Iron Carbide Manufacturing Process

Summary

Iron carbide is a premium quality feed for steelmaking in electric arc furnaces (EAFs) and basic oxygen furnaces (BOFs). It offers unsurpassed metallurgical advantages and excellent cost savings.

The process also achieves the lowest carbon emission of all virgin-iron steelmaking processes.

The iron carbide manufacturing process is clean and simple. The process converts iron ore to iron carbide in a fluid-bed reactor, by contacting the iron ore with process gas consisting primarily of methane and hydrogen. The only direct by-product is water. An ancillary by-product is carbon dioxide generated from the production of hydrogen and from burning natural gas to provide process heat.

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. This is where 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.

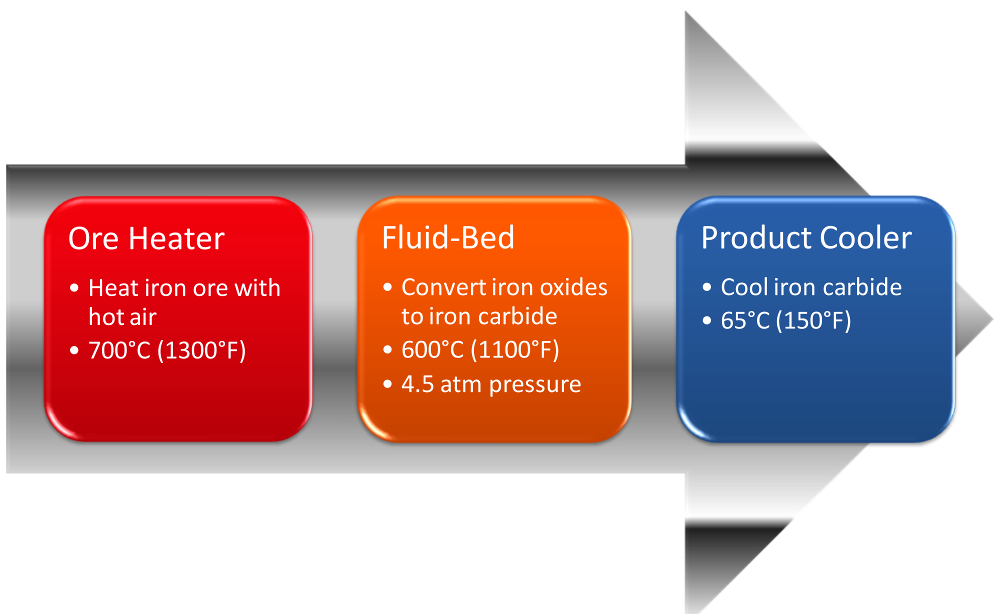

Figure 1 – Iron Carbide Simplified Manufacturing Process

International Iron Carbide LLC (a Colorado, USA based firm) owns 35 patents that protect the iron carbide manufacturing process.

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.

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%

Metallurgical Benefits

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

Iron carbide is far more effective and less costly than any other means for producing high-quality steel. 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.[1]

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 electric arc furnaces (EAFs) using submerged lances.

[1] 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.

Environmental Benefits

Iron carbide also offers compelling environmental advantages.

The process achieves 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), as Table 2 illustrates.

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 2 - Carbon Emissions from Various Iron Ore to Steel Manufacturing Processes[2]

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 only 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. The concentrated carbon dioxide is easy to sequester or use beneficially, such as for secondary oil recovery.

Process Overview

Figure 2 shows the iron carbide process flow diagram. The process converts iron ore—typically hematite (Fe_2O_3) or magnetite (Fe_3O_4)—to iron carbide (Fe_3C), using a strong reducing gas composed of methane (CH_4), hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and water vapor (H_2O). The process operates at a temperature between 565°C (1050°F) and 630°C (1165°F) and at an absolute pressure of 4.5 atmospheres. Overall natural gas consumption is 14.8 GJ/mt (12.7 decatherms/st) of product.

[2] 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.

