Direct Reduced Ironmaking Technology: Hot briquetting trials of DRI with higher carbon levels

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Abstract

Steelmakers have greatly increased the use of carbon as an energy source in the EAF to reduce electricity consumption and increase productivity. Ore-based metallics like pig iron and direct reduced iron (DRI) are frequently added to the EAF scrap charge for their pure iron units in EAF steelmaking, but these products can also provide those additional carbon units. Hot briquetted iron (HBI), a denser compacted form of DRI, is also used in the EAF, but HBI has been historically produced in the 1-2% carbon range because up until recently increasing carbon levels beyond that range would lower the briquetting temperature, and in turn lower productivity. Midrex developed the patented Adjustable Carbon Technology (ACT™) to produce DRI with higher carbon levels without loss of temperature in the lower part of the direct reduction shaft furnace. This technology is available for both existing and new MIDREX® Plants, and can be a unique differentiator for merchant HBI plants: HBI quality can be tailored to the specific needs of the customer and yet maintain a very high yield during transportation and during melting.

The clear benefit of ACT™ for HBI plants is to increase carbon while maintaining briquetting temperature; however, it is currently not possible to study the impact of increased carbon (at a given temperature) on HBI properties in commercial plants. To minimize the scale up risks associated with ACT™ for HBI plants, the Midrex Research and Technology Development Center undertook a series of tests at bench and pilot scale. The study shows that while there is a measurable reduction in both density and strength of the HBI as carbon increases, the HBI maintains adequate strength over a wide range of carbon. The first commercial implementation of this system is currently slated for North America’s HBI facility that Midrex is building for Cleveland Cliffs in Toledo, Ohio, which will be able to supply high-quality customized HBI to the Great Lakes region of North America.

Key words:
Introduction

The MIDREX® Direct Reduction Process is the world’s leading technology for production of DRI Products. DRI products are ore-based metallic raw materials made by removing chemically-bound oxygen from iron oxide pellets and lump ores without melting. Both hot/cold DRI (CDRI/HDRI) and HBI are used in EAF, BF and BOF in various amounts for their pure iron units. As modern electric arc furnaces (EAF) make better use of chemical energy, steelmakers have greatly increased the use of carbon and oxygen as an energy source to reduce electricity consumption and increase productivity. Ore-based metallic like DRI (CDRI, HBI, & HDRI) and pig iron are added to the scrap charge in part to provide those additional carbon units, especially in regions of scrap is abundant. Many steelmakers have espoused the practical benefits of higher carbon levels in DRI in EAF Steelmaking in recent years as the product can be more like pig in chemical composition.

By nature, the more carbon added to the DRI products, the less iron the product will contain. DRI product quality is also very dependent on the ore used; there is no universal optimum carbon level established for DRI products as the physical and chemical requirements are different for Hot DRI or cold DRI / HBI and are influenced by their respective amount in the metallic charge and the steel grade being produced. No application is the same, and product usage can vary greatly over time and within a company or even within a melt shop.

Despite no singular answer to the optimum DRI product specification, there is a growing need for product flexibility that can be tailored to meet the needs of each melter at a given time. To answer this changing market demand, Midrex introduced the Adjustable Carbon Technology (ACT™) in 2017 that allows the plant operator to add carbon in DRI without losing temperature, independently controlling carburization and temperature over a wide range of operating conditions. ACT™ can be applied to existing and new plants, and be used for HBI, cold DRI and Hot DRI.

1. The need for variable carbon within DRI Products

Although the primary appeal of DRI products in EAF steelmaking is for its virgin metallic iron units, the percentage of carbon within the DRI product can also play a key role to the steelmaker (figure 1). The percentages of carbon in direct reduced iron and the advantages of that carbon are situational based on various steelmaking conditions (figure 2). In the electric EAF carbon is used: (1) to reach the required melt chemistry specification of the steel desired or for further refining such as LMF; (2) to reduce any remaining FeO (in the scrap or DRI); and (3) lastly as an additional energy source to help melting. Carbon in DRI is first used to reduce any FeO to metallic iron. DRI at 96% metallization will need less than 1.0% carbon for this purpose. DRI around 93% met will require about 1.5% carbon (Note that each 100 kg of FeO requires 16.7 kg of carbon).

