"OPTIMIZATION OF TUNDISH FLOWS AND SUBSEQUENT CAST SLAB QUALITY IMPROVEMENTS"

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INTRODUCTION

Currently, over 70% of the slabs made by National Steel Corporation are produced by the continuous casting process. The slab casters are located at the Granite City Steel Division, Granite City, Illinois; Great Lakes Steel Division, Ecorse, Michigan; and Weirton Steel Division, Weirton, West Virginia. Granite City has a 60' radius single strand casting machine with a variable width mold, 49' to 84' x 8.75". Great Lakes has a 50' radius single strand machine with a 104' x 9.5" mold. Weirton has a 26' radius 4-strand machine with widths ranging from 30" to 40" and a 9" thickness. Many of National Steel's cast slabs are applied to thin gauge products which require excellent slab quality. The studying of continuous casting phenomena is, therefore, an area of prime importance to National Steel.

Most of National's continuously cast slabs are aluminum deoxidized. A problem inherent with aluminum killed slabs is the formation of an Al2O3 (alumina) inclusion quarterline defect band. Minimization of the Al2O3 quarterline defect can lead to improved machine operation and product quality. Al2O3 can be formed during ladle deoxidation with aluminum or from reoxidation when the molten steel containing aluminum is exposed to the atmosphere or other oxygen sources. Al2O3 particles may then be carried through the ladle into the tundish and subsequently become part of the cast slab when the metal solidifies. Quarterline defect occurrence in the cast slab can be reduced through the use of ladle stream shrouding to prevent formation of inclusions from reoxidation. Inclusions can be removed in the steel ladle, tundish, or mold.

It is desirable to remove inclusions at the earliest possible moment in the continuous casting process. For this reason, ladle metallurgy treatments have been installed to help in the removal of inclusions from the ladle. Ladle shrouding has been installed to protect the metal stream from exposure to the air when the metal flows from the ladle into the tundish.

Dams, weirs, and bubblers have been added to tundishes to aid in inclusion float-out. Artificial slags have been developed to shield the steel in the tundish from exposure to the air and to entrap free floating inclusions. Submerged entry nozzles from tundish to mold are used in slab casters for improved slab surface cleanliness and protection from reoxidation.

To study inclusion removal in the tundish, full scale water models have been constructed for the National Steel slab casters at the Granite City Steel Division, Great Lakes Steel Division, and Weirton Steel Division. The three full scale tundish models were constructed during 1981-82 and are located at the National Steel Research Center in Weirton, West Virginia. Full scale models were necessary to provide an accurate representation of turbulent flow conditions in the tundish. Water is used to simulate the flows since it has approximately the same kinematic viscosity as room temperature as steel has at 285°F. The prime objective of tundish modeling was to study dynamic tundish flow conditions which could lead to maximum inclusion entrapment in an artificial tundish slag cover.

EQUIPMENT

The equipment constructed for use in the tundish water model study consisted of full scale continuous caster tundish models for each of National Steel's three casting machines and a water head pressure tank, Figure 1. Model dimensions were based upon inside tundish refractory measurements. The models were constructed from sheet steel, angle iron, and plexiglass. Plastic pipe was used to provide plumbing to each of the models. On the water tank, Great Lakes and Granite City models, propeller type water meters with flow rate generators were used to provide a measure of water flow rates corresponding to casting speed for various mold widths. The Weirton model used splitter plate vortex generator flow meters to provide representation of casting speeds. The splitter plate type flow meters have proven to be more accurate and reliable, due to less clogging. A dye injection system was hooked up to the water tank outlet pipes so that dye could be injected into the water stream flowing towards each tundish. Water was supplied to the water tank via a 3" main line. The water tank held approximately 1000 gallons of water and had outlets for each tundish model. Due to water supply constraints only one tundish could be modeled at a time. The water tank rests on

![Figure 1 - Schematic Representation of Tundish Water Modeling Equipment at National Steel Research Center](image-url)
top of a 12' high platform. Individual valves were provided for water flow control to each of the models. Descriptions of the tundish models will be given later in this paper.

