

STATE OF THE DIRECT REDUCTION AND REDUCTION SMELTING PROCESSES

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Abstract

For quite a long time efforts have been made to develop processes for producing iron i.e. steel without employing conventional procedures – from ore, coke, blast furnace, iron, electric arc furnace, converter to steel.

The insufficient availability and the high price of the coking coals have forced many countries to research and adopt the non-coke-consuming reduction and metal manufacturing processes (non-coke metallurgy, direct reduction, direct processes).

This paper represents a survey of the most relevant processes from this domain by the end of 2000, which display a constant increase in the modern process metallurgy.

Keywords: iron, coal, direct reduction, reduction smelting, main processes, reduction.

1. Introduction

The processes that produce iron by reduction of iron ore below the melting point of the iron produced are generally classified as *direct reduction processes*, and the product is referred to as *direct reduced iron*. The processes that produce molten metal, similar to blast furnace liquid metal, directly from ore are referred to as *direct smelting processes*. In some of the processes the objective is to produce liquid steel directly from ore and these processes are classified as *direct steelmaking processes*.

These broad categories are clearly distinguished by the characteristics of their respective products, although all of these products may be further treated to produce special grades of steel in the same steelmaking or refining process [1].

Direct reduced iron (DRI) is a high-quality metal product obtained from iron ore and it is used as raw material in electric arc furnaces, blast furnaces, and in other more recent steelmaking processes [2].

2. Total DRI Output in the World

With the output of approx. 43.2 mil. tones in 2000 DRI accounts for 3 – 4 % of the total world ironmaking capacity. Figure 1 shows that DRI output has been increasing for 18 years in a row.

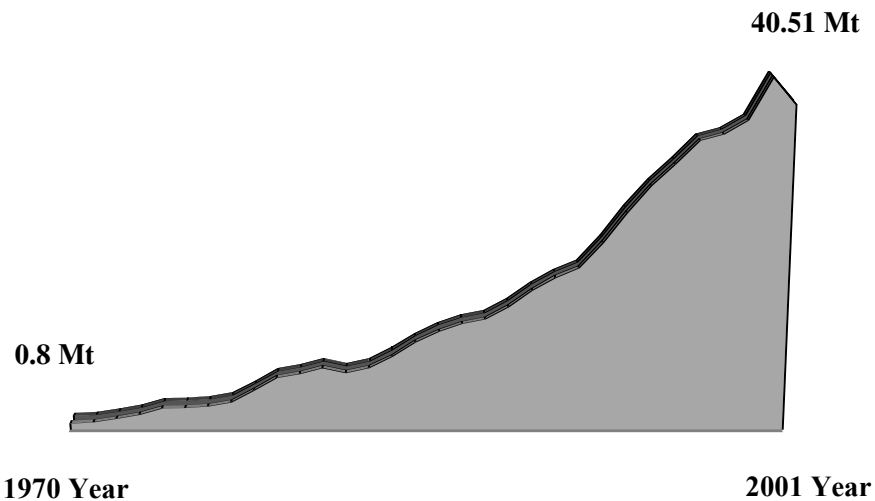


Fig. 1. DRI output between 1970 - 2001 [2]

The world's output of DRI is dominated by gas-based processes, especially MIDREX and HYL III which account for 80-90% of the world's DRI output, which is shown in Table 1 and Figure 2 (data for 2001.).

Table 1: Total world's DRI output in 1998, 1999, 2000 and 2001 (in %) [2]

YEAR	1998	1999	2000	2001
MIDREX	66.90	67.30	68.20	66.30
HYL III	17.80	20.60	18.60	17.10
HYL I	5.10	2.30	3.20	2.70
OTHER COAL-BASED PROCESSES	4.80	4.60	4.70	8.40
OTHER GAS-BASED PROCESSES	1.90	2.20	2.60	1.00

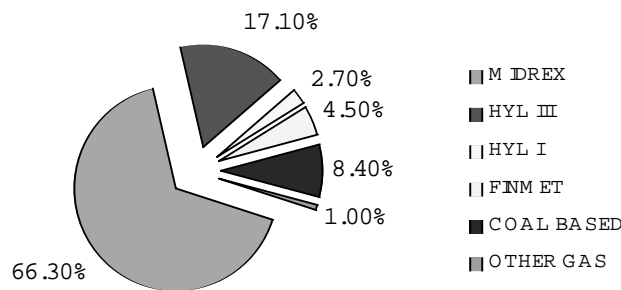


Figure 2. Total world's DRI output by processes in 2001 (in %) [2]

3. Direct Reduction Processes

Direct reduction is defined as a process of producing solid iron product out of small-grain ore, lump ore or pellets, applying natural gas or coal-based reducing agents at relatively low temperatures i.e. at around 1000°C.

