Developments in Continuous Casting of Gray and Ductile Iron

This article describes advances made by offshore foundries in melting practice, die design, dimensional accuracy and parameter optimization.

Yary S. Lerner, Univ. of Northern Iowa, Cedar Falls, Iowa
Gary S. Griffin, B&C Industries, Barberton, Ohio

Fig. 1. This schematic illustrates the main components of the horizontal continuous casting method.

Figure 1 presents a schematic view of HCC. Liquid iron is poured from a transfer ladle into a metal receiver. Typically, continuous casting machines are equipped with an iron receiver capacity of 1.5–3.0 tons. A water-cooled graphite die is attached to the side of the receiver and the cast bar is pulled out by an extraction system, which controls stroke length and frequency. A special mechanism cuts and breaks the bars to required lengths.

The major advantage of this process is its high casting yield (92–95%), since it eliminates traditional feeder needs that are very important when bars are cast in ductile iron or high tensile strength low carbon equivalent (CE) gray iron. Liquid metal in the receiver plays the role of a preheated riser that continuously supplies liquid metal to feed the bar during solidification. The absence of casting defects typically related to sand molding (such as sand inclusions)—in combination with a dense gas-and-shrink-free macrostructure—makes this product ideal for hydraulic and pneumatic component applications. Due to the absence of sand and chilled corners and a very uniform grain structure, continuously cast iron bars are features that provide excellent machinability.

Optimal balance between the iron chemistry, melt temperature, level in the receiver, drawing and cooling parameters ensures production of defect-free, high-quality bars. Typical shapes of continuous cast iron bars are shown in Fig. 2. Table 1 illustrates the current industrial market of continuously cast iron bars, which are produced in sizes varying from 0.5 to 20 in. in diameter and in rectangular shapes of 20 x 16 in.

Ductile Iron Mg Treatment

The specific operation conditions of continuous casting dictate the critical factors to consider when selecting a magnesium (Mg) treatment method. First, the Mg treatment method must be able to regulate residual Mg content depending on bar section size over a wide range of 0.025–
Table 1. Current Industrial Market of Continuously Cast Iron Bars

<table>
<thead>
<tr>
<th>Industrial Market</th>
<th>Typical Parts Produced from Continuous Bars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive</td>
<td>Valve guides, steering gears, pulleys, bushings, shock absorber bushings, transmission pump rotors</td>
</tr>
<tr>
<td>Glass Industry</td>
<td>Plungers, neck rings, bottle molds, funnels, bottom plates, thimbles</td>
</tr>
<tr>
<td>Machine Tools</td>
<td>Slides, ways, chuck, shaft, gears, &amp; plates, sprockets, sprocket shafts, gears</td>
</tr>
<tr>
<td>Power Transmission</td>
<td>Collars, v-pulleys, sheaves, gears, speed reducer shafts</td>
</tr>
<tr>
<td>Pumps &amp; Compressors</td>
<td>Pump gears, compressor valves, shafts, rotors, filters, piston rings, impellers</td>
</tr>
<tr>
<td>Metalcasting</td>
<td>Patterns, coreboxes, pattern plates, permanent molds, dies, inlet nozzle shafts</td>
</tr>
<tr>
<td>Hydraulics &amp; Pneumatics</td>
<td>Pistons, manifolds, valve bodies, rims, plungers, cylinders</td>
</tr>
</tbody>
</table>

0.065%. Second, residual Mg content in every new portion of iron added from the ladle must be moderately greater than that in the iron receiver to compensate for Mg losses during holding and casting. Third, in the case of using a channel-type induction heated iron receiver, it is also necessary to ensure proper iron nodularizing in the inductor channel at start-up. Thus, the first portions of new iron must have a significantly greater residual Mg content.

Commonly used Mg treatment methods are the sandwich method, teeming-process, tilting reactor method and pressure vessel method, which is most widely used in the former Soviet nations.

Recently, a foundry in the former Soviet Union developed a continuous casting method of ductile iron that combines a continuous casting machine with a Mg wire treatment unit. The principal scheme of the equipment is seen in Fig. 3. To achieve a desirable residual Mg level, two feeding units are mounted from both sides of the iron receiver. This process became economically effective when it was employed for nodularizing low sulfur base iron.

Blast Furnace Base Iron

One of the new developments in the melting of base iron in the practical utilization of cost-effective and reduced energy consumption technology that directly uses liquid base iron from blast furnaces. Currently used in many Brazilian foundries, this technology consists of producing liquid iron by the reduction of the iron ore contained in 69.75% of iron. The blast furnace productivity in a 24-hr regime is 8.3 tons/hr or 6000 tons/month. According to one foundry, this use of liquid pig iron has reduced energy consumption per metric ton of iron produced by as much as 300 kWh.

Gray Iron Chemistry, Procedures

The base iron intended for gray iron continuous casting has the following chemical composition (in %): 3.9-4.1 carbon (C); 2.0-2.5 silicon (Si); 0.4-0.8 manganese (Mn); 0.10 phosphorous (P) (max) and 0.02 sulfur (S) (max). The purification process consists of C removal and adjusting other elements. The C reduction is achieved by the ladle injection of oxygen. The other elements’ range is obtained by the heat composition.

After this process is complete, the liquid iron [at about 2336-2408°F (1280-1320°C)] is then transported to the 20-ton capacity channel-type induction heating furnace for further refining, where it is superheated to 2732-2786°F (1500-1550°C). The further variations of the C content in the bath are adjusted with the addition of steel scrap, and the Si and Mn contents are adjusted with the addition of adequate ferroalloys.

