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Understanding the role water-cooling plays during continuous casting of steel and aluminum alloys

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ABSTRACT

Water-cooling plays a major role in extracting heat from both the mold and solidifying metal during the continuous casting of steel and aluminum alloys and is characterized by complex boiling phenomena. Heat extraction rates during water-cooling, which have strong dependence on the metal surface temperature, can rapidly change with time as the strand cools down. Consequently, uncontrolled cooling may cause fluctuations in the temperature gradients inside the solidifying shell and generate tensile thermal stresses at the solidification front that can ultimately lead to the appearance of hot tears/cracks in the final product. This paper compares and contrasts the water-cooling techniques used for casting steel and aluminum and discusses their implications in terms of final product quality based on fundamental studies and predictive mathematical models. Finally, optimal practices for the control of cooling in casting processes for both steel and aluminum alloys are evaluated.

I. INTRODUCTION

The technology used for continuous casting of steel and aluminum has progressed significantly over the past several decades, although the two processes have developed distinct differences. The productivity of the continuous casting process is generally controlled by the casting speed, which varies with alloy composition and product geometry. For steel billets, blooms, and slabs, the casting speed increases with decreasing thickness from 10 mm/s (for 300 mm blooms) to over 80 mm/s (for 50 mm thin slabs)[1]. Owing to cracking difficulties during startup, aluminum alloy ingots are cast at much lower speeds, increasing from ~0.75-1.0 mm/s[2] during startup to steady state speeds ranging from 1.0-3.0 mm/s[3].

In the conventional continuous (or strand) casting of steel, shown in **Figure 1(a)**[4], liquid steel flows from the bottom of a ladle into a small intermediate vessel known as the tundish. It leaves the tundish bottom through a submerged nozzle, according to the position of a stopper-rod or slide-gate flow control system. The liquid flow is directed into the mold (usually ~700-1200 mm in length), and freezes a thin shell against the water-cooled copper walls. At steady state, the solid shell exiting the mold forms a stable strand, which has adequate mechanical strength to support the liquid metal core (5~30 m in depth, depending on the casting speed and thickness). Motor-driven drive rolls located far below the mold continuously withdraw the strand downward. Many closely spaced support rolls prevent the outward bulging of the shell due to the ferrostatic pressure arising from the liquid steel core. Water sprays emerge from high-pressure nozzles, which are interspaced between the support rolls and cool the strand during the solidification process. Other strategically placed rolls bend the shell to follow a curved path and then straighten it flat prior to torch cut-off into individual slabs. This allows fully continuous operation. Start-up of this process is a relatively rare occurrence, and is achieved by inserting a “dummy” bar to plug the mold bottom. Thus, the first steel cast in a sequence can be routinely downgraded or scrapped for defects without incurring a significant yield loss.

The D.C. casting process for aluminum alloys is shown schematically in **Figure 1(b)**[2]. In contrast to the continuous casting process for steel, D.C. casting is only semi-continuous, as the strand is withdrawn vertically for a short length (~10 m) until the process must be stopped and restarted when the cast ingot reaches the bottom of the casting pit. Thus, considerable attention must focus on the initial start-up stage, when defects are most likely to be initiated. To start the process, a bottom block is partially inserted into an open rectangular mold (usually ~100-150 mm in length). Superheated liquid aluminum flows through a launder, down the nozzle spout, through a distribution bag, and into the mold, at a predetermined, time-varying filling rate. Once the molten metal fills the bottom block to a prescribed height, the bottom block and cast ingot are lowered into a casting pit. The aluminum ingot is subjected to cooling by the transfer of heat to the water-cooled aluminum mold over a very short length (~70-90 mm), and to cooling through the contact of chill water with the solid shell after it emerges from the mold cavity. This water emerges from a series of holes, which surround the mold at

its base. The defining character of the D.C. casting process is the extraction of heat due to this direct impingement of water on the ingot surface – typically more than 80% of the total heat is removed by this method under steady state conditions[5]. The thermal field in this semi-continuous process can be considered to develop in two distinct stages. During the start-up, or Stage I, the liquid pool profile and thermal field continuously evolve with time. Finally, during steady state, or Stage II, the liquid pool profile remains essentially constant or "fully developed", relative to the mold (typically ~200-500 mm in depth depending on the ingot size and alloy composition[3, 6]). Steady state operation is usually achieved within a cast length of ~0.5-1 m.

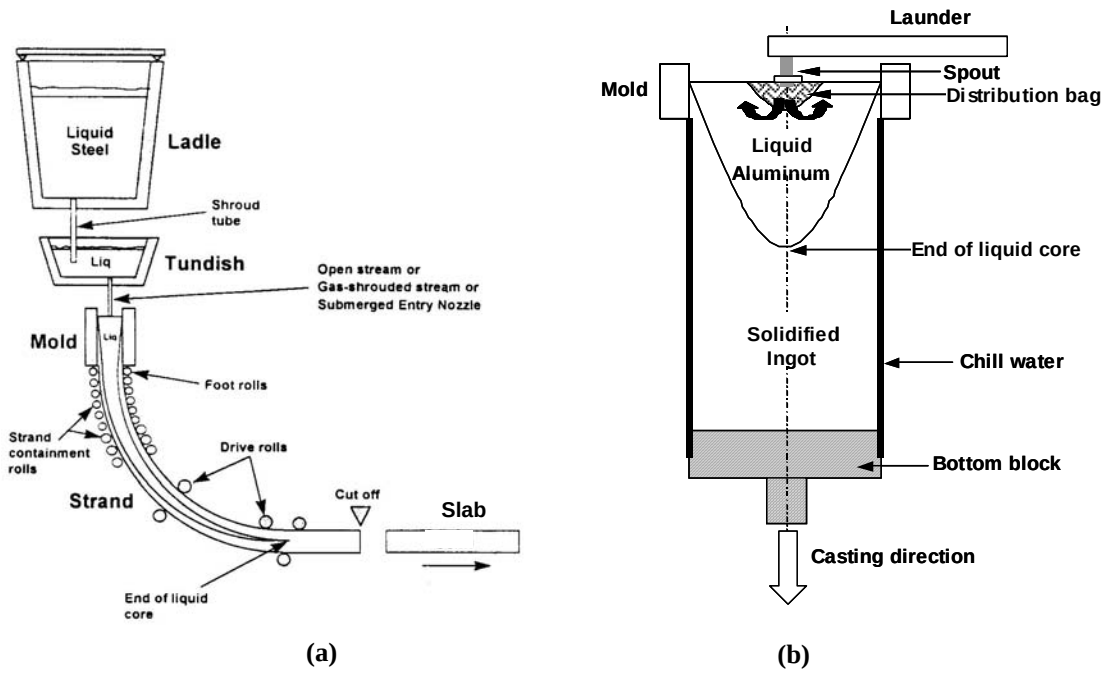


Figure 1: Schematic of (a) the continuous casting process for steel slabs and billets[4], and (b) the D.C. casting process for aluminum ingots[2].

