

RESEARCH ARTICLE

Towards a low-carbon future: Reassessing hydrogen plasma smelting reduction technology for sustainable ferronickel production

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Abstract – More than 95% of global ferronickel production is currently dominated by the Rotary Kiln-Electric Furnace (RKEF) process, which significantly contributes to Greenhouse Gas (GHG) emissions due to its reliance on fossil-based carbon reductants. The use of hydrogen as a sustainable and green reductant presents a promising pathway for mitigating these emissions. This study aimed to reassess hydrogen plasma smelting reduction (HPSR) at the lowest investigated total gas flow by linking hydrogen supply to stoichiometric demand and evaluating alloy quality and Fe–Ni recovery. Saprolitic nickel ore was characterized, calcined at 900 °C for 3 h, formed into a 3 g briquette, assessed using FactSage 8.2, and treated for 180 s at a total H₂–Ar flow of 2 L/min and H₂:Ar = 4:1; the products were examined using SEM-EDS and elemental mapping. The 2 L/min total flow comprised 1.6 L/min H₂ and 0.4 L/min Ar and supplied 4.8 L H₂, approximately 20 times the calculated stoichiometric requirement. The resulting alloy comprised 72.35% iron (Fe) and 24.82% nickel (Ni). The estimated recoveries of Fe and Ni were 61.09% and 94.39%, respectively, and the measured alloy composition differed from the equilibrium prediction by 2.04 percentage points for Fe and 0.52 percentage points for Ni. These results show that the 2 L/min condition provides sufficient stoichiometric excess to produce well-separated ferronickel within 180 s at the lowest gas throughput evaluated.

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1. Introduction

Addressing climate-related challenges associated with metallurgical processing technologies has become an increasingly pressing concern among researchers worldwide, especially in the context of ferroalloy production [1], [2]. Ferroalloys, such as ferrochromium, ferromanganese, and ferronickel, are essential to the iron and steel industry, driven by the rising global demand for stainless steel across domestic and industrial sectors [3]. Among the commercially applied ferroalloy industries, ferronickel production exhibits the highest greenhouse gas (GHG) emissions, estimated at 24.1 t CO₂e per tonne of ferronickel produced [4]. This significant emission level is primarily attributed to the rotary kiln-electric furnace (RKEF) process, which dominates the processing of lateritic nickel ores, particularly saprolite-type ores [5]. The RKEF route integrates a rotary dryer, rotary kiln, and electric furnace technologies, each serving a specific function: drying, calcination and partial reduction, and finally smelting and complete reduction of the nickel ore. In conventional practice, a significant portion of GHG emissions originates from the partial reduction stage within the rotary kiln, as well as from the combustion of fossil fuels at the kiln's discharge end [6]. Furthermore, the reduction reactions occurring in the electric furnace between the reductant and the nickel ore produce carbon monoxide and carbon dioxide as byproducts of the final reduction stage. Consequently, the overall process generates substantial GHG emissions from both combustion and reduction steps, primarily due to its dependence on fossil carbon-based fuel and reductant. Nevertheless, despite its environmental drawbacks, this method remains the most effective and widely adopted approach for processing lateritic nickel ores, particularly high-grade types [5]. In recent decades, researchers have increasingly focused on addressing emissions generated by metallurgical processing technologies to mitigate the annual rise in global temperatures. According to the Paris Agreement, global temperature increase should be limited to below 2 °C [7]–[9]. In response, numerous studies have explored various technological innovations, one of which involves the use of hydrogen-based reducing agents. The use of a hydrogen-based reducing agent results in water vapour as the reaction byproduct, thereby avoiding direct carbon-derived CO₂ emissions at the point of reduction. Although hydrogen production remains relatively costly, its application is considered crucial for mitigating the ongoing climate crisis [10].

From a process perspective, the carbon intensity of conventional ferronickel production is not associated with a single unit operation. Thermal energy is required during drying, calcination, partial reduction, and electric-furnace smelting, whereas carbonaceous materials directly participate in oxide reduction. Consequently, replacing only one fuel source does not fully eliminate the carbon-derived emissions associated with the conventional flowsheet. Therefore, a hydrogen-based route is technically relevant because it addresses the reductant itself, with water vapour formed at the point of reduction instead of carbon monoxide or carbon dioxide. This distinction provides the metallurgical basis for evaluating HPSR as a complementary pathway for lowering the direct emission burden of laterite processing [4]–[6].