Any remaining carbon is available for oxidation and can be burned to provide additional heat energy supplementing the heat from the electric arc. Carbon can be added through injection into the EAF or charged as contained carbon in the DRI itself.
Carbon contained in the DRI can be very valuable to the steelmaker if it can be adequately utilized. The idea is to use the additional carbon to help melt the steel quicker to reduce tap-to-tap time and increase productivity.
This is the primary reason that many EAF producers that mix scrap and DRI/HBI desire carbon levels above 3%; however, it must be noted that excessive carbon in the DRI will be in the bath until it is blown down with oxygen. Thus, even though additional carbon can be viewed as an extra form of energy, it is possible to have too much carbon. Too much carbon is defined as carbon that does not add any value to the production or further decrease the tap-to-tap time of a steal heat. Any carbon above specification of the steel after the iron is melted needs to be decarburized. The extra time consumed in decarburizing causes a decrease in productivity of the EAF.

2. Carbon in the MIDREX® Direct Reduction Process and the ACT™ Technology

In the MIDREX® Shaft Furnace, carbon is added to DRI in three places (see Figure 3):

- **The reduction zone.** In the MIDREX® Process, the main purpose of the reduction zone is to metallize the iron to the desired product metallization using reductants CO and H₂ produced by the MIDREX® Reformer. However, some carbon is added in the reduction zone by the nature of the reactions occurring in the reduction zone.

- **The transition zone.** A controlled flow of natural gas is added to transition zone, and this is the main means of adding and controlling the amount of carbon in MIDREX® DRI Products. The natural gas feedstock to MIDREX® Plants contains hydrocarbons, mostly methane, and using methane as an example, the carbon comes by:
  
  \[
  \text{CH}_4 \rightarrow \text{C} + 2\text{H}_2 \quad (I)
  \]
  
  \[
  3\text{Fe} + \text{CH}_4 \rightarrow \text{Fe}_3\text{C} + 2\text{H}_2 \quad (II)
  \]

- **The cooling zone.** MIDREX® Plants that have a cold discharge furnace use a cooling gas to cool the DRI to near ambient temperature; the cooling gas contains hydrocarbons, and carbon is formed in a similar manner as in the transition zone.

The carbon-forming reactions (I) and (II) are both endothermic (a reaction that absorbs energy) and cools the DRI; for plants producing CDRI, this is desired. For plants producing HDRI or HBI, this cooling is not usually desired.
The principle of the ACT™ innovation consists of adding an adequate ratio of two gases to the transition zone to promote the following chemical reactions:

- Carbon monoxide (CO) - made in the MIDREX® Reformer – to provide energy and carbon.
  - $3\text{Fe} + \text{CO} + \text{H}_2 \rightarrow \text{Fe}_3\text{C} + \text{H}_2\text{O}$ (exothermic) \hspace{1cm} (II)
  - $3\text{Fe} + 2\text{CO} \rightarrow \text{Fe}_3\text{C} + \text{CO}_2$ (exothermic) \hspace{1cm} (III)
  - $\text{CO} + \text{H}_2 \rightarrow \text{C} + \text{H}_2\text{O}$ (exothermic) \hspace{1cm} (IV)
  - $2\text{CO} \rightarrow \text{C} + \text{CO}_2$ (exothermic) \hspace{1cm} (V)

- Natural gas (mostly CH4) to produce additional carbon.
  - $3\text{Fe} + \text{CH}_4 \rightarrow \text{Fe}_3\text{C} + 2\text{H}_2$ (endothermic) \hspace{1cm} (VI)
  - $\text{CH}_4 \rightarrow \text{C} + 2\text{H}_2$ (endothermic) \hspace{1cm} (VII)

The CO contacts the DRI bed, and the resulting exothermic reactions (reactions that release energy) provide extra energy. This extra energy is used crack the hydrocarbons of the transition natural gas and produce additional carbon without sacrificing temperature. By adjusting the amount of CO in the transition zone, the MIDREX® plant operator can adjust the amount of energy added to the bed. Adjusting the methane addition will control the carbon content of the DRI. Using these simple principles, this technology allows for decoupling of the temperature and carbon formation, making control of both reactions virtually independent.

