HYFOR – HYdrogen-based Fine-Ore Reduction

Daniel Spreitzer[*1] **Johann Wurm**[*2]
Bernhard Hiebl[*3] **Norbert Rein**[*2]
Thomas Wolfinger[*4] **Wolfgang Sterrer**[*5]
Alexander Fleischanderl[*6]

The steel industry is a main contributor to industrial CO_2-emissions and therefore forced to transform into a low carbon economy till 2050. One promising approach to reach this target is the hydrogen-based direct reduction. Direct reduction utilizing the shaft technology is the dominating direct reduction technology but requires agglomerated DR-grade pellet feed as feed material. To overcome this, Primetals Technologies develops a direct reduction process, which is suitable to handle charging of iron ore concentrates (grain size <150 µm) directly into the process without need of prior agglomeration and using hydrogen as a reducing agent, named HYFOR (Hydrogen-based fine ore reduction). In this report, the status of development, including the erected pilot plant and a possible up-scaling, is demonstrated.

1. Introduction

The ever increasing economic and political pressure concerning the reduction of CO_2-emissions will pose a challenge for many steel producing companies. Currently, the integrated blast furnace (BF) – basic oxygen furnace (BOF) route is the dominating route to produce crude steel which has been well developed and improved over the last decades. Aside from the high amounts of accompanying CO_2-emissions (coal is used as a source for energy and reducing agent), the integrated route has several advantages, e.g., a high flexibility in handling different iron-containing raw material qualities or recycling of iron containing by-product materials. Therefore, a comparison of conventional shaft-based direct reduction (DR) technologies with the integrated route is difficult, as they require DR-grade pellet feed as input material for a subsequent melting in an electric arc furnace (EAF). Both process routes, the integrated BF-BOF and the DR shaft-based route require lumpy input materials as feed stock ensuring a sufficient gas permeability inside the BF or the reduction shaft. Therefore, additional agglomeration steps, e.g., sintering or pelletizing, are required, leading to additional costs (Capex and Opex) and significant CO_2-emissions. To overcome these problems, the ongoing HYFOR-process development by Primetals Technologies, is based on the fluidized bed technology which allows the exclusive use of green or low-carbon hydrogen (H_2) as reducing agent, avoiding the formation of CO_2 during reduction and the direct use of ore fines without prior agglomeration[1-3].

No technology existed till today to directly feed iron ore concentrates (pellet feed) as main iron source without prior agglomeration. The quality of ore from mines is continuously becoming lower (iron content and grain size), while huge amounts of fines (concentrates) are available. The HYFOR-process is the only process which allows using iron ore concentrates with particle sizes of 100% <150 µm, typical for various iron ore concentrates, directly without prior agglomeration. Any type of iron ore (e.g. hematite, limonite, magnetite) from high quality to low quality can be processed within the HYFOR-process. The process itself is based on a cross-current flow of the

*1 Primetals Technologies UP I&S DR TI, Technology Expert
*2 Primetals Technologies UP I&S DR TI, Senior Expert
*3 Primetals Technologies UP I&S DR&AG TI, Department Head
*4 K1-Met GmbH, Technology Expert
*5 Primetals Technologies UP I&S DR, Business Head
*6 Primetals Technologies UP-TI, Technology Officer, Dr.

reducing gas and the material to be reduced. Using such small-grained material in combination with the fluidized bed technology and hydrogen as a reducing agent, the HYFOR process allows a low temperature reduction which is beneficial for the fluidization behavior while at the same time high gas utilizations is obtained due to reasonable reduction kinetics.

Primetals Technologies has a long-lasting experience in the area of direct reduction, smelting reduction and fluidized bed-based solutions (FINORED® direct reduction process, FINEX® pre-reduction). Based on these competences, the HYFOR process is developed as the most flexible and lowest carbon emission direct reduction technology.

In the following chapters, the development of the HYFOR-process is described in detail.

2. HYFOR - From lab-scale experiments to pilot plant tests

In 2016, the first lab-scale investigations based on the HYFOR-technology were started at the reduction lab of the Chair of Ferrous Metallurgy, Montanuniversitaet Leoben. For that purpose, different fluidized bed reactor systems were used.

