CHAPTER EIGHT

METALCASTING INDUSTRY

by David W. Richerson

A wide variety of metals and alloys are processed by casting, as illustrated in Table 8.1. Casting involves transferring molten metal into shaped tooling. Complex shapes can be produced, generally requiring less machining and finishing operations than are required for other processes. As a result, casting is often the most cost-effective process for producing metal parts. Metal castings are used in more than 90% of all durable goods and in nearly 100% of machined tools, manufacturing machinery, and other industrial equipment. U.S. production of metal castings in 1994 was 13 million tons valued at $23 billion. This production included 11 million tons of ferrous (iron-based) castings and 2 million tons of nonferrous castings produced at 3,100 foundries across the United States. Energy consumption was 2.43 quads.

Table 8.1. Metals processed by casting

Process	Share of production
Sand casting	60%
Investment casting	7%
Die casting	9%
Permanent mold casting	11%
Centrifugal casting	7%
Shell mold	6%

The metalcasting industry, in collaboration with the U.S. Department of Energy's (DOE's) Office of Industrial Technologies, has established a technology roadmap with targets and research needs. Some of the industry targets and needs that can benefit from ceramic-based materials include the following:

1. Improving dimensional control of castings to improve net-shape capabilities.
2. Eliminating casting defects by approaches such as better tooling, refined process control, and improved ceramic molten-metal filters.
3. Increasing cast alloy properties to compete with forged alloys.
4. Increasing automated finishing.
5. Extending die-casting die life.
6. Achieving decreased casting-wall thickness without degrading properties or reducing yield.
7. Optimizing melting, holding and heat-treating furnaces to conserve energy and minimize pollutants emissions; establishing wider use of waste heat recovery.
8. Increasing life of refractories and other ceramic components that are exposed to molten metals and / or furnace environments.
9. Developing in-line sensors that are stable in the molten metal environment.

Through these and other projected advances, the metalcasting industry has established aggressive performance targets to be achieved by 2020. These include doubling productivity (tons produced per production worker), reducing lead time by 75–80%, reducing energy by 20%, achieving 100% pre- and post-consumer recycling and 75% reuse of foundry by-products, and complete elimination of waste streams.

Producing a casting involves multiple steps and support processes as illustrated in Fig. 8.1. Ceramic-based materials are important in these process steps currently and will play an important role in helping the metalcasting industry reach its 2020 targets. The following sections review each step shown in Fig. 8.1 and discuss existing and potential ceramic applications.

8.1 FEEDSTOCK PREPARATION, HANDLING, AND LOADING INTO THE MELTING FURNACE

This step involves sorting of scrap and recycled metal, conveying scrap / recycled metal and primary metal to the melting furnace, and loading

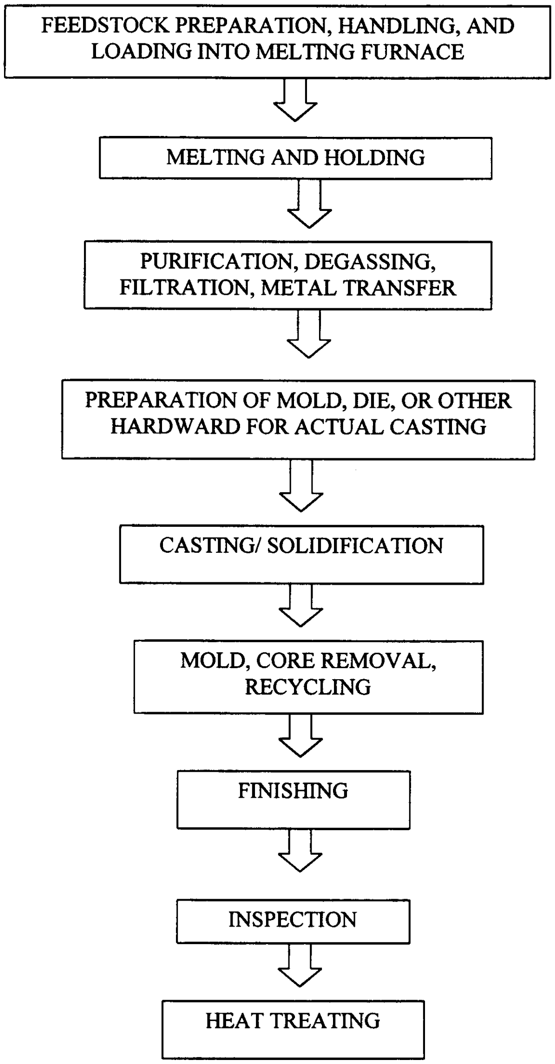

Fig. 8.1. General process steps to produce a metal product by casting.

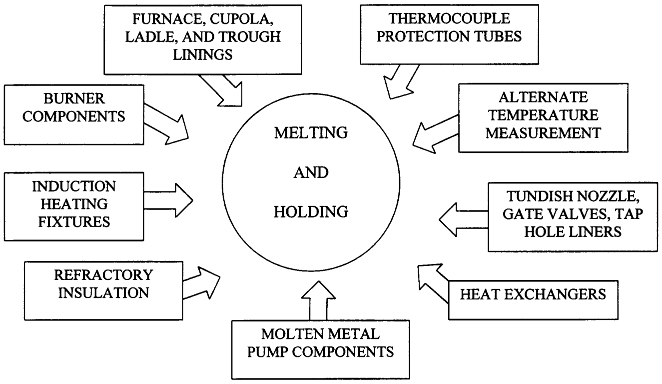

Fig. 8.2. Areas where advanced ceramic-based materials can provide benefits in melting and holding furnaces.

the metal into the furnace. Key issues are speed and reliability of sorting; abrasion / erosion / impact damage to conveying equipment; and the entry to the furnace.

To achieve the long-term industry vision of 100% recycling, technology and procedures will need to be established to rapidly and cheaply segregate metals and alloys and to efficiently separate different alloys / metals that are attached. Online sensors may also be needed to rapidly distinguish between different metals and alloys. Ceramics can contribute as sensor elements and as components in rapid-cutting systems. An example is the ceramic liner in a high-pressure, high-speed waterjet cutting system.

