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Substantiation of refractory lining influence on the electric furnace efficiency for the production of ferronickel

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Abstract

Purpose. The purpose of the research is to substantiate the possibility of replacing existing MgO bricks with the MgO-C bricks due to their resistance to the slag aggressiveness of the electric furnace and the Si content in the resulting metal, which can have a positive effect on reducing the consumption of refractory materials.

Methods. This research will be presented as the results of theoretical and experimental data determining the dependence of the electric furnace on the type of refractory material, walls construction, operating parameters and the electric furnace lining, that are expected to have a major impact on the cost output of production process.

Findings. Based on the presented results, it has been revealed that MgO-C bricks are more effective in terms of preventing the furnace damage depending on refractory materials. Therefore, to optimize the production process, it is recommended to improve the composition of melted metal and slag, as well as to strengthen the control of the process parameters.

Originality. Laboratory analyses are conducted in specialized laboratories, and the presented data have been obtained through the use of devices and equipment required for experimental research.

Practical implications. The refractory materials are one of the main indicators of technical performance and production costs at NewCo Ferronickel in Kosovo. Therefore, the higher performance of the refractory lining will have a positive effect on the furnace durability and the quality of the final product.

Keywords: *ferronickel, refractory materials, slag, optimization, graphite blocks*

1. Introduction

Laterite nickel ores are a very important part of the world's nickel reserves. The nickel content in laterite ore is usually low and is in the range of 0.8-3% [1].

The pyrometallurgical process for ferronickel production at NewCo Ferronickel foundry is very complex as it is accompanied by high temperature, use of metal with a high Si-content, low C-content, very aggressive immiscible slag layers with huge consumption of refractory materials and low level of production capacity utilization. The conventional Rotary kiln-electric furnace (RKEF) is now a worldwide widespread process for ferronickel production from nickel oxide laterite ore, despite its high power consumption. The same production process for ferronickel production is used in the Ferronickel foundry in Drenas [2].

The pyrometallurgical method for obtaining ferronickel from oxide-laterite ores, regardless of the degree of technical and technological improvement, even in newer processes, has many unresolved technical and technological problems. The company faced a number of problems related to the influence of refractory lining on the efficiency of electric furnace.

The proposed replacement of magnesite bricks with MgO-C bricks is related to an increase in the chemical stability of graphite blocks and, in general, with the optimization of the production process. Therefore, it is recommended to improve the composition of the melted metal and slag, as well as to strengthen the control of process parameters.

This research provides some important recommendations for ferronickel production when smelting in RKEF and indicates the importance of refractory lining wear in electric furnaces. The conditions have been determined, including reducing parameters (temperature and time of roasting) and smelting parameters (coke dosage, CaO dosage, temperature and time of smelting).

The electric furnace is a main equipment used in this chain of Fe-Ni production. Therefore, refractories materials that are used in an electric furnace must fulfill the following basic functions, such as:

– to act as a thermal barrier between a hot medium (e.g., flue gases, liquid metal, molten slags and molten salts) and the wall of the containing furnace;

– to represent a chemical protective barrier against corrosion;

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– to ensure a reliable physical protection, preventing the walls from erosion by the circulating hot medium;

– to act as thermal insulation, providing heat retention [3].

The practice of using refractory lining in electric furnaces is solely based on the behavior of various refractories used in different parts of the furnace at elevated temperatures. The selection of the correct refractory lining pattern is usually based on conventional concepts; therefore, this element of the furnace is the most important factor, ensuring high production efficiency [4].

2. Methodology

The refractory lining of the electric furnace consists of three main parts: floor/bottom, vertical walls and roof. According to the engineering specification, the permanent bottom of lining is made of magnesia bricks (Sitmag-N, IL-76, Keiltein, I-76, SA-I), while the working layer of the lining bottom is made of magnesia bricks (KELL). The lower part of the vertical wall is made of special magnesia bricks (ANKERDIB/B, ANKER-WIH/B, Sit Mag. VPK "S"). The smelting bath is made of graphite blocks, while the upper part of the vertical wall is made of magnesia bricks (Sitmag VPK and SA-O). The roof, which is under the exposure of erosive and chemical gasses, is mostly made of magnesia bricks (MSA4, HI4DA-300, MSA2, etc.) SGL Carbon Group and NewCo Ferronikeli [5].

Each of these zones has its own specificity and diversity of strains, but the most specific zone of operation is the smelting zone – the working bath. This zone is exposed to mechanical strains, high temperatures, extreme influence of vibrations and corrosion of metal with a low C-content, high Si-content and a very aggressive acidic slag. Thus, as a result of this concentration of molten crude metal, the three zones of the electric furnace are exposed to the influence of a strong oxidizing environment. Although the carbon oxidation of graphite in the burnt ore zone is minimal, at a temperature of 1300°C this reaction begins to develop rapidly, which affects the extreme corrosion of graphite blocks and magnesia or magnesia-chrome bricks in the zone between the slag and the crude metal. The digestion of carbon from graphite and magnesite occurs due to the formation of carbides: SiC, CoC and CrC of metals. Si, Co, and Cr are impurities of crude metal of the electric furnace. Decarburization of refractory lining with carbon composition in the smelting zone is one of many difficult problems. Although decarburization of the refractory materials still depends on many unresolved issues, it has allowed limited use of graphite blocks and MgO-C bricks in the electric furnace for the ferronickel production in Drenas-Kosovo.