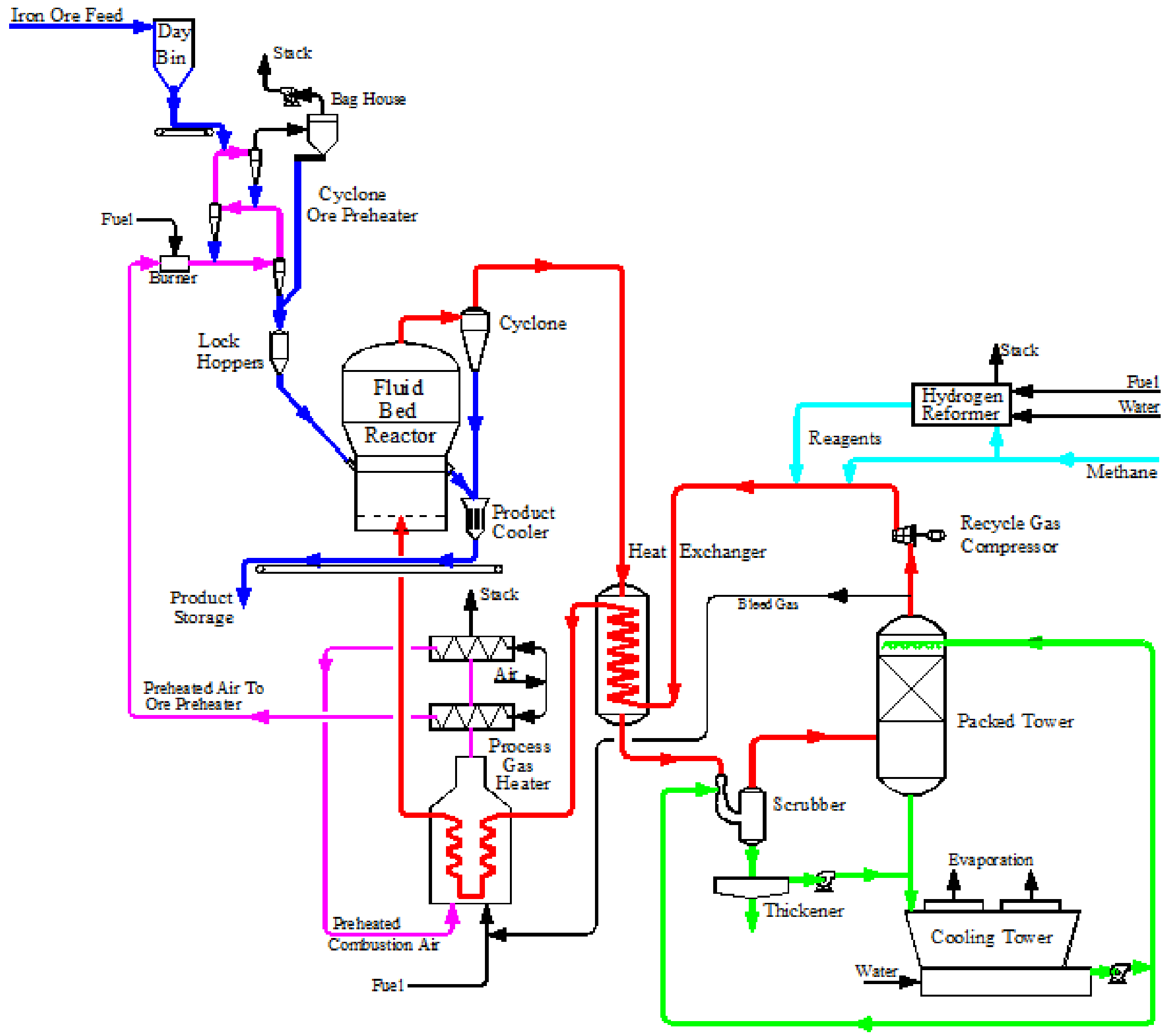

Figure 2 – Iron Carbide Process Flow Diagram

The nominal capacity of a single-module iron carbide plant is 1,000 metric tons per day (mt/d), or 330,000 mt/y (364,000 st/y) for a plant operating at 4.5 atmospheres of absolute pressure and 590°C (1,094°F), with annual production determined by the number of operating days and the economic trade-off of product quality versus quantity. The portion of iron converted to iron carbide (Fe_3C) can be controlled to make virtually any quality product, simply by adjusting the iron feed rate. The product quality that is most useful for steel production is 85% to 95% of the iron present as iron carbide (Fe_3C). The remaining iron content is normally present as magnetite (Fe_3O_4) with small amounts of wustite (FeO) and metallic iron (Fe). At a nominal daily production rate of 1,000 mt/d, product quality is expected to be about 90% of the iron as Fe_3C.

