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Development of Direct Reduction Processes and Smelting Reduction Processes for the Steel Production

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Although the blast furnace and basic oxygen furnace are going to be primary routes for steel production in future, the steelmaking industry using the electric arc furnace route will continue to grow. The importance of high-quality steel products manufactured by direct reduction of iron ore and/or by smelting reduction processes has been increasing. In the past decade the world steel production by direct reduction rose by 140 per cent, from about 20 to about 49.5 Mt/year. In this paper major industrial processes involving direct reduction and smelting reduction of iron ore are described, and their development is analysed.

Keywords: *Steel, direct reduction, smelting reduction, coal, natural gas*

Introduction

In 2003 the world production of crude steel was about 945.1 Mt, which was 6.7 % higher than in 2002.[1] About 63 % of the steel was produced by means of basic oxygen furnaces and about 33 % by electric arc furnaces (EAF). The rest of the production was by the open-hearth furnaces and other processes. Pig iron and scrap are still dominant primary charge materials for steelmaking. It is a generally accepted fact, that the blast furnace will continue to be the principal way of hot metal production serving the steelmaking industry for many years to come. A blast furnace has a daily output of above 10 000 tons of pig iron all of which is converted into steel in the integrated steel works.[2–5] Over the past 40 years the proportion of steel production by the EAF route has been experiencing a steady growth. The scrap, with the accompanying non-ferrous metals and nonmetallic components, shows a varied chemical composition. However, considering high investment costs, and also for ecological reasons, numerous investigations have been undertaken with the aim to develop new ways of steel production.[6–11]

The two basic alternatives are direct reduction and smelting reduction processes. The main advantages of those processes with respect to the pig iron production are lower investment costs, and the use of lump iron ore, fine iron ore, pellets and coal as raw material, without the need for prior preparation. The reduction gas is provided by natural gas, or coal. Owing to their clean chemical composition the directly reduced iron (DRI) products have become favourite charge material for efficient high-quality steel production. Their content of tramp elements is much lower than that of the scrap. The direct reduction process generates metallic iron in the solid form i. e. sponge iron, or DRI, which is used chiefly for the EAF steel production. The smelting reduction process serves to produce of the hot metal. These processes are highly important to the EAF steelmaking, which is the alternative to the blast furnace/basic oxygen furnace route.

The world DRI production has been increasing as have the industrial capacities. The overall output from the capacities put in operation in 2001 was about 80 %. The 2003 output of DRI/HBI products[12] was about 49.5 Mt (Table 1). Among numerous processes for direct reduction of iron ore by means of gas and coal the MIDREX, HyL, FINMET and SL/RN processes have found industrial implementation.[13] Among the smelting reduction processes the COREX process using lump iron ore stands out. A number of smelting reduction processes are presently at a certain stage of development or demonstration.[14–22] This work deals with the major technological processes for direct reduction and for smelting reduction of iron, which are currently applied in industry, and with their development.

Direct reduction processes

All direct reduction processes remove oxygen from the iron ores in the solid state and produce directly reduced iron or hot iron briquetted for feed into the electric arc furnace. The direct feed of DRI/HBI into the EAF is still under construction (Hytemp HYL and Hotlink MIDREX). At the moment shere is no industrial plant with direct charging into the EAF. The degree of metallization (the ratio of metallic to total iron) is from 85 to 95 % (often above 95 %). Depending on the type of reducing agent[22] the direct reduction process can be subdivided into the gas reduction and coal reduction processes (Table 2).

Table 1 – *World DRI production in the period 1992 – 2003*[12]*, 10^6 t*

Tablica 1 – *Proizvodnja izravno reduciranog željeza u svijetu tijekom 1992 – 2003. godine*[12]*, 10^6 t*

Land	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Argentina	1.16	1.27	1.33	1.42	1.50	1.54	0.99	1.42	1.28	1.46	1.74
Brazil	0.25	0.22	0.30	0.34	0.32	0.34	0.40	0.42	0.43	0.36	0.41
Mexico	2.73	3.24	3.70	3.90	4.54	5.68	6.24	5.83	3.67	4.90	5.62
Peru	-	0.02	0.003	0.02	0.12	0.11	0.05	0.08	0.07	0.03	0.08
Trinidad and Tobago	0.73	0.94	1.05	1.07	1.24	1.14	1.30	1.53	2.31	2.32	2.28
Venezuela	4.51	4.71	4.72	5.34	5.36	5.06	5.05	6.69	6.38	6.89	6.90
Latin America	9.38	10.4	11.203	12.09	13.08	13.87	14.03	15.97	14.14	15.96	17.03
Egypt	0.85	0.78	0.85	0.83	1.19	1.61	1.67	2.11	2.37	2.53	2.87
Iran	1.65	2.63	3.23	3.81	4.38	3.69	4.12	4.74	5.00	5.28	5.62
Iraq	–	–	–	–	–	–	–	–	–	–	–
Libya	0.94	0.85	0.97	0.83	0.99	1.01	1.33	1.50	1.09	1.17	1.34
Qatar	0.56	0.60	0.63	0.64	0.57	0.71	0.67	0.62	0.73	0.75	0.78
Saudi Arabia	2.01	2.11	2.13	2.30	2.11	2.27	2.36	3.09	2.88	3.29	3.29
Middle East /N. Africa	6.01	6 .97	7.81	8.41	9.24	9.29	10.15	12.06	12.07	13.02	13.9
Australia	–	–	–	–	–	–	0.32	0.56	1.37	1.02	1.95
Myanmar	0.02	0.01	0.02	0.04	0.04	0.04	0.03	0.04	0.04	0.04	0.04
China	–	–	–	–	0.07	0.08	0.11	0.05	0.11	0.22	0.31
India	2.21	3.12	4.28	4.84	5.26	5.26	5.22	5.44	5.59	6.59	7.67
Indonesia	1.50	1.62	1.86	1.80	1.60	1.64	1.74	1.82	1.48	1.50	1.23
Japan	–	–	–	–	–	–	–	–	–	–	–
Malaysia	0.71	0.99	1.09	1.48	1.72	0.91	0.96	1.26	1.12	1.08	1.60
New Zeland	–	–	–	–	–	–	–	–	–	–	–
Asia/Oceania	4.44	5.74	7.25	8.16	8.69	7.93	8.38	9.17	9.71	10.45	12.80
Canada	0.74	0.77	1.01	1.42	1.39	1.24	0.92	1.13	-	0.18	0.50
United States	0.44	0.48	0.46	0.45	0.51	1.60	1.67	1.56	0.12	0.47	0.21
North America	1.18	1.25	1.47	1.87	1.9	2.84	2.59	2.69	0.12	0.65	0.71
Russia (former SSSR)	1.54	1.71	1.68	1.50	1.73	1.55	1.88	1.92	2.51	2.91	2.91
Nigeria	0.04	0.04	0.02	0.02	–	–	–	–	–	–	–
South Africa	0.87	0.98	0.95	0.90	1.09	1.05	1.16	1.53	1.56	1.55	1.54
Sub-Saharan Africa	0.91	1.02	0.97	0.92	1.09	1.05	1.16	1.53	1.56	1.55	1.54
Germany	0.18	0.28	0.41	0.37	0.47	0.45	0.40	0.46	0.21	0.54	0.59
Italy	–	–	–	–	–	–	–	–	–	–	–
Sweden	–	–	-	–	–	–	–	–	–	–	–
Western Europe	0.18	0.28	0.41	0.37	0.47	0.45	0.40	0.46	0.21	0.54	0.59
World	23.65	27.37	30.67	33.30	36.19	36.96	38.59	43.78	40.32	45.08	49.45

