Circored Fine Ore Direct Reduction Plus DRI Smelting – One Route Towards Green Steel

Sebastian Lang[1], Max Köpf[1] (✉), and Timo Haimi[2]

[1] Outotec GmbH & Co KG, Oberursel, Germany
[2] Metso Outotec Oyi, Helsinki, Finland
sebastian.lang@mogroup.com; maximilian.koepf@mogroup.com; timo.haimi@mogroup.com

Abstract. The hydrogen-based direct reduction of iron ore combined with EAF smelting is being widely discussed as a possible replacement for the commonly used BF/BOF route in steelmaking when targeting carbon footprint reduction. One alternative to shaft furnaces is the Circored process of Metso Outotec, which uses fine ore as feed for fluidized bed reactors and is eliminating so the cost and energy-intensive pelletizing step. As a direct reduction process using 100% hydrogen as the reductant, Circored has already proven its functionality in an industrial-scale demonstration plant.

For the smelting of DRI Metso Outotec can use its rectangular six-in-line smelting furnace, which is based on a flash smelter body and Söderberg electrodes. This DRI smelting solution is able to replace small-/medium-sized BFs and produce hot metal with the desired carbon content in existing steel plants with BOF converters. The large furnace volume enables the processing of low-grade iron ore with high gangue content and thus the use of BF-grade feed for DRI production.

Keywords: Hydrogen · Direct reduction · DRI · HBI · DRI smelting

1 Introduction

In 2019, the United Nations announced that over 60 countries had committed to carbon neutrality by 2050. These targets were confirmed in 2021 at the COP 26 meeting, significantly accelerating the dynamics for the development of carbon-neutral or green steelmaking technologies. With limited investment cycles left until 2050, the steelmaking industry must decide within the next 5–10 years in which alternative technology for the reduction of iron ore to invest.

The hydrogen-based direct reduction of iron ore combined with EAF smelting is being widely discussed as a possible replacement for the commonly used BF/BOF route in steelmaking to decrease the carbon footprint over the steel value chain. However, applying this approach will generate the need for several hundred million tons of additional high-quality DR-grade pellets annually, with the associated impacts on the demand for high-grade iron ore concentrates, pellet availability, and consequently pellet prices. One alternative to shaft furnaces is Metso Outotec's Circored

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process, which uses fine ore as feed for fluidized bed reactors, eliminating the cost and energy-intensive pelletizing step. As a direct reduction process using 100% hydrogen as a reductant, Circored has already proven its functionality in an industrial-scale demonstration plant. Direct charging of hot DRI to a smelter would further increase the energy efficiency of the process and opens up for low-grade iron ores as feed materials.

As frequently discussed steelmaking route the direct reduction in shaft furnaces followed by EAF-steelmaking relies on the use of high-grade iron ore, it is evident that this will increase the already visible shortage of such feed materials. The Metso Outotec rectangular six-in-line smelting furnace combines a flash smelter body with Söderberg electrodes. The large furnace volume enables the processing of pre-reduced low-grade iron ores with, respectively, high gangue content and consequently big slag volumes. So it is a way to use BF-grade feed for DRI production and delivering pig iron into the present steel value chain. This DRI smelting solution can replace small-/medium-sized BFs and produce hot metal with the desired carbon content in existing steel plants with BOF converters.

This concept is new in the global framework and can be very competitive regarding both investment costs and technological risks and is an important enabler in decarbonizing steel production, thus contributing directly to the transition toward green steel.

2 The Circored Process

Circored is based on fluid bed technology, a field in which Metso Outotec has been leading the development now for several decades. The technology is state-of-the-art for industrial processes such as coal combustion in circulating fluidized beds (CFB) and alumina calcination. The main advantages of fluidized bed processes are excellent heat and mass transfer conditions, precise temperature control, short solids retention times leading to higher plant capacities, and lower investment and operating costs.

The technology can also be applied for the direct reduction of iron ore to eliminate the cost and energy-intensive agglomeration step of iron ore fines in the form of sintering or pelletizing.

The generic Circored process is based on the reduction behavior of iron ore, as shown in Fig. 1.

For the direct reduction of fine iron ore, Circored applies a two-staged reactor configuration with a CFB followed by a bubbling fluidized bed (FB) downstream. Below is a brief description of the Circored process, which is also visualized in the simplified process flow diagram in Fig. 2.

