STEEL INDUSTRY

by Douglas W. Freitag

The American steel industry—among the most productive, efficient, and technologically sophisticated in the world—is vital to economic competitiveness and security. Steel remains the material of choice by consumers because of its basic attributes and its low cost ($1–$10 / lb). According to the latest statistics, annual worldwide steel production was 727 million metric tons, with U.S. production at 95 million metric tons. Annual energy consumption for steel production is 1.8 quads, or 15% of production cost. Based on the Sloan Industry Competitiveness Study, total employment in the U.S. steel industry is 225,000, and production employee compensation exceeds that of the average manufacturing job by 50%.

Significant competitive pressures have forced major restructuring of the steel industry within the past two decades. These pressures continue and include worldwide overcapacity, high cost of energy, environmental and safety compliance, competing materials, customer demand for high quality, and the high cost of capital. In response to these factors, the steel industry, in cooperation with the U.S. Department of Energy (DOE) Office of Industrial Technologies, formulated and published its vision statement: "Steel: A National Resource for the Future." To achieve its vision and ensure that steel will be the material of choice for manufacturing in the 21st century, the industry identified four critical areas (targets of opportunity) in which continuous improvement will be necessary:

- Process Efficiency—to seek improvement in throughput, quality, and energy efficiency.
- Recycling—to increase steel recycling and recovery of iron units from plant solid wastes.
- Environmental Engineering—to achieve further reductions in air and water emissions and generation of hazardous wastes, and to develop new processes to avoid pollution rather than control and treat it.
- Product Development—to be increasingly responsive to ever-changing market demands and customer needs by achieving maximum flexibility in production capabilities. Increases in sales to key markets will occur as the industry introduces products with new properties to meet the demand for changing materials in the 21st century.

The following sections describe current steel manufacturing processes and how ceramic-based materials might contribute to achieving the steel industry vision.

5.1 PROCESS OVERVIEW

In the United States, two methods are used to produce steel: the ore based, or integrated process, and the scrap based, or electric arc furnace process. An overview of the two processes is shown in Fig.5.1. Two different approaches are used to prepare semifinished billet: the integrated process, which uses a blast furnace, and the minimill, which uses an direct electric arc furnace. Once steel is in the semifinished state, further processing is required in both the minimill and the integrated steel-making process.

The integrated process is "old line big steel" with facilities sprawling over several thousand acres and employing several thousand workers (Fig. 5.2). The manufacturing process uses a complex series of capital-intensive unit processes to produce value-added, high-quality steel. Annual production of an integrated steel mill is 3 to 5 million metric tons. The integrated mill represents several billion dollars of capital investment, which has typically been funded over several generations. Only 21 integrated steel mills remain in operation and are located in the Great Lakes region near sources of iron ore, coal, and water.

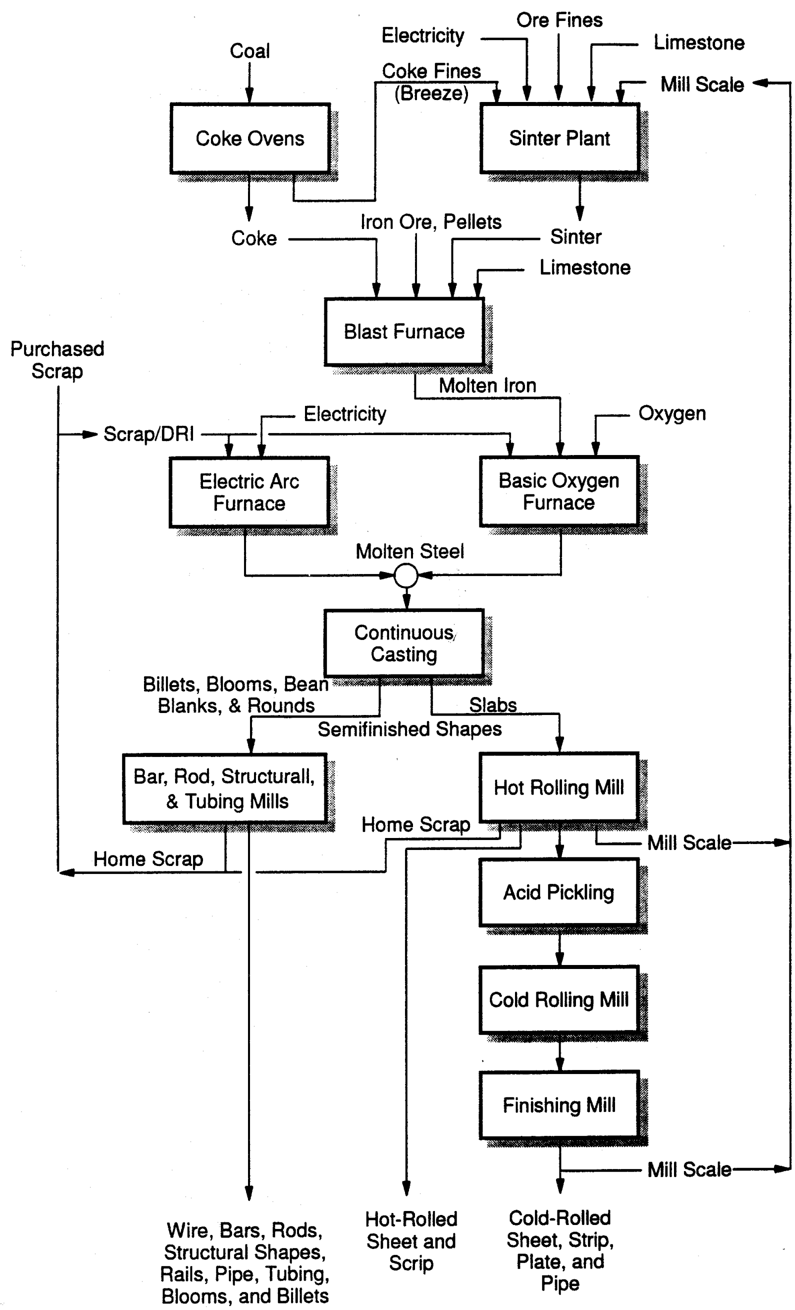

Fig. 5. 1. Overview of steel-making process. *Source: Steel Industry Technology Roadmap,* February 1998.

The electric arc furnace steel producer, also known as a minimill, is much more compact and can fit within an area as small as a city block (Fig.5.3). The small size of a minimill allows for installation closer to market demand. Annual production of a minimill is 0.5 to 2 million metric tons and requires several hundred workers. The lower capital investment needed for a minimill (several tens of millions of dollars) has fueled their growth. The conventional top-charged electric arc furnace currently produces 40% of the market share of steel and is expected to be the dominant process by 2005 to 2010. The minimill initially focused on lowest quality steel markets (e.g., reinforcing bar) but has recently taken over the structural steel market and is competing effectively in hot-rolled products. While scrap-based, electric arc furnace steel producers will continue to grow, "new steel" provided by the integrated process will always be required.

