The 2nd Generation of Iron Carbide Plants – Compelling Metallurgical, Cost, and Environmental Advantages to EAF Steelmakers

Revision 02[1]

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Key Words: iron carbide, DRI, EAF, nitrogen removal, carbon emissions, yield

INTRODUCTION

Iron carbide is a superior iron feed for EAF steelmaking. Iron carbide is more chemically stable than DRI and HBI. This makes it easy to handle and safe to ship. Steelmakers can easily inject iron carbide into EAFs using sidewall lances. This shortens heat times. Iron carbide dissolves instantly, generates swarms of tiny carbon monoxide bubbles, which rapidly eliminate dissolved nitrogen and hydrogen, create a foaming slag, and reduce iron oxides to metallic iron. Thus, energy efficiency is excellent and steel yield is high.

In addition, the iron carbide process achieves the lowest carbon emissions of all virgin-iron steelmaking processes.

Unfortunately, no one now directly manufactures iron carbide. Nucor built the first iron carbide plant at Trinidad during the 1990s, but that plant operated for only four years, and it no longer exists. Qualitech Steel also built a plant at Corpus Christi, Texas; but that plant was still being commissioned when the parent company went bankrupt and the plant was demolished. International Iron Carbide LLC has evaluated the successes and failures of the two 1st generation plants and developed a 2nd generation design, which builds on the many lessons learned.

IRON CARBIDE PROPERTIES

Iron carbide, Fe_3C, three iron atoms bonded with one carbon atom, also known as cementite, is an inter-metallic compound. It is a hard, dense ceramic. With a true density of 7,640 kg/m^3 (0.276 lb/in^3), iron carbide is slightly more dense than molten iron, which has a density of 6,980 kg/m^3 (0.252 lb/in^3). Being a ceramic material, iron carbide is stable at temperatures below 300°C (572°F).

Iron carbide is manufactured from iron ore fines that are screened to minus 1.0 mm and plus 0.1 mm. The 80% passing size (P80) is typically 0.4-0.5 mm. The feed does not need to be pelletized, and the product does not need to be stabilized or briquetted.

Iron carbide grains dissolve in less than 1 second in molten steel.[1] Iron carbide is completely free of sulfur and residual metals—such as copper, zinc, tin, chromium—elements that trouble many steelmakers. Table I shows a typical chemical analysis.

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[1] The authors presented revision 01 at the AIST conference on Scrap Substitutes And Alternative Ironmaking VI, held 28-30 October 2012 at Baltimore, Maryland. Revision 02 updates the operating requirements shown in Table II and the operating cost shown on page 4.

Table I. Iron Carbide Chemical Analysis Compared to DRI and HBI

		Iron Carbide	**Midrex DRI**	**Midrex HBI**
Iron total	Fe	89-93%	90-94%	90-94%
Iron metal	Fe°	0.5-3.0%	83-90%	83-90%
Carbon	C	6.0-6.5%	1.0-2.5%	0.5-1.5%
Iron carbide	Fe_3C	90-96%		
Magnetite	Fe_3O_4	2-5%		
Gangue	SiO_2, Al_2O_3	1-4%	3-6%	3-6%

These chemical and physical properties translate into attractive applications for steelmaking.

IRON CARBIDE METALLURGICAL BENEFITS TO EAF STEELMAKING

A 2004 report for the American Iron & Steel Institute and US Department of Energy Technology Roadmap Program identified iron carbide as the preferred material for nitrogen control in EAF steelmaking.[2] Iron carbide is more effective and less costly than any other means for removing nitrogen and producing high quality steel.

Being hard, dense, chemically stable, and granular, iron carbide is easy to handle and safe to ship. Being fine and heavy, steelmakers can easily inject it into EAFs using submerged lances, such as that at Pittsboro, Indiana, shown in Figure 1. This is an important advantage over DRI, HBI, and pig iron.