The smelting point of magnesia (MgO) or magnesia-chromite refractories ranges from 1700 to 2100°C, with the exception of carbon-based and graphite-based materials which can withstand temperatures from 2200 to 3000°C. A special characteristic is a metal with a high Si-content (on average 2.2-2.8%) and a low C-content (on average 0.3-0.6%). Occasional peak values of 3.5% Si are possible [6]. Due to the high Si-content in the crude metal, the furnace slag has a high acidity. Determining the dependence of the electric furnace (EF) efficiency on the type of refractory material, the composition of the melted products, as well as other operating parameters, will be performed on the basis shown in Figure 1.

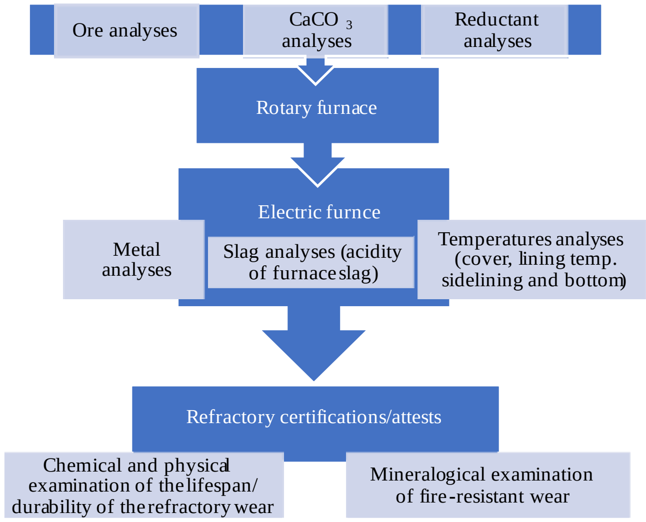


Figure 1. Flowchart for the research methodology

The verification of these performance indicators is based on certificates/attests of refractory materials, chemical analysis of the charge, electric furnace products and other technological materials. Other indicators of the production process performance at the Ferronickel foundry in Drenas have been also determined by a comparative method. Comparison of outputs, process parameters and production practices is based on an analysis of production period from October 2019 to May 2020. Given the fact that refractory materials after electricity are the main indicators that affect the EF optimization and in general the optimization of the ferronickel production process, then, to determine the lifespan/durability of the refractory cover, the operating parameters (chemical, thermal and technological), as well as the quality/properties and the content of refractory materials, have been studied.

3. Results and discussion

3.1. Features of the wear of the electric furnace refractory

Magnesia (MgO) bricks are known as refractory materials with a magnesium oxide content of more than 90% and are made of periclase. Periclase is the only stable MgO modification. These refractory materials are resistance to the action of alkaline slags and melts containing iron oxides. This property is based on the phase conditions in the MgO-FeO and MgO-Fe_2O_3 systems. MgO creates with FeO a full range of magnesiowustite solid solutions ((Mg, Fe)O). In the system, CaO is replaced by MgO, since it is also a highly alkaline, technically pure, readily available oxide with high stability and a smelting point of 2625°C. Depending on the degree of reactivity, technical magnesium oxide can be divided into calcined, sintered, melted [7].

The similar problems are associated with magnesia-chrome refractory bricks, which are composed of MgO-Cr_2O_3 with 17-20% of Cr_2O_3. Carbon-graphite refractory materials are ceramic materials composed of only one chemical element. Carbon materials are amorphous, while graphite has a specific crystalline structure. Graphite refractory materials can be natural and artificial. As a raw material for the production of carbon refractories, metallurgical coke, petroleum coke, heat-treated coal tar pitches and like can be used. These types of refractory are graphitized – manufactured in Acheson resistance furnace or by graphitization with a direct current flow in a continuous graphitization furnace [8].

Naturally occurring flake graphite or artificial graphite is sometimes mixed with amorphous carbon to achieve the desired thermal conductivity. These materials are combined with high-carbon resins or pitch and formed into blocks and slabs [3]. These materials have been used as refractory lining for blast furnaces, electric furnaces, and other metallurgical equipment. Due to excellent corrosion resistance, high thermal conductivity, low thermal expansion, high thermal shock resistance and chemical inertness to slag, these materials are used for bottoms of refractory lining: Si, FeSi, FeNi, FeMn etc. [9].

Table 1 and 2 show several properties of magnesia-carbon bricks and graphite blocks. These data correspond to technical information by SGL Carbon Group and Magnezit Group.