The trade-off between production and quality is not linear. If a higher quality product is desired, the loss in production will exceed the potential production increase if a lower quality product were accepted. Therefore, when the value of iron units is high, it may be more economical to produce a lower grade product.

Generally speaking, the iron carbide process does not remove impurities in the ore: gangue components, such as silica (SiO_2) and alumina (Al_2O_3), pass through the process unchanged. Like other direct reduced iron (DRI) processes, during the conversion of the iron ore to iron carbide, approximately one-third of the mass of the feed is removed, because most of the oxygen is removed, thus effectively increasing the gangue concentration in the product. For example, an iron ore with 3% gangue produces an iron carbide product containing 4% gangue.

The cooled iron carbide product is exposed to dry magnetic separation before being sent to product storage. If the gangue material contained in the ore is liberated (not physically bound to the iron compounds), then the dry magnetic separator removes most of the liberated gangue. The magnetic separator also imparts a small residual magnetism to the iron carbide product, which reduces dusting and transportation losses.

The iron carbide process is the most environmentally responsible process available for making virgin steel. The only effluents from the process are water vapor and carbon dioxide. The carbon dioxide generated by the process comes from the normal combustion of fuel to produce heat and from the reforming of natural gas to produce hydrogen. If the hydrogen is acquired "over the fence," then the carbon dioxide is limited to the material generated from producing the heat needed for the process. If a reformer is operated in conjunction with the process, which is typical, then the carbon dioxide created by the reformer is relatively pure and it can be used beneficially or sequestered.

Ore Storage

Hematite iron ore, which generally contains 63-65% iron, 1-3% gangue, and 4-10% moisture, is the normal feed. The stored ore need not be covered, if the weather permits. Factors influencing the decision to cover the ore include the cost of fuel, the natural moisture content of the ore, and the climate.

From the ore storage facility, conveyors move the ore to a day bin. This bin stores enough ore for approximately 24 hours of operation. A variable-speed weigh feeder supplies ore to the ore heater.

Ore Heater

The ore heater raises the ore to 710°C (1310°F). Typically, the process directly contacts the ore with a hot, oxidizing gas. Raising the temperature of the ore benefits the process. First, it removes moisture. Second, it oxidizes a portion of any magnetite (Fe_3O_4) to hematite (Fe_2O_3). This improves the conversion in the reactor, because hematite converts faster to iron carbide than magnetite. Third, the heater removes or passivates any sulfur. While most ore does not contain sulfur, if sulfur or iron sulfide are present, elevating the temperature oxidizes sulfur to sulfur dioxide (SO_2), which exits the process with the off gas or it causes sulfur to react with alkali material, such as calcium oxide (CaO), to form stable sulfates such as calcium sulfate ($CaSO_4$).

The heater discharges hot ore into bins, where it is held until being fed to the fluidized-bed reactor.

Reactor Feeding

Two refractory-lined, lock hopper bins feed the heated ore into the reactor. Typically, each feed hopper holds approximately 1 hour of feed and operates such that one hopper is being filled while the other feeds the reactor. Gas-tight inlet and outlet valves maintain ambient pressure in the bin being filled with ore and retain 3.5 atmospheres of gage pressure on the bin actively feeding the reactor.

The feed lock hoppers also prevent oxidizing gases from entering the reactor. The atmosphere inside the lock hoppers is converted to nitrogen by cycling the pressure in the freshly filled hopper with pressurized nitrogen in three cycles. After the ore has been purged with nitrogen and the pressure has been raised, the ore is continuously fed to the reactor at a rate that allows the bin to empty and to be depressurized before the other bin fills.