The preferred grain size for the process is 0.1–2.0 mm, though depending on decrepitation behavior, a grain size of up to 6 mm might also be acceptable. Ultrafine concentrate and in-plant fines can be microgranulated. The iron ore fines are dried and preheated in a CFB preheater to a temperature of approximately 850–900 °C before being introduced into the first-stage CFB reactor.

The initial reduction step is fast and controlled by the outer mass transfer of the reductant to the iron oxide particle. The CFB is the ideal reactor to achieve a prereduction degree of 65–80%, offering the following characteristics: high gas velocities of

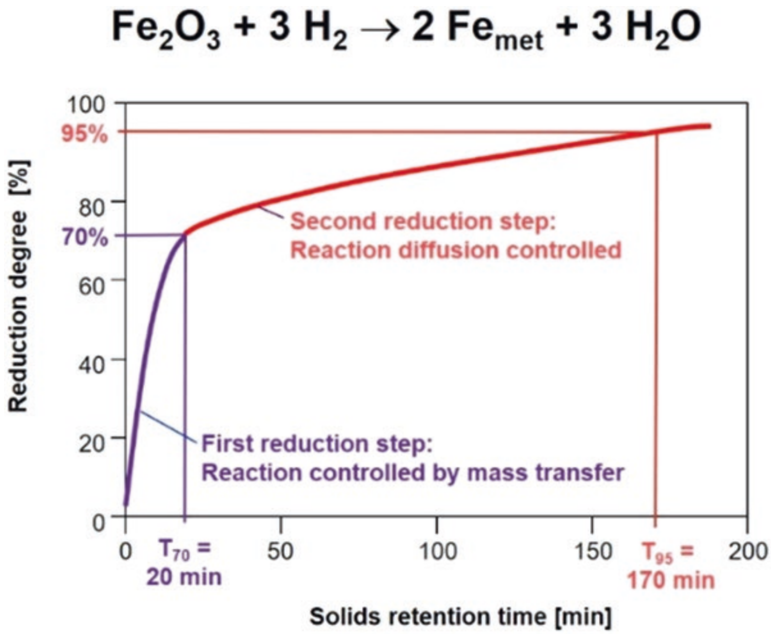

Fig. 1. Performance of H_2-based direct reduction process in fluidized beds.

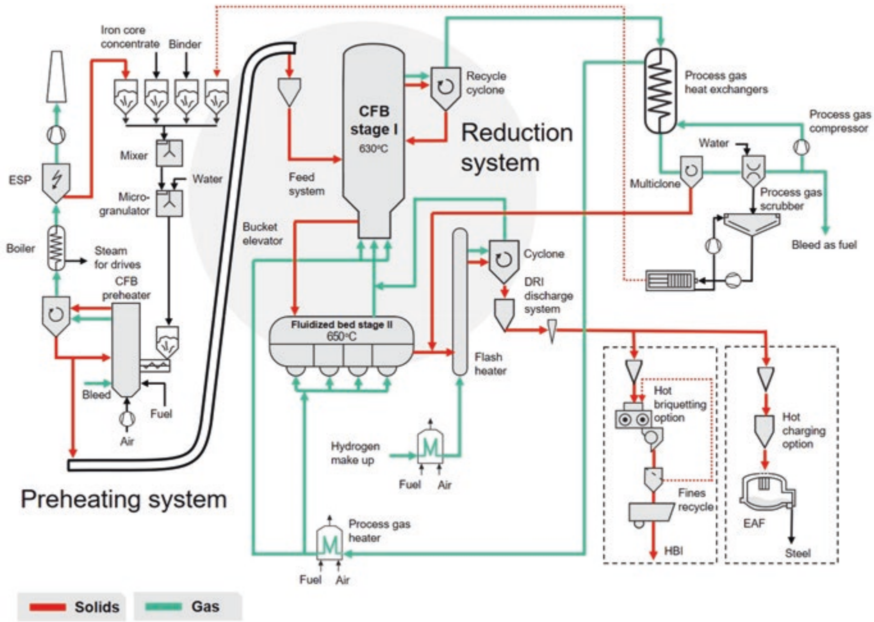

Fig. 2. A simplified process flow diagram of the Circored process including microgranulation.

4–6 m/s and high differential velocities between gases and solids leading to short solids retention times of 20–30 minutes, and the optimum lateral and vertical mixing of solids and gases ensuring uniform temperature distribution throughout the reactor.

