Challenges for the Refractory Industry to Support the Foreseen Large-Scale Transition to DRI Shaft Kilns

The global commitment to carbon neutrality by 2050 is a major challenge for society as a whole and steel plants in particular. Engineers at steel companies and original equipment manufacturers are working hard to understand how to tackle this challenge. The direct reduced iron (DRI) process is considered a logical replacement for the reduction task of the blast furnace, since it allows up to 38% carbon dioxide (CO₂) reduction using methane (CH₄) and up to 80% CO₂ reduction using hydrogen (H₂). A shared concern is the availability of quality iron ore and green hydrogen. This article addresses the challenges for refractory producers as the operating conditions most likely will change with possible effects on the current lining arrangement. A deeper understanding of these conditions would help achieve an optimum refractory lining concept for future DRI units.

Discussion

Iron Ore and Its Use in DRI
Iron ore is a natural-state raw material used in ironmaking with the purpose of being used in steelmaking. Mining starts with the extraction of the ore that later will be crushed, ground and beneficiated to enrich its iron content. As the ores are oxidized in their natural state, reduction processes need to be performed before this important feed can be used in steel production.

There are different types of DRI technologies, which may involve the use of ore fines, or as in many cases, pellets. Most DRI is produced through shaft furnace-type units and overall global production reached a total of 119.2 million metric tons by the end of 2021, with about 76% being produced using DRI shaft furnaces. During that year, the two main technologies used worldwide were Midrex® and HYL/Energiron®. The other 24% was produced through alternative processes such as rotary kilns and fluidized beds, among others.¹

 Shaft furnaces are usually fed with iron ore in the form of pellets, which are ore agglomerates that have been indurated, forming very

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Figure 1

Pellets for direct reduced iron (DRI) use.
stable and strong spherical pellets. After ore concentration and drying, these induration processes take place, starting by giving the oxidized iron ore the typical rounded shape by mixing it with specific binders that help the ores bind together with enough mechanical resistance for future processing and transportation. When sintering is done, iron ore pellets are ready to be used in DRI units or blast furnaces.

Iron ore pellet production began in the middle of the last century, but the history of the process dates to the year 1912, when the first pelletizing method was patented. Since then, different technologies have emerged, improving the efficiency of the overall process. Now, after almost 70 years, running units are more productive and cleaner, even allowing the use of different iron ores grades and different types of fuels.\(^2\)

For DRI applications, the agglomerate shape may influence the reduction process. The most important reasons why pellets are more desirable feeds in shaft furnaces are because of restricted size range providing good gas permeability, reduced quantity of ore fines, and better and more uniform mechanical properties. Over the years, it has been demonstrated that pellets may achieve higher levels of metallization after reduction if compared with lumps. In addition, pellets can bring a lower quantity of gangues that can even affect refractory lining performance.\(^3\)

Direct reduced pellets are used in the electric arc furnace (EAF). Their chemical composition plays an important role in all steel shops to achieve desired efficiency. Then, minimum values of gangue are preferred to avoid an excess of consumption of low-grade pellets. The main two parameters enabling cost efficient operation are: \(>67\%\) iron (Fe) and \(<2\%\) \(\text{SiO}_2 + \text{Al}_2\text{O}_3\).\(^4\)

As it has been mentioned before, only a few existing reduction processes can be run on iron ore fines. These technologies usually have fluidized bed reactors that perform the direct reduction in steps. At the end of the process, the iron will be briquetted for its transportation and proper conservation. The briquette shape provides some additional benefits such as lower risk of reoxidation, higher mechanical properties, and the capability of safe overseas transportation. This last item brings the possibility to some steel shops that don’t have local access to pellets or DRI to import it already reduced from a different location. Another possibility is to have a local DRI unit, which would only need transportation of indurated pellets.

### DRI Process and Steel Production

The DRI process starts with a gas reforming stage. Current available technologies for shaft furnace processes may achieve the target gas composition through an external primary reformer or by using novel technologies such as in-situ reforming.\(^5\) For the first case, usually natural gas is fed into the reformer, where catalyst elements...
facilitate production of a highly reducing gas mixture mainly containing hydrogen and carbon monoxide. In general, the process gas has a gas ratio $H_2/CO$ of about 1.6 on average, but in some cases may even get up to almost 3.9. This updated mix of gases is transported through ducts and fed into the shaft furnace at temperatures of about 1,800°F, with a partial pressure that may vary from one technology to another.

