

Review

Nickel Laterite Smelting Processes and Some Examples of Recent Possible Modifications to the Conventional Route

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Abstract: The treatment of laterites has been a research hotspot in extractive metallurgy over the past decades. Industrially, the pyrometallurgical treatment of laterites is mostly accomplished with a well-established method, namely, the rotary kiln–electric arc furnace (RKEF) process, which includes three main operations—calcination, prereduction, and smelting—followed by further refining for the removal of impurities from the raw ferro-nickel. As indicated in many studies of the RKEF process, the major downside of this method is its high energy consumption. Efforts have been made to lower this consumption. Furthermore, several new processes have been proposed. Among these, low-grade ferro-nickel production is regarded as the most widely and industrially used process after traditional RKEF operation. Although not widespread, other alternative processes of industrial scale have been generated since the start of the millennium. Recently, certain innovative processes have been tested either in the laboratory or at pilot-scale. In this paper, a literature review related to the smelting of laterites is made, and an emphasis on new processes and some examples of new developments in the RKEF process are presented.

Keywords: laterite; smelting; RKEF process; low-grade ferro-nickel

1. Introduction

According to a review published by Diaz et al., oxide-type nickel ores accounted for 64% of land-based nickel ores, but more than 60% of nickel production was based on the matte smelting of sulfide ores in 1988 [1]. This picture has significantly changed over the past three decades because of the decrease in the reserves of high-Ni sulfide ores, which are mostly deep underground, and therefore require costly mining. In this regard, laterite processing has become one of the research hotspots in extractive metallurgy. Depending mainly on the ore composition, laterites are treated pyrometallurgically (ferro-nickel and ferro-nickel with low-Nickel content), hydrometallurgically (pressure acid leaching), or both (Caron process). Historically, the smelting of laterites is as old as the smelting of sulfide-type nickel ores, although its share was not comparable to that of sulfide smelting at the very beginning. The use of electric furnaces before the mid-20th century was a common practice. Prior to the 1960s, conducting calcination and prereduction in a separate vessel, called a rotary kiln, was reported to be economically better. Therefore, the use of the rotary kiln–electric arc furnace (RKEF) process appeared in the introduction of the strategic Udy smelting process, proposed by M.J. Udy and M.C. Udy in 1959, for the treatment of lateritic ores containing nickel and chromium in order to obtain the products of refined steel, chromium iron, and ferro-nickel [2]. The industrial application of calcination kilns was first reported to be conducted at SLN before 1960 [3]. Fifteen years ago, Dalvi et al. reviewed the processing history of laterites starting from the treatment of New Caledonian ore bodies at the end of the 19th century up to future trends. In this review, it was indicated that

a significant expansion in the treatment of oxide-type ores could be expected [4]. For a historical perspective, a comparison of sulfide and laterite nickel mining can be found in the detailed review published by Mudd [5]. According to 2003 data, the share of laterites in primary nickel production was reported to be 42%, or ~510 kt Ni [4]. Wood Mackenzie predicted that, by 2022, 72% of the world's nickel production will be from oxide-type nickel ores [6].

Currently, the primary pyrometallurgical process for the treatment of laterites is the RKEF process. The Indonesian Morowali Industrial Park (IMIP), operated by Tsingshan Group, is probably one of the biggest investments in this area; it engages in stainless steel and crude steel production and uses installed RKEF lines for the production of ferro-nickel with low-Nickel content. The total accumulated investment for IMIP was reported to be more than US\$7 billion at the end of 2018 [7]. According to market data, in Indonesia, Tsingshan Group currently produces ~170,000 tons per year of nickel metal from its three low-grade ferro-nickel output phases that have 20 RKEF lines [8]. RKEF technology is being rolled out in Indonesia at a massive scale, suggesting that there is currently no viable alternative to RKEF despite its well-known drawbacks.

The main disadvantage with the RKEF process is its high energy consumption. In a review paper dealing with furnace technology for ferro-nickel smelting, it was indicated that with the evolution of technologies for furnace design, including furnace thermal issues, wall cooling, and high-voltage shielded-arc practice, furnace operation at over 75 MW could be achieved, resulting in specific energy consumption of less than 400 kWh/t dry ore, and enabling the treatment of ore bodies with high SiO₂/MgO ratios [9]. Other than enhanced charge flexibility and reduced energy consumption in the evolution of AC arc furnace technology, the use of DC furnaces was reported to be successful for the treatment of fines in that an open-bath DC furnace could process 100% fines, which is the other major issue with laterite smelting in the RKEF process [9,10]. As a typical energy consumption of 400 kWh/t for dry ore could still be regarded as relatively high, efforts have been made to lower it further. In fact, the high energy consumption of the RKEF process is inevitable, and only marginal improvements are possible with the process design. This major drawback of the conventional process, along with other factors, has provided the impetus for the generation of new processes. Among these, low-grade ferro-nickel production can be regarded as the most widely and industrially used process after the traditional RKEF operation. In China, low-grade ferro-nickel production became popular around the mid-2000s, when nickel metal prices reached unprecedented values. Another factor in China was that many small older iron blast furnaces were available to be transitioned to smelting calcined laterites. The production of pig iron (high-carbon material) from these blast furnaces led to the development of the term “nickel pig iron”. Although not widespread, other alternative processes of an industrial size have been proposed since the start of the millennium. Recently, certain innovative processes have been tested either in the laboratory or at pilot-scale. In this paper, a literature review related to the smelting of laterites is made, with an emphasis on new processes and with some examples of the new developments in the RKEF process provided. In the literature, a large number of studies focus on new options for the solid-state reduction of laterites followed by magnetic separation. While these are very valuable as far as nickel extraction is concerned, they are beyond the scope of the present manuscript, which relates specifically to smelting processes. In the last section, a few examples of the reduction roasting–magnetic separation route are included for comparison.

It should be emphasized that the ferro-nickel/low-grade ferro-nickel obtained from these smelting processes is called as raw ferro-nickel/low-grade ferro-nickel. Therefore, it contains impurities such as C, Si, P, and S. To obtain suitable iron–nickel alloys, these impurities must be eliminated with certain refining operations from the so-called “raw ferro-nickel”; for example, the refining of RKEF ferro-nickel is conducted in ladle furnaces or small oxygen steelmaking furnaces, and a refined ferro-nickel is obtained. Briefly, in both cases, oxygen blowing is conducted to remove carbon, silicon, and phosphorus. Next, deslagging, deoxidation, and desulfurization operations are conducted. Finally, the refined ferronickel is granulated and the commercial ferronickel product is obtained.