Fig 5.2. Integrated steel mill. *Source*: Bethlehem Steel Corporation brochure, Chesterton, Ind.

Fig. 5.3. Minimill. *Source: W*eb site of the North Star Steel Company, Beaumont, Tex., at http://www.cargillsteel.com/nss/plants/beau.htm.

Each of the processes, along with the role of advanced ceramics, is discussed in detail in the following sections. Refractories and ceramic coatings are currently being used throughout the processes, although advanced ceramics are emerging slowly because of their higher cost. Oxide-based ceramics of aluminum, zirconium, chromium, and magnesium are primarily used in a part of the process where contact is made with molten steel and low contamination is desired or where highly alkaline slags or flue gas species are present. Nonoxide ceramics of silicon, titanium, tungsten, and aluminum are used for hot handling because of their inherent thermal shock resistance and higher creep resistance and for component areas where high resistance to acidic species or wear is desired.

5.2 INTEGRATED STEEL-MAKING PROCESS

An overview of the integrated process for making steel is shown in Fig. 5.4. An integrated steel mill starts with iron-bearing materials, principally iron oxides, which are reduced to molten iron in blast furnaces using the carbon of coke as the reducing agent. The coke is produced on site from coal or is purchased. In coke making, coal is heated at 900–1200°C in an oxygen-deficient atmosphere to remove volatile components. The remaining residue is coke. About 1.23 metric tons of coal are needed to produce 1.0 metric ton of coke. This process is carried out in refractory brick-lined ovens, with coal introduced in a pulverized

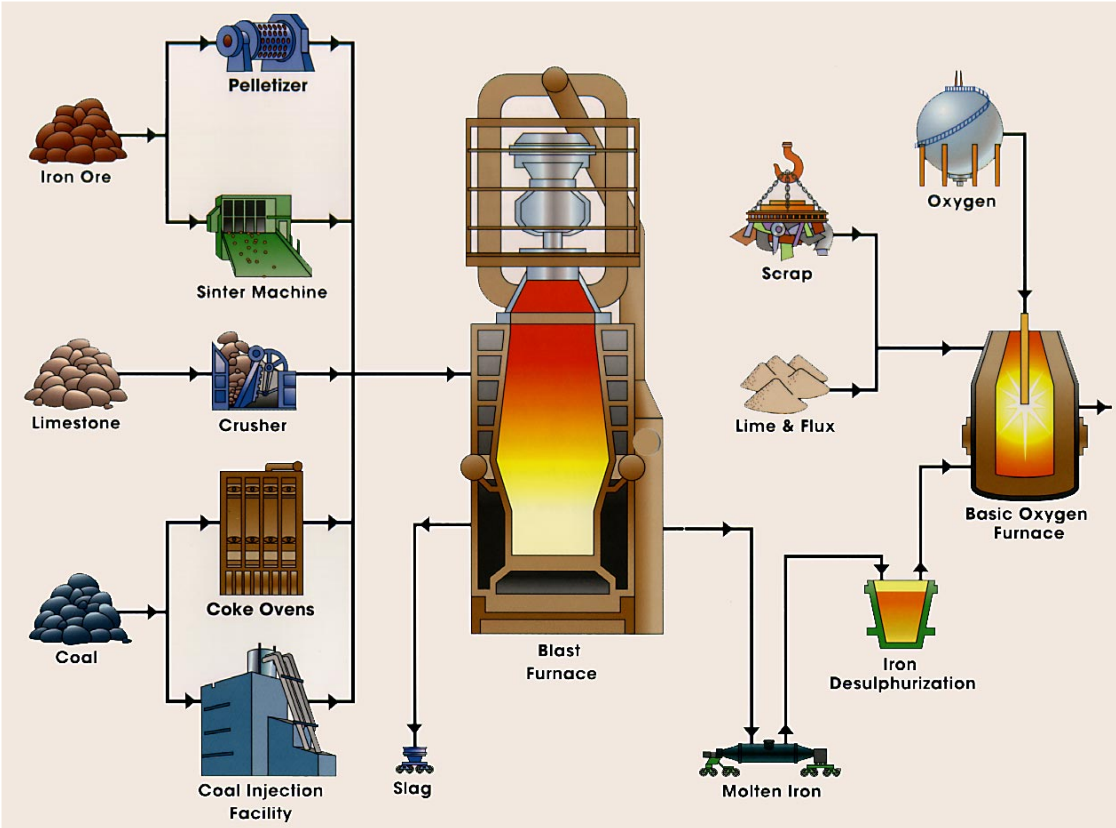

Fig. 5.4. Integrated steel-making process. *Source*: *Sales brochure, Bethlehem Steel Corporation, Chesterton, Ind.*

state through ports in the top of the ovens. The ovens are heated by coke-oven gas, which burns in flues located in the oven sidewalls. After conversion is complete, the oven doors are removed, and the coke is pushed out of the oven and transported to water quenching towers. The cooled coke is crushed and screened in preparation for the blast furnace. Volatiles removed from coal during conversion to coke are further processed to recover useful by-products. A single mill may operate as many as 500 coke-producing ovens. Currently about 4,321 coke ovens are operated in the United States, but this number is declining because of the high cost of regulatory compliance.

Current applications of advanced ceramics in the coke-making process include wear surfaces on grinders, fans and crushers, coke rolls, refractory linings, and pollution control devices. New opportunities include single piece fans, condensers, recuperators, and hot-gas filtration. Single-piece advanced ceramic fans could be used as replacements for ceramic-tiled or -coated fans with benefits in increased life and reduced weight. Ceramics are currently not used in equipment for the recovery of the volatile coke-making by-products but could be used to reduce fouling, a cause for high maintenance. Ceramic recuperators could also be used to recover waste heat from the coke furnaces and to preheat blast furnace combustion air. Ceramic recuperators have been demonstrated for applications where flue gas temperatures exceed the capability of metals (982°C) or are highly corrosive and can provide 25–50% fuel savings. Advanced ceramics could play an increasing role in controlling particulate emissions from coke ovens as Environmental Protection Agency restrictions become even more stringent. Flue gas particulate emissions from coke ovens are currently controlled with conventional gas cleaning equipment using a combination of cyclones, electrostatic precipitators, and fabric filters.

Two primary processes are used to prepare the charge for the blast furnace, pelletizing and sintering. In pelletizing, unbaked balls are formed from iron ore combined with a binder. These balls are heat treated in an oxidizing furnace at the mine and shipped to the mill where they are fed into the blast furnace along with coke, fluxes, and often sinter. In producing sinter, iron ore fines, coke fines, water waste sludge, limestone, and air pollution control dust are agglomerated and heated. Heat for producing sinter comes from ignition of the coke fines. The heated mass is fused, cooled, and sized before being sent to the blast furnace. The sintering process aids recycling of iron-rich waste products, but few installations remain because of difficulties in meeting regulatory compliance. Current uses of ceramics include wear surfaces on grinders, waste sludge pumps, crushers, and fans. New opportunities are similar to those discussed for the coke-making process.