An important cause of maintenance and occasional unplanned shutdown is damage to the entry of a melting furnace. Refractories with improved toughness to resist impact, abrasion, and thermal shock would increase furnace life and reduce production cost.

8.2 MELTING AND HOLDING FURNACES

Figure 8.2 identifies areas where advanced ceramic-based materials might provide benefits to the melting and holding steps of metalcasting. These are discussed in this section and include improved refractories for furnace, cupola, ladle, and trough linings; thermocouple protection sheaths; improved efficiency and longer life burners; heat exchangers to reduce fuel consumption; in-line composition sensors; tundish nozzles; taphole linings; and gate valves. Above-metal circulation fans and molten metal pumps may be beneficial for some metals.

Refractory Linings

Most melting and holding furnaces are lined with ceramic refractories. Selection of the refractory lining is based on prior experience for minimum reaction with the specific metal. Linings for steel melting and aluminum melting are discussed in Chaps. 5 and 7. Substantial improvements have been achieved during the past 20years, but there is still room for incremental improvements. For example, cupola linings for ferrous alloy melting in the automotive industry usually require weekly repairs, which are conducted during weekends. Extending the maintenance time to every other week or longer would be very beneficial.

An exception to the use of ceramic linings is "skull melting," which has cooled metal furnace walls. A layer of the metal being melted adheres as a solid to the cooled metal wall, providing a noncontaminating layer around the melt. This process is used for melting titanium (which has a strong affinity for oxygen and can extract oxygen from oxide refractories) and some other high-temperature metals.

Thermocouple Protection Tubes

Temperature control is critical in the melting and holding furnaces. Temperature measurement is typically achieved by inserting a thermocouple protected by a ceramic sheath consisting of a closed-end tube. The tube has a relatively short life. A thermocouple protection tube is needed that is stable enough in the molten metal to allow continuous submersion and continuous temperature measurement. The primary concern is catastrophic fracture due to thermal shock or mechanical impact. A piece of a broken tube could obstruct the tap hole and result in expensive furnace shutdown. Silicon nitride (Si_3N_4) tubes (Fig.8.3) have shown promise in some nonferrous metals. Silicon nitride has superior thermal shock resistance and high strength at temperature and is a candidate that could be considered. Closed-end Si_3N_4 tubes are available commercially. Another alternative is a ceramic matrix composite, which may be less susceptible to catastrophic fracture than monolithic ceramics. Closed-end ceramic matrix composite tubes, although they have been fabricated, are expensive and are currently not in production.

Fig. 8.3. Si_3N_4 thermocouple protection tubes. *Source:* Kyocera Corp., Kyoto, Japan.

Burners

Heat sources for melting and holding furnaces vary according to the metal, the casting process, and the quantity of metal being cast. Heating for melting iron and steel is reviewed in Chap. 5. Heating for primary aluminum production is natural gas burners directed from the roof of the furnace onto the melt. Heating for smaller aluminum foundries is provided predominantly by radiant tubes above the melt, with some efforts to immerse the tubes in the molten aluminum. Nitride-bonded silicon carbide has exhibited stability in the molten aluminum and is being evaluated both in monolithic and composite radiant tubes. Composite tubes under development by Textron Specialty Materials in Lowell, Massachusetts, are illustrated in Fig. 8.4. Immersion heating has the potential to reduce oxide formation on the surface of the aluminum and thus to reduce the dross formation. It also has the potential to heat the aluminum more uniformly and efficiently.

Fig. 8.4. Closed-end ceramic matrix composite radiant immersion tubes consisting of silicon carbide fiber-reinforced nitride-bonded silicon carbide being developed for aluminum melting. *Source:* Textron Specialty Materials, Lowell, Mass.

Many metal melting processes utilize induction heating, especially for investment casting where melts are typically less than 3000 lb and are contained in a ceramic crucible. The ceramic crucible is surrounded by the induction coil. The space between the coil and crucible is packed with ceramic insulation. When electric power is supplied to the coil, an electrical current is induced in the metal in the crucible, resulting in rapid heating and melting. Melting is accomplished within minutes, so electricity is consumed only for a short time. Also, the dwell time of the molten metal in the crucible is short and allows multiple melts with the same crucible.

Induction melting appears to be mature and thus is not a high priority for ceramic innovation. However, advanced ceramics such as Si_3N_4 have recently demonstrated benefits for other hot-forming processes performed below the melting temperature of the metal. Ceradyne, Inc. (Costa Mesa, California) supplies a Si_3N_4 part that supports steel strips that are induction heated during forming of leaf springs. Previously, Al_2O_3 was used but had to be replaced every week due to thermal shock damage. The Si_3N_4 parts have survived for several months. Perhaps there are spacers or other parts in current induction melting systems that could be replaced with advanced ceramics to obtain increased life.

Fig. 8.5. Si_3N_4 support fixtures for induction heating operations. *Source:* Ceradyne, Inc., Costa Mesa, Calif.

Heat Exchangers

Many metalcasting foundries do not recover waste heat from the melting and holding operations. This is an opportunity for reducing fuel consumption and increasing the overall process efficiency through the use of a heat exchanger. A heat exchanger employs the hot waste gas from a process to preheat inlet air or provide other process heating. This reduces the amount of fuel or electrical input required to reach and maintain the desired process temperature. Ceramic heat exchangers have demonstrated greater than 40% reduction in fuel requirement. A variety of heat exchanger designs have been evaluated under programs funded by DOE and the Gas Research Institute. Most used monolithic silicon carbide tubes (see example in Fig. 8.6). Ceramic matrix composites tubes are being explored under the DOE Continuous Fiber Ceramic Composites (CFCC) Program.

