Emerging Technologies for Iron and Steelmaking

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The iron and steel industry has undergone a technological revolution in the last 40 years. In a relatively short time, the North American industry has observed the complete disappearance of basic open hearth processing, as well as the wide spread adoption of continuous casting and the near complete shift of long product production to the electric arc furnace sector. These and other developments have dramatically affected the way steel is made, the price, quality and range of products generated, and changed the basic structure of the industry. The same trends can be observed in other industrialized nations and are reflected in the global industry as well. Competitive forces and market globalization will continue to drive the development and adoption of new iron and steelmaking technologies well into the 21st century. Industry response to specific local and global technology drivers will likely result in both incremental improvements in existing technologies, and in major developments in several key areas including direct iron making and near net shape casting.

INTRODUCTION

More than 3,000 years after the beginning of the Iron Age, modern iron and steelmakers still use the same carbothermic process discovered by early ironmakers. However, this industry continues to develop incremental and entirely novel technology improvements that are more efficient, more productive, and cheaper than existing processes to produce high quality ferrous alloys with a wide range of properties and end uses.

Modern ironmaking and steelmaking is extremely intensive in material and energy usage as well as in capital requirements. The industry is also faced with a wide range of environmental concerns that are fundamentally related to the high energy requirements, material usage, and the byproducts associated with producing more than 725 million tonnes of steel per year worldwide. A highly competitive steel market, due in part to rapid technological change and accelerating market globalization, requires the modern steelmaker to be sensitive to customer demands in terms of product properties, quality, price, and delivery. Although it is the product of an extraordinary array of high-tech processes, steel is a raw material in the modern economy and is at the front end of many complex manufacturing chains. As a result, the steel producer is very sensitive to a dynamic market with periods of economic boom and slowdown. However, the steel industry is bridled with high fixed capital costs and processes, which are constrained to high production rates by efficiencies and economies of scale. A highly competitive world steel market has, in turn, produced an environment where capital resources are short and the cost of failed technological ventures dear. Therefore, the risk associated with being a technology leader is very high. In spite of this, the last 30 years have shown several times over that the technology of steelmaking can change rapidly on a global scale. The risk associated with being a technology follower can also prove to be painful.

The Sloan Steel Industry Study, conducted by Carnegie Mellon University[2], identified four main technology drivers for the steel industry: high capital costs, raw materials shortages, environmental concerns, and customer demands.

The American Iron and Steel Institute (AISI) combined the Carnegie Mellon study and input from a large number of industry experts to develop a technology roadmap,[3] a guide for future R&D efforts in North America. The AISI Roadmap is intended to focus attention on clear research needs of the industry. Although some of the technology needs and drivers identified in the AISI roadmap are specific to the North American industry, many of the identified research areas are the focus of worldwide research efforts and reflect universal technology needs for the industry.[4–6]

RECENT TECHNOLOGY ADVANCES

The blast furnace, in various forms, has remained the workhorse of worldwide virgin iron production for more than 200 years, producing carbon-saturated "hot metal" for subsequent processing by steelmaking processes. However, the modern blast furnace has advanced a long way from its earlier ancestors. Most modern large-capacity blast furnaces represent extremely efficient chemical reactors, capable of stable operation with an impressive range of reactant feed materials. The injection of pulverized coal, natural gas, oil, and, in some cases, recycled plastics to replace a portion of the metallurgical coke used as the primary reductant and source of chemical energy represents an important development in the process. Coke is produced by baking coal in the absence of oxygen to remove the volatile hydrocarbons contained in coal. The resulting coke is mechanically strong, porous, and chemically reactive, which are all critical properties for stable blast furnace operation. In addition to supplying carbon for heat and the reduction of iron ore, coke must also physically support the burden in the blast furnace shaft and remain permeable to the hot air blast entering from the bottom. Coke-making is extremely problematic from an environmental perspective, as many of the hydrocarbons driven off during the coking process are hazardous. Also, not all types of coal are suitable for the production of coke. Recently, demand has decreased for the byproducts from coke-making for secondary processing into chemical products.[3] In developed countries, aging coking facilities and tightening environmental control have made coke-making an economic liability. Therefore, decreasing both the coke rate and the overall fuel rate of the blast furnace has been a major focus of recent developments. Figure 1 shows the evolution of blast furnace consumption of reductants in France in the last 30 years.

Similar trends can be observed in most developed countries. However, the relative proportions of coal, natural gas, and oil usage are dependant on several factors. These factors include local availability, fuel price, and the capital requirements of the injection equipment. Figure 2 shows the coke and coal consumption rates per ton of hot metal in Europe, Japan, and the United States. At high coal injection rates, partially combusted coal char builds up in the area near the injector. This can lead to reduced gas permeability and currently sets the practical limit for coal injection. Extensive experimentation in the United States and elsewhere has found an optimum combination of fuels that allows for stable operation at low coke rates.

Such an optimum fuel mix might include, per ton metal: metallurgical coke, 230 kg; nut coke, 40 kg; injected coal, 180 kg; and injected natural gas, 50 kg.

Improvements in process control and reduced refractory wear have increased blast furnace campaign life significantly, which is critical to the economics of the process. The current expected lifetime of newly rebuilt furnaces is 20 years or greater. Improved process control, burden design, regular maintenance, and reduction of unscheduled shut-downs has had a dramatic effect on the productivity of blast furnace operations.[4–7] Many steel companies have shut down older furnaces while maintaining or increasing hot-metal production by increasing the productivity of newer furnaces.

In the past 5 to 10 years, there has been a rapid increase in the production of iron via direct reduction processes. This new production has been dominated by the gas-based Midrex and Hyl processes, although several new plants based on other processes have begun production. This additional world wide ironmaking capacity has primarily served the electric arc furnace industry, providing an alternative to high quality and expensive scrap as a source of clean, low residual iron units.