II. HEAT TRANSFER DURING CONTINUOUS CASTING PROCESSES

Although the continuous casting machinery and practices are different for steel and aluminum, both processes have the same primary goal of extracting the heat from the molten and solidifying metal. The various heat transfer phenomena acting on the surface of the strand during the continuous casting of steel, and D.C. casting of aluminum alloys are schematically shown in **Figures 2(a)**[7] and **2(b)**[2], respectively. These heat transfer mechanisms not only control the liquid pool shape, which has important implications for productivity, but also the magnitude of thermal stresses and strains generated in the strand owing to thermal contraction of the metal upon cooling. The following sub-sections discuss the different heat transfer phenomena that occur during continuous casting process.

Mold (or Primary) Cooling

Heat is supplied into a water-cooled mold by the continuous flow of incoming liquid metal during the continuous casting process. Heat transport in the liquid pool inside the mold and at the mold/metal interface affects both initial solidification at the meniscus, and growth of the solid shell against the mold. Heat transfer at the metal/mold interface in continuous casting is referred to as mold or primary cooling. It varies with time, or distance down the mold, and can be subdivided into two regions of behavior[8, 9]: (i) mold/metal direct contact, and (ii) air gap cooling. In the beginning at the meniscus, the solidifying metal is in close contact with the mold, and the heat transfer rate is very high. Specifically, peak heat fluxes can exceed 10 MW/m^2 in steel continuous casting[10] and 1 MW/m^2 in aluminum D.C. casting[2]. Stage (i) of the primary cooling process ends with the formation of a significant air gap between the metal and mold as soon as the solid shell is strong enough to contract away from the mold faces. In steel continuous casting, this happens only near the corners. In the D.C. casting process, shrinkage of the shell away from the un-tapered mold produces gap formation around the entire perimeter. Once the gap has formed, the heat transfer rate is greatly reduced, resulting in a reheating effect within the solid shell. Within stage (ii), heat is conducted away from the shell via a series of thermal resistances[11]: (1) air gap, (2) mold wall, and (3) mold/cooling water interface. The interfacial gap comprises up to 85% of this resistance[12] and therefore, controls the heat transfer inside the mold.

It is estimated that primary cooling during continuous casting of steel in the mold removes about 40% of the total superheat, and about 30% of the total sensible heat[13]. The heat transfer coefficient typically decreases down the length of the

mold from a peak value of 1500-2000 W/m^2/K at the meniscus to about 600-800 W/m^2/K[14] near the mold bottom. Many strand defects, such as transverse mid-face and corner cracks, can be directly attributed to factors that control primary heat transfer in the mold, including oscillation marks, improper mold lubrication, metal level fluctuations in the mold, and improper mold taper[15, 16]. Primary cooling in the mold accounts for only about 20% of the total heat extracted[17] from the solidifying ingot during the D.C. casting of aluminum alloys, but it still has a critical influence on the ingot surface microstructure and roughness[18]. The heat extracted by primary cooling determines the surface temperature of the ingot at the point of exit from the mold. This subsequently influences the mode of boiling water heat transfer (film/nucleate boiling) below the mold[19], as discussed later. The peak heat transfer coefficient reported for aluminum contacting a chilled mold ranges from 2000-4000 W/m^2/K[20]. By comparison, in the air gap, the heat transfer coefficient may be as low as 150 W/m^2/K [21].

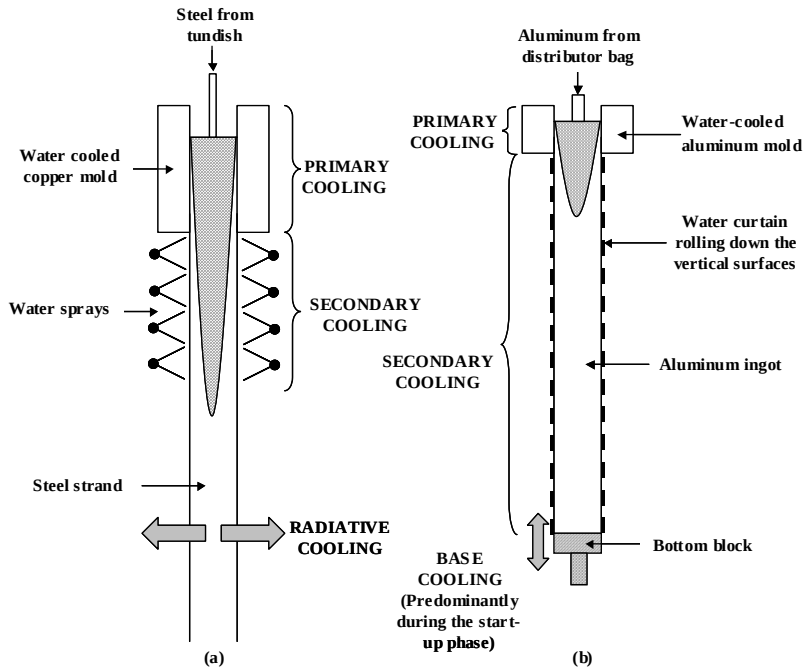


Figure 2: Schematic of cooling processes, for (a) continuous casting of steel[7] and (b) D.C. casting of aluminum[2].

An important factor controlling the extent of primary cooling is the effect of the cooling water on temperature and distortion of the mold itself. During the continuous casting of steel, cooling water flowing through the vertical slots in the copper mold extract heat from the mold and simultaneously control its temperature. The hot-face temperature of the mold indirectly affects the heat extraction rate, by altering the properties of the interfacial gap. Mold variables directly control mold temperature, but the effects on primary cooling are more complex. For example, decreasing the velocity of the cooling water lowers the heat transfer coefficient at the cold-face wall of the mold, causing mold temperature to increase[14]. Increasing the temperature of the hot-face wall of the mold may partially melt the slag rim, leading to increased heat extraction from the mold. The effect is counter-intuitive as primary cooling might increase with less cooling water. The impact of mold cooling water on primary cooling during the D.C. casting of aluminum has not been explored, perhaps because the mold cooling water also has an even more important role below the mold. Research has mostly focused on the secondary heat extraction process of direct impingement of water on the hot metal surface exiting the mold.

Water (or Secondary) Cooling

After emerging from the mold, the continuous-cast strand is cooled by direct contact of water with the hot metal surface, as shown in **Figures 2(a) and 2(b)**. This is referred to as secondary cooling. For steel casting, banks of nozzles located between contact rolls beneath the mold, spray water to cool the moving metal strand. Usually, the spray nozzles are arranged into banks or cooling zones, assigned to the top and bottom surfaces of particular strand segments[22]. The water is forced under high pressure as droplets that form a mist, which continuously impact upon the metal surface. Therefore, secondary cooling between each pair of rolls involves several different heat transfer mechanisms operating in different sub-zones, which are illustrated in **Figure 3(a)**[23]. These are: (i) roll contact cooling, (ii) radiation and air convection from the bare strand surface just in the roll bite just above the spray region, (iii) cooling due to spray water impingement, and (iv) water convection cooling just below the spray region, where water runs down the strand and collects in the roll bite. Bulging of the steel shell caused by ferrostatic pressure can affect these heat transfer sub-zones, especially near the roll bite and if the support rolls are spaced too far apart[24].