Direct reduction processes were introduced into industrial service in the late 1950s. The development of such processes demands time and money. The period of development, from the experimental stage to that of a reliable industrial capacity, can be ten years or more. The cost of developing a direct reduction process to the point where it can be considered a proven technology could range from 30 to 100 million US dollars. Among the 30 direct reduction processes currently in use, the MIDREX and HyL are the two globally leading ones. They are based on the use of lump iron ore charge (lump iron ores, pellets) and operate with the shaft furnace as reduction unit.

Globally, direct reduction processes which use gas as reducing agent and take place in shaft furnaces, retorts and fluidized bed reactors, are predominant. In 2000 they were 92.6 %.[19]

The MIDREX process (**Mid**land **R**oss **Ex**perimental) is the world's most successful technology in iron direct reduction production (Figure 1). For this process the lumpy iron ore is

Table 2 – *Commercial DRI processes*[12]
Tablica 2 – *Komercijalni procesi izravno redukcije Fe-rude*[12]

Process Proces	No. units Broj postro-jenja	Product Proizvod	Capacity, $Mt\ a^{-1}$ Kapacitet, $Mt\ a^{-1}$	Start-up, year Početak rada, god.
MIDREX	50	DRI/HBI	29 704	1971
HYL I	9	DRI	4 820	1978
HYL III	18	DRI/HBI	11 145	1980
FINMET	8	HBI	4 400	1999
SL/RN	20	DRI	1 830	1973
Iron carbide	3	DRI	960	1994
Jindal	10	DRI	880	1993
DRC	5	DRI	630	1983
GHAEM	1	DRI	600	1996
Codir	4	DRI	520	1973
Cicored	1	HBI	500	1999
Iron dynamics	1	DRI	500	1998
FIOR	1	HBI	400	1976
Purofer	1	DRI	330	1977
SIIL	11	DRI	330	1992
OSIL	2	DRI	250	1983
TISCO	2	DRI	360	1986
DAV	1	DRI	40	1985
KINGLOR-METOR	2	DRI	40	1981
POPURI	6	DRI	500	1991
Other/Ostali	3	DRI	1 740	1996
TOTAL/UKUPNO	159		60 479	

reduced in a shaft furnace at a pressure of 1.5 bar. As a counterflowing reduction gas it uses a hydrogen-rich gas mixture (about 55 % H_2). The first MIDREX commercial plant (capacity 15 000 t a^{-1}) started operation in Oregon Steel Mills, USA, in 1969. Today, there are over 50 modules operating in 20 countries with a capacity of 0.4 – 2.7 Mt a^{-1} (Venezuela, Argentina, Canada, Qatar, Germany, Trinidad and Tobago, etc.).

The MIDREX process comprises in a lot of cases four stages: reduction gas, reforming, heat recovery and hot briquetting system. Iron ore (in pellets or in the lump form with a minimum iron content of 67 %) is introduced through the shaft furnace. The charge is composed of 100 % pellets, or 100 % lump ore, or a combination of the two. To increase the yield up to of 10% fine iron ore can be used. The ore descends through the furnace by the gravity flow and is heated. Oxygen is removed by the action of counterflowing reduction gasses which have high hydrogen and carbon monoxide contents. The reduction gases react with the iron oxide in the ore and convert it to metallic iron, leaving water and carbon dioxide free:

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \quad (1)$$

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2 \quad (2)$$

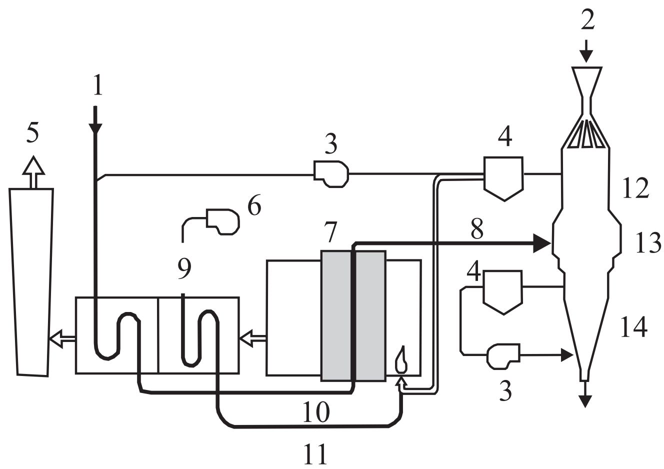


Fig. 1 – *Schematic illustration of the MIDREX process:*[19] *1 – natural gas, 2 – iron ore, 3 – compressor, 4 – scrubber, 5 – off-gas, 6 – air blower, 7 – gas reformer, 8 – reducing gas, 9 – heat recovery, 10 – reformer gas, 11 – combustion air, 12 – reduction zone, 13 – shaft furnace, 14 – cooling zone*