In the last 40 years, the basic open-hearth process has been almost completely replaced worldwide by various top, bottom, or combination blown basic oxygen steelmaking (OSM) processes.[1] Since the adoption of basic oxygen steelmaking, continuous incremental improvements on the various forms of the process have improved the productivity and efficiency of oxygen steelmaking vessels. Development efforts have included experimentation with various combination top and bottom blowing configurations, natural gas shielding of bottom oxygen tuyeres, bottom stirring, top lance design, post combustion, slag formation control, process monitoring and control, and refractory design. A recent, important development in oxygen steelmaking has been the adoption of slag-splashing practices to increase furnace lining campaigns to more than 20,000 heats.[3,8]

The abandonment of open-hearth steelmaking practices for oxygen steelmaking was accompanied by a parallel widespread departure from ingot casting and slabbing practices to the continuous casting of steel. The increases in productivity and yield associated with continuous casting have had a dramatic effect on the steel industry worldwide. From the mid- to late 1960s to present, the amount of continuously cast steel as a percentage of total steel production has risen from essentially 0% to more than 90% in most countries. Most of that change occurred in the relatively short period from 1970 to 1990.[9] Critical research regarding the fundamentals of solidification, defect formation and modification, fluid flow in the continuous-caster mold and developing steel shell, refractory interactions, and mold flux design have led to improvements in the control and reliability of continuous-casting processes. In North America, this knowledge base was developed through the research efforts of individual steel companies and through significant contributions by such universities as Carnegie Mellon University, the Massachusetts Institute of Technology (MIT), The University of British Columbia, The University of Illinois, and others.

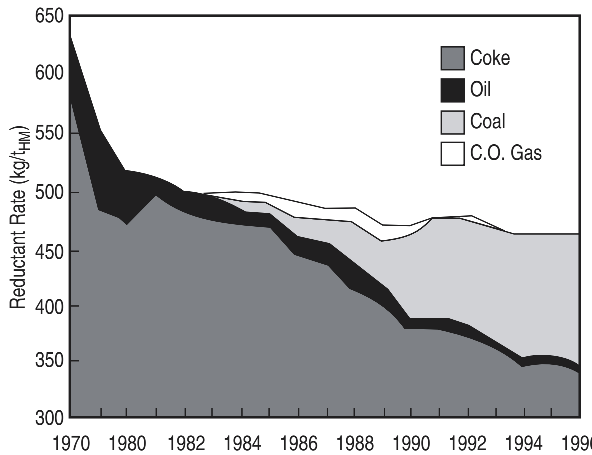

Figure 1.The average consumption of reductants in blast furnaces in France. Adapted from Steiler.[7]

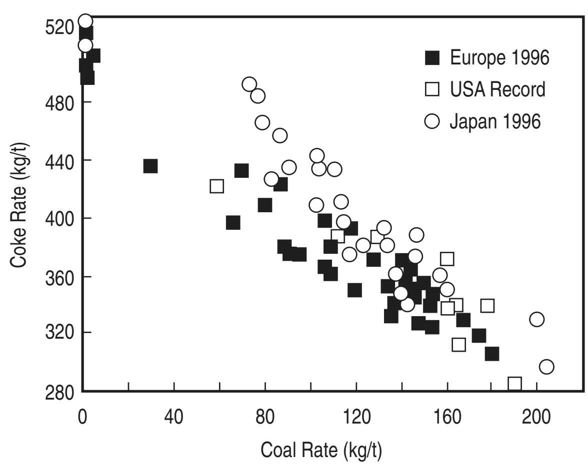

Figure 2. The coke and coal rates by region (average for Europe and Japan; record performance values for the United States). Adapted from Steiler.[7]

Because oxygen steelmaking processes melt less scrap than open-hearth steelmaking, the adoption of oxygen steelmaking in developed countries was associated with a decrease in the price of scrap steel.[1] This increase in scrap availability and decrease in price created an opportunity for growth of scrap-based steelmaking. With lower capital costs than an integrated mill, minimills based upon electric-arc furnace melting (EAF) of scrap were able to establish a cost advantage for the production of certain steel products. Figure 3 shows the proportion of crude steel production by process in the United States over the last 50 years.

The development of ultra-high-powered electric-arc furnaces and reliable billet and bloom continuous-casting machines provided a low-cost route for the production of lower quality steel long products, such as reinforcing bar and structural steels. As a result, integrated steel producers have been completely displaced from this low-end segment of the steel market in developed countries. This has allowed integrated producers to focus on the production of high-quality plate and thin-gauge flat products. The quality of steels produced via EAF is restrained by the level of metallic residuals such as copper, nickel, and tin, in the scrap metal charge and dissolved gasses such as hydrogen and nitrogen, which are contained in the scrap and picked up during processing. At very low levels these contaminants can significantly degrade the physical properties of many steel grades. However, continuous improvements in EAF process control and the use of ore-based scrap substitute materials such as direct reduced iron, hot briquetted iron, and pig iron to dilute tramp elements in scrap, have significantly increased the product quality range. Improved chemistry control and the successful implementation of thin-slab casting by Nucor has demonstrated that EAF producers can also be competitive in producing quality flat products as well. The continued expansion of EAF steelmaking for the production of higher quality steel products is projected to continue.[10] However, this expansion will require continued technological development of the basic process of electric furnace steelmaking.

In the last 30 years, a number of major technical modifications of the electric arc furnace have dramatically improved the efficiency and productivity of the process. Up to the present, the primary focus of electric furnace development has been to increase productivity and energy efficiency by decreasing tap-to-tap time. Large heat losses occur while the scrap pile or liquid steel is at high temperature. Greater energy efficiency is achieved when the rate of energy input is increased and the time at temperature is decreased. As a result, many of the developments in EAF steelmaking have focused on increasing the net energy density that the furnace is capable of delivering.[1] The development of foamy slag practices, whereby the hot electrode(s) and plasma arc are enveloped in foamed steelmaking slag, has significantly improved EAF performance. This practice protects the furnace roof and side walls from radiation and excessive heating, helps to stabilize the arc, and increases heat transfer to the steel, thus allowing furnace operators to run at much higher rates of power input.

