Circored Fine Ore Direct Reduction Plus DRI Smelting: Proven Technologies for the Transition Towards Green Steel

Sebastian Lang, Timo Haimi, and Max Köpf

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 Metso Outotec's Circored 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 the 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. Metso Outotec's rectangular six-in-line smelting furnace combines a flash smelter body and the Söderberg electrodes. 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. 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 Iron and steel · Environmental effects · Process technology

Introduction

In 2019, the United Nations announced that over 60 countries had committed to carbon neutrality by 2050 [1]. The European Green Deal, proclaimed in March 2020, translated this declaration into a legally binding target, significantly accelerating the dynamics for the development of carbon–neutral or green steelmaking technologies.

About 70% of the world's steel is produced via the blast furnace/basic oxygen furnace (BF/BOF) route, an efficient but highly carbon-intensive production method.

S. Lang (✉) · M. Köpf
Metso Outotec, GmbH & Co KG, An den Schwarzwiesen 13, 61440 Oberursel, Germany
e-mail: sebastian.lang@mogroup.com

T. Haimi
Metso Outotec Oy, Rauhalanpuisto 9, 02231 Espoo, Finland

F. Tesfaye et al. (eds.), *REWAS 2022: Energy Technologies and CO_2 Management (Volume II)*, The Minerals, Metals & Materials Series,
https://doi.org/10.1007/978-3-030-92559-8_7

With this process, on average 1.8 tons of CO_2 are produced for every ton of crude steel. In total, the steel industry is responsible for about 8% of global CO_2 emissions [2].

With limited investment cycles left until 2050, the steelmaking industry must decide within the next five to ten years which alternative technology for the reduction of iron ore to invest in. One widely discussed alternative to traditional carbon-intensive BF/BOF steelmaking is the hydrogen-based direct reduction of iron ore combined with electric arc furnaces (EAF). Most of the current projects focus on applying shaft furnaces for direct reduction with hydrogen. However, applying this method will generate the need for several hundred million tons of additional high-quality DR-grade pellets annually, with the associated impacts on the demand on high-grade iron ore concentrates, pellet availability, and consequently pellet prices.

An alternative is hydrogen-based direct reduction using fine ore instead of pellets. Metso Outotec's Circored technology is the first process for iron ore reduction based on 100% hydrogen and has proven its functionality and performance in an industrial-scale demonstration plant.

In addition, Metso Outotec has a proprietary technological solution for direct reduced iron (DRI) smelting in a six-in-line furnace, which links the new developments to the existing processing infrastructure of 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. As a continuously operating process, this solution would secure constant production at the steel plant. By combining Circored with smelting and feeding the hot DRI product from Circored directly into a smelting furnace, the energy efficiency of the process route can be further improved.

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 towards green steel.

In this paper, the principle of the Circored process and the results of the demonstration plant operation are described. The paper also introduces the six-in-line furnace technology and its possible application to treat low-grade iron ores. Finally, the possible role of the Circored process and DRI smelting in the industry's transition toward green steel will be outlined.

The Concept

Advantages of Fluidized Bed Technology

Metso Outotec has been involved in the direct reduction of iron ore (Lurgi legacy) since this technology was first introduced as one of the inventors of the SL/RN-process based on the rotary kiln and as a successful licensee of the Midrex shaft furnace process.

Circored is based on fluidized bed technology, which Metso Outotec has been leading the development of for several decades. The technology is state of the art for processes such as coal combustion in a circulating fluidized bed (CFB) with inherent SO_2 absorption and alumina calcination; in these applications, a CFB is used in place of rotary kiln technology because of the significantly lower energy consumption and lower CAPEX and maintenance costs.