Table 1. Technical data of MgO-C bricks

Description	A	B	C
MgO, %	98	> 97	> 96
Al_2O_3, %	0.1	< 0.2	< 0.2
Fe_2O_3, %	0.4	< 0.6	< 0.6
CaO, %	1.1	> 0.8	> 0.8
SiO_2, %	0.4	< 0.4	< 0.4
C-residual, wt %	14	> 12	> 7
Bulk density, g/cm^3	2.97	> 2.99	> 2.90
Apparent porosity, vol %	4	< 5	< 7
Cold crushing strength, N/mm^2	> 30	> 30	> 30
Thermal mechanical properties			
Thermal conductivity, W/(m·K)	500ºC		11
	1000ºC		9
Coefficients of linear thermal expansion, (K^{-1})	8.6-11.3 · 10^{-6}		

Table 2. Technical data of carbon and graphite blocks

Description	Semi graphite block	Graphite block	High thermal conductivity block
Fixed carbon, max %	78	98	–
Ash, max %	8	0.5	–
Bulk density, g/cm^3	1.50	1.52	1.65
Open porosity, %	20	20	18
Compressive strength, max MPa	30	19.6	30
Bending strength, max MPa	8	7.8	8
Thermal conductivity, W/m·K	–	–	> 30
Coefficients of linear thermal expansion (K^{-1})	8.6-11.3 · 10^{-6}		
Melting index of liquid iron, max %			32

Carbon is a preferable element for use in refractory materials, since it is not wetted by most molten metals and slags, has excellent resistance to thermal shock and its strength is increased when heated [3]. These types of materials have a tendency to oxidize, so this refractory should be used under reducing conditions. According to theoretical data, under conditions of a high oxidizing environment, the process of carbon oxidation of the refractory lining begins at 350°C. To minimize this oxidation effect of the refractory lining and for shaping, it is currently preferred to add oxidation inhibitors such as boron carbide, fine metals (Al, Si, and Mg) or by coating the mold with a protective glaze. Metal smelting crucibles made of clay-graphite were used as they had graphite shapes such as stopper rods and sleeves. Clay-graphite shapes have been replaced, for the most part, by alumina-graphite molds, which provide a longer service life. Clay-graphite shapes have been replaced, for the most part, by alumina-graphite shapes which provide longer service life [3].

3.2. Operating mechanisms and their influence on the refractory lining efficiency

Direct smelting technology is used in electric furnace of NewCo Ferronickel foundry. After electricity, refractory materials are the main indicators of technical performance and production costs at NewCo Ferronickel in Kosovo. The traditional method of refractory masonry in an electric furnace is based on magnesia (MgO), magnesia-chromite bricks, and graphic blocks, which have a positive effect on the service life of the furnace. However, the performance of the refractory lining depends on the composition of the melted products, operating parameters and the construction of the electric furnace lining. Figure 2 shows charge analysis and Table 3 shows the typical operational indicators of the crude ferronickel production process.

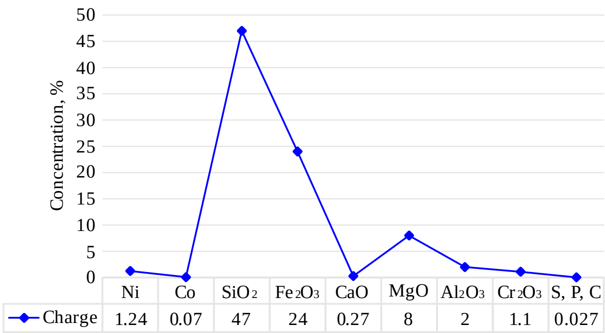


Figure 2. Analysis of the dosed charge in an electric furnace

Table 3. Typical operational indicators of the ferronickel production process in the foundry

No.	Operational indicators	Content value min	Content value max
1	Specific power, KW/m^2	167.5	
2	Dry ore capacity, t/24 h	1476	
3	The composition of the dry ore:		
	Ni + Co, %	1.39	
	Fe, %	18	
	SiO_2, %	46	
4	The composition of the crude metal:		
	Ni, %	11.33	15.3
	Co, %	0.30	0.40
	Si, %	2.0	3.5
	C, %	0.3	0.6
	S, %	1.3	2.02
	Fe, %	78	73
5	The composition of the EF-slag:		
	SiO_2, %	52	62
	FeO, %	17	20
	MgO_2, %	7	15
6	Temperature of:		
	Fire ore, °C	750	
	Ferronickel, °C	1380	
	Slag, °C	1500	
	Gas, °C	900	
7	Specific energy consumption, KW/t ore	630	
8	The composition of gas:		
	CO, %	45-60	
	CO_2, %	35-70	
	SO_2, SO_3, %	0.1	
	Other, %	2.9	
9	Dust, g/mm^3	50	

Kosovo lignite is used as a reducing agent, which is characterized by a low C^{fix} composition and a high ash composition. Among other things, this type of reducing agent also has a low reducing capacity [10].

