2 Process Development

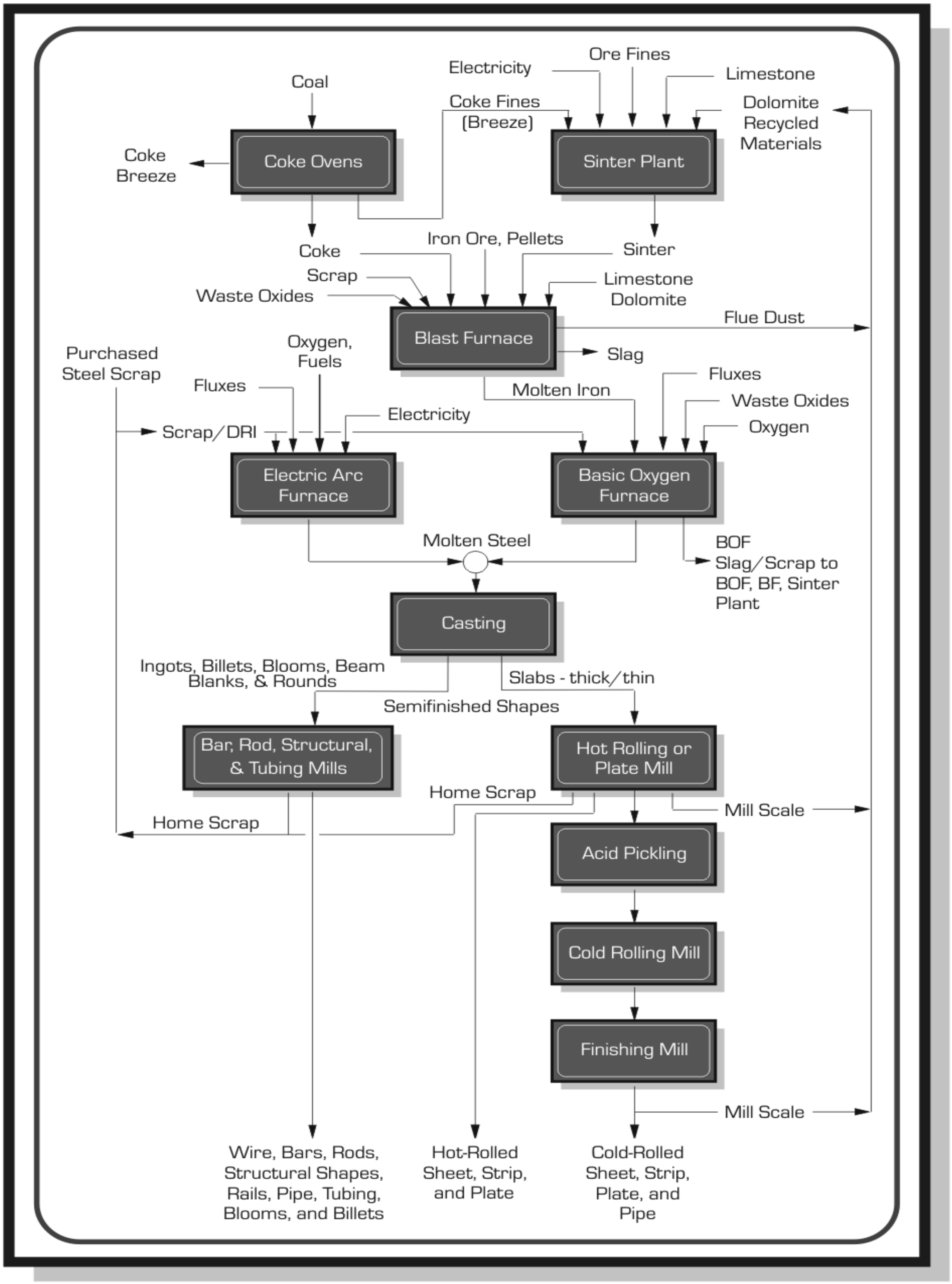
Steelmaking is a dynamic, ever-changing industry. The manufacture of steel involves many processes that consume raw or recycled materials from around the world, producing thousands of products and by-products (see Figure 2-1). Over the past 150 years, steelmaking processes have improved dramatically. Some processes, such as the Bessemer process, flourished initially but were then replaced completely. Other processes, such as the blast furnace, electric arc furnace, and hot strip mill, have evolved continuously over the decades and are likely to remain a part of steelmaking in the future. Currently, the two major steelmaking routes use either the basic oxygen furnace (BOF) or the electric arc furnace (EAF) or some combination of the two.

Advances in steelmaking, including the EAF and BOF processes, have historically evolved in response to factors such as industrial expansion, world wars, technological innovation, competition and sheer creativity. Global competition requires that North American steelmakers be low cost providers to the market, and it is this rule of economic survival that will drive innovation. The plan for that innovation is outlined in the Technology Roadmap. This chapter describes, process by process, the technical advances required for competitive advantage.

2.1 Cokemaking

Metallurgical coke is an important part of the integrated iron and steelmaking process because it provides the carbon and heat required to chemically reduce iron ore in blast furnaces to molten pig iron (hot metal). Because of its strength, coke also supports the column of materials in the blast furnace, and its shape provides permeability for gases to penetrate the material bed.

Despite the importance of metallurgical coke, naturally aging coke plants, tightening environmental regulations (which create higher production costs), and shutdowns threaten to reduce production capacity in North America. This gap between demand and reduced capacity is projected to exceed more than 12 million tons annually over the next 20 years, according to studies by World Steel Dynamics and CRU International.



Source: Adapted from U.S. Council on Wage and Price Stability, Report to the President on Prices and Costs in the United States Steel Industry, 1977 (COWPS, October 1977).

Figure 2-1. Overview of Steelmaking Processes

This gap also presents a challenge for coke manufacturers to explore new and emerging technologies that improve environmental controls at existing facilities and lend themselves to application at new ones. The need to improve controls will become more urgent as the demand for steel grows at an anticipated 2% annually over the next 10 years.

Metallurgical coke is usually produced by baking coal (coking) in a battery of large coke ovens, multiple vertical chambers separated by heating flues. A blend of metallurgical coals is charged into ports (holes) on the top of the ovens and is then heated at high temperature in the absence of air (to prevent combustion).

After hours of static heating at a high temperature during which the coal passes through a plastic stage, the volatiles are driven from the coal to form coke. When coking is completed, a pusher machine on one end of an oven removes the oven door and rams the hot coke out of an opened door at the other end and into a mobile container car. The hot coke is then quenched, either dry or with water.

As the coal turns into coke, the volatile content is recovered in the by-product plant where it is made into a variety of chemicals including tar, light oil, ammonia, and others. Until the 1950's, the value of these by-products exceeded that of the coke. However, the advent of petroleum refining has driven the price of these chemicals to such low levels that today the coke oven by-product plant is merely a very costly pollution control device.

Trends and Drivers. The entire cokemaking process, which has changed very little over its more than 100-year history, is subject to strict environmental regulations. These regulations and changes in steelmaking force higher production costs or shutdowns, pressuring the steel industry to improve the cokemaking process. Aging facilities, primarily in developed countries, also need to be replaced, and combined with tightening of environmental regulations, these factors are reducing the amount of coke produced. Studies by World Steel Dynamics and CRU International forecast a worldwide shortage of metallurgical coke by the year 2005. For example, the United States and Canada currently produce 22 million short tons of metallurgical coke each year. Normal aging of facilities will require the replacement of at least 12 million tons over the next 20 years.

Technological Challenges. Cokemaking is subject to government regulations to control emissions during charging, coking, discharging (pushing), and quenching. The primary concern over emissions focuses on the doors at either end of the ovens and on the oven charging ports atop the battery because improperly sealed doors and charging port lids allow gases to escape.

By-product processing presents additional environmental control issues for cokemakers. Throughout the cokemaking process, organic compounds are recovered as gas, tar, oil, and other liquid products for reuse or conversion into by-products for sale or internal use. Some of the recovered compounds, characterized as carcinogenic, are also classified as health hazards and therefore require special processing. In addition, the value of cokemaking by-products has decreased significantly and are generally uneconomical to recover.

New and Emerging Technologies. The need to improve environmental controls for existing cokemaking facilities and to find more cost-effective methods of producing high quality metallurgical coke has prompted several new and emerging technologies.

New technologies include the following:

- The European Jumbo Coking Reactor has reconfigured batteries for larger individual batch process ovens. Recent studies have indicated that capital costs for the technology, also referred to as the Single Chamber System, were significantly greater than conventional technology, and therefore, interest in utilizing the technology is minimal.

- Non-recovery cokemaking is a proven technology derived from the Jewell-Thompson beehive oven design. Beehive ovens operate under negative pressure, eliminating by-products by incinerating the off-gases. The technology also includes waste heat boilers, which transfer heat from the waste products of combustion to high-pressure steam for plant use and for conversion into electricity.

- The Coal Technology Corporation is using a formcoke process that produces coke briquettes from non-coking coals and waste coals. The process is currently referred to as the Antaeus Continuous Coke™ process, named for the Australian company which purchased the patent rights.

- The Japanese SCOPE21 project, still in its early stages of development, is using a formcoke process that combines briquetted formcoke and improvements in existing batteries. With this technology, cokemaking is performed in three sections: coal pretreatment, carbonization, and coke upgrading. The project is being developed as part of an eight-year research program.

Emerging technologies include the following:

- The Ukrainian State Research Institute for Carbochemistry is testing a continuous cokemaking process using a vertical shaft structure and a piston to push metallurgical coke blends through the heated zones. A pilot unit is said to exist at Kharkov.

- A Calderon Cokemaking Technology under development in the United States involves continuously producing coke from metallurgical coal and cleaning and cracking of the gases under completely sealed conditions. The cleaned gases are used as a syngas.

Research and Development Needs and Opportunities. The process of converting coal to coke produces by-product gases and liquids. These materials must be contained and handled in an environmentally safe manner. For those that contain valuable constituents, the components must be separated and safely processed and/or sold.

Particulates are emitted during the charging and discharging process of conventional coke oven batteries as well as in coke cooling and preparation of the blast furnace charge. Cost effective coke quenching and dust collection systems are required.

R & D Needs

Cokemaking

- Sealed, continuous coking process
- Cost-effective coke quenching and dust collection systems
- New cokemaking processes to produce valuable, environmentally friendly by-products
- Ways to extend life of existing coke plants.
- Improved process control
- Ability to use noncoking coals and low value carbonaceous material
- Improved refractory repair technology
- Particulate and sulfur control
- Methods to produce stronger coke
- Upgraded value of coke oven by-products
- Improved "form coke" manufacturing processes
- Development of comprehensive economic models incorporating coal and batter operating parameters

New cokemaking processes are needed to shift the by-product compositions to more valuable products. The off-gas from a coke plant could be used to produce direct reduced iron or serve as a feedstock for chemical processes. Also, technologies for extending the lives of existing coke plants should be developed.

On-line data collection is required to optimize process sequencing for highest energy efficiency and lowest cost coke production. The operation of conventional by-product plants or syngas-producing plants could be improved with the implementation of modern distributed control systems. However, research is needed to develop plant simulations and sophisticated control algorithms.

The industry needs take advantage of the availability of low value carbonaceous materials. The better utilization of contracting coals will lead to lesser wall pressure resulting increased oven life and higher productivity. The practice of using of low value carbon materials such as petroleum coke, coke breeze, coal fines, coal tar, and noncoking coals should be adopted to lower the operating costs.

Comprehensive economic models need to be developed encompassing coal quality and coke oven operating parameters and maximizing the use of low value carbon materials.

2.2 Ironmaking

Ironmaking involves the separation of iron from iron ore. Ironmaking is not only the first step in steelmaking but also the most capital- and energy-intensive process in the production of steel. There are three basic methods of producing iron: the blast furnace method, direct reduction, and iron smelting.

The blast furnace produced the vast majority of iron in the United States in 1999. The only exceptions were three Midrex Direct Reduction plants: Georgetown Steel, Corus Mobile, and American Iron Reduction, which together produced about 1.7 tons of iron in 1999, approximately 3% of the total iron produced in the United States.

In the next 15 to 20 years there will be a shift away from the blast furnace to new and developing technologies. In the year 2015, the blast furnace will continue to be the major process used to produce iron in the United States, but the blast furnace will be significantly improved in terms of fuel rate, fuel source, and productivity.

Direct reduction, including both gas- and coal-based processes, will likely grow to include 10 to 15% of the total iron production in the United States. Direct reduction products will be primarily used as a scrap substitute in the EAF, while some forms may be used in the BOF and blast furnace. Direct smelting processes could also represent a significant portion of production. These processes will replace older blast furnaces, add incremental hot metal to integrated plants, or possibly produce iron for use in an EAF. Recycled iron units such as blast furnace and steelmaking dusts will supply a significant amount of iron, possibly 1 to 2% through processing via direct reduction or smelting operations. Chapter 3 deals with recycled iron units in more detail.

Ironmaking may also be replaced by importing slabs and coils or expanded use of the EAF and thin slab casting to produce flat rolled products. However, improved manufacturing techniques may continue to decrease the amount of prompt steel scrap resulting in a further increase in residual content. Therefore the use of DRI and pig iron in the EAF is likely to rise.

2.2.1 Blast Furnace

Currently, the approximate 55 million tons of blast furnace hot metal produced in the United States annually requires about 23 million tons of coke.

Trends and Drivers. By 2015, it is anticipated that many of the smaller, older furnaces will be shut down while productivity in the larger furnaces increases. Most likely, no new blast furnaces will be built in the United States.

It has been estimated that by 2015 blast furnace production will decrease to 42 to 46 million tons, which will require only 14 to 18 million tons of coke (Fruehan 1996). Iron from scrap, direct reduced iron, and smelter metal will make up the remainder of the required iron units. Coal, oxygen, and, in some cases, natural gas injection will increase, possibly supplying up to 50% of total furnace requirements. Specific productivity in the blast furnace should also increase. The current and projected future performance of the blast furnace is given in Table 2-1.

The major drivers for technological developments related to the blast furnace are to reduce its reliance on coke and to extend campaign life to reduce capital costs of repairs. These goals will be achieved through increased coal and natural gas injection. The other major concern related to the coke plant/blast furnace is the high capital cost. However, since few if any will be built, the cost issue must eventually be solved with a more radical process such as direct smelting. Other developments related to the blast furnace, such as gas recirculation and the oxygen blast furnace, are not high priority.