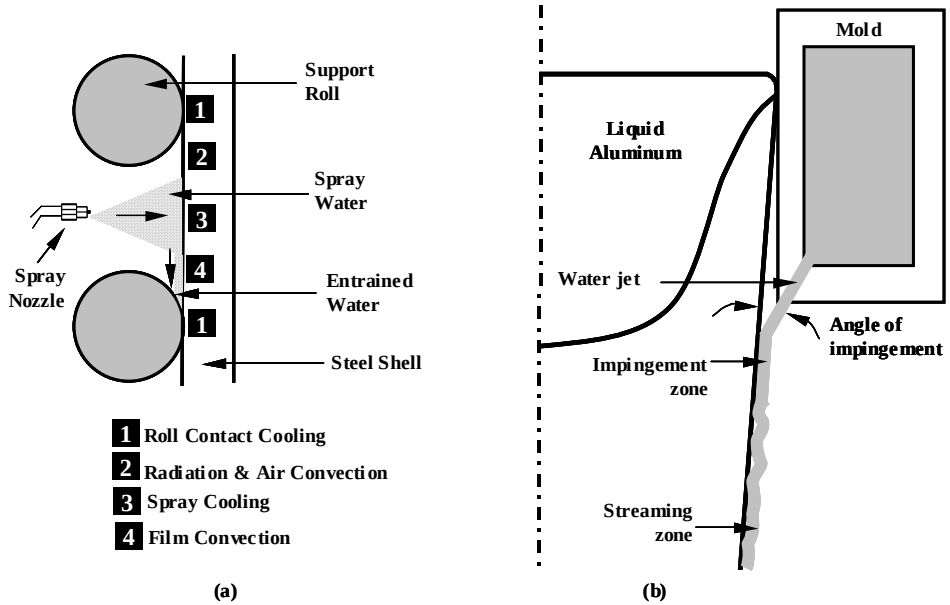


Figure 3: Schematic of (a) different cooling zones between the support rolls and spray nozzles during the continuous casting of steel[23], and (b) secondary cooling regimes during D.C. casting of aluminum[2].

For aluminum casting, water jets emerge from holes located below the water-cooled mold and directly contact the metal surface, as shown in **Figure 3(b)**[2]. These jets form a continuous film, which wets the vertical ingot surfaces and rolls downwards. Referring to **Figure 3(b)**, two distinct sub-zones can be distinguished on the ingot surface: (a) the water impingement zone, where abrupt cooling happens due to the direct contact with water, and (b) the streaming zone located below (a), where the heat flux diminishes as the water film loses momentum with increasing distance from the impingement point. The length of the water impingement zone is usually ~10-15 mm, depending on the diameter of water holes at the base of the mold and angle of impingement.

Secondary cooling mechanisms provided by water spray for steel and water film for aluminum have distinctly different characteristics[25], as presented in **Figure 4(a)** and **4(b)**. In spray cooling (**Figure 4(a)**), water droplets impinge onto the very hot steel surface and vaporize instantaneously to create a boundary layer, which prevents the water from wetting the surface. Heat extraction is higher towards the center of the impingement region, where more of the high-speed droplets have enough momentum to penetrate the vapor layer. Extremely irregular flow conditions develop within the vapor boundary layer and it eventually becomes wavy and is thinned out. The short contact times between the spray droplets and the strand surface increase with water velocity, owing to increased water momentum. Thus, the secondary cooling rate increases greatly with spray water flow rate, although it is almost independent of strand surface temperature. In contrast, under film cooling conditions (**Figure 4(b)**), water flows along the surface at a uniform velocity. As a result, the boundary layer of vapor between the water film and the metal surface tends to be thicker and unperturbed. However, as the metal surface cools, the vapor layer breaks down and the water film starts to contact the strand surface. The area of contact increases with decreasing strand surface temperature, and is accompanied by a sudden increase in heat transfer. The cooling process is transient and is difficult to control.

The extraction of heat by cooling water is quite complex for both water spray and film cooling conditions because it is governed by water boiling water phenomena[26], which depend greatly on temperature. As shown in **Figure 5**, four regions of heat transfer[26] can be clearly distinguished when cooling water comes in contact with a hot metal surface. In order of increasing surface temperature, they are: (i) Convective cooling at temperatures lower than 100°C, (ii) Nucleate boiling between 100°C and burnout temperature (500-700 ^{o}C for steel and ~ 200°C for aluminum), (iii) Transition boiling between burnout and the Leidenfrost temperature (700-1000°C for steel and 300-500°C for aluminum), and (iv) Film boiling at high temperatures (*i.e.* greater than Leidenfrost temperature). It is also important to note that two important points characterize the boiling curve in **Figure 5.** They are: (i) the burnout temperature, which indicates the maximum heat flux (and heat transfer coefficient), and determines the maximum ability of the water film to cool the metal surface by nucleate/transition boiling, and (ii) the Leidenfrost temperature, which indicates the change in heat transfer mode from transition to vapor film boiling. Due to the strong co-relationship between the heat transfer coefficient and the surface temperature, heat extraction rates by secondary cooling can change rapidly with time and location near the Leidenfrost temperature. High heat transfer rates associated with nucleate boiling can cause the surface temperature to decrease rapidly. In contrast, the low heat transfer rates associated with film boiling can allow the surface temperature to increase. As a result, abrupt changes in the metal surface temperature can occur as the boiling phenomena shift from nucleate to film boiling and *vice versa*, depending on whether the

Leidenfrost temperature is exceeded or not. Also, extreme variations of cooling can occur simultaneously at different locations on the metal surface, depending upon the local boiling behavior.

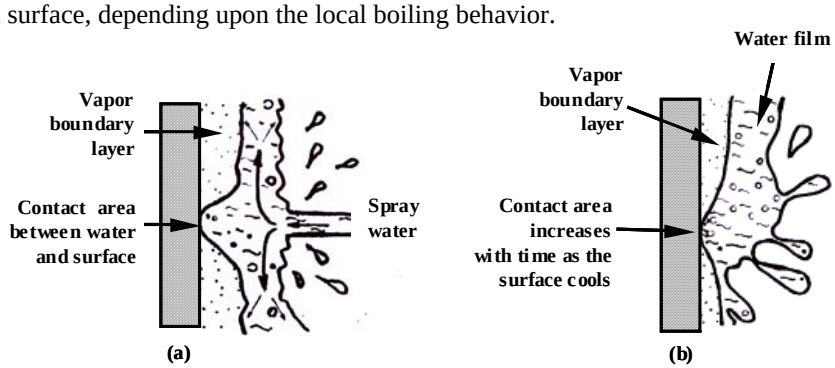


Figure 4: Details[25] of the water cooling process for (a) continuous casting of steel (by spray water), and (b) D.C. casting of aluminum (by water film).

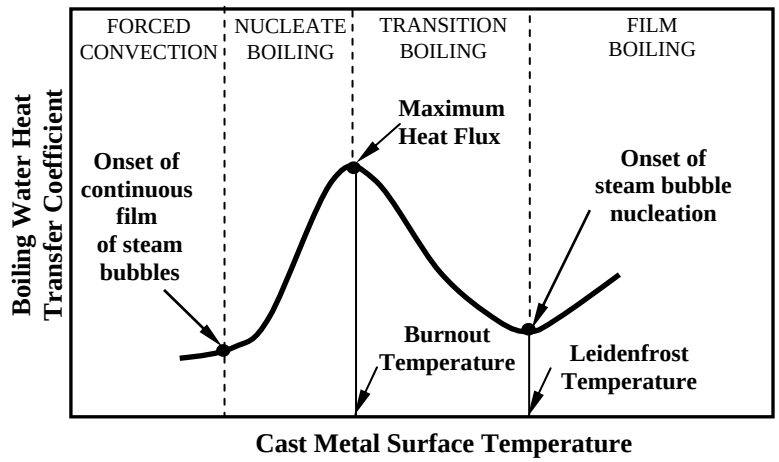


Figure 5: Generic boiling curve for water-cooling indicating the different heat transfer regimes[26].