The low degree of reduction in an electric furnace is one of the parameters that directly affects the operating environment and creates different phase relationships for the process products. In cases where the low degree of reduction of metal oxides and incomplete disintegration of C^{fix} and C of refractory lining prevail over the smelting process, one part of the burnt ore in the furnace will be oxidized, while the other part will be sintered. In this case, except for the C^{fix} reduction from the reducing agent, a portion of C from the graphite blocks will also be oxidized. In addition to graphite, the carbonaceous binder system of magnesia bricks is also oxidized. As a result, refractory materials lose their ability to inhibit wetting, and opened pores contribute to a more intensive penetration of slag. It is well known that iron oxide is able to dissolve in MgO crystals [11].

Figure 3 shows the chemical composition of the slag from the smelting of nickel oxide ores in the electric furnaces of the Ferronickel foundry in Drenas.

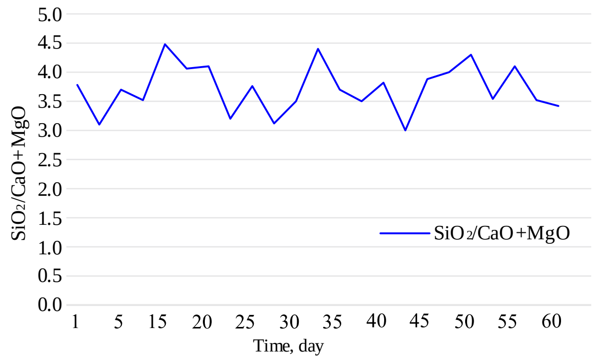


Figure 3. Chemical analysis of slags

Figure 4 presents the thermal variations in furnace components such are the sides and bottom of the furnace, which are influenced by temperature.

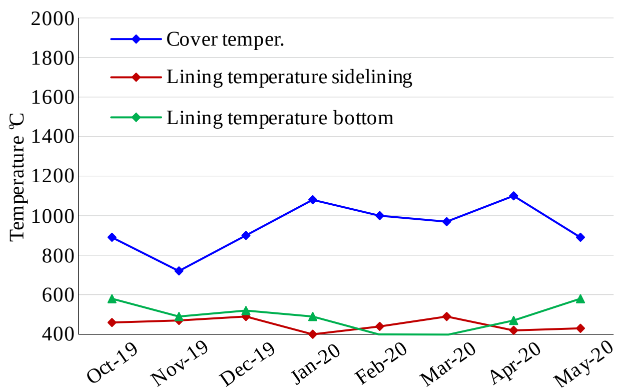


Figure 4. Temperature (°C) during the research period in the three main parts of the furnace

From density measurements in the temperature range of 700-800°C, it follows that magnesium oxidation in this range is slow, while in the temperature range of 1000-1100°C this oxide is very intense, and then chemical stability is observed. Figure 5 shows the damages of the refractory lining in the electric furnace 2.

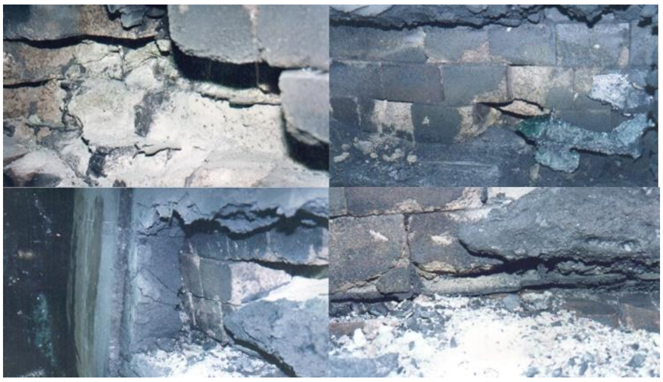


Figure 5. The damages of the refractory lining in the electric furnace No. 2

It has been observed from industrial experience and measurements that the resistance of the graphite blocks to the impact of water is very good. But, eventually, the water remained in the electric furnace, and this amount was absorbed by the magnesium material according to the reaction:

$$MgO + H_2O = Mg(OH)_2. \quad (1)$$

But, in many furnace environments oxygen activity is high enough to be involved in the corrosion process of refractory lining. High oxidation activity is associated with a highly oxidizing environment, while low oxygen activity is associated with a reducing environment, which is controlled by the ratio of CO/CO_2 or H_2/H_2O in this environment [12].

Although from a practical point of view, such reactions would stimulate corrosion of graphite blocks, however, CO due to the reduction of oxides and self-oxidation as a result of the reaction has little effect; ($2CO\ (g) \leftrightarrow C\ (s) + CO_2$), corrosion of mortar and graphite blocks occurs. In this case, above all, the catalytic effect depends on Fe from a poor metal with C, the catalytic ability of which depends on the composition of C in the metal (the maximum catalytic effect of Fe corresponds to the Fe_3C form) [13].

