The steel production is one of the most important industrial processes. Steel has accompanied the technological development of civilization because of its properties of high strength and ductility. (1) Actually, different production routes are used: the Blast Furnace Route, the Direct Reduction route and the Electric Arc Furnace route. The BF plants are created for the production of huge amounts of steel. (2) The beginning of each igneous metallurgical process consists in the reduction of iron ore. In the blast furnace, cast iron is produced then it is converted into steel by blowing oxygen in the converter (BOF). The electric arc furnace cycle is based on the melting of metal scrap. The manufacturing process of HBI involves the use of a reformer where there is the transformation from natural gas to hydrogen and carbon monoxide (reducing gas) in a vertical furnace which constitutes the reduction reactor and a “heat recovery unit” (2) (3). The manufacturing process is energetically less expensive, if compared to the production of cast iron, as it is not necessary to bring the iron ores to the melting temperature, unlike in the blast furnaces. Besides, installation costs are significantly lower than the full cycle of steel production. The Direct Reduced Iron (DRI) is often used in briquetted form (Hot Briquetted Iron HBI) and it can be charged in the blast furnace, inside the converters and in the EAF. (4) (5) The environmental impact reduction is the ultimate goal of modern society, particularly for the iron and steel making industries. Fruehan defines sustainable steelmaking goals as: (i) conservation of natural resources, (ii) reduction of greenhouse gas emissions, (iii) reduction of volatile emissions, (iv) reduction of landfill waste and (v) reduction of hazardous waste. (6)

Table 1 compares the selected parameters for each iron and steelmaking technology, based on a metric t of produced steel for BF/BOF and EAF and iron for DRI. Table 1 shows, if compared to EAF and DRI technologies, BF/BOF route has two to four times higher consumption of equipment and emissions and this requires more energy, water and land consumption. Moreover, the greenhouse gases, main pollutants, and metal emissions are higher than in the other cases. The most considerable difference between the technologies was in the level of emissions of main pollutants (SO\textsubscript{2}, NO\textsubscript{x} and CO), mercury and cadmium in the BF/BOF route, which are several orders of magnitude above the other two technologies. Only in the case of PM10 the BF/BOF emissions are of similar to EAF and DRI ones. (7)
### Tab. 1 - Comparison of sustainability parameters for the major steelmaking technologies

<table>
<thead>
<tr>
<th></th>
<th>BF/BOF</th>
<th>EAF</th>
<th>DRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption (GJ/t)</td>
<td>22</td>
<td>5.8</td>
<td>10</td>
</tr>
<tr>
<td>CO₂eq emissions (t CO₂eq/t)</td>
<td>2.1</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Water consumption (m³/t)</td>
<td>2.6</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Land use (m²/t)</td>
<td>1.7</td>
<td>0.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Emissions to air (kg/t)

<table>
<thead>
<tr>
<th></th>
<th>BF/BOF</th>
<th>EAF</th>
<th>DRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>1</td>
<td>0.04</td>
<td>0.2</td>
</tr>
<tr>
<td>SO2</td>
<td>1</td>
<td>7.4*10⁻⁴</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>56</td>
<td>9.8</td>
<td></td>
</tr>
<tr>
<td>PM10</td>
<td>0.15</td>
<td>0.14</td>
<td>0.13</td>
</tr>
<tr>
<td>PM2.5</td>
<td>1.4*10⁻²</td>
<td>0.3*10⁻²</td>
<td>7.7*10⁻²</td>
</tr>
<tr>
<td>Pb</td>
<td>2.6*10⁻⁴</td>
<td>1.4*10⁻⁴</td>
<td></td>
</tr>
<tr>
<td>Hg</td>
<td>9.8*10⁻⁶</td>
<td>0.1*10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>As</td>
<td>6.2*10⁻⁴</td>
<td>6.6*10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>Cr⁶⁺</td>
<td>4.5*10⁻⁴</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>3.5*10⁻⁴</td>
<td>1.6*10⁻⁵</td>
<td></td>
</tr>
<tr>
<td>Cd</td>
<td>8.1*10⁻⁶</td>
<td>0.5*10⁻⁶</td>
<td></td>
</tr>
</tbody>
</table>

The BF/BOF route requires the largest energy for steel production, this is due to the coke-making and sintering processes needed to treat the raw materials. As a consequence, CO₂ equivalent emissions are also the largest for this route. EAF has slightly larger greenhouse gas emissions per t of produced metal, if compared to DRI, mainly due to the use of electricity, while in case of the DRI process only natural gas is used to reduce the iron ore. SO₂, CO emission and main metals are negligible in DRI technology.