One hydrogen-based technology that has received increasing attention is hydrogen plasma smelting reduction (HPSR) [10]–[19]. This technology uses a versatile reductant and has been demonstrated at a small scale to produce metals using shorter processing routes. Similarly, other studies have reported that pure iron can be obtained within only 15 min of reduction [18]. Seftjani and Schenk also confirmed that iron oxide reduction is significantly facilitated when hydrogen

is in a plasma state [13]. Cavaliere stated that hydrogen in its plasma state offers a promising alternative because excited, atomic, and ionic hydrogen species significantly enhance the reducing capability from thermodynamic and kinetic perspectives [19]. In addition, our previous study [14] investigated the significance of reduction time, reductant gas flow rate, and sample mass on the quality and composition of ferronickel. It was shown that ferronickel could be produced within 3 min, and that increasing the total gas flow from 2 to 5 L/min did not produce a monotonic improvement in the Fe–Ni composition. However, the lowest-flow result was not specifically interpreted through stoichiometric hydrogen demand and Fe–Ni recovery.

Therefore, the relationship between the previous publication and the present study is deliberately focused. The earlier investigation established the general responses of the ferronickel composition to calcination, reduction time, sample mass, and gas-flow variation [14]. The present study does not repeat the broader parameter screening. Instead, it examines the lowest tested total flow in greater depth by connecting the supplied hydrogen volume with the calculated stoichiometric requirement, predicted equilibrium composition, observed metal-slag separation, and resulting Fe and Ni recoveries. This narrower analysis is important because a satisfactory alloy composition at lower gas throughput has a different technical meaning from simply demonstrating that reduction can occur at higher hydrogen flow. Building upon these research findings, further investigations have been conducted to explore the production of ferronickel from laterite nickel ore using this technology. This approach is expected to achieve a high degree of reduction, as outlined by Crundwell et al. [6], while offering a greener and environmentally friendly alternative. Such innovation contributes significantly to the advancement of sustainable metallurgical technologies. Accordingly, this study aimed to determine whether commercially relevant ferronickel can be produced within 180 s at a total gas flow of 2 L/min and to evaluate phase separation, alloy and slag compositions, and estimated Fe–Ni recoveries through integrated thermodynamic and laboratory-scale analysis.

2. Materials and Methods

This study commenced with the preparation of raw materials, which were subsequently subjected to characterization. Following the characterization phase, the chemical composition of the raw materials was determined, enabling thermodynamic simulations to be conducted using FactSage 8.2. These simulations were intended to provide predictive insights into the outcomes of the laboratory-scale experiments utilizing the hydrogen plasma smelting reduction (HPSR) method. Prior to smelting and reduction, the nickel ore underwent a calcination step. The resulting product was then embedded in epoxy resin, ground, polished, and subsequently characterized using scanning electron microscopy coupled with energy dispersive X-ray spectroscopy (SEM-EDS) to examine the microstructure and chemical composition of both the metal and slag phases. The chemical composition of the products was used to estimate the metal recovery achieved through the application of this technology. All procedures were the same as those performed in our previous study [14]. The detailed experimental procedures are presented in the following subsections. The focused variables were calcination condition, briquette mass and geometry, total H_2 –Ar flow, H_2 :Ar ratio, and reduction time.

The experimental workflow was arranged such that each stage supplied the information required by the next stage. XRF characterization first defined the oxide inventory used in the equilibrium calculation. The same characterized feed was then calcined and formed into a briquette with controlled mass and geometry, thereby providing a consistent basis for plasma exposure. FactSage was used to define the hydrogen requirement and expected phase distribution before the selected laboratory condition was applied. Finally, SEM-EDS composition and elemental mapping were interpreted together with the thermodynamic results and two-phase mass balance. This sequence links feed chemistry, process selection, product characterization, and recovery estimation without altering the operating variables previously established [14].

2.1 Analysis and Preparation of Lateritic Nickel Ore

The nickel ore used in this study was saprolitic laterite ore. It was dried at 150 °C, sieved to obtain a particle size of 65 mesh, and characterized to determine its chemical composition. X-ray fluorescence (XRF) analysis showed 9.75% Fe and 2.16% Ni, with a loss on ignition (LOI) value of 10.19%. The chemical composition of the nickel ore utilized in this study is presented in Table 1. After calcination, the powder was compacted without a binder at approximately 7.5 t to form a 3 g briquette approximately 15 mm in diameter and 7.5 mm high.

Table 1. Chemical composition of the saprolite nickel ore used in this study

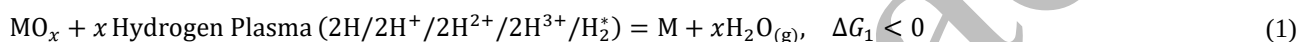
Component	Content (wt.%)
Fe ₂ O ₃ (Fe)	13.97 (9.75)
NiO (Ni)	2.76 (2.16)
SiO ₂	45.13
MgO	24.27
Loss on ignition	10.19