Corrosion of a refractory material, the structures of which are saturated with carbon, develops in two stages [14]; oxidation of a brick matrix under the action of free oxygen during digestion and formation of a decarburization zone and decomposition of MgO, as well as oxidation of C from refractory materials with a C content in the decarburization zone. At high temperatures, in addition to the corrosion of the refractory material under the action of slag, simultaneously with 1450°C, different reactions may develop:

$$C + SO_2 = CO + SO; \quad (2)$$

$$C + SiO_2 = CO + SiO; \quad (3)$$

$$CO_2 + C = 2CO; \quad (4)$$

$$SiO + 3CO = SiC + 2CO_2; \quad (5)$$

$$2SiO_2 + SiC = 3SiO + CO; \quad (6)$$

$$C + MgO = CO + Mg. \quad (7)$$

The process, which would guarantee sufficient chemical stability of the graphite blocks, will take place when the metal temperature is between 1450 and 1500°C, while the slag temperature should be maintained at 50°C above the metal temperature. The boundary between the temperature of a liquid and a solid is within narrow limits, which theoretically stimulates SiO_2 interaction with other basic oxides, and especially the interaction between CaO and MgO. For temperatures higher than the temperature of the liquid, the size of SiO^{4-} and other smelting anions, as well as the electrostatic forces between cations and anions, play a decisive role in the viscosity of the slag, especially for its reactivity. Ferronickel with a composition below 1.25% is considered a poor carbon metal, which at a temperature of 1150°C (in the fire zone) simulates the carbon digestion reaction in the metal, while a fast reaction begins at 1300°C.

The main reaction is Fe and Ni carbonation from graphite carbon:

$$3Fe + 2CO = Fe_3C + CO_2; \quad (8)$$

$$3Ni + C = Ni_3C. \quad (9)$$

These reactions occur at high temperatures, and nickel carbide is unstable in an oxidizing environment because it easily reacts with nickel oxide. In this case, dissolution occurs of NiC and C on the refractory lining with the formation of SiC, CoC and CrC, but the products of these reactions have little effect on the corrosion of graphite blocks.

3.3. Influence of operating conditions on the electric furnace lining

In fact, it is only in the slag zone of the furnace that graphite blocks are used, which generally have highly acidic slag resistance and other good mechanical properties, but show weak chemical stability in contact with molten metal, since it is characterized by a low C-content. From the results of research on the operating conditions influencing on the service life of MgO, Mg-Cr and graphite bricks, is noted that highly acidic slag and poor crude metal with carbon have a major influence on corrosion and other proprieties of refractory materials.

Table 4 compares the technical properties of graphite blocks used in an electric furnace. Graphite blocks are produced by SGL Carbon Group. Blocks of this type have been developed to improve corrosion resistance; their high corrosion resistance is mainly due to the formation of a protective layer on the hot face in direct contact with the molten metal [5].

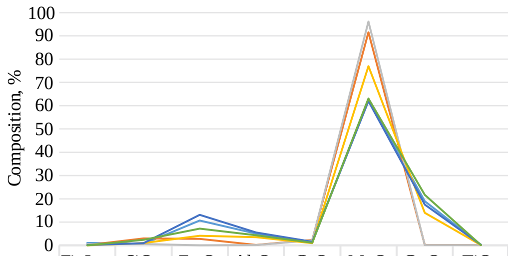
Table 4. Typical properties of used graphite blocks in Fe-Ni-electric furnace

Block	Samples	Density	Porosity	Comprehensive strength	Expansion coefficient	Thermal permeability
Standards		DIN 51918	DIN 51918	DIN 51910	DIN 51909	DIN 59908
No.	No.	g/cm^3	%	N/mm^2	µm/K-m)	µm/K-m)
1	1.1	1.67	20	28.3	2.5	156
	1.2	1.67	20	26.6	2.3	
	1.3	1.66	20	25.3	2.4	
2	2.1	1.68	20	35.1	2.9	
	2.2	1.65	20	32	2.9	151
	2.3	1.66	20	28.5	2.9	
	2.4	1.67	20	29.1	3	
3	3.1	1.65	21	29.1	2.7	
	3.2	1.65	21	26.7	2.8	138
	3.3	1.65	21	26.6	2.8	
	3.4	1.64	21	23.3	2.7	
Average		1.66	20.4	28.4	2.7	148

Figure 6 shows the BC – II1 and II3 samples taken from slag bath of electric furnace No. 2 (BC – is the symbol of the blocks used in the company). A corrosive structure is observed at a depth of about 80 mm and a length of about 400 mm from the face side between the graphite block and the magnesia bricks. No penetration of crude metal is observed, but corrosion resulted from the digestion of carbon from the graphite block in the area of contact with the molten metal. This is presumably due to the fact that NewCo Ferronickel crude metal has rather low carbon content, on average 0.3-0.5%, and in this case, the digestion of the refractory material carbon in the molten metal will increase.