Figure 3: Diagram of MIDREX® Shaft Furnace Zones
The Midrex Research and Development Technology Center fabricated a test stand to verify the concept and to perform experiments that provided the data needed to develop a commercial design. Several papers have described ACT™ (1), (2), (3) in more details. A simplified flowsheet is shown in Figure 4. The ACT™ “starts by diverting a portion of the reformed gas, which is rich in H₂ and CO. Both gases are separated in a membrane unit and re-injected in the process. All equipment needed are well-proven and reliable.

The key features of ACT™ are:

- Can be used in every type of MIDREX® Plant; CDRI, HDRI, HBI or a combo plant (old or new)
- Easily added to new or existing Plants
- ACT™ can be integrated into existing MIDREX® Plants and used for new MIDREX® Plants.
- Allows amount of carbon in DRI to be adjust up or down.
- Added carbon comes without cooling off the DRI.
- Approximately 90-92% of the carbon in MIDREX® DRI Products will be in the form of iron carbide, Fe₃C.
- The technology can be turned on and off to suit the desired carbon level; the MIDREX® Process can operate without it.

Additional OPEX comes mainly in the form of added electrical consumption. The technology is a “bolt on” type design; the MIDREX® Plant can continue to operate without ACT™ and produce MIDREX® DRI Products at lower carbon content as they desire. The equipment used in this technology is proven and the design carries the same robust nature as all MIDREX® technologies.
3. Effect of variable Carbon on physical properties of HBI

Operating commercial HBI plants (of any process) have not produced HBI above 3% carbon in large quantities due to the degradation in the HBI. Carburization by methane is endothermic, leading to lower briquetting temperature that is very detrimental to the briquette quality. Temperature and carbon control are decoupled with ACT, giving HBI producers the ability to adjust carbon while maintaining a high briquetting temperature. So, in addition to the known benefits of HBI in terms of yield and reactivity (during transportation), HBI of various carbon levels can be produced with desirable physical properties of strength and density.

While the overall effect of carbon and temperature on HBI properties have been experienced by plant operators for years, there is very limited data available. Only one pilot-scale study has been published by Tenova HYL/ Köpper ([4]) but was very limited in scope. To our knowledge, there has never been a complete study on the effect of carbon and temperature independently on HBI properties.

According to the theories of Powder Metallurgy and compaction of metal powders, the overall strength of the resulting compact is proportional to the amount of plastic deformation during compaction. During plastic deformation, highly metallic particles interlock and form metallic bonds or “cold-weld”. The amount of plastic deformation is a function of the materials overall ductility and compaction parameters such as pressure and temperature. An increase in compaction pressure and compaction temperature increases the amount of plastic deformation therefore increasing the overall mechanical properties. Conversely, an increase in the amount of carbon, as iron carbide, in iron will decrease the materials ductility, lowering the amount of plastic deformation and the mechanical properties of the compaction. Losses in compaction strength of iron due to carbon addition can therefore be offset by an increase in compaction pressure and temperature.

3.1 TESTING METHODOLOGY AND ASSESSMENT OF HBI QUALITY

The development of ACT™ for commercialization to HBI producers involved a number of tests to better understand how ACT™ will impact the HBI quality and to minimize scale-up risks. Our approach is to conduct several tests on small scale that are cheaper and easier to perform, then increase to pilot scale then commercial scale. As with every new technology, the real proof will be in the operating plant. For this particular study, we started with hot compaction tests, then moved to our hot briquetting pilot plant and finally confirmed trends in industrial plant trials.