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 Circored Process

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

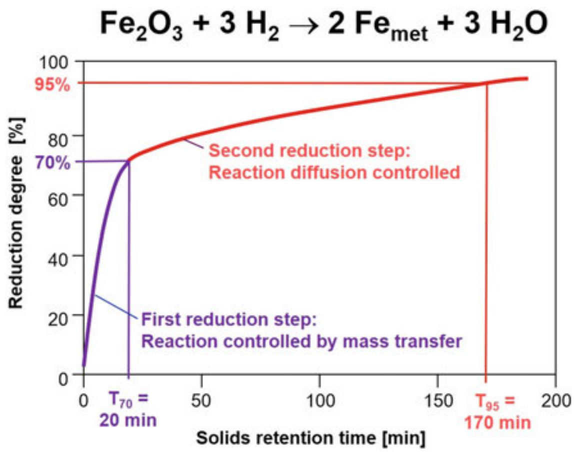

Fig. 1 Performance of H_2-based direct reduction process in fluidized beds

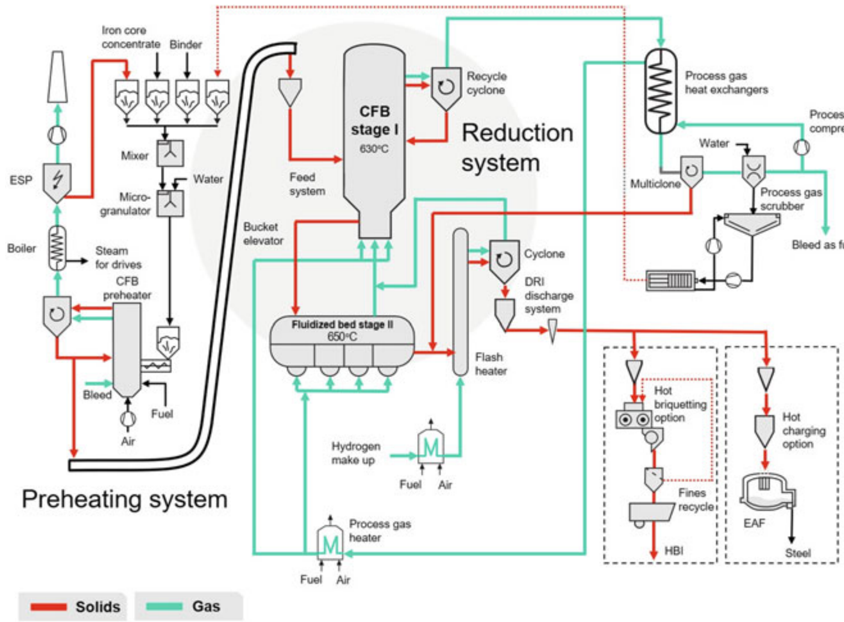

Fig. 2 A simplified process flow diagram of the Circored process including microgranulation

For the direct reduction of fine iron ore, Circored applies a two-stage 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 4–6 m/s and high differential velocities between gases and solids leading to short solids retention times of 20–30 min, 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 a 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 (also shown in Fig. 2).

After prereduction, the material is discharged into the secondary FB reactor, which is compartmentalized for better process control. 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 min depending on the nature of the ore. Operation at 4 bar(a) avoids the excessive equipment and piping costs that would result from large gas volumes needing to be recycled within the process.

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 particle 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 much more significant. One could say that the hydrogen-based Circored process was developed 20 years too early.

For better briquetability, the reduced fines, which are discharged from the FB reactor at a temperature of about 630–650 °C, are heated in a flash heater up to about 700–720 °C, where preheated make-up hydrogen is utilized for heating and transporting the reduced fines to the top of the continuous discharge system.

Within the discharge system, the hydrogen atmosphere is gradually replaced by nitrogen and the pressure lowered to atmospheric level, thereby ensuring safe conditions for briquetting. A minimum briquetting temperature of around 680 °C is required to obtain high-density hot briquetted iron (HBI, >5.0 g/cm^3).

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

The off-gas from the recycle cyclone of the CFB reactor is passed through a process gas heat exchanger and a multiclone to recover ultrafine dust particles, which are recycled. The off-gas is then scrubbed and quenched simultaneously to remove any dust and water produced during reduction. The cooled and cleaned process gas is then recompressed and subsequently preheated to a temperature of approximately 750 °C before being reintroduced into the reactor system.

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 two-fold 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 min 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.

Comparison of Different Steelmaking Routes

When comparing the Circored/EAF steelmaking route 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

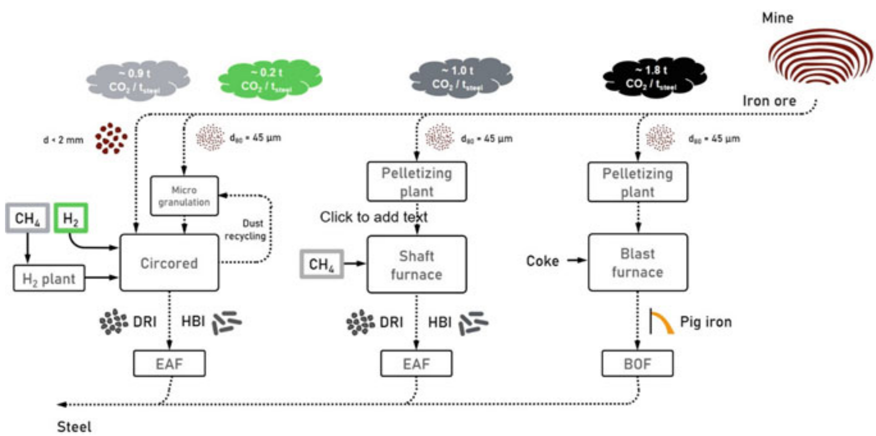

Fig. 3 A comparison of the main components, feeds, and products of different steelmaking routes

DRI or HBI that can be used directly in an EAF. The product from the blast furnace, pig iron, is fed to an oxygen converter (BOF). These downstream processes are considered in the CO_2 and cost figures.

