Iron Carbide for Electric Arc Furnaces

Summary

Iron carbide is a revolutionary feed for steelmaking. This new feed material for electric arc furnaces (EAFs) will profoundly impact the steel industry during the coming decade because of its outstanding metallurgical, economic, and environmental benefits.

Iron carbide is ideal for EAF steelmaking. It 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 any 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.

Large commercial tests by Nucor, North Star Steel, and Qualitech Steel showed that iron carbide handles easily and provides the promised benefits.

Iron carbide also reduces costs and produces 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.

Steel Industry Trends

Understanding the steel industry helps appreciate the economic potential of iron carbide. As Figure 1 illustrates, EAFs produce over 400 million annual tons[1] of steel.

China, Korea, Taiwan, India, the Middle East, and Turkey heavily rely upon imported scrap. This high demand caused scrap prices to increase 400% between 2003 and 2008. Although the scrap price slumped during the 2008-2009 Recession, the price strongly recovered in 2010. Heavy scrap was selling for $523-542/mt in eastern China as of late November 2011.[2]

[1] The units “tons” and “mt” indicate metric tons throughout this document.
[2] Metal Bulletin, 23 Nov 2011, http://www.metalbulletin.com/Article/2939132/Ferrous-all/Chinas-heavy-ferrous-scrap-prices-edge-up-in-hesitant-market.html.

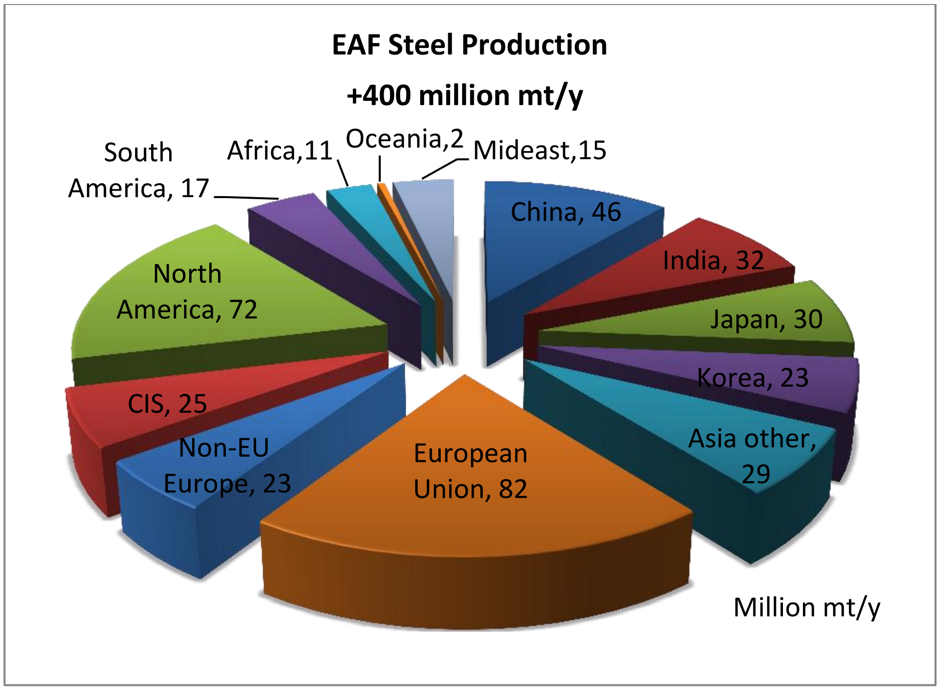

Figure 1 – World Electric Arc Furnace (EAF) Steel Production[3]

Timothy Brightbill and Scott Nance observed "the amount of scrap available for export … hit a plateau" in 2004. "Major scrap exporters are at or near the limits … they can make available."[4] See Figure 2.