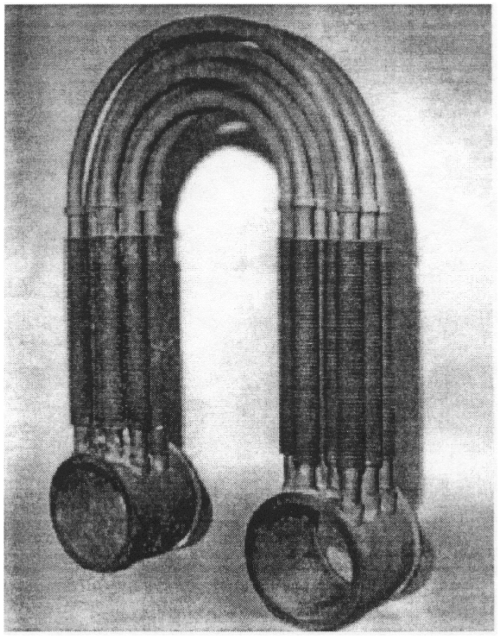

Fig. 8.6. Silicon carbide heat exchanger tubes. *Source:* Saint-Gobain / Norton Advanced Ceramics, Northboro, Mass.

Composition Sensors

Rapid-response or in-line sensors that can monitor composition or key impurities will become increasingly important to achieve increased process efficiency and optimum control of alloy properties and to accommodate higher levels of recycling. An example of a successful sensor is the oxygen sensor used in steelmaking. It consists of a small closed-end tube of oxygen-conducting zirconium oxide coated with electrically conductive electrodes. When inserted into molten steel, it can determine the oxygen concentration within about 20 s, compared to prior sampling and analysis that required about 20 min.

Nozzles, Valves, Tap-hole Linings

Smooth, controlled release of molten metal from a furnace, ladle, or cupola into the casting mold is critical. The lining, valve, or nozzle through which the metal flows is ceramic and is typically a high-maintenance item. Improvements in life and reliability are desired by the metalcasting industry. Engineered ceramic materials have potential for substantial benefits. For example, an engineered composite mixture of magnesium oxide and aluminum nitride manufactured by Lanxide Thermo Composites (Newark, Delaware) recently demonstrated double the life of prior materials for a slidegate valve releasing molten steel at 1650°C. Other options for the steel industry are discussed in Chap. 5.

Molten Metal Pumps

Molten metal pumps are replacing pouring and dipping operations in small aluminum foundries. The pumps are safer, minimize oxidation of the aluminum, and decrease bubble and inclusion defects in the cast parts. One type of pump manufactured by Metaullics Systems (Solon, Ohio) is lined with a combination of graphite and silicon carbide and in some models contains a built-in filter of a porous bonded silicon carbide ceramic.

Molten metal pumps can improve the efficiency and control for other metalcasting operations, but will require advanced ceramic linings stable for each specific alloy. Better ceramic materials and a nonoxidizing alternative to graphite for molten aluminum pumps would also be beneficial.

8.3 PURIFICATION, DEGASSING, FILTRATION, METAL TRANSFER

Figure 8.7 identifies current and potential applications of ceramics in purification, degassing, filtration and metal transfer.

Purification and degassing are conducted in the melting or holding container or in a separate refractory-lined structure. These steps involve additions that modify the chemical environment and generally increase the severity of attack on linings, stirrers, gas lances, and other components exposed to molten metal or slag. Ceramic refractory systems have evolved to address the needs of each metal, and incremental improvements are continually being sought.

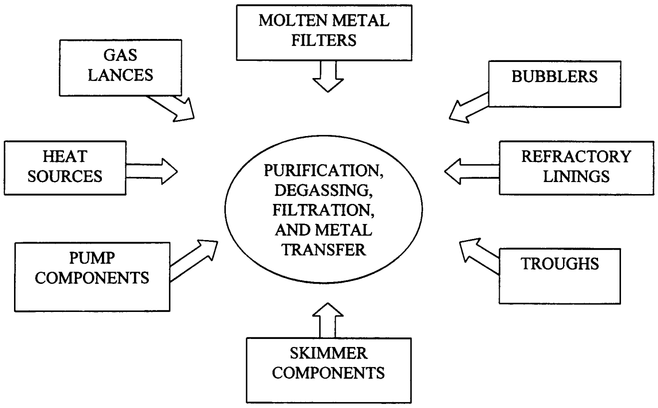

Fig. 8.7. Areas where advanced ceramic-based materials can provide benefits in purification, degassing, filtration, and metal transfer.

Filtration of molten metal has undergone a major revolution during the past 20 years. Most molten metals are now filtered through ceramic filters prior to entering the mold. The filters remove oxide scale, debris from refractories or other external sources, and accidentally entrained slag or dross. Filtration has dramatically reduced defects in castings and substantially increased yield.

Several types of filters are currently used. An older approach that is still in use is a bed filter, especially for continuous processes such as primary aluminum. The molten metal percolates through a bed of ceramic balls or pebbles that trap inclusions. Other filters consist of porous blocks, plates, or cylinders that are built into a tundish or a mold. Some of these have a honeycomb structure with small parallel channels that the metal must flow through. Others have a “reticulated foam” structure that forces the metal to flow through a tortuous path (Fig. 8.8). Another filter design is a vertical gate filter that serves as a baffle between the hearth and open well in many aluminum melting and holding furnaces. All the aluminum in the furnace percolates through the controlled-porosity filter. Some of these are fabricated from bonded silicon carbide. The same material is used for box filters as “dip-out wells” in reverberatory furnaces, crucible and pot furnaces, and die casting holding/casting furnaces. The gate and box filters typically provide 1–2 months service before they become clogged enough to require replacement.

Ceramic filters are relatively mature, but incremental improvements in material, filter design, and system design can provide additional improvements in quality of cast metals.

Fig. 8.8. Reticulated foam filters. *Source:* Hi-Tech Ceramics, Inc., Alfred, N.Y.