For processing ultrafine ores (<50 μm) or scrubber dust, Metso Outotec has patented a very simple microgranulation process. In this process, the ultrafine particles are agglomerated under the addition of a binder to microgranules of an average size of approximately 350 μm. This process variant does not require any additional equipment as the hardening of the granules takes place in the preheating section of the Circored plant (also shown in Fig. 2).

After prereduction, the material is discharged into the secondary FB reactor. For the prolonged diffusion-controlled final reduction step, the bubbling FB reactor offers optimum conditions for achieving reduction degrees in excess of 93–95%, with low gas velocities of 0.5–0.6 m/s and longer solids retention times of 60–180 minutes depending on the nature of the ore.

For the Circored process, hydrogen was selected as the sole reducing agent. Its specific reduction reaction temperature characteristic lowers the temperature of the process to 630–650 °C and avoids particles sticking in the reduced material. Because of this, at the time of its development, hydrogen was the enabler for a new process; today, with the steel industry under pressure to decarbonize, the use of hydrogen as the sole reductant is nowadays getting much more significance. From this perspective, one could say that the hydrogen-based Circored process was developed 20 years too early.

As the reduction of iron ore with hydrogen is an endothermic reaction, the energy must be supplied by heating both the ore and process gas. In the past, this was done using natural gas and process bleed gas. To achieve a totally carbon emission-free process, it is now foreseen to replace natural gas with electric heating powered by (green) renewable energy.

A further significant advantage of the CFB reactor is the ability to inject dust-laden, partially reacted gas from the second-stage FB reactor, which creates a counter-current flow of gases and solids throughout the dual-reactor system. This has a twofold advantage: the nozzle grate of the CFB reactor is only exposed to clean recycled process gas, thereby minimizing nozzle wear, and the overall gas utilization of the entire process is maximized. The Circored process generates no residues or relevant emissions besides water and unavoidable heat release.

Key Features of the Circored Process

- Preheating the iron ore fines to 850–900 °C in a separate CFB reactor for calcining prior to charging in the primary CFB reduction stage. This method also allows the processing of magnetite ores, which can be difficult to reduce as the preheating stage oxidizes the magnetite to hematite. In addition, the microgranules produced can be hardened to avoid the generation of ultrafine particles in the reduction stage.
- Prereduction in a CFB in about 20–30 minutes to a reduction degree of 65–80%.

- Final reduction in a compartmentalized FB reactor to 93–95% reduction.
- The use of hydrogen as the sole reductant enables low temperatures of 630–650 °C in the CFB and the FB; this low temperature avoids particle sticking and means that the reaction is easy to control.
- A zero-carbon process variant is possible with electrical heating from renewable sources to provide the energy for the endothermic reduction reactions.

2.1 Comparison of Different Steelmaking Routes

When comparing Circored/EAF steelmaking with other state-of-the-art routes, especially in terms of CO_2 emissions and cost, common battery limits need to be defined. We look here at the conversion of an iron ore concentrate to raw steel with all the required intermediate steps, forming the references for this comparison (see Fig. 3). Both Circored and shaft furnace direct reduction technologies produce DRI or HBI which can directly be used in an EAF. The product from the blast furnace, pig iron, is fed to an oxygen converter (BOF). All these downstream processes are considered in the CO_2 and cost figures.

If an ultrafine concentrate is used, a microgranulation step should be applied to narrow down the particle size distribution and make the material properly fluidizable. Along with this option comes the opportunity to recycle any kind of dust or fines originating at different points in the plant. In a classical set up, the Circored process would use a natural gas reformer to provide hydrogen for the reduction. In future scenarios, green hydrogen produced from renewable sources is used for direct reduction and electric heating.

It is apparent that the BF/BOF route is by far the largest emitter of CO_2; furthermore, the technical solutions to minimize emissions are limited for this route. While the CO_2