The innovative nature is to use the DRI as replacement of cast iron, to increase the cold charge in BOF. The lower use of cast iron reduces the coke consumption and, as a consequence, environmental impact is reduced.

The HBI’s advantages are:
- high bulk density, which results in saving space;
- chemical composition is well known and certified by the manufacturer;
- minimum amount of armful elements, such as Cu, Ni, Cr, Mo, Sn, Pb and V;
- high thermal and electrical conductivity;
- low reactivity with fresh and salt water. (8)

### USE OF DRI/HBI IN BLAST FURNACE (BF)
DRI/HBI can be used in blast furnace for the production of pig iron. The introduction of such a raw material is consistent with the production process of the blast furnace, because even during a traditional process, performed by the introduction of coke and iron ores, the metal direct reduction takes place in the lowest part of the divergent section. Just before the melting period, the blast furnace is interested by the presence of direct reduced iron and thus, the charging of DRI/HBI aims at avoiding the reduction processes needed to reduce a fraction of the charged raw material. This implies:
- a decrease of the coke consumption, because a fraction of the charged raw material has been already reduced under the form of direct reduced iron (DRI/HBI) (Figure 1);
- a decrease of CO₂ released in the atmosphere, due to a lower intensive use of coke;
- a decrease of the sulphur concentration in the pig iron, due to a lower amount of the introduced coke;
- a possible increase of the pig iron productivity that can be expected at a maximum level of 10%.

Fig.1 - Expected values of the decrease of the coke consumption and the expected increase of the productivity on the basis of the data published by several steelmaking companies during the last decades.
Recent data revealed by AK Steel (9) are used to charge an average amount of about 200kg/t-HM (HM-Hot Metal/Pig Iron) of the metallic charge and nowadays it is the highest ascertained value. The collection of the data revealed by Voest Alpine and Ilva (10) allow determining the equivalent coke (Cokeeq) needed to complete a reduction process as function of the charged fraction (f) of HBI per 1t if the produced hot metal:

$$Coke_{eq} \left[ \frac{Kg}{t_{HM}} \right] = 478 - 392 \times f$$

On the other hand, this decrease of the charged coke involves the amount equivalent coke (including PCI-Powdered Carbon Injection) and not the large coke. At the moment the minimum value of this last parameter has been stated at 274kg/t-HM (11). Lowest values have not been tested and they can be detrimental for the gas permeability and for the structural stability of the material during its descent.

A promising further decrease of the coke consumption and an increase of the blast furnace productivity can be reached by the introduction of DRI/HBI enriched by carbon to form Fe₃C that represents a well established product in the Energiron technology developed by HyL (Figure 2).

Several issues will be clarified in the future:
- what is the contribution of DRI/HBI in the structural stabilization of the raw materials descent within the blast furnace. It points out an intermediate behavior between the iron ores and the coke but it has not been clearly quantified;
- what is the variation of the gas permeability in the blast furnace after the HBI addition and its thermal softening.

**USE OF DRI/HBI IN BASIC OXYGEN FURNACE (BOF)**
The process of steelmaking performed by the BOF consists in three main steps:
- charge of the converter;
- oxygen blowing;
- tapping into the ladle.

The overall metallic charge, composed by cast iron and scrap, is influenced by the local availability of scrap and liquid iron. The metallic charge in the BOF converter, is mainly composed by cast iron (85%) and the remaining part by steel scrap. (12)

The cold charge is a mix of different scrap typologies:
1. heavy demolition scrap
2. light demolition scrap
3. busheling
4. turning chips
5. discarded section of slabs and billets
6. granulated cast iron
7. DRI/HBI

The amount of light and heavy scrap fraction is always maintained constant for each heat. In the scrap box, the light scrap is located on the bottom to promote the material sliding during the charging step. At Ilva Taranto an experimental campaign has been realized in order to increase the cold charge inside 365t BOF up to 90t through the use of metal scrap and HBI. For the experimental trials the metal scrap has been set at 45t, while the HBI has been added by a step of 5t up to an overall amount of 45t. Thus, for the forty observed heats, seven groups of conversion trials have been characterized by the same cold charge, that is sum of 25t scrap and of the added HBI. The cast iron and the HBI average chemical composition were measured (Table 2, Table 3).
Direct reduction

The yield of each type of charged material has been computed on the basis of the tapped steel (Table 4).