Once pellets are ready to use in the following reduction stage, transportation belts charge the shaft furnace from the top, from where the pellets descend by gravity. While this happens, pre-heating and reduction stages take place inside the vessel barrel. The reducing gas mixture is evenly distributed around the vessel circumference, passing to the reactor vessel through several nozzles. As the gas comes into contact with the oxidized iron, different exothermic and endothermic reactions occur, achieving a very high metallization grade of the ore that includes a low content of iron carbide coming from the additional carburizing reactions. The main target of the direct reduction process is to remove the oxygen from the pellets. Basic main reactions with both gases are shown in Eqs. 1 and 2:

$$\text{Fe}_2\text{O}_3 + 3\text{H}_2 (g) \rightarrow 2\text{Fe} + 3\text{H}_2\text{O} (g)$$  
(Eq. 1)

$$\text{Fe}_2\text{O}_3 + 3\text{CO} (g) \rightarrow 2\text{Fe} + 3\text{CO}_2 (g)$$  
(Eq. 2)

After the described stage, pellets would move to the bottom region of the shaft furnace, where discharge of the sponge iron occurs. In general, cold and hot discharge are possible depending on the technology and plant layout. For sure, the second option brings an important energy saving, as during melting, reduced pellets (sponge iron) would arrive in the steel shop already pre-heated.

Usually, the DRI process achieves lower emissions than other well-known ironmaking alternatives based on coal, making it a very interesting option to pursue for future greener processes. On the other hand, as described earlier, this type of unit would need reforming gas and high-quality iron ore availability, in addition to electrical energy for subsequent melting through the EAF or smelter units. For this reason, future developments intend to increase the ratio of hydrogen as a reductant, enabling a cleaner carbon footprint of overall steel production.

The final stage of the sponge iron would be the melt-shop. Over the years, EAF has developed the capacity of processing DRI pellets or briquettes with some changes in the operational parameters if compared to scrap-based processes. Availability of electrical power, dolomite and lime demand, and hot heel, among others, are important factors that may come into consideration when DRI is used as feedstock. Another alternative is to use a smelter, which is a well-known technology mainly used in non-ferrous industries and not proven technology yet for producing pig iron based on blast furnace–grade pellets. So far, this technology is considered a possibility mainly for the European market.

Current Refractory Linings in DRI Applications

The layout of current DRI units may vary from one technology to another. Most of the worldwide installed capacity has an external gas reformer as a first stage of the process. This is where reducing gases are generated, achieving a very efficient mixture that will perform the iron ore reduction inside the shaft furnaces. From this point on, increased challenges for the refractory materials are expected when hydrogen contents will significantly rise above the typical values.

Current state-of-the-art direct reduction processes use natural gas as a base feed for the reforming stage. A mixture of hydrogen and carbon monoxide is formed and transported to the shaft furnace during operation. This feed gas starts to interact with the refractory lining inside the ducts and transfer line until it arrives to the shaft furnace in which the iron ore reduction occurs. The reforming stage as it is now may vary depending on the technology under development.

Refractory linings in DRI units may be divided into two groups working independently: (1) Reforming and (2) Reduction. Either by using stoichiometric or steam reformers, this first stage of the process (1) needs mostly insulating refractory materials for the vessel lining. A combination of insulating castables, insulating firebricks, and ceramic fiber blankets and modules are common arrangements widely used as standard linings in most of the current operating vessels. Some of these units have a heat recovery stage that uses a similar type of lining. In both cases, the target of installed refractory materials is the process efficiency along with vessel shell protection. Basing the material selection on the objective to minimize heat loss, insulating materials are the best choice due to their low thermal conductivity profile and thermal mass. In addition, the absence of major mechanical needs in these regions allows the use of this type of lighter material, reducing the use of dense refractories to a minimum, only where needed.

For the reforming stage (1), main insulating firebricks and castables are usually rated as 2,300°F and 2,600°F according to processing temperatures. Walls might be lined either with bricks or castables, depending on each specific case. From the refractory project standpoint, final selection of materials would be done according to available budget, installation time, expected performance and state-of-the-art references. Alternative solutions such as multi-layer ceramic fiber blankets and
modules linings are possible arrangements, bringing an interesting efficiency in terms of heat transfer.

As stated earlier, in this stage, the refractory lining is not directly exposed to the reducing atmosphere as in stage (2). When an external primary reformer is in place, reducing gases are generated in a series of pipes filled with a catalyst element that boosts main reactions to achieve the desired gas composition.

Novel technologies have shown a possibility to take advantage of in-situ gas reforming. For this type of unit, no external reformer is needed as the gas mix would be developed before feeding the shaft furnace’s bed of pellets. Once the gases have been reformed, a strong reducing atmosphere starts to be in contact with the refractory lining, beginning with the transfer line and corresponding ducts. The gas composition would remain about the same until the bed of pellets is reached. From here on, up to the top of the vessel, reduction reactions take place, mainly with the iron oxide in the pellets, but possibly also with the refractory materials.