Table 2-1. Current and Future Projection of Blast Furnace Ironmaking

Measure	1998	2015
Annual Production (10^6 tons)	53	44
Number of Furnaces	38	25
Fuel Rate (Average)		
Coke (lbs/ton)	820	640
Coal (lbs/ton)	220	400
Fuel Rate (State of Art)		
Coke (lbs/ton)	650	500
Coal (lbs/ton)	300	500
Productivity[a]		
Average (tons/100 ft^3 day)	7.2	9.2
State of Art (tons/100 ft^3 day)	12.1	12.6

a Productivity with up to 5-10% reduced iron or scrap. Higher productions are possible with higher rates of scrap or DRI.
Source: Stubbles, 2000

The blast furnaces remaining in operation will need to improve their efficiency. One of the key factors to an energy-efficient blast furnace operation is maintaining stability, which in turn is affected by consistent taphole performance. Consistent performance of the taphole clay is required for stable taphole operation, and key to maintaining the clay performance is its resistance to erosion and curing properties.

Technological Challenges. Technical barriers to replacing more coke with injected coal are:

- The practical limit and limiting process for coal injection are not known precisely. The major challenge in injecting more coal lies in the strength of the pellets. Pellets will be reduced with a gas of higher reducing power, higher heating rate, and longer residence time. The specifications of iron ore quality must be re-evaluated for the new practice. Furthermore, any new DRI product for the blast furnace must have sufficient physical strength for the same reasons.

- Since less coke is charged into the furnace, coke must be stronger. There is concern as to whether current coke production methods can economically yield a coke of sufficient strength.

- The lack of an economical process to produce partially reduced (50 to 75%) pellets or sinter is a barrier to significantly increasing productivity.

- Technology developments have outpaced modeling capabilities. There is no comprehensive blast furnace model (including fluid flow and kinetics) or accompanying lower-cost sensors.

- There is a lack of effective uses of process gas and sequestration of CO_2.

New and Emerging Technologies. New and emerging blast furnace technologies include the injection of coal and natural gas to displace coke, improved refractories, and new control technologies. The Japanese may have developed a blast furnace model that includes fluid flow and kinetics. It may also be possible to develop other attractive fuels, for example wood wastes or plastics.

2.2.2 Direct Reduction

For the purposes of this roadmap, direct reduction is defined as a process used to make solid iron products from ore or pellets using natural gas or a coal-based reductant. Direct reduction processes can be divided into four basic categories, provided in Table 2-2 along with some examples of each. Also given in Table 2-2 is the year 2000 annual production of each listed process and comments concerning the status of each.

Several of these direct reduction processes have been commercially available for over a decade and have been optimized to a reasonable degree. The Midrex and HyL processes produce over 85% of direct reduced iron worldwide (total world production was 47.6 million tons in 2000). However, these processes use pellets or lump ore, have relatively high capital costs, and require relatively large production units (1 million tons per year) to be economical. Incremental improvements are expected to be made.

Fluid bed, fines based processes are an additional technology, but except for FIOR, have yet to be proven long term. Higher productivity and lower energy consumption are desirable, but difficult to achieve, as the processes must operate at relatively low temperatures to prevent sticking.

Rotary Hearth Furnace (RHF), Rotary Kiln Furnace (RKF), and the Circofer fluid bed processes offer a coal-based option for reduced iron units. These processes are drawing more attention as the increased cost of natural gas has made the gas-based processes unattractive in North America.

Trends and Drivers. There is a pressing need for virgin iron units as North American (N.A.) EAF capacity continues to become a larger share of total N.A. steel production. However, recent and catastrophic increases in natural gas prices have shut down all U.S. gas-based DRI plants. As a result, gas-based DRI processes are not expected to be profitable in the United States anytime in the near term, dimming the prospect of additional U.S.-based DRI capacity. Most likely, near-term U.S.-based DRI activity will center on captive coal-based RHF units by either recycling waste oxides or combining recycling with smelting to produce liquid iron for the EAF.

The potential exists to develop a process that produces low-cost, partially reduced material (50 to 70% reduced versus 85 to 95% for conventional processes) for use as a blast furnace feed. The trend toward implementation of large, gas-based furnace processes and improvement of fluid-bed processes will continue offshore. In N.A., there is need for continued improvement in the economics and efficiency of coal-based technologies.

Technological Challenges. The gas-based shaft furnace processes are commercially available and further improvements will be incremental. Barriers for fluid-bed processes are primarily related to productivity and equipment, while those for the coal-based processes are related to the undesirable extra gangue and sulfur associated with the coal reductant and the poor physical quality of the reduced iron product. Specific challenges include:

- Productivity of fluid-bed processes is not high enough. Better understanding of rate controlling steps and optimization of process variables, including temperature and pressure, are needed. The influence of feed material size consistency on the various processes, including iron carbide, is not fully defined.

- There are engineering problems associated with the design of fluid-bed processes, including heat exchangers, gas distribution systems, and reliability of compressors and valves.

- Multi-stage reactors are used to improve energy efficiency in fluid bed processes. In systems with highly reducing gases containing CO and H_2, metal dusting occurs, causing metal failure. Generally small amounts of H_2S are used to control this phenomenon; however, neither the mechanism of metal dusting nor its control are well understood.

- The products produced by the rotary hearth processes FASTMET, INMETCO, and IDI contain large quantities of gangue and sulfur which are associated with the coal reductant. The methods presently used for de-ashing and desulfurizing coal prior to making the composite pellet for reduction are inadequate because they are either too costly or they degrade the coal's properties. Improved methods for separation of the hot reduced iron from the sulfur and gangue are also needed.

New and Emerging Technologies. Table 2-2 lists the status of selected direct reduction technologies.

Table 2-2. Major Direct Reduction Processes and their Current Status		
Process	Worldwide Production - 2000 (million Tons)	Comments
Gas/Shaft		
Midrex	32.03	Proven technology, requires pellets or lump ore and large scale to be economical
HyL I, III, & IVM	10.18	Similar to Midrex
Gas/Fluid Bed		
Fior	0.30	Proven technology
FINMET	0.76	Improved FIOR
Circored	0.001	Became commercially operational in March 2001
Coal/RHF or RKF		
FASTMET	0.00	Pilot facility in Japan (3 tons/hr)
INMETCO*	0.02	Waste oxide plant combined with EAF smelter producing high alloy pig
IDI*	0.06	Restarted after modification in 2001
SL/RN	1.29	Kiln process with high coal consumption rate
Coal/Fluid Bed		
Cicofer	0.00	Small developmental pilot unit in Germany

Key: RHF - Rotary Hearth Furnace RKF - Rotary Kiln Furnace

* Note: The INMETCO and IDI processes include a smelting step and could also be classified under new smelting technology.

Source: Midrex Technologies, Inc. 2000 World Direct Reduction Annual Statistics

2.2.3 Iron Smelting

The objective of iron smelting is to develop processes that produce liquid iron directly from coal and ore fines or concentrate. Liquid iron is preferred to solid iron because there is no gangue and molten iron retains its sensible heat. Coal is the fuel of choice, as opposed to natural gas, because of its abundance and lower cost. Use of coal directly also would eliminate the need for blast furnace coke, a costly commodity in increasingly short supply. The ability to use ore fines or concentrate could eliminate agglomeration costs. These new processes should have a high smelting intensity or productivity. High productivity, combined with elimination of cokemaking and ore agglomeration, will significantly reduce the system capital cost.

The COREX process, which is commercially available, does use coal directly, but is still capital-intensive, requiring pellets or lump ore and producing excess energy that must be used for the process to be economical. The new processes that appear to possess most of the required attributes are the iron bath smelting processes, which have been under development over the past decade or so. These include the AISI Direct Steelmaking, the

TABLE 2-3. PROCESSES CHARACTERISTICS AND STATUS FOR DIRECT SMETING PROCESSES

PROCESS	FEED	STATUS
COREX	Coal/Pellets or Lump Ore	Plants built in India, Korea, and South Africa (the newest South African plant uses the off gas to operate a Mildrex DRI module).
DIOS	Coal/Fine Ore	Pilot plant closed in 1996.
AISI	Coal/Pellets or Waste Oxides	Smelting and waste oxide trials completed at pilot scale.
HIsmelt	Coal/Fine Ore	Pilot tests completed. Demo plants being discussed for Australia and US.
ROMELT	Coal/Ore or Waste Oxides	Semi-commerical plant has operated. Process is inefficient.
CCF	Coal/Fine Ore	Cyclone furnace tested, but not linked to smelter.
TECNORED	Coal (and Coke if available)/Fine Ore	Pilot tests completed. Demo plant in Brazil slated to be operational in 2002.
CleanSmelt	Coal/Fine Ore	Cyclone and smelter tested in combination.

Japanese DIOS (Direct Iron Ore Smelting), the Australian HIsmelt, the Russian ROMELT, the Hoogovens CCF (Cyclone Converter Furnace) processes, the Italian CleanSmelt process (cyclone/smelter combination), and the Brazilian TECNORED. These processes have been reviewed in numerous publications, and the basic phenomena are fairly well known. Table 2-3 summarizes the characteristics and status of selected direct smelting processes.

Trends and Drivers. The drivers for these new technologies are reduction in capital costs, elimination of cokemaking, reduction in agglomeration requirements, and flexibility in location and economic size. Aside from the already commercial COREX process, the remaining iron smelting processes have only reached the pilot or demonstration stage. Commercialization is still 3 to 10 years away.

Successful pilot trials of several processes have led to recent plans for demonstration plants using the HIsmelt and TECNORED concepts that can operate with or without prereduction. Other concepts favorably viewed include cyclone technology for prereduction combined with smelting technology similar to either the AISI or DIOS processes. These concepts use fines and coal directly, have a single step to prereduce and preheat the ore, and are energy efficient at reasonable levels of post combustion.

Technological Challenges. Before the successful commercialization of any iron smelting processes can occur, several technical barriers must be overcome:

- As smelter metal can contain two to three times as much sulfur as blast furnace hot metal, improved methods for desulfurizing smelter metal are needed.
- Efficient prereduction processes for fines and concentrates have not been demonstrated. Both the cyclone and fluid bed technologies have promise, but have not been fully proven in direct coupling with the smelting processes.

- Process control technology must be developed for maintaining critical levels of char in the slag for optimum reduction rates and for slag foaming control without decreasing post combustion.

- Smelter off-gas should be used as much as possible, preferably within the process but perhaps as a fuel for input in another process.

There are also several environmental issues that must be addressed. These are discussed in Chapter 4.

New and Emerging Technologies. Direct iron smelting represents an entirely new generation of ironmaking technology. Selected processes are listed in Table 2-3.

2.2.4 Ironmaking Research and Development Needs and Opportunities

R & D Needs

Blast Furnace

- Investigation of factors limiting coal injection and methods of overcoming these limitations
- Coal-oxygen injection systems that obtain more complete coal combustion
- Process to economically produce partially reduced pellets or sinter
- Comprehensive model of the blast furnace
- Improved taphole clays and taphole/refractory systems
- Iron ore pellets for furnaces with high levels of coal injection
- Sequestration of CO_2
- Improved use of blast furnace off-gas
- Use of substitute fuels, e.g. tars, light oil, wood wastes, plastics
- Coke rate reduction (per NTHM) through injection of alternative fuels
- Research of hot O_2, which may increase the injection rate/NTHM
- Evaluation of the mini-blast furnace's ability to viably resolve the coke strength issues
- Determination of how much scrap or DRI units can be charged to increase productivity

Along with continuing research of the direct smelting technologies listed in Table 2-3, R&D needs have been identified for the blast furnace, direct reduction, and iron smelting as follows:

Blast Furnace

As listed in the text box, blast furnace R&D needs are primarily based on incremental improvements around current operating practices. One key need for improving this process is the development of a comprehensive model of the blast furnace, including fluid flow and kinetics and low-cost sensors to measure gas composition, temperature, and bed permeability. Such a model could help steelmakers optimize in-plant coke oven and blast furnace off-gas utilization, as well as evaluate recent tuyere injection developments

Another blast furnace need is for improved raw material development. This includes new types of iron ore pellets more suitable for blast furnaces with high levels of coal injection. In addition, a process is needed to economically produce partially reduced pellets or sinter of sufficiently high physical strength.

Direct Reduction

Direct reduction development needs are focused on improved understanding of the process. Determination of the rate-controlling step and the effect of operating variables on the rate of reduction and carburization relevant to fluid-bed processes is needed to increase productivity. Fluid flow and kinetics in fluid-bed reactors should also be investigated to improve productivity and energy efficiency. Finally, the phenomena of metal dusting and how to reduce it as it applies to direct reduction processes needs further investigation.

R & D Needs

Direct Reduction

- Coal based direct reduction process that has lower gangue and sulfur
- Investigation of fluid flow and kinetics in fluid-bed reactors
- Understanding of fluid bed processing steps and variables
- Improved types of iron ore pellets and methods to reduce sticking
- Investigation of and how to reduce metal dusting

Iron Smelting

R & D Needs

Iron Smelting

- Understanding of and methods to increase post combustion and heat transfer
- Improved metal containing systems for smelters
- Control models for smelting systems
- Efficient methods of adding coal and pre-reduced fines or concentrate
- Low cost methods of desulfurizing smelter metal
- Demonstration of cyclone technology
- Investigation of coal and waste oxide injection into the smelter or production of agglomerates for smelting
- Investigation of microwave reduction technology
- Development of a cleaner coal or coal substitute

Control models and methodology improvements are needed to advance iron smelting techniques. One need is improved metal containing systems for smelters, including new refractory and energy-efficient water cooling systems. Control models need to be developed for reduction, char control, foaming, and post combustion/heat transfer for smelting systems. Efficient methods of adding coal and pre-reduced fines or concentrate while maximizing the performance of the smelter also need further work.

Other iron smelting needs include improved understanding of synergies between processes. For example, submerged arc furnace technologies need to be further developed to take advantage of the characteristics of reduced iron feed from RHF's. Also, opportunities exist to combine EAF and submerged arc furnace technologies in developing a unique smelting furnace to most efficiently melt and refine the RHF product.

2.3 Basic Oxygen Furnace Steelmaking

BOF steelmaking accounts for just under 60% of the liquid steel output in North America. While this figure may decline with the growth of EAF use, the BOF will continue to be a major source of steel for many years. BOFs include conventional top-blown furnaces, Q-BOP (bottom blown) furnaces, and various mixed blowing configurations and inert gas bottom stirring modifications.

Because significantly higher new blast furnace capacity is not expected, steel plants must find ways to meet demand by extending liquid pig iron production. One way to extend production is to optimize both blast furnaces and BOFs, but technological challenges exist. Steelmakers are applying or experimenting with new and emerging technologies that, with more R & D, could overcome challenges.

2.3.1 BOF Furnace

The predominant advantages of the BOF are very high production rates and low-residual-element, low-nitrogen liquid steel tapping. The BOF is fed liquid pig iron, almost always from blast furnaces, in amounts ranging from 65 to 90% of the total metallic charge. The average pig iron is approximately 74% of the charge; the balance is recycled scrap.

