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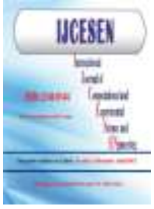

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Research Article

Research of Reactions on Ferronickel Laterite by Rotary Kiln Furnace Process

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Abstract:
Nickel is an important strategic metal, which is mainly used for the production of a wide range in the production of various anti-corrosion steels. Electric furnace, rotary kiln and smelting is currently the world-wide integration process for the production of ferronickel from nickel laterite ore, despite its high energy consumption. In this study, with the aim of providing some meaningful analysis for the production of ferronickel and reactions formed in the rotary kiln. The samples obtained were analyzed under conditions including reducing parameters (temperature and time) and smelting parameters (CaO, Al_2O_3 and MgO ratios). The metal content as well as the Ni, Fe, S and P content of ferronickel were taken into account. The results showed that Ni-containing ferronickel from a laterite with 0.88 wt. % Ni during the process in the rotating furnace is characterized by different reactions which have been verified by XRD diffraction.

1. Introduction

The extraction and processing of ferronickel from lateritic ores have garnered considerable attention in the metallurgical industry, driven by the increasing global demand for nickel. Nickel is a crucial component in the production of stainless steel and various high-performance alloys, which are essential in sectors ranging from construction and automotive to aerospace and electronics [1,2,3]. Lateritic ores, abundant in tropical regions, are one of the primary sources of nickel. However, their complex mineralogy poses significant challenges for efficient extraction and processing.

Among the various techniques developed for nickel extraction, the rotary kiln furnace process is prominent due to its operational efficiency, scalability, and adaptability to different ore types [2]. This process involves the thermal treatment of lateritic ores in a rotary kiln, where the ore undergoes a series of chemical and physical transformations. These transformations include the reduction of nickel and iron oxides to produce ferronickel, a valuable alloy containing nickel and iron.

This research focuses on an in-depth investigation of the reactions occurring within a rotary kiln furnace during the processing of ferronickel laterite. Understanding these reactions is crucial for several reasons. Firstly, optimizing the operational parameters, such as temperature, residence time, and the composition of the reducing agents, can significantly enhance the yield and quality of the ferronickel produced [1]. Secondly, a detailed knowledge of the reaction mechanisms can help in identifying and mitigating the formation of unwanted by-products, thereby improving the overall efficiency of the process.

Furthermore, the study aims to address environmental concerns associated with the rotary kiln furnace process. By analyzing the emissions and by-products, the research seeks to develop strategies to minimize the environmental footprint of ferronickel production. This includes exploring the potential for recycling waste materials and reducing greenhouse gas emissions [3].

2. Material and Methods

The chemical composition of ferronickel was determined by X-ray fluorescence analysis (XRF, PANalytical, Axios). The recovery ratios of nickel and iron were calculated and taken as evaluation indices, and the contents of ferronickel in Fe, Ni and S were taken into consideration.

Nickel ferrous laterite ore. The nickel ferrous laterite ore sample used in this study was obtained from the Qikatove-Kosovo mine and Indonesia ores. Its chemical composition at the beginning of the rotary kiln is shown in table 1, while at the end of the rotary kiln it is shown in table 2, the samples are characterized by a high content of magnesium and silicon. Moreover, the results of the XRD analysis (see Figure 1) show that the nickel ferrous laterite mainly consists of different reactions according to the XRD analysis.

3. Results and Discussions

The chemical composition of the laterite nickel ore sample, as presented in Table 1, reveals significant insights into the mineralogical and chemical characteristics of the ore. These findings are further corroborated by the X-ray diffraction (XRD) analysis conducted on the sample [1,2]. The key components identified in the chemical analysis include Fe (11.75%), Ni (0.88%), SiO_2 (54.15%), MgO (15.46%), Al_2O_3 (1.01%), and Cr_2O_3 (0.68%)[3,4]. Integrating these chemical composition results with the XRD findings helps in understanding the behaviour of the ore during the rotary kiln furnace process and optimizing the nickel extraction [5,6].

The X-ray diffraction (XRD) analysis figure 1 and the chemical composition table 1 of the laterite nickel ore sample provide complementary insights into the mineralogical and chemical characteristics of the ore [6]. By integrating these findings, we can better understand the behaviour of the ore during the rotary kiln furnace process and optimize the nickel extraction. Here is a detailed analysis of the XRD findings in conjunction with the chemical composition results.