Based on our previous study, high Loss on Ignition (LOI) content must be removed [14]. To address this issue, the nickel ore was subjected to a calcination step using a muffle furnace before the smelting and reduction processes. Calcination was conducted at 900 °C for 3 h. This treatment was conducted to eliminate both surface and associated moisture, thereby enhancing the efficiency and effectiveness of the subsequent metallurgical operations. Our previous studies have also highlighted the critical importance of this calcination step, as elevated LOI levels can result in the

ejection of ore particles from the crucible during high-temperature exposure, leading to inefficiencies in the process [14]. Drying, calcination, and briquetting served different functions in the preparation route. Drying and sieving improved feed uniformity, whereas calcination removed the volatile fraction represented by the measured LOI. This was particularly important for plasma treatment because the rapid release of retained moisture can disturb the compact and eject fine particles from the effective reaction zone [14]. Binder-free compaction then converted the calcined powder into a defined 3 g body, allowing the same feed mass to remain concentrated beneath the plasma source. The approximately 15 mm diameter and 7.5 mm height also reduced geometrical variability when relating the gas supply and 180 s treatment period to the resulting metal and slag phases.

2.2 Thermodynamic Considerations of Hydrogen Plasma Smelting Reduction (HPSR) Technology

The thermodynamic principles that underpin the advantages of this technology have been extensively reviewed in previous studies and are now well established [10]–[19]. Thermodynamic data indicate that the reduction of iron and nickel oxides becomes increasingly favorable when diatomic hydrogen (H_2) is transformed into its monoatomic (H) or ionic (H^+) forms. Theoretically, the standard Gibbs free energy change (ΔG°) for equilibrium involving monoatomic hydrogen and hydrogen ions is approximately 3 and 15 times lower, respectively, than that for diatomic hydrogen [11]. This transformation is highly promising because these hydrogen species exhibit a much greater affinity for oxygen. However, such conversion into atomic and ionic forms can only occur at extremely high temperatures [20], which can be effectively achieved through hydrogen plasma smelting reduction (HPSR) technology. In the HPSR process, diatomic hydrogen gas is introduced into the plasma zone, where the reduction of metal oxides takes place. Within this high-temperature environment, H_2 molecules can dissociate into atomic hydrogen, ionize into H^+ , or become vibrationally or electronically excited [19]. The general form of the metal oxide reduction reaction is represented in Eq. (1) as follows:



The spontaneity and feasibility of any chemical reaction are governed by its Gibbs free energy change. For a reaction to occur spontaneously, ΔG must be negative. Under hydrogen plasma conditions, the presence of H radicals, H^+ ions, and vibrationally excited H_2 significantly lowers the Gibbs free energy of reduction reactions, even at relatively low temperatures. This highlights the key thermodynamic advantage of hydrogen plasma, in which monoatomic, ionic, and vibrationally excited hydrogen species play a critical role in facilitating the reduction of various metal oxides under milder conditions compared to conventional reductants such as fossil-based carbon. Equilibrium calculations were used as an operating reference rather than a description of the reaction rate. The purpose was to determine how the stable phase assemblage and ferronickel composition should change as hydrogen availability increased. In this interpretation, one stoichiometric equivalent represents only the molecular hydrogen required to remove oxygen associated with Fe and Ni oxides in the feed. The higher experimental supply accounts for the fact that the flowing gas is not consumed completely during its short residence in the plasma zone. Thus, the approximately 20-fold value is an operational excess relative to the calculated chemical requirement, while the equilibrium result remains independent of the 180 s experimental duration.

2.3 Hydrogen Plasma Smelting Reduction Technology Used

The reactor configuration and its components are illustrated in Figure 1. The reactor was equipped with multifunctional electrodes that served both as plasma sources and inlets for the introduced gases. For safety considerations, the reactor was fitted with an exhaust gas channel integrated with a combustion system to ensure that all flammable off-gases are properly combusted and do not escape freely into the environment. Furthermore, the copper crucible and nozzle within the reactor were equipped with a water-cooling system to prevent material degradation at elevated temperatures. The plasma generator was rated at 40 V and 35 A, and the same generator setting was maintained throughout the reported experiment. The reactor was not deliberately pressurised; the gas flow was maintained continuously, and the chamber remained connected to the off-gas combustion line.