Figure 6. Measurement of dissolution of graphite blocks II3 and II1 in contact with a metal with a low C-content

Figure 7 shows the type of bricks on the bottom of the working lining without graphite blocks and the chemical composition of these types of refractory bricks prior to use in an electric furnace. Figure 8 shows structural roentgen analysis of the brick face. For analysis, a brick sample is selected, the faces of which are in contact with molten products.



	Fir.Los.	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Cr_2O_3	TiO_2
Mg brc. Kell 50	1.04	0.66	10.66	5.04	1.54	62.7	19	0.21
Mg brc. VPK	0.1	3	2.76	0.2	2.38	91.6	0.16	0.1
Mg brc. Kell DH	0.48	0.54	0.01	0.1	2.15	96.2	0.11	0.1
Mg-Cr brc. Wacher	0	1	4.1	3.53	0.9	77	14	0.1
Mg-Cr brc. Radex	0.12	0.9	13.1	5.48	1.53	62	17.5	0.27
Mg-Cr brc. VPS-K	0	2.4	7.15	4.3	1.13	63.1	21.7	0.1

Figure 7. Type and chemical composition of refractory materials before use in an electric furnace

For structural analysis, samples are selected in the area of the working bath between the carbon blocks and magnesia bricks. Photomicrograph images of a RB KELL 50, GB in contact with highly acidic slag and molten metal of FeNi in the electric furnace. Distribution of Mg, Si, Fe, and Ni on the observed surface of RF-1, 2 KELL 50 and BC in contact with crude metal is shown in Figure 8.

As a result of chemical analysis of the refractory material samples used in the electric bath (Fig. 9), one can see the RF-6 sample with a high FeC content, in which the face of the brick or graphite block is in contact with molten metal. In this case, the molten metal has a high Si-content and low C-content.

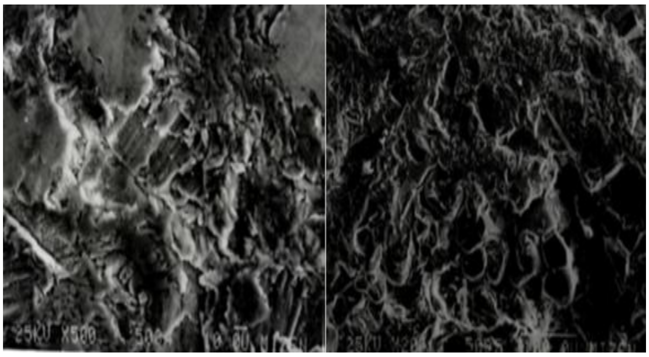
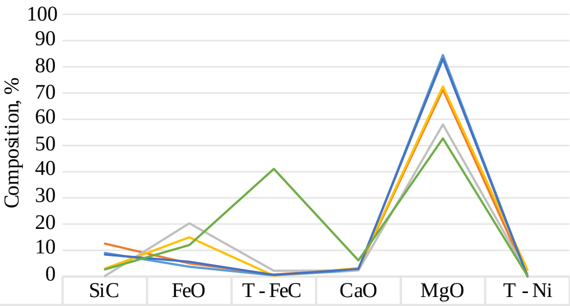


Figure 8. Photomicrograph images



	SiC	FeO	T - FeC	CaO	MgO	T - Ni
RFK-1	9	3.7	0.5	2.4	84.5	0.06
RFK-2	12.6	5.05	0.8	2.88	71.3	0.04
RFK-3	0.2	20.3	2.2	2.33	58	1.02
RFK-4	3	15	0.3	3.26	72.5	2.5
RFK-5	8.4	5.61	0.6	2.86	83	0.09
RFK-6	2.7	12	41.1	6.1	52.7	0.25

Figure 9. SiC, FeC and other compositions of used refractory materials in an electric furnace

The smelting bath of the electric furnace is constantly exposed to highly aggressive acidic slag, oxidizing environment, high temperatures and corrosion of molten metal with low C-content. A specific feature of the NewCo Ferronikeli crude metal is a rather high SiO_2 content, on average 52-62%. These types of slags are acidic (on average FeO ~ 20%, MgO ~ 15%) and are characterized by a high degree of aggressiveness. This aggressiveness depends on the content of SiO_2, which is the main component of the slag. SiO_2 interacts with oxides (CaO, FeO, MgO, MnO, etc.), forming the systems: MgO, SiO_2, $2CaOFeSiO_2$, MgO-FeO-SiO_2, etc., included in the mineralogical composition of galenite, acanthite, dicalcium silicate and other minerals [15].

This attribute depends on the SiO_2 content and is the main component of electric furnace slag. SiO_2 content is the main indicator influencing on the operating conditions of the refractory lining. When analyzing the thermophysical parameters of the electric furnace coating, when the furnace power exceeds 20 MVA during the process of burning or with a high SiO_2 content, the magnesia bricks shown weakness in oxidizing environments. In particular, they show poor resistance to water activity. The operating environment also negatively affects the chemical stability of even graphite blocks, especially when exposed to CO_2, air, and CO. Figure 10 shows a new lining made of MgO-antioxidant brick that has proven successful during application in furnace zones where the refractory lining is exposed to an oxidizing environment.