Slika 1 – *Shematski prikaz MIDREX procesa:*[19] *1 – prirodni plin, 2 – željezova ruda, 3 – kompresor, 4 – pročistač, 5 – izlazni plin, 6 – ventilator zraka, 7 – konverzor plina, 8 – reduktivni plin, 9 – iskorištenje topline, 10 – konvertirani plin, 11 – izgaranje zraka, 12 – redukcijska zona, 13 – šahtna peć, 14 – zona za hlađenje*

To obtain cold DRI products the reduced iron is cooled and carbonized by means of the counterflowing gasses in the lower portion of the shaft furnace:

$$3Fe + CO + H_2 \rightarrow Fe_3C + H_2O \quad (3)$$

$$3Fe + CH_4 \rightarrow Fe_3C + 2H_2 \quad (4)$$

By means of this process it is possible to manufacture cold DRI products, hot briquetted iron, or hot direct reduction iron (Table 3).

To enhance the reforming efficiency the offgas from the shaft furnace is recycled and blended with fresh natural gas. The new reforming gas which contains 90 – 92 % H_2 + CO is then fed directly to the shaft furnace as reducing gas. Reforming is carried out with CO_2 and H_2O:

$$CH_4 + CO_2 \rightarrow 2CO + H_2 \quad (5)$$

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (6)$$

The thermal efficiency of a MIDREX plant is greatly enhanced by the recovery system.

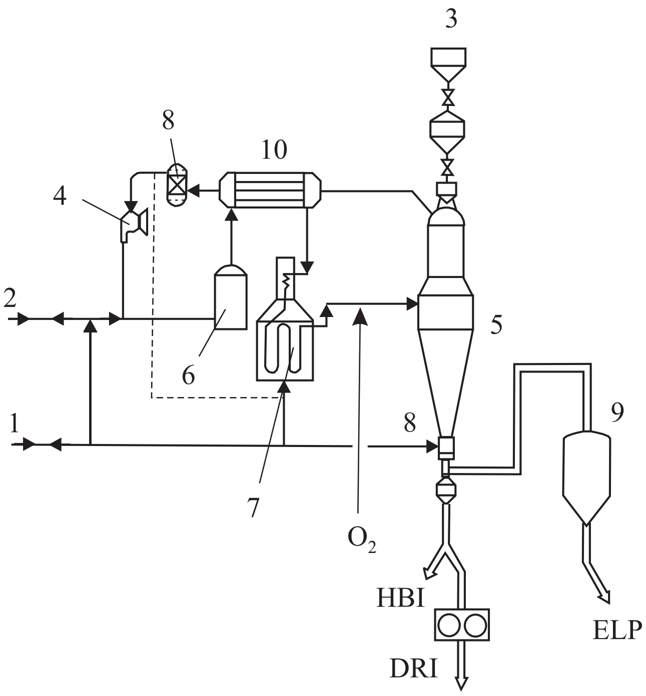
The utility of DRI/HBI products is not determined by their chemical characteristics. In the electric arc furnaces fed DRI/HBI high density can be eliminated by making use of the second and third basket scrap. This can save energy and improve productivity. Usually one basket scrap is added.

The direct reduction process in the retort (HYL) was developed in 1957. Pellets or lump iron ores were treated in four reactors.[23] The process was modified as the HYL II process. Today, the retort processes HYL I and HYL II are no longer of any importance and are used only in a few older facilities. High production costs led to the development of the HYL III process, in 1979, by the Hoyalata y Lomina Company in Mexico. Iron ore was reduced in a shaft furnace at a

T a b l e 3 – *Typical characteristics of products obtained by the MIDREX process*[12]

T a b l i c a 3 – *Tipične karakteristike proizvoda dobivenih MIDREX-ovim procesom*[12]

Product, Proizvod	DRI	HDRI	HBI
Fe Total, % Ukupno Fe, %	90–94	90–94	90–94
Fe Metallic, % Metalno Fe, %	83–89	83–89	83–89
Metalization, % Metalizacija, %	92–95	92–95	92–95
Carbon, % Ugljik, %	1.0–3.5	1.0–3.5	0,5–5,2
Phosphor, % Fosfor, %	0.005–0.09	0.005–0.09	0,005–0,09
Sulphur, % Sumpor, %	0.001–0.03	0.001–0.03	0,001–0,03
Gangue, % Jalovina, %	2.8–6.0	2.8–6.0	2.8–6.0
Mn, Cu, Ni, Cr, Mo, Sn, Pb, Zn, %	trace trag	trace trag	trace trag
Bulk density, gm^{-3} Obujmna gustoća, gm^{-3}	$(1.6–1.9) \cdot 10^6$	$(1,6–1.9) \cdot 10^6$	$(2.4–2.8) \cdot 10^6$
Apparent density, gm^{-3} Stvarna gustoća, gm^{-3}	3.4–3.6	3.4–3.6	5.0–5.5
Discharge temperature, °C Temperatura prženja, °C	40	700 min	80



F i g. 2 – *Schematic illustration of the Hyl-ZR process:*[8] *1 – natural gas, 2 – reformed gas, 3 – iron ore, 4 – compressor, 5 – reactor, 6 – CO_2 scrubber, 7 – heater, 8 – reducing gas scrubber, 9 – pneumatic conveyor, 10 – recuperator*

