OVERVIEW OF DIRECT REDUCTION & ALTERNATIVE IRONMAKING PROCESSES & PRODUCTS

Joseph J. Poveromo[1] and Jan van der Stel[2]

1 Raw Materials & Ironmaking
Global Consulting
1992 Easthill Drive
Bethlehem, PA 18017, USA

Ph: C (610) 442 3527
Email: joe.poveromo@rawmaterialsiron.com

2 Tata Steel, Research & Development
P.O. Box 10.000
1970 CA Ijmuiden, The Netherlands

Ph: +31 2514 97485
Email: Jan.van-der-Stel@tatasteeleurope.com

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ABSTRACT

This symposium covers the development and application of alternative (to the blast furnace) ironmaking processes where the objectives include the following:

- hot metal processes to feed oxygen converters or electric arc furnaces,
- direct reduction processes to produce
  - DRI/HBI to feed electric arc furnaces or to produce DRI/HBI to feed blast furnaces, oxygen converters, etc,
  - DRI to smelting/melting processes to produce merchant pig iron or hot metal to feed EAF or BOF steelmaking vessels,
- direct reduction or hot metal processes to process waste oxides from either EAF mini-mills or fully integrated plants.
- Other novel processes to produce either hot metal or steel, such as electrochemical processes

Accordingly, in this introductory lecture, we will present an overview of these direct reduction and alternative ironmaking, steelmaking processes and the products they produce.

Development of Competitive Processes & Process Routes

The long standing major driving forces for development of competitive processes such as smelting reduction processes have been to avoid the cokemaking and sintering steps preceding the blast furnace. The blast furnace process itself is well recognized as a very efficient process such that any new process can only approach but not surpass the blast furnace for efficient production. In the current decade, the emerging major driving force is the need to reduce CO2 emissions.

We can offer some observations on smelting reduction (to feed BOF's) and alternate steel processing routes, mainly involving EAFs:

Bath Processes

Smelting-reduction - HIsmelt - The bath smelter segment of the **HIsmelt** process had been coupled to a circulating fluid bed pre-heat/pre-reduction step using iron ores. A commercial HIsmelt plant (0.8 MTPY capacity) started up in 2005 in Kwinana, Australia. This project involved JV partners: Rio Tinto, Nucor, Shougang, Mitsubishi; the plant did produce (at > 75 % capacity in early 2008) merchant pig iron using Australian higher phosphorus iron ore. The plant was shut down and later dismantled and moved to China where the Molong Petroleum Machinery **(Molong**) company rebuilt and upgraded it to perform substantially better, as reported in the recent versions of this symposium and at AISTech meetings in Pittsburgh, with a further update being presented here.

HISARNA process - The HIsmelt bath smelter segment is now coupled to a pre-reduction process called the CCF (Cyclone Converter Furnace) in the HISARNA process, part of the ULCOS program in Europe. A pilot plant with a capacity of 8 t/h of hot metal was built and tested at the site of Tata Steel in IJmuiden, The Netherlands. Between 2011 and 2015 the plant was operated by the R&D organization at IJmuiden in short campaigns of 3 months per year, which were focused on process research. In 2016 the decision was made to upgrade the HIsarna pilot plant. After completion of the plant modifications in 2017 the responsibility of the HIsarna plant shifted from the R&D organization to the operational organization, as reported in 2017. Further updates will be reported at this symposium.

Tecnored process - Tecnored produces blast-furnace type molten iron in a cupola arrangement using self-reducing agglomerates (briquettes of iron ore fines, biomass, fluxes) as the primary feedstock. The briquettes are cured at low temperatures prior to feeding to the furnace. Additional fuel is used directly in the furnace only to provide the required heat to drive the chemical reactions. The process owner, VALE, is building a 500 KT/yr commercial plant in Brazil.