Figure 1. Qualitech Steel Injecting Iron Carbide into an EAF at Pittsboro, Indiana, 1998

Injection rates of 2,000 kg/min (4,400 lb/min) are attainable. Injection gas can be nitrogen or air. After carrying the iron carbide grains into the bath, the injection gas rises to the bath surface without significantly reacting with the metal. This explains why injecting inert gas into an EAF fails to remove dissolved nitrogen and hydrogen and why vacuum degassing is so slow and expensive. In contrast, iron carbide forms swarms of fine bubbles through a different mechanism.

When iron carbide enters an EAF, it dissolves instantly. Next, the dissolved carbon reacts with the small amount of iron oxide left in the iron carbide product. The carbon and iron oxide form carbon monoxide. The reaction occurs on a minuscule scale, but extensively. This generates an immense quantity of very fine carbon monoxide bubbles. The tiny bubbles create a vigorous metal boil, rapidly homogenizing the bath, absorbing nitrogen and hydrogen, and creating a foaming slag. These properties are extremely beneficial. Steel produced in an EAF with 15% iron carbide can meet stringent quality standards. This steel is suitable for deep-drawn products. Tap-time measurements run 30 ppm nitrogen and 3 ppm hydrogen.[3]

Injecting iron carbide directly before the completion of the EAF batch provides the best nitrogen and hydrogen removal. If iron carbide provides a large portion of the iron units to an EAF batch, injection of iron carbide can commence as soon as the EAF has sufficient molten steel to submerge the injection lance.

The furnace heat does not damage the injection pipe, because the transport gas adequately cools the lance. Dust losses are not evident. The widespread generation of tiny carbon monoxide bubbles thoroughly mixes the bath. The mixing is far more effective than argon injection mixing, with iron carbide attaining full mixing in 1 minute, versus 4 minutes with high rates of argon injection.[4]

DRI, HBI, and pig iron fail to provide mixing and reduction of nitrogen and hydrogen.

Detailed material balances have shown the process provides high yields. In some instances, the iron carbide yield exceeds 100%, because the powerful chemical reducing action of the carbon monoxide reduces iron oxide in the slag to iron, which is recovered in the hot metal. This is not true with scrap or DRI, where the iron yield often is 92-95%.

In addition, the metal boil engendered by iron carbide creates a foaming slag, which promotes metallurgical reactions, insulates the hot metal, improves energy efficiency, and reduces roof refractory wear.

For these reasons, iron carbide is the premium material for electric arc furnaces. Foremost, iron carbide's primary benefit is its ability to enable steelmakers to produce higher-grade steels. These sell at higher premiums. This ability to penetrate higher quality markets attracted Nucor, Qualitech Steel, and other companies to license the iron carbide technology during the 1990s.

A secondary benefit is iron carbide's ability to reduce EAF operating costs. Iron carbide can decrease steel production costs by enabling steelmakers to blend iron carbide with lower grade, less expensive scrap.

POSSIBLE FUTURE BENEFITS

Dr. Gordon Geiger has projected further opportunities when iron carbide becomes commercially available. He has suggested the simultaneous injection of nickel oxides and/or chromium oxides with iron carbide to produce high nickel steels or stainless steel.[5] Another possibility is the continuous production of steel directly from iron carbide in a revolutionary new steelmaking process.[6] These future possibilities, which await the mass production of iron carbide, possess high economic potential.

IRON CARBIDE MANUFACTURING PROCESS

The iron carbide manufacturing process is clean and simple. A fluid-bed reactor converts iron ore to iron carbide, by contacting the iron ore with process gas consisting primarily of methane (CH_4) and hydrogen (H_2). The only direct by-product is water.

$$Fe_2O_3 + 2CH_4 + 5H_2 \rightarrow 2Fe_3C + 9H_2O \tag{1}$$

Burning natural gas to provide process heat generates small amounts of carbon dioxide as an ancillary by-product.

The process steps include:

- Heating iron ore to approximately 700°C (1300°F).
- Contacting the hot iron ore with pressurized methane and hydrogen at an absolute pressure of 4.5 atmospheres in a fluidized bed reactor. Here the strong reducing gases convert iron oxide to iron carbide.
- Cooling the product to 65°C (150°F).