Most modern electric furnaces also use a combination of oxy-fuel burners, pulverized coal injection, and oxygen injection to supplement electrical energy input. For modern EAF operations, 35% of the energy input is in from chemical energy sources.[3] Recently, additional chemical energy has been recovered via post-combustion of reducing product gases by the controlled injection of additional oxygen into the furnace above the slag. In the most modern furnaces, oxygen injected to combust pulverized coal injection and carbon charged into the furnace in scrap steel, direct reduced iron, pig iron, coke or coal can be as high as 40 Nm3/ton. For furnaces with post-combustion systems, the oxygen usage may be as high as 70 Nm3/ton.[1] At these very high rates of oxygen usage, significant additional heat energy is released by the exothermic oxidation of iron at high temperature. The additional heat input is gained at the expense of yield, due to the loss of iron as iron oxide in the slag. As a result, slag chemistry control and yield will become a focus of future developments in process control. Figure 4 shows the progress of EAF steelmaking in the last 30 years with respect to several key performance indicators.

The large quantities of hot combustion product gasses generated in the modern EAF have led to the development of several novel scrap preheating systems, whereby the heat energy of the exhaust gas is used to preheat scrap prior to melting. Between 10–30 percent of the energy input into an EAF can leave the furnace with the hot exhaust gas. Theoretically, 10 kWhr/ton of energy can be saved for every ~50°C of preheating of the scrap charge.[2] In practice, capture of the heat from furnace exhaust gas has been problematic, primarily due to emissions control complications. Until recently, relatively low energy prices have made the economics of scrap preheating marginal, particularly in cases where the efficient heat transfer could not be achieved. The Fuchs shaft furnace, the Consteel process, and the Nippon Steel/Davy-Clecim twin shell electric arc furnace concept are some examples of scrap preheating systems that are currently in commercial use. Several processes are under development that allow for continuous preheating, feeding, and melting of scrap.[1]

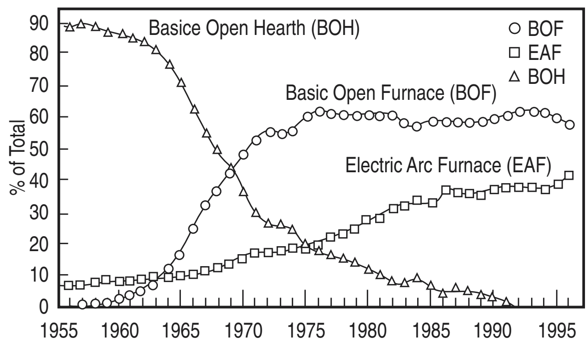

Figure 3. Evolution of steel by process from 1955 to 1996. Adapted from Fruehan.[1] (Original source: International Iron and Steel Institute.)

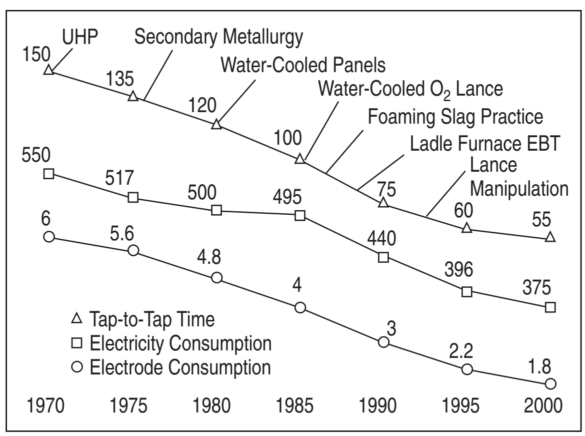

Figure 4. Evolution of EAF performance from 1970 to 2000. (Source: *AISI Technology Roadmap*.)[2]

NEW TECHNOLOGIES FOR IRON AND STEELMAKING

Worldwide, direct-reduction capacity via existing gas-based technologies is likely to increase in order to support the expansion of EAF steelmaking to new, high-quality products. However, the blast furnace is likely to remain the backbone of worldwide iron production for several decades. Current fluidized bed and shaft furnace direct-reduction processes rely on natural gas as the primary reductant and source of heat for the reaction. One exception is the hydrogen-based Circored process. In regions where an abundant and inexpensive source of natural gas (or hydrogen) exists, gas-based direct reduction of iron followed by melting in an EAF can provide a cost-competitive alternative to quality steel products. However, in areas where low cost natural gas is not available, coal-based iron reduction processes will have an advantage. The efficiency and productivity of modern large-capacity blast furnaces will be difficult to surpass. However, high capital requirements make it unlikely that any new blast furnaces will be built in developed countries in the near future. Nevertheless, the shutdown of aging coking operations and older, smaller blast furnaces will force the industry to pursue one or a combination of three options:

- Stretch remaining hot metal supply with increased scrap melting in new steelmaking processes
- Increase the productivity of remaining large capacity furnaces
- Adopt or develop an entirely new process(es) for the production of hot metal or steel to complement or replace the blast furnace

There are several methods by which a limited supply of hot metal could be stretched by increasing scrap utilization. Process optimization of current oxygen steelmaking technologies will result in small improvements in yield by reducing both the iron content and total volume of slag produced. Scrap preheating and improved post combustion in conventional oxygen steelmaking vessels could be used to increase the scrap usage in these processes. Entirely new oxygen steelmaking furnace designs have been proposed, such as the energy optimizing furnace,[11] which makes use of high rates of post combustion, additional fossil fuel additions, and elaborate scrap preheating to increase scrap melting to as high as 70% during hot metal refining. Alternatively, direct hot metal addition and increased oxygen usage in a conventional EAF can dramatically decrease the electrical energy requirements per tonne of steel. The latter option allows the steelmaker to produce steel using anywhere from 20% to 100% scrap, producing the entire range of steel qualities with respect to residual content. Such a hybrid EAF-OSM process offers flexibility using proven and well-understood processes.