Bed Processes - **Smelting reduction – Corex, Finex –** these processes are commercially proven, but for Corex up to 3000 T/day using a high percentage of pellets while Finex is producing 4,000 tons/day using ore fines. Both reportedly use also a small amount of coke. Although the Corex process has been criticized for the above limitations and high capital cost it must be recognized that the process is less than three decades old and there is much time available for evolutionary improvement. The blast furnace process has been evolving over hundreds of years, by comparison. However, a limitation of all of the above are CO2 emissions that could be minimized with use of biomass or possibly addressed with CCUS (carbon capture utilization & storage) options, although CCUS is a controversial option that could be the topic of a symposium by itself.

Other Process Routes

Direct reduction/scrap/EAF steelmaking route - the EAF mini-mill route is now suited for flat-rolled steel production with the move up the quality ladder strongly dependent upon feed of iron ore based iron units to the EAF. The shaft furnace DR processes such as **Midrex** and **EnergIron HyL** are well established but dependent upon DR grade iron ore pellets. With the DRI/EAF process route identified as a competitor to the blast furnace process, the key factor is natural gas pricing for the established Midrex or HyL processes. Where natural gas is available at less than $1/MSCF, there can be an overall economic advantage for the DRI/EAF route. The economics (and CO2 emission concerns) of coal based DRI are not attractive enough to be competitive in areas with high gas prices. DRI process developers are now exploring switching to using H2 to replace some or all of the natural gas as the reductant as part of the CO2 emissions reduction effort. The use of H2 is technically straightforward; the major barrier is the current high cost of H2 gas; accordingly much research effort is being aimed at developing more economical methods of H2 gas production. The Hybrit DRI process will be presented at tis Symposium, a project based on availability of economical H2.

DRI/ESF (Electric Smelting Furnace) process route – The above mentioned concerns about DR grade pellet availability and cost has driven the emergence of an alternative process combination: Production of DRI in shaft furnace using BF grade pellets followed by an electric smelting step (ESF) to produce liquid hot metal suitable for charging into an existing BOF steelmaking furnace. Such a DRI/ESF combined process provides for use of BF grade pellets while allowing the continued use of existing BOF facilities. Since the last SSAI Symposium in 2023 much attention has been focused on such DRI/ESF processes although only one commercial project (at TKS in Germany) is proceeding. Variants of ESF technologies are being offered by leading engineering companies: SMS, Primetals, Tenova, Metso and Hatch; all have some experience in ESF applications in other areas such as ferroalloy production and smelting of coal based DRI, such as the Iron Dynamics Process (IDI), as discussed elsewhere.

Fines based DRI and Fines Based DRI/ESF Processes - The fines-based processes have attracted much attention but only one VAI (now Primetals) **FINMET** (now renamed **Finored**) plant remains in commercial operation; such a plant was built with very high capital costs. Since the last SSAI Symposium, Primetals has made significant progress with pilot and demo plants of their fluid bed technologies, including H2 based processes: The **HYFOR** process (Hydrogen-based Fine Iron Ore Direct Reduction) pilot scale plant has started operation at the Voestalpine site at Donawitz in Austria. It consists of a preheating-oxidation unit, a gas treatment plant and the reduction unit. In the preheating-oxidation unit, fine ore concentrate is heated to approx. 900 °C and fed to the reduction unit. HYFOR produces DRI whereas the **HyForSMELT** option smelts this DRI in an ESF. Primetals has another collaborative fines-based DR process under development, designated **HyREX**, with the Korean steelmaker POSCO, HyREX will adopt the proven FINEX fluidized bed reactor technology and use hydrogen, instead of coal, as the reducing agent where DRI from HyREX is refined to hot metal in an electric power based ESF. Another fines based process, based on H2, the **Circored** process (developed by Lurgi/Outotec/Metso), demonstrated technical feasibility decades ago, using a combination of a CFB (circulating fluidized bed) followed by a FB (fixed bed) fluidized bed reactor, but not commercial success; it is now being reintroduced by Metso, also with an ESF option, as well. Earlier this year SMS acquired the Metso ferrous portfolio and plans to couple the Circored to its ESF technology.