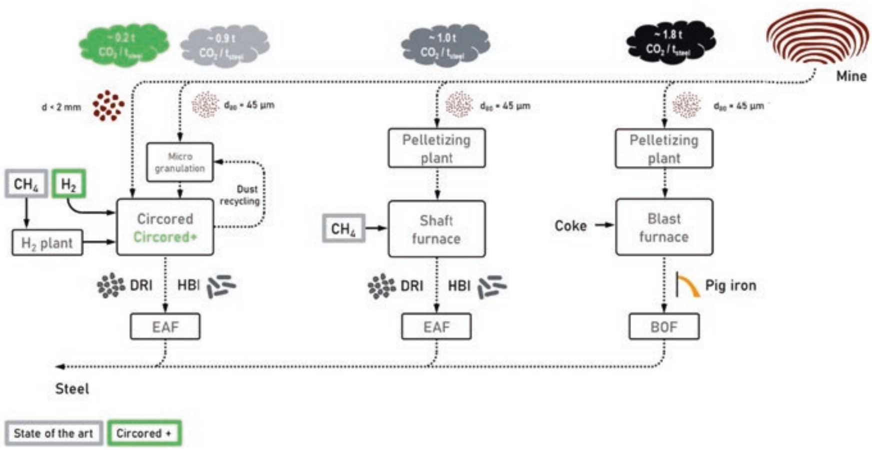

Fig. 3. A comparison of the main components, feeds, and products of different steelmaking routes.

emissions of the Circored process and shaft furnace direct reduction are in the same order of magnitude, Circored benefits from the omission of the pelletizing step. As Circored+ (fully decarbonized process variant) is designed to produce real green steel, the CO_2 emissions of the process become negligible.

When it comes to cost, Circored is a very competitive route, partly because the CO_2 taxation costs are lower than for the BF/BOF route and because there is no pellet premium compared to the shaft furnace route. In terms of CO_2 emissions and cost, the "regular" Circored process is already competitive today, and the Circored + variant is predicted to be even more so in future.

3 The Circored Plant in Trinidad

There were two main drivers for the development of the Circored process: the growing demand for a direct reduction process utilizing iron ore fines directly to decrease HBI production cost by avoiding a costly agglomeration step, and Metso Outotec predecessor's desire to apply its vast experience of utilizing fluidized bed technology also for direct reduction.

In 1996, the contract for the first Circored plant, to be built in Trinidad, was awarded by Cliffs and Associates Limited. The plant started operation in May 1999; after the discharge system was modified it reached its process design parameters in March 2001 and was operating at up to 105% of its design capacity.

Despite functioning normally, the plant was unfortunately idled after a short period of successful operation, which produced 300,000 tons of high-quality HBI (Fig. 4). This was due to several changes in ownership and to economic and political reasons including steel-market developments and the lack of availability of natural gas. The Trinidad plant fulfilled process expectations in terms of a high and uniform degree of metallization achieved from the outset.

Key Achievements of the Circored Plant in Trinidad

- Over 300,000 tons of high-quality HBI were produced and were subsequently processed in electric arc furnaces located in the US.
- Plant design HBI production of 63 t/h periodically exceeded.
- High HBI product quality with maximum metallization degrees greater than 95% and constant briquette densities above 5.2 g/cm^3.

Since the design, erection, and operation of the first Circored plant in Trinidad, numerous modifications to the original setup were investigated and developed:

- Plant capacity increased to 1.25 Mt/year per line, now considered the technical and economical optimum for an industrial-scale plant.
- Replacing natural gas with green electricity for preheating to achieve complete carbon neutrality.

Fig. 4. Trinidad plant with HBI stockpile.

- Microgranulation: for processing ultrafine (<50 μm) ores and scrubber dust, Metso Outotec has patented a very simple microgranulation process. In this process, the ultrafine particles are agglomerated to microgranules to an average size of approximately 350 μm with the addition of a binder. The process does not require any additional heat-hardening equipment as the hardening of the granules takes place in the preheating section of the Circored plant.
- Direct feeding of hot DRI into an EAF to further improve energy efficiency.
- For low-grade iron ores, a combination of a single reduction stage Circored process (metallization degree of 75–85%) with smelting reduction in an electric smelter for hot metal production is feasible.

4 DRI Smelting

By utilizing the existing products and wide experience of the Metso Outotec Ferroalloys and Non-Ferrous Smelting organization, a new solution has been developed for smelting DRI that has been produced from low-grade iron ore to produce hot metal for further use in BOFs. Such DRI feed would be a challenge for standard steelmaking EAFs because of the excess slag volume, which causes unacceptable losses of Fe units to the slag. In addition, incorporating this type of process into existing steel plant facilities using BOF converters can be a challenge, at least on a larger scale and for more demanding steel grades.

The Metso Outotec solution, therefore, aims to replace the blast furnace and achieve continuous production of suitable hot metal quality for an existing steel plant, to enable the use of existing BOF converters. The main idea is to use a closed EAF for the smelting of the pre-reduced iron ore feed (DRI from Circored). For fossil-free production, sustainable sources of carbon reductant would be needed for the smelting furnace, since the final reduction takes place there.