In addition, the operational procedure consisted of several sequential stages. The process began with a conditioning phase, during which argon gas was purged into the reactor at a flow rate of 5 L/min to remove any residual air. Subsequently, hydrogen gas was injected for approximately 60 s, or until combustion was observed at the off-gas combustion system. During the 180 s smelting and reduction stage, the H_2 :Ar ratio was maintained at 4:1 and the total combined flow was 2 L/min, consisting of 1.6 L/min H_2 and 0.4 L/min Ar. Upon completion of this stage, argon gas was reintroduced into the system at 5 L/min for 60 s to purge any remaining hydrogen gas, ensuring the internal atmosphere was inert and safe for post-processing operations. These stages are illustrated in Figure 2. At 1.6 L/min H_2 for 180 s, 4.8 L H_2 was supplied, approximately 20 times the calculated stoichiometric requirement for the 3 g feed. Thus, 2 L/min was selected because it was the lowest tested total flow that provided the stoichiometric excess associated with the near-plateau ferronickel composition. In addition, the resulting product from the smelting and reduction processes was embedded in epoxy resin, prepared and subsequently analyzed using SEM-EDS, JCM-7000, and NeoScope. The gas sequence also separated process control from reactor safety. The initial Ar purge displaced residual air before H_2 introduction, whereas observation of combustion at the connected off-gas line confirmed that hydrogen had passed continuously through the reactor. During reduction, the constant 2 L/min total flow preserved the 4:1 H_2 :Ar ratio without deliberate pressure build-up. The final Ar purge then removed residual hydrogen before the product was handled. Under this sequence, the 1.6 L/min H_2 component delivered 4.8 L over 180 s, while the 0.4 L/min Ar component supported the plasma atmosphere. Accordingly, the selected flow should be interpreted as a combined H_2 –Ar operating condition rather than as 2 L/min of hydrogen alone.

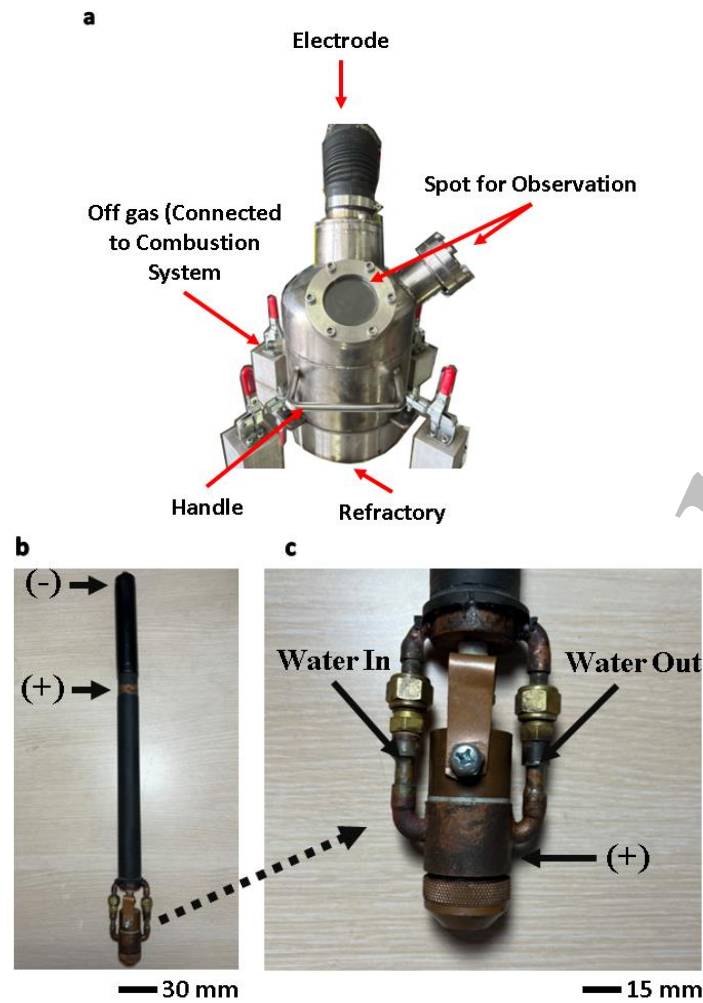


Figure 1. (a) Hydrogen plasma smelting reactor, (b) electrode rod, and (c) plasma nozzle