Hot metal/EAF steelmaking route – this route could also rely on hot metal from nearby blast furnaces or new on-site hot metal processes. An example of the latter is at Steel Dynamics where the **Iron Dynamics (IDI)** Process (to be described later) is feeding hot metal to an EAF. Examples of the former are found mainly in China as elsewhere, including in the USA, owners of existing blast furnaces, even if idle, are reluctant to provide hot metal to EAF based competitors.

Summary of Direct Reduction Processes

The above discussion mentioned a number of alternate hot metal and direct reduction processes. For clarification and reference purposes we will elaborate further on these processes. We will first discuss processes to produce DRI or HBI with the aid of the following table:

DIRECT REDUCED IRON (DRI/HBI) Processes

Reductant:	coal-based			gas-based		
Vessel:	Rotary Kiln	Rotary Hearth	Fluid Bed	Shaft Furnace	Fluid Bed	Shaft Furnace
Iron Ore:	lump ore fines	fines	fines	pellets, lump ore	fines	fines
Process	**SL/RN** **DRC** **others** IMBS	**Inmetco** **Fastmet**	Circofer	**Midrex** **HyL**	**FINMET** Iron Carbide Circored HyFOR	ZESTY

All processes that have attained commercial status are shown in bold.

Established processes - Worldwide DRI/HBI production is dominated (nearly 80 %) by the gas based shaft furnace processes (MIDREX, HyL, etc) using pellets and lump ore. For regions with low-cost, local coal and iron ore, such as India, South Africa, China, etc, the smaller scale coal-based DRI processes will continue. Coal based DRI processes have been studied in North America but the EAF penalty for coal ash and gangue along with economy of scale issues are too difficult to overcome for merchant (or even captive) plants producing DRI as an end product. However, the coal based DRI process can feed a hot metal (or pig iron nugget) process where the coal ash and sulfur (and ore gangue) are removed by the slag. The latest variants of pig iron nugget processes involve use of biocarbon reductants such as the E-Nugget Process, as presented by CarboTec in this Symposium.

Fines-based DRI processes - These were discussed earlier where we noted that only the Orinoco Iron FINMET (now called FINORED process) plant remains in operation after being built with very high capital costs. One of the driving forces for fines-based direct reduction processes is the avoidance of the pelletizing processes. The economic incentive is the cost differential between pellets and fine ore, typically > $50/Fe ton. However, the challenges (higher capital costs, energy consumption, dust losses, etc) posed by fluidized bed processes can essentially eliminate this initial cost differential. However, as noted earlier, Primetals is making good progress with their HyFOR process and other fines based process developments, Other fines-based direct reduction processes that have been commercialized include the rotary hearth furnace (RHF) processes for waste oxide processing and the RHF segment of the IDI hot metal process. It should be recognized that many of these RHF processes do involve an agglomerating (pelletizing or briquetting) step to prepare feed for the RHF.

Other attempts at fines based processing are:

- **Flash Smelting** - , developed at the University of Utah and based on copper flash smelting technology; A comparable flash ironmaking process is being developed in China.
- **Calix's Zero Emissions Steel Technology (ZESTY) process** - proven at pilot scale to reduce fine iron oxide with a minimum amount of hydrogen in a narrow but high reactor (non-fluidized), where the energy for this endothermal reduction reaction is provided through electrical heating from the outside; It produces a solid, fine DRI product, ready for briquetting or melting. A 30 KT/yr demo plant is planned.
- **H_2 based Plasma Smelting Reduction** - The Hydrogen Plasma Smelting Reduction (HPSR - SuSteel) process pilot plant/demo plant is located at the voestalpine Stahl Donawitz/Austria site; H_2 and iron ore fines are fed through a hollow electrode into a plasma arc reaction zone in an electric furnace. H_2 is ionized into plasma and the iron ore is melted and converted into steel; only water vapor and liquid steel exit the process. The partners here include Voestalpine and Fortescue.
- **BioIron Process** - a joint laboratory effort by Rio Tinto and the University of Nottingham to process iron ore fines and biomass via microwave technology to produce iron; green briquettes (composed of iron ore fines) are fed onto a moving bed; a preheating/prereduction zone precedes a reaction zone featuring microwave energy input, resulting in production of DRI.