Refractory materials can be classified according to different properties, such as density and thermal conductivity (dense/insulating), product presentation (brick/castable), reactivity according to mineralogy and chemical composition (basic/non-basic), installation method (casted/gunned/rammed), etc. Current refractory linings for the shaft furnace of DRI units are based on non-basic products, having Al₂O₃ and SiO₂ as main refractory oxides in their chemical composition. There are some other minor phases and compounds of iron, titania or alkalis that are known to influence the lining performance as well. As per current technology status, one of the main concerns for the installation regions exposed to reducing atmospheres is the iron oxide content. The iron oxide may be easily reduced at a given process temperature and pressure, which is a reason why one of the main targets is to have very low iron content in all refractory materials installed in the reduction regions.

The reduction region (2) is certainly the most complex area inside a DRI shaft furnace. Once the feed gas has been transported to the shaft furnace or generated in-situ, it will pass through the lining nozzles into the barrel. Here is where the actual direct reduction of the iron ore will start. While pellets are moving from the top to the bottom of the vessel, the reformed gas mixture will flow in countercurrent; then, its composition will start to change as the H₂ and CO start to form offgases by taking oxygen from the oxidized ore, leaving a very rich iron pellet known as sponge iron. As the gases flow to the top of the vessel, the reducing capacity of the mixture will decrease along with temperature, while pellets that go in the opposite direction are pre-heated for the following stage.

The refractory lining needs to withstand the highest temperature of the whole process of around 1,832°F, in addition to the highest reduction capacity of reformed gases. The complexity of this arrangement is due to a double-sided working layer wall, which would need to self-support while having a bed of pellets on one side and a hollow chamber at the back, which evenly distributes the feed gas to each nozzle. Therefore, a special arrangement of shaped refractory bricks or pre-fabricated parts is needed, varying depending on the DRI vessel technology. These special shapes must be produced fulfilling a very tight dimensional tolerance, including pre-assemblies prior to on-site installation.

An arrangement of non-basic high-alumina (Al₂O₃) products based on raw materials like corundum, bauxite, fireclay and/or mullite, having ceramic or chemical bond, in combination with insulating materials, are common selections that can withstand these specific process conditions over years. The refractory materials lining is engineered to withstand different mechanical stresses and possible reduction by process gas at operating temperature and pressure. In addition, insulating materials need to be considered as a back layer to keep an efficient process, targeting the lowest possible thermal loss to the ambient. The result is a harmonized concept adapted to each technology, which minimizes the risk of hot spots, reduction of any component within the refractory material, and premature failures of the refractory lining.

DRI shaft furnaces are designed to produce in continuous operation and the refractory lining is one of the most important items to consider in this regard. An unexpected shutdown of these units may bring extended production loss and complex maintenance procedures. The main wear mechanisms to consider are chemical attack by process gas, mechanical stress at high temperature, abrasion and thermal shock. This last condition is mostly related to the cold discharge units, where cooling gases are fed into the bottom of the vessel to reduce sponge iron temperature. Sponge iron may also be discharged hot, depending on each technology and unit layout. When hot discharged, the refractory lining will cover the shaft furnace vessel including the conical region, where it has a more even temperature distribution until the bottom. Finally, all process parameters must be considered when designing the refractory lining, targeting a material selection that withstands the process specific characteristics but also keeping a cost-wise alternative for each project.

In the upper barrel of the vessel, wear mechanisms are expected to be almost the same. However, as elevation increases, the reducing atmosphere would tend to decrease its reactivity and temperature. Then, other conditions such as the abrasion of the ore fines will turn out to be more critical.

Refractory Challenges for H₂-Enriched DRI Process

The worldwide steel industry is willing to contribute in developing a cleaner process for the future. Several possible alternatives have emerged, especially in Europe, and are being studied and referenced during recent years. Initiatives such as carbon capture and usage, use
of biomass reductants, optimizing blast furnace and basic oxygen furnace efficiency, are clear demonstrations of a group effort to achieve decarbonization goals. It is foreseen that the increase of use of DRI as iron feedstock may also be an important contributor in this path.7

Even though current DRI processes bring a significant emission reduction when compared with the blast furnace route, there's still space for improvement when future developments are targeting an environment with 100% hydrogen. Main technology owners are developing enhanced gas mixtures that would allow these plants to run completely without the need of natural gas as feed for reducing atmosphere generation.

Hydrogen can be produced through different processes such as reforming, gasification, pyrolysis and electrolysis. Depending on the input, output and waste, hydrogen may be tagged with a different color. Green and yellow hydrogen stem from electrolysis, where water is split into H2 and oxygen (O2) using green renewable or solar energy, respectively. In this hydrogen, would mean an environmentally friendly low-carbon alternative as compared to NG. Generating no waste, this type of hydrogen would be the preference for a future cleaner industry. Other types of hydrogen may also be used but would not contribute to the green steel road maps, since they come with undesired byproducts such as CO2, carbon or nuclear waste.