Fluidized-Bed Reactor

In the reactor, methane and hydrogen convert the heated iron ore to iron carbide. Oxygen combines with hydrogen to form water, and carbon combines with iron to form iron carbide. Equation 1 describes the overall chemistry.

$$3Fe_2O_3 + 2CH_4 + 5H_2 \rightarrow 2Fe_3C + 9H_2O \qquad \text{Equation 1}$$

Natural gas reformed with steam, according to Equation 2, provides the necessary hydrogen.

$$CH_4 + 2H_2O \rightarrow CO + 4H_2 \qquad \text{Equation 2}$$

The reactor, which operates as a dense-phase, bubbling fluidized bed, receives feed on one side and discharges product on the opposite side. Internal baffles channel the solids through the reactor to minimize short-circuiting and to create a uniform residence time. Instrumentation closely monitors the gas composition, temperature, and pressure. The process produces a non-pyrophoric product, which can be safely stored and transported.

The 40-ft internal diameter fluid-bed reactor operates at 590°C (1094°F), receiving process gas composed principally of hydrogen and methane. Hydrogen is introduced to maintain the freeboard pressure at 4.5 atmospheres absolute pressure (355 kPag, 66.1 psia, 51.4 psig), and compressors circulate the process gas to achieve a superficial gas velocity of 0.92 m/sec (3.0 ft/sec). The solids retention time is approximately 16 hours. The reactions to form iron carbide are mildly endothermic. Thus, to be able to maintain the reactor temperature at the desired 590°C (1094°F), it is necessary to heat the process gas to 633°C (1171°F).

The reactor produces approximately 42 mt/h (46 st/h) of product. The product discharges continuously into lock hoppers and then simultaneously through a reactor product cooler and a cyclone product cooler.

Product Handling

The iron carbide product discharges from the reactor via two lock hoppers, which release the product to ambient pressure. Similar to the feed lock hoppers, the reactor product lock hoppers alternate filling and emptying, with the one hopper receiving hot product from the reactor at 3.5 atmospheres gage pressure, while the other hopper discharges product into the product cooler at atmospheric pressure. Process control maintains the product discharge rate at a level to allow the bin to empty and be re-pressurized before the alternate bin fully fills.

The iron carbide product exits the reactor product lock hoppers at approximately 587°C (1089°F) and cools to approximately 65°C (150°F) as it passes through a plate and frame, water-cooled, product cooler.

A variable speed feeder controls the product draw rate from the product cooler, so that the product lock hopper empties and is available to be re-pressurized before the other product lock hopper fills. The variable speed product feeder discharges to a conveyor, which transports the product to the dry magnetic separator. As described earlier, the magnetic separator removes a significant amount of liberated gangue (typically 50%), with the quantity dependent on the ore characteristics. The magnetic separator also imparts a small residual magnetism to the product, lending it a lower dusting property and thus making it better to handle and ship.

Gas Handling System

The gas, which exits the reactor at 590°C (1094°F), passes through four refractory-lined reactor cyclones, which remove most of the entrained solids from the gas. Dust collected by the cyclones, at a rate of approximately 36 mt/h (40 st/h), flows by gravity to a surge bin before a portion is recycled back to the reactor. Any solids above this rate (usually about 15% of the reactor's throughput) pass through a set of lock hoppers and then advance to the cyclone product cooler, which cools them to below 65°C (150°F), typically 38°C (100°F), before adding these solids to the cooled reactor product upstream of the magnetic separator.

Process gas exits the reactor cyclones and passes through four parallel, gas-to-gas, process gas heat exchangers, reducing the gas temperature to 150°C (302°F).

A venturi scrubber and a packed-bed tower further cool the process gas to 28°C (83°F) to remove the water produced in the reactor and knocks out the remaining entrained fine particles, which escape the cyclones. This ensures that the entrained dust is sufficiently low to protect the process gas compressors.

In the venturi scrubber, water scrubs the gas, removing most of the particulate, and dropping the gas temperature to 60°C (140°F). The packed tower scrubber further cools the gas to a final temperature of 28°C (83°F).

A bleed stream of process gas exits the gas circuit ahead of the compressors to prevent nitrogen from building up in the circuit. The quantity of bleed depends on the natural gas purity, the volume of purge gas, and the amount of ore heater flue gas that enters the reactor with the hot ore feed.

Make-up reagent gas, consisting of hydrogen and natural gas, enters the re-circulating process gas stream ahead of the compressors. The pressure in the fluidized-bed reactor freeboard determines the exact quantity of hydrogen introduced to the system. The addition of natural gas to the process gas determines the methane concentration.