One limitation of stretching hot metal through significantly increased scrap utilization is related to the control of residual elements. As mentioned earlier, the quality of steels that can be produced via conventional EAF steelmaking is currently limited by control of residual metallic tramp elements in scrap and dissolved gasses. If scrap is used in increasing quantities for the production of all steels, levels of residual elements can be expected to rise in the entire scrap supply. One solution to this dilemma is an economical process by which residual tramp elements can be removed from scrap, thus upgrading the scrap quality. Several processes have been demonstrated on laboratory and pilot scales[12–17] that have been successful in removing certain tramp elements. However, in each case, unfavorable economics have prevented widespread implementation.

One alternative to removing metallic tramp elements is to reduce their deleterious effects on steel properties. Most metallic residuals reduce steel hot strength and hot and cold ductility by segregating to and weakening grain boundaries. Tolerance to such chemical impurities could be improved through the design of alloys in which these elements were tied up in heterogeneously nucleating second-phase particles, which might not have the same negative effect on steel properties. Also, new near net shape casting processes, which will be described in following sections, may dramatically reduce the overall effect of residual elements for two reasons. As its name implies, near net shape casting describes solidification processes by which steel is cast in dimensions near to the specifications of the final product. Although hot reduction at some level may still be required for microstructure control, near net shape casting significantly reduces the dimensional forming requirements of hot reduction processes and may reduce problems such as hot tearing. Even more importantly, near net shape casting processes for the production of thin gauge steel involve much higher rates of heat removal, solidification, and cooling than conventional casting or thin-slab casting processes. As a result, microstructural evolution in strip cast materials is fundamentally different from conventionally processed materials. Macro-segregation in strip-cast steel is significantly suppressed. This has significant implications for the future of residual element control in steelmaking.

Industry leaders continue to demonstrate the significant potential for increased productivity of the blast furnace.[18] Figure 5 shows the production rate at AK Steel's Middletown No. 3 blast furnace over a ten-year period.

For blast furnace production to continue into the future even at current levels in the United States and other developed countries, continued progress must be made on reducing the coke rate of furnaces through coal injection. Significant progress has been made in evaluating the benefits of oxygen enrichment of the hot blast. Industrial trials are in progress to evaluate an oxy-coal injection system, which promises to allow for complete combustion at elevated coal injection rates.[19] New, environmentally acceptable and economically feasible processes for new or replacement coke production capacity should be evaluated. In addition, if less coke is to be used in the blast furnace, the mechanical property requirements of the coke that is used will become more critical to maintaining permeability and stable furnace operation.

NEW TECHNOLOGIES FOR HOT METAL PRODUCTION

Several new processes for producing hot metal are in various stages of development around the world. Several processes based upon the direct reaction of coal and iron ore in a rotary kiln, such as the SL/RN process, have reached various stages of development since the 1960s.[20] Due to the high gangue and low specific productivity of these processes, they have not received a great deal of attention for commercial production. Several processes are currently commercially available that use a rotary hearth furnace to reduce composite pellets containing both iron-oxide fines from ore or wastes and carbon from coal, coke, wood char, or mill wastes. Due to the intimate contact between the carbon and iron oxide in the composite pellets, iron reduction is very fast at elevated temperatures. The off gasses from the reduction reaction and/or coal devolatization can be post combusted in the rotary hearth chamber to provide a significant portion of the heat required for the process. Midrex is currently marketing a rotary-hearth-based process, Fastmet, for recycling mill waste oxides.[21] Two commercial Fastmet units have been installed at Kobe Steel and Nippon Steel, both in Japan. Iron Dynamics, a subsidiary of Steel Dynamics, currently operates a rotary hearth furnace to produce 85 percent reduced iron pellets. Those pellets are subsequently melted in a submerged arc furnace to produce hot metal for use in a nearby Steel Dynamics EAF shop. The Iron Dynamics rotary hearth-submerged arc process uses proven technologies to produce liquid iron at a reasonable cost for use in the EAF.[22] However, the total energy efficiency of this process is not very high as compared with the blast furnace or other new coal-based technologies.

Several new technologies take advantage of the rapid-reaction kinetics and high specific productivity of smelting

NOVEL PROCESSES FOR IRON PRODUCTION

As the supply of coke becomes more critical, smaller blast furnaces are closed down, and additional hot metal capacity is needed, an opportunity exists to develop an entirely new process that better fits the needs of contemporary and future steelmakers. The characteristics of a new, ideal process for increased iron unit production should include the following:

- Very high efficiency with respect to energy and materials usage—A new technology will be replacing conventional reactors, which are extremely efficient at present and will only continue to improve in the near future
- Greater flexibility in feed materials—Dependency of the modern blast furnace on coke is the greatest weakness of the process. Any process that could use coal directly would have an enormous advantage over the blast furnace. In addition, the direct use of fine or lump iron ore and/or waste iron oxides without agglomeration would further reduce capital costs as compared with conventional processes.
- Reduced capital costs—Due to efficiencies of scale, which are inherent to the process, high-efficiency, high-productivity blast furnaces represent a daunting capital investment for most individual steel companies without state subsidization. A process that could be operated on a smaller unit scale without compromising efficiency would greatly reduce the capital requirements for adding new ironmaking capacity. Also, as mentioned above, a process that could use coal and unprepared ore directly would eliminate the additional capital requirements of coke making and pelletizing/sinter plants. As was discussed previously, the direct use of hot metal in the EAF as a scrap substitute offers the advantage of excellent process flexibility in terms of electrical versus chemical energy usage and in product quality. The combination of a new technology for small-scale hot metal production with the EAF minimill concept could offer a new route to high quality steel products with very favorable economics.
- Operational flexibility—Although recent advances in blast furnace productivity exhibit that the process can be operated at a range of production rates, even greater flexibility would be advantageous. The economics of steelmaking are very sensitive to the cycles of economic boom and slowdown. Therefore, an ideal process would be capable of operating at a range of production rates without compromising efficiency or the economics of the process. Because the production costs associated with a new process will not vary significantly from those of conventional processes, the economics of the overall process are largely tied to the capital costs of the process. Provided production costs do not increase dramatically, a process with lower capital costs can be operated at lower production rates while maintaining profitability.
- Capability of producing steel or low carbon iron directly—The highly reducing environment of the blast furnace produces "hot metal" or carbon saturated iron (~5 wt.% C). However, most steel products have a carbon content of less than 1 wt.% C. During oxygen steelmaking, most of the carbon is removed via reaction with injected oxygen to form carbon monoxide. This practice has evolved over centuries as a result of the extreme difficulty in controlling the reduction of iron ore to low-carbon iron in a highly productive and cost-effective process. Using modern monitoring and control technologies and expanded fundamental knowledge of reaction thermodynamics and kinetics, a new process capable of producing steel or low-carbon iron in a single continuous reactor might be possible. By this process, the conventional unit processes of the coke plant, sinter or pelletizing plant, blast furnace, and oxygen steelmaking furnace could be replaced by a single reactor.