2. Alternative Nickel Laterite Smelting Processes to the Rotary Kiln-Electric Furnace (RKEF) Process

2.1. The Vaniukov Process

The Vaniukov process is a well-established technology for pyrometallurgical treatments, especially for the smelting of copper ores [11,12]. Its use in laterite smelting was studied in the last decade. The process for laterites is very similar to that in copper smelting. Oxide-type nickel ores are charged to the Vaniukov furnace after calcination in a rotary kiln at ~ 900 °C. This furnace has two zones: the smelting zone and reduction zone. In a study related to the treatment of laterites [13], the details of the pilot-scale Vaniukov furnace were outlined. In the smelting zone, at the top side, there are two ports for charging an ore + flux + coal mixture and one off-gas hood. At the top of the reduction zone, a charging port is dedicated for coal addition, and one off-gas hood is present. Coal addition to the reduction zone is made to obtain the required oxygen potential (i.e., P_{O_2}) for producing ferro-nickel that has the target nickel content. In both zones, hydrocarbon and oxygen-enriched air are sent into the slag from the ports situated in the side of the furnace at the melt level. In the reduction zone, an O_2 + air mixture is also introduced from near to the top. Hydrocarbon and air are also sent from the top, just near the tapping holes, for ferro-nickel and slag. Ferro-nickel is tapped into the ladle for further refining in an ASEA-SKF furnace, and the slag is washed with water, granulated, and then dumped. In the aforementioned study, low-grade Kempirsay laterites (Kazakhstan) containing 0.90% Ni, 53.2% SiO_2 , and 6.5% MgO were treated in a pilot-scale Vaniukov furnace after calcination, resulting in mass loss of $\sim 25\%$. Limestone was used as a flux, natural gas was used as a fuel, and coal was used as a reducing agent. The operation of the furnace can simply be described in three stages. (1) Heating of the furnace: Preheating is performed with O_2 + air injection, and the temperature rises as oxygen enrichment increases. (2) Smelting mode: Ni-ore is charged together with limestone, and blast enrichment is increased. Charging continues until a melt level greater than 300 mm is reached. (3) Reduction mode: Blast enrichment is decreased, and hard coal, which is 4% to 12% of the weight of the melt present in the furnace, is charged into the reduction zone. Afterwards, ferro-nickel and slag are tapped. The process is conducted in a batch-wise manner. From the pilot test results, the authors concluded that the process was suitable for ores having a high Fe/Ni ratio (for the Kempirsay deposit, it was reported as 16.7/1), resulting in a refined ferro-nickel product containing 20% Ni with a recovery of at least 90%. The details of the refining in the ASEA-SKF furnace were not provided. The impurity levels of the refined alloy were 0.5%Si, 0.06%Cr, and 0.07%C. The levels of these elements in the RKEF process after the refining were noted as $\sim 0.05\%$ C, $<0.5\%$ Si, and trace Cr [14]. Tsybulov and Kongoli conducted a similar pilot study in relation to the smelting of saprolitic Buruktal ores (Russia). In their work, briquetted and roasted ore was charged into the two-zone Vaniukov furnace. Readers are referred to the conference paper for the test results [15]. The simple flowsheet for the Vaniukov process is shown in Figure 1. The major disadvantage of this process is the inability to lift the tuyeres above the slag for maintenance or in a blower emergency [11]. This may be one of the reasons why the process is not commonly used.

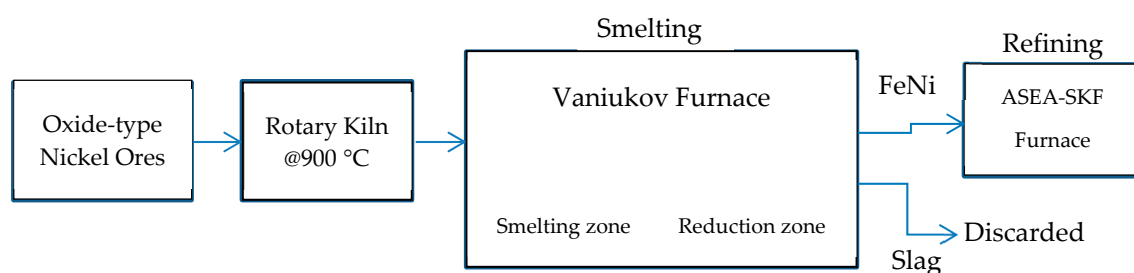


Figure 1. Flowsheet of the Vaniukov process.

2.2. Low-Grade Ferro-Nickel Production

2.2.1. Low-Grade Ferro-Nickel Production in China

Low-grade ferro-nickel production became popular in China—the leading country in stainless steel production—during the mid-2000s when nickel prices reached unprecedented values. A detailed review indicated that according to 2011 data, the share of low-grade ferro-nickel production in the total nickel production in China was 56.5%; the rest involved the production of primarily electrolytic nickel [16]. According to more recent monthly data from May 2019, low-grade ferro-nickel production and electrolytic nickel production were reported at 47,800 and 12,900 nickel tons, respectively. Therefore, the share of low-grade ferro-nickel in the total nickel production exceeded 75% [17].

Low-grade ferro-nickel production started in China in 2005, when electrolytic nickel prices reached a peak. Many companies dedicated their small-size blast furnaces to low-grade ferro-nickel production. Low-grade ferro-nickel is simply an iron–nickel alloy that contains lower nickel than standard ferro-nickel does (i.e., minimum of 15%). According to the literature, within a very short period of time (~2 years), plants producing low-grade ferro-nickel grew to more than 300. Therefore, blast furnace operations heralded the start of low-grade ferro-nickel production. The operations are very similar to the conventional blast furnace operation for hot metal production. First, low-grade nickel ore, coke breeze, and fluxes are blended and subjected to sintering. Second, sinters are charged to the blast furnace together with certain additional fluxes. After, blast furnace smelting yields the low-grade ferro-nickel and slag phases. Depending on the ore and operational parameters, the low-grade ferro-nickel obtained from a blast furnace, in general, may contain nickel in the range of 1 to 8%, as a crude alloy; the corresponding nickel recoveries are ~80% [16]. Blast furnace low-grade ferro-nickel production involves some difficulties in both the sintering and blast furnace stages. Because of the presence of water and refractory components in laterites, poor sinter quality (i.e., low tumbling strength, high sinter return proportion, and high-FeO composition), low productivity, and high coke breeze consumption were reported as the main problems in the sinter-making stage. Excessive slag formation, low temperature, and poor fluidity of the low-grade ferro-nickel, high energy consumption, high slag viscosity because of the Cr_2O_3 content of the slag, and the negative impacts of fluorite addition, as well as a shortened refractory life and poisonous gas emissions, were the main problems associated with the blast furnace stage. Furthermore, high levels of sulfur and phosphorus were reported as disadvantages of low-grade ferro-nickel production in blast furnaces. It was noted that decarburization refining would be applied to crude low-grade ferro-nickel if a low-carbon product was desired [16]. The differences between conventional iron blast furnaces and low-grade ferro-nickel blast furnaces can be found in the literature. Improvements in sinter quality, blast furnace enlargement, and high coal injection technology have been reported as some of the new trends in blast furnaces producing low-grade ferro-nickel. According to 2017 data, the largest low-grade ferro-nickel blast furnace was designed by Wuhan Iron and Steel Design and Research General Institute, and its size was reported to be 580 m³; its other dimensions are a total height of 20.8 m, a hearth diameter of 5.97 m, a belt diameter of 7.2 m, and a stack height of 9.8 m [18].