S l i k a 2 – *Shematski prikaz procesa HyL-ZR:*[8] *1 – prirodni plin, 2 – konvertirani plin, 3 – željezova ruda, 4 – kompresor, 5 – reaktor, 6 – pročistač CO_2, 7 – grijač, 8 – pročistač redukcijskog plina, 9 – pneumatski prijenos, 10 – rekuperator*

pressure of 5–8 bar. Natural gas was cracked in the catalytic gas reformer, following equation:[19]

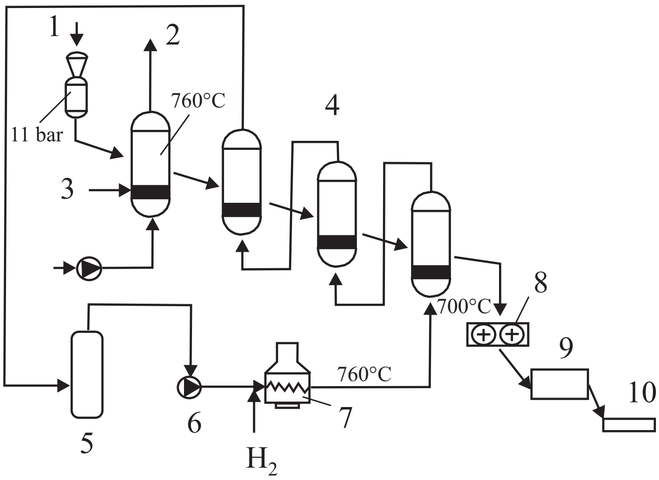
$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (7)$$

Fig. 2 shows the new HYL-ZR process (HYL-Self Reforming process). The ore charge of the HyL III process averages about 80 % pellets and 20 % lump ore. As with the MIDREX process, the DRI product may be either cold or hot, but with a high carbon content in the form of Fe_3C (up to 5.0 % carbon).[24]

This HYL Self-Reforming Process is based on the reduction of iron ores with reducing gases, which are generated from partial combustion and *in situ* reforming of natural gas, taking advantage of the catalytic effect of the metallic iron inside the HyL reduction reactor. This process scheme includes the following features which, when combined, eliminate the need for a reformer: partial combustion of the reducing gas, *in situ* reforming in the lower part of the reactor's reduction zone, adjustable composition of the reducing gas.[25]

Among numerous processes[26-28] using a fine iron ore charge (0 – 100 mm fractions), which have been tested in industry, the best known is the FIOR process (**F**luosolid **I**ron **O**re **R**eduction). For a long time it has been the only large-scale industrial gas-based reduction process making use of fine iron ores (Figure 3). A FIOR plant was put in operation in 1976, having a capacity of 400 000 tons HBI/year (Table 2). The reducing gas (90 – 92 % H_2) is produced by cracking natural gas. Reduction of iron ore fines takes place in a series of fluidized beds at 700 and 800 °C. The time from the heating stage to the final reduction stage is about 90 min. The fine-grained DRI products are hot briquetted. The briquettes are 93 % metallized and the carbon content can be adjusted to between 0.6 and 3 %.

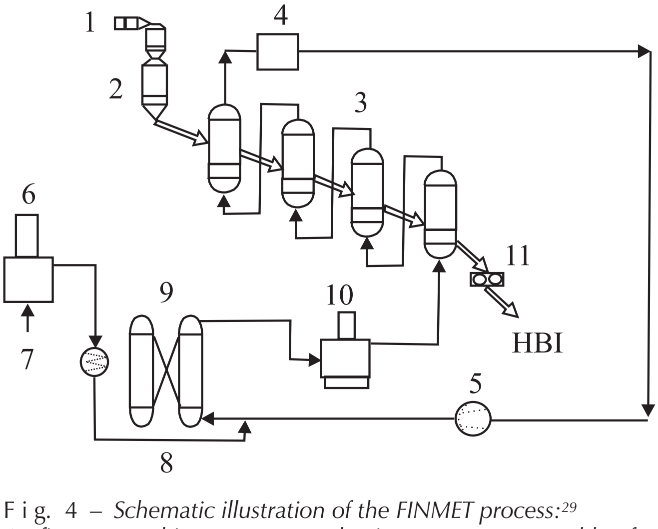
In the early 1990s Voest-Alpine Industrieanlagenbau (VAI) and Fior de Venezuela developed an improved fluidized-bed reduction process known as FINMET (Figure 4). The reducing gas (H_2 and CO) is generated by the catalytic conversion of a mixture of natural gas and steam in a reformer. The optimum reduction temperature is about 830 °C. There are four fluidized bed reactors in the cascade system. The reactors are interconnected with gas and solid transfer lines. The process is based on the use of iron ore fines, with fractions under 12 mm. After being charged through the lock hopper system dried iron ore fines are reduced in the fluidized bed reactors. The pressure within the reactors is between 10 and 12 bar. The ore is preheated in the first reactor with the gas coming from the previous reactor. The ore is progressively reduced and heated in each subsequent



F i g. 3 – *Schematic illustration of the FIOR process:[19] 1 – fine ore, 2 – natural draught, 3 – natural gas, 4 – reduction reactors, 5 – scrubber, 6 – compressor, 7 – reducing gas heater, 8 – briquetting machine, 9 – separation drum, 10 – cooler*

S l i k a 3 – *Shematski prikaz procesa FIOR:[19] 1 – željezova ruda, 2 – prirodni odušak, 3 – prirodni plin, 4 – redukcijski reaktori, 5 – pročistač, 6 – kompresor, 7 – grijač redukcijskog plina, 8 – uređaj za briketiranje, 9 – bubanj, 10 – hladnjak*

reactor until the desired degree of metallization is achieved (91 – 92 %). The highly metallized product is discharged from the final reactor and hot briquetted[29].