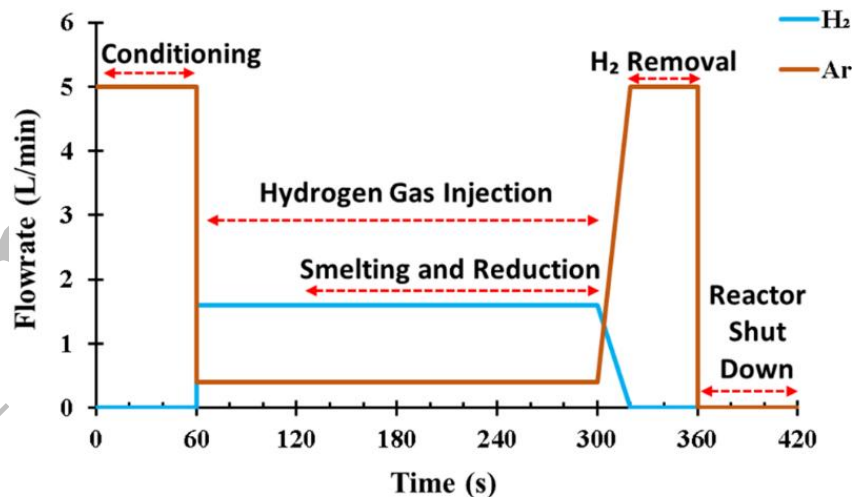


Figure 2. Operating sequence for ferronickel production using HPSR

The SEM-EDS analysis provided insights into the microstructure of the resulting ferronickel alloy and slag via HPSR technology, along with the elemental distribution—particularly of iron, nickel, and oxygen species. In the SEM images, the bright regions correspond to metallic phases, attributed to the higher atomic numbers of the constituent elements, whereas the darker regions represent the slag phase, composed of elements with lower atomic numbers. The JCM-7000 SEM-EDS was operated at 20 kV. Experimental interpretation was checked by comparing XRF feed chemistry, FactSage equilibrium predictions, SEM-EDS phase compositions, and Fe–Ni–O elemental maps. The measured and predicted alloy compositions differed by 2.04 percentage points for Fe and 0.52 percentage points for Ni. The material recovery calculation assumed that Fe and Ni did not volatilize and was based on a simplified two-phase mass balance. Fe and Ni recoveries were estimated as the mass of each element assigned to the metal phase divided by its mass in the feed.

FactSage sensitivity checks at 1600, 2000, and 2200 °C predicted negligible gas-phase Fe and Ni near the ferronickel melting range, whereas Fe volatilization becomes more relevant above approximately 2000 °C. The reported recovery values are therefore conditional estimates based on negligible Fe–Ni volatilization.

Validation was based on the convergence of independent forms of evidence. XRF established the elemental basis of the feed, FactSage predicted the equilibrium alloy and phase distribution, and SEM-EDS measured the compositions of the physically observed product regions. Fe–Ni–O mapping then verified that the compositional distinction was spatially associated with separate metal and slag areas. The 2.04 and 0.52 percentage-point differences for Fe and Ni, respectively, express the deviation between the equilibrium prediction and the measured alloy composition. Recovery was evaluated separately through the two-phase elemental balance; therefore, the reported 61.09% Fe and 94.39% Ni values retain the stated basis of negligible Fe–Ni volatilization.

3. Results and Discussion

3.1 Thermodynamic Calculation

Prior to conducting laboratory-scale experiments using this technology, thermodynamic calculations were performed using the FactSage 8.2 software. The databases employed in the simulation included FTmisc, FToxid, and FactPS. It is important to note that these calculations were based on several assumptions: the smelting and reduction processes were considered to occur under steady-state conditions, and kinetic factors were not considered. Moreover, the reductant species were limited to diatomic hydrogen (H_2) and atomic hydrogen (H), as the current database does not support calculations involving ionic hydrogen (H^+) as a reductant. The thermodynamic assessment aimed to determine the stoichiometric requirement of hydrogen necessary to produce ferronickel with a composition comparable to that of commercially available grades. Figure 3 shows the simulated equilibrium result using FactSage 8.2. The left axis reports the calculated Fe and Ni concentrations in the metal, while the right axis reports the calculated masses of metal, slag, and gas per 100 g ore.

To predict the required amount of hydrogen, a stoichiometric assumption was made: one stoichiometric equivalent of H_2 corresponds to the amount necessary to reduce Fe and Ni from their respective oxides. Based on thermodynamic simulations using FactSage 8.2, it was determined that a minimum of approximately 20 times the stoichiometric ratio of H_2 is required to produce ferronickel. Under these conditions, the metal phase achieved an Fe content of 74.39%, while Ni was diluted to 25.34%. At low H_2 input, preferential NiO reduction produces a small Ni-rich metal phase. Increasing H_2 progressively reduces iron oxides, increases the metal-phase mass, and dilutes Ni with Fe; above approximately 20 times stoichiometric H_2 , further compositional change is limited. According to Crundwell et al. [6], a high degree of reduction in ferronickel production is typically characterized by Fe concentration ranging from 45% to 65%, and Ni concentrations between 20% and 25%. The detailed correlation between Fe and Ni contents, stoichiometric H_2 ratios, and the resulting metal, slag, and gas phases per 100 g of ore is illustrated in Figure 3. If the stoichiometric ratio of H_2 correlates with the extent of ore exposure to hydrogen during the reduction process, the thermodynamic results indicate that H_2 reduces nickel oxide first prior to iron oxide. This reduction pattern leads to an initially high nickel content in the metallic phase, which is subsequently diluted by increasing iron incorporation as the ore becomes more extensively exposed to hydrogen gas. This sequence explains why Ni recovery can be high while a controlled fraction of Fe remains in the slag: additional H_2 mainly transfers Fe into the metal and progressively lowers the alloy Ni grade.