2.2.2. Other Technologies for Low-Grade Ferro-Nickel Production

Submerged arc furnace (SAF) and the traditional rotary kiln-electric furnace (RKEF) processes have also been used for low-grade ferro-nickel production. In general, these processes yield low-grade ferro-nickel containing Ni in the range of 10 to 15%. SAF is very similar to RKEF ferro-nickel production, so the details of the process are not included in the present work.

The Krupp–Renn process was invented for sponge iron production as an alternative to blast furnace operation. The Nippon Yakin plant in Oheyama used this process for the treatment of laterites to obtain ferro-nickel lumps during the Second World War, and the process is called the Oheyama process. This is based on solid-state reduction, but with operation of the rotary kiln at significantly higher temperatures (~1400 °C) so that low-grade ferro-nickel production has the conditions required

to form a semifused product. However, the formation of slag and metal rings was reported as the temperature in the kiln increased, which, in turn, precluded the commercialization of the process for low-grade ferro-nickel production [16].

Other than the RKEF process, a process consisting of low-temperature reduction followed by magnetic separation is regarded as a possible alternative to low-grade ferro-nickel production. This process was reported to be important, especially for low-grade laterites and the case where ferro-nickel particles are large enough for effective magnetic separation [16]. As this process is not a smelting type, it is outside of the scope of this paper. The two main routes of low-grade ferro-nickel production are shown in Figure 2.

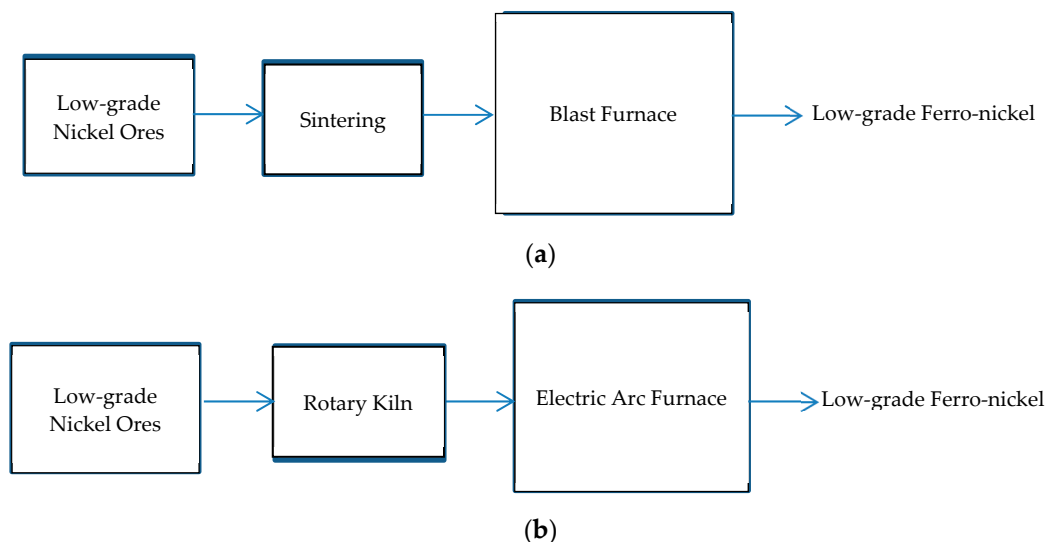


Figure 2. Two main routes of low-grade ferro-nickel production: (a) blast furnace and (b) rotary kiln–electric arc furnace (RKEF).

2.2.3. Modern Low-Grade Ferro-Nickel Production and its Application in Indonesia

Low-grade ferro-nickel production originated in China. One of the major contributing factors to this was the import of a significant amount of nickel ore from Indonesia. According to a report published by Glencore in 2013, nickel ore exports from Indonesia reached ~48 million tons, and the value exported to China was reported to be 43 million tons. Indonesia's export to China increased significantly between 2006 and 2012 [19]. During this period, low-grade ferro-nickel production in China exhibited continuous growth. When the mineral export ban from Indonesia took effect in 2014, however, the picture changed. The policy of the Indonesian government was successful in encouraging many Chinese companies to invest in low-grade ferro-nickel plants in Indonesia. The Indonesian government subsequently changed the policy somewhat in 2017, allowing exports of nickel ore having nickel less than 1.7% to recommence [20]. Together with the start of low-grade ferro-nickel production in Indonesia, many Indonesian studies examined this process. Andika et al. investigated the effect of basicity and type of reducing agent on low-grade ferro-nickel production by using a 30 kg capacity electric arc furnace. A limonite-type Sulawesi Island laterite sample containing 1.26% Ni was mixed with the reducing agent and pelletized to a diameter of 10–20 mm. Coal, coke, and shell charcoal were used as reducing agents. The basicity values of the limestone were 0.8, 1, and 1.4. The optimum results were obtained when the basicity was 1 and the reducing agent was coke, which contained the highest carbon content of the reducing agents used. Under these conditions, nickel recovery was 82.8%. The conclusion was that 4% Ni-containing low-grade ferro-nickel could be produced from Sulawesi Island laterite by using an electric arc furnace [21].

According to literature published in 2019, 577 million tons of nickel reserves was reported to be present in Indonesia. The largest export commodity in Indonesia was nickel, with an export value of

~36.6 million dollars or 53.3% of the total export of the country [21]. In the future, continuous growth in low-grade ferro-nickel production is expected for Indonesia. The authorities also indicate that the Philippines will remain a major nickel-mining country, although it is not involved in primary nickel production [20].