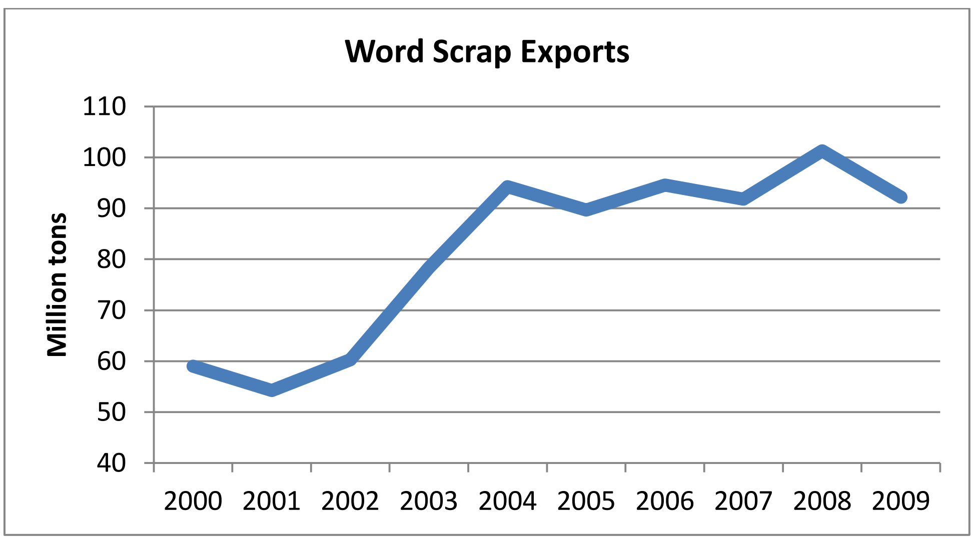

Figure 2 – World Scrap Exports Plateaued Since 2004[5]

Iron carbide can supplement this shortage. In fact, the price of high-grade scrap sets a low-risk floor price for iron carbide.

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[3] World Steel Association, *Steel Statistical Yearbook 2009*.
[4] Timothy C. Brightbill, partner with International Trade Group, and Scott Nance, counsel with Wiley Rein LLP, Washington DC, "World Steel Scrap Trade 2011," *Iron & Steel Technology*, May 2011, p. 30.
[5] World Steel Association, *Steel Statistical Yearbook 2010*, page 116.

Steelmakers in the US, the Middle East, India, and elsewhere are increasingly interested in direct reduced iron (DRI). The scarcity and high cost of clean scrap are driving this attention. For instance, Nucor announced during early 2011 plans to provide 5.5 million mt/y of DRI capacity in Louisiana to feed its US steel mills.[6] This piggybacks on 19 million mt/y of other new DRI capacity coming online between 2010 and 2012.[7]

These trends have set the stage for the broad adoption of iron carbide.

Iron Carbide Characteristics

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 200°C (390°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 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.[8]

Iron carbide is completely free of sulfur and residual metals—such as copper, zinc, tin, chromium—elements that trouble many steelmakers. Table 1 shows a typical chemical analysis.

Table 1 – 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	5-2%		
Gangue	SiO_2, Al_2O_3	1-4%	3-6%	3-6%

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

Metallurgical Benefits

A 2004 report for the US Department of Energy Technology Roadmap Program identified iron carbide as the preferred material for nitrogen control in EAF steelmaking.[9] Iron carbide is far more

[6] Nucor news release "Nucor Announces Ground Breaking in St. James Parish Project," 7 Mar 2011.
[7] World Steel Association, *Steel Statistic Yearbook 2009*; and Midrex, *World Direct Reduction Statistics 2009*.
[8] Gordon H. Geiger, "Injection in Electric Furnace: Transformation from an Energy Source to a Chemical Reactor," keynote lecture at 22nd McMaster Symposium on Enhancement of EAF Performance by Injection Technology, May 1994, McMaster University, Hamilton, Ontario, p. 4.
[9] Dorel Anghelina, Geoffrey A. Brooks, and Gordon A. Irons, "Nitrogen Control in EAF Steelmaking by DRI Fines Injection," American Iron & Steel Institute and Department of Energy (AISE/DOE) Technology Roadmap Program, 31 Mar 2004.

effective and less costly than any other means for removing nitrogen and producing high quality steel. When Nucor produced iron carbide between 1996 and 1998, iron carbide provided the clean iron units that enabled the company to break into high-margin steel markets.