EXPERIMENTAL PROCEDURE

The tundish model selected for experimentation was first run in a base case mode (i.e., no dams, weirs or bubblers) at a water flow rate corresponding to the standard casting speed for a low carbon aluminum killed steel. The model was filled and outflow was started. After achieving steady state flow conditions in about 12 minutes, plastic particles were added to simulate inclusions. Next, methylene blue dye was injected into the inlet stream. Water samples from the outlet were taken at specific times and analyzed for dye concentration on a spectrophotometer. If more rapid (but less precise) analysis of results was desired, a visual method of watching the flow through the tundish was used to determine the retention time. Motion pictures were taken during some experimentation to provide a record of turbulent flow conditions for that particular trial. Many times, motion pictures were shown to hourly crews in the mills to illustrate inclusion removal and fluid flow in their particular tundish. The spectrophotometer analysis determined retention times while the motion pictures provided a visual check on inclusion movement towards the slag layer. After determining base case data, the tundish model was modified with dams, weirs, bubblers and varying water levels for further trials. The model trials that showed the most success were then recommended to operators for field experimentation.

A number of methods were developed to determine the improvement in internal cleanliness of the continuously cast slabs once an experiment was moved from the tundish model to a field trial in the mill. Macroetching of slab cross sections is a standard quality control practice for qualitatively evaluating segregation and internal cleanliness. A metallographic method has been developed to quantitatively determine the inclusion area of a macroetched slab, using the image analysis system (IAS). The IAS consists of a scanner which resolves the optical image by scanning along parallel lines. Depending upon the object of interest, the instrument is set to register black or white features. In the case of inclusion area determination, the instrument is set for white features. This is because etched areas of the macro were filled with chalk. The IAS then counts the number of etched inclusion areas.

<table>
<thead>
<tr>
<th>Rating</th>
<th>Alumina Inclusion Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>None Detected</td>
</tr>
<tr>
<td>1</td>
<td>Light Al2O3 Inclusion Clusters</td>
</tr>
<tr>
<td>2</td>
<td>Light - Medium Al2O3 Clusters</td>
</tr>
<tr>
<td>3</td>
<td>Many Al2O3 Clusters</td>
</tr>
<tr>
<td>4</td>
<td>Heavy Al2O3 Clusters</td>
</tr>
<tr>
<td>5</td>
<td>Very Heavy Al2O3 Clusters</td>
</tr>
</tbody>
</table>

Figure 2 - Layout of the Two Weirton Tundishes

pits in a 3-3/4" x 5" area and determines the total area formerly occupied by the inclusions, giving a quantitative measure of inclusion content. A Polaroid picture can be taken as a record of the screen display. Macroetched slab faces may also be permanently recorded using a standard copying machine.

A second method used to qualitatively judge macrocleanliness is visual inspection. Etched areas of slabs are rated as to inclusion cluster severity on a scale of 0-5 with 0 being inclusion free and 5 being very heavily clustered, Table 1. Close correlation has been found between the quantitative and qualitative methods. However, the IAS method provides an objective record of slab macrocleanliness.

WATER MODEL TRIALS AND IMPLEMENTATION

Weirton

At the Weirton plant a 360 ton ladle with twin rotary nozzles feeds two tundishes at the continuous caster. The two tundishes in turn control head pressure to the four strands labeled A, B, C and D, Figure 2. The tundishes have asymmetric shapes and offset inlets. The tundishes are 16' long and have a width ranging from a 7' 1-5/8" maximum to a 3' minimum. The tundish depth has recently been increased from 20 to 36".

The tundish model shell was fabricated at a welding shop from 1/4" steel plate. The thick plate was used so that the shell would be self supporting with a minimum of bracing. The completed shell was sent to the Research Center for modification. Large sections of the steel shell were removed to allow space for windows. Panes of 1/2" plexiglass were cut and bolted into place over a foam rubber gasket material. Actual stopper rods were hung in the model to control water outflow, as in the operating tundish. A taper was turned on the welded steel
flange, thereby simulating the actual tundish nozzle and providing a tight seal for the stopper rods.

In determining retention times, a casting speed of 42 ipm was used at various tundish depths.

