resistance from 5 to 20% as a result of nanomodification with these compositions.

The analysis of the effect of nanomodifiers on the characteristics of steels is one of the promising areas in modern metal science.

For manufacturing rollers for metallurgical furnaces using high-manganese steels, steel grades are usually selected that have high wear resistance, heat resistance and good mechanical strength. The main element affecting these characteristics is manganese, which, in combination with the other alloying elements, improves the properties of steel.

Various grades can be used for the manufacture of rollers for metallurgical furnaces. These steels must contain a large amount of manganese. As an example, the following steel grades can be mentioned: 110G13L, 20H13, 27HGSA, 16HN60, 30HGSA, 40HNMA, 40HNMF, 40HN3MF, etc.

In work (Likholobov, 2012), steel grade 110G13L was selected as the material. This steel was melted in an arc furnace with the basic lining, ensuring an effective process of remelting and alloying of components. In another work (Issagulov, Ibatov, Kvon, & Arinova, 2019), the object of study was steel grade 30H3MF, which belongs to the group of chromium-molybdenum steels with the possibility of improving properties.

The chemical composition of steel 30H3MF is similar to grade 30HN3MF but the absence of nickel causes reduced viscosity indices. The study focused on increasing the material wear resistance through additional microalloying with vanadium and titanium, which are effective carbide-forming elements. The consequence of this is decreasing the Mn concentration in (Al) in the cast state and decreasing the amount of Al_6Mn dispersoids formed during annealing (Toleuova, Dostayeva, Zharkevich, & Adilkanova, 2020; Kulikov, Aubakirov, Kvon, et al., 2019; Batessova, Omirbay, Sattarova, et al., 2023; Aubakirov, Issagulov, Akberdin, et al., 2022; Dostayeva, Yerahtina, Zholmagambetov, Medeubayev, & Zholmagambetov, 2021; Kovalyova, Yeremin, Arinova, Medvedeva, & Dostayeva, 2017; Belov, Dostaeva, Shurkin, et al., 2016). Table 1 shows comparative indicators for steels 40HNMF and 110G13L.

Steel 110G13L is suitable for rollers operating under conditions of intense abrasive wear and impact loads at moderate temperatures. It is a good choice for furnace areas with high mechanical impact.

Steel 40HN3MF is better used for rollers that are exposed to high temperatures and require corrosion resistance and heat resistance. It is suitable for areas with stable thermal loads and moderate mechanical impacts.

Table 1. Comparative indicators for steels 40HNMF and 110G13L

Characteristic	Steel 40HNMF	Steel 110G13L
Composition (basic elements)	C (0.4%), Cr (1.0-1.5%), Ni (1.5-2.5%), Mo (0.2-0.3%), Mn	C (0.95-1.05%), Cr (11-13%), Mn
Strenth	High	Medium
Wear resistance	Medium (uncreases after treatment)	Very high
Heat resistance	High, up to 600°C	High, up to 400°C
Corrosion resistance	High (due to Ni and Mo)	Medium (less stable in aggressive environments)
Impact toughness	High	Medium
Treatability	Good	bad
Welding	Good	Complicated
Use	High temperatures, aggressive media	High mechanical loads, intense wear
Note – compiled by the authors		

Figure 2. Comparison of steels 40HN3MF and 110G13L properties
Note – compiled by the authors

Based on the conducted monitoring and information analysis, steels of the 40HN3MF grade were determined as the object of research. Grades of this type are widely used at the plants of the Republic of Kazakhstan for producing various parts of metallurgical equipment: couplings of conveyor belts, baskets, elements of shut-off valves, as well as for furnace rollers.

The 40HN3MF grade of steel is complex-alloyed, since it contains alloying elements of different nature. The steel has a unique set of strength and ductility properties, which makes it a promising material for the production of critical parts.

Table 2. Chemical composition of steel 40HN3MF (SS 4543-2016)

Main elements content, %					Mechanical properties		
C	Mn	Cr	Ni	Other elements	σ_B, MPa	δ, %	KC, J/cm^2
0.33-0.40	0.3-0.8	1.2-1.5	3.0-3.5	0.35-0.45 Mo 0.1-0.18	880	≥ 10	≥ 59
Note – compiled by the authors							

This steel belongs to the class of improved chromium-nickel-molybdenum steels; it is one of the best grades of structural engineering steels. Due to nickel alloying, this steel has a large reserve of toughness; the presence of molybdenum in the composition significantly reduces the tendency to temper brittleness that is typical for steels of this class. The main advantage of chromium-nickel-molybdenum steels is their high hardenability, up to sections of 80-100 mm; they provide a martensite and lower bainite structure after complete quenching in oil. This combination of properties makes this steel extremely common for producing large-sized parts that require a combination of high strength and toughness. However, the possibilities for improving the properties of steels of this class are almost exhausted. This steel is alloyed with a small amount of vanadium, which provides a fine-grained structure and some increase in strength properties compared to the 40HN2M grade. However, it should be noted that additional vanadium alloying requires additional introduction of scarce nickel to maintain toughness, which is undesirable. Thus, the use of modification-type treatment is a good alternative for improving properties compared to changing the steel composition.

