An Optimized Ladle Refractory Configuration for Steel Refining and Vacuum Degassing Processes at SSAB Americas

In the steel industry, ladles are subject to cyclic and changing thermal conditions along with varying loads. Steel processed through a vacuum tank degasser (without heating capability) must be heated to higher temperatures during ladle refining to avoid freezing during vacuum treatment. The mechanical effect from the load and prolonged high-temperature exposures can result in creep damage. To avoid damage and extend the life of the ladle shell, it is important to ensure that the shell temperature does not exceed the specified design maximum. In this study, a mathematical modeling method was employed to investigate the effect of refractory configurations on the ladle shell temperature under various conditions. An optimum ladle refractory configuration was established to ensure that ladle shell temperatures are always within the design range.

In the steel industry, ladles were initially designed for storing, transporting and teeming liquid steel. With advancements in steel refining techniques, it became necessary to conduct additional metallurgical treatments in the ladle. These treatments, which include alloying, homogenization, desulphurization, non-metallic inclusion modification/removal and vacuum degassing, are referred to as the secondary refining of steel. Typically, with continuous casting technology, a certain number of ladles must be kept in rotation in order to continuously feed liquid steel to the caster to maintain the continuity of casting a sequence of heats of similar chemistries. Once the steel is drained from a ladle, the temperature of the ladle refractories will immediately begin to fall, and hence the ladle must be pre-heated back to high temperature to avoid thermal shock from the next heat. Process delays, process routes, steel temperature, varying refractory types and thicknesses are factors that affect the refractory thermal state. Thermal cycling and the varying load in ladles can induce severe stress on the ladle shell. These conditions can ultimately cause creep damage to the ladle shell and shorten its lifespan. Therefore, for efficient and safe operation of ladles, it is important to ensure that the design of the ladle is optimal and the refractory lining has a high resistance to mechanical, thermal and chemical wear.

SSAB Americas has installed vacuum tank degassers (VTDs) at both its Iowa and Alabama steel mills. With the vacuum tank degasser, impurities such as hydrogen and nitrogen can be removed from the liquid steel before casting. The duration of degassing depends on how much hydrogen and nitrogen must be removed from the liquid steel before degassing, to ensure that the steel remains liquid in the ladle for the duration of treatment under vacuum and casting. The additional superheat is needed because SSAB Americas’ vacuum tank degassers have no heating capability. In 2011, several ladles exhibited bulging of the steel shell near the slagline regions and between the belly bands at the Iowa mill. A preliminary investigation indicated that the ladle shell around the slagline area was above 1,000°F.

This article is available online at AIST.org for 30 days following publication.
after vacuum degassing. To avoid creep damage and extend the lifespan of the ladle shell, it is important to ensure that the shell temperature does not exceed the specified maximum design temperature during the service cycle. The ladle shell temperature is primarily affected by the refractory configuration (type and thickness), pre-heating practice, ladle campaign life, steel temperature and steel processing time. Of these factors, the nature of the refractory configuration is considered the most critical. In the present study, a mathematical modeling method was employed to investigate the effect of refractory configurations on the ladle shell temperature under various steel processing conditions. Together with mill trials, an optimum ladle refractory configuration was established for application at SSAB Americas to ensure that ladle shell temperatures are always within the design range.

**Ladle Condition**

In 2011, typical cylindrical ladles were used at SSAB Iowa with a 150-ton (short ton) load capacity. In the original design, the sidewall working linings consisted of 7-inch-thick magnesia-graphite brick in the slagline, 6-inch-thick alumina-magnesia-carbon brick in the barrel, and 6-inch-thick resin-bonded magnesia-carbon brick in the transition region between the slagline and barrel. The backup safety lining consisted of a layer of 3.5-inch-thick alumina-based dry vibratable material and a 0.25-inch-thick insulation layer in front of a 1.125-inch-thick steel shell. The bottom of the ladle was protected with a 10-inch-thick pre-cast bottom plus a layer of 8-inch safety lining material underneath. Details are shown in Fig. 1.