Still other early stage research includes:

- Using blue lasers with H_2 reduction,
- H_2 Smelting Reduction heated by concentrating solar thermal (CST),
- Laser furnace conversion of iron ore to iron without reductants,
- Processing of "red mud"; the residue from aluminum production; melting the red mud in an EAF and simultaneously reducing the iron oxide using a plasma that contains 10% hydrogen.
- SuSteelAG - hydrogen-based reduction in a rotary furnace
- Flex-HERS™, powered by natural gas, hydrogen, and electricity by Hertha Metals for high purity iron from any grade of iron ore or waste oxide. It is a semi-continuous, single-step process and has been demonstrated at a pilot facility in Conroe, Texas at a tonnage-per-day scale.

MIDREX, HyL(EnergIron) Progress and Issues - these processes have responded to the challenges of competitive processes and process routes with continuous improvement in scale, efficiency, flexibility, etc. The evolution of the MIDREX process has been impressive: For example, productivity in a standard sized Midrex module has increased from < 90 to nearly 130 tons/hour, an increase of > 45 % while electricity consumption has decreased from 135 to < 95 kwh/T, or about 30 %. One major issue for the MIDREX and HyL processes in North America had been the natural gas pricing. With gas consumption at roughly 10 MMBTU/NT, a gas price increase from 2.00 to 7.00 $/MMBTU raises the energy cost from 20 to 70 $/T, making DRI less competitive. However, the sharp drop in gas prices starting around 2009 (due to the Marcellus shale development) has led to a resurgence in USA gas based DRI production. The first was the Nucor Louisiana project, a 2.5 MTPY HyL (EnergIron) DRI plant that started up in late 2014, followed by the Voest Stahl HBI project where a 2.0 MTPY plant started up in late 2016 and the Cliffs Toledo HBI Plant, rated at 1.8 MTPY, started up in 2020. Other projects are being studied in the USA and Canada. Both Midrex and EnergIron will present their progress at this Symposium.

<u>**Summary of Hot Metal Production Processes**</u>

The process routes for hot metal production can be divided into two types:
Single Vessel Processes - blast furnace, HIsarna, cupola, smelter
Multi-vessel processes - production of DRI followed by smelting or melting step: Corex, FINEX, HyREX, HIsmelt, HY4smelt, RHF/SAF

Reductant	coke		Coal (with biomass possibilities)					H2 gas		None
Process vessel	shaft	shaft	fluidized bed + melter gasifier	shaft + melter gasifier	vessel	rotary hearth / submerged arc furnace	rotary hearth furnace	fluid bed + melter gasifier	reactor	electrolytic cell
Iron bearing material	sinter, pellets, lump	scrap, waste oxides, iron ore fines	iron ore fines	pellets, lump	iron ore fines (+green pre-agglomeration)	iron ore fines, waste oxides	iron ore fines	iron ore fines		iron ore fines
Process	**blast furnace**	**OxyCup** (cupola)	**FINEX**	**COREX**	**HIsmelt**	**Iron Dynamics**	ITmk3	HyREX	SuSteel (+plasma)	molten oxide electrolysis (MOE,Boston Metal)
	mini blast furnace*	Tecnored*	**HIsmelt**		Hisarna	Fastmelt		HY4smelt		Siderwin (ArcelorMittal)
					AISI	Redsmelt				
	Low CO2 blast furnace				DIOS	**Primus** (multiple hearth)				Other electrochemical processes
					Circosmelt					
					Romelt					
Product	hot metal	hot metal	hot metal	hot metal	hot metal	hot metal	nuggets	hot metal	steel	Steel
***charcoal/biomass option**										

We have classified the hot metal processes according to reductant type, vessel type and iron oxide raw material. **All processes that have attained commercial status are shown in bold.**