reactors to accomplish at least part of the reduction of agglomerated, lump, or fine iron ore using coal directly. Coal devolatization and gasification also occurs in the smelter reactor. Volatile hydrocarbon compounds make up 10–15 percent of low-volatile coals and 40–45 percent of high-volatile coals.[23] In theory, the high-temperature removal and controlled combustion and/or reaction of these compounds to CO/CO_2 and H_2/H_2O alleviates some of the environmental problems associated with conventional coke making.

The Corex process,[24] commercialized by Voest Alpine, combines an iron melter/coal gasifier vessel with a pre-reduction shaft to produce a liquid product that is very similar to blast furnace hot metal. Coal, oxygen, and pre-reduced iron are fed into the melter/gasifier to melt the iron and produce a highly reducing off-gas. The primarily $CO\text{-}H_2$ off-gas is then fed through a pre-reduction shaft furnace, where lump and/or agglomerated ore is reduced to over 90 percent for feeding into the melter/gasifier. The gas exiting the pre-reduction shaft still has a very high energy content, which can be used elsewhere in the steel plant or for electric power generation. Voest Alpine and POSCO jointly continued to develop the original commercialized process, leading to several important modifications including the limited direct reduction and smelting of ore fines[25]. If the high energy content of the exhaust gas from the reduction shaft is not utilized, the Corex process requires a relatively high fuel rate as compared with a blast furnace. Although Corex has a relatively high capital cost[23], it is so far the only smelting process to be operated on a commercial scale. The first commercial Corex plant with a capacity of 300,000 tonnes per year began production in 1989. Other installations are operating, under construction, or planned in Korea, South Africa, and India.

In the HIsmelt process, iron reduction and coal gasification take place in a liquid metal bath. The fundamental processes of HIsmelt began with early experiments in Germany with bottom-blown oxygen steelmaking converters (LD, LD-AC, KMS, among others) to allow for coal, lime, and/or iron ore injection through the bottom nozzles.[26] Experiments with combination blown oxygen converters serendipitously discovered that simultaneous bottom oxygen blowing and soft or low velocity top oxygen blowing resulted in post combustion of the decarborization product gases in the area above the bath. High heat transfer rates from the hot post combusted gasses to the metal bath were achieved via heat transfer to metal droplets ejected into the gas above the bath, which then fell back into the molten pool. Bottom injection of coal augmented this post-combustion phenomenon and allowed for significantly increased scrap melting (100% in the KS process) or smelt reduction of iron ore. Early experiments by Klöckner Werke and CRA (now Rio Tinto) with smelt reduction via simultaneous bottom injection of coke and ore

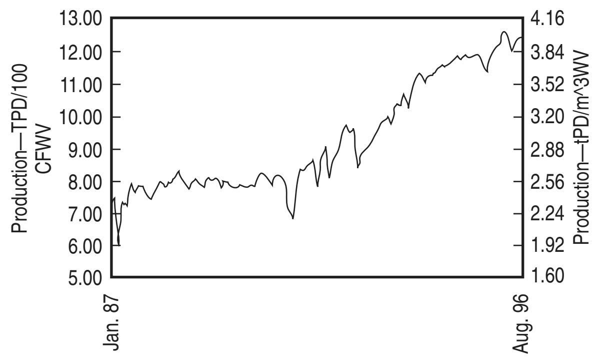

Figure 5. Productivity at AK Steel's Midland No. 3 blast furnace from June 1987 to August 1996. Adapted from Rabold and Hiernaux.[18]

into a KMS converter indicated that the reduction reaction kinetics were extremely fast and that the iron reduction, coal gasification, and post combustion reactions could be predicted and controlled. A small-scale test facility was built in Germany in 1984 to produce hot metal.

In 1989, CRA and Midrex formed a joint venture to build a demonstration plant in Western Australia to further develop the HIsmelt process. Since that time, the process has been significantly modified, simplified, and improved, allowing for extended continuous operation and very high specific productivity performance. The extensive pilot scale testing in Australia resolved many of the technical problems, such as refractory wear, post-combustion control, and slag-foaming control, which limit the stable operation of all bath smelting processes.[27] One unique feature of HIsmelt is that all reactants are injected through submerged lances. Pilot scale testing data indicate that this results in much better coal utilization than with top-charged processes. Like Corex, HIsmelt produces a hot exhaust gas with significant thermal and chemical energy content, which can be used for pre-reduction and preheating of the iron feed or on-site power generation. A production-scale demonstration HIsmelt plant producing around 600,000 tonnes per year is planned for Kwinana, Western Australia.