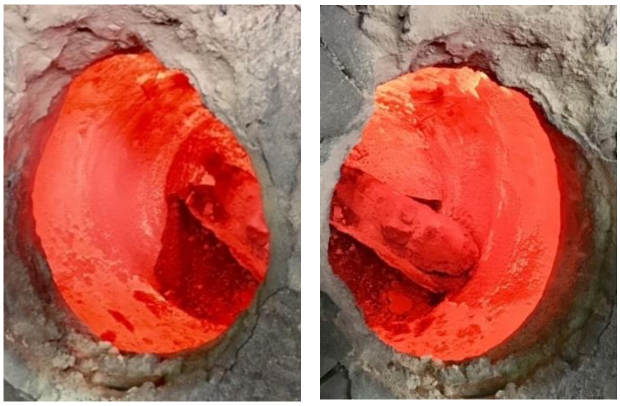


Figure 10. New lining made of MgO - antioxidant bricks

According to the research results of the chemical corrosion of graphite blocks, it has been revealed that the main damage is in the zone of the molten metal. This damage is caused by the digestion of carbon from the graphite block in molten metal with a low C-content.

4. Conclusions

In terms of operational indicators, it can be concluded that the FeNi-electric furnace operates under the influence of slag with high SiO_2-content, metal with low C-content and high Si-content, high temperatures and a very high oxidizing atmosphere. To optimize the process and increase the service life of refractory lining, carbon blocks have been used in electric furnaces for several years.

Under operating conditions, when the smelting bath operates with metal of low C-content and has a high tendency to dissolve the carbon of the graphite blocks, replacing the current refractory materials with composite refractory materials based on MgO-C to improve the electric furnace technical performance would be the best solution.

Refractory wear is identified as sections of the refractory that are either delaminated or extensively immersed in molten metal. Impregnation occurs when the molten material infiltrates into the refractory matrix. In this case, this leads to several changes in the refractory material properties; therefore, to avoid such problems, it is necessary to carefully consider the use of proper bricks in the smelting zones of electric furnace.

Regular inspections of the furnace refractory is proposed, which provides information on the current situation, and, in addition, shows the degree of wear and critical points of wear of the damaged furnace lining. These results are important to the maintenance schedule and can improve the efficiency of the process in terms of refractory materials.

Based on theoretical aspects and from technical report No. 98, this type of material and especially some of the carbon blocks have been developed through measures such as:

– addition of fine alumina, which has high resistance to hot metal;

– reduction of pore diameters to prevent penetration of foreign substances and the hot metal;

– increase in thermal conductivity to reduce the hot face temperature to improve corrosion resistance [10];

– a flat floor will be a constructive solution for furnace bath;

– use of lignite with a higher C^{fix}-content;

– creation of a protective layer from a “solid metal” covering the bath walls in the smelting zone.

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References

[1] Fritsch, R.S., & Muller, H. (2013). Refining of ferronickel, INTECO special melting technologies GmbH, Bruck/Mur, Austria. *The Thirteenth International Ferroalloys Congress Efficient Technologies in Ferroalloy Industry*. Almaty, Kazakhstan.

[2] Guanghui, L., Hao, J., Peng, Zh., Zang, Y., & Jiang, J. (2016). *Ferronickel preparation from nickeliferous laterite by rotary kiln-electric furnace process*. Changsha, Hunan, China: Central South University.

[3] *HARBISON-WALKER Handbook of refractory practice Harbison*. (2005). Moon Township, United States: Walker Refractory Company.

[4] Narasimham, A.V.L. (2007). *Refractory lining failures in FECR furnaces an over view*. INFACON, 7 p.

[5] *Specification for fire retardant material from graphite and carbon products for furnace linings*. (2007). Made by SGL CARBON GROUP dhe New Co "Ferronickel", Glogovc.

[6] Schemmel, T.H., Schade, L., Kouzoupis, P., & Beqiri, F. (2013). Magnesia-carbon refractory lining for ferronickel converters-optimization and lining improvement at NewCo Ferronikeli (Kosovo). *The Thirteen International Ferroalloy Congress, Efficient Technologies in Ferroalloy Industry*. Almaty, Kazakhstan.

[7] Ovčačik, F., & Ovčačikova, H. (2015). *Technology of refractory materials and heat insulating materials*. Ostrava, Czechia: Technical University of Ostrava.

[8] Trisvetov, A. (2012). *The use of graphite in the refractory*. Industry Magnezite Group.