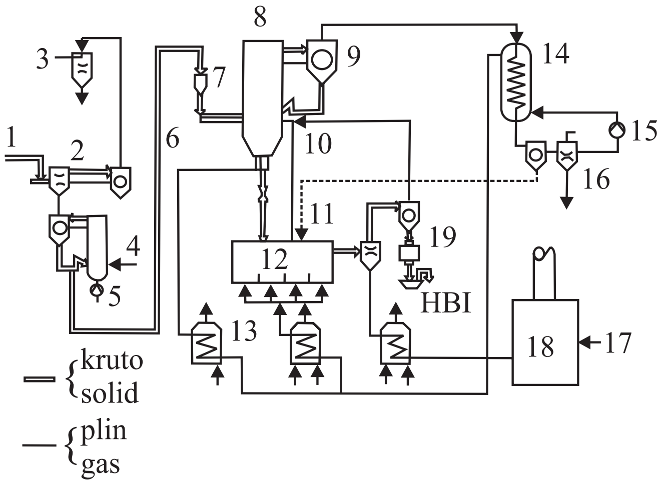


F i g. 4 – *Schematic illustration of the FINMET process:[29] 1 – fine ore, 2 – bin system, 3 – reduction reactors, 4 – scrubber for recycled gas, 5 – compressor for gas recycling, 6 – reformer, 7 – natural gas, 8 – reformed gas, 9 – CO_2 scrubber, 10 – reducing gas heater, 11 – briquetting machine*

S l i k a 4 – *Shematski prikaz procesa FINMET:[29] 1 – željezova ruda, 2 – sustav koševa, 3 – redukcijski reaktori, 4 – pročistač povratnog plina, 5 – kompresor za povratni plin, 6 – konverzor, 7 – prirodni plin, 8 – konvertirani plin, 9 – pročistač CO_2, 10 – grijač reduktivnog plina, 11 – uređaj za briketiranje*

The FINMET is a semi-continuous process in which DRI/HBI is directly produced from fine iron ore in two stages without intermediate discharge. During the first stage the DRI fines are generated from iron ore fines in an integrated FINMET direct reduction plant. After that they are hot-charged into an electric arc furnace and melted to liquid steel. The technology can be expected to find application in industry in the future. The direct connection between FINMET and EAF is called FINMELT.[30]

The Circored process has been developed by Lurgy Metallurgie GmbH. It is a relatively simple two-stage fluidized-bed reduction process that uses only hydrogen to reduce iron ore fines (Figure 5). The raw ore fines (90 %, < 1.0 mm fractions) are preheated (up to 630 °C) in a circulating fluidized bed. The second reduction phase takes place at 680 °C and a pressure of 4 bar. About 70 – 80 % of the reduction is accomplished in the first phase, in a relatively short time (around 20 minutes). The fines then pass to the second stage, to the conventional fluidized bed reactor where they undergo the final metallization process (93 – 95 %) during the residence time of three to four hours. After that final reduction step, the fines are flash-heated to the briquetting temperature and fed to the briquetters.[10]

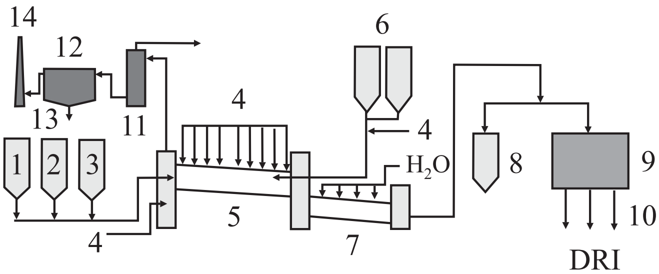


F i g. 5 – *Schematic illustration of the Circored process:[10] 1 – fine ore, 2 – venturi system, 3 – offgas scrubber, 4 – fuel, 5 – air, 6 – skip lift, 7 – ore bin, 8 – stage 1, 9 – return cyclone, 10 – secondary process gas, 11 – heater, 12 – fluidized bed, stage II, 13 – process gas heater, 14 – process gas exchanger, 15 – process gas compressor, 16 – process gas scrubber, 17 – natural gas, 18 – reformer, 19 – hot briquetting machine*

S l i k a 5 – *Shematski prikaz procesa Circored:[10] 1 – željezova ruda, 2 – venturi sustav, 3 – pročistač izlaznog plina, 4 – gorivo, 5 – zrak, 6 – podizni lift, 7 – koš za rudu, 8 – stadij I., 9 – povratni ciklon, 10 – sekundarni procesni plin, 11 – grijač, 12 – fluidizirani reaktor, stadij II., 13 – grijač procesnog plina, 14 – izmjenjivač procesnog plina, 15 – kompresor procesnog plina, 16 – pročistač procesnog plina, 17 – prirodni plin, 18 – konverzor, 19 – uređaj za briketiranje*

There are two more modules of Iron Carbide in Texas (USA), at Qualitech Steel. They were build in 1998. The production of iron carbide is based on the transformation of iron ore fines (0.1 – 1.0 mm) without briquetting. Iron ore fines are reduced by reformed natural gas at 600 °C and a pressure of 4 bar by the addition of carbon for carbonization (up to 6 %).

In industrial conditions the coal-based reduction processes are carried out in rotary kilns (e.g. SL/RN, DRC) (Figure 6) or in rotary hearth furnaces (e.g. FASTMET, Inmetco, Comet, etc.). Feed materials are iron ore (pellets and/or lump ore), coal and fluxes. Iron ore fines are also used. The obtained sponge iron has a low carbon fraction (0.1 – 0.2 %) and a high sulphur content (0.1 – 0.3 %). The operating temperature is between 900 and 1 100 °C. The advantages of these processes are quality charge for the electric arc furnace (substitute for scrap), metallization level of above 95 %, relatively low maintenance costs, absence of liquid phases, poor susceptibility to explosion as compared to other DRI products, etc.