The model was first run at a depth of 20". Retention times in the tundish were found to be 140 seconds for C strand and 15 seconds for D strand. At an increase of depth to 27", retention times were found to be 145 seconds for C strand and 20 seconds for D strand. In the base case, the depth was increased to the maximum 36" and retention time was found to increase to 150 seconds for C strand and 25 seconds for D strand, Table 2. At the caster, refractory changes have made it possible to increase the depth of the Weirton tundish from a nominal 20" to a maximum of 36." Retention time gains have been correlated to a marked increase in internal slab cleanliness when the 36" base case was applied as an operating practice, Figure 3. The deeper tundishes are now a standard operating practice for all continuously cast heats.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Depth</th>
<th>Casting Speed</th>
<th>O Strand</th>
<th>P Strand</th>
<th>Remarks</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>20&quot;</td>
<td>42 ipm</td>
<td>140 sec</td>
<td>25 sec</td>
<td>Open Stream</td>
</tr>
<tr>
<td>2</td>
<td>27&quot;</td>
<td>48</td>
<td>145</td>
<td>20</td>
<td>Open Stream</td>
</tr>
<tr>
<td>3</td>
<td>36&quot;</td>
<td>42</td>
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<tr>
<td>4</td>
<td>36&quot;</td>
<td>42</td>
<td>90</td>
<td>30</td>
<td>Bubbler in Use Area</td>
</tr>
<tr>
<td>5</td>
<td>36&quot;</td>
<td>42</td>
<td>90</td>
<td>90</td>
<td>Symmetrical Flow</td>
</tr>
</tbody>
</table>

Figure 4 - Dead Area in Weirton Tundish

Figure 5 - Optimum Bubbler Placement for Elimination of Dead Area in Weirton Tundish

Additional experiments have been performed with the tundish model and tested in the mill. In the tundish model, a large area of dead flow was observed occurring near the back wall, Figure 4. A porous plug inert gas bubbler was installed in the tundish to provide stirring to this area. At first, the bubbler was installed in the tundish model in the center of the dead area. The model was allowed to achieve steady state and then the dye was added. It was found that the bubbler increased rather than decreased the dead area. As a second trial the bubbler was moved to a live flow area, about one half the distance between the inlet and C strand. At this point the bubbler was observed to mix the liquid from the live flow area with that of the liquid in the dead flow area. This bubbler location was subsequently recommended to Weirton and implemented as a standard operating procedure, Figure 5. Whenever the bubbler was installed in the tundishes and operated at correct pressures and flows, improvements were seen in internal cleanliness of the continuously cast slabs produced, Figure 6. At this point, it was also concluded that stirring of the tundish bath was an important factor in removing inclusions. Another trial currently underway involves developing a tundish design with symmetrical flow. It has been desired to eliminate the asymmetric flow in the tundish by relocating the ladle stand or redesigning the tundishes to accommodate a center pour entry. Either of these changes would require high capital expenditures. A preliminary tundish design with symmetrical flow patterns has been made possible at low cost through the use of refractory modifications in the tundish. The walls of the tundish were brought inward to eliminate the triangular shape of the tundish and to modify it into a T shape.

A tundish board was installed in the center to provide a center outlet for the flow into the tundish, Figure 7. On the water model, retention times were found to be equal for either strand, Table 2. The symmetrical flow tundish is currently undergoing trials at the Weirton Division utilizing a magnesite tundish board for the center divider. The magnesite tundish board has the
advantage of low cost and easy replacement. Problems have been encountered in using castable refractories and ram materials for the center dam due to their high heat capacities.

Weirton has shown significant improvements in internal cast slab quality due to a few simple tundish modifications derived from water modeling, Figure 8.

**Granite City**

The Granite City tundish has tapered side walls and is rectangular in shape. The tundish measures 14'6" in length x 4' wide x 4' deep, with the ladle inlet and mold outlet situated on opposite diagonal corners. Only one tundish is necessary for the Granite City machine since there is only one strand. The tundish is fed from a 250 ton ladle where the metal outflow is controlled with a slide gate. The ladle stream is shrouded with a refractory tube system. Steel flows from a tundish through a slide gate system and enters the mold through a submerged entry nozzle.

The tundish model was constructed from sheet steel, angle iron, and 1/4" plexiglass panels. The tundish model itself was set on top of a 40" stand to allow for a valve and water meter control unit. Structural modifications that affect flow may be set in the tundish or welded in place. Overhead lights are provided for photographic purposes.

During the base case trials, retention times were surprisingly found to increase with decreasing tundish level. Flow patterns in the tundish were also dramatically altered when the level was dropped in the tundish. In normal practice at the 37" depth, an undesirable short circuit flow pattern was observed in the tundish; most of the live flow would travel along the back wall around the corner to the outlet nozzle, while the front one-quarter volume of the tundish would experience sluggish flow. At lower tundish levels the liquid was found to flow uniformly across the width of the tundish, in a plug flow which increased the retention time, Table 3.