The various heat transfer mechanisms associated with secondary cooling during continuous casting of both steel and aluminum are important because they determine the temperature gradients that develop inside the solidifying strand. Thus, they significantly influence the development of internal thermal stress/strain below the mold, and can aggravate defects generated inside the mold or introduce new defects. Quality problems related to secondary cooling will be discussed in Section III.

Radiative Cooling during Continuous Casting of Steel

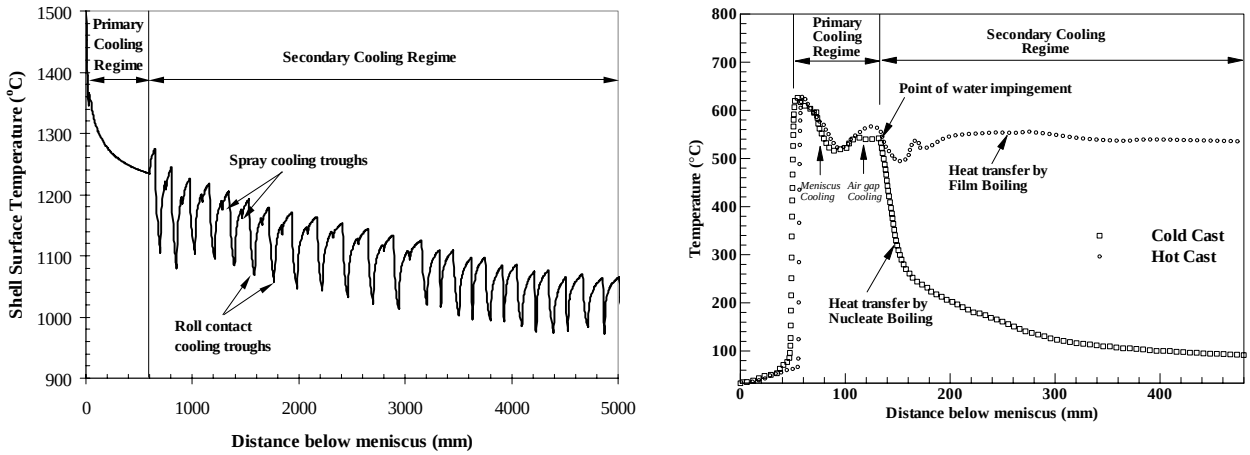
Beyond the spray zone region, the heat transfer process simplifies to radiation and natural convection. The smaller cooling rate of radiative cooling results in reheating of the solidified strand, which causes the strand surface to expand. If the surface reheats too much before complete solidification, then plastic deformation of the hot austenitic shell and semi-solid core may not be able to accommodate this expansion. This may cause sub-surface hot-tear cracks to form at the solidification front[27]. These cracks can cause internal segregation defects, or they may propagate through to the surface during later processing, such as rolling.

Ingot base cooling during the D.C. Casting of Aluminum Alloys

Secondary cooling also plays an important role in cooling the ingot base during the beginning of the start-up phase of the D.C. casting process. As the liquid metal enters the bottom block, the initial rate of heat transfer from the molten metal to the cold bottom block is extremely high. After a very short time, a small gap at the interface forms due to solidification shrinkage and the rate of heat transfer drops. This gap remains relatively small until the ingot begins to withdraw from the mold and is subjected to the secondary cooling water. At this point the base experiences a large macroscopic thermal distortion, called “butt curl”. This is aggravated by the slow cooling of the base, owing to the large gap and lack of water, combined with high thermal contraction of the vertical sides of the ingot, which experience higher heat extraction from the direct contact of a stable curtain. As the base continues to deform (or curl), water flowing down the sides may enter the bottom gap (water incursion) and enhance the heat transfer from the ingot base[2]. This in turn will influence further deformation of the base.

Strand Cooling Behavior

Figures 6(a)[23] and **(b)**[28] compare typical surface temperature profiles along the strand length observed during the continuous casting of steel and aluminum alloys, respectively. **Figure 6(b)** also compares two aluminum ingots, produced by D.C. casting at different cooling rates (lower water flow rates were used for the hot cast). The primary and secondary cooling heat transfer regimes can be easily identified in the cooling curves of both processes (refer to the cold cast in **Figure 6(b)**).



(a) **(b)**

Figure 6: Typical surface temperature profile and cooling regimes along strand length during continuous casting of (a) steel[23] and (b) aluminum[28].

For steel, the extent of primary cooling is important, as it results in a temperature drop of ~250 °C, whereas for aluminum the initial drop in the mold is ~100 °C. This is followed by reheating caused by the long air gap. Below the mold, the temperature during the continuous casting of steel varies over ~100 °C over each roll pitch, as shown in **Figure 6(a)**. Near the top of the caster, the greatest surface temperature drop occurs beneath each spray jet, while a tiny dip occurs at each small region of direct contact with a contact roll. Lower in the caster, the growing ferrostatic pressure increases the local heat extraction during roll contact, which makes the relative size of the spray and roll-contact dips become closer.

In contrast, during the D.C. casting process, **Figure 6(b)** shows that aggressive cooling from direct impingement of water at a high flow rate onto the metal surface causes the ingot surface to cool monotonically by ~450-500 °C in only 300mm. With less water, the hot cast did not achieve sufficient cooling at the impingement zone, allowing the surface temperature of the ingot to exceed the Leidenfrost temperature. As a result, the heat transfer was in the film boiling range (refer to **Figure 5**), such that the rate of heat transfer was low and kept the solidifying shell dangerously hot near the solidus temperature for a long time. This also caused the macro-deformation of the ingot base to decrease from ~50 mm for the cold cast to ~6 mm for the hot cast.

III. QUALITY PROBLEMS RELATED TO SECONDARY COOLING

One of the most important objectives of continuous casting is to attain a defect-free slab or ingot. Two such quality issues are: (i) hot tearing and cold cracking, and (ii) dimensional control (e.g. bulging of the steel shell and butt curl for aluminum ingots). These problems are directly attributed to tensile mechanical and thermal stresses/strains generated during the casting process. The variety of crack defects that affect continuous cast steel slabs and D.C. cast aluminum ingots are shown schematically in **Figures 7(a)**[29] and **(b)**[30] respectively. Mechanically generated tensile strains, such as caused by inadequate mold lubrication or bending/straightening of the strand, usually act in the longitudinal direction and cause transverse cracking. During the casting process, rapid cooling can result in steep temperature gradients in the solidifying shell that can generate thermal strains as the shell expands and contracts. Sudden localized cooling can introduce tensile strains at the surface, whereas reheating can generate tensile strains at the solidification front. Thermals strains act predominantly in the transverse direction and are responsible for causing longitudinal cracks. Cracks can form if the generated tensile strain locally exceeds the strain-to-fracture of the metal. In steel, different regions of low ductility have been reported[29]. The most important one lies within ~50 °C of the solidus temperature, and is responsible for "hot tear" cracks. Aluminum experiences a similar rapid loss in strength and ductility between the solidus temperature and the tensile coherency point (*i.e.* the temperature corresponding to about 90% solid fraction)[31]. Other mechanisms involving sulfide, oxide, and nitride precipitates at the grain boundaries operate in steel at lower temperatures, between ~700 and 900 °C[15], and cause intergranular cold cracks.