Commercial processes - The **blast furnace** is the dominant hot metal process worldwide while the **mini blast furnace (MBF)** plays a role both in small scale steelmaking (EAF or BOF feed) and in production of merchant pig iron, mainly to feed EAFs. One type of the MBF is the use of charcoal as a reductant, mainly in Brazil; this provides CO2 reduction benefits. The **cupola** is mainly used on a smaller scale as a melter of already reduced materials such as scrap but some current applications (**OxyCup** Process) are aimed at processing self-reducing agglomerates of waste oxides. As noted already, **Corex** and **Finex** are the only commercial smelting-reduction processes. Corex does have a niche as a processor of high alkali ores. The development of the **Finex** option (fines-based) was welcome while the future development of the HyREX (Finex with H2 reduction) offers significant CO2 emissions reduction potential.

"Low CO2 Blast Furnace" - this refers to European and Japanese research initiatives to modify the blast furnace by equipment changes: "nitrogen free flow sheet" including stack injection, recycled top gas, 100% oxygen, etc and by raw material changes: ore/coal composites, metallized sinter, biomass usage, etc. These efforts are aimed at reducing CO_2 emissions by 50 % and are in the early stages; implementation is well beyond 2020. Progress on Japan's Course50 research and other blast furnace initiatives will be presented at this symposium.

Other smelting reduction processes - The other large scale processes listed above, DIOS**,** AISI, CCF**,** are all dormant. These did have pre-reduction steps, but were higher risk and not as well suited to EAF plants. However as noted above, CCF, Cyclone Converter Furnace, has been revived by coupling it to a HIsmelt vessel in the HISARNA project sponsored by ULCOS in Europe.

Iron Dynamics (IDI) hot metal process - The first North American stand-alone hot metal plant dedicated to EAF application is the IDI Plant at the Steel Dynamics Plant in Butler, Indiana. The IDI process concept originally combines the rotary hearth furnace (RHF) direct reduction of a briquette (iron ore fines/waste oxides/coal greenball followed by submerged arc furnace (SAF) melting of this DRI. The plant produces about 250 KT/year of hot metal that is fed to an adjacent EAF.

Other RHF/SAF-type processes – these are the Midrex Fastmelt and the SMS/ Paul Wurth Redsmelt processes along with the multiple hearth furnace Primus process. Midrex has commercialized the RHF portions of its process (Fastmet) via waste oxide plants in Japan and elsewhere. A demonstration Redsmelt plant has been operated at thel Piombino plant in Italy. Commercial scale Primus plants has been built in Luxembourg (to process EAF plant waste oxides) and Taiwan.

ITMk3 (Iron Nugget) Process – another development had been the ITMk3 rotary hearth process to produce pig iron nuggets for EAF charging. This process involves the greenballing of iron ore and coal fines, followed by reduction of these greenballs in a rotary hearth furnaces where temperatures are high enough to effect melting and slag separation into pig iron and gangue; subsequent magnetic screening steps ensure production of a pig iron nugget suitable for use in an EAF. The first commercial Mesabi Nugget plant started up in Minnesota but has been shutdown for nearly a decade. Other iron nugget type processes have been studied at the pilot scale, including the PSH (Paired Straight Hearth) and the E-Nugget Process, developed by Carbotec (presented at the Symposium). Some work on the PSH may be ongoing in China.

Electrochemical processes; all in the early development stage and designed to produce iron or steel.

- **MOE (Molten Oxide Electrolysis),** developed at MIT, and now being advanced by Boston Metals to the pilot stage, as outlined in the 2020 edition of this Symposium; MOE technology uses a reaction vessel containing a molten electrolyte which dissolves the metal oxide. The molten oxide solution is then electrolyzed by passing an electric current from an anode suspended in the solution from the top of the vessel to a cathode located at the base of the vessel. Only oxides are used in the electrolyte. MOE has a much higher temperature capability: it can process high temperature metals as liquids (i.e. Fe, Ti, etc.).
- **Volteron** – a JV of Arcelor Mittal and John Cockerill, Volteron is a carbon-free, cold direct electrolysis process that extracts iron from iron ore using electricity. The process has proven highly efficient in a pilot plant using standard iron ore. The iron plates produced during electrolysis are then processed into steel in an electric arc furnace. The Volteron plant, 40-80 KT/capacity, will start up in 2027; plant's capacity will be increased to 300-1000 KT. John Cockerill will make a presention at this Symposium.
- **Electra** - The Electra process is another low temperature electrolytic process that has attracted significant funding support from the industry and others but few details about the process have been publicly released.