At any time, there are generally six ladles in service. The slagline layer is relined after approximately 60 heats (after one campaign) and the entire ladle refractory is rebuilt after two to three campaigns. The thermal history of each ladle varies with the severity of steel treatment during refining. The steel treatment can be largely classified into three main categories: (1) non-degassing: ladle is sent for continuous casting directly after refining; (2) castability degassing: steel is subjected to degassing during degasser pump down-time to 133 Pa before casting; and (3) deep degassing: steel is degassed for a longer time period at a vacuum pressure below 133 Pa to reduce both its hydrogen and nitrogen contents. The typical variations in the ladle hot face or steel temperature during different processing stages for each of the above categories are summarized in Table 1. It is obvious that the steel temperature at both the ladle metallurgy furnace (LMF) and VTD increased tremendously for the degassing treatments, creating the most severe working condition for the ladles. Infrared temperature measurements confirmed that the ladle shell temperature typically stays above 1,000°F during the entire casting time after deep degassing. Compared to ladles that did not undergo degassing, the shell temperature is about 200°F higher. Hence, the ladle shell temperature can exceed the design temperature, increasing the propensity for creep damage.

**Ladle Shell Material Testing** — The bulged area of a ladle shell is illustrated in Fig. 2a. Steel samples...
were secured from the bulged area and a new plate for metallographic analysis to determine the extent of damage to the ladle shell during use. High-temperature tensile testing was performed at temperatures of 72, 800, 1,000, 1,200 and 1,400°F. As shown in Fig. 3, both yield strength (YS) and ultimate tensile strength (UTS) decrease significantly with increasing temperature, especially for temperatures above 1,000°F. Compared to the new material, the degradation of the used material is obvious, and thus material failure is imminent when the shell stress exceeds the yield strength. In addition to mechanical property testing, metallographic analysis was performed. A polished and etched (2% nital) sample was examined in a scanning electron microscope (SEM). The micrograph in Fig. 2b shows evidence of void formation at grain boundaries, indicating the onset of creep damage in the used material. To avoid creep damage and extend the lifespan of the ladle shell, the temperature
of the ladle shell must not exceed the specified design maximum.5

Ladle Refractory Inspection — Ladle refractories were inspected. Two major findings include: (1) the thickness of the slagline bricks was significantly reduced due to the erosion/corrosion interactions of steel and slag. As demonstrated in Fig. 4, the brick thickness has been reduced by more than half at multiple locations in the slagline region; and (2) no insulation layer was observed between the safety lining and ladle shell at the end of the ladle campaign life. To provide a lasting solution to the bulging problem, it was decided to explore the possibility of improving the refractory thermal properties and modifying the refractory configuration.

Ladle Refractory Configuration Optimization

Methodology — At the initial stage, a three-dimensional numerical model was developed to evaluate the effects of various lining designs on ladle/refractory interface and shell temperature. The model includes ladle geometry, refractories and processing history. The refractory configuration being employed by the Iowa mill was selected as a baseline, as shown in Fig. 5a. All of the subzones in the working linings (slagline, transition, barrel and bottom), safety lining, insulation layer and ladle shell were modeled. The major focus of the present study is refractory configuration, so other auxiliary parts of the ladle structure, i.e., trunnion and slidegate, were not considered. The temperature variation during ladle service was assigned to the inner surface of the ladle (hot face). The basic setups are summarized below:

- Air and molten steel media inside the ladle were neglected.
- Different temperature boundaries and heat loss rates were applied to the ladle hot face for different ladle treatments, such as pre-heating, tapping, refining and degassing.6 The hot face temperature as a function of time for a typical deep degassing process is shown in Fig. 5b. To simulate the ladle used in cyclic operation, 10 cycles of ladle treatment were simulated for each case.
- Possible air convection and radiation were considered for the boundary conditions outside the steel shell.7,8
- Most of the refractory properties, such as thermal conductivity and specific heat, change with temperature. The evolution of properties is automatically handled by the model. The material properties used by the model were

![Figure 4](image_url)

Ladle refractory inspection showing brick thickness.
collected from vendors or the literature, as listed in Table 2. To ensure accuracy, some of the material properties were verified by an external laboratory.9

The governing equation for a transient heat transfer problem in cylindrical coordinates can be presented by Eq. 1. The model is solved using commercial code partly with user-developed subroutines.

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( kr \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \phi} \left( \frac{k}{r} \frac{\partial T}{\partial \phi} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + S = \rho c_p \frac{\partial T}{\partial t}
\]  
(Eq. 1)

where

\( r, \phi, z \) = cylindrical coordinates,
\( T \) = temperature, °C,
\( t \) = time, seconds,
\( k, \rho, c_p \) = heat conductivity (w/m·°C), heat capacity (J/kg·°C), and material density (kg/m³) and
\( S \) = heat gain or loss per unit volume from other than conduction, w/m³.