F i g. 6 – *Schematic illustration of the reduction process in the rotary kiln furnace:*[19] *1 – ore, 2 – coal, 3 – limestone, 4 – air, 5 – reduction kiln, 6 – blown coal, 7 – rotary cooler, 8 – surge bin, 9 – production separation, 10 – DRI, 11 – WG cooler, 12 – waste gas bag filter, 13 – waste dust, 14 – stack*

S l i k a 6 – *Shematski prikaz procesa u rotacijskoj cijevnoj peći:*[19] *1 – ruda, 2 – ugljen, 3 – vapnenac, 4 – zrak, 5 – redukcijska cijevna peć, 6 – injektiranje ugljena, 7 – rotacijski hladnjak, 8 – koš, 9 – separacija proizvoda, 10 – DRI, 11 – WG-hladnjak, 12 – filter otpadnog plina, 13 – otpadna prašina, 14 – dimnjak*

Circofer and Primus processes can be included into other processes. A new direct reduction process known as Circofer, which has been developed in Germany, uses iron ore fines and coal as reducing agent. The first pilot plant had a capacity of 5 t d^{-1}. The process involves a two-stage configuration, combining a circulating fluidized bed with a bubbling fluidized bed.[31]

The Primus process was developed in Luxemburg and first applied in a plant for recycling metallurgical waste (dust, slime, mill scale). The raw material is fed to a multiple hearth furnace system (a vertical configuration of several similar furnace compartments) at the temperature of 1 100 °C. As a result of separation of heavy metals (zinc, lead), alkali metals (sodium, potassium) and chlorine, the DRI products have an enriched iron content.[31] A pilot plant was built in 1999, with an output of 1 – 2 t h^{-1}. Since 2002 it has been operating as the first industrial plant.

Among the rotary hearth processes currently under development or at the initial phase of industrial application are the FASTMET, Inmetco, Itmk3, Comet, Iron Dynamics Inc. systems, etc.[3,19,20]

FASTMET is a coal-based rotary hearth furnace technology that uses a mixture of iron ore fines or steel mill wastes, with pulverized coal as carbon reducer, to produce high-quality DRI.[28] The first commercial FASTMET plant started operation in 2000. The end product, directly reduced iron, can be hot briquetted, discharged as hot DRI into transfer containers, cooled if required, or directly charged to the electric iron furnace to yield the high-quality hot metal known as FASTIRON. The DRI/HBI of FASTMET and FASTIRON could be charged into Submerged Arc Furnace (SAF).[12]

The Itmk3 process presents a new generation MIDREX technology. The charge materials are green pellets (made of iron ore fines or mill iron oxide dusts), coal, and binder. The furnace operates at a temperature in excess of 1 350 °C, and the final heating zone products are molten iron droplets, and separately, the molten slag.

The Iron Dynamics process is a two-stage process that first produced DRI in a rotary hearth furnace. Green pellets are made from coal and iron ore fines, and the resultant hot DRI is then available for smelting in a submerged arc furnace. The process is currently used for making hot metal.

The Comet process has been developed by the Centre for Research in Metallurgy in Belgium. This process does not use pellets but iron ore fines, coal fines and limestone fines, which are continuously laid down on the furnace hearth in layers. Subsequent reduction and sintering produce a continuous strip of sintered and reduced iron. This process has been further developed into a two-stage operation by the Belgian company Sidmar and is known under the name of Sidcomet. The Sidcomet process is not under operation at the moment.

The Mannesmann Demag company has developed Redsmelt, a two-stage process for manufacturing hot metal. Iron ore fines and mill scale reverts are mixed with coal and coke blends and binders to produce green pellets. After that DRI products from the rotary hearth furnace are charged into the submerged arc furnace for smelting.

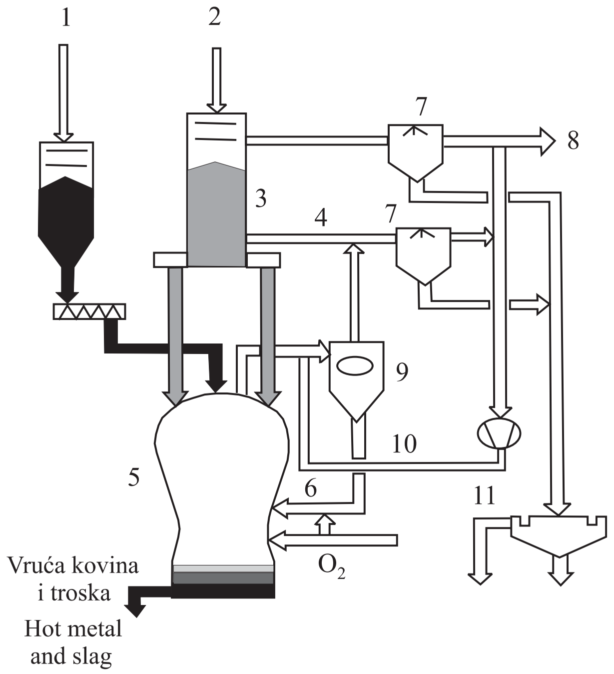
The KWIKSteel combines production of hot DRI in a conventional shaft furnace with that in a rotary hearth furnace to produce steel nuggets. The advantage of the process lies with a very clean, very low-sulphur steel nugget product, which can be melted using non-oxygen-based melting technology without the desulphurizing slag.

The Hi-QIP (High-quality iron pebble) is a new coal-based process for the production of high-quality DRI in the electric arc furnace. Reduced iron is produced directly from a mixture of fine ore and fine carbonaceous material. It is then melted to separate the metal from the slag in a rotary hearth furnace.[32]

Smelting reduction processes

Smelting reduction designates a process for the production of hot metal without the use of metallurgical coke.[33] The revolutionary reduction process COREX has been developed by the VAI group (Figure 7). The hot metal produced by this process is cheaper than the one obtained by the blast furnace route. All metallurgical work is carried out in two separate process reactors (the reduction shaft and the melter gasifier). Raw materials (a mixture of lump ore, pellets and/or sinter) are charged into the reduction shaft and reduced to approximately 93 % of metallized DRI by a counterflow of process gas. Discharge screws convey the

DRI into a melter gasifier where, apart from final reduction and melting, all metallurgical metal and slag reactions take place.