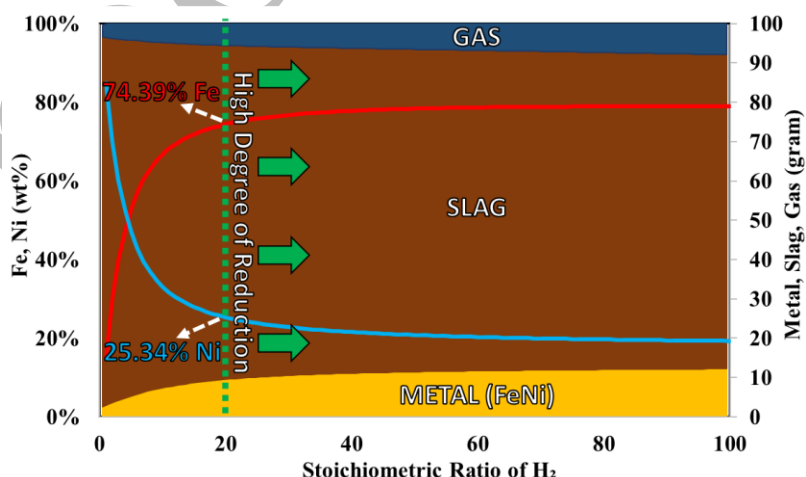


Figure 3. FactSage equilibrium prediction of Fe and Ni contents in the metal (left axis, wt. %).%) and metal, slag, and gas masses (right axis, g per 100 g ore) as a function of the H_2 stoichiometric ratio

Figure 3 shows why the region near 20 times the stoichiometric H_2 was selected instead of a substantially higher input. At low hydrogen availability, the metal phase is small and comparatively rich in Ni because NiO is reduced before the extensive reduction of iron oxides. As hydrogen availability increases, additional Fe enters the metallic phase, the amount of ferronickel increases, and the Ni concentration decreases through dilution. Near the selected point, the predicted Fe and Ni contents approached 74.39% and 25.34%, respectively, and subsequent hydrogen addition only slightly changed

the composition. Therefore, the curve provides both a compositional target and a stoichiometric explanation for evaluating the lowest total flow experimentally.

3.2 Laboratory-Scale Hydrogen Plasma Smelting Reduction (HPSR) Process

The smelting and reduction experiment of lateritic nickel ore was conducted with a total gas flow rate of 2 L/min, using a hydrogen to argon ratio of 4:1, and a total reaction duration of 180 s. Accordingly, the individual flows were 1.6 L/min H_2 and 0.4 L/min Ar. Stoichiometrically, the total amount of H_2 injected was approximately 20 times the required stoichiometric amount. The resulting smelting and reduction products were analyzed using scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS) and elemental mapping of Fe, Ni, and O, as shown in Figures 4 and 5, respectively. As shown in Figure 4, the product of this process demonstrated a clear separation between the metal and slag phases, attributed to the density difference. The bright Fe–Ni-rich region and its distinct interface with the darker oxide matrix indicate metal-droplet coalescence and metal-slag separation during the 180 s treatment. The metal phase consisted of a ferronickel alloy enriched in Fe and Ni, with concentrations of 72.35% and 24.82%, respectively. These values were consistent with the thermodynamic calculations discussed previously. The measured values differed from the FactSage prediction by 2.04 percentage points for Fe and 0.52 percentage points for Ni. It is noteworthy that although the thermodynamic calculations did not consider reaction kinetics or time—assuming equilibrium conditions—the experimentally produced ferronickel achieved comparable Fe and Ni contents within a remarkably short duration of only 180 s.

Microstructural observation and chemical analysis describe the same separation process from complementary perspectives. The brighter region identifies material with a higher average atomic number, while the darker surrounding region corresponds to the Mg–Si–O-rich oxide phase. The defined interface indicates that the reduced Fe–Ni material was able to collect into a distinguishable metallic region during the short treatment. This interpretation is supported quantitatively by the 72.35% Fe and 24.82% Ni measured in the metal and by their close agreement with the equilibrium composition. Thus, Figure 4 provides physical evidence that smelting, reduction, and phase separation occurred within the same 180 s plasma exposure.

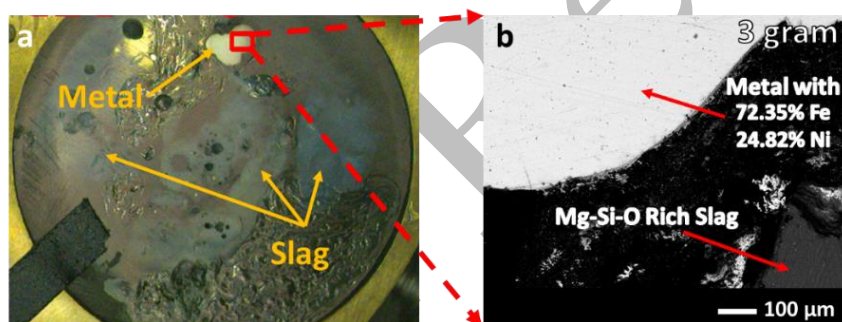


Figure 4. (a) Cross-section of the epoxy-embedded product and (b) SEM image showing ferronickel metal and slag phases