On the one hand, cold fluidization test series have been performed in a stationary fluidized bed reactor investigating the general fluidization behavior of such fine-grained material. Aside from the visible observation of the material in fluidized state, different pressure measurements were installed to verify the fluidization behavior of different iron ore concentrates. On the other hand, also stationary hot reduction tests were executed based on the data gained during cold fluidization tests. The hot reduction tests were used for the investigation of the fluidization behavior and reducibility of different iron ore brands using pure hydrogen as a fluidization and reducing gas. A variation of the process parameters, such as the superficial gas velocity inside the reactor, the reduction temperature, or the sample input mass (typically between 5 and 7.5 kg), allows the determination of an operation window for those materials which were used later as a design basis in the HYFOR pilot plant.

The results obtained during the lab-scale test period proofed, that a low reduction temperature is suitable, and a high gas utilization can be achieved due to the use of the fine-grained material in combination with hydrogen as a reducing agent. The low reduction temperature ensures therefore a stable and constant fluidization, also at high metallization degrees(4).

Nevertheless, the lab-scale investigations were not finished after the first successful tests. Every new potential iron ore is first tested regarding its suitability for the HYFOR-process in the lab scale because there is a possibility that the iron ores behave differently in terms of fluidization behavior and reducibility.

Based on the promising results of all the lab-scale test work, in 2018 the decision to start the design and engineering for a HYFOR pilot plant was made. The pilot plant should serve as a testing facility to verify the results obtained during the lab-scale investigations and to provide basic data for the design for a future industrial application. The erection of the pilot plant took place in the second half of 2020, followed by cold and hot commissioning in the first half of 2021.

A schematic flowsheet of the pilot plant is given in **Figure 1**. In principle, the layout allows two possible ways the material can pass throughout the experiment. The first one is executed during pre-heating of the material before reduction. At this stage, the material is charged directly from the material bins into the flue gas stream of a hot gas generator (air heater) and become transported to a cyclone. In the cyclone, a separation of material from the gas stream takes place while afterwards, the material is pneumatically transported back to the material bins. This arrangement allows to cycle the material inside the system more than once to achieve the desired material temperature before starting the reduction phase. The cyclone´s off gas passes afterwards a scrubber and a demister for cooling and cleaning before leaving to atmosphere.

In case of using a magnetite-based iron ore, additionally an oxidation takes place during material pre-heating. The exothermic character of the oxidation reaction is beneficial as it supports the pre-heating of the material and lowers therefore the primary energy consumption for the iron ore heating. Another advantage can be gained in terms of the materials reducibility. Generally, magnetite provides poor reduction behavior. A prior oxidation leads to different morphological changes during reduction which improves the reduction rate and therefore the reducibility(5).