Most cracks in steel slabs and billets are hot tears, due to the zone of low ductility near to the liquid front. Internal cracks are often seen near the corners, at the centerline or diagonally between opposite corners. Surface cracks can appear

near both the midface or corner regions. Some cracks form below 900 °C during the straightening of the shell have been attributed to the embrittlement caused by precipitation of AlN near the grain boundaries[32]. In aluminum ingots/billets, hot tears or "pre-solidification" cracks can also form near the solidification front, when a tensile stress is imposed across partially solidified grains, and the surrounding liquid cannot fill the gap between the grains. Hence, these cracks are always inter-granular. In contrast, cold cracks in aluminum ingots are initiated at temperatures below the solidus due to extremely high thermal stresses, and are always trans-granular.

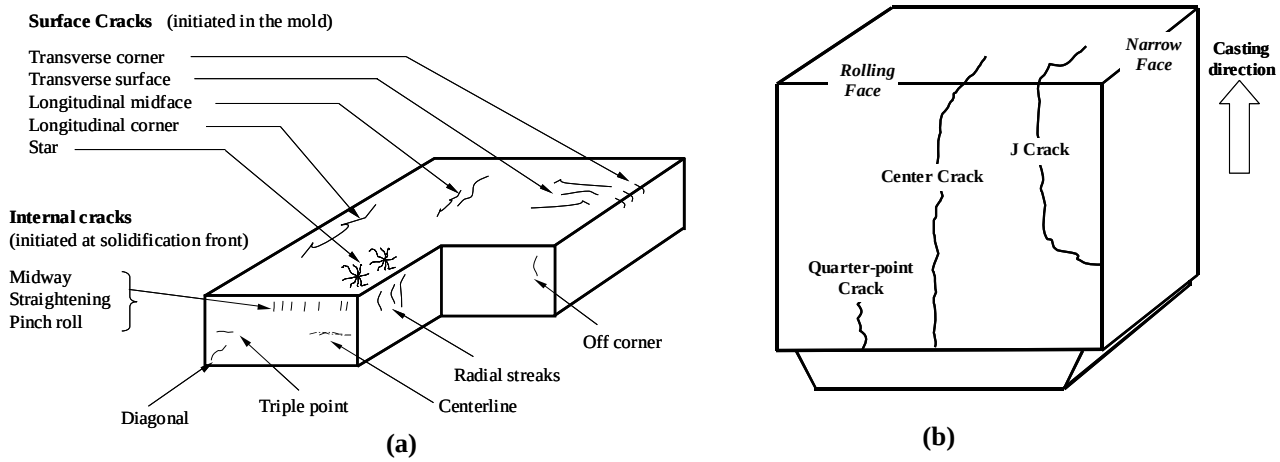


Figure 7: Schematic of crack defects related to (a) continuous casting of steel[29], and (b) D.C. casting of aluminum[30].

Brimacombe *et al*[7] have summarized the causes of cracking problems in continuous cast steel. Improper secondary cooling practices contribute to many of these. Excessive spray cooling and/or insufficient spray length lead to surface reheating, which induces tensile stresses beneath the surface, including the solidification front. This can cause internal cracks such as midway cracks in billet casting. Unsymmetrical cooling at the billet corners induces distortion and diagonal cracks. Excessive spraying of water can lead to rapid cooling and large tensile strains at the surface of slab castings, which can open up small cracks formed in the mold. However, insufficient spray cooling below the mold can allow the slab to bulge out if the surface becomes too hot. This can lead to several defects, such as triple point cracks, midface cracks, midway cracks, centre-line cracks and centre segregation, as shown in **Figure 7(a)**. Transverse surface and corner cracks begin in the mold, but can open up due to axial tensile stresses induced by spray cooling during slab casting, when the surface temperature is within the low-ductility range of 700-900°C. Secondary cooling practices that lead to excessive surface temperature fluctuations also aggravate these cracks, especially in this critical temperature range.

The thermal stresses and strains generated in the ingot during the transient start-up phase of D.C. casting process can initiate hot tears and cold cracks, especially in high strength aluminum alloys[33]. As shown in **Figure 7(b)**, hot tears generally form between the quarter points of a rectangular ingot and may not be visible on the ingot surface. Cold cracks also originate at the ingot base and are usually located in the centre half of the ingot width. High casting speeds tend to cause hot tears and low casting speeds increase the risk of cold cracks[3]. The formation of hot tears has also been linked with the frictional forces between the ingot and mold (which is related to mold cleanliness)[34] and the variability in cooling conditions during the transient start-up phase[35]. In addition to cracks, thermal stresses related to secondary cooling also generate macro-deformation of the ingot base or butt curl especially during start-up. As reported by Droste and Schneider[36], production problems related to butt curl include: run outs of the melt, cold shuts, reduced rigid standing (instability) of the ingot on bottom block, and low recovery rates. Ultimately, if the magnitude of butt curl is excessive, the ingot bottom may have to be removed.

IV. FUNDAMENTAL INVESTIGATIONS OF WATER COOLING PROCESSES

Experiments have been conducted to quantify heat transfer from water cooling and to establish boiling water curves (refer to **Figure 5**) in controlled laboratory experiments on small steel[7, 37-42] and aluminum[43-51] samples, in plant measurements of secondary cooling in the continuous casting of steel[52], and in D.C. casting of aluminum[53-56]. Generally, empirical relationships are developed by applying inverse heat transfer analysis to the measurements recorded by thermocouples embedded in the plate or casting. **Figure 8**[7, 43] compares typical boiling curves for steel and aluminum alloys obtained from such laboratory studies. Although the basic features of the boiling curves for the two systems are the same, the magnitude of the maximum heat flux and Leidenfrost temperatures will differ due to the differences in thermo-physical properties[25] of the two metals as well as surface effects such as oxide layers and surface roughness.

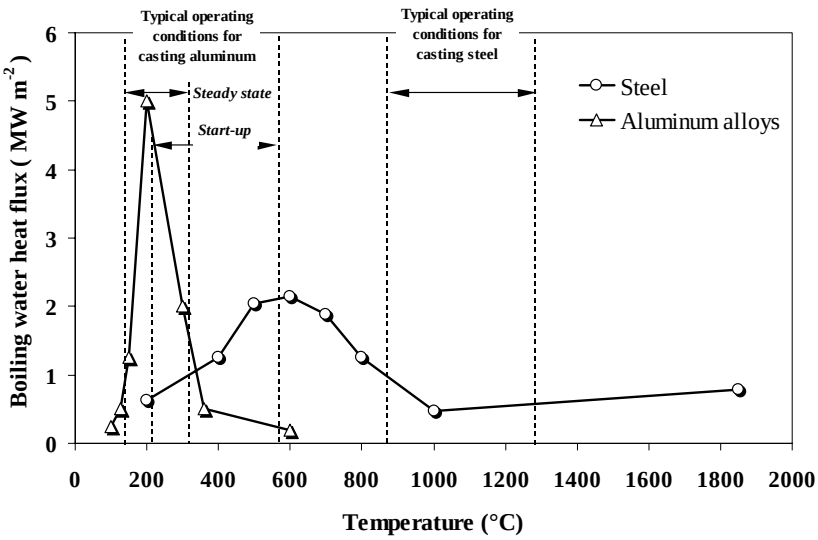


Figure 8: Typical boiling curves and operating temperature ranges in the secondary cooling regime for continuous casting of steel[7] and D.C. casting of aluminum[43].