Ancillary equipment includes a hydrogen reformer and a process gas system. The gas system consists of a gas heater, heat exchangers, compressors, and gas scrubber.

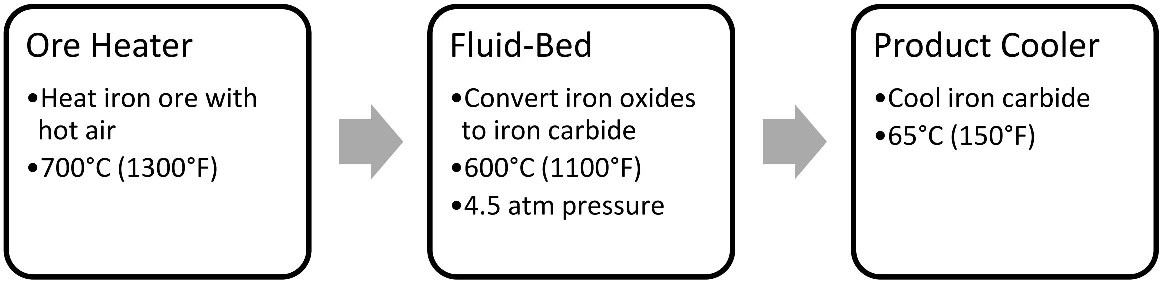

Figure 2. Iron Carbide Manufacturing Process

The operating cost depends upon the price of the commodities used for its manufacture. Table II lists those commodities and their consumption rates. Assuming a natural gas price of $4/GJ, carbide can be produced for approximately $90/mt plus the cost for iron ore.

Table II. Operating Requirements

Item	**Unit**	**Units to Produce 90% Fe as FeC3**	**Units to Product 85% Fe as FeC3**
Iron ore	mt	1.42	1.42
Natural gas	GJ	13.62	12.91
Electricity	MWh	0.22	0.18
Labor	hr	0.15	0.13
Nitrogen	Nm^3	3.8	3.8
Water	m^3	1.20	1.10
Supplies	$/mt	2	2
Maintenance	$/mt	7	7

ENVIRONMENTAL BENEFITS

Iron carbide offers compelling environmental benefits.

The process offers a route to achieving the lowest carbon emissions of all virgin-iron steelmaking processes, producing only 1.09 kg of carbon dioxide (CO_2) for each kg of steel produced. This is far less than the 2.01 kg for the conventional blast furnace to basic oxygen furnace (BOF) technology, 3.09 kg for coal based DRI (such as Corex), and 1.87 kg for natural gas based DRI (such as Midrex, HyL, or Energiron). See Table III.

Only steel totally made from scrap achieves a lower emission. This is only possible when producing the lowest grades of steel or when using very expensive scrap.

Table III. Carbon Emissions from the Entire Iron Ore to Steel Manufacturing Process[7]

Process	**kg CO_2/ kg steel**
Iron ore pellets; coke; blast furnace; BOF	2.01
Iron ore pellets; Corex DRI; BOF	3.09
Iron ore pellets; Midrex DRI; EAF	1.87
Iron carbide direct to steel	**1.09**
Scrap; EAF	0.64
Scrap + 50% Fastmet; EAF	1.87
Scrap + 40% iron carbide; EAF	**0.98**

Iron carbide also is the most environmentally favorable DRI addition for EAFs, achieving 0.98 kg CO_2 emission versus 1.87 kg of CO_2 for Fastmet.

As an additional carbon benefit, the iron carbide process produces much of its carbon dioxide in a concentrated stream. Concentrated carbon dioxide is easy to sequester or use beneficially, such as for secondary oil recovery.

PROCESS HISTORY

The process for manufacturing iron carbide, although simple, has been hindered by economic and contractual factors. In fact, at this time there are no operating plants.

