Steel's Workhorse: The Basic Oxygen Furnace

Understanding this primary steel production method will help inspectors realize how the inherent discontinuities found in the steel can affect the end product

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In this, the second of a four-part series, the author explores the production of steel from molten pig iron utilizing the basic oxygen process. Additionally, inherent defects associated with the steelmaking process are introduced. The next issue will detail modern steelmaking with an electric arc furnace.

Throughout the world, the basic oxygen furnace (BOF) produces more steel than any other process, and it is the primary steel production method in the United States. While the basic oxygen furnace is an improvement over the earlier open hearth and Bessemer processes, the vessel for converting pig iron into steel in a basic oxygen furnace is similar in design to its predecessor, the Bessemer converter. There is no heat source associated with the converter; it relies on the exothermic reaction between iron and oxygen. Therefore, a basic oxygen converter is not a furnace. However, there are some vessels that may use an additional hydrocarbon heat source. Keep in mind that the terms basic oxygen furnace (BOF) and basic oxygen process (BOP) and their abbreviations are often used interchangeably, and that there are multiple variations of the process.

The earth's atmosphere is composed of approximately 21% oxygen. Early on, ironmasters understood that air (in actuality, it is the oxygen in air) purified molten iron by removing certain elements such as carbon. The larger the quantity and the more quickly air is supplied to the molten metal, the faster the reduction reaction occurs. To deliver air, the use of bellows gave way to blowers powered by steam engines and then electric blowers. However, this technology relied on the use of air as a source of oxygen; delivering pure oxygen in the volumes needed for steelmaking was not possible. Once economical means were developed to provide the necessary quantities of pure oxygen, the basic oxygen process was the obvious next step in steelmaking technology. The first BOF vessel went into production in Austria in the early 1950s. A typical BOF vessel is capable of making between 250 and 350 tons of steel per heat in about one hour; therefore, one BOF vessel replaced almost one dozen open hearth furnaces. This was a major leap in efficiency and production. By the 1970s, the evolution from open hearth furnaces to the BOP was well under way.

The Basic Oxygen Furnace

A BOF converter is a stout, oblong vessel lined with refractory material. The outer vessel is constructed with steel. Two massive pinions allow the vessel to tilt for pouring and charging. The refractory material is several feet thick. Oxygen can be introduced through an overhead oxygen lance or through several tuyeres located at the bottom of the converter. A taphole allows for the removal of slag from the vessel and pouring of the finished molten product.

Fig. 1 — A ladle is shown charging the BOF. After charging the furnace, it will be raised upright and the oxygen blow will be initiated.

The process is called "basic" due to the nature of the refractory lining and the slag used to help refine the melt. The term "basic" refers to the pH level of the slag. In the late 1800s it was found that a basic lining helped expedite removal of phosphorus and helped retain contaminants in the slag. Within the vessel, molten steel and slag interact. Impurities in the steel combine with the slag, which forms a frothy, viscous layer on top of the molten metal. As slag is skimmed off the top of the melt, impurities in the steel are removed.

Typically, a magnesia refractory lining is used inside the vessel. As consecutive heats are performed, the lining is slowly consumed. Slag added to the heat not only removes impurities, it prolongs lining life. After a heat is completed, a process called slag splashing may be performed. The vessel is rocked back and forth to spread the slag up the sides of the vessel. The converter is then tilted upright and the oxygen lance is lowered into the converter. Nitrogen is blown through the lance and additional slag is propelled up the sides. This additional step has greatly added to the life of the refractory lining. The lining is replaced during a shutdown of the BOF vessel.