2.3. *Envirosteel Smelter Technology*

The IFCON[®] process developed in South Africa can be regarded as an important milestone from the 1990s in the treatment of iron ore and coal mixture to obtain steel in a single vessel [22]. Similarly, envirosteel smelter (ESS) technology can be adapted to produce ferro-nickel in a single furnace, in which oxide-type nickel ore is charged together with the reductant coal [23,24]. The calcination, prereduction, and smelting stages are conducted in the ESS furnace. The major difference of ESS technology compared to the use of an electric arc furnace is that the alloy is not heated by the slag, but by induction. The ESS furnace has a rectangular shape with a huge free board, and the ore and coal mixture are charged together to form a heap that remains stable throughout the process. The ESS furnace is equipped with three channel inductors. There is a tiny slag layer below the heap, and the alloy is present below the slag. Cooled alloy settles to the location where a channel inductor heats it. The heated alloy is circulated upwards, and the sensible heat of the alloy is used to heat the heap for calcination, prereduction, and smelting. The top surface of the heap is subjected to radiation heating, and the metallurgical conditions allow solid-state reduction. A schematic drawing of the ESS smelting technology is given in Figure 3a. The authors indicated that this technology is especially advantageous for the smelting of limonites, which possess high-Fe/Ni ratios, whereas controlling the reduction of iron in the RKEF process is difficult. Another difficulty with the RKEF processing of limonite occurs when the melting temperature of the alloy is higher than that of the slag, so a significant amount of additional heat must be applied to the slag to keep the alloy molten. This, of course, requires a higher extent of arc heating of the slag, causing an increase in electrical consumption. The authors outlined the results of ESS technology and compared these with those of the RKEF process. With the use of ESS technology, it was found that 15% Ni-containing crude ferro-nickel could be obtained from high iron limonite ore having 1.5% Ni. The recovery of the ESS process was noted as 91.2% [23]. The corresponding energy consumption was reported as ~189 kWh/t limonite. This value is only ~40% of the electricity usage in the RKEF process, noted to be 483 kWh/t limonite. Other than its advantage in terms of energy consumption, ESS technology was reported to be better than the RKEF process in that solid-state reactions were more controlled in the ESS furnace than in the rotary kiln. The ESS furnace gave better results, including the issue of dust losses. Dust loss in the ESS furnace was found to be limited, whereas a significant amount of dust loss was reported during and after rotary kiln operation (i.e., during the transfer of the reduced calcine from the kiln to the EAF). A similar conclusion related to heat losses was drawn. Moreover, the alloy and slag temperatures in the ESS furnace were lower than those in the EAF; the differences were noted as 30 °C and 100 °C, respectively. The authors concluded that ESS technology can be used for laterites, and it is especially a good alternative for the treatment of high-Fe–low-Ni limonites, which are generally only suitable for low-grade ferro-nickel production. The authors also compared the production capacities of the ESS and RKEF processes. The annual nickel production of a typical 75 MW RKEF unit was reported as ~18,000 t, whereas that of a single ESS furnace was only 995 t. Therefore, batteries of ESS furnaces are needed to enable commercial-size production. The authors indicated that refining and granulation systems must be included. On the other hand, no result for refined alloy was provided [23]. The authors have since published more detailed case studies for the application of ESS technology to iron ore, titaniferous magnetite, and chromite, as well as to saprolite and limonite [25].

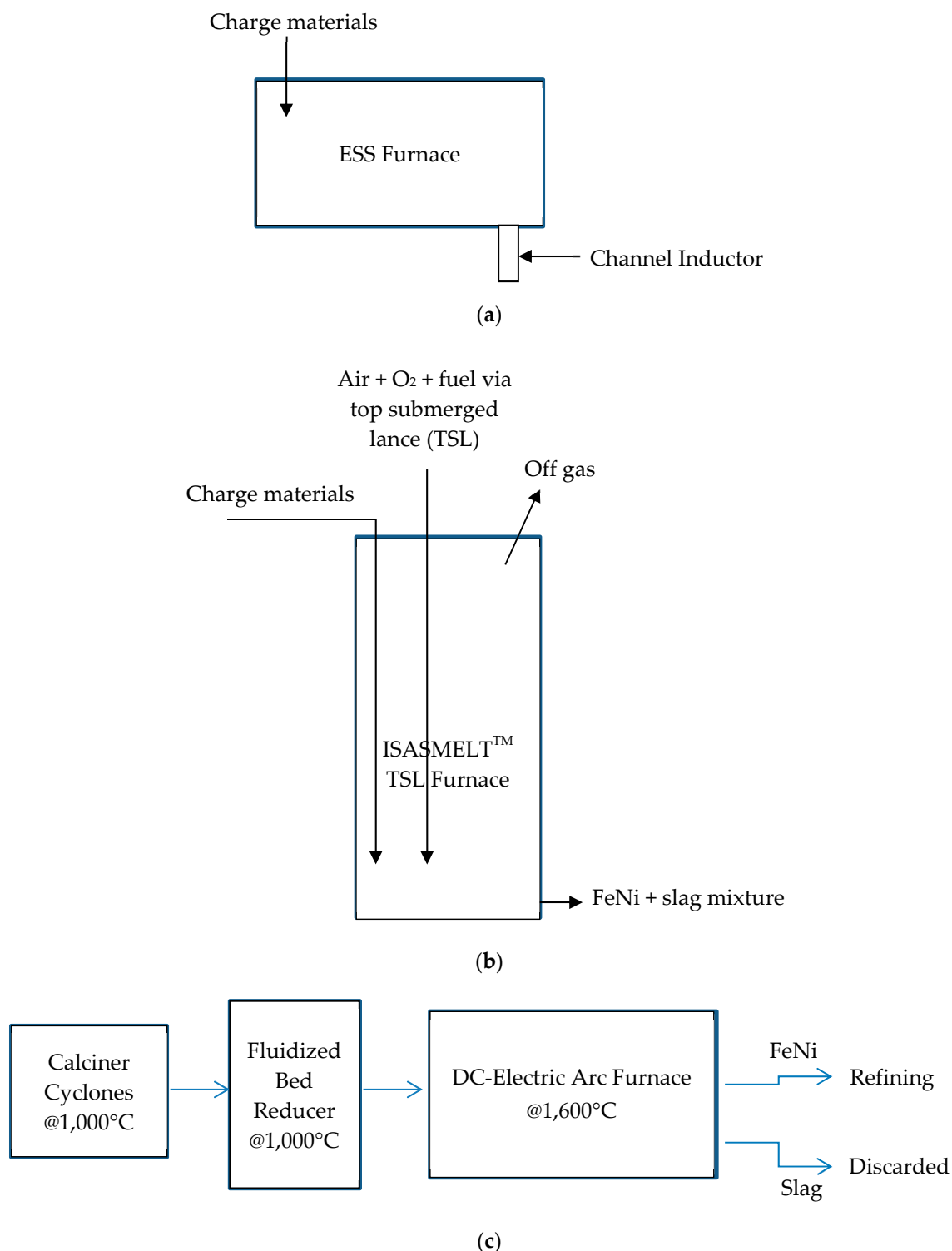


Figure 3. (a) Schematic drawing of envirosteel smelter (ESS) smelting technology. (b) Schematic of the ISASMELT™ top submerged lance (TSL) technology. (c) Main steps in nickel smelting technology (NST).