Simultaneous independent development of the direct iron ore smelting (DIOS) process in Japan[28–30] and the AISI direct steelmaking process in North America[31,23] produced two similar routes to hot metal production. Both processes utilize a smelting reactor where the primary reactions occur in a deep slag bath as opposed to in the metal phase as in HIsmelt. Pre-reduced iron ore, coal, and oxygen are injected into a deep steelmaking slag. The coal is devolatilized and partially combusted to CO. The uncombusted coal char either directly reacts with iron oxide dissolved in the slag to form iron and carbon monoxide or dissolves in the iron bath. Dissolved carbon in the metal also reacts with iron oxide in the slag to form iron and carbon monoxide. Stirring gas injected through the bottom of the reactor and gas evolved within the slag and at the slag-metal interface result in foaming of the slag and energetic mixing and intermixing of the slag and metal phases. Secondary low-velocity oxygen is injected either above or into the top portion of the slag layer to partially post-combust the CO and H_2 produced by coal devolatilization, combustion, and iron-oxide reduction reactions. The thick slag layer separates the iron-carbon melt and char from the oxidizing post-combustion products, providing a medium for heat transfer. The exiting gas is then used to preheat and pre-reduce the iron ore feed materials. The DIOS process uses a series of fluidized bed reactors for preheating and pre-reduction of iron ore fines. The AISI process uses a Hyl or Midrex type shaft furnace for pre-reduction and must use primarily lump or agglomerated ore as its feed material. In these smelter reactors, post combustion provides approximately 60% of the required energy. Pilot-scale plants of both the DIOS and AISI smelter processes have been built and operated using a variety of feed materials, including low and high volatile coals, different types of ore, and steel mill waste-oxide materials. The AISI smelter has been evaluated as a potential method for the recycling of high iron content steel mill waste oxides. No commercial production facilities are currently planned for these two processes.

Several additional combinations of smelting reactors and pre-reduction reactors are also under consideration. The cyclone converter furnace (CCF), developed initially by Hoogovens Staal BV, has been considered for use in combination with the bath smelting reactors described previously.[23]

The Center for Iron and Steel-making Research at Carnegie Mellon University is currently conducting a study, partially sponsored by the U.S. Department of Energy, regarding the use of biomass energy sources for hot-metal production.[32] The scheme that is currently being evaluated uses a rotary hearth furnace to heat and partially reduce composite pellets of iron ore fines and wood char. These pellets are then fed into an AISI smelter or DIOS-type reactor, where the final reduction and melting occurs. The off-gas from the smelter would be fed back to the rotary hearth to provide a portion of the energy requirement of that reactor.

DIRECT STEELMAKING

A process which could produce steel or low carbon iron directly and continuously would be a revolutionary development in ferrous process metallurgy. The AISI direct steelmaking project evaluated a continuous refining process for the conversion of hot metal as from a bath smelter to steel.[10] Final decarborization occurs in the second reactor. It was found that the slow kinetics of the final oxidation of carbon from iron at low concentrations resulted in excessive oxidation of the iron and related control and containment complications. IRSID had developed a unique design for a continuous steelmaking reactor, which has been tested on a demonstration scale.[10] The IRSID continuous-steelmaking process decarborizes hot metal in a slag-metal emulsion, which results when oxygen is impinged upon the entering hot metal. Due to the violent stirring and large metal droplet surface area present in the emulsion, mass transfer rates in the IRSID reactor are predicted to be 3.3 to 5 times higher as compared with a BOF. However, the violent nature of this reactor may also result in rapid refractory wear and containment problems.

The IFCON process, developed by ISCOR in South Africa, is capable of producing steel directly from coal and iron ore.[1] In this process, coal and ore are added continuously to a channel type induction furnace containing a slag-metal bath. Electrical energy is supplied by the induction furnace for heating and stirring the bath. Oxygen is added for post combustion of hydrogen and carbon monoxide released from the iron reduction reaction and the coal. Although the claims of this process are revolutionary, few details regarding the process or test results have been reported.

DIRECT IRON AND STEELMAKING CHALLENGES

Because the new iron and steelmaking technologies described previously share some common attributes, they also share some common technical challenges.[33] For example, technologies that use coal directly will have to deal with higher levels of sulfur than the blast furnace. Coal contains both volatile organic sulfur and mineral sulfur as FeS. During coke making and initial coal pyrolisis in smelting reactors, the organic sulfur is driven off primarily as H_2S. In the blast furnace and smelter reactors, mineral FeS dissolves in the slag and a portion is transferred to the metal. In coke making, the volatile organic sulfur is captured and processed. During smelting, the H_2S will exit with the exhaust gas, where it will likely react with CaO and FeO dusts to form CaS and FeS. Subsequent dust recycling will result in dissolution of these phases in the slag and eventual transfer to the metal. In addition, higher FeO levels in bath smelting slags as compared with the blast furnace will also promote higher sulfur transfer from the slag to the metal phase. As a result, highly efficient hot metal desulfurization practices will be necessary when using bath smelter metal to produce high quality steel products. Fundamental research at Carnegie Mellon University regarding the kinetics of sulfur transfer resulted in the development of a kinetic model that can be used to predict and control sulfur in smelter metal.[34]

New iron-making processes that use coal directly will generate a large volume of carbon monoxide, hydrogen, and hydrocarbons, which must be utilized to avoid condensation of complex and hazardous hydrocarbon compounds and improve the energy efficiency of the processes. Most new technologies under investigation use some form of post combustion to supply a large amount of the energy required for the endothermic reduction of iron oxide. The post-combustion degree (PC) can be measured as the proportion of the combustion products and reactants in the off gas of the reactor.

$$PC = \frac{CO_2 + H_2O}{CO_2 + H_2O + CO + H_2}$$

In conventional reactors such as the BOF and EAF, additional oxygen injected at low velocity above the slag-metal bath combusts CO and H_2 to CO_2 and H_2O, releasing a large amount of heat energy. However, the oxidizing product gasses must be shielded from the metallic iron and carbon in the metal and char to prevent de-post-combustion reactions, namely:

$$CO_2 + C \rightarrow 2CO$$

$$CO_2 + Fe \rightarrow FeO + CO$$

$$H_2O + C \rightarrow H_2 + CO_2$$

$$H_2O + Fe \rightarrow FeO + H_2$$

These reverse reactions can make it very difficult to attain high degrees of post combustion when the hot metal and post combustion gasses are in intimate contact. At the same time, the intended goal of post combustion is to transfer the heat generated by the combustion reactions downward to the slag and metal. Poor heat-transfer efficiency (HTE) to the slag and metal can result in an unacceptable increase in thermal load imposed on the vessel roof and sidewalls and the gas handling system. In bath-smelting reactors, the iron reduction and coal pyrolisis reactions are endothermic, thus heat transfer to the site of the reactions can be a rate-limiting factor for the process. In addition, special care must be taken when designing the gas handling system for bath-smelting reactors. The large volumes of hot gas produced and high particulate content of the gas can easily overwhelm an insufficient system. The HIsmelt process uses preheated air instead of oxygen for post combustion.[26] The post-combustion products are diluted by the nitrogen content of the air, allowing for simultaneous high post-combustion degrees and high heat-transfer efficiency. This also increases the total volume of gas exiting the vessel. In the DIOS and AISI smelter reactors, submerged post combustion, or post combustion in the top portion of the deep slag layer using submerged oxygen injection, was investigated.[33] Combustion within the slag layer should result in high heat-transfer efficiencies from the post combustion reactions to the slag and, subsequently, to the metal. If the post combustion is limited to only the top portion if the slag bath, the metal droplets and char should be shielded from the oxidizing product gasses by the thick slag layer. Both the potential benefits and limitations of post combustion were studied extensively for each of the bath-smelting processes described above. Experience gained from the continued development of post combustion systems for conventional reactors will aid in the design of future post-combustion systems for bath-smelting reactors.

Steelmaking slags tend to foam when gas is passed through them. In the deep slag-melting processes such as DIOS and the AISI smelter, a highly stirred, foamy slag forms the medium in which the iron reduction and coal pyrolisis reactions take place. A large amount of gas is passed through or generated within the thick slag layer due to bottom stirring gas injection and the in situ production of carbon monoxide and hydrogen from the reduction, pyrolisis, and combustion reactions. The control of slag foaming is critical to the stable operation of the processes. The fundamentals of slag foaming were studied extensively on a laboratory scale[35,36] and also in the actual pilot-scale reactors [28-31]. It was found that by maintaining a certain amount of char in the smelter slag and/or operating at an elevated pressure-slag foaming could be controlled to an acceptable degree.

Process monitoring and control are critical for stable operation of smelting reactors. The development or implementation of inexpensive, durable sensors capable of continuous real time measurement of key process parameters, such as slag height, post combustion degree, temperature, reactant feed rates, and possibly slag and/or metal chemistry, are critical to the commercial success of a smelting process. Significant recent advancements have been made in the development of such technologies for use with conventional iron and steelmaking processes.[37]

All the bath-smelting reactors described previously are vigorously stirred reactors intended for continuous operation possibly at elevated pressures. Refractory wear is a significant concern for bath smelting processes and all conventional iron- and steelmaking processes. The use of water-cooled panels can alleviate this problem, but also reduces the energy efficiency of the process. The development of erosion-resistant refractories and hearth designs, combined with water-cooled panels in problem areas, has significantly extended blast furnace hearth life. Reliable containment is possible in similar solutions for smelting reactors, but continued refractory development will make these and conventional processes more reliable.

Fundamental research has played a critical role in the development of conventional and emerging technologies for iron and steelmaking.[38] In the case of each process described, simultaneous fundamental reactions and physical phenomena were investigated along with the applied development of the processes themselves. In North America, an extensive fundamental research program conducted by participating companies and universities accompanied pilot-scale testing of the AISI bath-smelting process.

CASTING

Nearly all the current and future developments discussed so far have been related to alternative routes to liquid steel. These past, present, and future changes are mirrored by developments in steel casting technology. Beginning 35 years ago, the revolutionary industry wide implementation of continuous casting changed the way liquid steel was solidified for subsequent mechanical shaping to finished products. Continuous casting brought global changes to steel mill productivity, the chemistries of steels produced, the secondary processing that was required, and the properties of the final products. Roughly 15 years ago, successful implementation of thin slab casting at Nucor shook the established balance of the steel products produced by minimills and integrated steel-makers. The next wave in the casting revolution is close at hand. Near net-shape casting is the solidification of steel to geometry near the dimensions of the final product. Near net-shape casting processes reduce hot reduction or forming requirements, thus decreasing capital costs, energy requirements, and delivery time for steel products. Thin slab casting for flat products and dog bone shaped casters for structural steel members such as I or H beams represent a step closer toward near-net-shape casting processes.

Sheet steel is an important segment of worldwide steel production in both tonnage and value. Quality flat products for such applications as exposed automotive body components represent high value products. Presently, integrated steel mills using conventional thick slab continuous-casting machines produce the majority of these high end products. Conventional slab casters produce a continuous strand of steel approximately 250 mm thick and of various widths. The continuous strand is cut into slabs that are cooled and stored or shipped directly to the hot rolling mill. At the hot rolling mill, the slab is reheated and rolled in a series of strands to a thickness of a few millimeters and coiled for subsequent cold rolling, heat treating, surface cleaning, and coating.

Thin slab continuous-casting machines produce a slab approximately 50-60 mm thick. This significantly reduces the amount of hot rolling required to produce thin sheet, thus allowing for in-line hot rolling of steel as it comes off the caster.[39] However, because the slab produced by thin slab casting machines is 1/5 the thickness of that produced by conventional thick slab casting, the thin slab caster must cast approximately five times faster to match the productivity of the conventional caster. Unfortunately, there are limits to the casting speed that can be safely and reliably achieved in thick or thin slab casting machines.[40] The residence time of the steel in the caster mold must be long enough to allow the solidification of a steel shell strong enough to contain the liquid metal core of the slab as it exits the bottom of the mold. To increase the casting speed, the length of the mold must be increased proportionately such that this minimum residence time is maintained. However, as the length of the mold increases, the friction force between the mold and the moving steel slab also increases, requiring a greater force to pull the steel out of the mold. The maximum casting speed is reached when the length of the mold results in a friction force and associated pulling force that exceeds the hot tensile strength of the steel shell of the solidifying steel slab. Schwerdtfeger calculated a maximum safe casting speed of five meters per minute and ten meters per minute for ferritic and austenitic steels, respectively, assuming that dry, solid/solid friction will occur between the caster mold and the solidifying steel.[40] In modern continuous-casting practice, complex low melting temperature mold slags or fluxes are used to provide lubrication between the mold and solidifying steel shell, as well as to improve heat transfer. Ideally, a continuous liquid film of mold flux would eliminate dry friction between the solidifying steel and the mold, in which case there would be no limit to casting speed. However, in practice, the performance of mold fluxes as lubricants is not as reliable as would be desired for very high casting speeds. Advances in the fundamental understanding of the behavior of continuous-casting fluxes will aid in improved design and more reliable performance of these important materials.[41,42]