Efforts to improve BOF productivity and annual production capacity in recent years have included various automation technologies to optimize the blast furnace and the BOF relationship, better use of secondary refining processes (driven both by productivity and by new steel grades), and improved coordination with downstream facilities.

Trends and Drivers. Advances in slag splashing that extend refractory life and use of post-combustion lances have improved furnace availability. Relines are down to one per year per furnace or less; lining life is in the range of 10,000 to 25,000 heats. Use of the post-combustion lance has reduced the time and effort involved in controlling BOF mouth and lance skulls (a build-up of steel that occurs with use).

Increasing demand for ultra-low-carbon (ULC) steels has made secondary processes more important. Lower interstitial element content in flat-rolled steel is a major worldwide trend. Many shops have focused on coordination among the BOF, ladle treatment station, ladle refining arc furnace, steel desulfurization, and degasser to achieve temperature and chemistry control and timely delivery to the caster. Some shops have found that optimizing secondary processes helps productivity by allowing the BOF to aim for a wider target.

It may be possible to make ULC steel in the EAF route and much cheaper if tank degassing can be employed. Tank degassing has been used by several plants to make ULC, but the cycle times are too long. Techniques to improve the kinetics, cycle times, or logistics could reduce cost dramatically.

Another trend is hot metal desulfurization, usually done in the BOF transfer ladle. When 100% desulfurization can be attained, the blast furnace can operate at higher hot-metal sulfur and lower fuel rates, which may reduce hot metal costs.

Meanwhile, steelmakers constantly experiment with BOF oxygen lance configurations, oxygen batching and flux additions practice to achieve better slag making and chemistry, better control of refractory wear, and higher production rates. There is a gradual trend toward softer blowing, or blowing at a lower velocity, with more oxygen nozzles (holes in the lance).

Technological Challenges. Slag splashing has increased furnace life to well beyond the life of the lower hoods. To cope with this incompatibility, shops must consider new maintenance schedules for hoods, environmental control equipment, and new hood materials.

Environmental standards are getting tougher, requiring better air-cleaning technologies for fugitive emission control and in-shop work environments. Current environmental control equipment may not be adequate to meet future standards.

Furnace vessel shell distortion and destruction during a long campaign must be overcome. Slag carryover from furnace to ladle, a key to clean steel, should be controlled using electromagnetic sensors and other techniques. This will improve the control and consistency of secondary treatment.

Many shops are beginning to feel the pinch of lower phosphorus specifications. Reducing the recycle of BOF slag to sinter plants and blast furnace to reduce steel phosphorus has its benefits and its problems. While lowering the recycle reduces steel phosphorus, it also increases the amount of slag for landfills as well as hot metal costs by increasing the cost of replacing blast furnace charge materials. Using separate dephosphorization stations, as in some Japanese shops, increases the liquid steel costs and adds another major source of emissions.

Refining of hot metal with a low manganese-silicon ratio reduces recycle of BOF slag to the blast furnace and sinter plants, which produces a low manganese content in the hot metal. This impacts slag formation in the BOF vessel in addition to BOF operating issues.

New and Emerging Technologies. Work is being conducted to improve chemistry, temperature, and process control in the BOF. The use of in-blow sensors with possible feedback control is being developed to improve carbon and temperature control to measure lance height and detect the advent of slopping. Improving techniques of adding alloys, usually with the aid of secondary processing, will increase control over chemistry levels to meet new grade demands and allow consolidation of grades. Upgrading computer and expert systems will also help operators achieve consistent process control.

Using inert gas bottom stirring achieves better iron yields and alloy recovery through reduction of furnace slag iron oxide, but maintaining effective stirring continues to be a major inconvenience in many shops that have tried the technique.

Many shops need techniques that enable the aggressive use of post-combustion lances or supplemental fuels to extend the use of hot metal. These techniques will increase their capacity without requiring investment in new hot metal capacity . These techniques would also minimize production loss during periods of blast furnace relines.

2.3.2 Other Related Technologies

Other technologies that support oxygen steelmaking also require development. These include scrap preparation and handling, fluxes and methods of additions, recycling of waste oxides, and process sensors with feedback capability (for example, light meter, lasers, infrared temperature detectors).

Trends and Drivers. Scrap handling is unique in each plant. Use of home scrap usually requires preparation before recharging into the BOF. Use of outside or purchased scrap is subject to the same demands and problems experienced by EAF operators. In addition, the trend in scrap prices (especially for premium scrap) in recent years has been upward due to competitive buying pressures from EAF shops.

Some integrated plants are experimenting with lower-grade, higher-residual (and thus cheaper) scrap because it can be diluted by low-residual hot metal.

Flux quality, size, and method of introduction are becoming more important because of increased demands on slagmaking, both for refractory maintenance and for control of sulfur and phosphorus. Investigations of flux batching and related oxygen lance schedules are contributing to ongoing improvements in charge recipe calculations and the consistency of slagmaking.

Increasingly, recycling in-plant waste oxides in the BOF is addressing environmental pressures and presenting opportunities for low-cost sources of iron and/or coolants in the furnaces.

The use of industrial gases is also increasing. Many shops have nitrogen circuits tied into the main lance circuit for slag splashing as well as for bottom stirring. Nitrogen gas can be used for nitrogen chemical control when required on certain grades to replace expensive nitrided ferro-manganese.

Technological Challenges. BOF steelmaking improvements must overcome many technological challenges. One area that requires technological development is scrap systems. Scrap delivery and analysis systems are complicated, unreliable, and inefficient. Without better systems, the amount of scrap used and effect on quality is limited.

Also challenging BOF steelmaking is the difficulty of maintaining reliable sensors and automated systems. The lack of fully developed, reliable automatic flux batching systems, particularly bin level detectors for dusty environments, limits slag making consistency. Also, the hostility of the BOF environment for lasers and other sensors makes it difficult to find suitable protection and locations for these sensors. Without speedy, comprehensive optical sensors, scanning and reviewing historical data on the condition of furnaces and ladles is difficult.

Another technological challenge that must be overcome is slag analysis. A speedy, reliable slag oxide analysis technique is not available, particularly for iron oxides or for controlling lance height, making slag, and calculating alloy efficiencies. In addition, slag analysis is expensive and slow and involves sampling separation problems related to the use of iron versus iron oxides.

How to utilize the high levels (up to 85%) of uncombusted carbon monoxide leaving the BOF vessel is another difficult technological challenge.

New and Emerging Technologies. Recent and developing BOF process improvements primarily affect scrap and process sensors. Additionally, development is ongoing in burners and nozzles for the BOF process. This work could improve post-combustion performance.

Preheating techniques and quality improvements lead the emerging scrap technologies. A number of investigations are looking for economical ways to remove residual elements from scrap to replace expensive but successful techniques, such as detinned bundles. Also, effective scrap preheating techniques are being developed. Smelt-refining processes and EAFs have developed submerged dust injection and scrap preheating technologies, but their application to BOF steelmaking remains unexplored.

Light meters, lasers and infrared cameras and sensors are being studied to control carbon, temperature, slopping, waste gas composition, and lance height above the bath. Improved sensors, instrumentation, computer power, and process models are used to provide data that enable an operator to consistently optimize production processes. Industry-sponsored work (though AISI and DOE) on various sensors in BOFs that apply laser measurement and in-lance cameras are presently undergoing commercialization tests.

2.3.3 BOF Steelmaking Research and Development Needs and Opportunities

Despite all the ongoing research to improve BOF performance, numerous other research opportunities exist.

R & D Needs

BOF Furnace

- Robust process sensors for the BOF to measure process variables
- Reliable sensors to detect lance-to-steel bath distance
- Clear understanding of the hydrodynamics of the oxygen lances
- Improved laser scanning system to characterize the condition of the furnace and ladles
- Improved flux raw materials analysis and size, and reliable computer controlled batching
- Improved, easy-to-maintain hoods
- Economical and environmentally friendly methods of removing or controlling phosphorus
- Inexpensive and fast slag sample preparation and composition analyzer
- Longer-life, easily replaced stirring elements
- Environmental controls for primary and secondary control systems
- Improved understanding of micro-alloying element recovery through the process

Long-life refractories. Investigate ways to increase use of long-life refractories to improve stirring elements for furnaces or ladles and use in BOF tap holes. Also, the hood life should be extended to equal that of the refractory lining.

Process sensors. Develop various user-friendly, robust process sensors with feedback capability to detect bath carbon, temperature, and the advent of slopping, waste gas composition, dusty bin levels, and furnace shell temperatures. The temperature sensor should be able to measure continuously during the final minutes of the blow. Sensors for quick analysis of turndown manganese, sulfur, and other elements are also needed.

Lances. Develop a reliable sensor to detect lance-to-steel bath distance to control the path of the process, particularly slag making and possibly slopping. Heat-to-heat feedback or real time feedback of lance height will improve the consistency of the process reaction path. Also, a clear understanding of the hydrodynamics of the oxygen lances and its effect on splash generation and decarburization kinetics needs to be developed.

Laser scanning for refractories. A comprehensive laser scanning system is needed that is fast, robust, and user-friendly for characterizing the condition of the furnace and ladles. This technology could also provide refractory condition feedback and lance height control by integrating the volume of the furnace.

Flux and oxygen batching. Improved flux raw materials analysis and size and reliable computer controlled batching are needed for better slag making consistency. This research also applies to developing better oxygen batching methods for early slag making.

BOF hoods. Improved, easy-to-maintain hoods, possibly in conjunction with protective coating techniques and/or constant temperature/pressure control techniques need to be researched.

Dephosphorization. Economical and environmentally friendly methods of removing or controlling phosphorus need to be developed. Alternatively, find other viable uses for BOF slag rather than recycling to the sinter plant. This will reduce the input phosphorus load from the hot metal.

Slag oxide analysis. Inexpensive and faster slag-sample preparation and a composition analyzer would improve slag analysis.

Stirring elements. Longer lasting and more easily replaced stirring elements could make maintenance and bottom stirring easier.

Environmental controls. Primary and secondary environmental control systems need to be developed and upgraded to Best Available Technology (BAT) in all areas of emission concern. Constant technical review is necessary to meet environmental standards of the future.

R & D Needs

Other BOF Steelmaking Needs

- Method to use DC/EAF in a BOF vessel to preheat scrap
- Comparison of process parameters vs. results of models for fluxing and oxygen blowing
- Predictive maintenance procedures for drive bearings
- Process to decrease the percent of hot metal through the use of external energy units
- Refining technology for low Mn/Si ratio metal
- Submerged dust injection for recycling
- Integrated melter guidance system
- Scrap preheating techniques for stretching hot metal
- Maintenance techniques to take advantage of increased BOF lining life from slag splashing
- Model to optimize blast furnace and BOF operations
- Charge control model for better end-point control

Other BOF steelmaking R&D needs include using models, maintenance procedures and new technologies to improve performance. One essential requirement is the development of scrap preheating techniques for stretching hot metal. Also needed is an integrated melter guidance system to take advantage of multiple sensors, instrumentation, and models. Production pacing models are needed for BOF's trying to supply steel for multiple casters. These models should consider steel ladle requirements and "what-if" production alternatives.

Research into processes to remove residual elements, such as tin, copper, antimony, and others during the steelmaking process is needed. Maintenance techniques for mechanical and ancillary systems need to be developed to take advantage of increased BOF lining life from slag splashing. Regarding ULC steel production, better understanding of vacuum kinetics and pre-casting chemistry is required for improvement.

2.4 Electric Arc Furnace Steelmaking

In the 1960s the "mini-mill" began to revolutionize the steel industry. The mini-mill is based on the dual concepts of recycling abundant, inexpensive steel scrap through a small, low capital steel mill consisting primarily of an electric arc furnace and a continuous caster. The process grew from obscurity until today nearly half of all steel in the United States is produced in EAFs. In the 1960s and 70s EAFs produced long products and growth was primarily at the expense of the open hearth. But with the advent of thin slab casting its growth has continued into the flat roll market at the expense of the BOF. Today there are approximately 100 mini-mills in the U.S. capable of producing 50 million or more tons per year.

New technology has vastly increased EAF productivity. Originally production ranged from 10-30 tons/hour but today there are numerous furnaces producing in excess of 100 tons per hour. The "mini-mill" has grown from a plant producing 250,000 tons per year to plants producing in excess of 2 million tons per year. Once relegated to producing inexpensive concrete reinforcing bar, today mini-mills can produce over 80% of all steel products.

Although EAF productivity has significantly increased, steelmakers must still optimize the EAF with the finishing operations so their production rates and sequencing are the same.

Figure 2-2 shows some of the new technologies that have propelled this growth and indicates the reduction in tap-to-tap times, electrical energy and electrode consumption.

