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

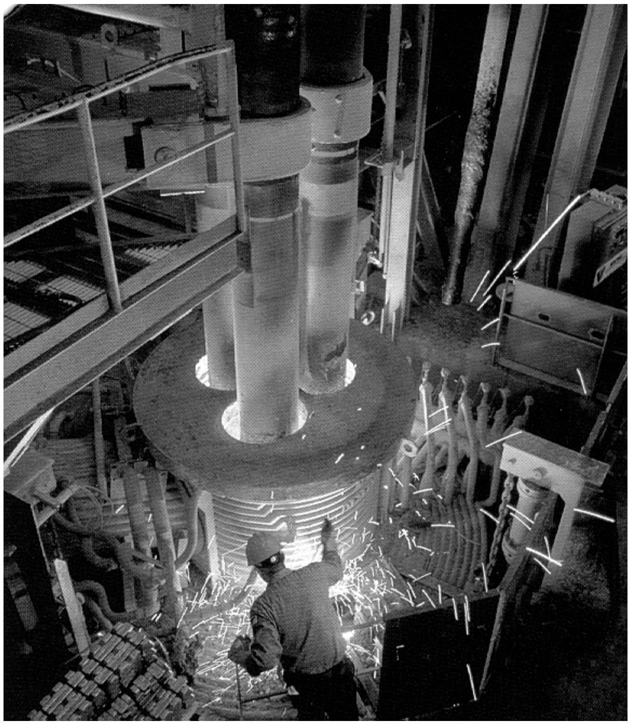

Fig. 5.6. Electric arc furnace. *Source*: Reproduced from *Steel: An Engineered Material, Advanced Materials and Processes*, January 1998, p. 35.

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

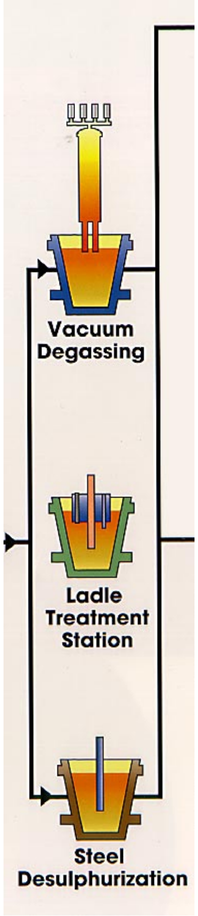

Fig. 5.7. Steel ladle refining processes.
Source: Sales brochure, Bethlehem Steel Corporation, Chesterton, Ind.

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

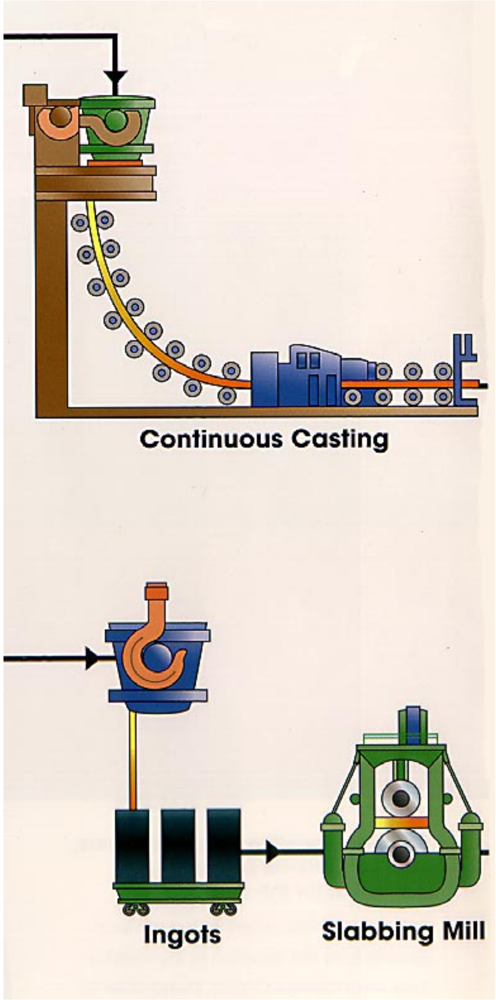

Fig. 5.8. Steel-casting operations. *Source*: Sales brochure, Bethlehem Steel Corporation, Chesterton, Ind.

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

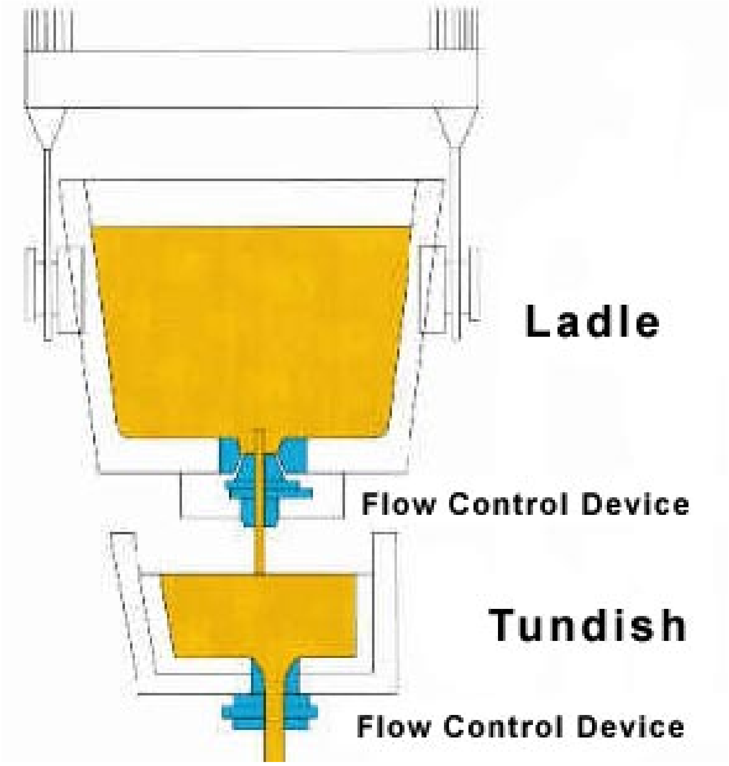

Fig. 5.9. Steel-casting flow control. *Source*: Adapted from Hepworth Refractories Web site at http://www.heprefs.co.uk/sgplate1.html.