Studies on secondary cooling and the boiling water curve for the continuous casting of steel reveal the following observations:

1. Typical values of maximum heat transfer coefficient measured by different researchers[39, 40, 52] lie between 2.0-3.0 kW/m^2/K at the burnout temperature of ~500-700 °C.
2. Within the desired surface temperature range of 900-1200 °C for spray cooling, the surface temperature of the strand has little impact on the spray heat transfer coefficient. This relative lack of dependence clearly indicates that the heat transfer mechanism is dominated by the convective heat transport occurring between the surface of the casting and a stable film of steam adhering to it (film boiling).
3. Within the film boiling regime, the spray heat transfer coefficient has a strong correlation with the water flow rate, as represented by the following empirical relationship[41]:

$$h_{spray} = A\dot{W}^{c} \qquad [1]$$

   where h_{spray} is the spray heat transfer coefficient (in W/m^2/K), A and c are fitting parameters, and $\dot{W}$ is the water flow rate (in l/m^2/s). Typically, A is 0.45 to 0.75, and c is 0.5-1.0[7].
4. Increasing the discharge velocity of the spray droplets increases their momentum to break through the vapor layer, which suppresses stable film boiling, and thus increases the heat transfer rate[39].
5. The Leidenfrost temperature is ~1000 ^{o}C and increases sharply with increasing water flow rate, for the same reason.

From the secondary cooling studies conducted for D.C. casting of aluminum alloys, the following observations can be made:

1. There is a general agreement between different measurement techniques that the maximum heat flux is between 1-5 MW/m^2, and the maximum heat transfer coefficient lies between 40 and 50 kW/m^2/K. The corresponding burnout temperature is ~200-250 ^{o}C.
2. Fundamentally, the operating temperature range of 220-620 ^{o}C is wider than for steel casting, extending down to the burnout temperature, so the ingot surface temperature has more effect on the heat transfer.
3. The Leidenfrost temperature is ~250-350 ^{o}C and increases with increasing water flow rate, in the same way as observed for steel. The heat transfer coefficient at the Leidenfrost temperature is very sensitive to water flow rate at low flow rates. Thus, water flow rate determines whether stable film boiling or water ejection will occur during start-up of D.C. casting. The Leidenfrost temperature can also be influenced by the water quality as well as the water temperature[48].
4. The oblique orientation of the water nozzle used in D.C. casting greatly affects the heat transfer. Because flow is directed downward along the ingot surface, the heat flux varies greatly with distance above or below its maximum at the impingement point. It drops significantly in the region of back flow above the impingement point. It decreases only gradually with distance below the impingement point as the water film loses momentum, and can be ejected from the surface by the formation of a stable vapor barrier.

5. The rate of heat extraction is a strong function of metal surface temperature[43]. The heat flux also depends strongly on the initial temperature of the surface when water is first added, which affects the transient co-evolution of the water layer and the metal surface temperature.

Model Applications

The heat transfer relations obtained from experimental measurements described in the previous section allow the study of thermomechanical behavior in continuous casting processes using mathematical models. These relations can be implemented as Cauchy type boundary conditions into finite-difference (FD) or finite-element (FE) based computational models to describe the cooling processes. These models can then predict the evolution of temperature, shell thickness, stress, and strain in the strand as it is cooled first in the mold and then during the secondary cooling zones. Predicted results from some of these models are presented here to provide further insight into the heat transfer phenomena acting during the continuous casting of steel and aluminum.

The shell thickness predictions from a 2-D[24] FE based thermal model for casting steel is shown in **Figure 9**. Profiles at mold exit and in the secondary cooling are compared. Temperature gradients through the shell are linear at mold exit. The shell thickness at mold exit is ~20 mm for a typical case, as shown in **Figure 9**, and its surface temperature drops to 70% of the melting (liquidus) temperature, T_m in absolute degrees (K). Inside the mold, the interfacial gap offers most of the resistance to heat extraction. However, beyond the mold exit, the resistance offered by the thickening shell in the secondary cooling zone becomes the rate-limiting factor in the process of heat removal from the strand for both continuous casting processes. It is, therefore, desirable that the secondary cooling process avoids any sudden increase or decrease in the surface heat extraction rate, in order to maintain a linear temperature gradient and avoid surface temperature variations that can generate local thermal strains and cracking problems. **Figure 9** shows the predicted temperature distributions through the shell thickness in the secondary cooling regime for continuous casting of steel between a set of roll pitches. The steel shell is shown to experience rapid changes in the surface heat extraction rate while moving beneath the support rolls, as it moves between regions of intense and less-intense spray cooling. This greatly changes the thermal fields close (~10 mm) to the surface. Intensifying the spray cooling does not improve the rate of solidification, as indicated in **Figure 9** by the almost unchanged linear temperature gradients deep inside the shell. It does, however, cause surface temperature variations that generate high local thermal strains near the shell surface that can aggravate cracking problems. Sharp drops in surface temperature can generate surface cracks, while the subsequent sharp increases can extend sub-surface cracks. Thermal cycling near the surface around the A_{r3} temperature of the steel is particularly dangerous because it encourages precipitation of detrimental phases such as AlN and large internal stresses due to volume changes associated with the austenite-to-ferrite phase transformation.