The refractory industry will face an important challenge during the development of future DRI processes. Some investigations have been conducted in the past to understand hydrogen as a reductant and its effect on different types of refractory linings. Available literature suggests that when the hydrogen content is raised in the gas mix, other components may also be reduced, such as SiO2. Experiences in petrochemical applications related to syngas have shown that SiO2 may be reduced from the refractory lining as well. Steam reformers and autothermal reformers are examples of high-hydrogen-content reducing atmospheres, with H2/CO ratios between 2.75–4.75 and 1.75–3.75.

Transportation of the reformed gas into the shaft furnace is where reducing gas starts to interact with the refractory lining. Currently, as the gas mixture contains hydrogen and carbon monoxide, one of the main concerns weighs into the iron content of the refractory materials. In addition, SiO2 may also become an element of analysis, because of the possible risk of reduction and volatilization. Recent thermodynamic modeling suggested that even a small amount of vapor in the gas mixture will significantly reduce the risk of reduction and volatilization if compared with a hypothetical 100% hydrogen atmosphere. This observation is related to the activity of SiO2, which may vary with temperature, pressure, CO and H2 content.

Following the important goal of increasing the knowledge of expected performance and possible reactions that can happen in the refractory materials, different types of refractories have been tested at high temperatures in an atmosphere of 100% hydrogen for a set time of 200 hours. Three main temperatures and materials were considered for this analysis: mid-alumina and two high-alumina bricks at temperatures of 1,832°F, 2,192°F and 2,552°F.

It has been observed that at 1,832°F, the investigated materials have shown almost no weight loss. With the increase of temperature, reduction of SiO2 increases as

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**Table 3**

<table>
<thead>
<tr>
<th>Material</th>
<th>Density [lb/ft³]</th>
<th>Al2O3 [%]</th>
<th>SiO2 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-alumina brick</td>
<td>139</td>
<td>42</td>
<td>54</td>
</tr>
<tr>
<td>High-alumina brick 1</td>
<td>157</td>
<td>63</td>
<td>34</td>
</tr>
<tr>
<td>High-alumina brick 2</td>
<td>193</td>
<td>88</td>
<td>9</td>
</tr>
</tbody>
</table>
well. In addition, chemical composition of the refractory materials would also affect this behavior. The higher the Al₂O₃ content, the lower this weight loss is observed. Furthermore, a loss of phosphate was observed with the increasing temperature in the chemically bonded material. Additional investigations must be done to have a better understanding of these findings and its impact on the refractory material’s mechanical and thermal properties, especially the thermal shock and abrasion resistance.

Hydrogen-enriched processes are still under development. Main technology owners are setting stages for the upcoming years to reduce the use of natural gas in their units. Changes are expected in terms of plant layout, equipment and process parameters. As described, H₂-enriched DRI and other emerging sustainable solutions generate important questions on a future greener high-temperature industry, such as ore quality and availability, energy sources, and hydrogen generation, among others. These open questions must consider that the final objective is to achieve a greener process that also makes sense for steel producers in terms of cost and reliability. Being one of the most important manufacturing groups in terms of contribution to worldwide emissions, steel producers will definitively develop a customized and viable solution that may include the use of DRI as iron feedstock; but still, there is a long way to go. Producers of refractory materials are now facing an important challenge: to support the industrial transformation by providing an updated refractory lining solution and at the same time lowering its own carbon emissions. To achieve this difficult task, different targeted research and development studies are pursued, with the expectation of bringing a deeper technical understanding of DRI future operational conditions and its possible impact on the refractory lining performance.

**Conclusions**

The steel industry is constantly growing. Over many years, processes have evolved, and new technologies have emerged, achieving more efficient and safer production lines. Global initiatives are currently set for developing greener steel fabrication before 2050. There are different paths or alternatives to reduce emissions in the industry; for example, optimizing the blast furnace route or, on the other hand, by investing in a greenfield project that brings along either a DRI unit or a smelter.

Current DRI technologies brought an important emission improvement compared to blast furnaces. Nonetheless, to fulfill the goal of net-zero steel production, changes must be implemented to current processes in relation to the reducing gas atmosphere. The use of natural gas would decrease while hydrogen takes over until reaching a process that uses 100% of this gas. For sure this important change generates several open questions like green hydrogen availability, iron ore and pellets availability and quality, and green energy availability. The lack of industrial experiences with such a production process also contributes to some uncertainties for all steel producers.

Refractory material producers are facing an important challenge to support main DRI technology owners. It has been described that the increase of hydrogen in the reducing gas atmosphere may be linked to Fe₂O₃ and SiO₂ reduction in the refractory material itself. Thermodynamic modeling and refractory material exposure to a 100% H₂ atmosphere for 200 hours have been done, observing a weight loss of the samples that increases with temperature and with SiO₂ content. Additional studies are underway to understand how these observations may affect overall properties and possible performance of the refractory lining during operation.
Technical Article

References


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