Evaluation of the Original Ladle Refractory Design — The original ladle design was built into the model for validation. As shown in Fig. 5a, slagline brick wear was properly treated by the model to reflect the real condition. Ten repeatable deep degassing cycles were simulated using the transient method. The model calculation indicates that the hottest spot on the ladle shell is in the slagline region with temperature ranging between 977 and 1,039°F, as shown in Fig. 6. Infrared temperature measurement verified that the major part of the slagline area exceeds 980°F, matching the model prediction. Compared to the shell temperature in the slagline zone, the rest of the ladle shell temperature remains relatively low. The reason could be the application of low-thermal-conductivity materials in these areas. After this calibration, the model was used to evaluate other types of ladle refractory configurations.

Refractory Optimization — Due to the low thermal conductivity, insulation is one of the most effective methods to reduce the ladle shell temperature. Based on the initial studies, three types of insulation layers were proposed: (1) 0.5-inch-thick Insulation-I in solid form, (2) 0.4-inch-thick Insulation-II in solid form, and (3) 0.275-inch-thick Insulation-III in packaged powder form, as illustrated in Fig. 7. Among these insulations, Insulation-III has the most stable thermal properties based on an assessment of ladle shell temperature control. Other material properties can be found in Table 2. The effect of different insulation materials on ladle shell temperature control was evaluated by modeling and mill trials.

Prior to the trials, all of the insulation layers were tested by the mathematical model. Ladles containing Insulation-I, II and III were identified as Ladle-I, II and III. The calculation includes 10 operation cycles for either castability or deep degassing. As shown in Fig. 8, the shell temperatures for Ladles-I and II vary from 650 to 750°F for castability degassing and from 680 to 880°F for deep degassing. In contrast, the
**Table 2**

*Ladle Refractories and Shell Thermal Properties*

<table>
<thead>
<tr>
<th>Refractory</th>
<th>Density (kg/m³)</th>
<th>Thermal conductivity (W/m·°C) @ temperature (°C)</th>
<th>Specific heat (J/kg·°C) @ temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ladle lip cast</td>
<td>2,563</td>
<td>1.63 → 1.46 @ 538 → 1,093</td>
<td>1,000 @ 20 → 1,600</td>
</tr>
<tr>
<td>Slagline brick</td>
<td>3,000</td>
<td>19.60 → 7.52 @ 150 → 1,510</td>
<td>790 → 830 @ 200 → 600</td>
</tr>
<tr>
<td>Transition brick</td>
<td>3,000</td>
<td>11.50 → 7.20 @ 260 → 1,371</td>
<td>1,090 @ 20 → 1,000</td>
</tr>
<tr>
<td>Barrel brick</td>
<td>2,960</td>
<td>7.30 → 5.80 @ 200 → 1,100</td>
<td>842.76 → 1,397.22 @ 25 → 1,600</td>
</tr>
<tr>
<td>Safety backfill</td>
<td>2,594</td>
<td>1.20 → 2.11 @ 77 → 1,588</td>
<td>829 → 1,285.4 @ 77 → 1,588</td>
</tr>
<tr>
<td>Bottom floor</td>
<td>3,284</td>
<td>3.41 → 2.09 @ 260 → 1,093</td>
<td>1,000 @ 20 → 1,600</td>
</tr>
<tr>
<td>Bottom subfloor</td>
<td>2,243</td>
<td>1.63 → 1.84 @ 0 → 1,500</td>
<td>924 → 1,137 @ 0 → 1,500</td>
</tr>
<tr>
<td>Insulation-I</td>
<td>1,202</td>
<td>0.23 → 0.31 @ 195 → 593</td>
<td>900 → 910 @ 200 → 600</td>
</tr>
<tr>
<td>Insulation-II</td>
<td>1,000</td>
<td>0.15 → 0.21 @ 25 → 760</td>
<td>1,310 → 1,780 @ 200 → 600</td>
</tr>
<tr>
<td>Insulation-III</td>
<td>320</td>
<td>0.022 → 0.034 @ 100 → 800</td>
<td>680 → 1,080 @ 0 → 800</td>
</tr>
<tr>
<td>Ladle shell</td>
<td>7,800</td>
<td>55.07 → 39.35 @ 20 → 700</td>
<td>487.5 → 808.7 @ 0 → 700</td>
</tr>
</tbody>
</table>

**Figure 6**

Temperature distribution on the ladle shell: model prediction (a) and infrared image (b).