Charging the Furnace

There are three primary steps involved with the basic oxygen process: charging the furnace, blowing, and tapping. A combina-

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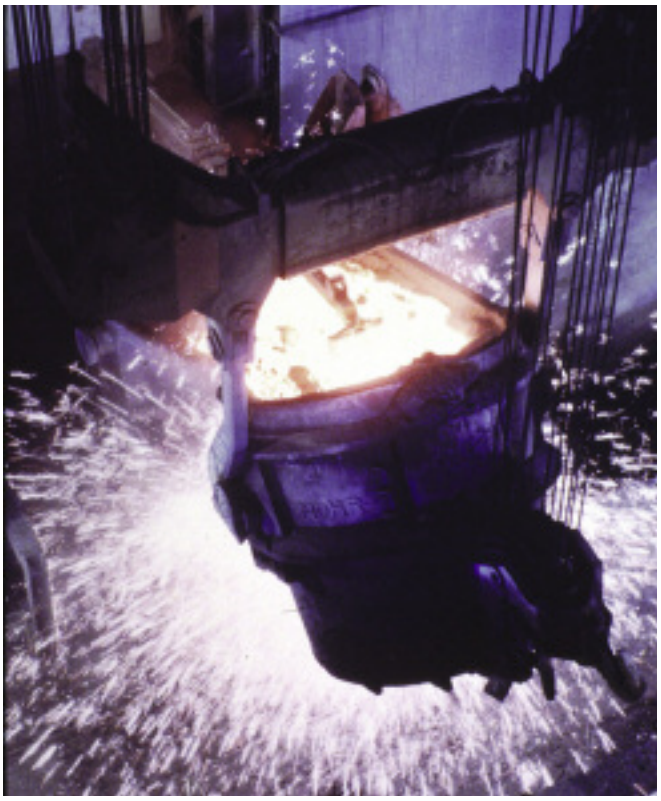

Fig. 2 — An overhead view of pig iron being charged in a BOF. This basic oxygen furnace is located in Gary, Ind.

tion of steel scrap, molten pig iron, and slag-forming ingredients are charged into the furnace. By utilizing scrap, several objectives are achieved. Recycling steel reduces raw material usage, reduces expenses, and has the added benefit of keeping the furnace cooler during blasting as heat is used to melt the solid metal. This is important to help minimize oxygen pickup at high temperatures. The use of scrap in the BOF makes the steel manufacturing industry one of the largest recyclers in the world.

To charge the furnace, it is tilted on its pinions at an angle. A charging box carries the scrap steel to the converter. The box is typically propelled on rails and may be hydraulically actuated for ease of operation. The scrap has previously been magnetically sorted and ground into predetermined sizes. This ensures thorough melting in the heat and minimizes additions of waste such as polycarbonates and nonferritic materials. Smaller pieces of scrap are placed in the front of the charging box; larger pieces are kept toward the back. The smaller pieces fall into the vessel first and help keep the larger, heavier pieces of scrap from damaging the refractory lining.

Molten pig iron is then charged into the furnace. Delivered in torpedo railcars, the molten pig iron is poured into a ladle. An overhead crane picks up the ladle and delivers it to the furnace. A blast may weigh in excess of 350 tons. The furnace is then tilted upright. The oxygen lance is lowered to a predetermined height and oxygen flow is commenced. Slag-forming compounds are added to the furnace after the blow has started — Fig. 1.

Fluxes, which form a slag blanket on top of the melt, are an integral part of the BOF process and are added to help facilitate removal of some elements. The flux may be burnt lime, silica, dolomite, or other elemental agents. Elements such as phosphorus cannot be removed from the molten steel through the reduction process but, instead, must combine with the fluxing agent and float to the top. Beneficial properties of a good flux are its ability to combine with unwanted elements and then keep those elements contained within the slag throughout the blow — Fig. 2.

Nowadays, computer control is an important part of the BOF process. Computers track the temperature and the amount of molten pig iron, scrap, and flux. This information will be processed to determine the approximate required heat input, blast time, and desired product alloy content. A typical blast runs from 45 to 65 minutes long. Sampling during the blast process ensures product quality and fine-tunes the addition of fluxes and alloying elements.

Blowing

There are several steps to the blowing process. With each consecutive blow, samples of the metal are taken and adjustments to the lance height and flux additions are made. The first blow is a violent event during which much agitation of the molten bath occurs. More than 20,000 ft^3/min of oxygen is utilized at high pressure. When the supersonic blast of oxygen is introduced over the top of the melt, a vigorous reaction occurs that is caused by the rapid assimilation of carbon by the oxygen. The resulting carbon monoxide bubbles out of the melt and rises out of the furnace. The exhaust from the process is sent through a series of scrubbers and environmental controls to meet regulatory requirements.