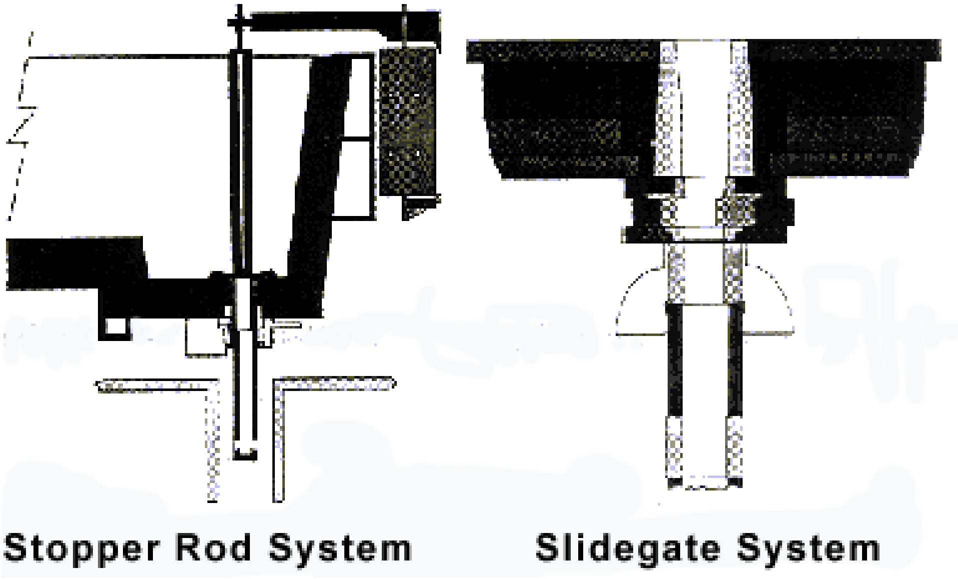

Fig. 5.10. Steel-casting flow control devices. *Source*: Reproduced from “Future Ceramic Needs for the Steel Industry,” a presentation by Maureen Madden, United States Steel.

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

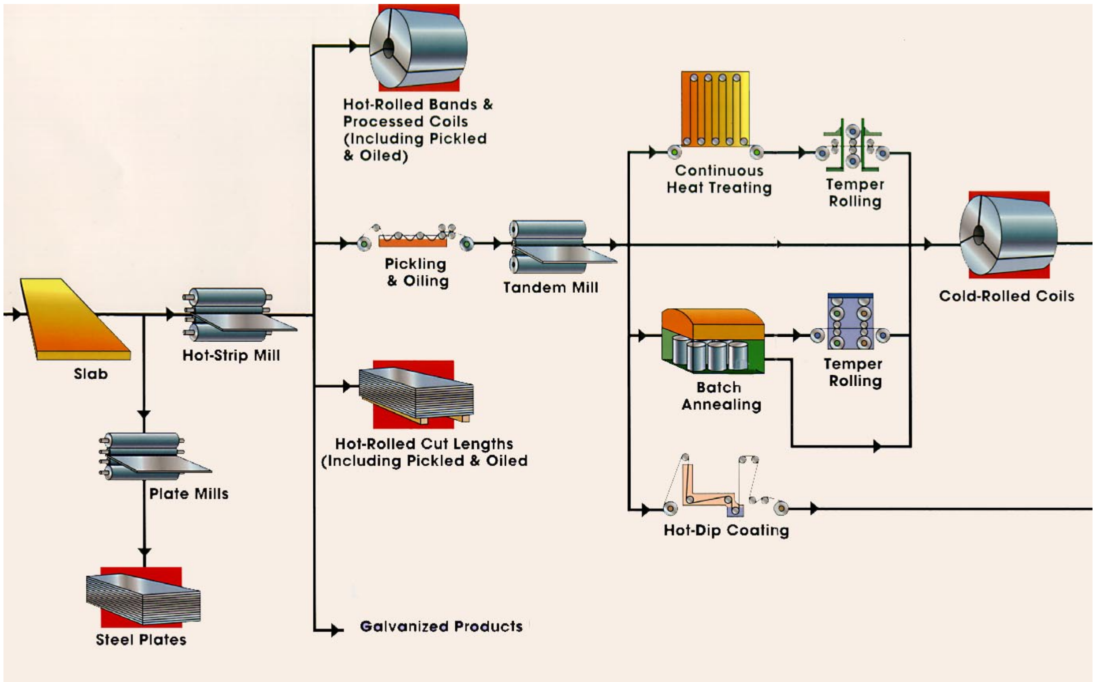

Fig. 5.12. Steel forming and finishing operations. *Source*: Sales brochure, Bethlehem Steel Corporation, Chesterton, Ind.

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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