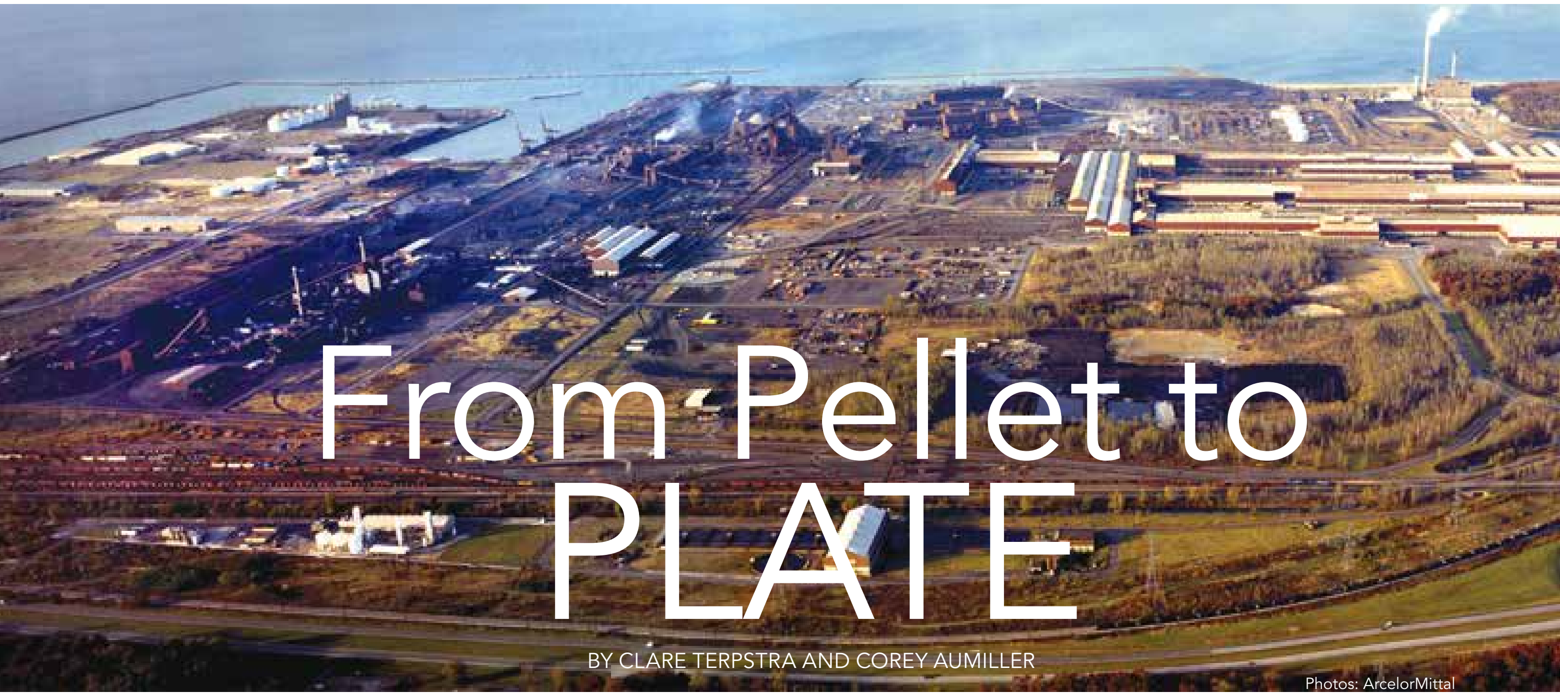
A step-by-step look at the production of flat steel.



From Pellet to PLATE

BY CLARE TERPSTRA AND COREY AUMILLER

Photos: ArcelorMittal

THE SMALL TOWN of Burns Harbor, Ind., has been home to one of the country's largest steel mills since 1964.

Originally built by Bethlehem Steel, the Burns Harbor mill is now owned by ArcelorMittal, the world's largest steel producer. At this fully integrated mill, one can witness the steelmaking process in its entirety: from pellets of iron ore to finished steel plates and sheets. What starts out as rock becomes the strongest ductile material per dollar used in construction.