2.4. The ISASMELT™ TSL Process

The ISASMELT™ process is a well-established technology for the commercial treatment of copper and lead ores, dating back to the beginning of the 1990s. The ISASMELT™ furnace is simply a vertical vessel equipped with a top submerged lance (TSL). At the top of the furnace, there is a conveyor for charge materials, whereas air, oxygen, and fuel are injected through the TSL. Off-gases are collected

in the boiler. Most of the time, a metal/alloy–slag mixture is obtained from the furnace via a single tap hole, so a slag settling/cleaning furnace is needed for the separation of the slag. The effective elimination of emissions, the high extent of mixing in the vessel, the presence of charge material reactions in the slag, its vertical nature, and the corresponding small floor size are the main advantages of the process. A schematic of ISASMELT™ TSL technology is illustrated in Figure 3b.

Bakker et al. investigated the application of the ISASMELT™ process in the nickel pyrometallurgy field, including the smelting of sulfide-type nickel ores, conversion of nickel mattes, and ferro-nickel production from laterites. Only trials of ISASMELT™ technology for ferro-nickel production are of interest here. Saprolite-type laterites were subjected to smelting tests. The authors conducted two kinds of experimental work: bench-scale tests (small crucibles holding ~1 kg of melt) and pilot-scale tests (charging at a rate of 150 to 200 kg/h). According to the bench-scale test results, refined ferro-nickel alloys containing nickel in the range of 15 to 40% were obtained from the nickel ore having a SiO₂/MgO ratio of 1.2:3.1 and a Fe/Ni ratio of 10–20. Pilot-scale experiments resulted in higher-grade alloys of nickel content 60–85%. The ore used in the pilot-scale tests had SiO₂/MgO and Fe/Ni ranges at 2.0 to 3.6 and 5 to 12, respectively. The details of refining were not included in the paper. The authors indicated that a separate calcination unit could be used before the ISASMELT™ furnace and that the addition of sulfur-bearing charge to the laterite ore could be made to obtain low-iron matte. It was reported that both bench-scale and pilot-scale tests produced liquid slags. According to thermochemical software for the MgO–FeO–SiO₂ system, the liquidus temperatures of the slags were predicted in the range of 1400 to 1550 °C. Pyroxene, olivine, or tridymite/cristobalite was reported as the possible phase of the slag system. In relation to the future development of the ISASMELT™ process for nickel ores, the authors suggested some improvements related to furnace cooling, tapping block designs, pneumatic injection, and the enhancement of the slag settling/cleaning process [26]. The need for a second furnace for metal–slag separation was one of the disadvantages of the ISASMELT™ process [11]. In literature describing the application of the ISASMELT™ process for converting PGMs, one further disadvantage was reported—the rapid wear of the refractory lining of the furnace [14]. The limited number of applications of the ISASMELT™ process for laterite smelting may be attributed to these drawbacks.

2.5. Nickel Smelting Technology (NST)

One of the major problems with the traditional rotary kiln process is the difficulty with material transfer, as a significant portion of laterite ore consists of fine particles. Correspondingly, dust generation, as well as plant hygiene, is a problem. The use of fluidized bed reactors was identified as an alternative during the mid-1990s.

The Koniambo deposit present in New Caledonia is one of the largest deposits in the world containing both saprolite and limonite. Koniambo saprolites were reported to contain 300 million tons of ore with a grade of ~2.2% Ni. For the treatment of these saprolite bodies, Société Minière du Sud Pacifique and Falconbridge agreed to establish a ferro-nickel plant in New Caledonia with the aim of producing 54,000 ferro-nickel tons/year [27]. After ~10 years of process development and feasibility studies, Falconbridge Nickel Smelting Technology (NST) was commercialized for the ferro-nickel plant at Koniambo Nickel. Falconbridge is now owned by Glencore. NST consists of the following steps [28].

1. Transporting the ore.
2. Milling and drying.
3. Filters (collecting the powdered nickel ore in the gas from the hammer mill flash dryers).
4. Calciner cyclones operating at 1000 °C.
5. Fluidized bed reducer operating at 1000 °C.
6. DC electric furnace operating at 1600 °C.
7. The slag is discarded, and ferro-nickel is sent to the refining unit (see Figure 3c).

The main difference of NST from RKEF is the use of a fluidized bed for calcining and preheating instead of a rotary kiln. NST is also based on DC-type arc furnace technology, which is better for the

treatment of fines. In a conference paper dealing with NST, there were two fluidized bed prereduction units installed at Koniambo Nickel, and each had a maximum capacity of 4200 tons/day of calcined laterite ore. Prereduction was reported to be conducted with the direct injection of pulverized coal [29]. The company indicated that the power required to perform the arc furnace operation at ~ 1600 °C was 210 MW [28].

A feasibility study conducted by Reinecke and Lagendijk applied twin-cathode DC arc smelting at Mintek to siliceous laterite ores from Kazakhstan. It was reported that, before charging to the DC smelter, the ores were calcined in a fluid bed calciner. It was indicated that more efficient heat and mass transfer was possible in moving bed reactors and that fine materials, including ore and recycle dust, could be charged to the reactor without agglomeration. This confirmed that a fluidized bed–DC arc furnace route was beneficial to the elimination of the dust problem associated with the conventional RKEF process [30].