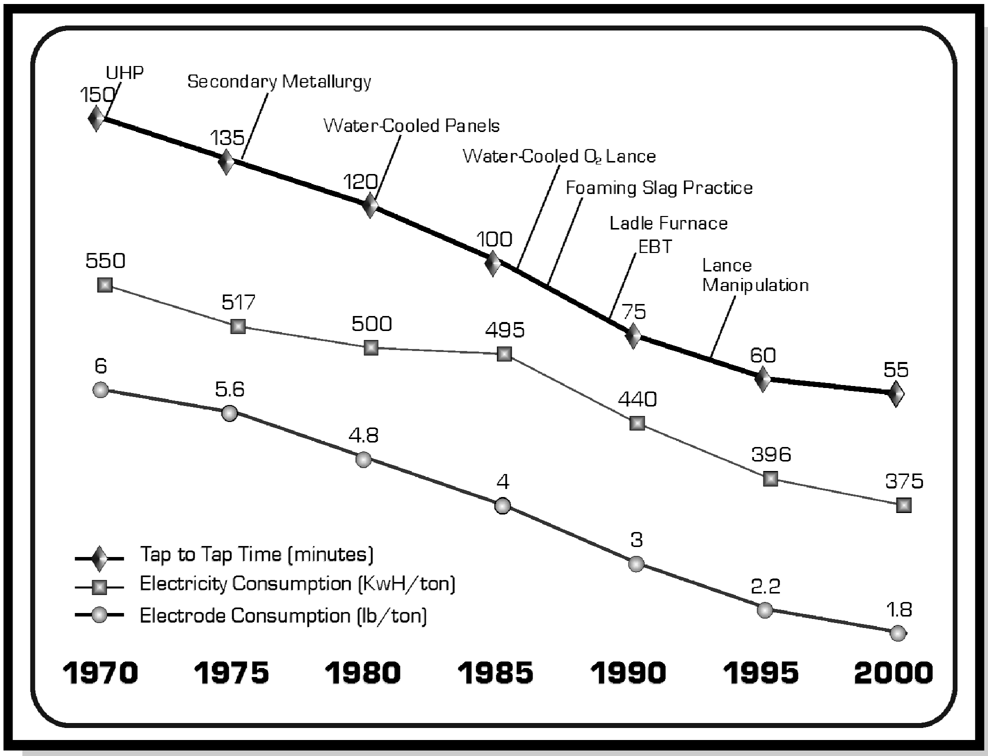


Figure 2-2. EAF Evolution

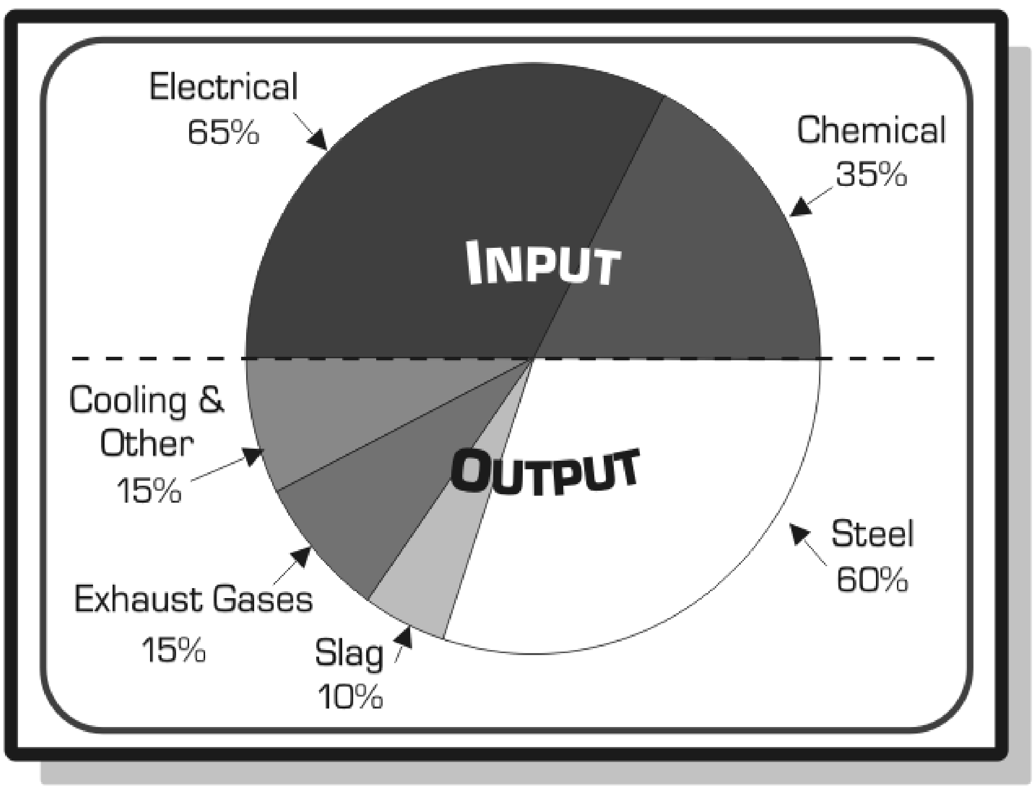


Figure 2-3. EAF Energy Input/Output

EAF energy consumption is generally reported in kWh per liquid ton. The electrical energy is only about 65% of the total energy input. The other 35% comes from chemical energy generated by the exothermic oxidation of carbon and iron and by oxy-fuel or natural gas burners. Schematically, the energy balance for an EAF is shown in Figure 2-3. The tapped steel and slag require a specific amount of energy (approximately 70% of the input), regardless of heat time; heat losses to waste gas, cooling water, and radiation, which are all directly related to heat time and directly account for the remaining 30%.

Consequently, there has been a relentless drive to shear minutes from the process by maximizing the rate of energy input when the power is on and to minimize the power-off time. As a result, the terms Power Utilization and Time Utilization have been coined. The former is the average power input/maximum power input when power is on. The latter is the percent of tap-to-tap time when the power is on. All EAF developments are directed at maximizing the product of Power Utilization and Time Utilization.

2.4.1 Raw Materials

Raw materials and operating practices affect EAF efficiency and yield. The traditional EAF charge has been 100% cold scrap. Even in 1995, less than 1 million out of the 40 million tons of metallics charged to domestic EAFs was direct reduced iron (DRI), hot briquette iron (HBI), or iron carbide.

The iron unit situation is critical for several reasons:

- The product mix served by EAFs is moving more towards value-added steels, which are specified with low metallic residuals and low nitrogen levels (automotive flat rolled, cold heading-rolled and wire).

- The availability of scrap needed to meet these requirements is limited to prompt scrap, which is decreasing as more and more near-net-shape metalworking operations appear.

- Yield and energy consumption are both strongly dependent on the quality and physical characteristics of the iron units available.

The following topics are of central importance to raw material issues: supply of manufactured iron unit (which includes DRI, HBI, carbide, and pig iron), upgrading of purchased scrap, and the physical nature of purchased scrap. These topics are discussed in more detail below. Process yield is not discussed because process yield has been determined to be a function of charged metallics quality, rather than of the process itself, and intrinsic iron losses are not likely to be further reduced.

Trends and Drivers. Manufactured iron unit supply is a major concern. As the new greenfield mills increase their output, demand for prime scrap will begin to outstrip supply. Pig iron is an excellent charge material for an EAF because of its high density, low melting point, carbon contribution ability, and low metallic residuals. However, the availability is low as integrated producers consume nearly all they produce.

Upgrading of purchased scrap has been another way to increase raw material quality by controlling residuals, including S, P, Sn, and Cu. Several chemical approaches to remove the copper that is physically associated with junked cars (shredded scrap, #2 bundles) have been developed. However, physical separation (shaking, magnets) seems preferable to any of the chemical methods, all of which either create environmental problems (coping with H_2S, chlorine) or require auxiliary operations (molten aluminum bath). Phosphorus in DRI is tied up as an oxide and thus enters the slag, probably remaining there since normal distribution ratios for phosphorus in melting are well below equilibrium (i.e., phosphorus in pig iron will enter the steel, not the slag, and must be oxidized out like phosphorus from scrap).

Sizing of scrap is important to maximizing bucket density and minimizing energy losses. Proper scrap sizing limits the number of required recharges, thereby saving energy lost during roof swings, and minimizes refractory damage due to impact of heavy pieces at charge and flare from uneven charges.

The physical preparation of scrap is important for efficient preheating and fast melting. Furnace designs are not being tailored to optimize scrap handling, so a physically homogeneous charge is desirable. To this extent, manufactured iron units are ideal. Iron carbide can and possibly must be injected, and rates of several hundred pounds per minute have been achieved. Although overall quantities may be limited as injection cannot be used throughout the entire process, alternate iron forms that can be used in the conventional scrap buckets will enable regular use in current shops.

New and Emerging Technologies. The Iron Dynamics plant, in production early in 2001, is based on RHF and SAF technology and is the newest entry into the North American manufactured iron arena. It produces liquid pig iron for consumption in an EAF. Other RHF/SAF processes and advanced iron smelting processes are being considered by both EAF and integrated steelmakers to provide needed virgin iron units for their operations. Continued development and installation of these processes will help relieve pressure on future prime scrap supplies and lessen domestic dependence on imported cold pig iron.

For chemical upgrading, a pilot plant for removing zinc from prime flat-rolled automotive sheet is in operation in Chicago. The process in use is based on a caustic solution of zinc coating followed by electrolytic recovery to remove the zinc. The economics of this operation seem favorable at this point, but are still questionable as long as zinc prices hold around \$.50 / pound.

An economic cryogenic technology to break up scrap has not yet been developed. The use of hollow electrodes to feed small-sized iron units has been explored in ferro-alloy operations, but electrode current-carrying capacity is then reduced.

2.4.2 Energy

Productivity is a function of the net rate of energy input. Efforts are ongoing to maximize the energy delivery rate and its effective use to achieve reduced heat times. Electrical energy is dominant on the input side and often cheaper than chemical energy when consumables are considered. Conservation of energy by minimizing heat time is critical because of the large heat loss per minute during the EAF process and significantly increased heat loss during the final stages of heat.

The limitations of the conventional EAF have been identified and are forcing the builders of "greenfield" furnaces and those operating less efficient EAFs to consider new and advanced designs. The new generation of EAFs covers a multitude of configurations. Another key issue in EAF efficiency is the ability to pace and balance EAF production with the other parts of the steelmaking process.

The following topics related to energy are discussed: chemical/electrical energy input ratios, AC/DC power, and energy load.

Trends and Drivers. There is increased emphasis on chemical energy input, which is generally concurrent with electrical energy input and thus supplements it to reduce heat time. The post combustion of CO and H_2 gases leaving the furnace is an important issue. Ideally, the gases should be burned in the furnace with the resulting heat load applied to the slag/metal system. The oxidation of CO while the scrap is still solid and relatively cold provides a better opportunity to capture the heat. The level of CO and H_2 leaving the furnace through the off-gas duct provides some measure of the effectiveness of post combustion and are key process parameters for an on-line energy balance model for furnace practice optimization.

The introduction of direct current (DC) furnaces and the projected savings in electrode consumption has reinvigorated the EAF industry. Current carrying capacity depends on electrode diameter, and as furnaces have increased in size (greater than 150 tons), diameter has become a potential limiting factor. Large electrodes (greater than 32 inches) sell for a premium which may offset the electrode savings. One solution is dual- or multiple-electrode DC furnaces. At the same time, AC power circuits have been improved to compete with the electrical efficiency of DC power supplies.

Energy load can be reduced by reducing tap temperatures. A 100° F reduction in tap temperature is worth 10 kWh/ton. At the front end of the process, preheating of iron units (including scrap, alloys, and fluxes) can reduce energy requirements. This approach has been known for years, but both the economics and logistics defeated the simple approach (for example, heating the scrap in the bucket).

Technological Challenges. Bottom problems with DC furnaces are no longer a major deterrent to installing such furnaces, but bottom configurations could restrict bottom injection technology.

Capture of heat from the waste gas has been fraught with environmental and other problems, including difficult logistics, damaged buckets, and limited benefits. The typical savings is 25 kWh/ton, representing a poor return on investment.

New and Emerging Technologies. New and emerging technologies are mainly in the area of reducing energy load. One way to reduce load is to design the furnace to capture the waste gas heat in a scrap-filled shaft atop the roof. However, the hot waste gas is supplemented by natural gas burners in the shaft when using this method. The scrap must be extremely hot to conserve that much electrical energy and therefore must be oxidized since the shaft atmosphere is oxidizing.

A second answer is to build twin furnace shells and pass hot waste gas to one vessel while a heat is being melted in the other. Burners can also be used. Additionally, continuous scrap feeding systems that eliminate top charging and its energy losses have been developed. All these processes also may reduce the EAF dust load on the baghouse by "filtering" some of the dust. This dust is returned to the furnace, and no data exist to show the net effect of dust reduction per ton or the problem of ZnO build-up.

2.4.3 EAF Steelmaking Research and Development Needs and Opportunities

Major research needs in the area of EAF steelmaking include raw material and energy issues.

Raw Materials

R&D opportunities regarding raw materials include needs of characterization and understanding. The heat transfer coefficients for different scrap types and mixes, including hot metal as a charge, need to be determined. Also, methods need to be developed to reduce nitrogen and hydrogen pick-up from carbon sources and ferro alloys added to furnaces and ladles.

An understanding must be developed of how preheating feed materials affects the process conditions, for example, the degree of oxidation. Also, how the feed material size and shape affects melting time and yield needs to be researched. Further research is needed on the effects of injecting DRI fines on yield, tap-to-tap time, and final chemistry.

Modeling of the EAF process with variable air infiltration, flexible charges, and variable degrees of post-combustion is needed to benchmark the optimum process and improve EAF design. This modeling could also help steelmakers minimize air infiltration to provide for continuous charging of DRI and batch charging of hot metal and scrap. These and other raw material R&D needs are summarized in the text box.

R & D Needs

EAF Raw Materials

- Determination of heat transfer coefficients for different scrap types and mixes
- Defined role of section size, melt carbon, time, and temperature in dissolving scrap
- Economics evaluation of cryogenics in scrap sizing and separation of non-ferrous metals
- Reduced nitrogen and hydrogen pick-up from carbon sources and ferro alloys
- EAF modeling to enable continuous charging of DRI and batch charging of scrap and hot metal
- Technique to inject EAF dust so only Zn is recycled
- Defined limitations of hollow electrodes for feeding materials
- Practical coatings to minimize electrode oxidation
- Extended life of expendable injection pipes

Energy

One main area for EAF energy research is artificial intelligence (such as neural networks). The complexity of the EAF process is such that artificial intelligence techniques need to be applied to optimize and control the electrical input, especially with the high-voltage, high-impedance UHP furnaces and chemical energy sources. The field results of installing a neural network system on a working furnace were positive in terms of kWh/ ton, but also showed that maximizing power input at all times during melt-down was not necessarily the optimum approach.

EAFs have not taken full advantage of existing solid fuel injection technology. One AC shop in Italy is employing solid fuel injection, significantly reducing electrical energy consumption. This shop has 100-ton twin-shell furnaces equipped with tuyeres for coal and oxygen injection and plugs for argon.

R & D Needs

EAF Energy Needs

- "Superconducting" electrodes
- Limitations of secondary voltages determined
- Higher-power induction melting
- Economic microwave applications
- Instant steel bath and off-gas chemistry and volume analysis to enable feedback control
- Improved flicker control
- Artificial intelligence techniques for EAFs
- Solid Fuel Injection
- Maximized Time Utilization

Another EAF development need is the continuation of time utilization improvement. Time utilization maximization is approached in conventional shops by minimization of tapping and turn around procedures, the use of robotic analytical units even on the floor, and disciplined electrode changing practices. The typical power-off time can be as low as 15 minutes. With new furnace designs, time utilization is improved through scrap preparation and the use of a high percentage of continuously charged iron units.

2.5 Ladle Refining

Ladle refining refers to the metallurgical processes that occur in the ladle. These include alloying, deoxidizing, degassing, and the reheating and stirring of the bath. Ladle refining affords the steelmaker with the flexibility to control the processing of heats in order to achieve greater production efficiencies and superior metallurgical traits.

Ladle refining vessels range in sophistication from in-house designs built with plant equipment to engineered, multi-function stations. Most refiners use electric arc reheating although a limited number use plasma torches. These facilities are equipped with systems to add alloys in bulk; some also are equipped with powder injection and/or wire feeding. The refiners provide stirring of the bath for thermal and chemical homogenization and expedite metallurgical reactions using an inert gas introduced near the bottom of the ladle by a porous plug, tuyere, or lance.

In addition to adjusting temperature, the primary function of ladle refining is to fine tune the steel's chemistry. This adjustment can be accomplished by means as simple as bulk alloy additions during the tapping of the melt vessel, to additions of smaller lumps or chunks added at the bath surface, to injectable or wire-encased powders added below the surface. Powders tend to be used for the more exotic or micro-alloying elements that are added in small quantities. Tighter chemistry ranges can now be attained through the iterative process of small additions and chemistry checks. Additions for other purposes such as slag formers or modifiers can be made in these ways as well.