SiO_2 (Silicon Dioxide)

SiO_2 is identified as a major phase in the XRD analysis. The high concentration of SiO_2 indicates that it is a predominant component of the ore. Silicon dioxide is a stable mineral that forms the gangue material. In the rotary kiln furnace process, SiO_2 will primarily contribute to the slag formation. Managing the SiO_2 content is essential for maintaining appropriate slag viscosity and facilitating the separation of the metallic phases from the slag. According to the chemical composition in the SiO_2 constitutes 54.15% [3,4,5,6].

Table 1. *Main chemical compositions of ferronickel laterite ore at the beginning of the rotary kiln*

Chemical Composition	Fe total	Ni	SiO_2	MgO	Al_2O_3	CaO	Cr_2O_3	Co	Crystal water
Percentage	11.75	0.88	54.15	15.46	1.01	0.58	0.68	0.03	Bal %

Table 2. *Main chemical compositions of ferronickel laterite ore at the bottom of the rotary kiln*

Chemical Composition	Fe total	Ni	SiO_2	Co	Cr	MgO	Al_2O_3	CaO	C-fix	S	FeO
Percentage	18.19	1.10	46.55	0.04	1.71	17.06	3.57	4.2	3.21	0.23	4.14

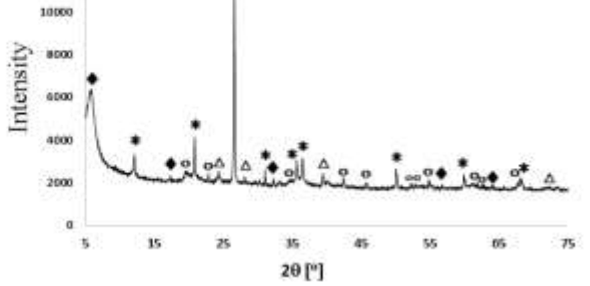

Figure 1. *XRD analysis for sample in the beginning of rotary kiln furnace.*

NbS_2 (Potential Nickel-Bearing Phase)

NbS_2 was identified, although its precise nature requires further clarification. If NbS_2 is a nickel-bearing sulphide or silicate, it is a crucial phase for nickel recovery. The nickel content, although relatively low, can be significantly extracted if NbS_2 undergoes effective reduction reactions during the thermal treatment. Optimizing the kiln conditions, such as temperature and reducing atmosphere, is vital to maximize the conversion of NbS_2 to metallic nickel. According to the chemical composition Nickel content in the ore is 0.88% [1,2,3]. NbS_2 is identified as a nickel-bearing phase. If it undergoes reduction, the reactions could include:

$$NbS_2+2C \rightarrow Nb+2C_S$$

Effective reduction conditions are necessary to maximize nickel recovery.

$Cs_2Ce(SiO_4)_3$ (Cerium Silicate)

$Cs_2Ce(SiO_4)3$, a complex cerium silicate, was identified. Cerium silicates do not significantly impact nickel extraction. However, understanding their stability and behavior ensures they do not interfere with the reduction of nickel-bearing minerals. $Cs_2Ce(SiO_4)_3$ remains relatively stable under high-temperature conditions and does not participate in the reduction process [2]. $Cs_2Ce(SiO_4)_3$ remains stable and does not participate in the reduction process, indicating it acts as an inert component in the kiln process.

$MgAl_2(SiO_4)O(OH)_2$ (Magnesium Aluminium Silicate Hydroxide)

$MgAl_2(SiO_4)O(OH)_2$ was identified, indicating the presence of magnesium and aluminium in complex silicate form. The significant amounts of MgO and Al_2O_3 suggest that is an important phase in the ore. Under high temperatures, $MgAl_2(SiO_4)O(OH)_2$ will decompose, releasing water and forming simpler oxides or silicates. This decomposition influences the slag properties, particularly viscosity and smelting point, which are crucial for efficient metal separation. According to the chemical composition the ore contains 15.46% MgO and 1.01% Al_2O_3 [3,4,5,6]. This complex silicate decomposes under high temperatures, releasing water and forming simpler oxides or silicates:

$$MgAl_2(SiO_4)O(OH)_2 \rightarrow MgAl_2(SiO_4)+H_2O$$

Fe (Iron) and Oxides

Iron is present in various oxides and silicates within the ore.Iron oxides are reduced alongside nickel oxides to form ferronickel. The significant iron content aids in forming the ferronickel alloy, enhancing the overall yield. Effective reduction conditions are essential to maximize the conversion of iron and nickel oxides to their metallic forms. According to the chemical composition Iron constitutes 11.75% of the ore [1,3,7,8,9,10]. Iron is present in various oxides and silicates within the ore. The reduction reactions involving iron oxides include:

$$Fe_2O_3+3CO \rightarrow 2Fe+3CO_2$$

These reactions convert iron oxides to metallic iron, forming part of the ferronickel alloy.

Cr_2O_3 (Chromium Oxide)

Chromium phases were not explicitly identified but can be inferred to be part of the complex ore mineralogy. Chromium oxides can impact the reduction reactions and the quality of the ferronickel alloy. Managing Cr_2O_3 levels is essential to prevent contamination and ensure the production of high-quality ferronickel. According to the chemical composition the ore contains 0.68% Cr_2O_3 [3,4]. Chromium oxides can impact the reduction reactions and the quality of the ferronickel alloy. The reduction of Cr_2O_3 is given by:

$$Cr_2O_3+3C \rightarrow 2Cr+3CO$$

Managing Cr_2O_3 levels is essential to prevent contamination and ensure high-quality ferronickel production. The chemical composition of the laterite nickel ore sample is crucial for understanding its behaviour during the rotary kiln furnace process table 2. The chemical analysis provided the following composition: Fe (18.19%), Ni (1.10%), SiO_2 (46.55%), MgO (17.06%), Al_2O_3 (3.57%), CaO (4.2%), and FeO (4.14%)[1,6]. X-ray diffraction (XRD) analysis performed on samples at the end of the rotary kiln furnace process identified the following phases: SiO_2, Al_2O_3, $CaCO_3$, $FeCO_3$, Fe_3O_4, FeO+MgO, and Mg_2SiO_4+Fe_2SiO_4 Figure 2, [2,5].

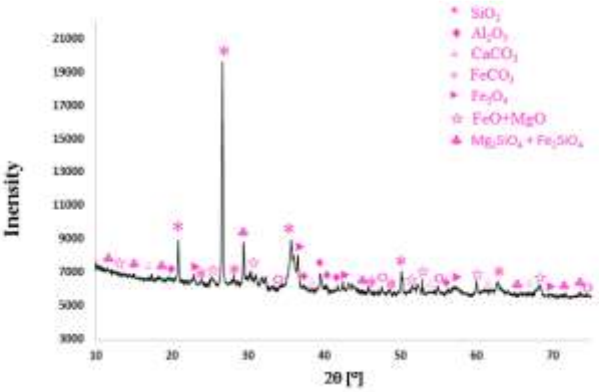

Figure 2. *XRD analysis for sample in the end of rotary kiln furnace.*

SiO_2 (Silicon Dioxide)

The high concentration of SiO_2, making up 46.55% of the chemical composition, is corroborated by its identification as a major phase in the XRD analysis. SiO_2 remains a predominant component throughout the rotary kiln furnace process, primarily acting as a gangue material. Its stability means it does not actively participate in reduction reactions but significantly influences the bulk properties of the processed material, particularly in maintaining structural integrity during high-temperature operations [1,2,4,8].

SiO_2 is a major phase in the XRD analysis, comprising 54.15% of the chemical composition. In the rotary kiln furnace process, SiO_2 primarily contributes to slag formation. The primary reactions involving SiO_2 are:

$SiO_2+FeO \rightarrow Fe_2SiO_4$

This reaction indicates the formation of fayalite (Fe_2SiO_4), which is a common silicate slag component.

Fe (Iron) and FeO (Iron(II) Oxide)

Iron is a major component, with Fe making up 18.19% and FeO contributing 4.14% of the chemical composition. XRD analysis identified iron in multiple phases: $FeCO_3$ (iron carbonate), Fe_3O_4 (magnetite), and a solid solution of FeO+MgO. These phases are crucial for the reduction process, where they convert to metallic iron, forming part of the ferronickel alloy. The presence of FeO+MgO indicates potential interactions with magnesium, affecting reduction efficiency. Effective reduction of these iron compounds is essential for maximizing nickel and iron recovery [1,7,9].