Blast Furnace Process

The blast furnace process produced most of the iron in the United States in 1996. Currently 43furnaces ar e in operation. During the production of iron, iron ore, coke, limestone, and sinter are fed into the top of a blast furnace while heated air, sometimes augmented with fuel, is fed in through the bottom. As the charge descends through the furnace, carbon monoxide generated by the burning coke reduces the iron ore to form iron. The acid part of the ore reacts with the limestone to produce slag, which contains unwanted impurities in the ore. The molten iron is collected in the bottom of the refractory-lined furnace at temperatures of 1560°C. The slag is removed from the top of the molten iron and sold as a by-product. The molten iron is tapped from the bottom of the furnace and placed into refractory-lined cars for transfer to a desulfurization ladle.

Opportunities exist for improved refractories in the lower part of the blast furnace where coal is injected and for improved refractories for the desulfurization ladle. Opportunities also exist for the coal injection tubes themselves (tyueres), which are short lived because of wear. On average, 24 tyueres are used for coal injection in a single furnace, each tyuere being 5–25 cm in diameter by 3 m long. Refractories in the remainder of the blast furnace, with a life of 6–7 years, are not considered a problem. Additional opportunities exist in the fans used to handle the hot flue gases.

The blast furnace flue gas is recovered for use in preheating the blast furnace air or in producing steam for use in the plant. Advanced ceramic recuperators provide an opportunity for life extension and greater efficiency by locating the recuperator closer to the hot-gas source. About 45kg of dust ar e contained in the flue gas stream per metric ton of iron. Main components of the flue gas dust include the oxides of silicon, aluminum, calcium, and magnesium. Particulate emissions are processed first through a cyclone, which requires a high volume of precooled air, and then by wet scrubbers, which make reclamation difficult, or by electrostatic precipitators, which are generally less efficient and higher in cost. Advanced ceramic filtration processes could prove to be more efficient because of their ability to operate at higher temperatures and ultimately could be necessary to meet the 2.5-µm standard, when imposed.

Basic Oxygen Furnace Process

During the making of molten iron, the iron absorbs 3.0 to 4.5% carbon. While this carbon content is acceptable for cast iron, modern steels contain less than 1% carbon. Thus, the excess carbon must be removed by controlled oxidation in steel-making furnaces. The integrated steel process uses iron with up to 25% scrap as a charge to produce steel in a basic oxygen furnace (BOF). The BOFs in operation today include conventional top-blown furnaces, bottom-blown furnaces, and various combinations of top- and bottom-blown furnaces.

The BOF process generates heat by injecting from above into the molten iron high-purity oxygen that reacts with the carbon and silicon to melt the scrap and remove impurities. No additional heat source is required. Various materials, including fluxing agents to produce metallurgical slags, are required for the refining process. Alloying materials, in the form of alloyed scrap or ferroalloys, may be added singly or in combination to the molten steel during or after the carbon removal process to produce steel.

While particle emissions are lower than those generated during coking and blast furnace operations (18kg of dust per metric ton of steel produced), substantial quantities are generated when combustion gases and fumes are released during oxygen blow periods. Methods used for particle emission control are similar to those discussed for coking and blast furnace gas cleanup and provide opportunities for advanced ceramics. Other opportunities for advanced ceramics include the tap hole gun nozzle, taphole sleeve, sensor shields, refractories in runners used to flow the molten steel from the furnace to refining ladles, and bottom stirring elements. Refractories are generally not a problem in BOFs because slag is splashed against the refractory to protect them.

A tap hole gun is shown in Fig 5.5. When the steel is removed from the furnace, a hole is drilled (tapped) through the refractory liner. A tap hole

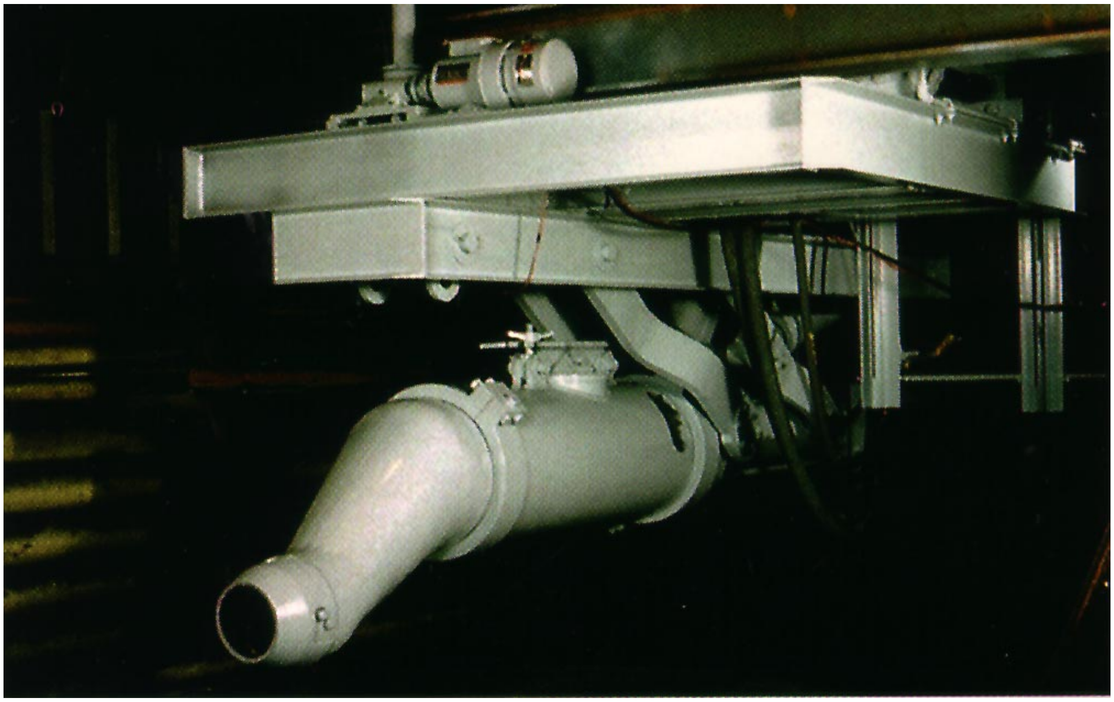

Fig. 5.5. Tap hole gun. *Source:* Sales brochure, Bailey Engineers, Canonsburg, Pa.

gun is used to plug the hole with a refractory clay mix. The nozzle of the tap hole gun must have high-thermal-shock resistance, high-temperature capability, and high-impact resistance. Monolithic ceramics of silicon carbide and mullite have been evaluated, but success with these ceramics has been limited because of their unpredictable, brittle behavior.

Shields are sought for sensors that can monitor melt temperature, uniformity of the melt, and off-gas composition. Even though lightly loaded, these sensor shields must operate at temperatures in excess of 1650°C while exposed to highly oxidative and corrosive gases. Runners for transferring the molten steel from the BOF to the refining ladle are often fireclay brick maintained with plastic and ramming mixes. Because of their high maintenance cost, castable refractories high in aluminum oxide and chromium oxide are being used, although operating life is still limited to one to two weeks. Further environmentally acceptable improvements in the lifetime of runner refractories are sought.