There are two different types of direct reduction processes:

- a) processes based on solid reducing agents,
- b) processes based on gaseous reducing agents.

Depending on the type of reactor being used today, these processes can be categorized into processes using pit furnaces, fluosolid reactors or rotation furnaces.

The accelerated development of the direct reduction process has been conditioned by the following facts:

- Rapid development of steelmaking by smelting in an electric furnace, where apart from scrap iron direct reduced iron is increasingly used.
- Content of harmful substances in DRI is lower compared to scrap, the quality of which constantly deteriorates.
- A considerable number of countries had access to inexpensive natural gas (gaseous reducing agent) and to rich iron ores.
- Non-coking coals and lignite can also be used (as solid reducing agents).

Processes using static layers in retorts (HYL I, HYL II) are no longer applied and they have been replaced by pit furnaces with movable layer [3,4,5].

It has already been emphasized that MIDREX and HYL processes produce over 85% of the world DRI output. These two processes, however, require charge in the form of pellets or lump ore. They also require huge capital investment demanding relatively high production capacities (1 MT/y) to secure profitability.

Although the processes using fluosolid reactors (FINMET, CIRCORED, IRON CARBIDE) have been confirmed as reliable but their energy consumption is above and productivity below the desired level [6, 7].

4. Reduction Smelting Processes

The processes which are not classified as direct reduction are reduction smelting processes using coal as reduction agent. At the final reduction stage molten iron is produced from small grain ores ore concentrates. The advantage of these processes is the fact that they use non-toxic coal as elementary source of energy i.e. as reducing agent. Coal is preferred to coke or natural gas because of its good availability and lower cost. If possible, sintering cost is to be eliminated when using small grain ore or concentrate.

The elementary premises for reduction smelting processes are:

- Reduction processes require higher temperatures.
- Use of powder ores (concentrates) without previous sintering.
- Use of non-coked coal.
- Production of molten iron.

- Providing grounds for the construction of smaller mills with lowest possible investment and production cost.
- Securing proper environmental protection.

Thus, for instance, the COREX process, which is used for commercial purposes, uses coal directly but it is still widely distributed, it requires pellets or lump ore and results with surplus energy, which needs to be used in order to keep the process on the economical side [6].

5. Classification of Process [7]

I) By product type:

- **Liquid iron / pig iron:** blast furnace, COREX, REDSMELT, TECNORED FASTMET/FASTMELT, HISMELT, DIOS, ROMELT, AISI, CCF
- **Direct reduced iron (DRI) – “sponge”:** MIDREX, HYLSA, SL/RN, CIRCOFER, FINMET, CIRCOFER, INMETCO
- **Iron carbide:** IRON CARBIDE

II) By application degree:

- **Commercial application** in production plants: blast furnace, MIDREX, HYLSA, COREX, SL/RN, IRON CARBIDE, CIRCOFER.
- **Semi-commercial application:** at the moment it is undergoing the first stage of commercial application or it is still at the demo-stage. This also includes the processes which are no longer in use: FINMET, INMETCO, REDSMELT.
- **Trial operation:** TECNORED HISMELT, FASTMET/FASTMELT, DIOS, ROMELT, CCF.
- **Semi-trial testing of components:** parts of the processes are put into trial operation: AISI, CIRCOFER.

* the latest data about CIRCORED direct reduction process [8].

III) By charge material:

- **Lump ore, pellets, bricks, re-circled iron:** blast furnace, COREX, MIDREX, HYLSA, SL/RN, TECNORED, FASTMET/FASTMELT, REDSMELT, INMETCO, AISI.
- **Small-grained ore:** FINMET, CIRCORED, CIRCOFER, HISMELT, DIOS, ROMELT, CCF, IRON CARBIDE.

IV) By the reducing agent type:

- **Coke:** metallurgical coke ore semi-coke (lower-quality coke, e.g. for TECNORED) is the basic reducing agent: blast furnace, TECNORED.
- **Coal:** non-metallurgical coal (as reducing agent or fuel): COREX, TECHNORED, SL/RN, FASTMET/FASTMELT, REDSMELT, INMETCO, CIRCOFER, AISI, CCF.
- **Natural gas:** MIDREX, HYLSA, CIRCORED, FINMET, IRON CARBIDE.
- **Mixture of coal and natural gas:** HISMELT, DIOS, ROMELT.