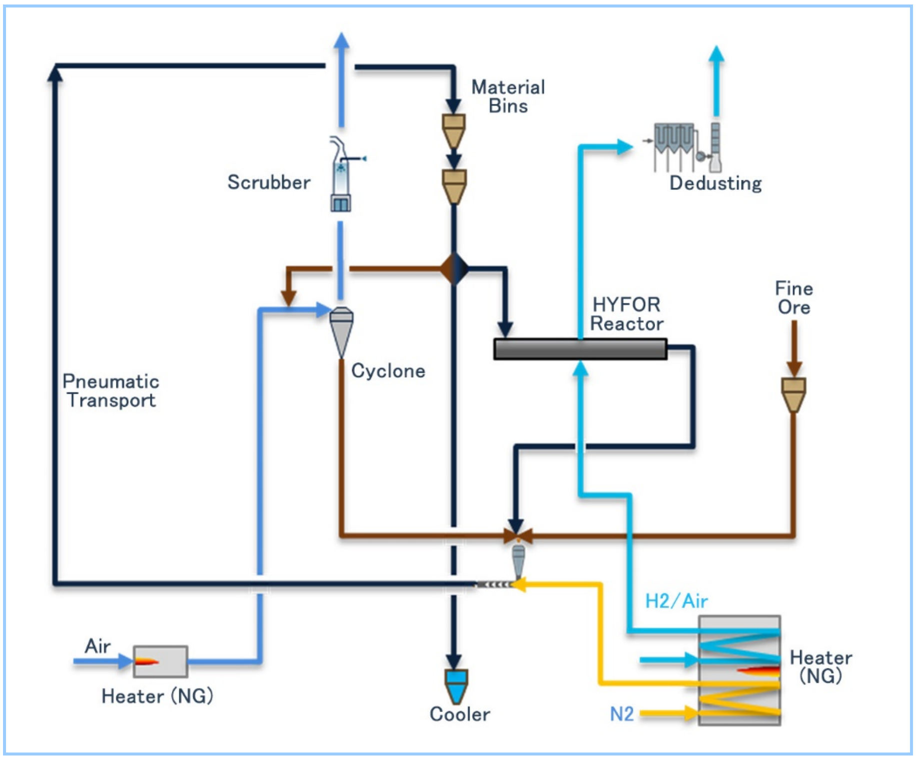

Figure 1　HYFOR Pilot plant － Schematic flowsheet

Generally, a separate pre-heating of the material is required in case of the HYFOR-process due to the use of a cross-current flow of gas and solids during reduction and the endothermic character of the reduction reactions of iron oxides with hydrogen.

After successful pre-heating of the material, the reduction itself takes place. Therefore, the material is charged from the material bins to the HYFOR reactor. The reactor itself has a cross section of less than 1 m^2. The material enters the reactor on one side, while on the other side, a weir is installed ensuring a defined bed height of the material inside the reactor and therefore an adjustable residence time. Material passing the weir can be again pneumatically transported back to the material bins and charged again into the reactor to ensure the overall required reduction time for achieving the targeted metallization degree.

The hydrogen needed for reduction is first pre-heated in a heat exchanger, before entering the reactor. To ensure a uniform gas distribution inside the reactor, a propriety gas distributor design is applied also avoiding solid back flow into the wind box in case of unscheduled shutdowns. After fluidizing and reducing the material, the dust-loaden off-gas leaves the reactor and passes through a dry dedusting unit before it is post-combusted and leaves to the ambient. A recirculation of unreacted hydrogen would certainly be applied at an industrial plant. The separated dust is recharged into the reactor improving the yield of the process. After reduction and final material sampling, the whole material is collected again in the material bins and discharged afterwards into a quenching vessel (cooler).

After the commissioning phase mid-2021, first material tests were started with the main objective of testing the facility and to develop an optimized testing procedure. Modifications and improvements have been also applied.

After implementation of these plant improvements, the focus in 2022 is now on testing different iron ore brands to verify the industrial ability of the technology. The following four questions are addressed based on different test campaigns: first, required residence time for achieving defined metallization degrees; second, gas consumption and/or gas utilization in dependence of superficial gas velocity and reactor pressure; third, optimum reducing gas inlet temperature for avoiding sticking of particles in the area of the gas distributor and fourth, in case of magnetite-based iron ores, effect of different oxidation procedures on the reduction rate and therefore on the reducibility.

Once these questions have been sufficiently answered by the appropriate testing campaigns with the pilot plant, a decision for an up-scaling towards an industrial prototype can be done.

3. HYFOR Industrial Prototype Plant – The next step

An industrial prototype plant can be defined as an intermediate step between pilot plant and an industrial (commercial) plant with a production capacity of approximately 5-15 tons per hour considering continuous operation. A possible schematic flowsheet of a HYFOR industrial prototype plant is shown in **Figure 2**.