Oxygen is supplied to the furnace through an oxygen lance. The lance is liquid cooled and contains orifices that allow the oxygen to impinge upon the surface of the melt. It also may have smaller orifices to help prevent splashing metal from sticking to the lance that becomes "skulls." Cryogenic distillation typically is utilized to separate atmospheric gasses at plants on-site. Oxygen is piped to the furnace location where the final pressure is approximately 250 lb/$in.^2$. The oxygen must be of high purity (99.5% pure), and be vapor (condensation) and particulate free.

After the initial reaction occurs, the furnace settles down into a more stable routine. A change in the color of the flame indicates the melt has now reached the low carbon range. Agitation of the bath is still occurring, but not at as high a rate as previously. At this point, additions of alloying elements and fluxing agents may be made to fine-tune the process. Additionally, dissolved oxygen may be removed through the addition of silicon. Steel that has been deoxidized is referred to as "killed" steel.

Tapping the Furnace

After the oxygen blow is complete, the molten steel must be poured into a ladle that will transport the steel to the next step in the process. If the molten metal is to be used in the continuous casting process, the ladle will deliver the metal to a tundish. The tundish holds the metal and controls the speed of pour into the C-caster. A furnace that is not part of a continuous casting facility will pour steel into ingots. During tapping, additional alloying elements may be added to the stream.

The furnace is tilted and steel starts to flow out the tapping hole. The slag is kept away from the tapping hole as it floats on the molten steel. Any time molten metal is poured, care must be taken. Pouring too vigorously can entrap air in the steel that may be detrimental to the final product. Additionally, care must be taken to avoid slag from contaminating the steel. Toward the end of the tapping cycle, a vortex can form in the furnace and slag may be drawn into the ladle. Once poured into a continuous caster or into an ingot, the slag will be a permanent part of the final product.

Steelmaking and the Inspector

Now that we know how steel is made with the basic oxygen process, how do we relate it to the work we do as inspectors? As

inspectors and NDE technicians, understanding this steelmaking process will give us a better understanding of what inherent discontinuities are, where they originate, and how they may affect the end product for client use. For many applications, steel's inherent discontinuities may be acceptable; however, in other instances, the use of the material could result in a catastrophic event. Here we will discuss the inherent discontinuities associated with ingot casting. Discontinuities associated with the continuous casting process will be expanded upon in the fourth article in this series.

Inherent Discontinuities

In the United States prior to 1970, more than 90% of all steel was poured as ingots. Since 1970, a major shift has occurred. Now, more than 90% of all steel is produced through the continous casting process. Therefore, if you are performing inspections on steel used in infrastructure fabricated before 1970, it may contain inherent defects due to the ingot casting process. Although the two processes are drastically different, they have a shared problem: Once nonmetallic inclusions and slag enter the steel production stream, they will not be removed and inherent defects are the result.

Ingots can be poured after a heat is completed. The molten metal is poured into ingot molds. During this step, an inherent defect called "pipe" may occur. The pipe is concentrated at the top of the ingot. Differential cooling rates as well as the physics of solidifying metal create a shrinkage cavity. Entrapped air may become entrained in the solidified metal. The ingot first cools and solidifies against the walls of the ingot mold. Meanwhile, the interior of the ingot is still liquid. Dendritic growth occurs inward toward the center of the ingot, forming long columnar grains perpendicular to the mold wall. Entrapped gases in the liquid metal migrate upward toward the top of the ingot. If the journey is not completed, the gas will become pores. Mill scale, a product of the reaction between iron and oxygen, may form on and around any porous shapes and on the outside of the ingot. The "hot top" of the ingot is cut off to minimize the likelihood of inherent discontinuities. The top is recycled back through the BOF.

Once steel has solidified, inclusions will stay in the material throughout the finishing process. Hot rolling may close some small pores, but nonmetallic inclusions will not be removed. After primary processing, steel may be forged, cold formed, welded, or machined into a final product. Through the manufacturing process, discontinuities that were once below the surface of the steel may be made open to the surface. Once a discontinuity is open to the surface, techniques such as liquid penetrant (PT) or magnetic particle (MT) inspection may be used to detect these discontinuities.