Because Midrex has vast experience and plant data, all tests performed in the lab include commercial pellets and conditions similar to existing MIDREX® HBI plants for benchmarking purposes. It is important to note that these tests are meant to be comparative, not absolute. Results from hot compaction cannot be extrapolated to an operating briquetting plant. There are too many variables that cannot be replicated on a small scale. We are looking for trends and confirmation that the trends scale up.

Density is a very important characteristic for merchant HBI and how it is shipped around the world over international waters. The International Maritime Organization (IMO) published the International Maritime Bulk Cargoes Code (IMSBC) that defines HBI as “Direct Reduced Iron (A) is produced by reducing iron oxide lumps, pellets, or fines and compressing at a temperature of at least 650°C to achieve an apparent density of 5.0g/cm³”. Domestic shipments by rail or truck are not impacted by the density requirements.

Compacts and briquettes produced for the trials were analyzed at the Midrex Research and Technology Development Center. Apparent HBI Density is measured according to ISO 15968:2000, and HBI
Tumbling index according to ISO 15967, although Midrex uses 6.7mm screen rather than 6.3mm, Hot Compactions are tumbled in a 0.5m tumble drum for 100 and 300 revolutions.

3.2. HOT COMPACTION
Hot compaction tests (also called piston-tests) are designed to simulate the hot-briquetting process by placing approximately 180g of hot DRI into a die that is pressed hydraulically. While the productivity is very low, this method gives us the ability to control many variables for parametric studies, and does not require large DRI samples.

Procedure
Midrex has the ability to use DRI produced in industrial plants or produce our own DRI in small, medium, or large batches. With these furnaces, we can easily replicate DRI produced in MIDREX® plants, make DRI with untested iron ore, and make DRI outside of typical production ranges as needed for testing. All furnaces have full control of reduction / carburization time, temperature, and gas composition so we can optimize the desired metallization (%met), carbon (%C) and cementite (%Fe₃C). The limitations are that these furnaces are externally heated batch processes (i.e. not adiabatic) and the bed is not moving like in a MIDREX® shaft furnace. For the hot compaction tests, we used the medium furnace that produces batches of 1,500g of DRI.

![Figure 5: Reduction furnace and hot compaction test apparatus](image)

The hot compaction equipment design and procedures were developed in collaboration with Köppern Equipment, Inc. The DRI samples and dies are pre-heated according to our established procedure, which also defines heating rates and soak times. The pre-heated die is placed under the piston press and the hot DRI vessel is placed on top of the die. Hot DRI is then discharged into the die by opening a slide gate on the bottom of the preheat vessel. For safety, the steel door must be locked and compression is triggered by two buttons on opposite sides of the door. Pressing force and pressing time are controlled by the PLC. Despite all the controls in place, proper execution and timing by the technician is critical to obtain quality data. For each data point, a total of 6 compacts are made: 3 samples are used for compression testing and for chemical analysis while the remaining 3 are used for tumble drum testing.

DRI used was produced in the lab-scale reduction furnace at various levels of carbons from two commercial iron ore pellets. The DRI was produced at a high degree of metallization to minimize carbon
loss during reheat – all compacts finished above 97% metallization. Similarly, carburization was designed to achieve an elevated level of cementite to account for losses in reheating.

Validation tests were performed to verify repeatability and reproducibility. Based on Midrex experience with commercial HBI, we used oxide pellets from 2 different plants and made DRI in the lab using our procedures. One supply of oxide is notoriously difficult to briquette commercially, while the other is much easier. Under the test protocol developed, we can see a difference between strong and weak compacts as shown in Figure 6.

![Compact, before tumble](image1.png) ![Compact, after tumble](image2.png)

**Strong**

**Weak**

![Compact, before tumble](image3.png) ![Compact, after tumble](image4.png)

**Figure 6: Pictures of compacts, before and after tumble**

A complete parametric study was performed and presented by Ruthenbeck\(^{(5)}\) to quantify that effect over a larger scale than what can be achieved in commercial HBI production. In this paper, only the key findings are presented.