F i g. 7 – *Schematic illustration of the COREX process:*[18] *1 – non-coking coal, 2 – ore, 3 – reduction shaft, 4 – reduction gas, 5 – melter gasifier, 6 – dust, 7 – scrubber, 8 – export gas, 9 – hot gas cyclone, 10 – cooling gas, 11 – settling pond*

S l i k a 7 – Shematski prikaz COREX procesa:[18] *1 – nekoksirani ugljen, 2 – ruda, 3 – redukcijska kolona (peć), 4 – reduktivni plin, 5 – otplinjač taline, 6 – prašina, 7 – pročistač, 8 – izlazni plin, 9 – ciklon vrućeg plina, 10 – hladni plin, 11 – talog*

Non-coking coal enters the dome of the melter gasifier directly, through the lock hopper system. The reduction gas consists of 95 % CO + H_2 and is produced in the melter gasifier as the result of a coal gasification with oxygen. Flowing from the melter gasifier, the gas is cooled by the recycled process gas to the required reduction gas temperature between 800 and 850 °C. After that it is fed to the reduction shaft where the lump ores or pellets are converted to DRI. By means of especially designed screw conveyors the DRI drops into the melter gasifier, where it melts. The tapping procedure, the tapping temperature, and further processing of the hot metal are the same as those for the blast furnace hot metal.[34]

The main benefits of the COREX process concern its use of a wide range of iron ores, elimination of environmentally unfriendly coking plants, high operational flexibility with respect to output, production stops and raw material changes, lower hot metal production expenditures of up to 20 % in comparison with a blast furnace of similar capacity, very good hot metal quality for all high-quality steel applications, possible utilization of export gasses, outstanding environmental compatibility (Table 4). The hot metal and slag tapping are comparable to those in conventional blast furnace practice. The COREX slag has a composition similar to the blast furnace slag and can be used in a likely manner (e.g. in the cement industry). Due to its specific properties the COREX export gas can replace natural gas for the majority of applications including power generation, DRI production, heating, and generation of synthesis gases for the chemical industry.

Voest-Alpine Industrieanlagenbau (VAI) has developed an alternative application for the export gas.[30] The alternative suggests injecting the COREX export gas into a blast furnace in order to substitute oil or natural gas or to the reduce the blast furnace coke consumption. After leaving the COREX reduction shaft the export gas is cooled and cleaned. After compression the gas is fed to a CO_2 scrubbing system. Afterwords the gas is heated by a heat exchanger to 400 °C and then injected via the tuyeres into the blast furnace. A further alternative would be the separate injection of treated export gas (by additional partial combustion to 850 °C) into the blast furnace shaft.

T a b l e 4 – *Materials for the production of 1000 kg hot metal at a COREX plant*[34]

T a b l i c a 4 – *Materijalna bilanca postrojenja COREX za proizvodnju 1000 kg vrućeg metala*[34]

	Material Materija	Value Količina
Input Ulaz	Coal/Ugljen	500 – 600 kg
	Fe-ore/Fe-ruda	1450 – 1500 kg
	Additives/Aditivi	200 – 500 kg
	Oxygen/Kisik	500 – 600 m^3
	Nitrogen/Dušik	60 – 80 m^3
	Industrial water/Industrijska voda	1.0 – 2.0 m^3
	Electric energy/Električna energija	60 – 70 kWh
	Other fuels/Druga goriva	0.5 GJ
	Refractories material/ Vatrostalni materijal	1.3 kg
	Steam/Para	15 kg
	Maintenance/Održavanje, Operating personel/ Operativno osoblje	4 – 6 $ 0.14 people h^{-1}
Output Izlaz	Hot metal/Vruća kovina	1000 kg
	Granulated slag/Granulirana troska	200 – 450 kg
	Export gases/Izlazni plinovi	13 GJ

The first commercial COREX plant started up in 1989 in South Africa. By the year 2001 there were four COREX plants worldwide (Table 5), with a joint production of about 2.35 Mt hot metal/per year.

The development of the COREX process has been directed towards using non-sintered iron ores fines (the FINEX process). While the COREX process makes use of iron ore pellets or lump ore as charge material, the FINEX has been designed to work with fine ores and mill scale reverts. Today, there are numerous development technologies for the smelting reduction process (Table 6). The Hismelt, DIOS, ASI/DOE, CCF, Romelt, Ausiron, and IFCON belong among the processes involving iron bath reactors. Owing to those processes the silicon content has been lowered to under 0.01 % and the carbon fraction is between 2.5 and 3.5 %.

The Hismelt is an air-based direct smelting reduction process. This process is invented by RIO TINTO.[36] The iron ore

T a b l e 5 – *COREX plants in operation*[34]
T a b l i c a 5 – *Postrojenja COREX u radu*[34]

Company Tvrtka	Land Država	Type plant Tip postrojenja	Capacity, $Mt\ a^{-1}$ Kapacitet, $Mt\ a^{-1}$	First working Početak rada
POSCO Pohang Works	South Korea	C-2000	0.6 – 0.8	1995
SALDANHA STEEL	South Africa	C-2000	0.65	1998
JINDAL Vijayangar Steel	India	C-2000 Module 1	0.8	1999
JINDAL Vijayangar Steel	India	C-2000 Module 2	0.8	2001

T a b l e 6 – *Development technologies of smelting reduction processes*[19]
T a b l i c a 6 – *Razvojne tehnologije procesa redukcijskog taljenja*[19]