- **Element Zero -** A pilot plant in Perth, Western Australia, uses an alkaline solution and electric current to separate pure iron from silica, alumina and oxygen; the pilot plant processes 100 kg ore per day. WA government approval is being sought for a plant on a 25 ha site near Port Hedland, to be capable of processing 5 mtpy iron ore to produce 2.7 mtpy green iron; Element Zero will make a presentation at this Symposium.

Other electrochemical process developments:

- Reducing iron with a sodium-based chemical looping process,
- electrowinning of iron in chloride molten salts,
- electrolytic reduction in acid solutions or alkaline solutions
- decarbonized iron electrowinning enabled by oxide-ion stabilized anode in molten salts,
- molten sulfide electrolysis,
- electrolysis following acid baking water leaching of iron ore.
- using acid leaching & selective electrochemistry to feed high purity iron oxides to direct electrochemical reduction processes.

Obstacles to Alternate Hot Metal Process Development

Inspection of the table in the preceding section indicates that few of the alternate hot metal processes have attained commercial status. The barriers facing commercial implementation include the following:

- Fundamental Technical Challenges
- Engineering, Scale-up, Maintenance
- Competing Process Routes
- Competing Alternate Iron Materials
- Changing Economic Conditions
- Need for Long –Term Financial Backing
- Need for Strategic Partner

Fundamental Technical Challenges – these may be classified according to process type:

Smelting reduction processes:

- attack of refractories by FeO-rich slag, low carbon efficiency, high gas volumes, high coal rates, drainage of liquids due to absence of coke, high dust losses with fines-based processes, ➔ high capital costs

Fluidized bed processes:

- drying, pre-heating of ore fines, sticking of iron ore fines, temperature control, dust losses, gas cleaning, handling, product discharge

RHF/melter, RHF/smelter processes:

- production of consistent DRI, production of quality greenballs, briquettes, materials handling, process control of coupled processes, gas cleaning

Engineering, Scale-up, Maintenance – the shortcut of moving directly from pilot to commercial scale without a demonstration plant contributed to problems for the following processes: Iron Carbide, Circored and Iron Dynamics (RHF/SAF). Other issues relating to proper scale for a hot metal plant and requirements for real estate, etc, were discussed earlier.

Competing Process Routes – continuous improvement of the two major, established competing routes:

- Continuous evolution of blast furnace process for large coastal BF/BOF plants
- DRI/EAF steelmaking route:
  continuous improvement of gas-based direct reduction processes (as discussed earlier)
  competitiveness of this route in regions with low gas prices – Mid-East, Venezuela

Competing Alternate Iron Materials - these include scrap, DRI, HBI, and pig iron; steelmakers will prefer to buy these materials if prices are low enough to avoid investment in on-site processes; these materials will be evaluated according to value-in-use, also liquid hot metal from nearby sources will be preferred over on-site production.

Changing Economic Conditions – this refers to changes in prices of process inputs for new hot metal processes such as coal, natural gas, H2, iron ore, electrical energy, etc as well as changes in prices of competing materials.