Inclusions are particles of nonmetallic compounds left within the steel as a result of the ingot casting process. Nonmetallic inclusions are broken down into two subcategories depending on their origin. Exogenous inclusions originate outside the molten metal. Examples of an exogenous inclusion would be slag, refractory material from furnace linings and/or ladles, handling tools, etc. Indigenous inclusions are chemical compounds left over from the refining (removal) of unwanted elements in the heat. These are typically sulfides and oxides that are randomly scattered throughout the metal.

Slag entrapped in steel will create an area where there is no metallic bond. Upon hot or cold rolling, the slag will be pressed thinner and become elongated in the direction of rolling. This type of discontinuity is called a lamination. Laminations may be unacceptable for structural uses depending on the application intended for the steel. Many applications requiring tensile strength parallel with the direction of the long axis of the lamination may be acceptable. However, for applications where the primary stress is transverse to the long axis of the lamination, use of the steel may result in catastrophic consequences. In compression, the presence of a lamination may have virtually no effect on its application — Fig. 3.

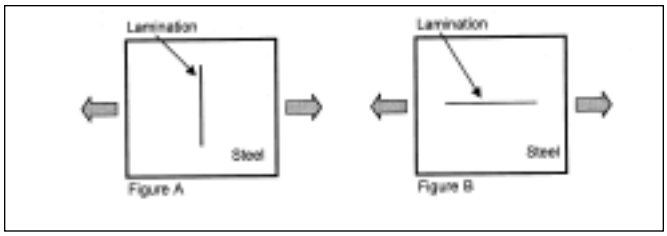

Fig. 3 — Types of laminations. A — Stress applied perpendicular to a lamination may cause delamination with possible catastrophic consequences; B — tensile stress applied parallel with a lamination may not be a problem for many applications.

Sulphides and oxides contained within the steel are rolled flat during the rolling process. Smaller in area, these inclusions form long thin lines often referred to as stringers. Both exogenous and indigenous inclusions will be parallel with the major surfaces of the steel in the direction of rolling. Ultrasonic inspection with longitudinal waves from the primary surface is an effective method to detect these types of discontinuities as the sound will be perpendicular to the major face of the discontinuity.

The American Society for Mechanical Engineers (ASME) *Boiler and Pressure Vessel Code* specifies that steel incorporated in pressure vessels be inspected by longitudinal ultrasonics to determine if lamellar inclusions are present. Most codes specify that an inspection using longitudinal (0 deg) ultrasonics be utilized to detect these lamellar discontinuities prior to a volumetric shear wave inspection. Presence of these discontinuities can reflect the shear wave and make areas of interest inaccessible to wave propagation. If lamellar discontinuities are detected, they are documented on the inspection report and alternative inspection techniques are sought to inspect the masked area.

Summary

The basic oxygen furnace is the workhorse that produces more steel than any other process in the world. Large volumes of quality steel may be made in a relatively short time frame. Although the process produces a high-quality product, inherent discontinuities may be introduced in the steel. Once entrapped in the solidified steel, these discontinuities are permanent and will stay entrained through roughing and finishing of the product. These discontinuities may be encountered by the inspector and NDE practitioner in the field.❖

Bibliography

1. ASME *Boiler and Pressure Vessel Code.* 2003 Addenda. New York, N.Y.: The American Society of Mechanical Engineers.

2. Cramb, A. 2003. *The Making, Shaping and Treating of Steel 11th Edition – Casting Volume.* Pittsburgh, Pa: The AISE Steel Foundation.

3. Dell, K. A. 1969. *Metallurgy Theory and Practice.* Homewood, Ill.: American Technical Publishers, Inc.

4. Freuhan, J. R. 1998. *The Making, Shaping and Treating of Steel 11th Edition — Steelmaking and Refining Volume.* Pittsburgh, Pa.: The AISE Steel Foundation.

5. Linnert, G. 1994. *Welding Metallurgy,* Vol. 1, Hilton Head Island, S.C.: GML Publications.

6. Neely, J. E. 2000. *Practical Metallurgy and Materials of Industry.* Upper Saddle River, N.J.: Prentice-Hall, Inc.