3. Some Examples of Recent Approaches Related to Conventional Nickel Laterite Smelting Processes

Nowadays, one of the general trends in laterite smelting is to find ways to treat so-called low-grade laterites (i.e., Ni < 1.6%). Other than their low-Ni content, other important characteristics of ore bodies can be regarded as problems, such as their high iron content, high SiO₂/MgO ratio, and high concentrations of Al₂O₃, Cr₂O₃, and phosphorus, creating serious challenges for commercial smelting processes. Solar and Mostaghel [31] referred to these ores as difficult laterite ores. The authors clearly underlined the importance of the extent of iron reduction. It was indicated that the melting temperature of ferro-nickel decreases from 1440 °C to 1290 °C when the level of iron reduction increases from 30% to 45%. This is due to the increased carbon content of ferro-nickel as iron reduction increases. This increase in reduction extent was reported to yield a carbon increase in ferro-nickel from 0.1% to 2%, resulting in a melting temperature drop at ~ 150 °C. Such changes are generally not desired in a steady-state operation. Therefore, iron reduction levels are strongly inhibited in commercial plant operations. The authors also discussed the melting temperature differences of ferro-nickel and slag from an operational point of view, and indicated that high slag temperatures have not been a major problem because of the installation of sidewall cooling systems in ferro-nickel smelters [31]. In conclusion, the paper gave a summary based on years of experience in the industry, so the findings were important for the industrial treatment of difficult ores.

In a study investigating material and energy flows in RKEF smelting, two energy-saving measures were theoretically analyzed together with the use of Sankey diagrams. The first one was the use of the waste heat of the rotary kiln for heating the rotary dryer. The second one was the use of electric arc furnace gas as a fuel for the rotary kiln. The authors calculated that the first energy saving method could save 1.64 t/h bituminous coal, corresponding to $\sim 46\%$ of coal consumption. The authors reported that the second proposal could save 3.21 t/h bituminous coal, which accounted for a $\sim 38\%$ reduction in coal consumption in rotary kiln [32]. The potential energy savings achieved by using heat recovery from the off-gases of the rotary kiln, electric arc furnace, or both are interesting, but the authors also need to address how it is to be engineered.

The energy-intensive nature of the RKEF process prompted investigations into decreasing the furnace operating temperature by reducing the alloy and slag melting temperatures. This could be achieved by making appropriate changes in the alloy and slag compositions. Ma et al. studied the production of Fe–Ni–Mo alloy by using nickel laterite obtained from Dongying Fangyuan Nonferrous Metals Co. Ltd.; based on investigations using thermochemical software, the authors used Fe₂O₃, CaO, and Mo/MoO₃ in a laboratory-scale laterite smelting system. Fe₂O₃ and CaO were used to reduce the melting point of the slag, whereas Mo/MoO₃ was used to decrease the melting temperature of the alloy. The authors reported that alloy and slag were successfully produced at 1723 K, which is at least 100 K less than the electric arc furnace smelting temperatures. The authors also underlined the effect of Mo/MoO₃ addition, which was not only found to be beneficial in reducing the melting temperature of

the alloy but also behaved as a collector to aggregate the ferro-nickel sponge, thus providing better alloy–slag separation. The authors concluded that the Fe–Ni–Mo alloy produced could be used as an additive in stainless steelmaking or for magnetic alloys [33].

A study conducted by Park et al. aimed to decrease ferro-nickel slag melting temperature by adding red mud to ferro-nickel slag. Red mud and ferro-nickel slag samples were obtained from Korean companies. The authors hypothesized that the $\text{MgO-Fe}_t\text{O-Al}_2\text{O}_3\text{-SiO}_2$ oxide system would form after red mud addition, as the majority of the red mud was composed of Fe_tO (37.4%), Al_2O_3 (23.1%), and SiO_2 (10.0%). Therefore, based on an analysis using thermochemical software, laboratory-scale experiments were conducted together with in situ observation of the softening and melting behavior of the composite pellets via a digital camera between 1673 K and 1823 K. The authors concluded that red mud addition to ferro-nickel slag was beneficial for reducing the slag melting temperature. For the charge with 12.5% red mud, melting took place at 1773 K. The melting temperature was reported to lower further with a charge having 25% red mud. Even a melting point of 1693 K was achieved when red mud content was 37.5%. The authors also noted that an olivine to spinel phase change occurred when the red mud content was increased to 50% [34]. According to the findings, the use of flux was beneficial to lowering the operating temperature. On the other hand, the disadvantage with using fluxes to lower the temperature of operation is that it requires more material to be smelted, tending to increase the energy requirement. It is true that lower operating temperatures do decrease some operating costs, for example, by increasing furnace life. However, the fluxes must be very effective in order to be attractive in terms of cost.

Ferro-nickel smelting generates too much slag. More than 95% of the charge material to furnaces report to the slag phase, which is regarded as waste. For a number of decades, the recycling of wastes has drawn increased attention, so ferro-nickel slags should be regarded as by-products, rather than materials to be dumped. Efforts have been made to utilize ferro-nickel slags in different industries. Two examples are given in this review. Sakkas et al. investigated the utilization of ferro-nickel slag for the production of inorganic polymeric materials used for construction and fire protection purposes. The granulated ferro-nickel slag provided by LARCO was ground below 90 μm , mixed with pure alumina powder, and, to obtain geopolymers, sodium, and potassium hydroxide, sodium silicate solution, and deionized water were also used as needed. The mixtures were cured at specific temperatures for certain periods. Compressive strength and water absorption percentages were measured. Successful and promising results were obtained from the materials produced for both purposes [35].

Gu et al. studied the utilization of ferro-nickel slag for the production of refractory materials. A slag obtained from a ferro-nickel smelter in China was mixed with sintered magnesia of 94.5% purity and briquetted. The sintering of the briquettes was performed using a muffle furnace in the temperature range of 1200 to 1500 $^{\circ}\text{C}$ for three hours. The authors reported the optimum conditions as a sintering temperature of 1400 $^{\circ}\text{C}$ and a sintered magnesia amount of 20% of the charge mix. These conditions produced a refractory material having refractoriness of 1680 $^{\circ}\text{C}$, a bulk density of 2.93 g/cm^3 , a porosity (apparent) value of 1.81%, and a compressive strength of ~ 167 MPa [36]. The authors indicated that these properties, which were found to be better than those of commercial refractory products, met the Chinese national standard for the production of refractory materials. The authors concluded that ferro-nickel slags could be used for the preparation of refractory materials [36]. These findings are valuable for the recycling of ferro-nickel slags.

In this section, some interesting examples related to conventional laterite smelting are outlined. Although some of these are not advances directly related to the RKEF process, the approaches are important and may have relevant impacts, such as reducing energy requirements and a more efficient use of the smelting by-products.

4. Reduction Roasting–Magnetic Separation Method

The reduction roasting–magnetic separation route is a popular pyrometallurgical method for the treatment of laterites, especially in the last decade. Dong et al. [37] claimed that this route was the most environment-friendly and economical method to process laterite ore. Given this claim and the number of related studies on it [38–41], its inclusion in the current paper is thought to be beneficial, although such an approach is not a smelting process. Dong et al. [37] described in detail the reduction roasting–magnetic separation process by using various additives. These additives included chlorides, sulfur and sulfates, alkali oxides, fluorides, sodium carbonate, and sodium hydroxide. The simple flowsheet for this route is shown in Figure 4.