The alloys or alloy carriers can become oxidized, carrying undesirable inclusion forming elements. With the need for cleaner steels containing fewer inclusions, the sources of oxygen entering the heat during refining must be limited.

Trends and Drivers. Issues in ladle metallurgy are related to productivity, yield, chemistry control, inclusion morphology, chemistry and size distribution, and refractory life. Some specific trends include:

- Decreased inclusion mass and size distribution
- Rapid and accurate determination of chemistry and inclusion content
- Shorter processing times
- Minimization of waste
- Increased lining life

In the past, the extent to which metallurgical goals could be achieved in the ladle was limited by the bath temperatures and hold times due to the refractories of the fireclay ladle lining materials. Innovations of high alumina and basic refractories have made it possible to tap heats at higher temperatures and hold heats for longer times.

Now available are refractories that resist damage from the electric arc and wear from the stirred bath, while resisting the corrosiveness of refining slags and remaining chemically stable with respect to the chemistry of the steel. For example, magnesia and magnesia-chrome materials have carbon and metallic additions for slag resistance and added strength.

Ladle refining stations are equipped with in-process sampling and temperature measurement capabilities. For example, expendable immersion thermocouples are the most commonly used method of measuring temperatures, producing a reading accurate to $10^{\circ}F$ within seconds. Immersion samplers have been developed for most common grades. The sample is sent to the laboratory where it is analyzed for selected metallic elements using x-ray fluorescence or spectrography, or gaseous elements by evaporative techniques.

Technological Challenges. Currently all steel ladle processes are limited to ppm levels of solute elements and of oxide inclusion contents. Future levels of solutes and inclusion contents will be driven to lower than ppm levels; however, the analytical techniques and processing steps necessary for such developments have not yet been developed.

In addition to decreasing the mass of inclusions, an increasing body of literature indicates that product properties, such as fatigue life, and processing issues, such as die life, are related not only to the mass of inclusions but the chemistry and size distribution of inclusions. In addition, solidification initiation in the mold and solid state phase transformations are now understood to be related to the chemistry and distribution of inclusions formed in the liquid steel. Thus the future focus of ladle metallurgy will be strict chemistry control and deoxidants other than aluminum. Future ladle metallurgy developments must include the development of rapid sensors for steel and slag chemistry and inclusion chemistry, mass and size distribution determination. These sensors would minimize time and increase the potential for highly accurate chemistry determination.

During recycling, unwanted residual elements are inadvertently added to the liquid steel. Future developments will involve actively controlling reactive residual elements such as calcium, aluminum, magnesium and zirconium and developing methods to minimize the effects of other non-reactive residuals.

Ladle refining vessels demand refractory lining systems that are environmentally sound and low in cost in addition to being chemically inert and operationally safe. The refractory lining must also be easily and expeditiously installed. In the future, landfilling of spent refractories will not be as affordable or permitted to the extent it is today.

Metallurgical barriers deal with the development of processes to meet a given product requirement where a solution is possible, but not yet proven or practical.

In the area of process technological barriers, affordable systems are needed that enable concurrent processing or eliminate unproductive time. The future of ladle metallurgical developments include the development of rapid or continuously operating sensors for steel and slag chemistry and temperature, as well as inclusion mass and size distribution determination. These sensors would minimize time and increase the potential for highly accurate chemistry determination.

Other challenges are as follows:

Slag control, manipulation, and recycling. Future developments in slag usage will involve slag recycling and reuse within the steel plant in order to minimize waste. Manipulation of slag viscosity and solidification characteristics will lead to slags that are not easily emulsified but easily removed from the ladle.

Inert or long life refractories. Steel and slag interaction with container refractories remains a limitation of ladle processing.

Temperature control. Techniques for stream temperature prediction and control are necessary.

Modeling. Coupled heat and mass transfer models are necessary to allow prediction of the effect of ladle metallurgy on chemistry and inclusion control. Current computational abilities could enable a ladle model that would include heat transfer with the container and the slag, reaction between the steel and the slag, reheating, degassing, and refining.

Yield. New ladle design and other methods to prevent metal mixing during ladle draining are necessary to increase yield from the ladle and preserve quality. Vortex prevention, development of repeatable free opening performance, and design are key components of this technology.

Productivity. Future developments in steel plant design will include better matching of steelmaking casting and rolling mill productivity, significantly reducing ladle refining times in the future. Thus, rapid refining methods, rapid chemical sensors, and new linings at the ladle metallurgy station must be developed to meet the new ladle refining productivity requirements.

New and Emerging Technologies. Work continues on engineering steels with fewer harmful inclusions, desired inclusion composition and morphology, and ultra-low residual element content. For many of these goals, the key steps are known for the process (i.e., desulfurization and dephosphorization). For others, such as simultaneous desulfurization and dephosphorization, the process has only been conceptualized or tested on a laboratory scale.

New technology and automated processes are being applied to analysis and reporting to minimize cost and time. A laser-based immersion probe system that provides elemental analysis within a minute is one new technology being tested.

2.5.1 Ladle Refining Research and Development Needs and Opportunities

R & D Needs

Ladle Refining

- Alternative forms of carbon or better addition method to improve the carbon dissolution rate
- Minimized component process times or develop parallel/concurrent processing methods
- Better sensors and control systems for chemistry, cleanliness, and temperature
- Methods to limit exposure of steel to air
- New fluxing agents and inclusion modifiers

There are two areas in which alloying material improvement would improve refining. The first opportunity is the slow dissolution of carbon which retards recovery and causes the uncertainty of subsequent analysis. An alternate form of carbon or better method of addition could improve the dissolution rate.

To improve the flexibility of ladle refining, component process times must be minimized or the processes must be executed in parallel. For example, sampling and analysis time must be minimized, and reheating and degassing must occur concurrently.

New fluxing agents and inclusion modifiers could be developed. These might either flux undesirable residual elements or tie them up in engineered inclusions that impart beneficial properties.

2.6 Casting

Steel casting processes represent one of the major areas of technological development within the steel industry. New technologies such as strip casting are under rapid development and commercialization. The steel industry is undergoing major changes in North America due to the growth of these new technologies as companies realize that specific technologies are appropriate for specific markets and that product-specific casting technologies will have a role in the near future of steel plants. The advent of strip casting for carbon and alloy steels and near-net-shape part production could radically change the conventional view of a steel plant from a large production facility of semi-finished material into a smaller, product-oriented concern. Continuous casting has led to a major reduction in ingot steel production. In 1995, 97.4% of the crude steel production was continuously cast. However, ingot casting continues to be the preferred method to produce steel for some uses, such as intermediate and large bar applications (e.g., power transmission) and high-performance bar and tubing applications (e.g., bearings and gears). Foundries and specialty producers also continue to use ingot casting and to produce large cross-sections or thick plates.

Figure 2-4 outlines schematically current and potential directions in casting. Current technologies include ingot, thick slab, thin slab, billet and bloom casting. Future developments will lead to ultra-thick slab casting for thick plates, direct strip casting for sheets 0.03 to 0.15 inches thick, continuous casting products with fewer inclusions, rod casting, rapid prototyping of complex geometries via droplet consolidation or laser/wire technologies, rheocasting, and direct part fabricating via computer-controlled casting/milling machines.

New and Emerging Technologies. Commercial strip casting of carbon and stainless steels at Nucor Crawfordsville by the end of 2001 represents a major new technology in flat rolled steel production.

2.6.1 Generic Casting Issues

Trends and Drivers. Future developments largely will be directed towards the technology associated with continuous casting. All other technologies, including ingot casting, will have specific niche markets in the next 10 to 20 years for economic or quality considerations. The technological drivers for current operations are increased productivity, yield, and quality.

New technologies are driven by:

- Low capital and operating costs
- Flexibility
- Niche markets
- Potential for new product development

In addition, casting developments will need to consider environmental factors and recyclability of waste products, such as wastewater, refractories, and slag.

All of the above requirements drive casting development towards more streamlined near-net-shape processes. This results in the cast surface becoming the finished part surface and leads to the necessity of defect-free castings that must be produced at geometrical tolerances defined by the end product. Strip cast products will undergo little or no rolling. Research on as-cast structure and properties is required. New alloys and alloying techniques may be needed for strip cast products to develop properties comparable to conventionally cast products. This progression results in a number of generic requirements in casting R&D.

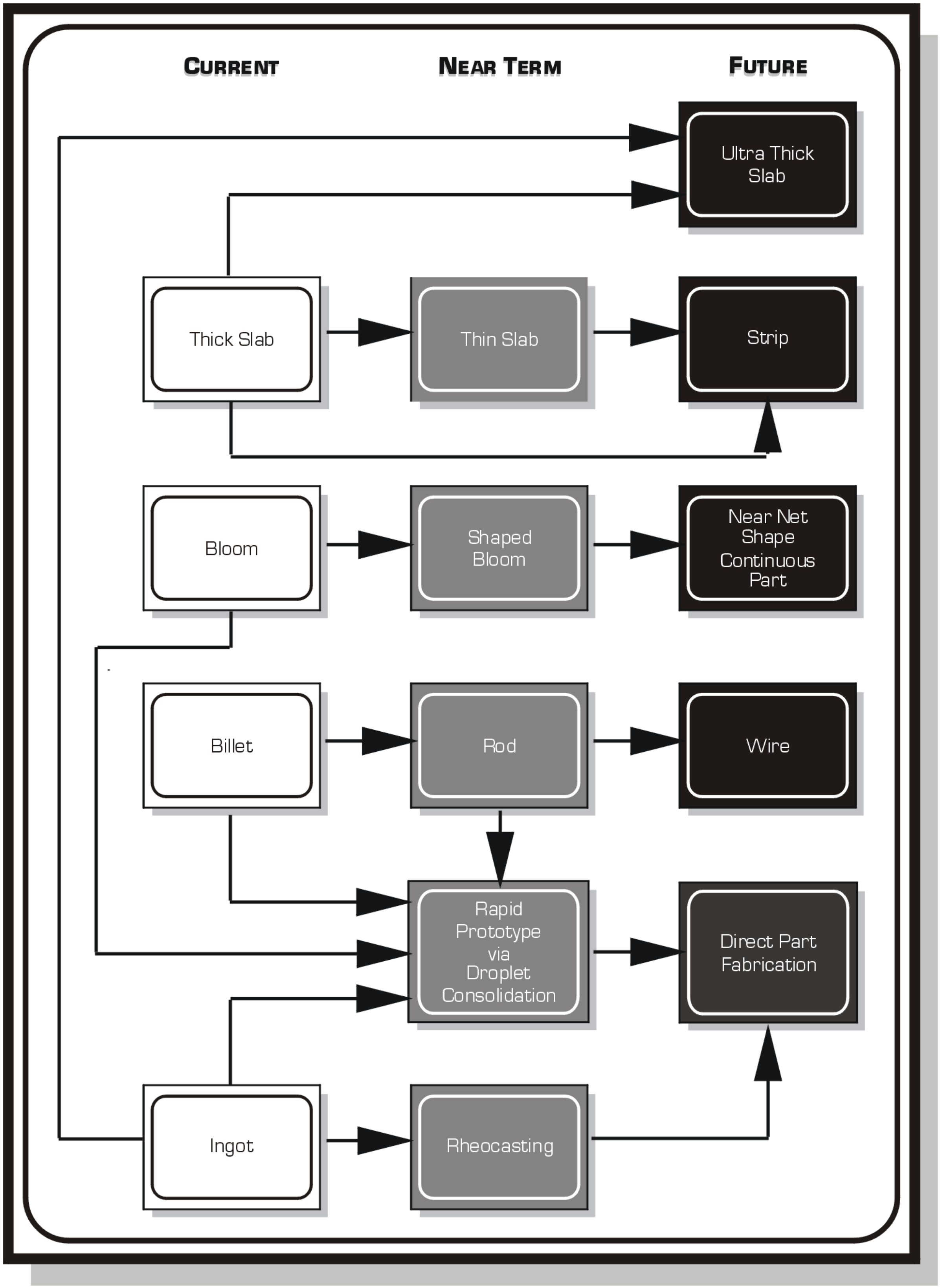


Figure 2-4. Current and Potential Future Casting Strategies

Technological Challenges. Modern continuous cast steels must be consistently produced to the highest level of quality. The presence of inclusions or clusters of inclusions greater than the minimum size for defect formation, or of the wrong chemistry, often leads to inconsistent product quality.

Nozzle clogging is a common operational occurrence that can result in quality and production problems when steels containing solid inclusions are cast. One solution to this problem is to transform the solid inclusions by chemical treatment to a liquid or a non-clustering solid inclusion. This "inclusion engineering" is often not achieved in practice, as the exact stability of all possible inclusions must be calculated for a particular alloy to ensure that the designed inclusion chemistry is achieved. "Inclusion engineering" will lead to the design of new alloys with alternative processing strategies to achieve specific properties, as well as retention of desirable inclusions.

There is a lack of economical materials for containment vessels and molds that are sufficiently inert, long-lived, and able to withstand large thermal gradients.

Active control of fluid flow and temperature is necessary to avoid the production of defects during casting and to ensure product consistency. Current gravity-fed flow systems only allow gross control of the above parameters, not independent control of flow and temperature in the tundish and mold of a continuous caster. Process consistency is essential for a successful casting operation. Extensive automatic on-line monitoring of cast processes can significantly improve process control and process consistency.

Instead of having cast surface defects or imperfections removed by grinding, oxidizing, or treating, technology must be developed to eliminate casting or oscillation marks. As these casting technologies develop to the point that cast surfaces are used directly, casting an exact geometrical shape to tolerances measured in smaller units than those used currently will also become more important. Therefore, the ability to predict and control the exact geometric profile of a casting will become vital to the design and operation of casting machines.

Operators do not always have the most up-to-date information when operating a caster. Sophisticated casting machines require a detailed knowledge of the science and engineering principles involved in the design and operation philosophy of the machine in order to solve any problems that occur.

New and Emerging Technologies. Strip casting (discussed in Section 2.6.3) is the most obvious new technology. However, there are a number of ancillary technologies that are under development for currently operating casters that could potentially be adopted in the future. These technologies include:

- Applications of electromagnetics in the area of fluid flow control, heating, and containment
- Advanced vision systems for defect detection and identification
- Advanced computer diagnostic controls
- Liquid steel temperature control in the mold and tundish
- Advanced ceramics for clean steel production

Future developments will focus on near-net-shape production of all castings and droplet consolidation technologies for rapid prototyping and rheocasting.

2.6.2 Slab, Billet, and Bloom Casting

Trends and Drivers. Issues in casting are related to productivity, operating cost, quality, and the energy content of the cast piece before rolling. Issues vary between thin and thick slab casters; however, there are a number of common issues, especially in the areas of control and quality.