[9] Geerdes, M., Chaigneau, R., & Kurunov, I. (2015). *Modern blast furnace ironmaking: An introduction*. Amsterdam, the Netherlands: IOS Press. https://doi.org/10.3233/978-1-61499-499-2-i

[10] Ibrahimi, I., Deva, N., & Mehmeti, S. (2020). Optimalization of the ferronickel production process through improving desulfurization effectiveness. *Civil Engineering Journal*, *6*(5), 907-918. https://doi.org/10.28991/cej-2020-03091516

[11] Schacht, C.A. (2004). *Refractories handbook*. New York, United States: Marcel Dekker Inc. https://doi.org/10.1201/9780203026328

[12] Meettham, G.W., & Van de Voorde, M.H. (2000). *Materials for high temperature, engineering applications*. Berlin, Germany: Springer. https://doi.org/10.1007/978-3-642-56938-8

[13] Wilkening, S. (2020). *Testing of the alkali sensitivity of carbon and graphic martials*. Bonn, Germany: Vereinigte Aluminium-Werke.

[14] Vullkov-Husovič, T. (2007). *Vatrostalni materiali svojstva i primena*. Belgrade, Serbia.

[15] Nitta, M., Ishii, A., & Nakamura, H. (2008). *Development of carbon blocks for blast furnace hearths*. Nippon Steel Technical Report No. 98.

Обґрунтування вогнетривкої футеровки, яка впливає на ефективність використання електропечей для виробництва феронікелю

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Мета. Обґрунтування можливості заміни існуючої цегли MgO цеглою MgO-C через її стійкість до жорсткого впливу шлаків електричної печі та вмісту Si в отриманому металі, що може позитивно вплинути на зменшення витрат вогнетривких матеріалів.

Методика. Дослідження представлене як результати теоретичних та експериментальних даних, що визначають залежність електричної печі від типу вогнетривкого матеріалу, конструкції стін, експлуатаційних параметрів та футеровки електропечі, які, як очікується, матимуть значний вплив на вартість виробничого процесу. Для визначення терміну служби/довговічності вогнетривкого покриття були вивчені робочі параметри (хімічні, термічні та технологічні), а також якість/властивості та вміст вогнетривких матеріалів на заводах. Лабораторні аналізи проводилися у спеціалізованих лабораторіях.

Результати. Виявлено на основі проведених досліджень, що цегла MgO-C є більш ефективною з точки зору запобігання пошкодженню печі. Рекомендовано для оптимізації виробничого процесу поліпшити склад розплавленого металу та шлаку, а також посилити контроль над основними параметрами процесу. Запропоновано регулярний огляд огнеупору печі, який надає інформацію щодо поточної ситуації і, крім того, показує ступінь зносу та критичні точки зносу пошкодженої футеровки печі.

Наукова новизна. Вперше встановлено, що FeNi-електрична піч працює під впливом шлаку з високим вмістом SiO_2, металу з низьким вмістом C і високим вмістом Si, високих температур і дуже високої окисної атмосфери.

Практична значимість. Вогнетривкий матеріал є одним із основних технічних засобів, що впливає на показники витрат нового підприємства феронікелю у Косово. Більш висока продуктивність вогнетривкої футеровки позитивно вплине на довговічність печі та якість кінцевого продукту.

Ключові слова: *феронікель, вогнетривкі матеріали, шлак, оптимізація, графітові блоки*

Обоснование огнеупорной футеровки, которая влияет на эффективность использования электропечей для производства ферроникеля

Н. Дева, И. Ибрагими

Цель. Обоснование возможности замены существующего кирпича MgO кирпичом MgO-C из-за его устойчивости к жесткому воздействию шлаков электрической печи и содержания Si в полученном металле, что может положительно повлиять на уменьшение затрат огнеупорных материалов.

Методика. Исследование показывает результаты теоретических и экспериментальных данных, определяющих зависимость электрической печи от типа огнеупорного материала, конструкции стен, эксплуатационных параметров и футеровки электропечи, которые, как ожидается, будут иметь значительное влияние на стоимость производственного процесса. Для определения срока службы/долговечности огнеупорного покрытия были изучены рабочие параметры (химические, термические и технологические), а также качество/свойства и содержание огнеупорных материалов на заводах. Лабораторные анализы проводились в специализированных лабораториях.

Результаты. Выявлено на основе проведенных исследований, что кирпич MgO-C более эффективный с точки зрения предотвращения повреждения печи. Рекомендовано для оптимизации производственного процесса улучшить состав расплавленного металла и шлака, и усилить контроль над основными параметрами процесса. Предложен регулярный осмотр огнеупора печи, который дает информацию о текущей ситуации и, кроме того, показывает степень износа и критические точки износа поврежденной футеровки печи.

Научная новизна. Впервые установлено, что FeNi-электрическая печь работает под влиянием шлака с высоким содержанием SiO_2, металла с низким содержанием C и высоким содержанием Si, высоких температур и очень высокой окислительной атмосферы.

Практическая значимость. Огнеупорный материал является одним из основных технических средств, который влияет на показатели расходов нового предприятия ферроникеля в Косово. Высокая производительность огнеупорной футеровки положительно повлияет на долговечность печи и качество конечного продукта.

Ключевые слова: *ферроникель, огнеупорные материалы, шлак, оптимизация, графитовые блоки*