Two new near-net-shape casting technologies are under development for flat steel products. Henry Bessemer first envisioned twin-roll hot-strip casting in the mid-1800s. In its simplest form, the process involves pouring liquid steel between two large counter-rotating water-cooled rolls. As the rolls rotate, the liquid steel begins to solidify a thin shell against the cold rolls, and at the “kissing point” of the two rolls, the two solid shells are pressed together and exit the bottom of the mold as a single strip of steel. This process is intended to produce steel strip with a thickness of approximately 2 mm or less. Therefore, in order to match the productivity of a conventional thick slab caster operating at a casting speed of roughly 1 to 3 meters per minute, a twin roll strip caster would have to produce 2 mm strip at speeds on the order of 200 meters per minute or higher. Heat removal from the steel by the cold rolls is limited by the heat-transfer coefficient between the two materials. Therefore, the casting speed can only be increased by decreasing the gap between the two rolls and the thickness of the steel sheet produced or by increasing the diameter of the rolls. Several steel companies worldwide have maintained active research programs into the fundamental and operational aspects of twin-roll strip casting in the past decade.[43] Due to the high heat fluxes required for twin-roll strip casting, the fundamental aspects of heat transfer and solidification are different from conventional casting processes. Extensive fundamental research programs have been necessary to develop this technology.[44,45] A twin-roll casting process for stainless steel strip production has been developed in Japan. Through its extensive, decade-long research effort code named “Project M,” BHP has developed a strip-casting process capable of producing low carbon strip steel with excellent dimensional tolerance and surface quality.[46] Material produced by the BHP commercial-scale demonstration facility in Port Kembla, Australia has been evaluated and found to exhibit truly unique properties. Recently, Nucor, BHP, and IHI formed a joint venture to install a commercial-scale twin-roll strip-casting facility at a Nucor facility in the United States. Construction of this facility has been completed and start-up is scheduled for later this year. Results regarding the performance of this facility over an extended period are eagerly awaited.

The high rate of heat transfer and rapid solidification that occurs in the twin-roll strip caster produces a microstructure unlike any other steel-casting process.[47,48] Tests with strip cast steel samples indicate that a wide range of mechanical properties can be obtained from a single steel chemistry through variations in the casting speed (solidification rate) and subsequent hot and cold rolling and heat treating. Macro-segregation of impurities in strip cast steel is significantly suppressed. Therefore, the rapid solidification rate of strip cast steel may also lead to a greater tolerance for impurity elements, which degrade the properties of conventionally processed steel products. Precise control of the mechanical properties of steel products without the stringent steel chemistry control that is currently required would have a revolutionary effect on the steel industry.

A second technology for hot strip steel production has received less attention than twin-roll casting. The single-belt casting process,[40,49] developed at the Institut für Allgemeine Metallurgie of Technische Universität Clausthal in Germany, possesses some unique attributes and capabilities. In this process, liquid steel is distributed evenly onto a water-cooled steel belt via a dispenser and air knife. The steel belt is cooled from the bottom and held in place by a vacuum so that little warpage occurs during solidification. The resultant steel strip, approximately 10 mm thick, is then fed from cooling belt into an in-line hot-rolling stand for subsequent hot reduction. Critics of near-net-shape casting processes claim that internal porosity remaining after solidification can only be healed by subsequent reduction by a factor of 70-80 percent. In-line hot rolling of the 1 cm strip from the single belt caster to a thickness of 1 to 2 mm is adequate for this purpose. Higher casting speeds are possible with single-belt casting by extending the length of the cooling belt and table. This feature offers greater process flexibility with more favorable economics as compared to the varying diameter of the large copper alloy rolls of twin roll casting processes. The ability to cast a thicker strand allows for greater flexibility in subsequent thermo-mechanical processing of the steel for microstructural development and control of mechanical properties. Both laboratory-scale and pilot-scale single-belt casters have been operated at Clausthal Technical University.[49] Most of the technical problems associated with operation of the pilot scale caster have been solved. However, problems associated the scale up of the process to continuously cast wider strands over the course of many heats can only be addressed when the process is implemented on a production scale.

New and conventional casting technologies will continue to strive toward the production of cleaner steels, free from oxide-inclusion defects. In conventional casting processes, the significant mechanical deformation required to reduce the steel to the product dimensions tends to break up inclusions, thus reducing their effects on mechanical properties. In near-net-shape casting processes, little mechanical deformation will be required. Therefore, inclusion control may be critical to the success of these processes. Basic research regarding the fundamental mechanisms of inclusion formation and separation will play an important role in the continued improvement of steel properties and performance and the success of near-net-shape casting processes. Conventional mechanical filters similar to those used in aluminum processing have not been successful in removing inclusions from steel due to rapid degradation at steelmaking temperatures. However, an innovative chemical/mechanical filter is under development at the University of Alabama, which offers great promise.[50]

CONCLUSIONS

The steel industry is often regarded as a fully matured industry, using proven processes with only incremental technological developments. However, the past 30 years have witnessed several dramatic technological developments, which have changed the organizational structure, productivity, efficiency, and product properties of the steel industry worldwide. Several exciting new technologies for the production of steel have advanced to a fairly developed stage and will likely be implemented on a production scale sometime in the future. The new technologies will develop in parallel with continued incremental improvements in reliability and energy and materials efficiency of conventional processes. However, the extremely competitive marketplace of the modern steel industry has resulted in an environment where capital resources for research and development are limited and tolerance for failed technology concepts is very low. Therefore, the continued improvement of conventional processes and development and implementation of new technologies will depend heavily upon the determination, creativity, and resourcefulness of the men and women who are up to the challenge.

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