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 3. This is an important advantage over DRI, HBI, and pig iron.

Figure 3 – 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 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.[10]

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 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

[10] Gordon H. Geiger, "The Potential for Use of Iron Carbide as an Electric Furnace Raw Material," paper presented at the 16th Advanced Technology Symposium, Iron & Steel Society (ISS-AIME), held at Myrtle Beach, South Carolina, May 1993; and Geiger, 22nd McMaster Symposium.

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.[11]

DRI, HRI, 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 ware.

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 technology.

A secondary benefit is iron carbide's ability to reduce EAF operating costs. Iron carbide can decrease steel production costs by $50-100/mt 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.[12] Another possibility is the continuous production of steel directly from iron carbide in a revolutionary new steelmaking process.[13] 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.

$$3Fe_2O_3 + 2CH_4 + 5H_2 \Rightarrow 2Fe_3C + 9H_2O$$

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

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[11] Gordon, 22nd McMaster Symposium, p. 5.

[12] Gordon, 22nd McMaster Symposium, p. 10.

[13] Gordon H. Geiger and Frank A. Stephens, "Steelmaking with Iron Carbide," *1993 Ironmaking Conference Proceedings*, Iron & Steel Society (ISS-AIME), Warrendale, Pennsylvania, 1993; and Gordon H. Geiger, "Iron Ore to Steel via the Iron Carbide Route: an Analysis of the Environmental Impacts of the Route," paper presented at the International Symposium on Global Environmental and Iron and Steel Industry, Beijing, 1997, p. 4.

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.

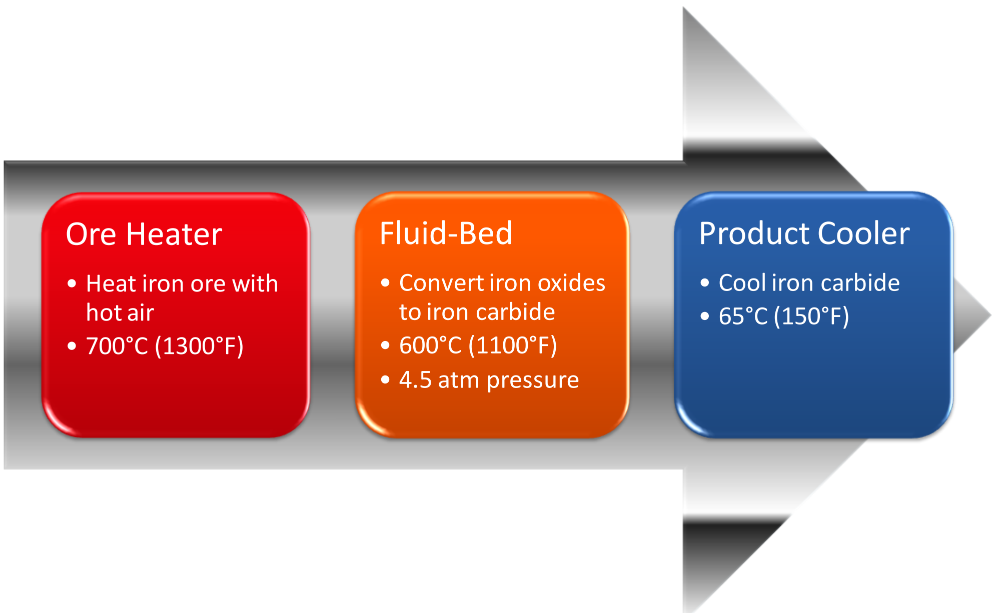

Figure 4 – Iron Carbide Manufacturing Process

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.