Iron and iron(II) oxide (FeO) are significant components, contributing 18.19% and 4.14%, respectively. The reduction reactions for these phases are:

$FeO+CO \rightarrow Fe+CO_2$

Ni (Nickel)

Nickel, accounting for 1.10% of the chemical composition, is essential for ferronickel production. While specific nickel-bearing phases were not identified in the XRD analysis, nickel is typically associated with iron oxides and silicates, such as Fe_3O_4 and FeO+MgO. Optimizing kiln conditions, including temperature and reducing atmosphere, is vital to ensure the effective reduction of these compounds, enhancing nickel recovery [6,7].

MgO (Magnesium Oxide)

Magnesium oxide, comprising 17.06% of the chemical composition, is identified in XRD analysis as forming phases like Mg_2SiO_4 (forsterite) and Fe_2SiO_4 (fayalite). These interactions influence the properties of the remaining solid material, including its smelting point and mechanical stability. MgO role is crucial in stabilizing the phases during high-temperature processing, impacting the overall efficiency of the reduction process [2,4,6].

Magnesium oxide (17.06%) forms phases like forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4):

$2MgO+SiO_2 \rightarrow Mg_2SiO_4$

Al_2O_3 (Aluminum Oxide)

Aluminum oxide constitutes 3.57% of the chemical composition and is identified as a distinct phase in the XRD analysis. Al_2O_3 adds complexity to the solid material, influencing its viscosity and smelting behavior. Although it does not directly participate in nickel reduction, its presence affects the physical properties of the material processed in the kiln, aiding in maintaining structural stability [2].

Aluminum oxide (3.57%) influences the viscosity and melting behavior of the material but does not directly participate in reduction:

$Al_2O_3+6FeO \rightarrow 2Fe_3O_4+2Al$

CaO (Calcium Oxide)

Calcium oxide, present at 4.2% in the chemical composition, is identified as $CaCO_3$ (calcium carbonate) in the XRD analysis. During high-temperature processing, $CaCO_3$ decomposes to form CaO, acting as a fluxing agent. This decomposition impacts the smelting behavior and stability of other phases, despite the lack of slag formation in this particular furnace setup. Managing CaO content is important for optimizing the properties of the processed material [6,8,10].

Calcium oxide, present at 4.2%, is identified as $CaCO_3$ in the XRD analysis. During high-temperature processing, $CaCO_3$ decomposes:

$CaCO_3 \rightarrow CaO+CO_2$

Calcium oxide acts as a fluxing agent, influencing the melting behavior and stability of other phases.

4. Conclusions

The combined results from the chemical composition and X-ray diffraction (XRD) analyses provide valuable insights into the behavior of laterite nickel ore during the rotary kiln furnace process. From the chemical composition analysis, it is evident that the ore consists predominantly of SiO_2, Fe, MgO, and other oxides such as Al_2O_3 and CaO. These components play crucial roles in influencing the properties and behavior of the ore during thermal processing. SiO_2 acts as a major gangue material, contributing to the bulk of the material processed. Fe, present in various forms including FeO and iron oxides like Fe_3O_4 and $FeCO_3$, is essential for ferronickel production through its reduction to metallic iron. Nickel, though present in lower concentrations, remains pivotal for ferronickel alloy formation, primarily associated with iron phases identified in the XRD analysis.

The XRD analysis further confirm the presence of SiO_2, FeO, MgO, Al_2O_3, and $CaCO_3$, identifying their crystalline phases and interactions within the ore. These phases undergo thermal transformations and reduction reactions during the rotary kiln furnace process, influencing the efficiency of nickel extraction and the quality of the ferronickel product. MgO and Al_2O_3 contribute to slag stability and viscosity, while Fe phases undergo reduction to facilitate metal recovery.

In conclusion, the integration of chemical composition and XRD analysis provides a comprehensive understanding of how different mineral phases behave under high-temperature conditions in the rotary kiln furnace. This understanding is crucial for optimizing process parameters to maximize nickel recovery, minimize energy consumption, and ensure the production of high-quality ferronickel. Future studies could focus on further smelting and refining process conditions to enhance efficiency and sustainability in ferronickel production from laterite nickel ores.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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