Invention and Process Development

Prior to 1975, Dr. Frank M. Stephens, Jr. conceived a process to commercially produce iron carbide as a feed material for steel production. At that time, Dr. Stephens was Technical Vice President for Hazen Research, Inc. at Golden, Colorado. Following initial laboratory tests, Hazen Research, Inc. applied for a patent on October 14, 1975, and the US Patent Office issued US Patent No. 4,053,301 on October 11, 1977.

In 1985, Dr. Stephens retired from Hazen Research, Inc. and simultaneously acquired the rights to the iron carbide patent. He formed the company Iron Carbide Development Corporation (ICDC) and began marketing the process. In 1988, ICDC and the Australian venture capital group PACT Resources, Pty. Ltd. created Iron Carbide Holdings, Ltd. (ICH), with PACT Resources investing approximately AU$7,000,000 to operate a demonstration plant at Wundowie, Western Australia (near Perth) to make the first commercial quantities of iron carbide.

During 1989, ICH produced 310 mt (350 st) of iron carbide at the demonstration plant, which operated at near atmospheric pressure. The company sold the product to seven clients; and five companies—Nucor, North Star Steel, Mitsubishi, Qualitech Steel, and Cleveland Cliffs—acquired a license or an option to use the technology.

Figure 3. Nucor’s Iron Carbide Plant at Point Lisa, Trinidad

Nucor

Nucor Corporation was one of the recipients of the Wundowie iron carbide. In 1992, Nucor licensed the technology and authorized PLS Engineering, at Denver, Colorado (now part of the Harris Group) to begin engineering and procurement to place a 300,000 mt/y (330,000 st/y) iron carbide plant into operation by late 1994. Nucor selected a plant site at Point Lisas, Trinidad, where they negotiated a low-cost, long-term contract for natural gas and acquired a free-trade zone, where they paid no local taxes.

Nucor began construction in 1993. Unfortunately, Nucor cut off funding to PLS before completing engineering, feeling they could complete the plant with only partial design. In addition, Nucor minimized expenditures on some plant equipment including the process gas heat exchangers. As later discussed, the lack of engineering and inferior plant equipment hurt plant availability and limited production.

In late September 1994, Nucor introduced the first iron ore into the reactor, with the reactor atmosphere being air. The company started the process gas compressors, identified several problems, and then shut down the plant, but left the cooling water pumps running. During this time, an instrument technician removed the level sensors in the packed tower scrubbers for recalibration. He removed the level indicating instruments and informed the control room operator, who blocked out the liquid level alarms on the distributive control system (DCS). Block valves had not been installed in the water lines to the packed towers, and at least one of the water control valves leaked, despite being in a closed position. The leak went undetected for several days. Once discovered, Nucor operators immediately drained the tower, but damage had been done. Water had backed through the process piping to the main process gas heat exchangers, and, mixing with the iron oxide dust, the water and iron oxide severely fouled the exchangers.

The original process gas heat exchangers were of a low-cost design. Nucor lost approximately one year unsuccessfully trying to clean the heat exchangers before replacing them with more robust, shell and tube heat exchangers.

Other operating problems, Nucor encountered at Trinidad included:

- The process gas piping was undersized. This limited the gas flow to a maximum of 65% of design capacity.
- The fluidized bed reactor tuyere plate gas seal ruptured.
- The ore heating system experienced abrasion, and Nucor bypassed the ore heating system. This compromised the reactor chemistry and further limited production quantity and product quality.
- The process gas scrubber collection tank proved undersized.
- The reactor off-gas cyclones failed to limit the process circulating load.
- The product cooler proved deficient.
- The product pneumatic lift required extensive maintenance.
- The ore feeder was too small and the packing glands failed.

Nucor spent four years working through these problems, but in 1998, steel prices plummeted, and Nucor fell under severe economic pressure. Coincidentally, the price of pig iron dropped in half. Able to buy pig iron as cheaply as it could produce iron carbide, Nucor shut down the iron carbide plant. Dissatisfied with the corporation's overall performance, Nucor's board replaced the CEO and COO. Everything connected with the ousted senior management became pariah, including iron carbide. The Trinidad plant sat idle until 2002, when National Gas Company of Trinidad and Tobago Limited (NGC) acquired and demolished the plant.