One of the ways to improve the properties of this steel by developing a defect-free homogeneous structure, the combined effect of introducing nanomodifiers and inoculants was determined as an internal factor.

DISCUSSION

To conduct experimental studies and to determine the optimal steel composition, the analysis was performed using the Thermo-Calc software package. The results obtained allowed studying in detail phase transformations, thermodynamic characteristics and the effect of alloying elements on the properties of the alloy.

Phase transformations in the Fe-Si-Al ligature were studied using the Thermo-Calc software package by constructing polythermal sections for this ternary system. The con-tents of silicon in the range of 45 % and aluminum 15% were considered as variable parameters.

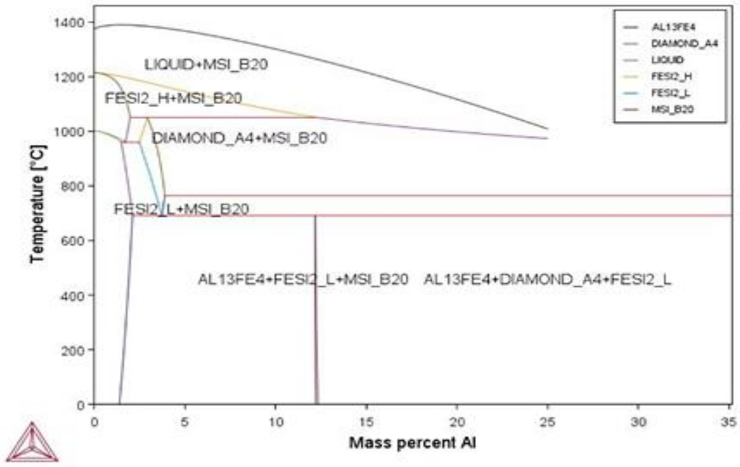
Figure 3 shows an example of polythermal sections for Fe-45Si-15Al alloys. The analysis of the diagrams shows that crystallization of the Fe-Si-Al alloy begins with the release of a double eutectic from the liquid phase, including crystals of silicon and the intermetallic compound FeSi2 (in the range of 49-50 at. % Si).

At the temperature of about 800°C, the intermetallic compound Al13Fe4 undergoes peritectic formation from the residual liquid phase and silicon. Subsequently, when the temperature decreases to 600°C, this intermetallic compound decomposes with the release of aluminum and the formation of the FeSi2_L phase. However, in real conditions, this transformation may not occur due to the low mobility of atoms at such temperatures.

Micro-X-ray spectral analysis of the phase composition of ferrosilicon aluminum shows that the alloy structure consists mainly of silicon grains, iron-aluminum intermetallic compounds Al13Fe4 and the iron-silicon phase FeSi2.

According to the diagrams, the Fe-45Si-15Al alloy is eutectic or near-eutectic with the melting-solidification temperature in the range of 1005-1018°C. When ferrosilicon aluminum is introduced into liquid steel, the phase transformations occur in the reverse order. However, due to a high speed of the processes of extra-furnace treatment and crystallization of steel, these transformations may not have time to be fully realized. In particular, the intermetallic compound Al13Fe4 can be temporarily preserved in liquid steel.

If particles of this phase remain in the melt before crystallization begins, they can serve as nucleation centers for austenite grains that help to refine the structure of cast steel. This is especially true for steel cast at 1400-1450°C, where the ladle processing temperature is relatively low.



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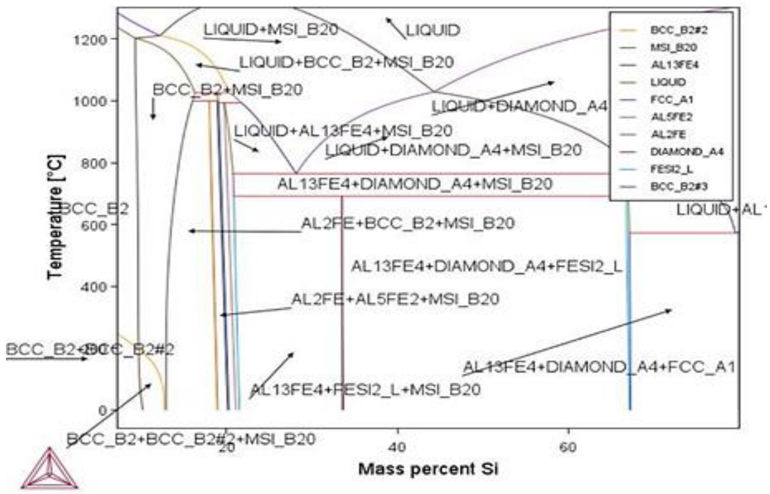

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Figure 3. Polythermal sections for Fe-45Si-15Al alloys:
(a) With different aluminum content; (b) With different silicon contents.