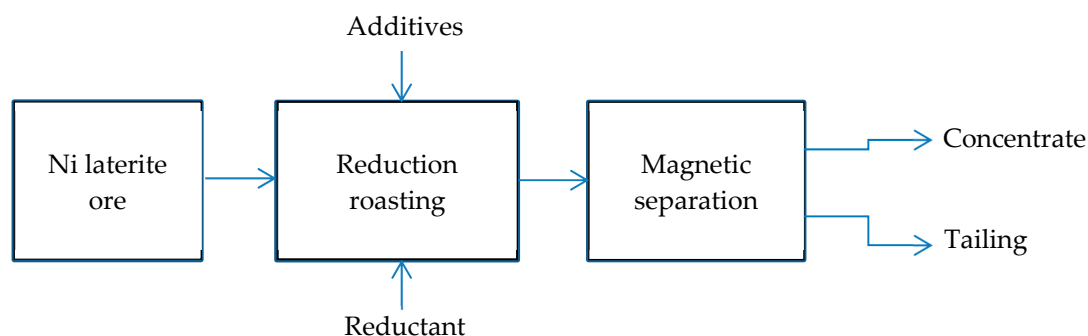


Figure 4. Flowsheet for the reduction roasting–magnetic separation process.

When chlorides are used as additives in the presence of water vapor, the proposed mechanism is as follows. First, the alkali/alkaline-earth chloride (NaCl , CaCl_2 , and MgCl_2) reacts with silica/silicates in the ore and the water vapor to generate hydrochloric acid. Second, the hydrochloric acid reacts with metal oxides (oxides of iron, nickel, and cobalt) to form metal chlorides. Third, the metal chlorides are reduced with a suitable agent (e.g., C , CO , and H_2) to yield the metal (Fe , Ni , and Co). The authors also proposed that the metal oxides could directly react with the alkali/alkaline-earth chlorides to give the metal chlorides if water vapor was not present. It was emphasized, however, that neither hydrochloric acid formation nor direct formation of metal chlorides was experimentally proven, and that further studies are needed to understand the mechanism further. The reduction roasting is followed by wet magnetic separation, and a concentrate is obtained. Nickel content greater than 5% and corresponding nickel recoveries greater than 90% were reported [37]. Dong et al. [38] investigated the effect of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ addition on the reduction roasting–magnetic separation behavior of low-grade garnierite ore. Anthracite was used as a reducing agent. Yunnan (China) laterite ore containing 0.82% Ni, 31.5% MgO , and 37.4% SiO_2 was used in the experiments. The effects of the amount of chlorination agent, chloridizing temperature, and time on the grades of Ni and Fe and their corresponding recoveries were studied. The optimum conditions were reported as 12% of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, a chloridizing temperature of 1150 K, and a chloridizing time of 40 min. The authors concluded that a concentrate with a Ni grade of 11.8% and the corresponding recovery of 97.4% were obtained under the optimum conditions. The addition of calcium chloride accelerated the aggregation of iron–nickel alloy particles and their growth.

Liu et al. [39] investigated a reduction roasting–magnetic separation process applied to low-grade Yunnan laterite ore using MgCl_2 as the chlorination agent. The ore was reported to contain 0.87% Ni, 20.4% MgO , and 32.2% SiO_2 as the main components. Metallurgical coke was used as a reducing agent. The laterite ore was mixed with pure MgCl_2 and metallurgical coke and then pelletized. After roasting at a specified temperature, wet magnetic separation was applied with a magnetic field strength of 0.2 T. The authors studied the effects of the quantities of the chlorination agent and reductant, the chloridizing temperature, and time on the grades of Ni and Co and their corresponding recoveries. The optimum conditions were 6% of MgCl_2 , 2% of metallurgical coke, a chloridizing temperature of

1253 K, and a chloridizing time of 90 min. The authors concluded that a concentrate with a Ni grade of 5.25% and a corresponding recovery of 91.5% were obtained under the optimum conditions.

Lu et al. [40] studied the effect of sodium sulfate addition on the hydrogen reduction of nickel laterite ore. A low-grade Indonesian nickel laterite ore containing 1.38% Ni, 25.3% Fe, 15.0% MgO, and 19.1% SiO₂ was used in the experiments. Reagent-grade sodium sulfate was used as an additive, and H₂ reduction was conducted. In each run, 1 kg of the total material mixture was charged to a stirred fluidized bed reactor. The reduced particles were ground and subjected to wet magnetic separation with a magnetic field strength of 0.156 T. The authors investigated the effects of reduction temperature and time, P_{H2}, and the quantity of sodium sulfate on the nickel reduction process. The optimum conditions were determined as a reduction temperature of 800 °C, a reduction time of 220 min, 20% sodium sulfate addition, and reducing gas atmosphere containing 70% H₂ and 30% N₂. These conditions were reported to yield a concentrate with a Ni grade of 6.38% and a corresponding recovery of 91.1%. The authors concluded that sodium sulfate enhanced the reduction kinetics and that its catalytic activity was improved by increasing the addition and the reduction temperature. One of the benefits of the formation of the Fe–S solid solution with sodium sulfate usage was the accelerated coalescence of alloy particles.

The benefits of forming the Fe–S solid solution were also reported in a study conducted by Li et al. [41]. They investigated solid-state nickel extraction with a reduction roasting–magnetic separation method with and without sodium sulfate addition. Coal was used as the reductant. Sulawesi Island laterite ore containing 1.91% Ni, 22.0% Fe, 13.4% MgO, and 26.5% SiO₂ was used in the experiments. The authors examined the effects of Na₂SO₄ amount, reduction temperature, and time on the reduction roasting–magnetic separation behavior of the ore by analyzing Ni and Fe grades and their corresponding recoveries. The optimum conditions were reported as 20% Na₂SO₄, 1100 °C, and 60 min. The Ni grade in the concentrate was reported to increase from 2.33% to 9.48% with the use of Na₂SO₄. The usage of Na₂SO₄ also resulted in a significant rise in recovery from 57.0% to 83.0%. One of the most important findings of this study was related to the average size of the ferro-nickel grains: the size was noted to be around 50 µm when Na₂SO₄ was introduced to the system, whereas it was only 5–10 µm when no Na₂SO₄ addition was made. This could be regarded as a clear confirmation of accelerated aggregation and increased growth rate with Na₂SO₄ addition.