Not everything at the Trinidad iron carbide plant failed. In spite of all of the difficulties encountered, Nucor produced 357,712 mt (394,310 st) of iron carbide. Production proved the process design was valid. Nucor's mechanical failures also underscored the importance of adequate engineering, conservative equipment design, and risk mitigation when pioneering metallurgical processes.

Qualitech Steel

A second effort to produce iron carbide on a commercial scale occurred at Corpus Christi, Texas, when Qualitech Steel Corporation built a 2,000 st/d plant. Qualitech obtained a process license from ICH, but modified the process, because Mitsubishi Corporation financed the project. Mitsubishi modified the ICH process to use two reactors, and they utilized a pipe-grid gas distribution system in the fluidized bed reactors. Unfortunately, during commissioning in early 1999, the pipe grid in one of the reactors failed. Simultaneously, the parent company ran out of money and filed for bankruptcy. Without having produced more than a few tons of product, the bankruptcy court shut down the plant, and in 2004, the plant was demolished.

PROCESS IMPROVEMENTS

During 2010 Frank A. Stephens, son of Dr. Frank M. Stephens, Jr., acquired the exclusive ownership of the iron carbide process rights. During early 2011, he formed International Iron Carbide LLC. The company owns rights to 35 patents. During the last two years the company has thoroughly analyzed the problems encountered at Trinidad and Corpus Christi and prepared robust solutions. Many of the improvements are proprietary. Major improvements include:

- Process heat exchangers—Robust shell and tube design.
- Process gas piping—Adequately designed to achieve full capacity.
- Fluidized bed reactor tuyere plate and gas distribution system—Robust design, capable of supporting instantaneous unexpected shutdowns of a fully loaded reactor.
- Fluidized bed reactor tuyere plate gas seal—Dual gas seal with robust strength and flexibility to accommodate thermal expansion, eliminate dust penetration, and sustain production.
- Ore heating system—Pneumatic heater with high efficiency, rapid dynamics for quick startups and shutdowns, and minimal angular jogs to avoid erosion, and modular construction to accommodate refurbishment.
- Process gas scrubber and liquid collection tank—Adequately designed to achieve full capacity.
- Process dust circulating load—Process balanced to remove a portion of cyclone underflow as final iron carbide production, rather than fully recycling the cyclone underflow back to the reactor; and large diameter piping (250 mm (10 inch)) to convey solids to eliminate plugging.
- Product cooler—Mass flow cone to control flow.
- Product handling—Elimination of pneumatic lift by positioning the product cooler higher above ground.
- Ore feeder—Pneumatic injector in place of problematic screw feeder.

International Iron Carbide is actively looking for clients to build the 2nd generation of plants. The company is confident it can provide the design to build and operate iron carbide plants that are safe, reliable, and economical.

SUMMARY

Iron carbide holds promise as a revolutionary feed for steelmaking—especially for EAFs—because of its superb metallurgical, economic, and environmental benefits.

Iron carbide's chemical and physical properties make it an ideal feed for EAFs. Iron carbide is granular, non-pyrophoric, and dissolves instantly in molten steel. This makes it easy to ship and simple to inject into EAFs. Iron carbide is free of residual metals and sulfur. Iron carbide contains excess carbon relative to any iron oxide, and this excess carbon reduces iron oxides. This results in high yield.

The carbon reacting with iron oxide generates swarms of tiny carbon dioxide bubbles. The bubbles homogenize the furnace bath, produce a foaming slag, and powerfully remove dissolved nitrogen and hydrogen from steel.

Commercial use by Nucor and industrial tests by North Star Steel and Qualitech Steel showed that iron carbide handles easily and provides the promised benefits.

Iron carbide also has the potential to reduce steelmaking costs and produce high-margin products.

In addition to the metallurgical and economic benefits, iron carbide is friendly to the environment. Iron carbide generates the lowest carbon emissions of all processes to produce virgin steel, emitting one-half to one-third the carbon dioxide of other production routes.

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