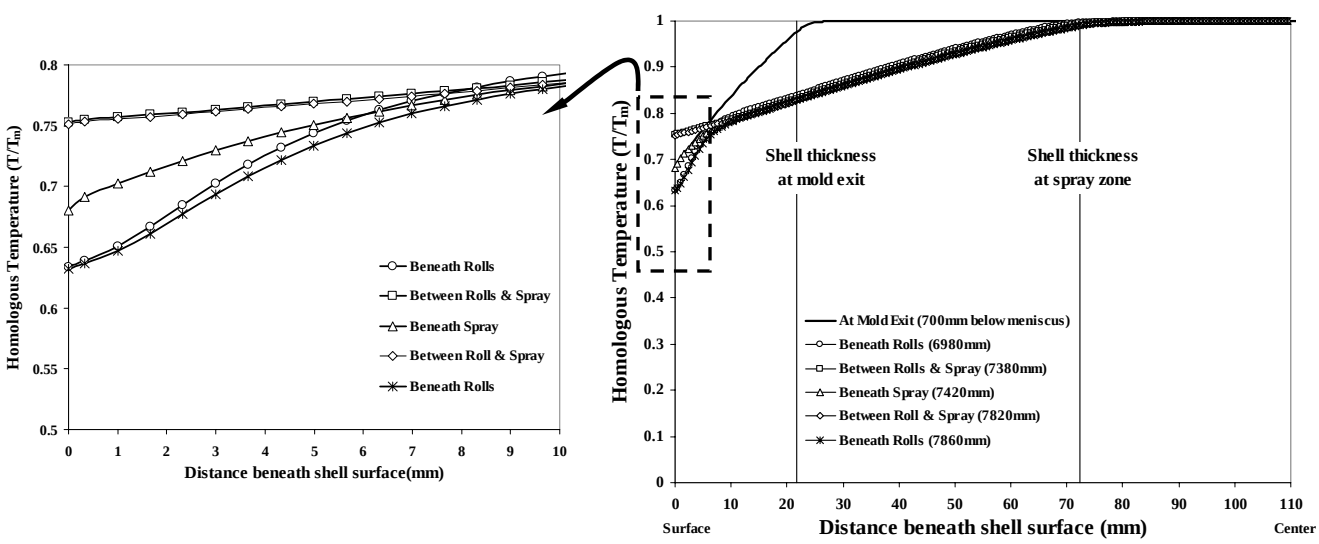


Figure 9: Temperature profiles and shell thickness predicted in cross-sections through the strand taken at mold exit and during secondary cooling for continuous casting of steel[24].

Figures 10 (a) and **(b)** show contour plots of temperature and stress along the rolling face obtained from a 3-D[57] FE based coupled thermal-stress analysis of a D.C. cast ingot under aggressive (*i.e.* higher water flow rates) start-up cooling conditions (cold cast). **Figures 10 (b)** and **(c)** show the corresponding contour plots for another ingot, which was cast with a much lower (~25%) water flow rate and faster (by ~20 s) bottom block filling time (hot cast) for the sake of comparison. Comparing **Figures 10 (a)** and **(c)**, it can be clearly seen that a stable film boiling front is present on the rolling face for the hot cast. This reduces the heat transfer coefficient, delays solidification and keeps the centers of the rolling and narrow faces of the ingot hot for a longer time than the ingot corners. A steam barrier exists on the vertical faces 20 mm below mold exit

owing to the ejection of water film (accompanied by generation of steam) from those places where the temperature exceeds the Leidenfrost temperature. **Figure 10 (a)** also indicates that the base of the ingot near the centre of the rolling face is in the mushy state during the start-up phase. Referring to **Figure 10 (b)**, it can be observed that this region is subject to tensile stress, in contrast to the region just above, where the material is cooler and in a state of compressive stress. This creates hot spots with high tensile strains just beneath the shell surface at the center of the vertical faces, which explains the initiation of hot tears that have been observed at this location[2]. Referring to **Figure 10 (d)**, which contains the results from the hot cast, compressive stresses exist higher up on the ingot face in the region of the casting where the ejection front has begun to collapse. Lower down, within the ejection region, the material is in a state of moderate to low tension. Comparing the time history of plastic strain generation at Location "A" in **Figures 10 (b)** and **(d)**, as shown in **Figure 10 (e)**, the hot cast has substantially reduced plastic strain. This suggests less tendency for the accumulation of damage in the centre of the casting near the lip where hot cracks are often observed. These observations underline the necessity for optimal design of the secondary cooling processes during the continuous casting of both steel and aluminum alloys, in order to avoid the initiation and propagation of crack defects.

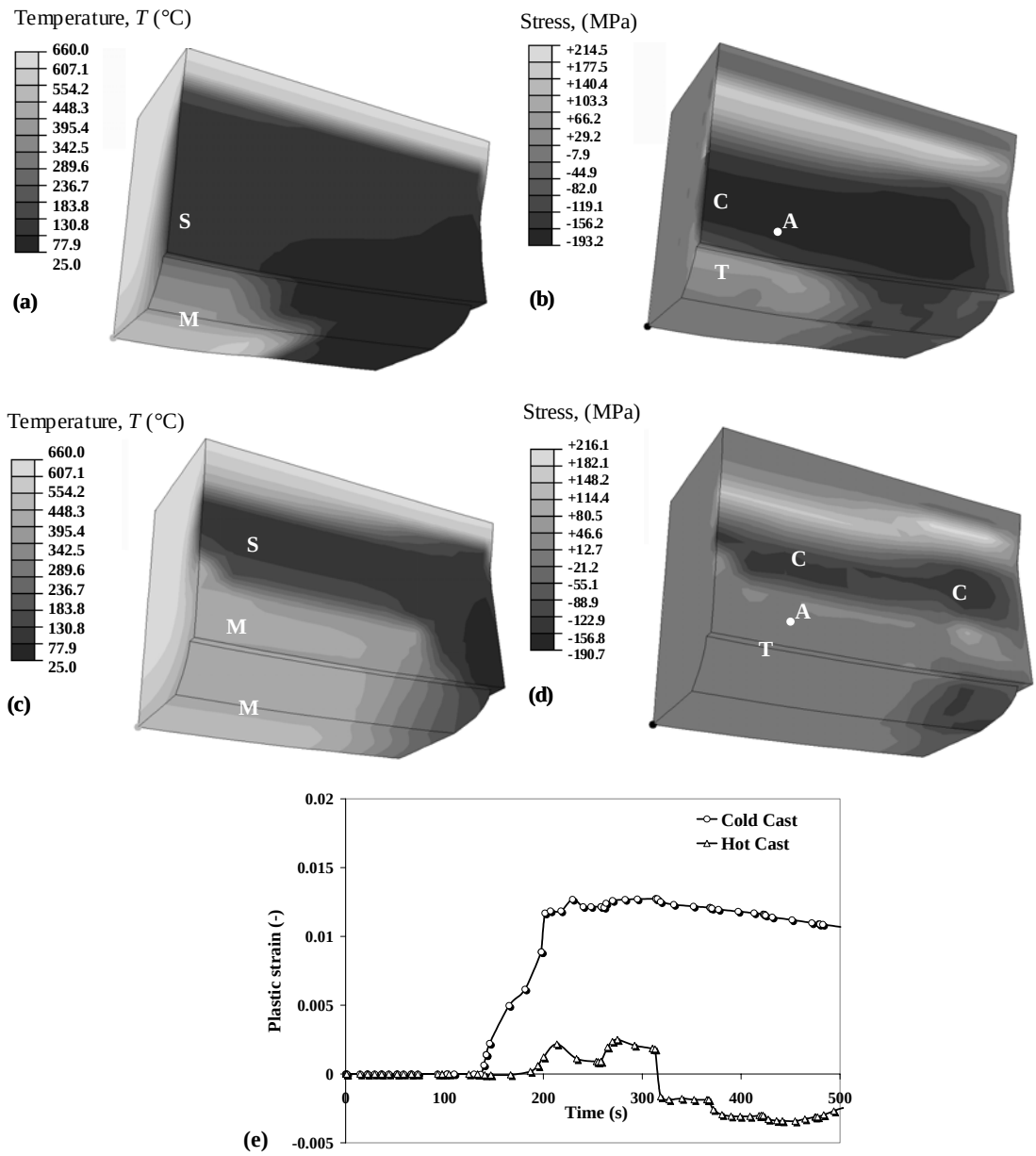


Figure 10: Contour plots of temperature and stress along the rolling face for D.C. cast ingots cast under two extreme cooling conditions – (a) & (b) for a cold cast), and (c) & (d) for a hot cast (refer to Figure 6b), and (e) comparison between plastic strain evolutions for the two castings at Location A[57]. *Legend: S: Solid, M: Mushy, C: Compression, and T: Tension*