Bottom stirring based on gas injection is used in the BOF to reduce slag buildup and improve temperature and metal uniformity. Bottom-stirring elements include water-cooled metal pipes enclosed in refractory (tuyeres) and porous plugs. Problems with tuyeres include burning back the metal pipe with a loss of flow control, plugging by molten metal flow into the tuyere, cupping of the tuyere end, and loss of furnace energy efficiency when water cooled. The problem with porous plugs is low gas flow and low abrasion resistance. Improved temperature capability is also sought for porous plug materials.

Opportunities for advanced ceramics in the integrated steel-making process are summarized in Table5.1.

5.3 ELECTRIC ARC FURNACE STEEL-MAKING PROCESS

Unlike the integrated steel process, electric arc steel-making furnaces use scrap metal as the charge that is melted and refined using primarily electricity. Traditionally the charge has been 100% cold scrap. As the demand for high-quality steel produced by the electric arc furnace (EAF) process increases and the availability of high-quality scrap decreases, alternative iron-base charges are being used to supplement the scrap. A typical EAF is shown in Fig. 5.6. Cylindrical, refractory-lined arc furnaces are equipped with carbon electrodes that are lowered through the furnace roof. During charging, the furnace roof is removed and scrap metal is placed into the furnace. Alloying agents

Table 5.1. Opportunities for advanced ceramics in the integrated steel-making process

Application	Industry needs	Opportunities for ceramics
Recuperator for coke ovens, blast furnace, basic oxygen furnace (BOF)	Longer life, higher temperature capable	Silicon carbide (SiC) ceramic matrix composite tubular structure; may require an environmental barrier coating
Hot-gas filters for coke ovens, pelletizer, blast furnace, and BOF	Higher temperature capable, higher efficiency, smaller particle size removal	Ceramic hot-gas filter
Fans for particle separation	Longer life, lighter weight, reduced cost	Ceramic matrix composites with a hybrid metal attachment
Condenser for reclamation of volatile coke-making products	Reduced fouling	SiC ceramic matrix composite
Coal injection tubes for blast furnace	Longer life, uncooled	Cermet, ceramic matrix composite
Refractories for coal injection area of blast furnace	Longer life, reduced erosion	Incremental improvements; potential improvements with ceramic coatings
Tap hole gun nozzle for BOF	Longer life	Incremental improvements; potential improvements with ceramic coatings
Tap hole sleeve for BOF	Longer life	Incremental improvements; potential improvements with ceramic coatings
Sensor shields for BOF	Uncooled thermocouple and chemical analysis shields	Mullite ceramic matrix composite
Refractories for metal transfer between BOF and ladle	Longer life	Incremental improvements; potential improvements with ceramic coatings
Bottom-stirring elements for BOF	Longer life, higher temperature capable, higher gas flow	Porous ceramic matrix composite

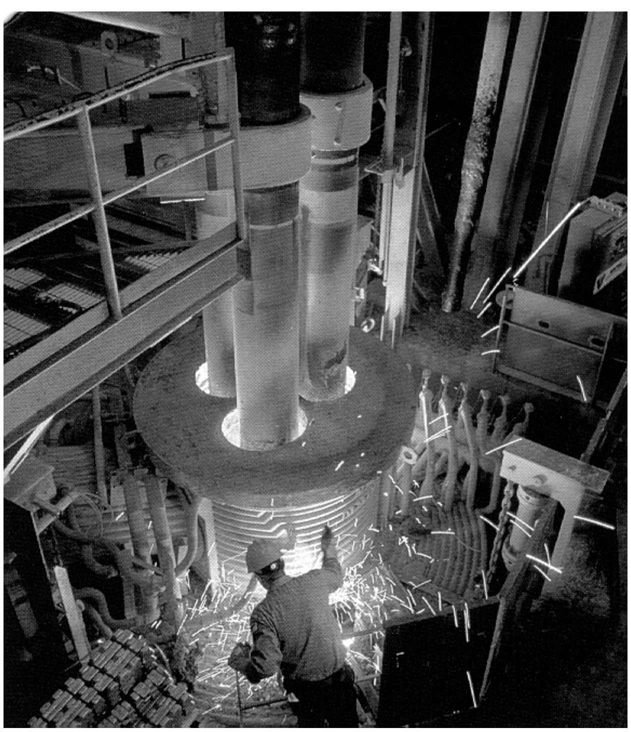

Fig. 5.6. Electric arc furnace. *Source*: Reproduced from *Steel: An Engineered Material, Advanced Materials and Processes*, January 1998, p. 35.

and fluxes are added through doors on the side of the furnace. The electrodes are lowered to within one inch of the metal surface and current is applied to generate heat above the metal. Oxygen is injected through a consumable lance to decarburize the steel and to supplement thermal energy. During melting, oxidation of impurities occurs and forms a slag on the molten metal surface. Similarly as in the integrated process, unwanted materials are removed and alloying agents added. The final product is removed from a tap hole on the side of the furnace.

An EAF can be as large as 5.5 m across with consumable carbon electrodes as large as 12.6 cm across. In addition to conducting electricity, carbon is used for its low cost and lack of contamination of steel. To simplify handling and charging, hollow electrodes have been considered, but their current carrying capacity is limited. In addition to oxygen injection, oxy-fuel-fired burners and scrap preheating are often used to improve heating efficiency. Of the total energy input, 65% is derived from electricity. The remaining 35% is derived from the exothermic oxidation of carbon and iron and from oxy-fuel-fired burners. Of the total energy input, 70% goes into the steel and slag, and the remainder is lost to waste gas, cooling water, radiation, etc. Consequently, recuperators are desired for recovery of waste heat that can be used to preheat scrap or combustion air.

Particulate emissions are much lower than those produced by the integrated process (16 kg of dust per metric ton of steel), with the major contributor being iron oxide. Particulate emissions are cleaned in a manner similar to that employed in the integrated process and thus present equal opportunities for advanced ceramics. Waste-gas temperature at the furnace approaches 1093°C and cools to 204°C at the baghouse. Opportunities for advanced ceramics also exist in longer life electrodes, oxygen injection lances, oxy-fuel burner nozzles, recuperators, runners for transferring the hot metal to the refining ladle, and as a replacement for high-maintenance refractories applied to the water-cooled panels of the sidewalls and top of the EAF. Current refractories are repaired on a weekly basis.

Opportunities for advanced ceramics in the electric arc furnace steel-making process are summarized in Table 2.