V) By smelting furnace type:

- **Shaft furnace:** including production of liquid metal and DRI: blast furnace, COREX, MIDREX, HYLSA, TECHNORED.
- **Rotary kiln:** many processes employ rotary kiln for primary reduction; solid or gaseous reducing agents (or the mixtures thereof) are permissible: REDSMELT, FASTMET/FASTMELT, INMETCO.
- **Fluosolid reactors:** Processes based on small-grained ore, in the course of which the ore is fluidized and transported by means of reducing gas: FINMET, CIRCORED, CIRCOFER, IRON CARBIDE.
- **Other:** HISMELT, DIOS, ROMELT, AISI, CCF.

6. The Most Relevant Direct Reduction Processes

6. 1. Gaseous Reducing Agent: MIDREX, HYLSA (HYL III, HYL4M), FINMET, IRON CARBIDE, CIRCORED

6. 1. 1. MIDREX

Process advantages [8]:

- World-wide commercial use
- Proven performance
- “Relatively-forgiving” operation
- Raw material flexibility
- CO₂ reformer eliminates need for steam system, reformed gas quench, reducing gas heating and CO₂ removal system

The Midrex™ Direct Reduction process is based upon a low pressure, moving bed shaft furnace where the reducing gas moves counter-current to the lump iron oxide

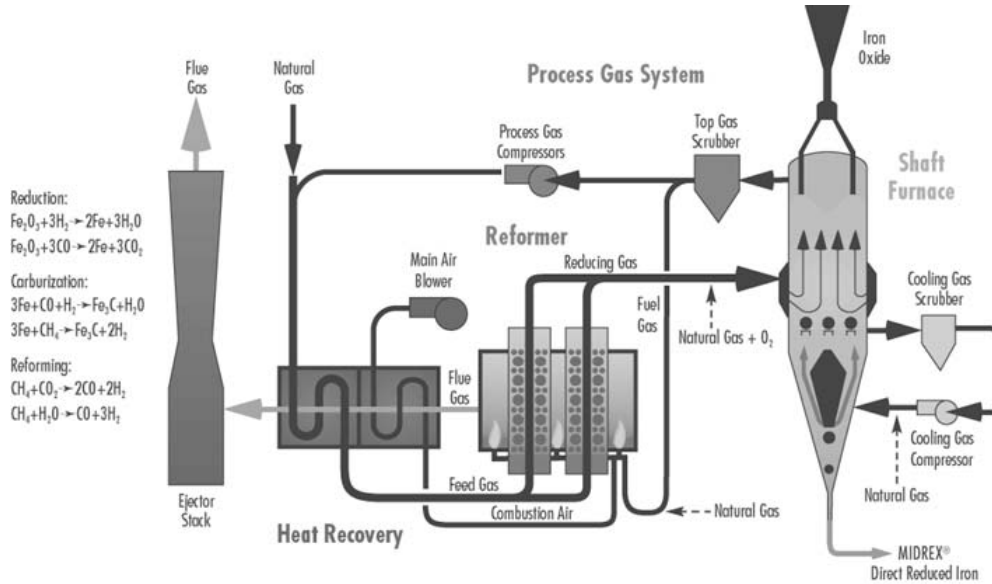


Figure 3. Schematic Review of MIDREX PROCESS [2]

ore or iron oxide pellet solids in the bed, Figure 3. The reducing gas (from 10-20% CO and 80-90% H₂) is produced from natural gas using Midrex's CO₂ reforming process and their proprietary catalyst (instead of steam reforming). A single reformer is utilized instead of a reformer/heater combination. The reformed gas does not need to be cooled before introduction to the process. There is also no need for a separate CO₂ removal system. The process can produce cold or hot DRI as well as HBI for subsequent use as a scrap substitute feed to a steelmaking melting furnace (SAF, EAF or oxygen steelmaking process). Over 50 Midrex™ Modules have been built worldwide since 1969. They have supplied over 60% of the worlds DRI since 1989 [7].

Process description [2]:

Reduction: Iron oxide, in pellet or lump form, is introduced through a proportioning hopper at the top of the shaft furnace. As the ore descends through the furnace by gravity flow, it is heated and the oxygen is removed from the iron (reduced) by counterflowing gases which have a high H₂ and CO content. These gases react with the Fe₂O₃ in the iron ore and convert it to metallic iron, leaving H₂O and CO₂. For

production of cold DRI, the reduced iron is cooled and carburized by counterflowing cooling gases in the lower portion of the shaft furnace. The DRI can also be discharged hot and fed to a briquetting machine for production of HBI, or fed hot, as HDRI, directly to an EAF, as in the HOTLINK™ System.

Reforming: To maximize the efficiency of reforming, offgas from the shaft furnace is recycled and blended with fresh natural gas. This gas is fed to the reformer, a refractory-lined furnace containing alloy tubes filled with catalyst. The gas is heated and reformed as it passes through the tubes. The newly reformed gas, containing 90-92 percent H₂ and CO, is then fed hot directly to the shaft furnace as reducing gas.