Figure 5 clearly illustrates the separation between the metal and slag phases, where Fe and Ni were concentrated in the metallic phase, whereas O was depleted in the metal and concentrated in the slag. The independent overlap of the Fe and Ni maps supports the phase assignment made from the SEM contrast. The slag produced from smelting and reduction using this technology was rich in silica (SiO_2) and magnesia (MgO), with concentrations of 51.95% and 36.34%, respectively. The composition of the resulting slag is comparable to that of commercially produced ferronickel slag, which is consistent with the fact that saprolite nickel ores are naturally rich in SiO_2 and MgO . The residual FeO and NiO contents were 5.36% and 0.32%, respectively; the low NiO content is consistent with preferential NiO reduction.

Table 2. Metal and slag compositions analyzed using SEM-EDS

Metal species	Metal (wt.%)	Slag species	Slag (wt.%)
Fe	72.35	MgO	36.34
Ni	24.82	SiO_2	51.95
		FeO	5.36
		NiO	0.32

The complementary elemental distributions also explain the slag chemistry reported in Table 2. The Fe and Ni intensities coincide within the metallic region, whereas oxygen is concentrated mainly outside that region. MgO and SiO_2 remain the principal slag constituents because these stable oxides are not the intended products of the selective reduction condition. In contrast, the residual 5.36% FeO represents iron that was not transferred to the alloy, while the much lower 0.32% NiO is consistent with the preferential reduction of NiO. The elemental maps, phase compositions, and thermodynamic sequence therefore provide mutually consistent evidence for selective nickel recovery followed by partial iron reduction.

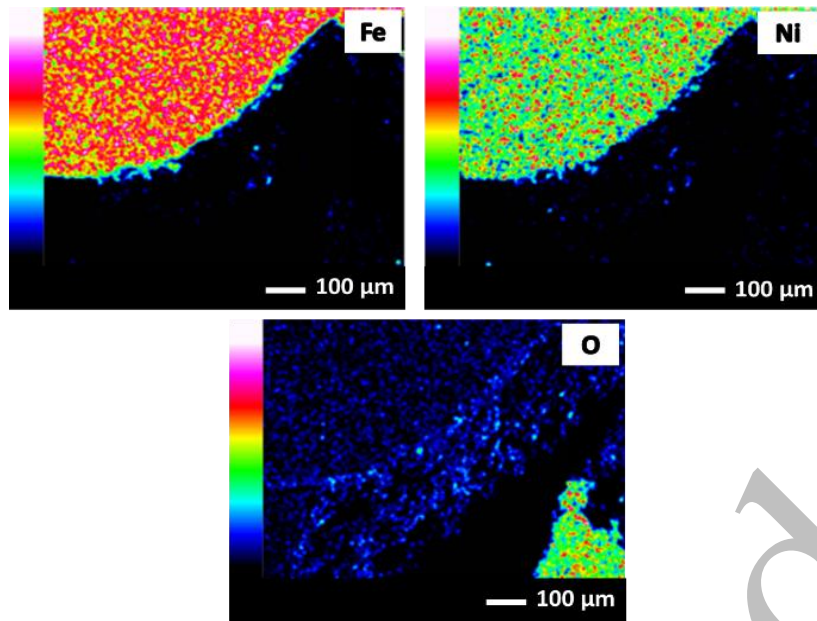


Figure 5. Elemental mapping of Fe, Ni, and O in HPSR product. The upper-left Fe–Ni-rich region is ferronickel metal, the lower/right O-rich region is slag, and all panels use the same 100 μm scale

Figure 6 shows the recovery estimation of iron (Fe) and nickel (Ni) using HPSR technology. The calculation assumed that Fe and Ni were distributed only between the metal and slag, with negligible Fe–Ni volatilization. Specifically, the recovery calculation was performed using the simple material-balance and metallurgical-balance equations presented in Eqs. (2) and (3), respectively. In these equations, F , C , and T denote the masses of the feed, concentrate (metal phase), and tailings (slag phase), respectively, whereas f , c , and t represent the corresponding grades of the target metal in each stream.

$$F = C + T \quad (2)$$

$$Ff = Cc + Tt \quad (3)$$

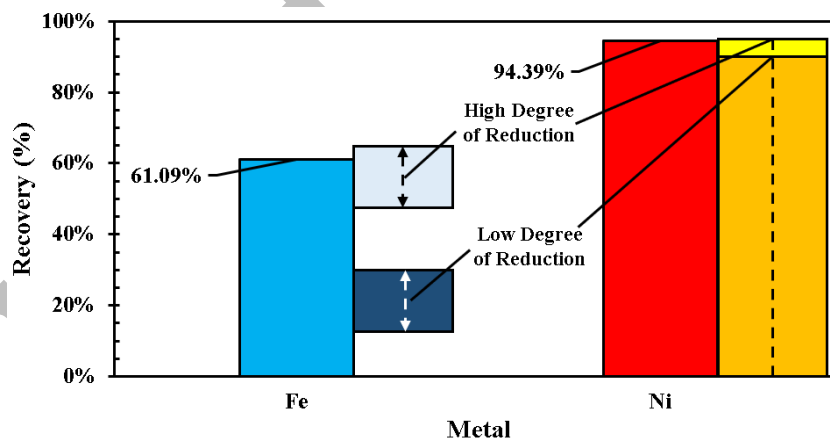


Figure 6. Estimated Fe and Ni recoveries at 2 L/min compared with typical high- and low-reduction ranges reported by Crundwell et al. [6]