5.4 LADLE REFINING PROCESS

The cost of refining and casting steel accounts for 95% of the total cost of the finished product. Thus, the use of new materials in these operations could potentially add high value by significantly lowering the overall cost. A number of processes are often used to refine the molten steel in a ladle after it leaves the BOF or EAF prior to casting (Fig.5.7). Ladle r efining processes include argon oxygen degassing, ladle metallurgy, vacuum arc remelting, and vacuum degassing. Processes selected are based on the desired metallurgy and

Table 5.2. Opportunities for advanced ceramics in the electric arc furnace steel-making process

Application	Industry needs	Opportunities for ceramics
Refractories for runners and sidewalls	Longer life	Incremental improvements; potential improvements with ceramic coatings
Electrodes	Longer life, center feed of scrap	Oxidation protected carbon/carbon composite or boride matrix composite
Particle emissions control	Higher temperature capability, greater efficiency, smaller-particle-size removal	Ceramic hot-gas filter
Oxy-fuel burner nozzles	Higher-temperature-capable burner nozzle with longer life	Silicon Carbide (SiC) or Molybdenum disilicide ceramic matrix composite, thermal barrier coating
Recuperator	Greater corrosion resistance, higher temperature capable	SiC or SiC matrix composite tubular structures; may require a coating for environmental protection
Oxygen injection lance	Longer life, uncooled	Ceramic matrix composite, oxide matrix or coated SiC matrix

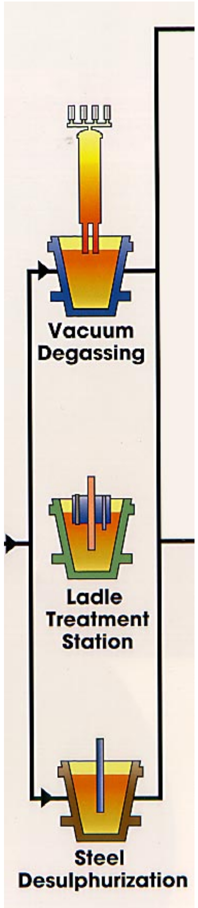

Fig. 5.7. Steel ladle refining processes.
Source: Sales brochure, Bethlehem Steel Corporation, Chesterton, Ind.

purity. In ladle metallurgy, alloys are added to the molten steel, which is then reheated to produce the desired metallurgy. In vacuum degassing, molten steel is subjected to a vacuum for vacuum control, temperature control, deoxidization, degassing (hydrogen removal), decarburization, and removal of other impurities from the steel.

Refining is performed in separate ladles to prolong the life of furnaces. Typical ladle dimensions are 4.5 m deep and 2–3 m in diameter. Ladle refining is generally performed by electric arc reheating. The molten metal bath is stirred throughout the process to provide for thermal and chemical homogenization and to accelerate metallurgical reactions. Stirring is provided by inert gas introduced near the bottom of the ladle using porous plugs, tuyeres, or lances. Gas injected from above using water-cooled, refractory-coated metal lances is considered safer than porous plugs or tuyeres, but maintenance is high and heat efficiency reduced. Disadvantages of tuyeres and porous plugs are discussed earlier under "Basic Oxygen Furnace Process." Porous plugs, which are the most commonly used during refining, last only 30 heats (batches of processed steel) due to erosion. Because of their many disadvantages, replacement of lances is a several million dollar a year business. Stirring elements are sought that will provide consistent stir performance for the life of the ladle. Induction stirring can be used, but it is more complex to implement.

Because of the high temperatures, erosion from the stirred bath, and high corrosiveness of the metallurgical slag, high-alumina and magnesia-based (slag line) castable refractories are preferred for ladle linings. Still, life remains short (30 to 50 heats). More recently, higher-temperature-capable oxide / carbon mixtures are being used to provide a balance of reasonable purity, high thermal shock resistance, and low erosion. Alternative refractories having longer life, lower cost, and safer disposal continue to be sought. In addition to use with porous plugs, tyueres, lances, and refractories, opportunities exist for advanced ceramics in ladle recuperators and impact pads. Recuperators for air preheating would operate at 980–1093°C and could be exposed to corrosive gases. Impact pads are located on the bottom of the ladle and ultimately determine the life of the ladle. Materials with higher strength capability at temperature, improved abrasion resistance, and high-thermal-shock resistance are desired.

Opportunities for advanced ceramics in the ladle refining processes are summarized in Table5.3.

5.5STEEL CASTING

After the steel has been refined, it is ready to be cast into ingots or continuous strips (Fig. 5.8). Ninety-seven percent of all steel produced in 1995 was continuously cast, while the remaining 3% was ingot cast. In the continuous-casting process, molten steel is delivered in ladles and poured into a reservoir, or tundish, from where it is released into the mold by gravity feed. The casting machine can have either one (single-strand caster) or multiple molds (multistrand caster). The steel cools as it passes through the mold and forms a solid shell or "skin." As the steel proceeds onto the runout table with a series of hot-handling rollers, the center of the steel solidifies, yielding a semifinished shape at a specified width and thickness. Depending on the type of caster used, billets, blooms, rounds, thin slabs, or thick slabs are produced. A cutting torch is used at the end of the roll line to cut the steel to the desired length.

Table 5.3. Opportunities for advanced ceramics in ladle refining

Application	Industry needs	Opportunities for ceramics
Refractories	Longer life, higher temperate capable, lower cost, easily disposed	Incremental improvements; potential improvements with ceramic coatings
Recuperators	Higher-temperature-capable, corrosion-resistant materials	Silicon carbide (SiC) or SiC matrix composite tubular structures; may require ceramic coating for environmental protection
Electrodes	Increased life	Oxidation protected carbon/carbon composite or boride matrix composite
Impact pads	Higher temperate capable, longer life, improved abrasion resistance	Ceramic matrix composites; chopped fiber design may be adequate.
Stirring elements	Longer life, higher temperature capable, greater resistance to corrosive gases	Porous ceramic matrix composites

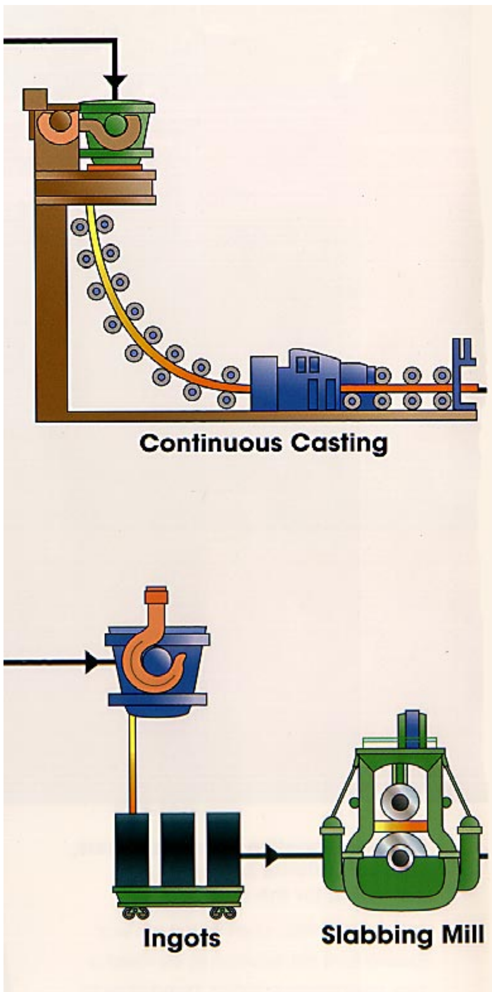

Fig. 5.8. Steel-casting operations. *Source*: Sales brochure, Bethlehem Steel Corporation, Chesterton, Ind.