Note – compiled by the authors

Left Diagram – Al-Fe-Si Based Phase Diagram

The left diagram shows the phase transformations in the Al–Fe–Si system depending on the aluminum content (mass percent Al) and temperature.

The upper region labeled LIQUID indicates the temperatures at which the alloy is completely molten.

Areas marked LIQUID + MSI_B20, LIQUID + DIAMOND_A4, etc., represent two-phase fields, where liquid metal coexists with solid phases such as:

1. MSI_B20

2. DIAMOND_A4
3. FESI2_H

The horizontal lines show invariant reactions or phase transformation temperatures, including fields where:

1. FESI2_L + MSI_B20
2. AL13FE4 + FESI2_L + MSI_B20
3. AL13FE4 + DIAMOND_A4 + MSI_B20
4. coexist.

As the aluminum concentration increases, the stability fields of intermetallic phases shift, indicating how the alloy structure changes upon solidification or during heat treatment.

Right Diagram - Si-Fe-Al Based Phase Diagram

The right diagram shows phase transformations depending on silicon content (mass percent Si) and temperature. The upper region labeled LIQUID corresponds to fully molten alloy at high Si concentrations. As temperature decreases, liquid metal coexists with solid phases:

1. MSI_B20
2. DIAMOND_A4
3. AL13FE4
4. FCC_A1
5. BCC_B2

Several two- and three-phase regions are visible, for example:

1. LIQUID + BCC_B2 + MSI_B20
2. AL13FE4 + DIAMOND_A4 + MSI_B20
3. AL2FE + AL5FE2 + FESI2_L

At lower temperatures, stable solid phases such as BCC_B2 and FCC_A1 begin to form, defining the final structure of the alloy after solidification. In general, both diagrams demonstrate how temperature affects the formation of various intermetallic compounds and how changes in aluminum or silicon content influence the melting behavior, the solidification process, and the development of stable structural phases. Together, these diagrams make it possible to evaluate the optimal alloy composition and select appropriate heat-treatment parameters to achieve the required mechanical and thermal properties for metallurgical applications, including the production of furnace rollers.

CONCLUSIONS

In the course of the study, a literature review was conducted on the technology of manufacturing metallurgical rollers and methods of improving the properties of the materials used. Based on a comparative analysis of various approaches, the most effective strategy for improving the performance characteristics of the rollers was identified.

The optimal option was recognized as ladle extra-furnace treatment of 40HN3MF steel with the addition of ferrosilicon aluminum (FeSiAl) and manganese (FeMn). This method can significantly improve the quality of steel due to deoxidation, structure modification, stabilization of the chemical composition and improvement of mechanical properties.

The choice of FeSiAl as the main deoxidizer is due to its ability to effectively bind oxygen and to prevent unwanted oxidation of the alloy. The complex composition of FeSiAl (aluminum content of 5-15% and silicon 20-50%) provides a high degree of deoxidation and improvement of the steel structure. The addition of manganese (FeMn) helps to increase the impact toughness, hardenability and heat resistance of the alloy, as well re-duces the risk of cracking during thermal cycling.

In further planned experimental studies, it is intended to investigate in more detail the parameters of ladle treatment, including the temperature range, sequence, and amount of alloying additions. Melting of 40HN3MF steel is planned to be carried out in an induction furnace at a temperature of 1400-1500 C using a base metal charge of 230 g. During the furnace melting stage, the addition of nickel — 10.6 g and aluminum — 0.33 g is planned. After tapping the melt from the furnace, alloying and modification during secondary (ladle) treatment are planned to be performed by stepwise addition of FeCrAl — 1.92 g and FeMn – 0.64 g.

After completion of ladle treatment, the molten metal is planned to be poured into pre-prepared and preheated molds made of a sand–polymer mixture, followed by cooling at room temperature. It is anticipated that separating alloying between the furnace and ladle stages will allow for more precise control of the chemical composition, improved metal homogeneity, and enhanced stability of steel structure modification.

The use of the selected treatment method helps to increase the service life of metallurgical rollers operating under conditions of high temperatures, intense mechanical loads and abrasive wear. Further studies are planned to include a detailed study of the effect of out-of-furnace treatment modes on steel characteristics, as well as experimental testing of the obtained material under conditions close to real operation. After heat treatment, ladle treatment is carried out using a mold made from a sand-polymer mixture. This material was chosen for its strength, density, porosity, and good technological properties such as flowability, gas permeability, and moldability, which ensure casting accuracy and mold durability.

CONFLICT OF INTEREST: The authors declare that they have no conflict of interest.

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