While it may appear bulky and imprecise to the layperson, the steelmaking process is actually quite complex and fine-tuned, and the chemistry is carefully controlled to tight tolerances at every stage in the process—e.g., a difference of just 0.01% in sulfur content can ruin a 300-ton heat of steel.

It all starts with raw materials. The mill's location on Lake Michigan allows for easy shipping access, and raw material is constantly pouring in—as long as the water hasn't frozen over. (In fact, in 2014 the stockpiles were the lowest in recent memory due to the polar vortex having frozen shipping access for longer than usual.) The iron ore comes in the form of taconite pellets from ArcelorMittal's mines in Minnesota. Limestone comes pre-ground from Michigan and coal comes from West Virginia and Canada.

Clare Terpstra (terpstra@aisc.org) is an AISC engineering intern and engineering student at Northwestern University. **Corey Aumiller** (aumille2@illinois.edu) is a former AISC engineering intern and current engineering student at the University of Illinois at Urbana-Champaign.

From Coal to Coke

The first step that takes place at the mill is transforming coal into coke, a substance with fewer impurities and a higher carbon content than coal. The coke will be used in the production of iron in the blast furnace, both as fuel and as a reactant in breaking down the iron oxide.

The coal is ground, mixed and then baked in massive ovens. Burns Harbor has two batteries—each containing 82 ovens that are 20 ft high, 50 ft deep and 18 in. wide—that produce 25 tons of coke apiece. The ovens are heated by natural gas and reach up to nearly 2,300 °F. The absence of air during the baking process prevents the coal from burning and allows gases, as well as other impurities, to be removed from the coal and converted into electricity using boilers and turbines. After 18 hours of baking, the coal has become coke and has a carbon composition of about 90%. A waiting quench car receives the batch of hot coke and transports it to a cooling station where it will be quenched, or rapidly cooled, by 10,000 gallons of water. Once cooled, the coke is sorted by size for use in the blast furnace where it will serve as a major source of energy for the production of iron.

Getting Blasted

The blast furnaces are the massive structures that extract iron from iron ore. The plant has two furnaces, "C" and "D," which are 38 ft and 35 ft in diameter, respectively; both stand

▼ ArcelorMittal's Burns Harbor, Ind., facility can produce over 5 million tons of steel per year.

150 ft tall. The furnaces run 24/7 and are only interrupted for routine maintenance.

The production of iron starts with three main ingredients: iron ore, coke and limestone, all of which are carefully measured in order to ensure proper chemistry. Conveyer belts drop the ingredients into the top of the furnace where they slowly descend to the bottom over the course of six to eight hours. The blast furnace gets its name from the blasts of preheated air that are blown in from the bottom of the furnace via a series of pipes called tuyeres. The hot air reacts with the coke to produce carbon monoxide and heat. The carbon monoxide then helps to break down the iron ore into pure iron and carbon dioxide. The limestone acts as a flux and reacts with various impurities in the ore to form a byproduct called slag, which will be removed later. At the bottom of the furnace, a tap hole is covered by a refractory clay plug. Every four hours, the plug is drilled through to drain molten iron into submarine cars waiting below. The tap hole is then covered again with a new refractory plug.

After the molten iron—called pig iron at this point—is tapped from the blast furnace, it is almost ready to be converted to steel. The pig iron is first desulfurized by adding various fluxes in an iron transfer ladle before it is ready for the basic oxygen furnace (BOF). The carbon content in the pig iron is around 4%; to become steel it needs to be reduced to 0.04 to 1.5% carbon, depending on the grade. Burns Harbor operates two BOFs at a time, which can produce over 5 million tons of steel per year.

Meltdown

The BOF is a giant barrel-shaped container lined with 3 ft of refractory brick that can withstand tem-

▲ A batch of coke ready to be removed from a coke oven.