Process Proces	Company and institutions/Land Tvrtke i institucije/Države
Melter gasifier:/Otplinjač taline:	
Corex	DVAI/VAI (Austria)
Finex	Posco/RIST/VAI/DVAI (South Africa, Austria)
Iron bath reactors:	
Hismelt	RIO TINTO
DIOS	Japan Steel & Steel Federation (Japan)
AISI/DOE	American Iron & Steel Institute/Department of Energy (United States)
CCF	CORUS
Romelt	MISiS/Novolipetsk, NSC (Russia)
Ausiron	Ausmelt, Ltd./Meekatharra Minerals Krakatau Steel/Maritosa Coalindo (Australia)
IFCON	Iscor (South Africa)
Schaft furnace/Šahtna peć:	
Tecnored	ICOMI (Brazil)
Rotary hearth + submerged arc furnace: *Rotacijska ognjišna peć + peć pod zaštitom električnog luka:*	
Sidcomet	Sidmar (Belgium)
Redsmelt	SMS Demag (Germany)
Fastmelt	Midrex (United States)
Rotary hearth + DIOS Rotacijska ognjišna peć + DIOS:	
Duplex-DIOS	NKK (Japan)

fines, coal and fluxes (pulverized lime) are injected directly into the melt by means of a lance.[37]

The direct iron ore smelting process (the DIOS process) uses iron ore fines and coal fines for manufacturing hot metal in a reactor which is similar to a converter. The duplex DIOS process involves prereduction of iron ore, and hot DRI is charged into the smelting reduction furnace. A pilot plant applying the AISI/DOE technology for the production of crude steel was built in 1993. The process is similar to the DIOS process. In the cyclone converter furnace process (the CCF process) iron ore fines are prereduced and smelt immediately. The CCF process is owned by CORUS. The Romelt smelting reduction runs on metallurgical waste and uses coal and oxygen enriched air. The Technored process makes use of self-reduced pellets and a single integrated shaft and hearth furnace to reduce and smelt the product in one continuous operation.

The steelmaking option for the future is the hydrogen plasma smelting reduction (the HPSR) process.[38] Iron ore fines (0.1 – 100 mm fractions) are preheated by a hot exhaust gas and transported continuously into the HPSR reactor. Small amounts of lime or dolomite serve to achieve suitable slag viscosity. Reduction is carried out by hydrogen gas.

The FASTEEL is a faster, more flexible and much cheaper route to steelmaking than the existing technologies. It combines the FASTMET process (production of hot metal in the electric iron furnace) and the CONSTEEL process. The raw materials for the FASTMET process can be iron oxides, reductants (carbon source), and binder. The CONSTEEL system implies continuous charging and preheating of the metallic charge (scrap, pig iron, HBI, etc.) to an electric arc furnace by means of a conveyer that connects the scrap yard and the furnace.

Collaboration between the MIDREX and Cobe Steel Companies led to the development of a new Itmk3 process in 1996. The process uses the rotary hearth furnace to convert iron ore fines and pulverized coal into iron nuggets of the same quality as that provided by the blast furnace pig iron. Iron ore fines and coal fines are converted into almost pure pig iron nuggets in the space of only ten minutes. In Minnesota, USA, a pilot plant using this process has a current production of 25 000 tons/year. In 2005 the plant can be expected to operate on a commercial basis.

The investigations carried out at the MIDREX also concern the HOTLINK system (hot DRI with a temperature of 700 – 750 °C is immediately charged into the electric arc furnace), production of high-carbon DRI products (up to 3.5 % carbon), the MIDREX-OXY process (a new generation of oxygen injection) and the Super Megamond plant operation (single shaft furnace capable of producing up to 2.7 Mt DRI/per year).

In general, it can be noted that the DRI products have not found a major global application and that their use tends to be confined to their place of production. Croatia is wanting in raw material (iron ore and coal) and energy (natural gas) and therefore lacks basic prerequisites for establishing own efficient DRI production. The interest in the DRI products can be expected to increase considering, that the steelmaking industry in Croatia relies solely on the electric arc furnace operation.

Conclusion

– A steady increase in direct reduction iron production and in the number of relevant industrial capacities can be noted worldwide. In the past ten years DRI production has risen (from 20 to 49.5 Mt/year).

– About 93 % of overall current DRI production is based on the reduction processes using gas, and about 7 % on those using coal.

– Today the leading direct reduction technologies are MIDREX and HYL, and the COREX – process is the dominant smelting reduction process. Those technologies are especially important to steel production which is dependent on the operation of the electric arc furnace.

– Plants for direct reduction and smelting reduction are built primarily in the countries which are rich in quality iron ore and have sufficient resources of natural gas and coal.

– Development has been directed towards setting up continuous steelmaking plants, where steel is manufactured directly from iron ore fines and metallurgical waste (dust, mill scale), without intermediate stops (discharge, tapping). A number of pilot plants implementing the Itmk3, HOTLINK, FASTEEL, and other technologies, have been in operation.

– New technologies are environmentally attractive. The solid wastes are recycled and carbon dioxide emissions have been brought to a minimum.

– We can expect the interest in DRI products in Croatia to increase, considering that the primary steelmaking route in this country relies on the electric arc furnace.

List of abbreviations
Popis skraćenica

DRI – direct reduced iron
– izravno reducirano željezo

EAF – electric arc furnace
– elektrolučna peć

HBI – hot briquetted iron
– toplo briketirano željezo

SAF – submerged arc furnace
– elektrolučna peć pod zaštitom luka

VAI – Voest-Alpine Industrienanlagenbau

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SAŽETAK

Razvoj procesa izravne redukcije i redukcijskog taljenja za proizvodnju čelika

M. Gojić i S. Kožuh

Iako će proizvodnja čelika u visokim pećima i kisikovim konvertorima i nadalje biti primaran način izradbe čelika u narednom razdoblju, proizvodnja čelika u elektrolučnim pećima nastavit će se uveličavati. Međutim, povećava se važnost proizvodnje visokokvalitetnih čeličnih proizvoda dobivenih izravnom redukcijom željezne rude i/ili redukcijskim taljenjem. Zadnjih deset godina proizvodnja izravnom redukcijom povećala se za 140 %, od 20 do 49,5 MTg a^{-1}. U ovom radu analizirani su glavni industrijski primijenjeni procesi izravne redukcije i redukcijskog taljenja kao i njihovi razvojni procesi.

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