Increased productivity, increased yield, and increased quality are driving new technologies. Net shape casting is sought to reduce forming and finishing capitalization.

The functions of the caster pouring system are to transfer metal from the ladle to the caster, control flow to the caster, minimize slag entrainment, minimize oxygen pickup from the pouring system, cause flotation of inclusions, and minimize heat loss. Flow is controlled both at the ladle and tundish. The ladle flow control system includes a hydraulic slide gate and a reusable shroud to control oxygen contamination. The tundish flow control system includes a hydraulic slide gate or stopper rod system; tundish block for positioning the nozzle over the mold; and weirs and dams or baffles to control flow, temperature, and composition uniformity. Because of the harsh operating conditions, the life of many components is less than one heat. Slide gates can either be of solid construction or contain integral gas passages to aid opening, reduce oxygen ingress, and prevent clogging. Stopper rods are a source of high maintenance because of erosion. Examples of flow control systems are shown in Figs. 5.9 and 5.10.

Wear of the refractories and reaction of the refractories with the highly corrosive slag (high in basicity from calcia) can generate defect-forming inclusions. Inclusions are formed from refractories contained in the ladles, tundish, and molds. Material systems used to contain the steel must be stable and not add to the inclusion count. High alumina refractories are commonly used throughout the process with application of zirconia-based (areas of high wear or themal shock) and magnesia-based (areas of high slag corrosion) materials as required. Carbon-containing refractories have been considered throughout the pouring system, but they react

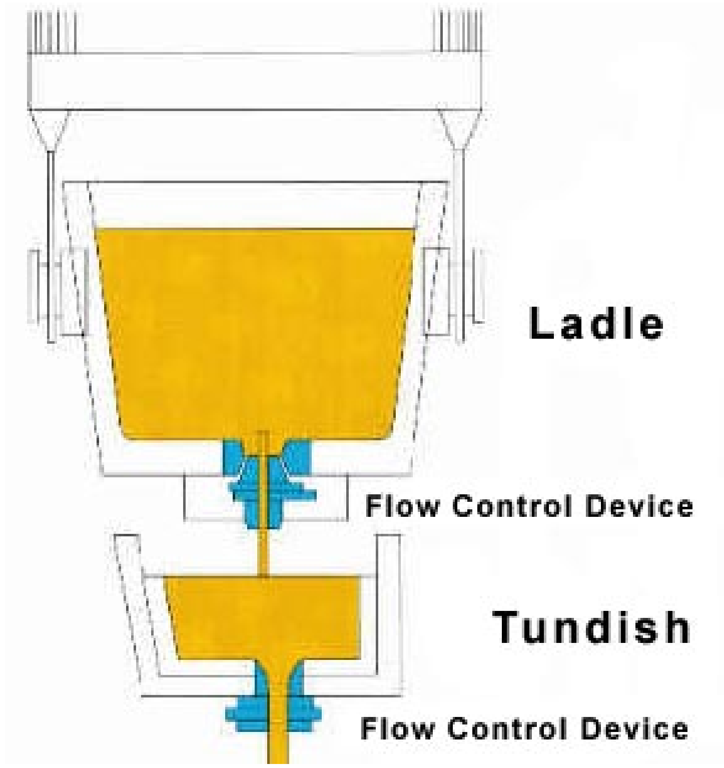

Fig. 5.9. Steel-casting flow control. *Source*: Adapted from Hepworth Refractories Web site at http://www.heprefs.co.uk/sgplate1.html.

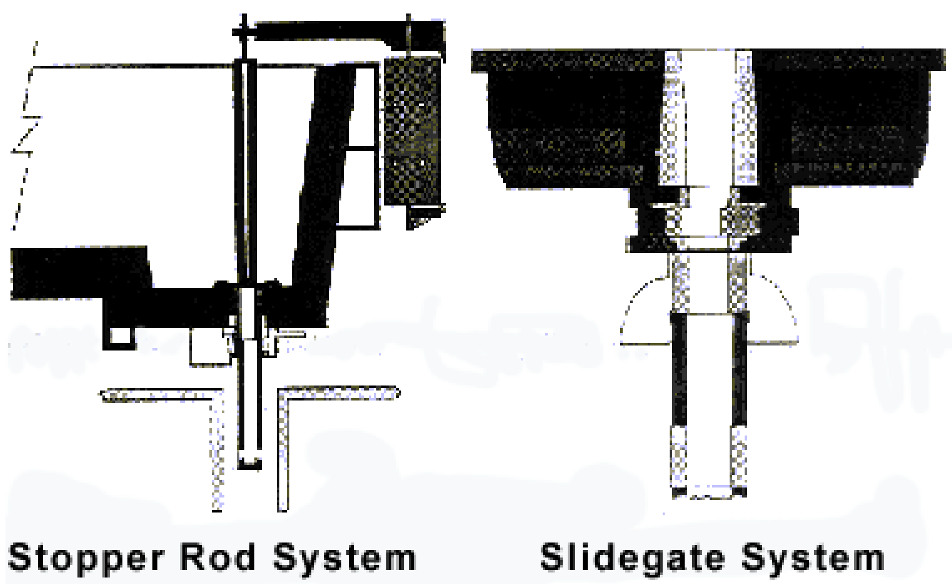

Fig. 5.10. Steel-casting flow control devices. *Source*: Reproduced from "Future Ceramic Needs for the Steel Industry," a presentation by Maureen Madden, United States Steel.

with oxide-based refractories to form carbon monoxide or with aluminum contained in steel to form alumina. Silica-based refractories are not used because of the potential for steel contamination. In some cases, defect-forming inclusions are removed with ceramic filters prior to casting.

Clogging of the caster pouring system is the single largest operational problem resulting in reduced quality and production delays. Sources of clogging include dirty steel, air infiltration, high iron oxide content, ladle slag, misalignment of the tundish suppressor pad, solid second-phase particles, and interaction of the molten steel or slag with the refractory. Solid second-phase particles occur from alloy additions or aluminum added to reduce residual oxygen. Remedies to clogging include alternate refractory materials, solid stopper rods, application of glazes to the refractory, nonclustering inclusions, alternate schemes for attachment of the nozzle to the top plate, alternate designs for entry of the molten metal into the nozzle, reduction of upstream effects, and reduction of residual porosity in the refractory. Because currently available remedies do not completely eliminate clogging, alternate materials are being sought.