V. OPTIMIZATION OF WATER COOLING

From the previous discussion, it is evident that water cooling plays a critical role during the continuous casting of steel and the start-up phase of the D.C. casting process for aluminum alloys. Hence, optimizing the parameters that control the cooling process is necessary to generate defect free castings. The task of optimizing secondary cooling is easier for steel continuous casting than for D.C. casting, because cooling is governed by film boiling phenomena so the heat transfer coefficient is relatively independent of the strand surface temperature. Relationships describing the variation of heat flux with nozzle type, nozzle-to-nozzle spacing, spray water flow rate, and distance of the spray nozzles from the strand surface are given in the literature[7, 39, 52, 58]. Under steady state conditions, spray practices can be designed to achieve cooling conditions that prevent defects. Specific techniques include "plateau cooling"[42] and air-water mist cooling[59]. The purpose of plateau cooling is to keep the surface temperature of the strand in the spray cooling zone always above 700°C, and to avoid reheating from below this temperature. This procedure can prevent cracks which are associated with the loss of ductility in steel at temperatures between 700-900°C. Air-water mist cooling has helped to provide more uniform cooling in both the casting and transverse directions, and hence avoids cracks by minimizing the localized temperature fluctuations caused by the undercooling and overcooling associated with water droplet spray jets. Furthermore, automatic control systems are available in the industry[22, 60] to adjust the sprays according to changes in casting speed and thereby optimize secondary cooling conditions for transient conditions as well. These control systems make use of online computational models to ensure that each portion of the shell experiences the same cooling conditions.

Unfortunately, in the case of D.C. casting, relatively little fundamental work has been done to optimize water-cooling phenomena to control the final ingot quality. Despite increased use of automation, the control of cooling conditions during start-up is difficult due to the many complex parameters and their interrelated effects on ingot cooling. A significant part of the problem to develop a fundamental approach to optimize the transient start-up phase is that the mold, the chill water, and the bottom block simultaneously cool the ingot surfaces. The combined interplay of primary and base cooling conditions determine the surface temperature of the ingot emerging from the mold, which in turn governs the boiling water-cooling conditions (film/nucleate boiling) that dictate the secondary cooling phenomena. The trend in the aluminum industry has been to control heat transfer by varying the bottom block filling rate, casting speed, and water flow rates during the start-up phase. Because the evolution of butt curl is directly linked with the amount of thermal stress generated in the ingot, attempts have been made in the industry to minimize the amount of curl by reducing the intensity of cooling during the start-up phase. It has further been suggested that combining low cooling water volume with high casting velocities during startup can reduce base deformation for some alloys[36]. If carried too far, however, these practices can cause extremely high local surface temperatures that can lead to extreme butt shrinkage and dangerous casting situations. Butt curl can also be reduced by solidifying a thick bottom shell, which bends to a lesser extent upon direct impingement of water. This can be achieved by appropriate bottom block design[61] or by using longer filling times[62]. Additional state-of-the-art water cooling systems include Alcoa's CO_2 injection[63], Wagstaff's Turbo process[64], and Alcan's Pulse Water technique[65]. Both the Alcoa and Wagstaff techniques use gases to promote film boiling. The gas bubbles in the water film quickly adhere to the ingot surface, generating an insulating layer that reduces the heat transfer coefficient. The Alcan process applies rotary valves to turn the cooling water on and off during the start-up phase. Thus, the average heat flux is lowered and the surface temperature of the ingot becomes high enough to trigger film boiling.

Over the past several decades, mathematical modeling has also been extensively used in the steel industry to control both the primary and secondary cooling processes. Models such as CASIM, DYNCOOL, and DYSCOS have been adopted by the industry for online process control[22]. The Continuous Casting Consortium at the University of Illinois at Urbana-Champaign have developed CON1D[23] and CON2D[66] programs to study the fundamentals of the complex but industrially-relevant phenomena in the mold and spray cooling regimes. Several industries and universities have formed consortiums to develop thermomechanical modeling tools to design and optimize the D.C. casting process using finite-element packages such as MARC[67], ABAQUS[67], and ALSIM/ALSPEN[17]. National laboratories in the United States have also collaborated recently to develop mathematical models to study ingot stress crack formation and butt deformation[68], and to reduce aluminum ingot scrap. In Canada, the University of British Columbia and Alcan International Ltd. are also jointly pursuing modeling activities to generate hot tearing criteria for the D.C. casting process[2, 57].

VI. SUMMARY AND CONCLUSIONS

Although continuous casting processes for steel and aluminum alloys have different process design and operating parameters, the basic heat transfer processes characterizing the removal of superheat, latent heat and sensible heat are similar. Both the mold and water play significant roles in dictating the complex cooling phenomena under both transient and steady state conditions.

This paper shows how water-cooling governs the temperature of the metal strand, and how unsymmetrical or localized cooling problems can cause defects leading to high rejection rates and low productivity. The reader is referred to a forthcoming reference[69] for additional details. Specific observations include:

(i) Empirical relations to describe cooling in the water channels are well established and used to optimize primary cooling in the mold during the continuous casting of steel. Perhaps the optimization of mold water cooling, which has been applied so successfully in the steel industry, could also help to improve the D.C. casting mold for aluminum.

(ii) In the case of continuous casting of steel, vapor film boiling dominates the heat extraction mechanism during spray cooling. As a result, the boiling water heat transfer coefficient is independent of strand surface temperature, and heat extraction is controlled by water flow rate. In contrast, transition/nucleate boiling often arises during D.C. casting to cause aggressive cooling of the ingot surfaces. However, film boiling is desired during the transient cast start-up phase to reduce the effect of butt curl. Effects like water ejection and water incursion coupled with the rapidly changing ingot surface temperature during the transient phase can significantly complicate the heat transfer process. As a result, the process is extremely difficult to control.

(iii) Empirical relationships describing the variation of boiling water heat transfer coefficient with spray nozzle type, nozzle separation, distance of the nozzle from the surface of the strand and water flow rate have been established for secondary cooling of steel. For D.C. casting of aluminum alloys, relationships describing boiling water heat transfer as a function of the water characteristics and interaction of the water with the surface of the material are not available. Only a few studies for certain specific aluminum alloys are available, which can describe the boiling water heat transfer during DC casting.

(iv) Secondary cooling should be designed to cool the strand surface in a controlled, monotonic manner, in order to avoid severe temperature gradient fluctuations that cause cracks. Developments such as plateau cooling, air-mist cooling, and online process control with mathematical models has helped to improve secondary cooling in continuous casting of steel. A variety of processes have been developed for D.C. casting of aluminum.

(v) Despite decades of plant trials and increased process automation, quality problems related to water cooling such as butt curl and hot tear cracks still nag the D.C. casting industry. Different proprietary “recipes” are currently used by different aluminum companies to change casting variables as a function of time and alloy during start-up. There is recent recognition of the need for well-validated, fundamentally based thermo-mechanical mathematical models of the D.C. casting process to aid further improvements, including the optimization of water-cooling practices.

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