Some specific trends include:

- Increasing strand cleanliness
- Thinner cast slabs
- Net Shape
- Higher cast speeds

Technological Challenges. The demand for steel with increasing cleanliness requires that metal with a low oxygen content be delivered to the caster, protected from exposure to the atmosphere, and exposed to minimal contamination from the refractories, tundish, and mold fluxes.

The materials systems used to contain and conduct the steel must be stable with respect to any steel grade and not add to the inclusion population. They also must be cost-effective and capable of long exposures associated with sequence casting. The tundish fluxes must have the proper fusing temperature and fluidity and not be corrosive to the refractories, while providing protection from reoxidation and the ability to capture inclusions. Flux design for continuous caster operation continues to be a difficult issue because the tundish and mold flux requirements are complex and there is not a complete understanding of the exact design requirement for fluxes.

Nozzle clogging remains an issue that impacts productivity and quality in casting. A solution that allows the casting of steel grades containing solid second-phase particles will ensure consistent production of aluminum-killed steels.

There is a lack of refractories for use in the ladle, tundish, and molds that are sufficiently long-lasting, stable, and non-porous to allow cast quality to reach its full potential. Ultra-clean steel production is limited by refractory interactions with the steel.

Higher surface quality of castings would allow the cast surface to be used directly in all applications without modification. Mold friction, surface defects (including meniscus marks), sub-surface defects, and argon and other bubbles are all quality problems that require attention.

2.6.3 Strip Casting

Cast speed in strip casting can vary from 160 to 325 ft/min, while conventional casters operate between 3 and 20 ft/min. Strip casting is quite unique in that solidification occurs against a chill mold and the cast surface must be defect-free. Cast tolerances must be on the order of tens of microns (ten-thousandths of an inch) across the width and length of the strip. Strip-cast materials are significantly different from conventionally processed strip because they have not undergone hot reduction.

Strip casting has great potential in the production of very thin materials to achieve cooling rates which, on the average, are significantly higher than conventional casting technologies. In addition, inclusion size ranges tend to be suppressed in strip casting, and the recrystallized structure can be significantly different than conventionally processed material. This leads to the potential of casting a number of different alloys (especially those that are difficult to roll) that have not been previously considered in sheet form.

New alloys with novel structures, chemistries, and properties may be cast by this technique. Metallic glasses and materials with ultra-fine structures are possible. The development of strip casting of steels for electrical and magnetic applications also seems to be an obvious way to make use of the inherent structure of strip-cast materials.

Trends and Drivers. Because of its novelty, many fundamental phenomenon need to be studied. These issues are related to process control, consistency, productivity, and quality (including tolerances). Because of the high speed of strip casters, the control tolerances must be significantly tighter than in conventional casting processes.

Technological Challenges. The technological challenges associated with casting include process knowledge and control deficiencies. For example, the required cast tolerances for strip casting cannot be achieved without intimate knowledge of the variation of heat transfer with casting conditions.

Process control at high casting velocities is not possible without good data on the thermal conditions in the growing shell and in the rotating roll, better knowledge of initial solidification phenomena, and control strategies for strip profile and gauge at high speeds.

The need for control of fluid flow and temperature is even more severe in strip casting than in conventional technologies. There are problems with liquid steel control, process consistency, productivity, and ability to make different structures.

The strategy for conversion of a strip-cast structure to a structure that allows equivalent or improved properties for all strip applications is at this time unknown for all but 304 stainless steels.

New and Emerging Technologies. The advent of commercial production of strip-cast 300 series stainless steels by Nippon Steel in 1997 represents a major new technology. Commercial strip casting of carbon and stainless steels at Nucor Crawfordsville by the end of 2001 is an important new technology in flat rolled steel production.

2.6.4 Casting Research and Development Needs and Opportunities

Some generic casting R&D needs have been identified, as well as specific R&D needs for slab, billet, and bloom casting and strip casting.

Generic

The ability to produce liquid steels with strictly controlled inclusion contents needs to be developed. This ability is necessary to restrict inclusion size to less than 0.0002 inch in diameter and to minimize the total mass of inclusions. In this area an understanding of the interaction of fluid flow at the slag-metal interface must be developed and modeled to eliminate formation and facilitate the removal of inclusions during processing.

Techniques need to be developed so that stability diagrams can be calculated for all grades of steel. This will allow the exact stability of all possible inclusions to be calculated for a particular alloy to ensure that the designed inclusion chemistry is achieved.

Process control research presents many opportunities for casting improvement. The ability to monitor and actively control fluid flow, temperature, and chemistry would improve casting performance. Given the high cost and reliability issues associated with wiring in the harsh environments common to the steel industry, sensors that emloy wireless technology to communicate data and diagnostic information could be beneficial to the infrastructure of iron and steel manufacturing facilities. Fluid mixing control in which mixing of unlike grades can be either enhanced or minimized in the tundish or mold, is also a necessary development to allow seamless grade transition and order size that is better matched with optimum heat sizes. Other needs include advanced process control strategies, vision systems for defect detection and identification, and the implementation of advanced computer diagnostic controls for identification of potential operation problems and the scheduling of maintenance.

R & D Needs

Casting

- Ability to produce liquid steels with strictly controlled inclusion contents
- Techniques to calculate stability diagrams for all grades of steel
- Ability to actively control fluid flow, temperature, and chemistry
- Ability to monitor the process to ensure consistent quality
- Improved surface quality through improved mold oscillation using hydraulic oscillation
- Ability to predict cast shape, inclusion, or bubble distribution and structure
- Advanced heat transfer and fluid flow models
- Techniques to minimize scaling or develop scales that are easily removed in post processing
- Enhanced education on the science and engineering principles involved in the design and operation of casters
- Direct rod or wire casting at high rates and production directly from liquid steel
- On-line control systems
- Development of products associated with thin slab rolling in the 2 phase (alpha & gamma) field
- Development of a heavy rod casting process with in-line rolling to variable diameters

The details of cast shape, inclusion or bubble distribution, and structure in three dimensions are currently unknown. Development of modeling techniques is required to gain a detailed knowledge of surface formation in castings, an area that has been somewhat ignored in conventional casting, and to predict on-line the details of micro- and macro-structure solidification and the inclusion or bubble distribution in the casting.

Advanced heat transfer and fluid flow models that include the free surface of liquid/liquid boundaries, the prediction of slag emulsification; the final position and shape of the cast surface; and a detailed prediction of cast structure, inclusion, or bubble distribution and segregation patterns are necessary. In addition, a detailed understanding of the interactions between steel shell, the flux, and the interface of the mold is necessary.

Processing techniques need to be developed to improve quality and production rates. For example, techniques are needed to either minimize scaling or develop scales that are easily removed in post processing to maximize yield and eliminate scale-related defects. This problem will increase in severity as castings become thinner and closer to a product dimension. Also, technologies are needed to produce direct rod or wire casting at high production rates directly from liquid steel, possibly through droplet consolidation or rheocasting.

Finally, more education is needed on the scientific and engineering principles involved in the design and operation of casters. A strong foundation in traditional engineering disciplines and metallurgy will be a necessary requirement for caster operation.

Slab, Billet, and Bloom Casting

Areas of development in slab, billet, and bloom casting include total inclusion content, mold design improvement, appropriate refractory systems that are less prone to clogging, and optimized fluid flow and heat transfer within steel pouring systems. This includes the need for stable refractory systems that will enable the next level of cleanliness to be achieved.

R & D Needs

<u>Slab, Billet, and Bloom Casting</u>

- Methods of reducing total inclusion content
- Improved bulk fluid flow and meniscus control, optimized mold flux design and heat flux control in the meniscus area
- Flux design improvements
- Nozzle development to allow a very controlled, stable fluid flow into the mold
- Fluid flow control and stream shrouding techniques for small-section billet casters
- Mold designs to control billet shape and to allow for increased cast speed and improved quality

Bulk fluid flow and meniscus control as well as optimized mold flux design and heat flux control in the meniscus area are needed to achieve improved surface quality. The production of a smooth cast surface without meniscus marks caused either by electromagnetics or the development of a "hot-top" mold may lead to the elimination of certain subsurface defects, especially at high casting speeds. The elimination or complete removal of argon and other bubbles from cast steels must also be developed to produce ultra-clean steels that are beyond the quality levels currently produced.

In the area of flux design, work is needed on flux crystallization phenomena, flux physical and chemical properties, and flux compatibility with liquid steel, refractories, and other surroundings. Nozzle development must continue to allow a very controlled, stable fluid flow into the mold that does not encourage mold slag emulsification and decreases the tendency of nozzle clogging.

Mold designs that incorporate instantaneously controllable taper and temperature profile are needed to control shape and allow further increases in casting speed. Technologies must be developed to improve surface quality so casting can be used for all applications without surface grinding or treatment. Also, soft reduction needs to be investigated as a potential technique to produce sound structures in near-as cast state.

Strip Casting

Strip casting R&D needs include gains in process and technical knowledge as well as control systems and techniques. One need is more complete knowledge of the variation of heat transfer with casting conditions and alloy chemistry. The details of the initiation of solidification and the effect of mold coating and texture on this phenomenon must be known to improve product quality.

R & D Needs

<u>Strip Casting</u>

- Knowledge of the variation of heat transfer with casting conditions and alloy chemistry
- New models, sensors, and control systems
- Novel techniques of liquid flow control
- Applications of strip casting for conventional and novel alloys
- Post-processing steps necessary for strip-cast material to have better mechanical properties than conventionally processed materials
- Determined inclusion engineering requirements

New models, sensors, and control systems are needed for process control at high cast velocities. The development of comprehensive heat transfer, fluid flow, and solidification models will also allow the thermal conditions in the growing shell and in the rotating roll to be defined and enable in situ compensation or correction for roll distortions.

Novel techniques of liquid flow control also need to be developed. Techniques to control fluid turbulence within the pool of a twin roll caster will result in improved process consistency. In addition, development of rheocasting or a superheat removal technology for use in the entry nozzle of a strip caster will lead to enhanced productivity and novel strip cast structures.

Another need is the development of the post processing steps for strip cast material to have equivalent or better mechanical properties than conventionally processed materials. For example, techniques can be developed to achieve texture control in strip cast materials without significant reduction in thickness of the strip.

2.7 Rolling and Finishing

Rolling and finishing convert cast or semi-finished steel into finished products that meet specific requirements for shape, mechanical behavior, and other properties. Rolling is performed both hot and cold. Finishing operations are often product-specific heat treatments, such as spheroidizing, normalizing, or annealing, or surface treatment operations, such as galvanizing, electroplating, carburizing, machining or surface induction treating.

Because rolling and finishing operations are often the last processes to significantly affect the bulk microstructure of the steel, they must be designed to give appropriate or optimized microstructures capable of yielding requisite properties.

Advances in steelmaking, casting, rolling, and finishing will redefine the combinations of properties obtainable from a particular composition, grade, or alloy. Defining the possible combinations of properties and the appropriate markets for evolving steel products should be the focus of considerable future efforts in rolling and finishing.

2.7.1 Rolling and Finishing– General

Trends and Drivers. Improvements in upstream processes are expected to have a dramatic effect on the shape and internal cleanliness of the semi-finished and finished products. Future developments will focus on obtaining the requisite microstructure and properties in light of process developments and essential service requirements.

The factors with the greatest influence on rolling and finishing include as-cast shape, improved process control, residual element content, and improved internal cleanliness. Microstructure control remains one of the most basic objectives for the selection of working conditions. Accelerated cooling, inter-stand cooling, and direct quenching technologies are also being used to refine the base microstructure and alloy carbide and nitride phases.

Heat treatment and chemistries are evolving with the goal of reducing the size and/or volume fraction of precipitates and inclusion particles. For many grades of steel, a major objective is grain refinement for strength and toughness. While near-net-shape casting reduces the amount of reduction that can be used to homogenize the microstructure, it also provides faster solidification and cooling rates, which limit the growth of second-phase particles.

For severe fracture critical applications, opportunities for grain refinement through hardenability will continue to emerge. The effect of residual elements and inclusions on hardenability remains an active area of research.

Microalloyed grades will continue to expand into markets, increasing the need for improved fracture resistance. Ways of strengthening thick sections with this approach and improving fracture resistance will be needed. Greater toughness and strength occurs concurrently with the refinement of second-phase particle distributions. Also, reduced carbon content and higher nitrogen contents are generally found to improve microstructures and range of property combinations pertaining to weldability, wear resistance, and fracture. Fixing processing temperatures and deformation passes to create a fine-grained austenite structure has become standard practice for products requiring higher strength and toughness.

In many instances, particularly when substantial hot deformation is required, energy savings are realized when as-cast or as-rolled products are immediately transferred to the hot rolling or forging soaking stations. Hot charging is increasingly being incorporated for process streamlining and energy savings.

Customers continue to drive rolling and finishing process developments. One example is the development of value-added products, such as metallic-coated, organic-coated, pre-lubricated, pre-painted, or powder-painted sheet steels, offering the customer process simplification. Customers require information to understand the technical issues associated with processing capabilities and property limitations. In the drive to facilitate informed decisionmaking, communication is increasingly more technical; metallurgists are often hired into sales positions.

Automation and step-by-step verification of heat treatment, galvanizing, and other processes have also been developed to improve product consistency. Developments of new sensors for measuring chemistry and temperature variations are also being sought. Computer models of thermal and stress distribution in parts, permitting selection of process parameters, have also been recently developed and allow prediction of residual stresses.

The following trends are indicative of the drive to improve the intrinsic engineering properties of steels and to reduce processing costs. Due to the continuing improvements in steelmaking and casting, property advancements continue to occur in weldability, formability, strength, corrosion, wear, and fatigue resistance. Reduced material costs allow the use of high-residual element-containing scrap and investigations into the effect of residual elements on properties.

Continued advances in the area of thin slab and strip casting will diminish the role of the hot rolling mill in the production of thinner strip. However, optimizing rolling mill performance will become increasingly critical. Current research focuses on understanding and controlling kinetic and thermodynamic aspects of the solidification, heat transfer, and mechanical behavior of stainless steels. Extension of ferritic grades will be further complicated by phase changes.

Technological Challenges. Many specific barriers to major advances in rolling and finishing exist, including inadequate characterization methods and models, as well as a lack of methods to quantify hydrogen content. The optimization of bake-hardening and mitigation of cold work embrittlement are limited by a lack of suitable methods capable of characterizing the influence of alloying and residual elements on the activity and thermodynamic behavior of carbon and nitrogen at very low concentration limits.

A lack of reliable, material-specific input data limits prediction accuracy of heat treatment and quenching models. Data for iron and alloy transformation behavior under stress need to be generated as do data for iron and alloy oxide heat transfer coefficients. Also, prediction accuracy of deformation (rolling, extrusion, etc.) models on quantitative microstructure-property relationships is limited. There is no framework within which complex materials information can be easily and confidently evaluated with respect to design, fabrication, and service.