8.4 CRUCIBLES, MOLDS, CORES, AND DIES FOR VARIOUS CASTING PROCESSES

The big advantage of casting is the ability to economically produce complex shapes close to the final dimensional requirements of a component. A variety of casting processes have been developed and are categorized in Table 8.1. Much of the key technology resides in the design and fabrication of molds, cores, and dies.

Figure 8.9 identifies some of the issues regarding crucibles, molds, cores, and dies that might benefit from advanced ceramic-based materials. The following paragraphs review various casting processes and the current and potential roles of ceramic-based materials.

Sand Casting

Sand casting accounts for about 60% of all metalcasting production. It is especially dominant for casting of ferrous alloys. Sand casting employs natural quartz (silicon dioxide) sand for fabrication of molds and cores, although zircon, olivine, or chromite sand have been used for special applications. The big advantage of quartz sand is very low cost, around $35/ton after size classification and cleaning. The mold forms the outer dimensional contours of a casting, and the core forms internal cavities and passages.

The many variants of sand casting are typically categorized according to the method used for bonding the sand grains together to form the mold and core. The three primary categories are (1) resin binder processes, (2)bonded sand molds (using inorganic binders), and (3) unbonded sand molds.

Resin-bonded molds or cores are formed by mixing the sand with an organic material such as a phenolic resin. The resin becomes soft or fluid at the mold processing conditions and forms necks between adjacent sand grains. The resin is cured (hardened) in some processes by heat or in other processes by chemical reaction such as with sulfur dioxide gas. The cured resin necks between sand grains provide a rigid or semi-rigid bond, but they also leave substantial open spaces and channels so that gases can escape during casting.

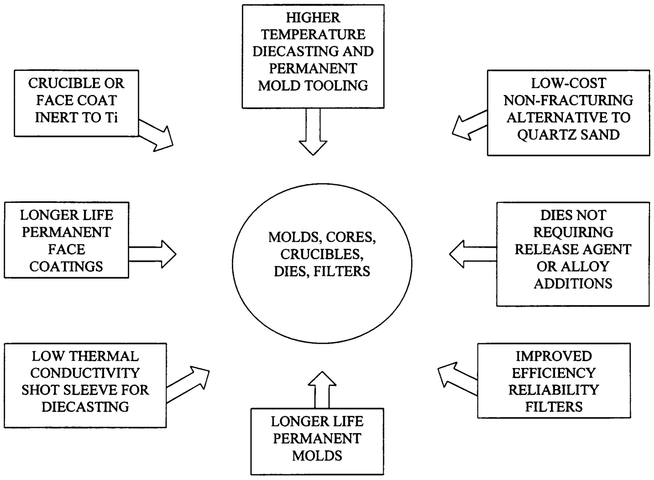

Fig. 8.9. Areas where advanced ceramic-based materials can provide benefits for tooling hardware in metalcasting processes.

Resin-bond processes pose environmental and recycling challenges. Current laws do not allow resin residues in landfills as solid wastes or in gases discharged to the atmosphere. Process gases during curing, casting, and recycling—especially containing binder vapors or decomposition products—must be constrained and pollutants removed before discharge to the atmosphere. Ceramics provide important options for exhaust gas cleanup as refractory linings, catalyst supports, and hot gas filters.

Most large foundries recycle the sand from resin-bonded molds and/or cores to reduce material costs and to minimize solid waste disposal. Ceramics can also offer benefits to sand recycling. An example is the rabble blades (plows) in a vertical shaft scrubber furnace. These blades stir the resin-sand mixture from used molds / cores in a furnace that is at a high enough temperature to decompose the resin. The blades are typically air-cooled metal. Ceramic or ceramic-coated metal blades could perhaps simplify the system and substantially reduce wear and corrosion.

Sand molds with inorganic bonds are also broadly used. A common example is "green sand" molds that consist of a mixture of sand, water, clay, and usually a few percent carbon. The clay plus water bond the sand particles together, again leaving substantial open porosity so that gases and steam can escape during metalcasting.

"Dry sand molding" also uses a clay binder, but the mold is dried to remove the water prior to casting. Dry sand molds are stronger and more rigid that moist green sand molds. They are typically coated with several coats of a surface "wash" of graphite, silica, or zircon to yield a smooth surface on the casting and to minimize chemical reaction of the mold and casting. The wash is prepared as a slurry in a mixing tank. Ceramics or ceramic coatings can increase the life of stirrers and other components in the mixing tanks.

Sand from green sand and dry sand molds also is recycled as an alternative to discarding the out-of-specification sand to landfill. Advanced ceramics might be considered for any components in the recycling operation that represent maintenance problems caused by erosion. They should also provide benefits in separating out clay particles and fractured sand particles that are below the size specification. With quartz sand, fracture is a problem that currently limits the ability to recycle. Fracture can occur at several stages in the process. The molds are generally formed by compacting the sand mixture into a shaped metal using tamping or pressure ("jolt-squeeze equipment"). This process can mechanically fracture some of the sand particles. During metalcasting, the sand rapidly changes temperature. Quartz undergoes a phase transformation (change in crystal structure) accompanied by a large dimensional change. This also fractures some sand grains. Finally, during mold breakup and recycling, other sand grains fracture.

Other inorganic bond sand casting approaches include skin-dried molds (green sand molds with the outer few centimeters dried), loam molding, sodium silicate–$C0_2$ bonding, and phosphate bonding. Each of these involves mixing, conveying, metering, recycling, and environmental issues that might benefit from ceramics.

The final category of sand casting uses unbonded (loose) sand. The primary processes are lost foam and vacuum casting. Lost foam casting is gaining in popularity, especially for aluminum casting. In the prior molds discussed, molten metal is poured into an open cavity, so the walls of the cavity need to be self-supporting and rigid. In lost foam casting, a styrofoam (polystyrene foam) pattern replaces the cavity. As the metal is poured in, the polystyrene decomposes to a gas and is replaced very precisely by the metal. The mold is prepared by forming a foamed polystyrene pattern in shaped metal tooling, assembling polystyrene patterns and gates, coating the polystyrene foam with a refractory ceramic face coating, setting the assembly onto a bed of loose sand in the bottom of the mold, and pouring loose sand around the pattern. Following casting, the sand remains loose and is easily poured or vibrated out of the mold enclosure and requires minimal preparation for the next casting.