To sum up, a reduction roasting–magnetic separation route is capable of treating low-grade nickel concentrates (~0.9% Ni) with recovery values of ~90%. Furthermore, the energy requirement of this route is surely lower than those involving smelting. Contrary to these promising results, such processes have not been applied on a commercial basis. This might be related to the nature of roasting and the large variability of the composition of laterites. As clearly outlined in the literature, traditional roasting necessitates higher temperatures and a longer roasting time. Moreover, the degree of reduction might remain lower in the middle of the pellets [42]. Regarding the laterites subjected to reduction roasting, some additives were reported to be beneficial only for some types of laterite. For example, the addition of sulfur in the reduction roasting of limonite ore was reported to be useful in increasing the average ferronickel particle size. On the other hand, the addition of sulfur to a saprolite ore caused a decrease in the average ferronickel particle size [43]. Therefore, ore characteristics should be considered in the selection of additive. Regardless of these limitations, the use of aforementioned new additives is expected to remain one of the hot topics in the treatment of laterites because of their high efficiency and low cost [37].

5. Summary of the Pyrometallurgical Nickel Extraction Processes Outlined in This Study

The typical nickel grades and recoveries for the RKEF process, the low-grade ferro-nickel production process, the ESS process, the Vaniukov process, and the reduction roasting–magnetic separation process are presented in Table 1. Among these, the RKEF process has the highest recovery values. Readers are referred to related references to examine the nickel grades and recoveries of some industrial RKEF plants [44,45].

Table 1. Pyrometallurgical nickel extraction processes reviewed in this study ¹.

Processes → Performances ↓	The RKEF Process ²	Low-grade Ferro-Nickel Production Process ³	The ESS Process ⁴	The Vaniukov Process ⁵	Reduction Roasting–Magnetic Separation Process ⁶
Ore Ni composition (%)	1.1–2.5	BF/SAF: ~1	1.5	0.90	(0.82–1.91) Avg.: 1.31
Crude Alloy Composition	Ni: ~25 Co: 0.60 Fe: Balance	Ni: <15 Co: 0.60 Fe: Balance	Ni: 15 C: 0.30 Si: 0.07 Fe: 84.6	Ni: 15 Co: 0.80 Fe: Balance	Ni: 9 Fe: Balance
Crude Alloy Ni grade (%)	~25	BF: 2–5 SAF: 10–15	15	~15	~9
Crude Alloy Ni recovery (%)	90–95	BF/SAF: ~80	91	~92.5	~90
Refined Alloy Composition	Ni: ~28 Co: 0.60 C: 0.05 Si < 0.5 S < 0.06 P < 0.03	Decarburization can be applied for low-C low-grade FeNi production.	NA	Ni ≥20 C: 0.07 Si: 0.5 Cr: 0.06	-
Refined Alloy Ni grade (%)	~28	<15	NA	≥20	-
Refined Alloy Ni recovery (%)	90–95	NA	NA	>90	-
Energy requirement	502 kWh/t of calcine	BF: ~750 \$/t alloy ⁷	189 kWh/t of limonite	6132 \$ per 1 ton of nickel ⁸	NA

¹ Nickel smelting technology (NST) is not included in the table. It is applied to the Koniombo laterites that have average Ni content of 2.2%. No other information is available. The ISASMELT™ is not included in the table. It was applied for the ores containing 0.6–1.8% (bench-scale) and 0.3–3.6% (pilot-scale) Ni. It was indicated that bench-scale tests resulted in a refined alloy of Ni composition 15–40% and that pilot-scale tests gave a refined alloy of Ni composition 60–85%. No other information is available. Abbreviations: BF: Blast Furnace; SAF: Submerged Arc Furnace; FeNi: Ferronickel; NA: Not available. ² Warner et al. [44] and Solar et al. [45]. ³ Rao et al. [16]. ⁴ Erasmus and Fourie [23]. ⁵ Tsybulov et al. [13]. ⁶ Dong et al. [37]. ⁷ VonKruger et al. [46], the RKEF cost was reported as ~2400 \$/t alloy. ⁸ Reference [47], the RKEF cost was reported as ~8700 \$ per 1 ton of nickel.

The low-grade ferro-nickel production process can be regarded as the second most important industrial operation after the RKEF process, and it is widely practiced, especially in China and Indonesia. The production of low-grade ferro-nickel can be performed using blast furnaces and electric arc furnaces. Continuous growth in the production of low-grade ferro-nickel is anticipated, together with the increased demand for stainless steel production.

The reduction roasting–magnetic separation process is expected to remain one of the research hotspots in the treatment of laterites, as it is environmentally friendly and economical, although the nature of roasting and the large variability of the composition of laterites somehow limit its industrial application to a certain extent [42,43].

The major disadvantage of the Vaniukov process was the inability to lift the tuyeres above the slag for maintenance or in the case of blower emergency [11]. This may be one of the reasons why the process is not commonly used.

The need for a second furnace for metal–slag separation was regarded as one of the disadvantages of the ISASMELT™ process [11]. In literature describing the application of the ISASMELT™ process for converting of PGMs, one further disadvantage was reported—the rapid wear of the refractory lining of the furnace [14]. The limited number of applications of the ISASMELT™ process for laterite smelting may be attributed to these drawbacks.

Other than its advantage in terms of energy consumption, ESS technology was reported to be better than the RKEF process in that solid-state reactions were more controlled in the ESS furnace than in the rotary kiln. The ESS furnace gave better results, including the issue of dust losses. Dust loss in the ESS furnace was found to be limited, whereas a significant amount of dust loss was reported during and after rotary kiln operation (i.e., during the transfer of the reduced calcine from the kiln to the EAF). A similar conclusion related to heat losses was drawn [23].

NST was reported to have more efficient heat and mass transfer with moving bed reactors and to have the ability to treat fine materials, including ore and recycle dust, without agglomeration. This confirmed that a fluidized bed–DC arc furnace route was beneficial to the elimination of the dust problem associated with the conventional RKEF process. It has an industrial application in Koniombo Nickel [28–30].

6. Conclusions

1. Major alternative smelting processes to the RKEF process applied for laterites, namely, the Vaniukov process, low-grade ferro-nickel production, ESS technology, the ISASMELT™ TSL process, and NST, were reviewed in detail.
2. Examples of recent modifications related to the conventional nickel laterite smelting process were provided.
3. Examples of reduction roasting–magnetic separation methods applied to laterites were given. Such methods will probably remain one of the major topics in the treatment of laterites because of their high efficiency and low cost.
4. The treatment of laterites will remain a research hotspot in the field of extractive metallurgy in the near future as the demand for, and production of, stainless steel continues to increase.

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