Generally, the Circored process can handle feeds with a particle size of up to 2 mm; depending on the decrepitation behavior, particle sizes of up to 6 mm are possible. If an ultrafine concentrate is used, a microgranulation step should be applied to make the material fluidizable. Along with this option comes the opportunity to recycle any kind of dust or fines originating at different points in the plant. The Circored process uses a natural gas reformer to provide the hydrogen for reduction. For future scenarios, we further included a Circored + process variant that applies green hydrogen produced from renewable sources for direct reduction and electrical heaters for drying and preheating.

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 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 the Circored + process is designed to produce fully green steel, the CO_2 emissions of the reduction process are negligible.

When it comes to cost, Circored is a very competitive route, partly because the CO_2 taxes are lower than for the BF/BOF route and because there is no pellet premium (versus 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.

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 Lurgi's desire to apply its vast experience of utilizing fluidized bed technology also for direct reduction.

After an extensive period of test work and process development, the investigations showed that the use of pure hydrogen as a reducing agent in a two-reactor (CFB and FB) combination would ideally suit the direct reduction characteristics of iron ore fines. Shortly after finishing test work and a conceptual engineering study, a contract for the first Circored plant, to be built in Trinidad, was awarded by Cliffs and Associates Limited in 1996. 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. 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

Fig. 4 Trinidad plant with HBI stockpile

plant shown in Fig. 4 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.

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 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 furnace body is familiar from flash smelting furnaces. Therefore, all equipment is proven technology and has many reference projects. Figure 5 shows an illustration of the furnace.

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 case of hot feed, the reductants and fluxes need to be fed from separate bins to the hot DRI.

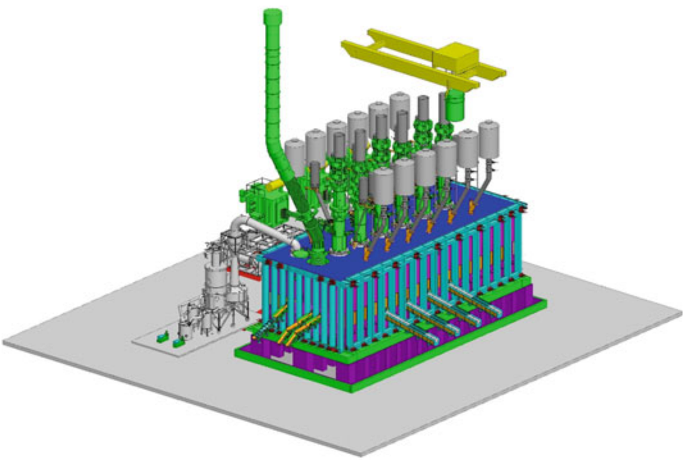

Fig. 5 The Metso Outotec DRI smelting furnace design

Table 1 Features and benefits of the Metso Outotec DRI smelting solution

Furnace feature	Benefits
Flexible feed systems	Allows a wide variety of feed materials to be used (HDRI, CDRI, HBI), reductants, fluxes, briquettes
Continuous process	High availability, similar to blast furnace
Blast furnace type hot metal	Only small adjustments needed to existing steel plant logistics
Large furnace volume	Enables high material flow and BF-grade pellets
	Can be used as a buffer
No need for extra scrap	Low level of tramp elements
Gastight construction	Low level of gaseous impurities
Long retention time	High metal yields
Separate metal/slag tap-holes	Optimal metal/slag separation
Black-top operation	Decreased heat flow to the roof
Spring-loaded furnace refractories	Expansion is easy to control
Six electrodes	Smaller electrodes needed; more active area, less passive area
Direct slag granulation from launders	No need for slag pots

The furnace is lined with refractories and cooled with water via different copper cooling elements. Table 1 describes the key features of the Metso Outotec DRI smelting solution and their respective benefits.

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 feeds, which means that the solution needs to be optimized according to the needs of each individual steel plant.

Perspectives

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/y 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.
- 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.

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 the high-quality steel products that have traditionally been the strength of integrated steel plants.

From discussions with clients, it became obvious that—at least for the transition period in existing steel plants—the feed material for the EAF is expected to be a mixture of different materials like HBI, DRI, and scrap. The carbon content can be adjusted to the required level in the EAF operation.

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/y.

Conflict of Interest The authors declare that they have no conflict of interest.

References

1. Climate Action Summit (2019) Report of the secretary-general on the 2019 climate action summit and the way forward in 2020, UN.org
2. World Steel Association