**Tab. 4 - Mean and standard deviation of the different elements of metallic charge**

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast Iron Yield</td>
<td>90%</td>
<td>1%</td>
</tr>
<tr>
<td>HBI Yield</td>
<td>89%</td>
<td>1%</td>
</tr>
<tr>
<td>Scrap Yield</td>
<td>89%</td>
<td>2%</td>
</tr>
</tbody>
</table>

The HBI yield is comparable with the scrap yield, but this last is featured by a higher standard deviation because of the organic and inorganic contaminants on the scrap surface or charged with it.

**USE OF DRI/HBI IN ELECTRIC ARC FURNACE (EAF)**

The physical properties of DRI/HBI and its correct allocation inside the EAF buckets affect the quality and the metallurgical yield. In North America and Europe DRI/HBI is used to lower the concentration of the metallic residuals (i.e. copper and tin) (13). The allocation of the charged material in the scrap bucket is realized according to a precise scheme (5) (Figure 3).

DRI/HBI melts fast when it is plunged in molten metal because of the excellent conductive heat transfer, so it has to be charged in the second bucket. A proper charging of DRI/HBI can help the arc stability and the protection of the furnace lining. The most important factors affecting electricity consumption, when DRI is charged, are:

- DRI/HBI quality, including metallic iron, carbon, gangue (SiO₂/Al₂O₃), sulfur, and phosphorus contents;
- DRI/HBI temperature;
- EAF power and thermal efficiency.

The experimental trials have pointed out that the best charging condition can be achieved when the DRI/HBI is charged in the second bucket and in a carburized bath. This behavior has been explained through an experimental investigation in a laboratory furnace to evaluate the interaction between the pig iron and the HBI. Different thermal conditions have been imposed in order to point out the interaction between liquid pig iron and HBI. The melting experiments have been performed for 10 minutes at 1200° C, 1300° C, 1400° C, 1500° C and for 20 minutes at 1500° C and they have involved 100g of pig iron and 100g of...
HBI featured by the same chemical composition used in the BOF experiments (Table 2, Table 3). At the end of the experiments the samples were water quenched. The specimens have been etched using Nital 2%, as recommended by the standard ASTM E407-07. In the specimen treated at 1200° C (Figure 4) neither pig iron nor HBI melted: they are completely detached, without any junction promoted by melting phenomenon. Moreover, no diffusion process takes place because of the low process temperature. In the other samples, the pig iron and portions of HBI melt partially, creating a mixed zone.
The HBI solved in the carbon-enriched bath formed by the pig iron melting. This process is promoted by the carbon diffusion into HBI. Actually, the increasing carbon concentration in HBI ensures the lowering of its melting temperature. This behavior is confirmed by the changes in the microstructure at the interface and nearby. The diffusive character of these phenomena is pointed out by the strong interaction shown in diffusional short circuits, such as grain boundaries. The performed experiments indicate that the carbon diffusion can induce two phenomena:

- the promotion of the melting process;
- the reduction of the oxide contained in HBI and so the increase of the metallurgical yield associated to the HBI use.

CONCLUSIONS
A study on the use of direct reduce iron along the main steelmaking processes has been performed. These considerations can be stressed:

- the use of DRI/HBI in blast furnace allows a decrease of the equivalent charged coke, of the CO\textsubscript{2} emission and of sulfur concentration in the tapped cast iron;
- in the basic oxygen furnace and in the electric arc furnace a properly carburized metal bath allows the recovery of the iron oxides in the DRI/HBI;
- the interaction between carburizing materials in the metal bath, such as pig iron, and the DRI/HBI has to be achieved in order to maximize the metallurgical yield of the conversion and of the melting process;
- in EAF route DRI/HBI has not to be charged by first bucket because such a raw material has to be added into a molten bath enriched by carbon.

REFERENCES