**Effect of temperature**

From many years of plant operation, it is well known that the DRI temperature during the briquetting process is the dominant factor in HBI quality. The next series of tests was designed to quantify that effect over a larger scale than what can be achieved in commercial HBI production. Temperature also affects factors like segment life, but this cannot be studied at laboratory scale.
Figure 7: Effect of DRI temperature on compact quality, for low and high carbon DRI (200MPa)

The temperature in Figure 7 above is the pre-soak temperature of the DRI prior to compaction. Some temperature loss is expected during the handling of the DRI prior to the compaction, but it cannot be measured accurately. Regardless, Figure 7 shows that the DRI temperature has a strong effect on both density and strength.

Effect of Carbon

Figure 8: Effect of total carbon on compact quality (700°C, 200MPa)

Both curves show the expected decrease in density as iron is being displaced by carbon. The curves are explained solely by mass balance and no other factor comes in play. This means that we can extrapolate HBI density as a function of carbon for existing plants interested in ACT™.
Tumble index decreased with increasing carbon as expected. However, the decrease in strength is not steep in the range of interest. Strong compacts can be produced at higher levels of carbon as long as the key parameters of DRI temperature and pressing force are maintained. Even above 4.5% carbon, there is sufficient plastic deformation to create the strong metallic bonds for a strong compact.

**Conclusion**

Not surprisingly, this parametric study confirmed the theory and the observed behaviors in a commercial plant: temperature and pressing force have a strong influence on briquette quality. Under the right conditions, any DRI can be made into strong compacts or briquettes. However, this small-scale testing allowed us to isolate and quantify the relative effect of those variables individually. While the results obtained on density and tumble index are not to be extrapolated to plant performance, we can see the relative impact of these factors that are known to effect HBI quality: DRI temperature and pressing force have a more significant impact than carbon.

The key learning from this study was the definition of a test protocol (matrix) that can estimate the briquetting performance of a given ore. The results are also benchmarked against known ores used to produce HBI in MIDREX® plants. For a small investment, we can make a go / no go decision on whether to proceed to larger scale testing and minimize risks doing so.

**3.3. HOT BRIQUETTING**

The hot briquetting tests were conducted following a similar approach to hot compaction. First, the DRI is made in the large reduction furnace, where reducing / carburizing gases are preheated, then passed through a fixed bed of DRI. The typical batch size is 400kg. After achieving the desired DRI quality, the retort is emptied carefully, keeping track of the location of the material in the retort. Each layer is analyzed independently (metallization, carbon and cementite). Depending on the desired DRI quality, layers are either mixed within a batch or combined with other batches (made under identical conditions) to minimize the variability of the material.

After carefully homogenizing the DRI, the DRI is loaded into a conical transfer vessel, which is then loaded in the furnace and heated under inert atmosphere. The heating profile is critical to maintain carbon as cementite, rather than dissociate into iron metal and graphite. The target DRI temperature for all data presented in this paper was set to 750°C which then cooled during transport to the briquetting press. Once the center bed thermocouple reaches the desired temperature, the retort is lifted over the Köppern briquetting machine. Proper execution and timing is crucial so the DRI does not lose excessive temperature in the transfer. DRI temperatures at the feed screw were approximately 700°C. Both DRI and HBI temperature were measured and recorded for each test. The steady-state HBI temperature varied for each test around 680°C.

Compared to a commercial HBI plant, our machine has smaller diameter rolls (0.75m vs. 1.0m typical), and operates at lower speed and lower pressing force. The other key limitation is that the dies are not preheated and do not achieve steady-state during the ~2minute run. The operation setpoints were selected based on several trials using known / commercial iron ores, with the aim to produce a HBI that has similar properties (such as density) to a MIDREX® HBI plant where the ore is used. In other words, the pilot-scale briquetter is used to produce HBI realistic to an actual MIDREX® HBI Plant.
The HBI is discharged in a pan. Immediately after the test, the HBI produced in near steady-state is segregated from the beginning and end-of-the-run material, which is lower in quality. It is spread and allowed to cool in ambient temperature. Initial trials with quenching the HBI did not indicate any significant difference in product quality.