**Figure 7**

Representative surface of the employed insulation layers: Insulation-I (a), Insulation-II (b) and Insulation-III (c).
temperatures on Ladle-III are lower, varying from 480 to 560°F for castability degassing and 440 to 750°F for deep degassing. The modeling results demonstrate that it is possible to reduce ladle shell temperature if the appropriate insulation is employed. To make sure there is no significant change in ladle capacity by changing refractories, an additional modeling effort was undertaken to evaluate the ladle size with different configurations. Assuming 40 inches of freeboard above the steel bath, the heat weight is around 146 tons for the proposed configuration and 147 tons for the original design. Obviously, the change on ladle capacity is minimal.

Insulation-I, II and III were installed on different ladles. The specific ladle service condition relies on the production schedule, but is identical for each ladle throughout their entire service. All of the shell temperatures were measured by contact thermometer to ensure high accuracy. Before each measurement, scale and debris that built up on the ladle shell surface were removed by an angle grinder, as shown in Fig. 9. The measurements show that the shell temperatures are different from ladle to ladle. Ladle-I has the lowest shell temperatures with a temperature around 760°F after castability degassing and 890°F after deep degassing. The temperature measurements for Ladle-I are very close to the model predictions. For Ladle-II, the shell temperature after castability degassing is approximately 890°F, matching the model results. However, the shell temperature rose up to 1,000°F after deep degassing and is much higher than the model prediction. For Ladle-III, the measured temperature is around 770 and 1,020°F after castability and deep degassing, respectively. These measurements deviated from the model calculated temperatures by 200°F. As shown in Fig. 10, the measured temperature for Ladle-III is near the temperature of an uninsulated ladle. Clearly, Insulation-III is not as effective as expected. All of the ladle insulations were inspected closely after their service life, which spanned three
campaigns (approximately 180 heats). Insulation-I was still intact (as demonstrated in Fig. 11); however, Insulation-II and III were not found. The inspections, in conjunction with the temperature predictions and measurements, demonstrate that there is a potential degradation of the insulation material during service. As a critical component, any degradation of insulation causes an elevated ladle shell temperature. Therefore, it is important when selecting an insulation material, in addition to thermal conductivity, that consideration should be given to thermal and mechanical stability. The ladle insulation should have adequate strength to tolerate cyclic loading and thermal expansion stress from the refractories. According to the trials, Insulation-I is the best one for these particular ladles, with a good combination of thermal properties and mechanical stability.

With Insulation-I, several additional measures were taken to further reduce the ladle shell temperature. These measures included a slight increase in insulation thickness and an upgrade of the slagline brick. With the optimized ladle refractory, the average ladle shell temperature has dropped from the original 832°F to 650°F before degassing, from 904°F to 692°F after castability degassing, and from 1,097°F to 836°F after deep degassing, as summarized in Fig. 12. Overall, the ladle shell temperature dropped approximately 200°F for all the processing conditions. Due to the similarity between the Iowa and Alabama mills, the optimized ladle refractory configuration has been applied at Alabama as well. In addition to the refractory optimization, other improvements made at SSAB Americas in recent years include:

- Upgrading ladle shell material from ASTM A516-70 to A204-B, which has greater tolerance to elevated temperature.
- Installing a vertical pre-heater to reduce ladle temperature loss while awaiting tapping.
- Monitoring ladle shell temperature regularly.
- Inspecting ladle working lining frequently using a laser measurement technique.
• Tracking ladle refractory life using in-house developed software in the mill’s level 2 system.

Conclusions

By combining mathematical modeling with mill trials to investigate ladle refractory integrity and configuration under various processing conditions, optimal refractory materials with good thermal and mechanical properties have been identified for ladle insulation. An optimal refractory configuration was developed to avoid degradation of refractories during high-temperature processing, such as vacuum degassing. In addition, the ladle shell steel material was upgraded and ladle shell temperatures are continually monitored. These measures have helped eliminate any ladle shell bulging issues.

Acknowledgment

The authors would like to thank SSAB for the permission to publish this paper. They would like to acknowledge Steve Hansen, Tom Toner, Andy Bramstedt, Randy Petty, Roger Gajeski, Jimmy Allen, Stewart Lynn, Sapto Susilo, Lingyun Wei, Justin Raines, Jake Ecklund, Brett Baer, and meltshop personnel of SSAB Iowa and Alabama for their contributions to this work. In addition, special thanks go to Mats Danielsson, Swerea KIMAB, for the ladle shell creep damage modeling assessment; Simon Lekakh, Missouri University of Science and Technology, for the material properties characterization; and Sanjay Gupta, former SSAB employee, for the material mechanical properties testing.

References


This paper was presented at AISTech 2017 — The Iron & Steel Technology Conference and Exposition, Nashville, Tenn., USA, and published in the Conference Proceedings.