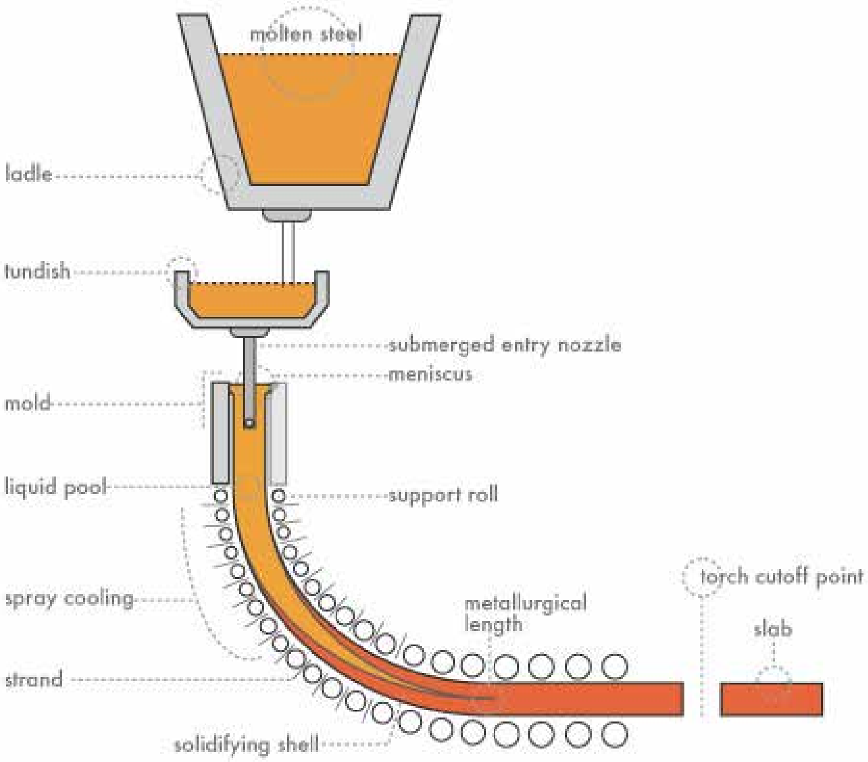
▼ A stockpile of coke.

▲ Removing slag from the ladle before it goes to the BOF.

▼ Charging the BOF with molten iron.

▲ Molten steel draining from a ladle into a tundish and then into a mold.

▼ A diagram of the continuous casting process.



peratures around 3,000 °F (the range needed to melt steel). Each "heat" is around 300 tons and takes an average of 50 minutes to produce. The process begins by tilting the BOF 45° and charging it—i.e., adding scrap steel and molten pig iron—and scrap usually accounts for around 25% of the charge. The BOF is then tilted upright, and lime and other fluxes are added from overhead while a water-cooled oxygen lance is lowered into the furnace. The lance then shoots out 99% pure oxygen at supersonic velocities for around 20 minutes; the time varies depending on the starting chemistry of the charge and the desired end composition. This oxidizes the carbon and other impurities in the pig iron, producing enough heat to melt the scrap. The waste product of these reactions forms slag, which floats on top of the more dense molten metal. Spectrographic chemical analysis is done at various stages in the process to determine if the desired chemistry has been met. (The lab at Burns Harbor performs these tests on lollipop-sized samples of steel and can get the results back to the process engineer within minutes.) Once the steel has reached the desired composition, it is tapped into a ladle in such a way that the layer of slag is kept separate and discarded elsewhere.

Once in the ladle, alloys (if needed) are added to the steel in a variety of solid forms, which gives the steel a variety of different properties for specific end uses. The hot metal mixture is stirred by pumping inert gas into the bottom of the ladle.

Casting Call

After the ladle metallurgy process is complete, the steel is ready to be cast. Burns Harbor has two continuous casters; one is a curved mold and the other is a straight mold. At the casting facility, the ladle is drained into a large bathtub-shaped container known as a tundish, which controls the flow of steel into the casters. The ladle is drained from the bottom through a tube made of refractory materials in order to protect the molten steel from contact with the air, which would cause oxides to form. Large open flames can be seen preheating these tubes in order to prepare them for contact with the molten steel.