In the finishing area, the life of molten bath hardware (e.g., rolls and bearings) used in the hot dip coating lines, such as galvanizing or aluminizing, is a serious concern. Because of the aggressive nature of the molten baths in these processes, the hardware lives are presently very short (in the order of a couple of weeks), which requires costly shutdowns of the continuous processing lines to replace the hardware.

An additional challenge is hydrogen, which remains a major concern because it contributes to lower fracture resistance and poor coating adhesion. Methods for reliably quantifying hydrogen content down to sub-ppm levels continue to be sought.

New and Emerging Technologies. Some recent developments in the area of rolling and finishing include models of steel microstructure and properties, methods to improve texture control and strength, and technologies to improve heating during finishing.

Recent studies have been directed at modeling the effect of thermal deformation conditions on microstructure and properties of steels produced in the hot strip mill. Advances in this direction must continue in order to obtain reliable and easy to use microstructure and property models. Once models have been verified, extension of the analysis to more sophisticated grades will make well-grounded process modifications possible. This modeling has also been used for optimization of bar and tube rolling.

Ferrite or warm rolling has been tested and shows promise as a means to impart essential shape change as well as texture control and strength to strip and plates. Good lubrication is essential in order to prevent through thickness texture variations. Ferrite rolling may require higher mill loads. However, the benefits to the resulting microstructure have not been completely documented.

Inter-stand cooling in the hot mill offers new temperature control flexibility and expands the attainable combinations of finishing temperatures and mill speeds. Further modeling of cooling of all products shapes are needed. Also, rapid heating technologies now permit heating rates in excess of 3600° F/second in thin sections. This is a novel thermal process for which the benefits have yet to be quantified fully.

Hot dip galvanizing production of bake-hardenable steels represents an advance that should combine the strength and room temperature aging resistance of batch annealed EG (electro-galvanized) bake-hardenable steels with the corrosion resistance and cost savings associated with hot dip galvanizing for automakers (exposed).

2.7.2 Rolling and Finishing– Plate

Trends and Drivers. Trends in plate rolling and finishing include:

- Continuous processing mills to achieve maximum efficiencies
- Advancement of computerized automation in melting and rolling operations
- In-line, direct detection and classification of surface imperfections in hot conditions
- Accelerated cooling after rolling to achieve enhanced properties and to harness all potential benefits of an in-line cooling process

Continuous processing techniques for plate include closer coupling of casting and rolling, the use of accelerated cooling or direct quenching, and the use of Steckel mills. Steckel mills are used to produce lighter-gauge coiled plate products and to provide good temperature control during rolling as well as good flatness and shape. Temperature retention provided by hot coiling on either side of the rolling stand eliminates the rapid loss in temperature experienced in standard reversing plate mills and the attendant high mill loads and shape problems.

The long-term impact of Steckel hot-rolling technology will be significant. A large portion of the market currently served by traditional plate mills will be serviced through new wide/heavy cut-to-length lines with plate-in-coil sourced from Steckel mills and from conventional hot strip mill facilities with new, more powerful coilers. As production shifts to these new sources, customer expectations will be significantly higher.

In terms of computer automation, the new and revamped mills servicing the plate market will feature highly sophisticated level 1 and 2 process control similar to that currently operating in modern hot strip mills. Process control will also be more fully deployed downstream from the mill in value-added processes such as shearing, trimming, leveling, burning, laser-cutting, and heat-treating.

Competitive mills will also feature an increasing degree of process/systems integration at the manufacturing plant level as it becomes necessary to balance competing demands for quick response times, minimal work-in-progress inventory, high capacity utilization rates, high yield, and process flexibility.

The in-line detection of surface imperfections during hot rolling has been examined for hot strip mills with moderate success. The application of these techniques to plate mills would be a natural extension, to Steckel mills for example, but even reversing plate mills should benefit from this technology.

More plate manufacturers are using in-line accelerated cooling after rolling to enhance the strength or toughness of the as-rolled plate. In-line accelerated cooling is often referred to as interrupted accelerated cooling because the plate is water-cooled to an intermediate temperature, then removed from the cooling facility and allowed to self-temper and/or precipitate-harden during air cooling. The process requires controlled rolling of plate before the accelerated cooling from approximately 1,450 to 1,000^{o}F to achieve its maximum benefits.

In-line accelerated cooling has traditionally been used in the continuous hot strip mill to produce strip mill plate. Over the last twenty years, it has been increasingly used in plate mills, and more recently in the Steckel mill process. Plate mills throughout the world use in-line accelerated cooling to produce low-carbon line pipe and ship plate with improved weldability, and this technique is being applied more and more to light-to-moderate thickness structural plates for similar reasons.

Plates that are controlled-rolled and accelerated-cooled exhibit a lower yield-strength-to-tensile-strength ratio than heat-treated plates. Low yield/tensile ratio is of particular importance when bridges and other structures must be constructed in earthquake-prone regions where maximum plasticity is required of plates and structural components. Yield strengths of 80 ksi and higher have been achieved in relatively light-gauge plates of low-carbon steels that have been controlled-rolled and accelerated-cooled.

Interest has increased in plates that are too long to be heat-treated. Plates longer than about 52 feet cannot be water-quenched by domestic plate producers. Bridge fabricators, for example, would welcome longer plates that do not have to be splice buttwelded with the attendant welding and inspection costs. Accelerated-cooled plates are one of the possible solutions to providing long plates in as much as they are totally processed in-line and are not heat-treated.

Technological Challenges. Centerline segregation in plate grades causes cracking during welding and joining and local variations in stress relief. This could be minimized if centerline segregation were better understood and predicted. However, most solidification models for centerline segregation have been developed in Japan where most major steelmakers utilize soft reduction capabilities in their slab casters.

Because very few casters in North America use soft reduction on slabs to improve center segregation, their use of solidification models is limited. Most solidification models in the North American steel industry generally treat only the thermal/mechanical and occasionally fluid mechanical aspects of solidification. Segregation modeling is mostly conducted at the university level.

New and Emerging Technologies. The new and emerging technologies for rolling and finishing plate were included in the Trends and Drivers discussion.

2.7.3 Rolling and Finishing - Rod and Bar Products

Rod and bar mills convert various shapes and lengths of semi-finished billets into hot rolled-as-rolled shapes. The shapes may be rounds, flats, squares, hexagons, or reinforced concrete bars. Rod and bar is manufactured to produce the characteristics specified by the customer.

These characteristics are classified by steel grade, dimensions, metallurgical properties, and qualities. These basic qualities are further defined for carbon steel (special quality) and alloys (regular quality). The basic qualities are used in many applications, such as hot forging and machining and structural uses. More critical qualities are specified in cold heading/cold extrusion, high carbon for tire cord and bead, wire rope, pre-stressed concrete, welding rod, and bearing applications. Merchant quality is specified for structural and less critical applications, such as reinforced concrete bar. The more critical qualities often require the HRAR rod or bar to undergo further processing, such as cleaning (mechanical or acid descaling), coating, quench and tempering, heat treating, straightening and cutting to length, surface inspection, internal soundness inspection, and surface removal.

Trends and Drivers. Market and customer requirements continue to drive rod and bar mills to improve product quality. One way to improve steel and billet quality is to use special melting and casting practices. An example is rolling at lower furnace exit temperatures to reduce decarburization levels. Also, the mills control the temperature profile so as to minimize the core to surface temperature differential of the section, producing grain refinement to enhance uniformity of physical properties. These as-rolled properties will respond to subsequent heat treatment as well as improve surface quality

Customers also demand rolling of larger billets to produce larger coil weights and improve the product yield of the coiled and straight bar products. These reduce customer and processor "set-up" times, thus reducing costs. Production of precise tolerance product in multiple sizes is an additional market need.

These practices and methods combine with downstream processing to positively affect the overall product quality of today's rod and bar products. These demands are responsible for higher manufacturing costs. Suppliers can overcome some costs by adding equipment with much faster production speeds and higher values of mill utilization to increase production capacity, improve product quality, reduce manning requirements and material costs, and thereby increase profitability. While higher production rates help decrease overall operating costs, the demands for cost control and consistency are still difficult to meet. Direct rolling to utilize satiable heat can help lower costs, as well as energy use. Other drivers include increased rolling cycle frequencies to reduce inventory and just-in-time delivery requests.

Technological Challenges. Future rod and bar suppliers will be forced to operate modular type, quick change rolling components that offer engineered set-ups, off-line technology for rapid mill start-ups, quick changeover times, precision sizing, and colder rolling capabilities. These components will require process control equipment to support customer driven menus, accurate and repeatable drive systems for tension free rolling, interstand cooling, and reduced roll and pass changes for equipment. The various types of modular equipment will not only provide high speeds and increased production rates, but they will also allow faster changes. These equipment design features will help decrease operating costs, and they will ensure consistency by allowing off-line setup, which greatly reduces errors, thus circumventing the tremendous cost of manning and training. Mill roll pass configuration should include "single family rolling" where only a single pass shape is utilized at each stand position in the roughing and intermediate trains to guarantee consistent setups in the rolling stands, increase mill utilization, and consequently produce tremendous cost savings.

New and Emerging Technologies. The rolling of large billet sizes in continuous rod and bar mills has brought about the increased use of breakdown mills which produce a "free bar" section (i.e., a bar of such length that when it exits the last stand of the breakdown mill, it has not started to enter the continuous train). This layout avoids excessively low entry speeds into the first stand of the continuous train. These breakdown mills are usually of horizontal/vertical layout configuration to avoid product twisting and thus minimize surface damage.

Rod and bar sizing stands are now available, offering many advantages regarding production, precise ovality, and "free size rolling" (the ability to produce other discrete sizes without roll or guide or pass changing). Quick change equipment means that these advantages can be achieved with a high level of mill utilization.

New developments in continuous/continuous billet rolling are surfacing. For example, "endless" rolling is achieved by "welding" billets together. This concept decreases the number of head ends, decreases the mill threading variables, reduces the opportunities for cobbles, and most likely increases mill yield. Endless rolling may lend itself well to present merchant quality products. If it can be perfected and applied to higher quality levels, the technique will surely help reduce process costs.

Further downstream processing costs can be off-set and eliminated by combinations of chemistry control, thermomechanical rolling, precision ovality, and sophisticated final product cooling menus. These attributes will either promote fine grain structure and the consistency of physical properties to greatly reduce the cost or eliminate heat treating.

Tight tolerance levels coupled with good decarburization control will also allow suppliers and customers to mass produce hot rolled-as-rolled parts of like grades into master sizes that can be subsequently surface prepared, or cold drawn, to the exact size needed for the respective part. This concept will alleviate mill changes, decrease overall inventory, allow longer shelf life (hot rolled-as-rolled inventory versus finished inventory), and meet the ever growing demands for just-in-time delivery.

Low-temperature rolling for grain refinement can be practiced with the latest equipment designs. New equipment is being designed with quick change and/or traversing capability to minimize downtime when changing product sizes.

High speed bar delivery systems, including special high speed shears for cutting in-line head and tail-ends, reduces inherent end conditions delivered to final stand/pass set-ups and the need for extensive trimming. Thus, the systems positively affects factors such as time, manpower, and worker safety.

2.7.4 Rolling and Finishing Research and Development Needs and Opportunities

The following list provides research topics that will advance rolling and finishing technology.

Characterization of thermodynamics and kinetics of phase transformations under stress. Determine the influence of stress on the decomposition of austenite and other transformations. The stress induced by physical constraint, gradient cooling rate, and point-to-point composition variations will influence the transformation and the microstructure evolution.

Sheet steels with good room-temperature aging resistance and bake hardening values in excess of 15 ksi. Examine the interrelationships among temper rolling strain, interstitial solute content, and the factors that control the return of the yield point. Expanding the obtainable combination of bake hardening values remains an active area of interest; the high dissolved carbon contents responsible for good bake hardening values decreases rate sensitivity.

Al-N particles and of alloy carbonitride particles. Establish conditions and limits for modification and refinement. Both direct quenching after hot working and sub-critical annealing before quenching and tempering have been used to modify second phase particle size distributions, thereby affecting strength and toughness favorably.

Influence of alloy and residual elements on the solubility and precipitation of carbide and nitride phases. Answer a number of basic questions through the application of techniques such as internal friction to measure the dissolved carbon and nitrogen. Such data can help refine model input and verify microstructure evolution during processing and/or service.

Material property characterization and the development of new coatings. Research directed at shape changing and surface modification technologies should continue in this area. Optimal conditions for forging and rolling and application of wear-resistant surface coatings depend critically on steel composition. The influence of residual elements needs to be documented to help establish appropriate processing maps.

R & D Needs

Rolling and Finishing

- Characterization of thermodynamics and kinetics of phase transformations under stress
- Sheet steels with good room-temperature aging resistance and BH values in excess of 15 ksi
- Determination of the conditions and limits for modification and refinement of Al-N particles and of alloy carbonitride particles
- Definition of the influence of alloy and residual elements on the solubility and precipitation of carbide and nitride phases
- Characterization of material properties and new coatings for shape changing and surface modification technologies
- Closed-loop control of heat treatment processes and deformation processes
- Methods to effectively communicate the interrelationship between end properties, production route, microstructure, and cost
- Development of longer-life molten bath hardware for hot-dip metallic coating processes
- Development of coating surface modification and surface alloying during the hot and cold rolling operations
- Elimination of acid pickling by finding ways to hot roll steel without scaling or economically remove scale mechanically
- Investigation of reduction ratio vs. microstructure and final properties for very thin and near-net shape cast products

Closed-loop control of heat treatment processes. Feedback from suitable microstructure sensors must be used to actively adjust process parameters. Systematic microstructure-property relationships should be established and correlated with the sensor output to ensure accuracy. These processes will reduce piece-to-piece variability and rejections.

Methods to effectively communicate the interrelationship between end properties, production route, microstructure, and cost. Research should be directed at developing a flexible scheme in which different processes and products can be evaluated and compared. Such a scheme would also be easy to use and include a degree of flexibility to accommodate different process routes and/or modifications of existing processing routes.

Continuous processing mills. The closer coupling of casting and rolling can involve hot and warm charging or, for light-gauge plate, a mini-mill concept of an intermediate strand cast thickness and a tunnel furnace followed by a finishing mill (either reversing or continuous). Such close coupling of casting and rolling would require an excellent cast surface or means to in-line surface condition.

Hot surface defect detection. In-line direct detection and classification techniques would improve detection of surface defects in hot and cold rolling operations.

Accelerated cooling. A need exists for accelerated-cooled plates or some other method of providing plates longer than approximately 52 feet that do not need to be heat treated.