Need for Long –Term Financial Backing, Need for Strategic Partner – these are grouped together and the following listing of processes already developed (shown in bold print) or with a high chance of success, mainly indicate significant corporate support:

- **Corex, Finex** – VAI, Posco
- **HIsmelt** – Rio Tinto; JV Partners: Nucor, Mitsuibishi, Shougang
- **Iron Dynamics** – SDI
- **Fastmet**/Fastmelt, **ITMk3** – Kobe
- **Primus** –ArcelorMittal/Paul Wurth

Backing for other processes outlined in this paper comes from the following: steel companies: ArcelorMittal, Posco, VoestAlpine, SSAB, Nucor; iron ore producers: VALE, Rio Tinto, BHP, Fortescue, AngloAmerican

OVERVIEW OF DIRECT REDUCED AND ALTERNATE IRON PRODUCTS

This section of our paper will discuss, in general terms, the most appropriate applications and characteristics of the products that are produced from alternative ironmaking processes and direct reduction processes. Before discussing some of the details of these products, it may be appropriate to review some definitions and commonly used terms within this industry.

Definitions

- **Direct Reduction**: Reduce iron oxide to metallic iron without melting. Unreduced ore compounds remain as undesirable oxides
- **Direct Reduced Iron**: Iron oxide feedstock exits in same form as entered (pellets in, pellets out; lumps in, lumps out)
- **Hot Briquetted Iron (HBI)**: DRI that has been hot (1200°F, 650°C) briquetted to a high density pillow shaped briquette
- **Hot Metal**: Molten iron in liquid form, above 2500°F, 1370°C
- **Pig Iron**: Solid product of the iron blast furnace
- **Residuals**: Undesirable elements such as copper, nickel, chromium, tin, sulfur, molybdenum and phosphorus
- **Gangue**: Rock minerals in the iron ore such as silica (SiO_2)**,** alumina (A_2O_3), calcium oxide (CaO), magnesia (MgO). These remain in the oxide form in DR processes.
- **Reduction**:
  $Fe_2O_3 + 3\ CO = 2\ Fe + 3CO_2$
  $2\ Fe_2O_3 + 3\ H_2 = 2\ Fe + 3H_2O$
  ($Fe_2O_3 > Fe_3O_4 > FeO > Fe$)

Product Chemistry

The final chemistry in ironmaking and direct reduction products derives in large measure from the input feedstocks. High quality iron ores will necessarily result in very low levels of undesirable "residual elements". The commonly accepted residual, or undesirable chemical elements that interfere with many steel products include: copper, nickel, chromium, tin, sulfur, molybdenum and phosphorus. The elements carbon, sulfur and phosphorus are process dependent and may be increased or decreased depending upon the particular reduction process.

Because reduction is defined as the removal of oxygen from the source iron oxide, the residual elements present in the feedstock will be concentrated in a ratio of approximately 1.45 times the content of that element in the feedstock.

Reduction processes that are primarily dependent upon carbon as a source of the reducing agent, which in reality ends up being CO, will normally impart some level of carbon to the resulting product, which is in equilibrium with the process conditions. In the familiar example of the traditional iron blast furnace, carbon saturation occurs at about 4.3% carbon, although it can vary above or below this level depending upon the operating characteristics of the blast furnace. For direct reduction processes, which utilize carbon from either coal or from natural gas (methane is CH_4); the resulting carbon will be typically in a range from 0.20% to 4.00%, again depending upon process chemical equilibrium.

The chemical conditions regarding sulfur are variable in that the preheating (in the direct reduction process) of many iron ores can serve to remove the sulfur from the feedstock material as SO_2 in the gaseous form, prior to the final reduction of the iron oxides. In other processes, some sulfur may be introduced by the required process characteristics that can release sulfur from the reductant and is absorbed into the reduced metallic iron product. Coal based reduction processes typically contribute significant quantities of sulfur from the reductant, which may be absorbed in the reduced iron product. Natural gas based direct reduction processes typically have a chemical pretreatment stage to remove sulfur compounds from the natural gas before the conversion of the natural gas into a reducing gas in what is called a "reformer". Therefore, natural gas reduction processes typically produce a product that has sulfur contents of less than 0.02% S.

The case for the element phosphorus is somewhat different depending upon whether the reduction process melts and reduces the phosphorus into the molten bath, or whether, as in direct reduction, the phosphorus oxides are not reduced and remain in the oxide form. Molten iron products from blast furnace and alternative ironmaking processes will result in most of the feedstock phosphorus reporting to the molten iron and therefore the phosphorus content may be higher in the product than in the feedstock. However, for direct reduction processes, in which temperatures are not as high and therefore no melting takes place, the phosphorus oxides, which arise in the gangue minerals, remain in the oxide phase, typically as P_2O_5.

There is substantial controversy with respect to the actual mechanism in which the removal of phosphorus from DR products arises during the chemistry of steelmaking. Empirical observations have conclusively shown that DRI and HBI with relatively high levels of phosphorus at about 0.100 to 0.080% P; can be effectively processed in electric arc steelmaking using a calcium oxide rich slag (approximately 3.0 V ratio) and by removing the slag prior to deoxidation of the resulting steel bath. These practices, with the use of up to 90% DRI, have resulted in production of flat steel products with phosphorus content below 0.030 % P.

The common steelmaking practice of ladle metallurgy can be a very effective tool to remove large quantities of sulfur from the liquid steel prior to refining and tapping into the casting molds. With the use of secondary metallurgy practices, a final steel product sulfur content of less than 0.010% S may be obtained.

Typical Product Chemistry

The following table shows what may be expected in typical product chemistry from an iron ore based feedstock with the resulting products in the form of hot metal, pig iron, DRI or HBI.

	Prompt Scrap	pig iron hot metal	DRI/HBI	High C DRI
Fe	98.0	94.5	93.0	90.4
Metallization, %	100	100	95	95
Metallic Fe	98.0	94.5	88.6	85.9
FeO	0	0	6.6	6.4
Carbon	0	4.5	1.5	4.5
Acidic gangue	1.0	1.0	2.2	2.1
Basic gangue, other	1.0	0	1.1	1.0

Whether or not the particular chemical analysis is desirable or undesirable depends upon the steelmaking process and steel products to be produced.

Steel Products

The ultimate use of alternative ironmaking and DR products is oriented to the production of steel products. The degree to which these products are desirable depends upon the requirements of individual steel requirements. In general, drawing quality applications require low levels of undesirable residual elements. The majority of drawing quality flat products is produced from the basic oxygen process, although EAF steelmaking, which utilizes a large amount of these alternative iron materials, has been proven to be able to produce deep drawing flat rolled products.

Commercial quality steels are produced in both the BOF and the EAF process, and generally can be produced from steel scrap with appropriate selection. Plate steel grades do not normally need low residual feedstocks as many of the required alloying elements can be derived from scrap. However, many specialty plate grades require low levels of both sulfur and phosphorus to meet ductility and impact strength requirements.

Long products typically contain higher levels of alloying elements, which are desired to give strength properties to these products. If there are long products that are required for deep drawing applications, then a low residual feedstock would be required to feed the process. However, most long product grades are commonly produced in the EAF and can be readily made from steel scrap. It is then a question of the economic substitution of the cost of alternative iron units vs. the cost of steel scrap iron units.

Conclusions

DRI production capacity based on natural gas is expected to grow the coming years in the USA. This is related to cheap natural gas due to ongoing shale gas production. In Europe, pressure to reduce CO2 emissions is motivating research based on using H2 gas as the DRI reductant. The economical production of H2 gas requires research and development. Adoption of hot metal production capacity based on alternative processes (such as Corex, Finex, HIsmelt and HIsarna) is expected to remain low the coming 5 years. Research on modifications to the blast furnace process to reduce CO2 emissions continues, led by efforts in Japan.

The road to the development of major new pyrometallurgical processes has proven to be long and costly. Examples of process development costing over one billion dollars and requiring more than twenty years are recognized. Some have become successful, others have failed, and others have not yet become economic.

Several novel technologies have attempted to scale up from pilot plant to commercial scale with poor results. Frequently, the capital cost of potential new technologies does not include required material handling and air pollution control facilities, and substantially underestimate both capital and operating costs in their optimistic proforma promotional materials.

We wish all of the efforts and developments in this activity the best of luck and economic good fortune to proceed to a successful result.