Heat Recovery: The thermal efficiency of the MIDREX® Reformer is greatly enhanced by the heat recovery system. Sensible heat is recovered from the reformer flue gas to preheat the feed gas mixture, the burner combustion air and the natural gas feed. In addition, depending on the economics, the fuel gas may also be preheated.

6. 1. 2. HYL

The second-largest DRI technology in terms of production tonnage is the HYL process developed by Hylsa of Mexico [9].

HYL III, based on HYL I, uses a single shaft furnace with a moving bed instead of HYL I's four fixed-bed reactors. HYL II was developed but never commercialized.

The HYL process is based on reducing gases, generally consisting of reformed natural gas and recycled furnace gas, heated to between 900°C and 960°C. These are fed to the reactor reduction zone and flow up through the furnace tower counter to the flow of the iron materials. Iron ore pellets or lumps are fed through the top of the furnace via a system of bins and pressure locks. As these materials progress down through the tower, the iron is reduced by reacting with the carbon monoxide and hydrogen in the gas. The HYL process incorporates a "self-reforming" process whereby part of the natural gas reforming occurs in the furnace itself, with the iron acting as a catalyst to crack the natural gas into its reducing gas components. Following reduction, carburization reactions add carbon to the metallised iron. The resulting reduced iron product is then discharged from the bottom of the furnace. DRI plants are equipped with a cooling circuit while the hot-discharge plants discharge the product at 700°C for briquetting into HBI. Alternatively, the hot product can be transported through a pneumatic system known as Hytemp and fed directly into an EAF to conserve energy and reduce power consumption and tap-totap time. HYL III is an updated version of the HYL I process using a moving bed technology rather than

the fixed bed concept used in HYL I. Metallisation and carbon content averaged 92.9% and 1.96% respectively for the HYL plants surveyed in AME's Cost Analysis. The cost of iron ore feedstock for the HYL plants surveyed averaged US\$55.46/t of product, translating to 61% of total average costs. The next major cost item was energy, constituting 28% of the production cost.

Only HYL offers three product options:

- Traditional DRI (cold product in pellet or lump form)
- HBI (Hot Briquetted Iron)
- HYTEMP Iron (hot product, pneumatically transported to the EAF)

Process Characteristics & Advantages:

- Low Investment Costs
- Reliability
- Low energy consumption
- Low operating costs
- Easy operation and maintenance
- Flexibility for inputs
- Flexible quality products
- Metallization and carbon can be independently adjusted to meet any steel specification:
 - Metallization: up to 95%.
 - Carbon: from 1.5 to more than 5.5%.
- Ecological
- Service and Support

The Hylsa 4M process is based on a moving bed shaft furnace (similar to HYL III process but without a reformer) which reduces iron ore pellets and lump ore, and operates at typical reduction temperatures and intermediate reduction pressures [7]. This process requires no reformer to generate the reducing gas as the reforming of the natural gas takes place inside the reduction reactor using the metallic iron of the DRI product as the catalyst. The process can produce cold/hot DRI as well as HBI.

The main differences between HYL and Midrex include:

- HYL employs high-pressure operations such as lock hoppers; Midrex operates at ambient pressure. The high pressure allows HYL operators to use smaller equipment. The high pressure allows HYL's reducing gas to

have a high concentration of hydrogen, while Midrex's reducing gas has more carbon monoxide. The Midrex process is simpler

- HYL has steam reforming; Midrex has a stoichiometric reformer. Midrex's reformer converts all input gases to gases for use in the operation, with no excess gas
- Midrex's reforming and reduction processes are intimately linked, while these processes are independent at HYL plants

6. 1. 3. IRON CARBIDE

Process advantages [7]:

- Lower operating temperature
- Lower production costs
- No storage costs as the product does not oxidize
- Steelmaking cheaper with Fe_3C