Based on this approach, the recovery rates of Fe and Ni were calculated to be 61.09% and 94.39%, respectively. These results indicate that nearly all nickel oxides were successfully reduced to their metallic species. The high Ni recovery is consistent with the 0.32% residual NiO in the slag and preferential NiO reduction. The lower Fe recovery reflects the retention of FeO in the slag, which limits excessive Ni dilution. When compared to the typical recovery values reported by Crundwell et al. [6], the metal recoveries achieved through this technology correspond to a high degree of reduction. The values are conditional mass-balance estimates based on negligible Fe–Ni volatilization. Supporting results from our previous study [14] showed that increasing the total flow from 2 to 5 L/min produced no monotonic improvement: Fe remained 69.95–72.35% and Ni remained 23.29–25.64%. At 2 L/min, the present condition supplied approximately 20 times the stoichiometric H_2 requirement and produced the highest Fe content in that series (72.35%) while retaining 24.82% Ni. This identifies 2 L/min as the lowest tested flow that met the stoichiometric demand without a systematic compositional benefit from higher gas throughput. However, the viability of this technology is highly dependent on the cost associated with producing hydrogen gas to be used as the reducing agent. The results distinguish sufficient hydrogen

supply from unnecessarily high gas throughput. The 2 L/min condition already delivered approximately 20 times the stoichiometric H₂ requirement, produced a ferronickel composition close to the equilibrium prediction, and left only 0.32% NiO in the slag. The previously reported 2–5 L/min series did not show a monotonic improvement in Fe or Ni composition at higher flow [14]. Therefore, the contribution of the present analysis is not a claim that 2 L/min is universally optimal for every reactor scale; rather, it demonstrates that this lowest tested flow was technically sufficient for the specified 3 g feed, 4:1 H₂:Ar ratio, and 180 s treatment used in the present system.

4. Conclusions

A series of thermodynamic simulations and laboratory-scale experiments were conducted using hydrogen plasma smelting reduction (HPSR) technology. A 3 g calcined briquette was treated for 180 s at a total gas flow of 2 L/min and H₂:Ar = 4:1, corresponding to 1.6 L/min H₂ and 0.4 L/min Ar. The 4.8 L H₂ supplied was approximately 20 times the calculated stoichiometric requirement. The results demonstrated that ferronickel production via this method can be achieved rapidly and yields a product composition closely aligned with thermodynamic predictions, with Fe and Ni contents of 72.35% and 24.82%, respectively. Furthermore, the recovery rates of Fe and Ni reached 61.09% and 94.39%, respectively, indicating a high degree of metallurgical reduction. The absence of monotonic Fe–Ni improvement between 2 and 5 L/min in the previously reported flow series supports 2 L/min as a gas-efficient operating point for this reactor and feed mass. These laboratory-scale results support further HPSR evaluation, while energy consumption, process scale-up, and techno-economic performance must be assessed before industrial deployment can be determined. However, the cost of hydrogen gas remains a critical factor that must be addressed to ensure the overall effectiveness and economic feasibility of the process.

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Declaration of Competing Interests

The authors declare no conflict of interest.

CRedit Author Contribution Statement

I. Islam: Project administration; Methodology; Investigation; Analysis; Data curation; Conceptualisation; Writing – original draft

D. Tandersen: Methodology; Investigation; Analysis; Data curation; Writing – review & editing

A. Taimullah: Visualisation; Methodology; Investigation; Writing – review & editing

Y.A. Sata: Investigation; Analysis; Writing – review & editing

Y. Hendrawan: Visualisation; Resources; Methodology; Investigation; Writing – review & editing

T. Hidayat: Validation; Methodology; Funding acquisition; Writing – review & editing;

Z. Zulhan: Validation; Software; Resources; Methodology; Funding acquisition; Writing – review & editing

Availability of Data and Materials

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Ethics Declarations

This study did not involve human participants or animal subjects. Therefore, ethical approval was not required.

Generative Artificial Intelligence Disclosure

The authors claim that artificially intelligent-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have used AI to enhance readability and refine the language. We used it under strict human control and oversight. The authors take full responsibility for reviewing and approving the content.

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