The walls of the tundish are lined with refractory brick, but there is also what's known as refractory "furniture" at the bottom. These refractory blocks are arranged to prevent splashing of the liquid steel as it is poured and also controls flow from the tundish into the molds. The steel in the tundish is then distributed into the molds, also via tubes of refractory materials. The rectangular molds are made of water-cooled copper and are constantly oscillated to promote even distribution and to keep the steel from sticking to the walls. A powdered flux lines the walls of the molds (and also helps to prevent sticking). The heat transfer during this early stage of casting has many complex variables and usually requires computer modelling to ensure that the steel cools properly. The molten steel, now with a very thin shell, travels to the secondary cooling stage: a series of water-cooled rollers that thicken the shell on the steel while moving the slab from a vertical to a horizontal position. Roll layout is carefully designed to minimize stresses in the solidifying shell. The slab exits the caster, still radiating heat at a temperature of about 1,700 °F, around 40 to 50 minutes after it first enters the molds. This 10-in.-thick continuous slab is then cut to length using a flame cutter that moves along with the steel as it travels down the rollers. After the slabs are cut, the impurities that have formed on the surface of the slab during the casting process are scraped off, and the slabs are then moved into a stockyard and allowed to cool until it is time to roll them. The slabs are carefully labeled and tracked throughout their time at the mill so as not to mix up any orders.

When the slabs are ready to be made into plate, they are transported to the rolling facility where they will first need to be reheated in a furnace. Once a slab has been heated to 2,260 °F over about four hours, it is placed on a conveyor that carries it to a series of roll stands. Before the slab can be rolled, it passes through a scale breaker, which uses high-pressure water jets to remove the scale that has formed due to the high temperatures of the steel and the presence of oxygen. The slab will then enter the roughing mill, where it is rolled to width and then down to a desirable transfer thickness. The roughing mill also has additional descale sprays to remove any scale that remains. Each roughing mill stand consists of a pair of rolls above and below the plate—work rolls, which actually contact the steel, and backup rolls, which reinforce the work rolls in order to minimize roll deflection and thus control the crown and flatness of the plate. The slab thickness is reduced from 10 in. to between 2 in and 7 in., depending on the desired final thickness of the plate.

Reaching the Finishing Line

Next, the plates enter the finishing mill where they will be reduced to their final thickness. Like the roughing mill, the finishing mill also uses work rolls and backup rolls to flatten the steel. The final plate thickness ranges from 3⁄16 in. to 4 in. After rolling is complete, the plates are sent to the burning operation (if over 1.5 in. thick), where they will be burned to final size using oxyacetylene torches, or to the shears (if 1.5 in. or under) to be trimmed to width and length. Plates can also be heat treated (quench and temper or normalized) to improve their mechanical properties.

The final products are shipped to customers around the country. Burns Harbor's largest output by volume is automotive sheet, but it also produces a significant amount of plate for the construction industry—e.g., high-performance steel plate from Burns Harbor is being used in the construction of the new Tappan Zee Bridge in New York.

As with steel produced in an electric arc furnace (EAF), steel made via the BOF process can be continually recycled without a reduction in strength, including being remelted in an EAF to create new plate or wide-flange shapes.

Due to the use of scrap and other efficiency improvements, carbon dioxide emissions per ton of steel produced have been reduced by 60% over the last 50 years and these efforts continue today. The steel industry has committed itself to continually improving energy efficiency in the steel production process. In particular, ArcelorMittal has been reducing carbon dioxide emissions by capturing and reusing coke oven and blast furnace gas, and replacing some of the coke used in the blast furnace with cleaner natural gas, among other strategies. In 2013, ArcelorMittal joined the Department of Energy's Better Plants Program, which involves a pledge to reduce the company's energy intensity by 10% over the next 10 years. ■

BOF vs. EAF
To see the differences and similarities between the BOF process explained here and the EAF steelmaking process, see "Keep on Rolling" in the February 2014 issue (available at **www.modernsteel.com**).

▲ A pot of slag left over from casting a ladle of steel.

▼ Flame cutting the 10-in. slab of steel as it exits the caster.

▲ A slab being removed from the furnace immediately prior to rolling.

▼ Plate exiting the 110-in. mill.