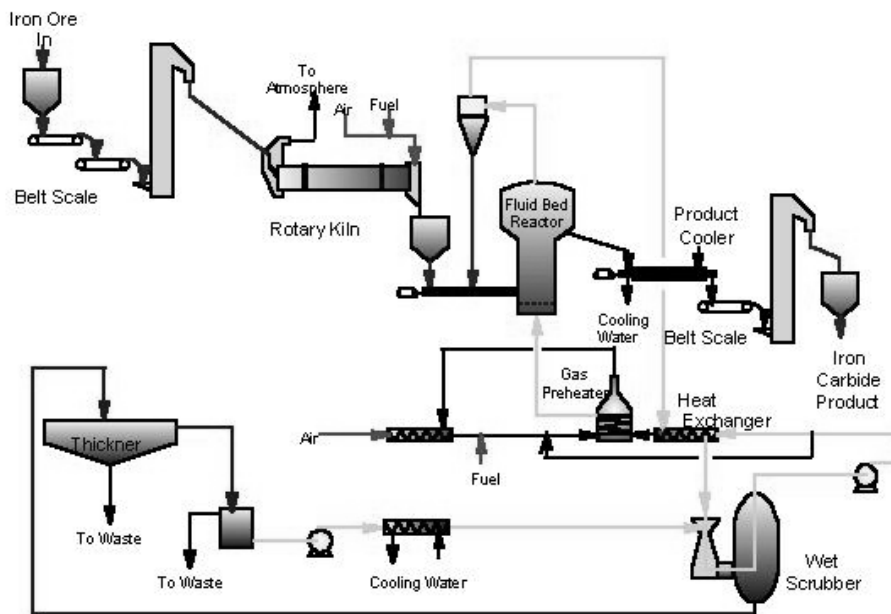


Figure 4: Schematic Review of IRON CARBIDE [12]

Iron carbide (Fe_3C) is a chemical compound of 93% iron and 7% carbon in pure form. It can be used as the only feed for BOFs and EAFs. In that role it eliminates the need for coke ovens and the blast furnace, and all the ancillary equipment for coal and lime. The Iron Carbide process is a two stage fluidized bed process that operates at a lower temperature than other DR processes. It operates at low pressures and uses steam reforming to produce the H_2 which is mixed with CH_4 to make the carburizing gas. It produces Fe_3C powder which contains about 6% carbon.

Process description:

The iron oxide feed to the iron carbide process is in the form of iron ore fines in the range of 1mm to 0.1 mm, Figure 4. Iron ore fines are preheated in a series of cyclones and then pressurized to reactor pressure in lockhoppers, and fed to the reactor by a screw feeder. The fluidized bed reactors have the upward moving stream of 600C gas composed of CO , CO_2 , H_2 , CH_4 and H_2O . The hydrogen reacts with the iron ore, combining with its oxygen to form water (the only process by-product). Carbon from the carbonaceous gases combines with the elemental iron to form iron carbide. The methane provides the gas system equilibrium. After the reactions in the fluid bed reactors, the off gases are condensed to get rid of water vapor, reconstituted with H_2 and carbonaceous gases, raised to reactor working pressure to 1.8 atm, heated to 600C, and reintroduced in the windbox of the reactor. An indication of the inherent thermal efficiency of the process is gained from the fact that the temperature of formation of iron carbide in the fluid bed reactor is only 600C as against around 1000C for reduction of iron in DRI processes and 1500°C to produce hot metal in the blast furnace.

6. 1. 4. CIRCORED [7]

Process advantages:

- Ability to process directly low cost fine ore
- Excellent heat and mass transfer conditions in CFB
- Low investment costs
- Low operating cost

Natural-gas process developed by Lurgi similar to Circofer. Iron-ore fines are reduced in a two-stage process, first in a circulating fluidized-bed (CFB) reactor, and then in a fluidized-bed reactor. The final product contains no carbon because the reductant is pure hydrogen produced from the natural gas, instead of methane.

Process description:

The iron ore fines are first dried and heated to about 800C in a fluid bed preheater system, Figure 5. The dried fines are then charged to a circulating fluidized bed (CFB). The heat required is generated by the combustion of natural gas and air that is introduced into the CFB. The fines are reduced to about 70% metallization in CFB. The process reactions are endothermic and the required energy is introduced in the form of preheated iron ore fines and process gases. The pressure in the CFB is about 4 bars and the reaction temperature is about 630C. This temperature is lower than that used for other reduction processes, and hence avoids the sticking problems that occur with high temperature fines-based processes. The fluidizing gas in the CFB is a mixture of heated process gas which enters the lower part of the CFB, and the off-gas from the second stage conventional fluidized bed reactor, Stage II Reactor, FB. The retention time in the CFB is relatively short, of the order of 15 to 20 minutes. A portion of the partially metallized fines are withdrawn from CFB and enter the FB reactor. The FB reactor is compartmentalized into several sections, and has gas velocities in the range of 0.5 to 0.6 m/s. The fines reach a final metallization of 92 to 93% in the FB reactor. The off-gas leaving the top of the FB passes on to the CFB. The product leaves the FB reactor at about 630C, is then heated to about 680C, and briquetted.