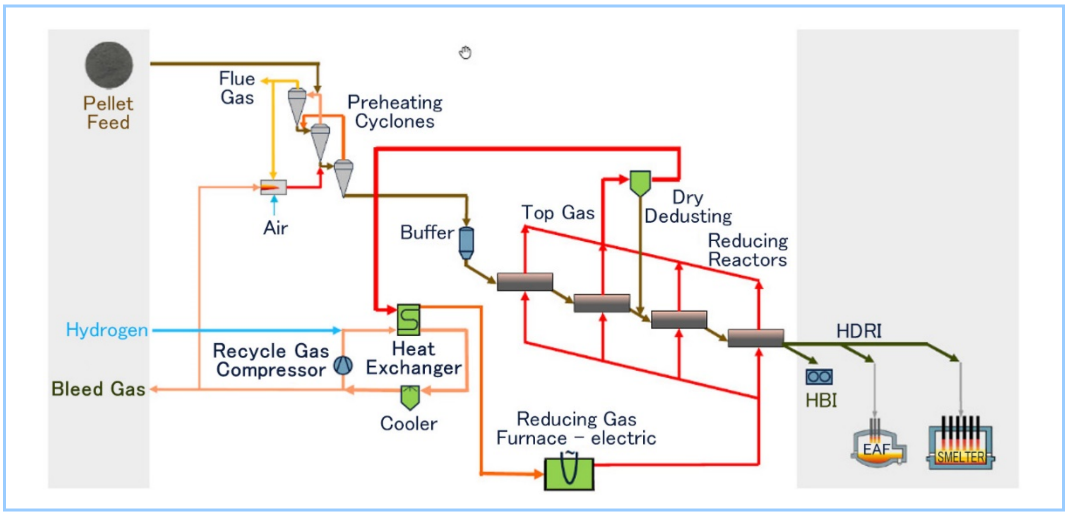

Figure 2 HYFOR Industrial prototype plant – Schematic flowsheet

The material pre-heating (and oxidation) takes place in a multistage cyclone cascade while the energy needed for pre-heating is provided by a hot gas generator which is fired with hydrogen containing bleed gas from the recycle gas loop. After pre-heating, the material is charged into a bin, acting as a buffer before being charged into the first reduction reactor. In total, several reduction reactors in series are applied for the reduction work and to ensure a sufficient residence time. Clean reducing gas is injected in each of the reactors. The off-gas of all reactors passes a dry dedusting unit for separating the dust from the gas. The dust is re-circulated back into the reducing reactors featuring a high yield. Depending on the quality of the iron ore used various product options can be applied. In case of high-quality ore (high iron content) the final product can be briquetted to produce hot briquetted iron (HBI) for subsequent feeding to different primary production units or it can be directly hot charged into an electric arc furnace (EAF) to produce steel. Hot direct reduced iron (HDRI) based on low-grade iron ore (low iron content) can be directly charged into a reducing smelting unit (Smelter). This demonstrates one of the biggest advantages of the HYFOR-process, the flexibility in use of different iron ore qualities.

After dry-dedusting, the recycle gas passes a heat exchanger and a gas cooler, for removing the formed water vapor during reduction. Unreacted hydrogen is recycled and re-used in the process again after passing a recycle gas compressor, the heat exchanger, and the reducing gas furnace. The reducing gas furnace is based on electrical energy. The hydrogen consumed by the reduction is added in form of make-up hydrogen to the process before the heat exchanger. Depending on the ore quality, between 550 and 600 Nm^3 hydrogen per ton of DRI are required. This arrangement of the equipment allows a fully continuous operation of the plant starting at the cold iron ore concentrate and ending with the final product.

Depending on the progress of the pilot plant test campaigns and on decision for a lead customer, such industrial prototype might be operational by 2025.

The advantages of the HYFOR process can be summarized as follows:

- Direct use of iron ore concentrates without need for prior agglomeration
- Usage of pure green or low-carbon hydrogen as reducing agent and therefore no CO_2 generation during reduction
- Flexibility in use of various iron ore brands (e.g. hematite, limonite and magnetite)
- Highest iron yield due to dry dedusting and recycling of dust
- Low energy consumption due to high iron yield and no prior agglomeration
- Highest availability due to low temperature reduction and avoidance of particle sticking

Potential customers of the HYFOR technology can be of course conventional steel producing companies but also mining companies with the intention to produce hot briquetted iron (HBI) or pig iron as value-add product.

The HYFOR process contributes essentially to the energy transition and decarbonization of the steel industry and will become a green steel production process.

4. Conclusion

To decarbonize the steel sector new innovative process technologies based on a hydrogen economy are required. Primetals Technologies, who has a long-lasting history and a broad portfolio base in direct and smelting reduction including fluidized bed-based solutions, is developing a new generation direct reduction process based on the direct use of iron ore concentrates and hydrogen as reducing agent, branded HYFOR (Hydrogen-based fine ore reduction). Based on previously generated lab-scale process data, a pilot plant was installed and commissioned in 2021, respectively. The pilot plant serves as a testing facility for various ore grades to generate relevant process data which can be used for further up-scaling to an industrial prototype plant which might be operational by 2025, depending on the results which will be obtained

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