Solidification modeling. Robust technologies for "soft reduction" at the caster would help achieve required through-thickness properties at 2:1 reduction or less. Solidification modeling may also potentially eliminate unsound centers and voids in casting.

Slab-reduction models. "Schedule-free" rolling technologies for applications in wide mills would improve production.

Hot steel identification technology. Technology needs to be developed that is not destroyed by processing (heating, rolling, shearing, parting, heat treatment).

On-line non-destructive evaluation technology. New technology could allow quick and accurate verification of mechanical properties and surface appearance.

Development of corrosion resistant hardware material for use in Galvanizing, Galfan, Galvalume baths. Galvinizing, Galvalume, and aluminizing are some of the popular methods of corrosion protection for steel. Molten metals are very aggressive in attacking the bath hardware, and often the galvanizing bath requires shutdowns after only ten days of operation. For Galvalume and aluminizing, the molten metals are even more aggressive, and the shutdowns occur after less than ten days of operation. The shutdowns are costly and done in order to replace the corroded hardware, among which bearings are replaced most often. There is high priority R&D need to develop cost effective molten metal hardware material for life extension by at least an order of magnitude.

Corrosion remains a high priority for the steel industry. Understanding the phenomena of corrosion in varying environments, including sensors and test methods to characterize corrosion, are very important. Such tools and techniques will lead to new steels and coatings that resist corrosion, a major factor in steel rejections and failures.

2.8 Refractories

Refractories are broadly defined as materials that have been engineered to withstand high temperatures and often highly corrosive environments. A range of refractory types are used for the working and safety linings of steelmaking vessels and for flow control of the molten steel.

Refractory materials are modified continuously to meet the evolving needs of the steel industry. As new advantageous processes and procedures are adopted, refractory modifications or new developments are required. Once the improved refractory has been engineered to withstand the service conditions, steel producers make additional changes to further increase productivity, improve cleanliness, or reduce costs, all of which require further modifications to the refractory. This cycle has been repeated for decades, leading ultimately to the steelmaking processes and associated refractory materials that are considered standard today. So long as improved steelmaking processes are developed and improved refractory materials are available, this trend will continue indefinitely.

Appropriate refractory selection is critical as productivity, energy efficiency, and manufacturing and labor costs are affected by the overall performance of the refractory linings. This dependence of steelmaking on refractory materials has two key ramifications: research that yields enhanced refractory material performance or reduced installation time will benefit the steel industry; refractory/containment material performance (reduced consumption) will affect steelmaking research.

Refractory research topics will not focus on furnace applications because improvements to refractories used in steelmaking furnaces offer less benefits than those used in blast furnaces, ladles, degassers, tundishes, and continuous casting refractories.

Trends and Drivers. The trends and drivers associated with the refractories used in the steel industry are as varied as the materials and applications for which the refractories are used. In general, reduced manufacturing costs per ton of steel produced and increased steel cleanliness drive enhancement of existing refractories and the development of new refractories.

Manufacturing cost reductions can be achieved by reducing initial refractory cost, extending refractory lining campaigns, reducing vessel tear-out and reline duration (lower production losses), and reducing or eliminating refractory disposal costs through reuse of the materials. Production of “clean steel” can be achieved by developing refractories that are inert to the steelmaking process or by establishing techniques to remove refractory inclusions from the steel. Other drivers include limiting the amount of landfilled refractory material and the need to measure high-temperature refractory properties in models used to design steelmaking vessels.

A general shift to monolithic, including castable, refractories is ongoing, and this trend is expected to continue until all refractory linings are based on cast-in-place technology.

Technological Challenges. Submerged entry nozzles (SENs) are a specialized group of refractories is used for molten steel flow control. These include nozzles and slide gates as well as other refractory materials that guide and protect the molten steel from the ladle through the tundish and into the caster.

The SENs are used in steelmaking to prevent reoxidation of molten steel directly from stream contact with the surrounding environment and from air entrainment and splashing when the molten stream strikes the liquid surface in the mold. Accretion formation and the associated clogging of tundish flow control systems is a major problem that leads to decreased strand speed, premature changing of SENs, or casting termination as well as the associated reductions in productivity, consistency, and steel quality.

Castable and monolithic refractories have been used successfully as linings for many steelmaking vessels. Castable linings have advantages such as reduced installation costs, limited/eliminated joints, and limited shape constraints. The main difficulty with castable materials in general is associated with removal of the moisture used to place the material. The low porosity and permeability inherent in the latest castable refractories can lead to explosive spalling or at least lining damage during dewatering. Effective dewatering procedures based on gas, electric, or microwave heating must be established in order to fully realize the advantages associated with castable refractories.

There is a lack of data on the types, quantities, and nature of refractories used throughout the steel industry, adversely affecting the development of recycling methods. Evaluating key engineering properties of refractory materials is so difficult and costly that producing relevant data has at times been impossible. Difficulties with making these measurements are either related to the way the test is conducted, costs, or to the material that is being evaluated.

Problems with the way the tests are conducted relate to the nature of refractory used because the temperature gradient that develops within the refractory during use must be accounted for when measuring properties. Sophisticated vessel design techniques being used require data on the temperature dependence of multiple engineering properties, such as modulus of rupture, modulus of elasticity, creep, and thermal conductivity. Because isothermal heat treatment of test specimens does not reproduce the phase development that occurs during use of the materials, the relevance of such data is questionable.

The presence of graphite, carbon, and/or metallic additives in steelmaking refractories further complicates measurement of high-temperature properties. Oxidation of the materials during testing often invalidates the test while likely damaging the test equipment. Operation in neutral-to-reducing conditions requires specialized equipment and does not prevent volatilization of various components within the refractory. The volatile components can damage test equipment and, since similar volatilization does not occur in normal use of the refractories, questions again exist about the validity of these tests.

New and Emerging Technologies. Steelmaking refractory development is moving away from the standard "single-component" materials to multi-component composite materials composed of high purity oxides, carbon, and graphite. Magnesia-graphite refractories (with and without metallic additions) have been used successfully in steelmaking vessel barrels and slag lines. Castable refractories, including self-flow types, are increasingly used to line low wear areas of steelmaking vessels while dry, vibratable, magnesia-based tundish linings have emerged as an alternative to sprayed magnesia linings.

New refractory placement techniques such as shotcreting have been found to provide superior properties over gunable or ramable materials while eliminating the need for expensive forms. Further advances in placement techniques are expected soon.

Slag splashing, although not a refractory issue by strict definitions, has gained wide acceptance as a way to dramatically increase BOF vessel lining campaigns. Coating the refractory lining with a modified slag and then operating with the new solidified slag coating has yielded campaigns in excess of 30,000 heats.

2.8.1 Refractory Research and Development Needs and Opportunities

Refractory research will focus more on applications "downstream" from the furnace in order to take advantage of the significant potential benefits that can be achieved through research directed towards ladle, tundish, and continuous casting refractories. This fact is clear when considering the refractory materials campaign durations for the various applications.

SENs, for example, may be replaced as often as once every two to four heats as compared to BOF linings that last many thousands of heats. Assuming a cost of $500 /SEN and three heats/SEN, a company would spend in excess of $2 million on SENs between furnace relines. This figure is even larger when considering other aspects such as the cost of physically replacing the SENs and the cost associated with decreased productivity and quality as nozzle accretion occurs. Similar cases could be made for ladle slag lines, tundish linings, and slide gates and shrouds.

Six refractory-related materials R&D topics present the greatest opportunities:

- Submerged entry nozzles that resist accretion
- Dewatering of monolithics
- Castable development
- Refractory recycling/landfill reduction
- High-temperature properties measurement
- Refractory wear gauge for steelmaking vessels

Submerged Entry Nozzles That Resist Accretion

SENs are often the limiting material in refractories used for molten steel control, so a program to address this issue alone is detailed in the following paragraphs. It is likely that advancements in SEN technology could be applied to other flow control refractories.

Characterization of Clogs. A detailed post-mortem microstructural analysis should be conducted to establish the prevailing wear patterns and accretion formation for the refractory nozzles currently used. Used nozzles should be sectioned in the area where accretion is most pronounced, providing a complete record of the phase formation as a function of distance from the refractory/molten metal interface. Data on accretion as a function of prevailing metallurgical conditions is essential for establishing the underlying mechanism(s) for SEN accretion

R & D Needs

Refractory Submerged Entry Nozzles that Resist Accretion

- Clog characterization
- Simulative tests
- Model to predict the location and rate of accretion
- Quantified degree to which molten metal wets a ceramic substrate

Simulative Test Development. The nozzle clogging phenomena is controlled by a combination of factors including steel composition, temperature, and flow characteristics through the nozzle area. A method for simulating the clogging of the nozzle interior is needed due to the cost and time constraints associated with field trials along with the potential for reduced steel quality and equipment damage. This simulation will allow rapid evaluation of candidate materials and metallurgical practices, providing insight into the mechanisms responsible for nozzle clogging and the amount of improvement that can be expected in field trials.

Mathematical and Finite Element Modeling. One of the greatest problems with controlling nozzle plugging is that it occurs in an enclosed area that cannot be observed during operation. This enclosure makes it difficult to determine the accretion formation mechanisms and the effects that practice or refractory changes make on the clogging or wear phenomena of the SENs. Flow modeling and finite element thermal analysis can be combined, and a new model can be created to predict the location and rate of accretion.

Contact Angle Measurements. The degree to which molten metal wets a ceramic substrate can be quantified by measuring the contact angle between the liquid metal and a flat and horizontal ceramic surface. Systematic investigations of the molten steel sessile drop contact angle on flat substrates of single phase components of typical nozzle materials will yield data providing insight into modifications to steel inclusions as well as optimal oxides to be used as nozzle components.

Field Trials. Promising results from laboratory experimentation should be validated through field trials, when interested steel producers will be identified, and side-by side performance comparisons of standard and improved nozzles will be conducted. Post-mortem comparison of the nozzles should be completed.

Dewatering of Monolithic Cast Refractories

R & D Needs

Refractories - Dewatering of Monolithics

- Laboratory-scale dewatering simulations
- Determined properties such as strength, elasticity, and permeability of castable linings
- Models to predict critical dewatering rates and lining performance as a function of dewatering practice

Dewatering Simulations. Laboratory scale furnaces that accurately simulate single-sided heating of a castable refractory lining should be developed.

Properties Determinations. Castable linings must be heated slowly. Properties such as strength, elasticity, and permeability should be measured and compared to results in increasingly accelerated dewatering tests. Dewatering rate versus property relationships for selected model castables should be established.

Establish and Validate Dewatering Models. Existing dewatering models should be modified to incorporate data from the dewatering rate studies. The models will then be available to predict critical dewatering rates as well as lining performance as a function of dewatering practice.

Castable Refractories Development

Development of improved high alumina, basic, and carbon/graphite-containing castables will lead to substantial reductions in steel manufacturing costs due largely to reduced reline labor costs and reline durations.

R & D Needs

Refractories - Castable Development

- Castable refractories based on high alumina and basic oxides
- Evaluation of castable refractories in highly variable slag line applications
- Castable refractory performance evaluated through field trials

Formulations. Castable refractories based on high alumina (90+ wt.%) and basic oxides, such as magnesia and dolomite, should be developed. These castables will require improved binders and additive systems to provide the necessary flowability as well as the service properties required for steelmaking application. A new class of castables containing carbon or graphite also should be developed. Graphite-containing castables will have many of the desirable properties that have made graphite-containing bricks so successful, but will require development of entirely new binder and additive systems to provide the required flow characteristics.

Corrosion Testing and Post-Mortem Characterization. Castable refractories will be subjected to a systematic series of dynamic slag corrosion tests to evaluate their potential in highly variable slag line applications. Post-mortem characterization of slag line castables and slag line bricks will be compared, and data will be used to make further castable improvements.

Field Trials. Castable performance will be evaluated through field trials conducted by interested steel producers. Slag linings of steelmaking ladles should be cast into place with the ladle operating "along side" ladles with brick slag linings. Performance should be evaluated by direct comparison of wear and by slag penetration determined by post-mortem analysis.

Refractory Recycling/Landfill Reduction

Refractory recycling should focus on highly efficient in-process separation of useful materials from components of the refractory waste stream as well as the reuse of the separated products within the steelmaking facility from which they were generated. A comprehensive refractory recycling program should include a collection of data on the types and quantities of refractories used throughout the steel industry, characterization of representative samples of spent refractories, and separation/beneficiation and post characterization of the reclaimed material. Subsequent research should focus on investigating the manufacture of co-products from these materials, maximizing efforts to develop in-house recycling.

R & D Needs

Refractory Recycling

- Detailed investigation of steel plant refractory types, quantities, and disposal techniques
- Characterized spent refractories
- Improved methods of beneficiation of spent refractories
- Characterized reclaimed refractory materials

Surveying and Sampling. Detailed investigations of steel plant refractory types and quantities used and disposal techniques and frequency must be completed and refractory sampling procedures established.

Characterizing Spent Refractories. Characterizing spent refractories is an essential part of a comprehensive refractory recycling and reuse program. Characterization should identify changes that have occurred in the refractories after extended, high-temperature operation in a corrosive environment and should provide insight into possible separation, beneficiation, and recycling techniques.

Characterizing Reclaimed Refractory Materials. Reclaimed refractory materials should be characterized using standard techniques that are applied to other refractory raw materials. These data should provide potential consumers with the information needed to incorporate reclaimed materials into a variety of products.

High-Temperature Properties Measurement

Development of a device or set of devices that would allow high temperature measurement is essential, as the data generated would allow for improved design of steelmaking vessels.

R & D Needs

Refractories

- Equipment that can provide relevant data on the high-temperature properties of carbon/graphite-containing refractories
- Good properties achieved by newer refractories
- Advanced ceramics that are long-life and inert and allow close chemical control of inclusions
- Thin-walled ceramics to facilitate fluid transfer from containment vessel to mold while minimizing cost and consumption and ensuring safety

Equipment Development and Properties Measurement. Equipment that can provide relevant data on the high-temperature properties of carbon/graphite-containing refractories will be developed. The equipment will evaluate one or more of the key engineering properties related to steelmaking vessel design at temperatures approaching 3100°F. The equipment will withstand the reducing environment while measuring the properties of the refractory material in a situation that considers the temperature gradient in which the refractories are used. The data resulting from measurements using this equipment will aid in vessel design and refractory selection.

The wide variety of refractories coupled with the myriad operating conditions may make it impossible to fully characterize the properties of spent refractory materials. Research to discover new, simpler products that reuse spent refractories without a complete knowledge of their chemistry and physical properties, should be started. Examples of potential products are ballasts, paving stones, asphalt additives, wearplates, and aggregate.

Research Priorities

Submerged entry nozzle accretion is considered to have the highest priority of the refractory research topics, followed by castable dewatering, castable development, and refractory recycling. High-temperature properties measurements are also needed, but innovative ideas will be needed to develop affordable new equipment.