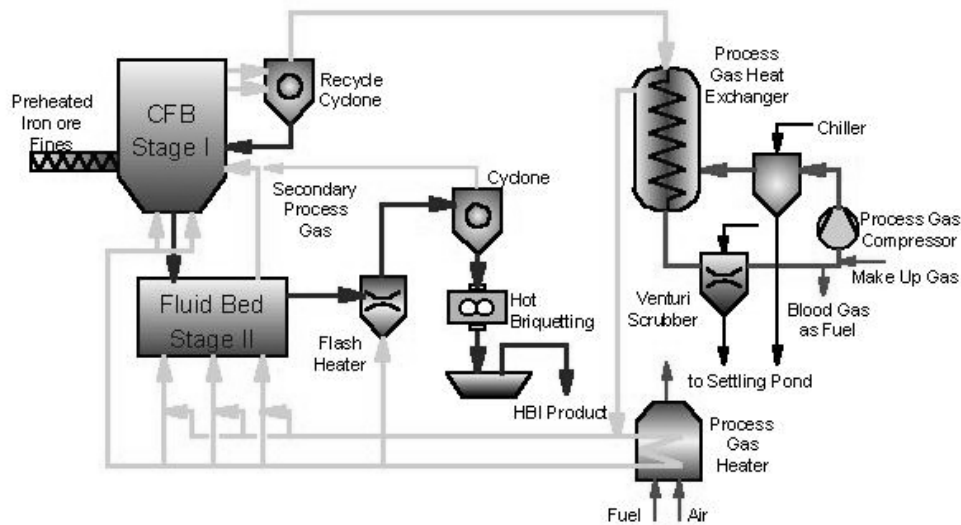


Figure 5. Schematic Review of CIRCORED PROCESS [12]

6. 2. Solid Reducing Agent: CIRCOFER, FASTMET/FASTMELT, INMETCO, SL/RN

6. 2. 1. CIRCOFER

Process advantages [7]:

- Direct use of low cost iron ore fines
- Proven fluid bed technology
- High quality product

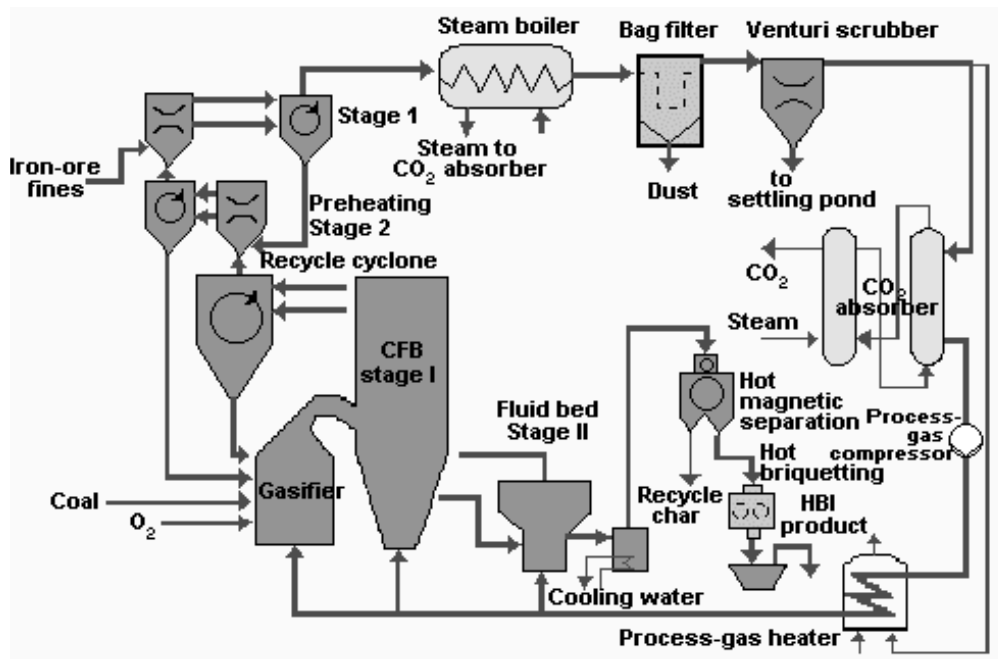


Figure 6: Schematic Review of CIRCOFER PROCESS [11]

Circofer is a coal-based process. Iron-ore fines and recycled char are preheated by off-gas in two stages, Figure 6 [12]. Then the ore fines drop into the gasifier, where coal and oxygen is injected. The ore goes to the circulating fluidized-bed (CFB) reactor for initial reduction. A fluidized-bed reactor performs final reduction. The DRI fines, ash, and excess char are discharged from the second reactor and separated. The DRI is briquetted.