The main driver of this solution is that there is no need to use high-quality DRI-grade pellets or to increase the usage of external (high-quality) scrap. It can use DRI produced from standard BF-grade pellets by direct reduction in a shaft furnace or Circored-DRI produced from low-grade iron ore fines and even utilize recycling of waste material like dust briquettes. Also, the slag can be modified to remove impurities and achieve the desired slag chemistry, targeting very good metal yields and good-quality slag products that can be used as raw materials by the cement industry. Furnace off-gas can be either utilized as combustible off-gas (in a similar way to coke oven gas/blast furnace gas in the possible existing power plant) or combusted to produce steam for other heating purposes.

The Metso Outotec DRI smelting furnace design uses six self-baking Söderberg electrodes, which are standard in ferroalloy and non-ferrous processes. The design of the furnace body is well known from in flash smelting furnaces and proven in numerous installed plants. Therefore, all equipment is proven technology and has many reference projects. Figure 5 shows an illustration of the furnace.

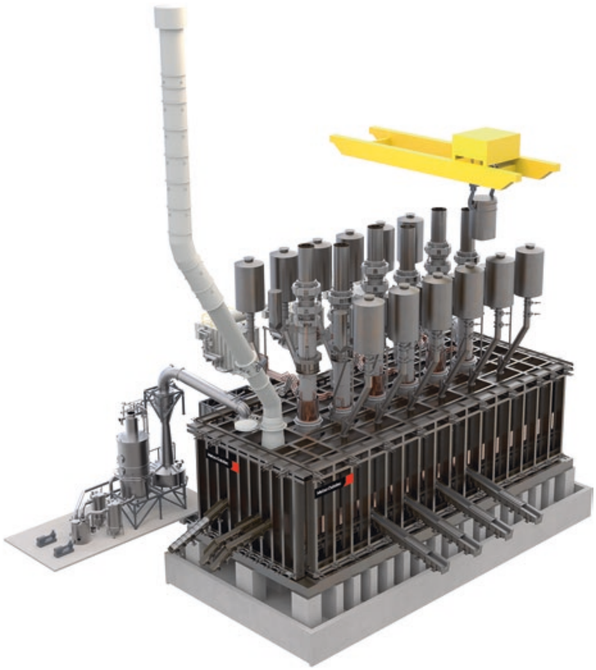

Fig. 5. Metso Outotec DRI smelting furnace design.

The feed can be fed into the feed bins on top of the smelting furnace, either hot or cold. There are several possibilities for the feeding system, but the most commonly used systems are conveyors and buckets. The hot feeding is highly efficient in terms of electrical energy consumption since a feed temperature of <600 °C reduces specific smelting electrical energy consumption by as much as 20%. In the case of hot feed, the reductants and fluxes need to be fed from separate bins to the hot DRI.

The furnace is lined with refractories and cooled with water via different copper cooling elements.

The carbon and silicon levels of the hot metal produced with the furnace need to be configured to the needs of each steel plant. Additionally, all DRI pellets use different iron ore feed, which means that the solution needs to be optimized according to the needs of each individual steel plant.

5 Perspectives

With the Circored process, Metso Outotec provides an alternative process route for the reduction of iron ores, using hydrogen as the sole reductant and fine ore instead of pellets as feed material. Circored is currently the only process for iron ore direct reduction based on pure hydrogen and has proven its functionality and performance in an industrial-scale demonstration plant with a capacity of 500,000 t HBI/year.

Circored technology is flexible in its production setup. Besides merchant cold HBI, which can easily be shipped, hot and cold DRI can be produced and directly linked to EAFs and BOFs as a substitute for hot metal and/or other virgin iron units. This guarantees the production of high-quality steel products that have traditionally been the strength of integrated steel plants.

As the frequently discussed steelmaking route direct reduction in shaft furnaces followed by EAF-steelmaking relies on the use of very clean raw material, it is evident that this will increase the already visible shortage of high-quality, clean raw material. The Metso Outotec DRI smelting furnace to produce hot metal would be able to handle large slag volumes without excess Fe-unit losses, thereby allowing the use of lower-quality raw materials. This DRI smelting solution can replace small-/medium-sized BFs and produce hot metal with the desired carbon content in existing steel plants with BOF converters.