A concern with sand casting is airborne fine particles of silica (due to fracturing) and the danger of silicosis. The primary approach of the casting industry has been prevention (i.e., to control work areas and air flows to minimize exposure of workers to silica dust). Another possibility is to substitute another material for silica sand that is less susceptible to fracture. This has not been done to any degree because of concerns about cost. Mullite, for example, has been demonstrated successfully, but costs 20–50 times more than silica sand. The mullite used is a commercially available spherical sand produced from kaolin clay by Carbo Ceramics in southern Alabama. It is currently used commercially as a proppant (pumped into oil wells to "prop up" the geological formation and retain high permeability as the crude oil is pumped out).

The results with mullite have been intriguing, especially when used with the lost foam process. Mullite does not have a phase transformation and does not fracture like silica sand. Because mullite can be reused much longer than silica sand, it can substantially reduce solid waste and airborne particles. Furthermore, mullite has a much lower change in dimensions with temperature change (thermal expansion) than does quartz sand and allows substantial improvement in dimensional control. Development of a low-cost, 100% reusable, low-thermal-expansion sand could provide substantial benefits to some segments of the casting industry.

Investment Casting

Investment casting is used extensively in the aerospace industry for turbine components and in the automotive industry for complex shapes such as turbocharger rotors. The big advantage is achieving near-net-shape as-cast parts. Generally, less than 5% final machining is required, compared to around 15% for sand casting.

Investment casting is also known as the "lost wax" process. A pattern of the desired complex shape is produced in wax, usually by injection molding into a multipiece metal tool. Wax patterns are bonded together with wax gating. This assembly is dipped one or more times into a ceramic slurry to deposit a uniform face coating on the wax surface. The face coating is a powdered ceramic composition that provides a smooth surface duplicating every intricate detail of the wax pattern and is selected to resist chemical reaction with the specific metal to be cast. The face-coated wax is then dipped into a ceramic slurry, allowed to drain but not dry, and immediately immersed in a fluidized bed (air bubbled through coarse ceramic sand particles). A layer of ceramic particles adheres to the damp slurry coating. This slurry dip / fluidized bed operation is repeated six or seven times to build up a mold wall that is strong enough and thermal shock resistant enough to survive later metal casting, yet permeable enough to allow air to pass through. The mold is then heated in an oven or autoclave to remove the wax by melting, leaving a ceramic mold with the interior precisely duplicating the shape of the part to be cast.

Sometimes a casting is desired with intricate internal passages, such as an advanced air-cooled blade or vane for a gas turbine engine. A core in the shape of the internal passages is fabricated from a ceramic-polymer mixture by injection molding. The polymer is removed thermally or by a solvent, and the core is mounted inside the ceramic mold. Figure 8.10 shows a ceramic investment casting mold and core for producing gas turbine rotor blades. The core is designed to survive the casting operation and afterwards to be removable by a leaching operation that does not attack the metal.

Ceramics are required for the crucible, lining / insulation of the induction furnace, mold, fibrous insulation to wrap the mold, core, and molten metal filter. Whereas incremental improvements in materials, processes, and quality control are possible, major innovations in ceramics are probably not required. The exception is casting of titanium. A ceramic material that does not react with molten titanium and could be used for the crucible, face coating, and filter would be an important breakthrough. Titanium extracts oxygen from current ceramic mold materials, resulting in a skin on the titanium that is not acceptable for most applications (with the exception of golf club shafts where the surface skin is not a problem).

Fig. 8.10. Investment casting mold cut away to show a core inserted in the interior of one of the gas turbine engine blade mold cavities.
Source: Howmet Research Corporation, Whitehall, Mich.

Die casting

Die casting is achieved by injecting superheated molten metal at low pressure into a shaped cavity. It is important in the automotive industry and other industries for producing thin-walled parts typically 2–4ft ^{2} in area. The tooling consists of a multipiece die to define the dimensions and shape of the part, a "shot sleeve," and a "plunger." Molten metal is pumped by air pressure into the shot sleeve and is pushed by the plunger into the die. The die contains internal channels for water or oil flow to quickly cool the casting and allow rapid cycle time.

Die casting allows relatively thin wall parts, good dimensional control with near-net-shape capability, and relatively rapid cycle time. The disadvantages include lower properties than those of some of the other casting processes (especially due to higher porosity), the requirement for a release agent before each casting, and a restriction to lower temperature metals such as aluminum, brass, and copper.

Ceramics could provide several major benefits. Current tooling is made of tool steel such as H13 for aluminum casting. The tip of the plunger is commonly BeCu. The metal tooling extracts heat rapidly from the molten metal, so substantial superheat is necessary. This wastes energy and decreases life of furnace / heater components. Ceramic tooling, inserts, or coatings could reduce heat loss and allow less superheat. Nonwetted ceramic tooling might also remove the need for a die release agent. Current release agents partially volatilize and can be a source of porosity defects. Nonwetted ceramic tooling might also allow die casting of purer aluminum. Currently about 2% iron is added to the aluminum to minimize chemical interaction and sticking to the steel tooling (caused by solubility of iron in aluminum). No iron additive would be required for ceramic tooling.

A silicon nitride monolithic ceramic is currently being evaluated, especially in Japan, for aluminum die casting (see Figs. 7.7 and 7.8). The results have been encouraging and warrant broader consideration. Information gained in use of Si_3N_4 for aluminum casting might also be a stepping stone to considering ceramic tooling to allow efficient die casting of higher temperature metals such as copper. Metal dies for copper typically survive for only about 15,000 castings.

Another potential application of ceramics for die casting is for lining molten metal pumps. Metal flow cannot be accurately controlled with current air pressure pumps, so foundries typically pour 2–5% more melt than required to be sure that the die fills completely. A ceramic-lined displacement pump would provide better control and allow less excess metal. This would significantly reduce scrap and increase process efficiency. Some development has already been conducted by General Motors. Their demonstrations extended life to 300,000 cycles, but their goal was one million cycles. The problem was cracks in the ceramic pump lining. Based on other case histories with ceramics, a solution is likely with design modification.

Semisolid casting is a variant of die casting that is currently under development. It is analogous to high-pressure injection molding. It is conducted at a lower temperature than die casting or squeeze casting and also uses H13 steel tooling. There is less heat in the tooling, so cycle time is decreased. Water or oil cooling can also be reduced or eliminated, simplifying the tooling. A die lubricant is still required with each cycle. Ceramics could provide for semisolid casting benefits similar to those discussed for die casting. Perhaps some of the technology demonstrated for ceramic tooling for fabrication of aluminum cans is applicable.

Permanent Mold Casting

Permanent mold casting involves flowing lower temperature metals into a shaped-steel mold. It is used for making bulkier, thicker-wall (>2–3 mm), less-detailed parts than are possible with die casting. The dimensional control is inferior to that of die casting, but the properties (especially lower porosity) are better. Cycle time is slower and tooling life shorter.

Permanent mold casting accounts for about an 11% share of production casting. It is used extensively for casting of aluminum and some other low-melting-temperature metals. There is some capability for cast iron, but not for steel or other high-temperature metals because metallic molds cannot survive the temperature. Ceramic molds could open up many opportunities, especially if they could allow casting of thinner wall, smaller parts needed for appliances and the automotive industry.

Permanent mold casting is well established for casting bulky, less-detailed parts. The molds are metal backed with ceramic refractory insulation. The inner surface of the metal die is coated with a ceramic face coat, usually zirconium oxide. Multiple castings are achieved per face coat. Increasing the number of castings before replacement of the face coat and increasing the total number of castings per mold are desired. Recent advances in the field of zirconium oxide ceramic thermal barrier coatings for gas turbine engines may be applicable to achieving improved face coatings and mold life. The thermal barrier coatings utilize a “bond coating” between the ceramic and metal that improves adherence and thermal shock damage resistance. Hundreds or even thousands of castings may be possible with this type of mold coating.

Centrifugal Casting

Centrifugal casting accounts for about 7% of casting production. Molten metal is poured into a sand or permanent mold that is either rotating or subsequently rotated to spread the metal uniformly against the mold wall. Ceramics should be considered for the same benefits discussed earlier for sand casting and permanent mold casting.

Composite Casting

An emerging technology is casting of a metal–ceramic composite such as an aluminum alloy containing a dispersion of aluminum oxide or silicon carbide ceramic particles. The ceramic-reinforced aluminum, for example, has properties competitive with those of much heavier iron-based alloys and has potential for many applications if a cost-effective, reliable fabrication process can be established.

8.5 CASTING

The previous chapter describes the various casting techniques in terms of variants in molds and other tooling. For the actual casting operation, the mold or die and other tooling (such as the core) are assembled, and the metal is melted and pumped or poured into the mold through the filters. The roles for ceramics in casting, other than the tooling, are thermocouple protection tubes, gates or valves controlling molten metal flow, pump parts, refractories for oven / furnaces for preheating molds (such as in investment casting), and exhaust gas cleanup systems. Most of these are discussed in prior chapters of this report. Exhaust cleanup merits further discussion.

Volatile hydrocarbons are produced during lost foam casting and during casting with resin-bonded molds / cores. Foundries generally use an afterburner to oxidize / decompose the hydrocarbons. This requires burning of extra fuel, which reduces efficiency. Ceramic heat exchanger tubes in the afterburner could salvage some of the waste heat and divert it to portions of the process where heating is required.

An issue with casting is rate and uniformity of solidification. Improvement in alloy properties will involve better control of solidification. Conventional ceramic molds have lower thermal conductivity than metals and result in a slow rate of solidification. For rapid solidification, cooled metal tooling is most effective, but often it cannot be used because of temperature or chemical interaction. Some advanced ceramics have thermal conductivity approaching that of metals. Examples are silicon carbide, aluminum nitride, some engineered compositions of Si_3N_4, and some ceramic matrix composites. They have potential to be engineered into tooling that can better control solidification to achieve optimum microstructure and properties.

8.6 POSTCASTING PROCESS STEPS

Postcasting process steps include mold / core removal and recycling, finishing of the metal part, inspection, and heat treatment. Ceramics provide benefits in all of these process steps and have potential to provide additional benefits, especially in the last three steps. Figure 8.11 identifies some of the key areas where ceramics can provide future benefits.

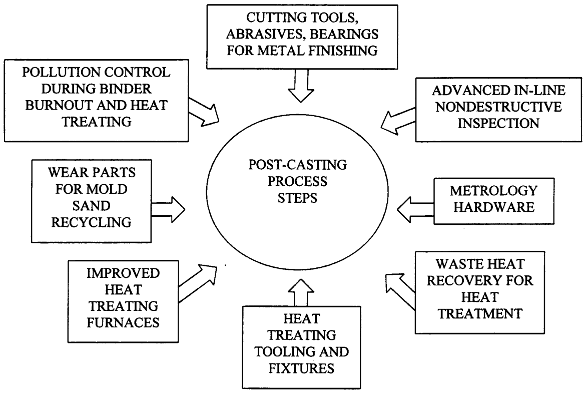

Fig. 8.11. Areas where ceramic-based materials can benefit the post-casting process steps of finishing, inspection, and heat treating.

Finishing

All castings require some finishing to achieve the final product dimensions. This may simply involve sandblasting, deburring, or removal of flash, or it may involve extensive machining. For example, a cast iron engine block requires many boring, milling, and grinding steps.

Major breakthroughs have occurred since the mid-1970s in the use of ceramics to machine metals more effectively and efficiently. One major innovation was the use of Si_3N_4–based ceramic compositions as inserts for machining cast iron, as is discussed in Sect. 2.1 of this report. The Si_3N_4 provided reliability equivalent to WC–Co cermet inserts at 4–6 times the metal removal rate. Composite ceramics consisting of aluminum oxide with silicon carbide whisker reinforcement provided similar improvements for other metal alloys. Ceramic materials and coatings and cutting insert designs are continuing to be optimized. A current area of development with great promise is the low-temperature, low-pressure deposition of diamond coatings from a gas phase precursor. Diamond is the hardest material known and also has the highest thermal conductivity. As the price of diamond coatings comes down, numerous applications to increase the efficiency of finish machining of castings and other metal parts should be possible. The coatings are already being successfully applied to machining of some difficult aluminum alloys.

Another important breakthrough in finishing is the use of Si_3N_4 in hybrid bearings. This is revolutionizing machine tools, allowing higher speeds and greater dimensional accuracy. The cost of the Si_3N_4 bearings is decreasing rapidly, so that ceramic bearings can be considered for other applications where they were previously cost-prohibitive.

Advances have also occurred in ceramic abrasives for sanding, lapping, and polishing. For example, the 3M Company has developed a process using sol-gel technology to produce very fine grained, high toughness abrasives. Incremental improvements are anticipated in the future.

Inspection

Ceramics are also important in both nondestructive inspection and dimensional inspection. Linking ceramics with advanced computing technology is making possible high-resolution inspection capability for internal defects, which should increase the quality of castings. For example, Howmet has demonstrated in-line inspection of complex turbine component castings by x-ray computed tomography (CAT-SCAN or simply CT). One of the keys is the high-resolution ceramic scintillator now available in CT units. Advanced ceramic technology is also available in piezoelectric transducers for ultrasonic scans, which provides another opportunity for in-line high-resolution inspection. These inspection capabilities can also be effective in monitoring casting experiments to guide process improvements.

Ceramics are gaining in importance in fixtures and tools for dimensional measurement. Aluminum oxide is replacing large-gauge blocks of granite and other large measurement fixtures. For many years replacement was not possible because ceramic manufacturers could not fabricate large enough pieces of ceramic. Now companies such Wilbanks (a Coors Company), Hillsboro, Oregon, routinely fabricate large aluminum oxide parts to high levels of precision and surface finish that upgrade the quality of dimensional measurement. Low-thermal-expansion ceramics are also now commercially available where tooling is needed that is dimensionally stable over a broad temperature range. Examples are the low-expansion glass and glass-ceramic materials from Corning (Corning, New York) and the NZP ceramics from LoTEC (Salt Lake City, Utah).

Heat Treating

Heat treating represents one of the most fertile areas where advanced ceramics can provide significant benefits to metalcasting and metals processing in general. Figure 8.11 identifies some specific aspects of heat treating where ceramics can play an important role.

Heat treating, which is conducted within large facilities such as steel mills, is also a vital industry for over 700 commercial shops and 140,000 employees. Commercial sales were about $1.5 billion in 1995. The industry consumes about 500 trillion Btu of energy per year and uses hazardous chemicals and gases subject to environmental control. The heat treating industry has prepared their own vision for the future and technology roadmap in collaboration with DOE's Office of Industrial Technologies. Specific goals that ceramics can help achieve include

- furnaces with improved efficiency,
- longer life materials for furnace hardware, and
- closed-loop systems with nonpolluting, nonflammable quenchants.

Heat treating is specialized for each metal, alloy, and application. This includes annealing, stress-relief, normalizing, quench hardening, tempering, precipitation hardening, case-hardening, and surface cleaning.

Annealing and stress relief are required for many alloys and probably represent the largest segment of heat treating, especially because they are used for large quantities of steel in every steel mill. Stress relief is conducted at an intermediate temperature for roughly 2–6 h to relieve residual stress resulting from processes such as casting, forging, or welding. Annealing is conducted at even higher temperature to increase ductility and uniformity prior to cold working or machining. Normalizing is a form of annealing, with the objective of homogenizing the microstructure.

Hardening is another critical segment of heat treating. Hardening can be achieved by rapidly quenching the metal from elevated temperature, usually followed by a controlled tempering reheating to establish specific mechanical properties.

Hardening also can be achieved by heat treating special alloy compositions to induce formation of hard precipitates dispersed in the alloy. Many applications require that only the surface be hardened. This can be accomplished by heating the metal in a controlled atmosphere that allows elements such as carbon and nitrogen to diffuse into the surface of the alloy to form hard phases.

Heat treating is conducted in furnaces that range from 2 to 20 or more feet square. Some of the furnaces are batch and others are continuous. Some are electric and use ceramic heating elements or induction heating. Most use a combustion heat source such as natural gas. Where a controlled atmosphere is required, the metal parts and atmosphere must be separated from the combustion source. This is accomplished either by sealing the parts and atmosphere in a retort or muffle and heating externally or by combusting the fuel in impermeable radiant burner tubes.

Ceramics can provide benefits in the furnace construction, in the heat source, in fixtures to support the metal parts inside the furnace, in waste heat recovery, and in pollution control.

Heat-Treating Furnace Components

Major advances have occurred in furnace construction and control during the past 30 years. Cycle time and energy consumption have been reduced by new furnace designs and by substituting fibrous ceramic insulation in place of firebrick. Circulation fans have been added to some furnaces to improve the temperature and atmosphere uniformity. Heat exchangers have been added to use waste heat to preheat inlet process gases, air, and fuel. Ceramic heat exchangers have demonstrated over 40% reduction in energy consumption.

Circulation fans currently used are constructed of metal and can only be used in lower temperature processes. Even in these processes they have limited life because of creep and fatigue. Ceramic matrix composites are being developed under the DOE CFCC program for circulation fans. Analyses show that the stresses are well within the capability of the ceramic composites and suggest that substantial improvement in fan life and temperature capability can be achieved. Prototypes are being fabricated for evaluation.

Several types of heat exchangers have been developed and tested in recent years including tubular and box-type designs. The most common designs have been tubular based on silicon carbide ceramic tubes. Although effective, these have not been widely used because of cost (too long a payback time). New tube fabrication technologies that are bringing tube cost down have been developed by companies such as INEX, Inc. and 3M. Because of the high potential payoff in process efficiency, ceramic heat exchangers represent an important technology to pursue for heat treating furnaces. They also will benefit pollution control and perhaps help in establishing closed-loop processes.

Other potential key applications of ceramics in heat-treating furnaces include conveyor belts plus bearings and chains in the drive systems. For example, Saint-Gobain / Carborundum Structural Ceramics has supplied silicon carbide links (see Fig.8.12) to produce a conveyor belt 18 in. wide and 120 ft long for a continuous powder metal sintering furnace that operates above 1090°C. This successful technology should be readily adaptable to continuous heat treating furnaces.

Fig. 8.12. Silicon carbide ceramic links for a continuous powder metal sintering furnace.
Source: Saint-Gobain / Carborundum Structural Ceramics, Niagara Falls, N.Y.

Heat-Treating Tooling and Fixtures

Metal parts require support structures or fixtures while in the heat-treating furnace. These need to be structurally strong enough to support the metal and survive handling, inert to chemical reactions with the metal or atmosphere, resistant to rapid temperature change, and reusable for many cycles. Advanced ceramics and ceramic-based composites have the potential to meet these requirements. Some of the ceramics that might be considered include Si_3N_4, silicon carbide, fused quartz, reticulated foam (similar to molten metal filters), and NZP. NZP is a relatively new ceramic that has near-zero thermal expansion and is very resistant to rapid temperature change. Specific compositions can be repeatedly quenched from over 1200° C into liquid nitrogen without fracture. NZP is supplied by LoTEC, Inc. (Salt Lake City) and has performed well in initial trials for heat-treating fixtures.

Pollution Control in Heat Treating

Most heat-treating operations produce airborne pollutants caused by combustion products, heat treatment atmospheres (such as carburizing or carbonitriding), quench vapors, and cleaning vapors. Pollution emission regulations are becoming more stringent. Future heat-treating operations will require improved pollution control processes or devices. Ceramic-based pollution control systems for automobiles (catalytic converter and No_x reduction) such as developed by Corning, Inc. (Corning, N.Y.) might provide baseline technology for achieving low-cost systems that are even affordable for the smaller heat treatment businesses.

8.7 SUMMARY OF POTENTIAL APPLICATIONS OF CERAMIC-BASED MATERIALS IN THE METALCASTING INDUSTRY

Ceramic-based materials can help the metalcasting industry to meet their goals of increased productivity, decreased energy, improved net-shape capability, minimization of casting defects, automated finishing, and reduction in pollution emissions. Specific opportunities are summarized in Table 8.2.

Table 8.2. Potential applications in the metalcasting industry

Application	Industry Needs	Opportunities for Ceramics
Furnace, cupola, ladle, and trough linings	Improved resistance to molten metals, abrasion and impact; longer interval between maintenance	Incremental improvements in ceramic refractories; alternate designs; insertion of premium materials such as tough composite compositions in high-maintenance areas
Burners	Longer life, increased efficiency, decreased pollutants	Advanced monolithic ceramics and ceramic matrix composites; thermal barrier coatings; new designs optimized specifically for advanced ceramic-based materials, including immersion radiant burners
Heat exchangers	Use of waste heat from melting, holding and heat-treating furnaces to preheat inlet air and reduce fuel consumption	Silicon carbide and ceramic matrix composite tubular designs and other designs for cordierite, mullite and NZP low-thermal expansion ceramics
Pollution control	Efficient removal of particulates and gaseous pollutants	Fibrous, honeycomb, and candle particulate hot-gas filters; ceramic honeycomb substrate catalytic hot-gas treatment systems

Table 8.2. Potential applications in the metalcasting industry (cont.)

Application	Industry Needs	Opportunities for Ceramics
Thermocouple protection tubes	Tubes that can withstand immersion and provide continuous readings	Si_3N_4, new high-toughness silicon carbide, silicon carbide/aluminum nitride and silicon carbide/molybdenum disilicide composites, ceramic matrix composites
Tundish nozzles, tap-hole linings, gate valves	Longer life, improved reliability materials/designs	Advanced composite materials
Molten-metal pumps	Liners and other components with improved resistance to molten metal and to thermal shock.	Advanced Si_3N_4, silicon carbide, and composite ceramics
Molten-metal filters	Improved efficiency and reliability ceramic filters	Incremental improvements in ceramic materials and designs
Bubblers, gas lances	Improved resistance to molten metals, reactive gases, and thermal shock	Monolithic ceramic inserts, one-piece ceramic matrix composites, and ceramic-coated metal
Crucibles, cores, molds, and face coats	Material stable in molten titanium, spall resistance, improved recycling	Incremental improvements; substitution of low-thermal-expansion, nonfracturing ceramic in place of silica sand
Permanent molds	Longer life, elimination of release coating, broader range of alloy suitability	Engineered ceramic compositions with high strength and toughness
Die-casting dies	Longer life, higher temperature alloys, thinner wall castings, less heat loss so lower superheat	Same. Si_3N_4 inserts in nonferrous alloy die casting
Cutting tools and abrasives	Increased number of parts machined per tool to decrease downtime while changing tools	Incremental improvements
Heat-treating fixtures	Reusable fixtures that do not distort or interact with the metal or atmosphere, conveyor belts for continuous furnaces	Advanced monolithic and composite ceramics and coatings
Circulation fans	Increased creep and fatigue life, lower weight	Ceramic matrix composites
Bearings	Longer life, increased tooling rigidity	Si_3N_4 hybrid bearings
Inspection equipment	Real-time inspection for internal defects	Advanced CT system with high-resolution ceramic scintillator, improved ultrasonic systems including acoustic resonance

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