6. 2. 2. *SL/RN*

Process advantages [7]:

- Use of any iron bearing material
- Wide variety of reductants
- Proven DRI technology
- Economic production of DRI

Coal-based process. Lump ore or pellets are reduced in a horizontal rotary kiln that is tilted slightly. The burden first passes through a preheating zone, which is usually 40-50 percent the kiln's length, before going into the reduction zone. After leaving the furnace, the remaining material is separated into DRI, DRI fines, non-magnetic material, and char.

Process description:

The iron oxide feed to a *SL/RN* kiln is in the form of lump or pellet iron ore, reductant (low-cost non-coking coal) and limestone or dolomite (to absorb sulfur from high sulfur reductant). The rotary kiln is inclined downward from the feed (elevated end) to the discharge end. The discharge end is provided with a burner to be used for startup or to inject reductant. Typical retention times are around 10 hours. The kiln is divided into two process regions; preheat and reduction. In the preheat section, the charge is heated to about 1000C, free moisture is first driven off and reduction to FeO occurs.

As the reductant is heated, volatile components are released and part of the gases are burned in the freeboard above the bed by the air injected into the kiln. This combustion transfers heat to the charge directly by radiation, and also by conductive heat transfer from the kiln lining, which is first exposed to the flame and heated before contacting the charge. The charge then passes into the metallization or reduction zone where the temperature is maintained at about 1000C to 1100C, depending upon the type of charge used. The final metallization is about 93% and carbon content about 0.1 to 0.2%. The product DRI can be discharged hot or cold.

The combustion off-gases from the kiln contain char particles and combustible gases. These are burned off in a afterburner and the offgas then passes through an evaporative cooler and an electrostatic precipitator and vented to the atmosphere.

7. The Most Relevant Reduction Smelting Processes: COREX, DIOS, AISI, HISMELT, ROMELT, CCF, TECNORED, REDSMELT

7.1. COREX

Process advantages:

- Use of low cost non-coking coal [7]

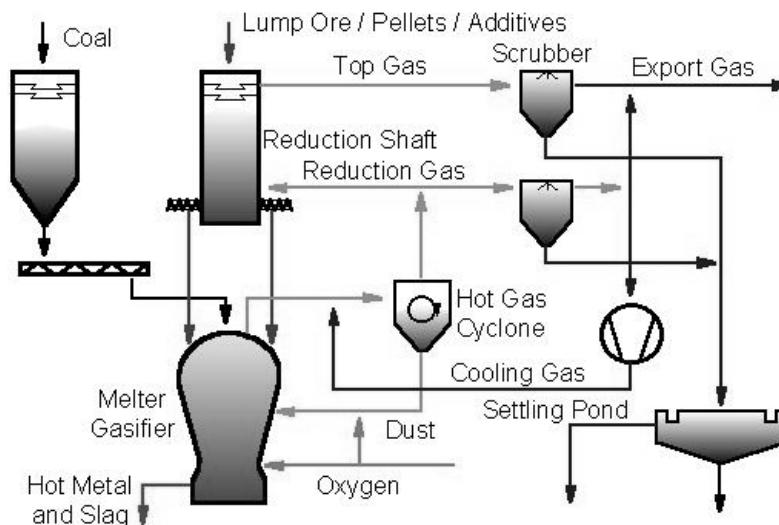


Figure 7. Schematic Review of COREX PROCESS [12]

The COREX® Process differs from the conventional blast furnace route mainly in that

- Non-coking coal is directly used as the reducing agent and energy source
- Iron ore can be directly and feasibly charged to the process in the form of lump ore or pellets

The coal reduction process (COREX), was developed by Voest-Alpine industries (VAI) and DVAI. This is a two-stage operation in which DRI from a shaft furnace like that used in the Midrex and HYL process is charged into a final smelter-gasifier, Figure 7. Reducing gas for the shaft furnace is produced by partial combustion of coal with oxygen in the fluidized bed of the smelter-gasifier. The energy needed to

complete the reduction of the DRI and produce the hot metal and slag is provided by the partial combustion. The liquid products are tapped periodically and partially spent off gas from the shaft reducer is exported along with excess gas produced in the smelter-gasifier. The smelter-gasifier operates at 3-5 bars and comprises an upper fluidized bed zone at approximately 1500°C (2730°F) and a lower melting and liquid collection zone at approximately 1550°C (2820°F). Coal and limestone are injected into the freeboard above the fluidized bed zone where they are heated rapidly to 1000-1200°C (1830-2190°F). The volatile matter is driven off and shattered fixed carbon particles fall into the gasification zone where a gas with high oxygen content is injected through blast furnace-type tuyeres to burn the carbon to carbon monoxide. The exothermic combustion provides the energy to complete the reduction of the hot DRI and to melt the slag and hot metal. The gas leaving the smelter-gasifier is cooled to 800-900°C (1470-1650°F) and cleaned in a hot cyclone to recycle entrained fines. A portion of the clean gas is then introduced into the shaft furnace as reducing gas containing more than 94% CO plus H₂. The remaining gas is mixed with the cleaned offgas from the shaft furnace and the mixture used as export fuel gas. COREX uses approximately one tonne of coal per tonne of hot metal, with approximately 45% of the total energy input used in ironmaking and the rest going to export fuel gas. The hot metal produced has carbon and silicon contents similar to blast furnace hot metal; however, the sulfur content is much higher because nearly all of the sulphur in the coal enters the slag and hot metal. In this connection, organic sulphur in the coal gasifies and is absorbed by the DRI and returned to the smelter-gasifier as iron sulphide.