Due to the low initial S content (<0.020%), pyrite (FeS2) is added to the liquid gray iron to prepare it for inoculation. During tapping from the channel holding furnace, gray iron is inoculated with SiC. Depending on bar size, inoculant additions vary from 0.15-0.3%. In order to stabilize pearlite, tin (Sn) additions in the range of 0.15-0.3% are made into the ladle. To meet the specified range of mechanical properties, gray iron base chemical composition varies depending on the size of bars made. For example, a typical overview chemical composition for a gray cast iron bar of 1 in. diameter is (%): 3.70 C; 2.50 Si; 0.55 Mn and 0.20 P.

Ductile Iron Chemistry, Procedures

Gray iron is a more ductile iron than gray iron. The different is that Si is in the 0.5-1.5% range, and maximum P is 0.08%.

Iron nodularization occurs in open ladles with a capacity of 0.5-2.5 tons using a conventional sandwich Mg treatment process with FeMg masteralloy additions of 1.3-1.5%. Ladle additions of Cu in the amount of 0.4-1.0% are made to stabilize pearlite and obtain mechanical properties of grade 80-55-06 in thick cross-sectional bars. Typical chemistry of ductile iron bars is given in Table 2.

Die Design

In conventional HCC, die construction consists of a water-cooled jacket inserted into a graphite die. The internal die cavity is machined from solid blocks of graphite and must have the same profile design as the vertical cross section of the bar to be cast. Figure 4 illustrates the typical design of graphite dies used to cast relatively simple shape bars.

Graphite is an excellent die material because of its high thermal conductivity, low coefficient of thermal expansion, high thermal resistance and good machinability. Another advantage of graphite die materials is that it provides non-fettting properties and does not require lubricant. Graphite can be ma...
chined readily due to its excellent surface finish.

Die life depends on die finish, part complexity and operational parameters. To effectively control solidification structure, a number of manufacturing techniques have been implemented for regulating the primary solidification conditions and the bar-cooling rate. One of these techniques consists of changing the length of the graphite die and the ratio of its cooled to non-cooled portions. Solidification conditions are also adjustable by changing the coolant flow pattern within the die. Another factor governing the microstructure and properties of cast bars is the water flow rate for cooling the graphite die.

A series of experiments investigated the effect of heavy section rectangular bar positions in horizontally mounted graphite dies on cooling rate and solidification structure of continuously cast bars. Results determined that the cooling rate and resultant solid skin growth from the wall to the center of the bar were not uniform. Thus, a slower rate was observed on the top section of the bar as skin sinks under gravity. The air gap, appearing between the top section of the bar and the die, decreases the cooling rate, which in turn reduces the effectiveness of die cooling, and slows down casting process speed and productivity. Considering this data along with ideal bar position recommendations, a specially designed die with a unique cooling jacket (Fig. 5) was developed to produce heavy section bars that provide a uniform cooling rate without a loss of productivity.

### Dimensional Accuracy

Dimensional variation of continuously cast bars is determined by die design, the accuracy of graphite die machining, graphite wear (which in turn depends upon the length of operations) and die complexity. Analyses of bar dimensions showed that when designing graphite dies, it’s necessary to account for linear shrinkage but also for the amount of die wear from operation. For ductile iron, this following formula was developed to calculate the initial die dimensions for which the maximum deviation of bar dimensions produced during operation will not exceed the desired tolerances:

\[
D_d = D_b + 0.472 \times T - W + S
\]

Where: \(D_d\) = dimension of graphite die, mm; \(D_b\) = required dimension of bar, T = desired dimension tolerance, mm; \(W\) = average value of die wear, \(S\) = iron linear shrinkage, mm.

Ductile iron continuous cast bars (105 x 175 mm) produced via a die designed by this formula were dimensionally analyzed. Results showed that after 16 hr of operation, actual bar dimensions never varied beyond the tolerance limits.

### Defects and Causes

In order to design a solidification model capable of optimizing process parameters, it was necessary to carefully investigate, analyze and systematize all typical casting defects and their causes. The study provided insight into defects and causes, as well as defect design.

Common defects experienced in HCC are typical for any casting method and are usually caused by metallurgical and operating parameter problems. The difference lies in preventive measures.

For example:
- discontinuities such as cracks may have been caused by misalignment of the machine, high drawing speed or inadequate iron chemical composition.
- pinholes may result from low iron level in the iron receiver or from oxidized iron.
- surface irregularities, called “onion skin,” usually appear as a result of cold iron in the receiver, variations in the drawing speed or inadequate chemical composition.
- out-of-round shape bars result from non-uniform tightening of the graphite die or from high drawing force.
- warpage can be seen when a short pause time in the drawing cycle occurs or with machine misalignment.
- structural anomalies, such as chill, result from inadequate chemical composition, insufficient inoculation or a short pause in the drawing cycle. Floated graphite is sometimes seen in the relatively thick bars caused by high CE, long pause time in the drawing cycle, low iron temperature in the iron receiver or low cooling rate of the die. Mechanical properties that do not conform to the specification are caused in various ways. For instance, in gray iron production, high hardness is caused by low CE iron, excessive pearlite or a long pause time in the drawing cycle. Low hardness may be seen as a result of high CE iron (which in turn reduces pearlite content) or a short pause time in the drawing cycle. In ductile iron, high hardness results from a high cooling rate in the die that may produce microstructural anomalies or a long pause in the drawing cycle. Low elongation usually results from high levels of pearlite, floated graphite or cementite in the microstructure, or low residual Mg content.

### Table 3. Computed Parameters of Continuous Casting of Non-Round Ductile Iron Bars

| No. | Grade of ductile iron in ASTM A-536 | Cross section size (mm) | Sectional area (mm²) | Casting speed (mm/min) | Drawbar speed (mm/sec) | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for common application | Bars for hydraulic valves | Bars for computer application: the production conditions and agreement were confirmed between the predicted and practical data.

**For a free copy of this article circle No. 342 on the Reader Action Card.**