One observation noted with the Granite City tundish model was that vortexing in the tundish
A problem has existed in operating the Granite City tundish in that a hard, thick skull would form across the top of the tundish while casting. A solution was needed to break up this hard skull without degrading internal slab quality. One method tried by Granite City involved placing a copper ring around the outlet nozzle. Problems were found with the copper ring due to poor reliability and uncontrolled gas flows. As an alternative to this copper ring, a commercially available porous tundish nozzle was used to provide upward gas flow into the tundish to break up the surface skull. The nozzle was made from a porous refractory encased in a steel can, with an orifice for argon or nitrogen purging. When the porous nozzle was installed on the tundish model and operated at less than 15 psig, all gas was entrained by the water outflow. At higher pressures, gas would flow upward in a burst pattern, Figure 9. The gas would displace plastic beads, representing slag, from the top of the bath and drive them directly through the tundish nozzle. This condition was determined to be detrimental to surface and internal quality of the slab being formed in the mold.

A preferred solution to the tundish skulling problem was found by placing a porous plug in the vicinity of the outlet nozzle. In the tundish model, a copper ring with gas flowing through it was placed at various distances away from the outlet nozzle. When the ring was placed closer than 1.75" to the inner radius of the nozzle, some of the inert gas was entrained by the outflow. At a distance of 2", none of the gas was captured by the outflow. This established a minimum distance requirement of 2" from the inner radius of the tundish nozzle to the perimeter of any bubbling device. Next, an abbreviated porous plug was installed in the tundish to see if the bubbles would be uniform in dispersion and would not drive slag from the slag layer down into the outlet nozzle. Bubble action was observed to be uniform in dispersion when the porous plug was in use. The ideal position for inclusion removal was determined to be in a live flow area (as indicated by methylene blue dye injection), parallel to the north tundish sidewall, but no closer than 2" to the outlet nozzle inner radius, Figure 10.

Great Lakes

The Great Lakes tundish contains approximately 15 tons of molten metal. The tundish has a rounded bottom and measures 16 5/6" long x 5 6/6" wide x 32" deep. A 230 ton ladle feeds the tundish, which in turn feeds the mold through a slide gate mechanism and shroud combination, in a manner similar to that described for Granite City.

The tundish model was fabricated in a welding...
Angle iron braces and 1/4" plexiglass panels were added to the model later. The water flows through a 3" pipe into the model and out through a 3" line with a valve water meter combination on the bottom. Dams and weirs have been added to the tundish to simulate current Great Lakes tundish configuration, Figure 11. At Great Lakes, a can bubbler is currently in use at the outlet nozzle to provide some upward flow to keep an open area for thermocouple insertion. The effect of increasing the gas pressure in this can bubbler was studied using the continuous caster water model. It was found that at higher pressures, the can bubbler increased the chance of vortexing and of inclusion entrainment in the mold. A base case study revealed a retention time of 95 seconds in the tundish with the dam/weir bubbler combination in use, Table 4. At Great Lakes, work is currently underway to increase the depth of the tundish as a standard operating practice.

CONCLUSIONS

The continuous caster tundish models for National Steel's casters have proven to be useful tools for the simulation of steel flows. The tundish models have provided a very inexpensive method of testing tundish design changes prior to implementation in the mill. The models also have saved a great deal of time when compared to field trials. Demonstration of the tundish models to management and hourly personnel has heightened the awareness of the correlation between flow condition and final cast slab quality.

Examining the effect of increased retention time and stirring action in the tundish has led to a significant improvement in cast slab quality. Flow pattern studies have shown how short circuiting can be minimized, thus extending the retention time. By adjusting and placing porous plugs in the correct location, tundish turbulence can be increased to promote inclusion entrainment by an artificial slag layer on top of the bath. As an operational tool, the models have been used to screen proposed tundish modifications that would have produced detrimental flow patterns. Increased tundish depth at all mills has led to cleaner cast slabs with less plugging in the submerged entry nozzle, due to greater Al₂O₃ removal in the tundish. Although the modeling of the gaseous phases in the tundish is only of a qualitative nature, close correlation between tundish results and field trials in the mills has been noted. The tundish models have provided National Steel with a method of improving cast slab quality and machine operation.

References