Two operating and one stand-by centrifugal gas compressors recycle the process gas, with the pressure running 4.17 atmospheres absolute (46.6 psig) at the compressor suction and 5.33 atmospheres absolute (63.6 psig) at the compressor discharge. The compressor discharge pressure controls the process gas flow to the reactor.

The four gas-to-gas heat exchangers, which cool the process gas leaving the fluidized-bed reactor, heat the process gas coming from the gas compressors, achieving a temperature of 520°C (968°F). A fired gas heater further heats the process gas to 633°C (1171°F). The gas heater uses the bleed stream gas and natural gas as fuels.

Flue gas exiting the gas heater provides energy to heat the combustion air supplying the process gas heater. It also provides heated combustion air and transport air for the ore heater.

Process Water

Two separate cooling water systems serve the plant. The “direct-contact” system provides cooling water to the venturi scrubber and packed tower. It directly contacts the process gas. On the other hand, the “non-contact” system provides cooling water to the product coolers, reformer, and other minor heat exchangers.

Hot cooling water from the packed tower flows to a cooling tower for heat removal, while water used in the venturi scrubber passes through a settling basin before going to the cooling tower. Underflow from the settling basin is batch filtered to remove solids.

Commercial Plants

Two commercial plants evaluated the iron carbide process. Nucor built the first plant at Point Lisas, Trinidad and began operation in 1994. Qualitech Steel built a second plant at Corpus Christi, Texas, with construction nearly reaching completion during 1999. Financial problems handicapped both plants.

The Trinidad plant was shut down in 1998 after producing 357,712 mt (394,310 st) of product, and the plant was demolished in 2002. Mechanical problems due to inadequate engineering and inferior equipment selection prevented the plant from attaining design capacity, but the operation demonstrated the viability of the iron carbide process and the high desirability of the product as an electric furnace feed.

Figure 3 – Nucor Plant at Point Lisas, Trinidad, 1994

Figure 4 – Qualitech Steel Plant at Corpus Christi, Texas, 1999

The Texas plant was just being commissioned when the parent company went bankrupt during March 1999, and the plant only produced a few thousand tons of product before being shutdown in 1999 and demolished in 2004.

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 basket of commodities used for its manufacture. Table 3 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 3 – 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 late 2011 was priced at more than $500/mt, and which reached $900/mt during mid-2008. Assuming a $200/mt margin, an iron carbide plant will generate an IRR of 30% and a payback of 2.7 years.

Advantages of Iron Carbide

The advantages of iron carbide and its manufacturing process include:

1. Iron carbide is a premium feed material for EAFs enabling steelmakers to make high quality steels easier and at a lower cost than by any other method.
2. Iron carbide is the most effective material for producing low nitrogen and low hydrogen steels.
3. Iron carbide is free of the common residual metals—copper, zinc, tin, chromium, etc.
4. Iron carbide is safe and easy to transport.
   - 4.1. Iron carbide is not pyrophoric.
   - 4.2. Iron carbide is a free-flowing, dense, granular powder, which readily dissolves in hot steel. Steelmakers can easily inject it into BOFs and EAFs, where it dissolves instantly.
5. Iron carbide contributes energy to steelmaking.
6. The iron carbide manufacturing process is the most environmentally friendly process for producing iron.

  6.1. The only process byproducts are water and carbon dioxide. The total carbon dioxide produced through full production of steel is half of that generated by the traditional blast furnace to basic oxygen furnace production route.
  6.2. Much of the carbon dioxide exits the reformer in a concentrated gas stream, which can be readily sequestered or used beneficially for secondary recovery of crude oil or other applications.
7. The process uses iron ore fines, which are less expensive than iron ore pellets.
8. The product does not need to be briquetted.
9. The process operates at a low temperature and is thermally efficient.
10. The process never generates sticking materials.
11. The process is a closed loop, using 100% of the reagent inputs.
12. The process is simple, consisting of a single-stage converter, which is easy to control.

Conclusion

The iron carbide manufacturing process is simple and robust. The process generates a product with outstanding metallurgical properties and powerful economic and environmental benefits.

International Iron Carbide LLC can provide much more information for those interested in exploring this revolutionary raw material for steelmaking.