7. 2. DIOS

Process advantages [7]:

- Direct smelting process
- Use of coal as reductant
- Low direct electrical power consumption

Two-stage process developed in Japan that uses coal to smelt iron-ore fines into molten iron [7]. The ore fines are pre-reduced in a furnace by off-gas from the smelting reduction furnace. Then they are charged in the smelting reduction furnace along with coal and fluxes. Oxygen is blown into the furnace.

Process description:

Iron ore is preheated in the first of two fluidized bed reactors in series and pre-reduced to 15-25% in the second reactor using cleaned offgas from the smelter, Figure 8. It is claimed that the high thermal efficiency through pre-reduction operation has the potential for using less expensive coal and lower consumption compared with BF route. In addition, a small amount of coal fines is injected into the smelter offgas to cool the offgas and provide additional CO and H₂ for pre-reduction. Coal is gravity fed into the smelter.

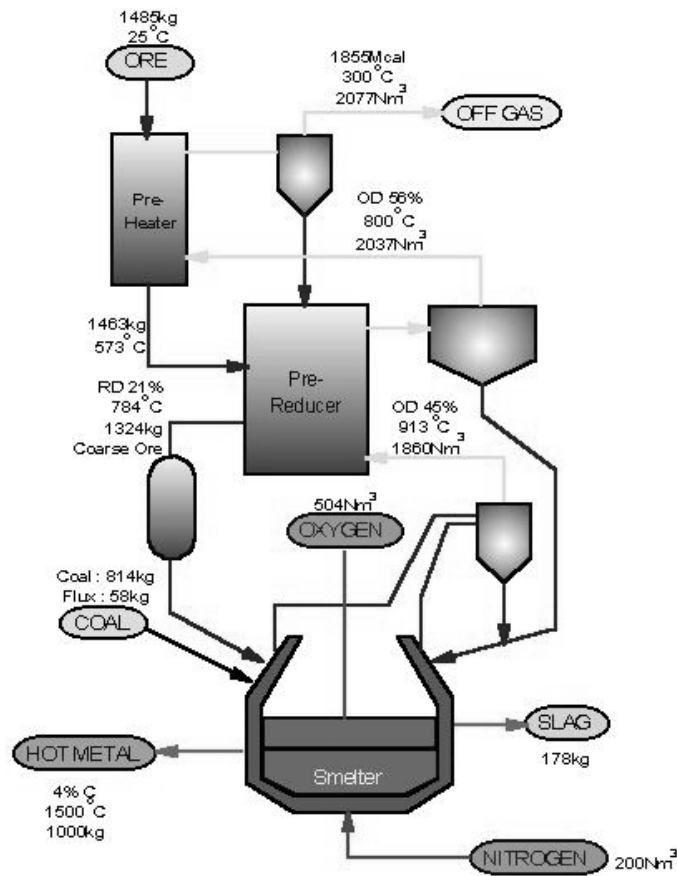


Figure 8: Schematic review of Dios process [12]

Process description:

The Technored process consists of pelletizing of the iron ore fines with cement and coke fines, Figure 9. The pellet size is controlled for the optimum reaction in the reduction furnace. The pellets are cured and dried at 200C and fed to the top of the furnace. The furnace internal pressure is about 3.5 to 5.2 psig. The total furnace residence time is 30 to 40 minutes against 6 to 8 hours in blast furnace. Lump coke is fed into side feeders in the furnace below the hot pellet area. Hot blast air at about 1550C is blown in through tuyeres located in the side of the furnace to provide combustion air for the coke. A small amount of furnace gas is allowed to flow through the side feeders to use for pet coke drying and preheating. Cold blast air is blown in at a higher point to promote post combustion of CO in the upper shaft. The use of coke with sulfur (pet coke) necessitates an elaborate furnace clean-up system in order to meet environmental regulations. The pig iron produced is tapped into a ladle on a ladle car, which can tilt the ladle for deslagging. The liquid iron is desulfurized in the ladle, and slagged into a slag pot.

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