International Iron Carbide LLC owns 35 patents protecting the iron carbide manufacturing process. The company's predecessor demonstrated the process at Wundowie, Western Australia during 1989. Seven steelmakers purchased the product for commercial plant tests, and five firms—Nucor, North Star Steel, Mitsubishi, Qualitech Steel, and Cleveland Cliffs—acquired a license or an option to use the technology.

The most important licensee was Nucor, who tested adding iron carbide to an electric arc furnace at Darlington, South Carolina during 1989. After investigating and rejecting many DRI processes[14], Nucor decided to construct a 300,000 mt/y plant at Point Lisas, Trinidad. This was the first commercial iron carbide plant. The plant operated until 1998, when iron and steel prices dropped sharply, putting severe financial pressure on the company, and Nucor closed the plant. The plant sat idle until 2002, when it was sold and demolished.

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[14] Between 1989 and 1992, Nucor investigated the Midrex, HyL, and FIOR natural gas based DRI technologies and the COREX, CODIR, PTC, and Fastmet coal based DRI technologies. Source: Leroy Richard, manager of new steel technology for Nucor, "Nucor's Search for Clean Iron Units," *Skillings Mining Review*, 2 Apr 1994, p. 4-5.

The next most important licensee was Qualitech Steel, who built a 600,000 mt/y iron carbide plant at Corpus Christi, Texas. Unfortunately, Qualitech just began to commission the plant, when the parent company entered into bankruptcy in March 1999. The plant sat idle until 2004, when it too was demolished. No other plant has been built since.

Economics

Iron carbide offers compelling economics for both those who produce iron carbide and those who use it.

The battery limits capital for a 1 million annual ton capacity plant is $333 per annual ton.

The operating cost depends upon the price of the commodities used for its manufacture. Table 2 lists those commodities and their consumption rates. In parts of the world, where natural gas is inexpensive, iron carbide can be produced for approximately $80/mt plus the cost for iron ore.

Table 2 – Operating Requirements

Item	Unit	Units
Iron ore	mt	1.42
Natural gas	GJ	14.78
Electricity	MWh	0.40
Labor	hr	0.22
Nitrogen	Nm^3	10
Water	m^3	1.20
Supplies	$/mt	2
Maintenance	$/mt	7

With respect to value, iron carbide imparts more value to EAF steelmaking than high quality merchant pig iron, which as of November 2011 was priced above $500/mt, and which reached $900/mt during mid-2008. Assuming a conservative $200/mt margin, an iron carbide plant will generate an IRR of 30% and a payback of 2.7 years.

Sustainability and Environmental Benefits

Iron carbide also offers compelling advantages regarding sustainability and environmental stewardship.

The process offers a route to achieving the lowest carbon emission 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 3.

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 3 - Carbon Emissions from the Entire Iron Ore to Steel Manufacturing Process[15]

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.

Another sustainability feature is the ability to ship the energy chemically stored in iron carbide. The process uses natural gas where it is abundant and inexpensive to create this chemical energy and then ships it to where energy is scarce and costly. This provides environmental, social, and economic benefits to both developing countries and to more advanced economies.

Iron carbide also can help iron ore producers add value to their product.

Conclusion

Iron carbide technology is an answer to steelmakers' search for efficient, clean, low-cost steel production.

Iron carbide is one of the most revolutionary developments in steelmaking to have arisen in the last half century. The technology provides an unparalleled opportunity for iron ore producers and steelmakers to capitalize on industry changes. Iron carbide provides powerful metallurgical advantages to EAF steelmakers. It reduces costs and minimizes carbon emissions not achievable with other materials.

References

You can find many of the papers referenced in this article at: http://iicarbide.com/archives/archives.htm

[15] Gordon H. Geiger, "Iron Ore to Steel via the Iron Carbide Route: an Analysis of the Environmental Impacts of the Route," paper presented at the International Symposium on Global Environmental and Iron and Steel Industry, Beijing, China, 1997.