After cooling, the HBI is tested for chemistry (metallization, carbon and cementite) and used for physical testing. All test runs experienced a minor loss in carbon and a reversion of cementite (Fe₃C) to iron and carbon despite our best efforts to minimize this loss. This is strictly due to heating and cooling in a large fixed-bed retort. Both graphs below show the HBI analysis, not the analysis of the DRI that was used to make it.

Figure 10 shows the effect of carbon on the HBI density for 3 different commercial iron ore pellets. The density is the average of 5 briquettes for each test. As expected, density decreases with increasing carbon for a given iron ore.
The effect of total carbon (in HBI) on the HBI strength is plotted in Figure 11. The Tumble index is measured using a 1000 mm diameter drum with 500 mm width for 200 revolutions at 25 rpm. In this graph, we elected to show the +6.7mm tumble index as it is more representative of strength in relation to yield losses.

The trend clearly indicates that increasing carbon reduces HBI strength, but this effect is limited in the carbon range of 1% to 5% (with other key briquetting parameters kept nearly constant). Strong HBI can be made even at high carbon, provided that the DRI is briquetted with sufficient temperature.

For this paper, we focused the hot briquetting tests on varying carbon / cementite, using 3 commercially available iron ore pellets. The trends observed are identical to the hot compaction tests: the presence of carbon does impacts the physical properties of the HBI:

- For density, the relationship is linear and according to the mass balance (where the weight of iron is displaced by carbon). While not surprising, this is a good point to prove. Density can be estimated based on the carbon content of the DRI and there is no additional risk.
- The strength of HBI is decreasing with increasing carbon (at a given briquetting temperature), but maintains adequate strength over a wide range.

While we cannot extrapolate the results to a commercial plant, we anticipate this trend to remain. Presently, there are no HBI plants (of any process) that can independently control carbon and temperature so this testing cannot be replicated at the commercial scale.

The first implementation of the ACT™ system is currently underway. In June 2017, Cleveland Cliffs announced that Toledo, Ohio will be the location of the company’s first MIDREX® HBI production plant. The plant will have a nominal capacity to produce 1.6 million metric tons of HBI per year and will be able to supply high-quality customized HBI to the Great Lakes region. The project broke ground for construction on April 11th, 2018 with the estimated production of HBI slated for mid-2020. Carbon in the HBI will be in the range of 1.8% to 3.0% with 95% metallization.
CONCLUSIONS

For the nearly the five decades that the MIDREX® Process has been in use, product carbon levels have varied based on location and use by plant. These levels have been historically in the range of 0.5% to 3% for CDRI; HDRI and HBI targets were lowered due to the endothermic carburization reactions, coupling product carbon and discharge temperature. The ACT™ system was developed at the Midrex Research and Technology Development Center to provide a means to increase the carbon content of DRI produced in a MIDREX® Plant up to 4.5% carbon without temperature loss. Temperature loss is particularly important to producers of HDRI and HBI. For example, HBI producers will benefit greatly from this innovative technology: carbon can be increased to meet specific customers requirement without affecting briquetting temperature – which is critical to making strong briquettes. Strong briquettes are critical to maintain high yield during transportation and handling.

In order to minimize the scale up risks, Midrex undertook a series of tests at bench and pilot scale to quantify the impact of carbon / cementite on HBI properties, independently of temperature. The results show that there is a measurable reduction in both density and strength of the HBI as carbon increases for a given ore. However, the HBI maintains adequate strength over a wide range of carbon (at a given briquetting temperature). Therefore, we expect that HBI produced with ACT™ will maintain is transportation advantages - superior yield and lower reactivity over DRI - while providing a value-added product tailored to meet specifications of their end users (such as carbon content).

In addition, this paper aimed at presenting the capabilities of the Midrex Research and Technology Development Center capabilities to conduct comprehensive research programs. As part of this study, Midrex developed tests protocols and expertise to perform hot compaction and hot briquetting testing and minimize the risks of scale up. Each ore performs differently for reduction, carburization and briquetting, so it is advisable to perform those tests on pellets of interest.

References:


