4.0 Casting

Steel casting processes represent one of the major areas of technological development within the steel industry. Besides the significant improvements in conventional thick slab casting, relatively newer technologies such as ultra-thick slab casting, thin slab casting and strip casting are under various stages of development and commercialization in the world. In North America, however, a huge gap exists in applied, new continuous casting technologies compared to the other parts of the world, especially at the integrated steel producers. Even so, the continuous casters in the US and Canada are able to make the highest quality cast products to compete in the world market by paying attention to process and practice details.

A recent trend in North America is the making of next generation Advanced High Strength Steel (AHSS) for light weight vehicles in the automobile industry. These steel grades require higher amounts of elements such as aluminum, manganese, silicon, and titanium than current steels, which lead to greater challenges in the continuous casting of these grades. Fundamental knowledge about the solidification process and thermal mechanical properties of these higher alloyed grades are needed, along with the corresponding caster technologies, in order to make defect-free cast products.

Ingot casting, in the meantime, continues to be the preferred method to produce steel for some uses, such as intermediate and large bar applications (e.g., power transmission) and high-performance bar and tubing applications (e.g., bearings and gears). Foundries and specialty producers also continue to use ingot casting to produce large cross-sections or very thick plates. Conventional thick slab casters around the world are continuing to get thicker and wider in order to reduce the share of this thick plate market from ingots.

Figure 4-1 outlines the current and potential directions in casting. Current technologies include ingot, thick slab, ultra-thick slab, thin slab, strip, billet, beam blank, round and bloom casting. Future developments will concentrate on defect-free continuous casting without surface and internal cracks, fewer inclusions, and with sound centerline and less segregation. Other future developments include rod casting, rapid prototyping of complex geometries via droplet consolidation or laser/wire technologies, rheocasting, and direct part fabricating via computer-controlled casting/milling machines. Energy savings is also a key driver in the technology being developed for casting and rolling final product.

New and Emerging Technologies. The commercialization of Arvedi's Endless Strip Production (ESP), POSCO's Compact Endless Mill (CEM), Danieli's Universal Endless (DUE) strip processes have pushed the thin slab casting-rolling process into a newer level of technological advance and energy savings. The commercial installation of a completely horizontal casting pilot plant of Belt Casting Technology (BCT) at Peine-Salzgitter in Germany offers further promise for steels to compete against materials such as aluminum and carbon fiber when building lighter car bodies. The completely vertical slab caster at Dillinger Hüttenwerke in Germany and the jumbo bloom caster at Timken Faircrest in the United States provide for less strain on the solidifying steel, better ability to float out inclusions for cleaner steel, and the production of higher alloyed steel grades than a conventional, curved radius caster. For traditional, integrated steel mills in North America, some of the established newer casting technologies such as in-mold or strand electromagnetic stirring and dynamic soft reduction may have to be adopted to meet today's quality demands.

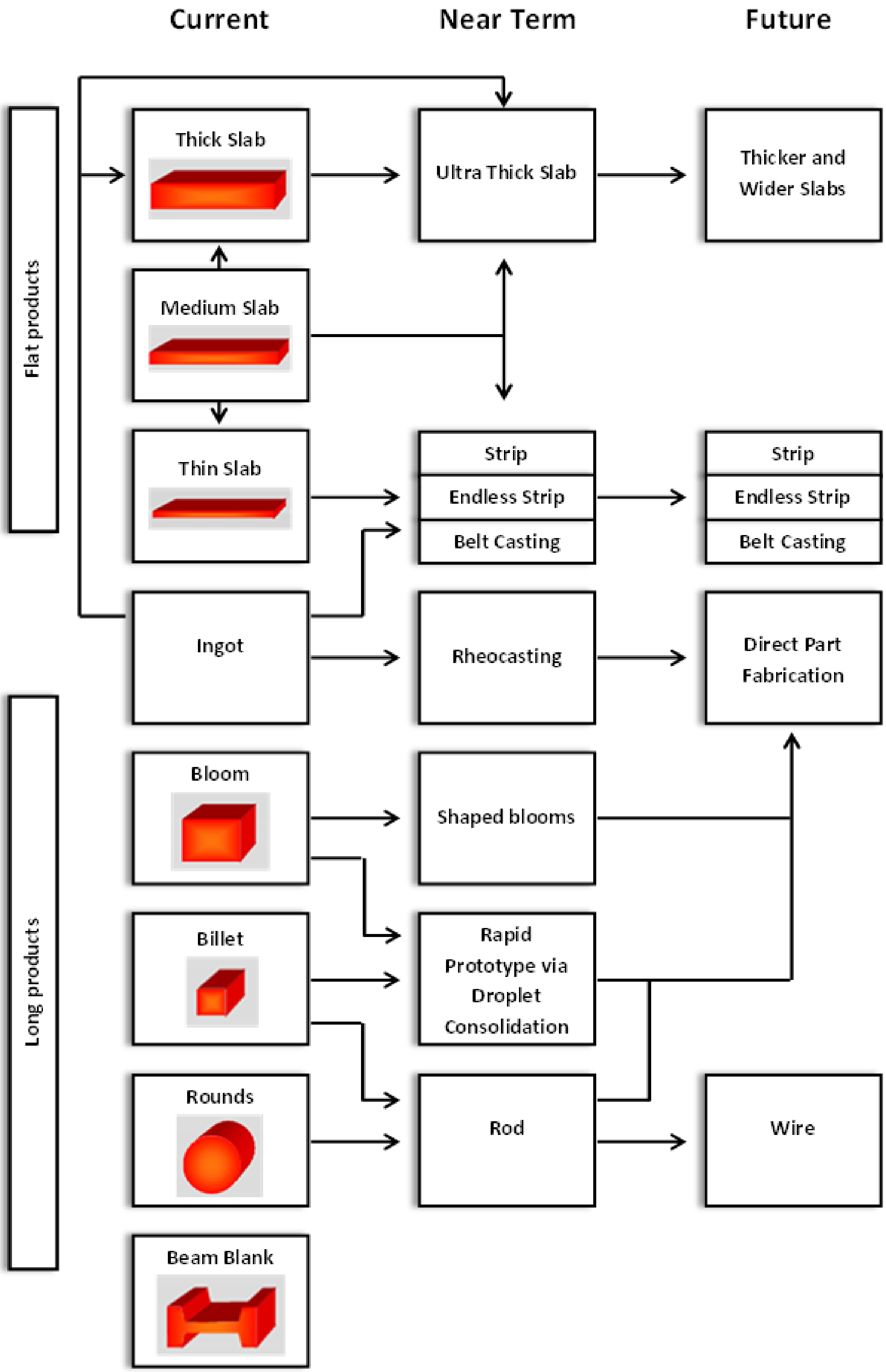

Figure 4-1. Current and Potential Future Casting Technologies

4.1 Generic Casting Issues

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

New technologies are driven by:

- Energy Savings
- Low capital and operating costs
- Flexibility
- Niche markets
- New product development

In addition, casting developments will need to consider environmental factors and recyclability of waste products, such as wastewater, refractories, and slag. One example is the reduction of fluorine in the casting mold powder as it can solve both environmental and caster equipment erosion problems.

All of the above requirements drive casting development towards more streamlined, near-net-shape casting with rolling processes at a meaningful economical production scale. This results in the cast surface much closer to the finished part surface. Many of the next generation AHSS grades need to be direct hot charged into a reheating furnace in the rolling mill after casting. Both trends have led to the necessity of defect-free castings that must be produced at geometrical tolerances defined by the end product. Strip cast and belt cast products will undergo little rolling. Research on as-cast structure and properties is required. New alloys and alloying techniques may be needed for strip cast products to develop properties comparable to conventionally cast products. This progression results in a number of generic requirements in casting R&D.

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

Clogging of the submerged entry nozzle (SEN), which shrouds the liquid steel traveling from the tundish to the mold, is a common operational occurrence that can result in quality and production problems when steels containing solid inclusions are cast. One solution to this problem is to transform the solid inclusions by chemical treatment to a liquid or a non-clustering solid inclusion during steelmaking. This "inclusion engineering" is often not achieved in practice, as the exact stability of all possible inclusions must be calculated for a particular alloy to ensure that the designed inclusion chemistry is achieved. Recent developments in analytical technology have enabled sophisticated tertiary diagrams to be created, to enhance the understanding of inclusion melting points; and optimize ladle metallurgy practices. At the caster, one must avoid contamination of the designed inclusions by reoxidation, when air infiltrates the liquid steel being cast. Caster design, such as a vertical section to allow the floatation of inclusions, is another important aspect to avoid inclusion entrapment in the solidifying steel shell. This is particularly important when casting Interstitial Free (IF) or Ultra Low Carbon steel grades. "Inclusion engineering" will lead to the design of new alloys with alternative processing strategies to achieve specific properties, as well as focusing on the retention of desirable inclusions.

Active control of fluid flow and temperature is necessary to avoid the production of defects during casting and to ensure product consistency. Current gravity-fed flow systems only allow gross control of the above parameters, not independent control of flow and temperature in the tundish and mold of a continuous caster. Extensive automatic on-line monitoring of cast processes can significantly improve process control and process consistency. Sensor technologies that are able to track the flow and temperature of liquid steel in tundish and mold have become extremely important for quality casting. Finite Element Analysis and fluid flow modeling can also be used to optimally design casting equipment such as the tundish, tundish furniture, SEN, etc. to encourage proper fluid flow.

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

The prevention of internal cracks is another important quality demand. As steel grades become more and more alloyed, their ductility and their allowable strain limit decreases. Caster design considerations including the bending / unbending radii and the roller spacing / diameter are vital to reduce the strain that is imparted on the solidifying shell. This is driving newer technologies like completely vertical or horizontal casting, which are free of any bending/unbending strains.

New and Emerging Technologies. Strip casting, belt casting and endless thin slab casting/rolling (discussed in Section 4.3) are the most obvious new casting technologies. However, there are a number of ancillary technologies that are currently used and under development for existing casters that could potentially be further adopted in the future. These technologies include:

- Applications of electromagnetics in the area of fluid flow control, heating, and containment
- Advanced vision systems for defect detection and identification
- Advanced computer diagnostic controls combined with new sensors
- Liquid steel temperature control in the mold and tundish
- Advanced ceramics for clean steel production
- Chamfered corner mold to produce corner cracking free slabs and improved rolling yield
- Hydraulic mold oscillation to dynamically vary the stroke and frequency of oscillation
- Air mist, width dependent secondary cooling systems to improve surface temperature uniformity
- Dynamic soft reduction to impart forces on the steel close to final solidification in order to improve centerline segregation.

Future developments will focus on near-net-shape production of all castings as well as defect-free casting of all highly alloyed steel grades, including AHSS, and droplet consolidation technologies for rapid prototyping and rheocasting.

4.2 Slab, Billet, Rounds, Beam Blank, and Bloom Casting

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

Some specific trends include:

- Increasing strand cleanliness
- Surface and internal quality improvements
- Net or Near-Net Shape
- Higher cast speeds

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

The material systems used to contain and transport the liquid steel must be stable with respect to any steel grade and not add to the inclusion population. They also must be cost-effective and capable of the long exposures associated with sequence casting. Tundish fluxes must have the proper fusing temperature and fluidity and not be corrosive to the refractories, while providing protection from reoxidation and the ability to capture inclusions. Flux design for continuous caster operation continues to be a difficult issue because the tundish and mold flux requirements are complex and there is not a complete understanding of the exact design requirement for fluxes. This is particularly true for the next generation AHSS which contain high amounts of highly reactive elements, such as Aluminum.

Nozzle clogging remains an issue that impacts productivity and quality in casting. A solution that allows the casting of steel grades containing solid second-phase particles will ensure consistent production of aluminum- killed steels. Better understanding and relatively quick inclusion analysis with automated electron microscopy through rapid analysis systems such as ASPEX and ASCAT that provide insight and compositional and size changes during processing, along with recorded process data have allowed casting operations to make quick process adjustments.

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

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

Higher internal quality standards are also a demand in the industry. Internal cracks and centerline segregation have detrimental effects on the final product and must be avoided. Proper roller apron design with regards to roller diameter and roller spacing can reduce the strain on the product and the likelihood for internal cracks. This, well-monitored secondary cooling, and dynamic soft reduction applied at the proper time close to final solidification, can mitigate centerline segregation. These requirements are particularly important for final applications in the pipe and plate industries as well as any highly alloyed steels, such as AHSS.

As productivity demands increase, cast speeds are also increasing. Higher caster speeds actually help keep the strand hotter and usually improve surface quality. But, higher cast speeds usually have a negative impact on internal quality and can greatly increase the likelihood of breakouts at the continuous caster (liquid steel not contained in the solid shell after leaving the mold). Modern mold mapping systems, using thermocouples or fiber optic technology, can provide insight into the solidification process in the mold to help avoid these problems. Liquid-solid interface strain models can help predict if internal cracking is likely and can be used to predict a maximum cast speed.

4.3 Strip Casting, Belt Casting, Thin Slab Casting coupled with Endless Rolling

Cast speed in strip casting can vary from 160 to 325 ft/min, the belt caster is capable of running at speeds of 33 to 100 ft/min, thin slab casters typically operate between 12 to 20 ft/min, while conventional thick slab casters operate up to 7 ft/min. Strip casting is quite unique in that solidification occurs against a rotating wheel mold and the cast surface must be defect-free. Cast tolerances must be on the order of tens of microns (ten-thousandths of an inch) across the width and length of the strip. Strip-cast materials, at a few millimeter cast thickness, are significantly different from conventionally processed strip because they have not undergone significant hot reduction. In belt casting, solidification occurs on the bottom side of the product against a water cooled belt and on the top side against only a purged atmosphere. Control of the thickness across the width is important and achieved by electromagnetic technology. There is the ability to apply some reduction to the cast product, as-cast thicknesses can vary from 8-20 mm.

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

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

The belt caster does not have a conventional mold, but rather a refractory vessel, and thus no mold powder. This allows steel grades with high amounts of reactive elements, like Al, Mn, Si, to be cast without issues. These steel grades are high strength, high ductility for use in light weighting of automobiles.

Thin slab casting, originally designed to cast low or medium carbon hot rolled material, has branched out to more difficult steel grades in recent years. Steel grades including API pipe, AHSS, peritectics, dual phase, and boron steels have all been cast on thin slab casters with varying degrees of success. Thin slab casters have recently been coupled with the rolling mill for endless production. There is a high potential for energy savings with this scenario.

Trends and Drivers. Because of their novelty, many fundamental phenomenon need to be studied for these new technologies. These issues are related to process control, consistency, productivity, and quality (including tolerances). Due to the high cast speeds of these technologies, the control tolerances must be significantly tighter than in conventional casting processes. The exact chemistries and steel grades which can be cast need to be studied, along with the potential properties which can be achieved, like ductility, tensile strength, etc.

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

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

New and Emerging Technologies. In general, the idea of directly casting flat rolled products is not new. H. Bessemer had a patent on twin-roll casting in 1865. Since 1890, various developments were initiated in steel strip technologies. However, these efforts did not materialize into commercial success until the thin-slab casting technology developments in 1980's. Since then, many strip casting R&D projects have been initiated world-wide since 1980 utilizing single-roll, twin-roll, and belt casting concepts. As of 2013, four thin-strip casting processes reached the industrial stage [Castrip (Nucor/BHP/IHI) at Nucor Indiana and Arkansas, Eurostrip (joint European R&D), Nippon Steel/Mitsubishi Heavy Industries at Hikari, and poStrip (POSCO)], while one is in full-scale testing at Baosteel in China. POSCO's poStrip and BaoSteel's Baostrip are advancing rapidly toward full commercialization. Nippon Steel/MHI project and Eurostrip have presumably been terminated. Belt Casting currently operates at the facility in Salzgitter Flachstahl GmbH in Peine, Germany.

4.4 Casting Research and Development Needs and Opportunities

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

Generic

The ability to produce liquid steels with strictly controlled inclusion contents needs to be developed. This ability is necessary to restrict inclusion average size to less than 5 µm in diameter and to minimize the total mass of inclusions. This is the process of steel refining. However, in the casting area, an understanding of the interaction of fluid flow at the slag-metal interface must be developed and modeled to eliminate formation, and facilitate the removal, of inclusions during processing. In the meantime, the prevention of steel reoxidation and inclusion buildup during casting are important to ensure the desired inclusions do not change and to avoid the breakup of the clogging material which will become a source of large inclusions in the as-cast product.

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

In the areas of defect-free casting, surface and internal defects are both important for various products with different end applications. The most common surface defects include inclusion-based defects, transverse cracking and longitudinal cracking. There needs to be a clear understanding on the mechanism of the formation of these cracks for particularly the novel advanced product steel chemistries. Add to this that surface quality is becoming more challenging due to the casting of more heavily microalloyed steels with added elements such as Niobium and Vanadium for higher strength steels and those with more reactive elements like aluminum, titanium and silicon, such as next generation AHSS grades with a balance between strength and formability. Secondary cooling systems with air mist nozzles and independently controlled spray zones across the width of the strand have shown to improve surface quality. Spray nozzle testing and heat transfer models exist and are constantly being tuned to calculate surface temperature and control secondary water flows. With regards to internal quality, inclusion distribution, avoiding internal cracking, and centerline segregation/soundness are important, especially for quality heavy plate and pipe production. Dynamic soft reduction has proven to be an effective technology to improve centerline segregation and eliminate centerline looseness. An accurate secondary cooling and solidification model is a must to make dynamic soft reduction work effectively. A more exact and definitive determination of the final solidification point would go a long way in improving the effectiveness of the applied dynamic soft reduction. Electromagnetic stirring can improve the equiaxed structure of the as-cast product and also aid in reducing segregation. Tools to examine the flow in the mold are needed to understand the stirrer's effect on the fluid flow. Understanding steel and gas flow in the mold and strand will also help control the concentration of inclusions inside the cast products.

New tools to analyze the casting process and the as-cast product are becoming more prevalent. Lasers are being used to analyze as-cast shape online. Surface inspection technologies visually inspect and document surface defects. Ultrasonic technology is being used to objectively analyze the internal quality and macrostructure of as-cast samples.

Process control research presents many opportunities for casting improvement. The ability to monitor and actively control fluid flow, temperature, and chemistry would improve casting performance. Given the high cost and reliability issues associated with wiring in the harsh environments common to the steel industry, sensors that employ wireless technology to communicate data and diagnostic information could be beneficial to the infrastructure of iron and steelmaking facilities.

Casting research and development needs and opportunities

- Ability to produce liquid steels with strictly controlled inclusion contents
- Techniques to calculate stability diagrams for all grades of steel
- Ability to actively control fluid flow, temperature (e.g. superheat), and chemistry
- Ability to monitor the process to ensure consistent quality
- Improved internal quality through proper roller apron design and dynamic soft reduction
- Improved surface quality through improved mold oscillation using hydraulic oscillation
- Improved surface quality through air mist, width dependent secondary cooling systems
- Ability to predict cast shape, inclusion, or gas distribution and structure
- Advanced heat transfer and fluid flow models
- Techniques to minimize scaling or develop scales that are more easily removed in post processing
- Enhanced education on the science and engineering principles involved in the design and operation of casters
- Direct rod or wire casting at high rates and production directly from liquid steel
- On-line control systems
- Choosing the correct caster design for the production and grade aims of the mill
- Development of a heavy rod casting process with in-line rolling to variable diameters
- Development of mold powders for improving castability and quality of HSS slabs

Fluid mixing control, in which mixing of unlike grades can be either enhanced or minimized in the tundish or mold, is also a necessary development to allow seamless grade transitions and order sizes that are better matched with production aims. Other needs include advanced process control strategies, vision systems for defect detection and identification, and the implementation of advanced computer diagnostic controls for identification of potential operation problems and the scheduling of maintenance.

The three dimensional details of cast shape, inclusion or gas distribution and structure are hard to predict, although studies on real slabs through 3D counting and numerical modeling have been carried out. Development of modeling techniques should continue to gain more detailed knowledge of surface formation in castings and to predict on-line the details of micro- and macro-structure solidification and inclusion or gas distribution.

Advanced heat transfer and fluid flow models that include the free surface of liquid/liquid boundaries, the prediction of slag emulsification, the final position and shape of the cast surface, and a detailed prediction of cast structure, inclusion, or gas distribution and segregation patterns are necessary. In addition, a detailed understanding of the interactions between the steel shell, the solid and liquid flux layers, and the interface with the mold is necessary. Understanding the heat transfer through the different layers mentioned above is very important.

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

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

Slab, Billet, Rounds, Beam Blank, and Bloom Casting

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

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

Slab, billet, rounds, beam blank & bloom casting research and development needs and opportunities

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

In the area of flux design, work is needed on flux crystallization phenomena, flux physical and chemical properties, and flux compatibility with liquid steel, refractories, and other surroundings. This is particularly true for the next generation AHSS grades when the mold slag chemistry changes during casting due to slag/metal reactions. New mold powder development is needed for this group of highly reactive steels. Nozzle development combined with in-mold EMS must continue to allow a very controlled, stable fluid flow into the mold that does not encourage mold slag emulsification and decreases the tendency of nozzle clogging.

Mold designs that incorporate instantaneously controllable narrow face taper and instrumentation that provides a temperature profile are needed to control shape and allow further increases in casting speed. Technologies must be developed to improve surface quality so casting can be used for all applications without surface grinding or treatment. Also, dynamic soft reduction has become a standard technique to produce sound centerline structures for conventional, ultra thick slabs, and blooms and should be utilized to produce best internal quality products.

Strip Casting

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

Strip casting research and development needs and opportunities

- Knowledge of the variation of heat transfer with casting conditions and alloying
- New models, sensors, and control systems
- Novel techniques of liquid flow control
- Applications of strip casting for conventional and novel alloys
- Post-processing steps necessary for strip cast material to have better mechanical properties than conventionally processed materials
- Determine inclusion engineering requirements
- Tie belt caster directly to rolling facility to maximize production and energy potentials

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

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

Belt casting requires further development, especially to tie the belt caster directly to a rolling facility as the Peine plant currently has casting and rolling separated. This will maximize the production and energy potentials of this emerging technology.