During ladle refining, aluminum is added to remove excess oxygen. If the molten metal is not adequately protected from exposure to air during the casting operation, oxygen contamination can recur. Oxygen contamination occurs from exposure to air while the molten metal is contained in an uncovered ladle or tundish or while it is being poured from the ladle to the tundish or from the tundish to the casting mold. Nitrogen pick-up also occurs and can be detrimental to the steel chemistry. Heating of the tundish is commonly provided by gas- or oil-fired burners in open containers. Electrical induction heating methods are being developed to allow heating of the tundish while covered to increase efficiency, reduce emissions, and reduce oxygen contamination. To limit oxygen pick-up during pouring from the ladle, a thin-wall ladle shroud is attached to the bottom of the ladle; the shroud extends into the molten metal contained in the tundish. Common causes of ladle shroud failure include plugging, throat cracking, erosion in the throat, bottom slag line erosion, or bottom vertical cracking. A similar shroud is used to protect the molten metal stream as it leaves the tundish when not protected by the nozzle itself. The high-alumina refractories commonly used for the shrouds have a life expectancy of 1–10 heats before they need to be replaced. Recently demonstrated two-piece refractory molds, which include a zirconia inner liner contained in an alumina seat, can provide up to 38 h of continuous casting (Fig5.1 1).

Conventional continuous casting occurs at speeds of 1–6 m / min with mold temperatures approaching 1600°C. These operating conditions result in mold friction, surface defects, and gas bubbles when uncooled refractory molds are used. Improvements in as-cast surface finish and dimensional control have been achieved by using water-cooled copper molds. Higher casting speeds (48–100 m / min) have also been demonstrated. Further improvements in dimensional control and casting speeds are desired and are currently limited by metallurgical constraints when using cooled metal molds.

To improve quality and reduce plugging of the ladle nozzle, slag detection is used. Physical probe, radiation, or eddy current sensing is used in the tundish to monitor molten metal levels. Sensing of changes in tundish weight has also been used. Active control of the molten flow into the caster is desired to improve quality, provide a better match of order size to optimum heat size, and allow seamless grade transition. On-line monitoring and feedback control of the casting process is desired. In all cases, longer life or higher-temperature-capable uncooled sensor shields are sought.

Fig. 5.11. Two-piece tundish nozzle. *Source*: Hepworth Refractories Web site at http://www.heprefs.co.uk/concas1.html.

Ingot casting is used for small batches of specialty steels or for end products with certain shape requirements (e.g., intermediate- and large-bar applications or high-performance bar and tubing applications). Ingot casting also continues to be used by foundries and specialty steel makers to produce large cross sections or thick plates. During ingot casting, the molten steel is poured (teemed) into a series of molds and allowed to solidify to form billets. After the molds are stripped away, the ingots are heated to uniform temperature in soaking pits to prepare them for rolling. Continuous casting is much more energy efficient than ingot casting because of the need for soaking pits and increased scrap with the latter. While significantly lower than in other steel-making processes, particulate emissions from casting occurs when molten steel is poured into the molds. Opportunities for advanced ceramics during ingot casting are discussed in detail in Chap. 8.

Opportunities for advanced ceramics in steel-casting processes are summarized in Table 5.4

5.6 FORMING AND FINISHING

After casting, the slabs, billets, and blooms are further processed to produce strip, sheet, plate, bar, rod, and other structural shapes through various hot-forming operations that can then be followed by cold-forming operations, depending on application (Fig. 5.12). Prior to hot forming, the semifinished shape must be reheated to rolling temperatures (950–1300°C) in a gas- or oil-fired furnace. The shapes may also undergo a surface preparation (scarfing) to remove defects. The most common hot-forming process is hot rolling (hot strip mill). During hot rolling, a heated steel slab is passed between two water-cooled metal rolls revolving in opposite directions. Each set of rolls produces an incremental reduction in thickness of the slab. Hot strip mills can accommodate slabs up to two meters wide with reduction from 23 cm to as low as 1.5 mm. Surface scale is removed from the heated slab by a scale breaker and water sprays prior to entering the roughing stands containing the sets of rolls. At the end of the roughing section, the steel enters the finishing stands for final reduction, then it is cooled and coiled. Edge heating by gas-fired burners can be used between the roughing and finishing stands to maintain uniform temperature across the plate.

Cold rolling is used to reduce the steel to final dimensions and surface finish or to form pipes and tubes. Cold rolling is performed similarly to hot rolling except the steel is not heated. During cold rolling, the steel is hardened and must be heated in an annealing furnace (800–1200°C) before use to make it more formable. After the steel is softened in the annealing process, it is typically run through a temper mill to produce the desired flatness, metallurgical properties, and surface finish.

During the finishing operations, steel must be heated in a protective atmosphere containing H_2, N_2, and CO with negligible amounts of O_2 or H_2O

Table 5.4. Opportunities for advanced ceramics in steel casting

Application	Industry needs	Opportunities for ceramics
Refractories	Reduced steel contamination, longer life, reduced porosity	Incremental improvements; potential improvement with ceramic coatings
Casting molds	Higher temperature capability, low erosion, longer life, anticlogging	Engineered material or cermet
Runout table rollers	Higher temperature capability, reduced surface defects	Cermet, ceramic matrix composite or improved ceramic coatings
Weirs, dams, and baffles	Longer life	Ceramic matrix composite; chopped fiber design may provide adequate strength
Stopper rod tips	Reduced erosion	Incremental improvements with a ceramic coating
Ladle shrouds	High hot strength, low erosion, reduced clogging	Ceramic matrix composite
Tundish nozzles	Reduced clogging, low erosion, improved surface finish	Engineered material and multipiece design
Sensor shields	Uncooled, longer life	Silicon nitride or ceramic matrix composite

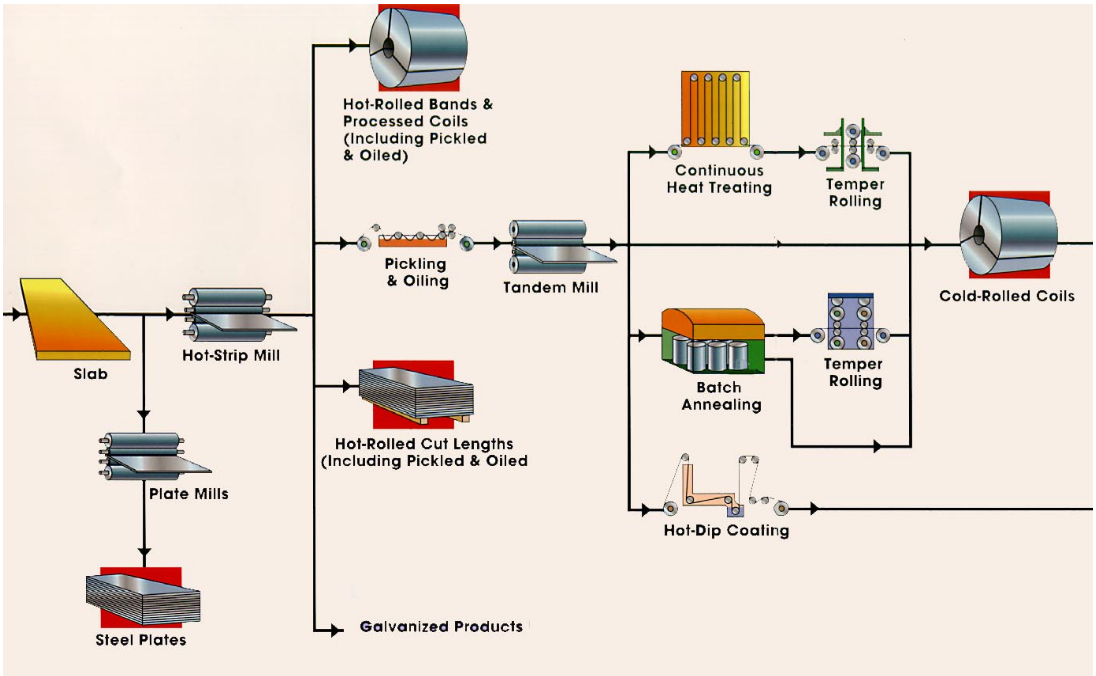

Fig. 5.12. Steel forming and finishing operations. *Source*: Sales brochure, Bethlehem Steel Corporation, Chesterton, Ind.

to provide the desired surface chemistry. Electricity or combustion has been used to provide indirect heating, with the later being the most common. When fossil fuel is used, combustion products must be kept separated from the furnace atmosphere. To effect this separation, the most common combustion systems employ radiant burner tubes. It was reported in 1994 that about 25,000 furnaces use radiant burner tube systems, 80% of these being located in commercial heat-treating shops and not large manufacturing operations. The survey indicated a radiant burner tube population of 250,000, the majority (170,000) being hairpin configurations. Included in the survey are about 40 steel mill strip annealing furnaces with 4,000 radiant burner tubes and some 650 continuous carburizing furnaces with 3,500 radiant burner tubes.

The radiant tubes are generally made of nickel / chrome alloys, mullite, silicon carbide, and, more recently, SiC composite. Nickel / chrome tubes can operate at temperatures of 1100°C for short periods of time with continuous operation limited to 980°C. Failure occurs from oxidation, creep, melt through, or embrittlement (carburization). Estimated downtime for tube replacement is 20–40 h. Tube size ranges from 1.4 to 3.1 m in length and 9 to 13 cm in diameter. Average life of metal tubes is 1–4 years. Average replacement cost is $250 for a straight tube and $1500 for a U-tube. Mullite and SiC provide superior temperature capability and increased resistance to corrosion and oxidation, but they lack the toughness provided by silicon carbide composites. Currently in operation are about 6,100 straight SiC composite tubes and 100 hybrid SiC composite U-tubes.

Finishing processes (pickling and oiling) are used to clean the surface of the semifinished, hot-rolled steel prior to cold rolling, forming, or coating operations. Mill scale, rust, oxides, oil, grease, and soil are chemically removed by a variety of chemical and physical processes. Salt bath descaling, which can be used to remove heavy scale, is limited to select specialty and hi-alloy steels. Acid pickling processes predominately use hydrochloric acid to remove oxide scales. Sulfuric, nitric, and other combinations of acids are also used. After pickling, alkaline cleaners may be used before cold rolling. Corrosion-resistant steels, ceramic-coated steels, graphite, engineered polymers, glass, and, in some cases, advanced ceramics (primarily nonoxides) are used throughout these processes. Opportunities for use of advanced ceramics include condensers, exhaust fans, pumps, spray nozzles, and processing tanks.

Because of the hot handling, high-temperature-capable steels and water cooling are used throughout the finishing and forming operation. Blistering, creep, oxidation, embrittlement, and thermal fatigue are common sources of failure for metal hardware and unpredictable, brittle failure of nonmetallics. High-maintenance components include furnace transfer rolls, furnace beams, exhaust fans, furnace transfer trays, and furnace hangers. Nickel / chrome steel alloys, advanced ceramics (silicon carbide, mullite, alumina, silicon nitride) and oxidation-resistant graphites are commonly used, with carbon / carbon composites and Ni_3Al finding increased use. Ceramic coatings are being applied throughout the process to improve oxidation and abrasion resistance. Component size ranges from small 30 × 10 × 5-cm trays that cost less than $200 to large 35-cm-diam by 3.5-m-long rolls that can cost $20,000.

Critical parameters for steel finishing and forming include temperature, uniformity of temperature during hot operations, flatness, steel chemistry, and surface finish. The demand for improved quality has produced an increased emphasis on monitoring temperature, surface finish, microstructure, and metal thickness throughout the process. Methods being used range from eddy current, physical probes, and spectroscopy. In areas where corrosion and high temperature exist, sensor shields are required that can protect the sensing element but not degrade the measurement process. Materials currently in use include water-cooled metallics, non-silicon-containing SiC, and refractory oxides. Opportunities exist for advanced ceramics with greater corrosion resistance and durability.

The largest users of energy during forming and finishing are the cold-rolling operation with 3.4×10^6 Btu per ton of product and the slab reheat operation with 2.8×10^6 Btu per ton of product. Particulate emissions are limited. Opportunities for increased energy efficiency exist with the installation of recuperators on reheat furnaces to use waste heat for preheating combustion air or for preheating the slab before it enters the furnace. Recuperators can also be used to preheat combustion air on hot-pickling tanks or other gas-fired annealing and heat-treatment furnaces. In many cases, flue gases are corrosive or exceed the temperature capability of metallics and will require advanced ceramics for acceptable life.

Additional finishing steps (i.e., tube rolling or wire drawing) are performed integrally to the steel-making process or as secondary operations at specialty vendors. Ceramic-coated metals and advanced ceramics are currently used in a number of these operations to provide the desired surface finish and dimensional tolerances while increasing throughput and reducing downtime. While the performance of ceramic-coated metals and advanced ceramics is considered superior to that of hard steels, a high incidence of failures occur from spallation of the ceramic coatings and unpredictable failure of the advanced ceramics.

Opportunities for advanced ceramics in steel-forming and -finishing operations are summarized in Table 5.5.

Table 5.5. Opportunities for advanced ceramics in steel forming and finishing

Application	Industry needs	Opportunities for ceramics
Radiant burner tubes	Reduced cost, increased temperature capability, complex shapes	Silicon carbide (SiC) or SiC ceramic matrix composite
Exhaust fans	Higher temperature capability, light weight, higher corrosion resistance	Ceramic matrix composite with an engineered attachment
Transfer devices, hangers	Higher temperature capability, low creep	SiC ceramic matrix composite
Sensor shields	Uncooled operation, higher temperature capability, increased toughness	Silicon nitride or ceramic matrix composite
Recuperators	Increased temperature capability, corrosion resistance	SiC or SiC ceramic matrix composite; may require an environmental barrier coating
Forming mandrels	Increased reliability	Graded ceramic with a titanium nitride, titanium carbide, or other hard ceramic face
Pickling pumps	Improved corrosion resistance, increased durability	SiC or SiC ceramic matrix composite

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