ArcelorMittal at Indiana Harbor has expressed interest in the characterization and elimination of solidification hooks in their ultra-low carbon automotive steel slabs. The entrapped non-metallic inclusion at the solidification hook is a defect. Through literature review, metallographic optical microscopy, hook length and depth study, and experimental etchant trials, recommendations for ideal casting parameters for hook elimination and optimal sample preparation for microstructure study could be made. Hooks measured after Trial 3 had a near 45% decrease in depth and a 64% decrease in length.

**Project Background**

Molten steel flows from a ladle, through a tundish into the mold. Slag cover over the liquid surface prevents oxygen from reacting to form detrimental oxide inclusions.

**Solidification Hooks**

Hooks are distinct subsurface microstructural features that accompany oscillation marks and can entrap gas bubbles, oxides, and other defects.

**Criterion for Identifying Solidification Hooks**

Hooks form and result in microstructure grains curving up and away from the oscillation mark and casting direction.

**Characterization of Hooks**

The predictive hook equation shown in the following section correlates casting parameters with hook dimensions, so in order to study these hooks within the microstructure, optimal etching techniques had to be developed and tested.

**Experimental Procedure**

**Empirical Equation For Hook Depth:**

\[ \text{Hook Depth} = \frac{V_c - F \times L_{	ext{fluctuation}}}{T_s - T_{	ext{solidification}}} \]

The equation predicts the average hook depth from the casting conditions: \( V_c \) is casting speed, \( F \) is oscillation frequency, \( T_s \) is superheat temperature, \( L_{	ext{fluctuation}} \) is mean level fluctuation during the microstructure, optimal etching techniques had to dimensions, so in order to study these hooks within the steel microstructure. The red arrow indicates the casting direction of the samples. The red curve line indicates the solidification hook shape.

**Table I. Casting Parameters for 3 separate trials**

<table>
<thead>
<tr>
<th>Trial</th>
<th>Casting Speed (mm/min)</th>
<th>Oscillation Frequency (cycles/min)</th>
<th>Superheat (℃)</th>
<th>Solidification Temperature (℃)</th>
<th>Hook Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1303 5.47</td>
<td>159 21</td>
<td>1035</td>
<td>430</td>
<td>0.128</td>
</tr>
<tr>
<td>2</td>
<td>1499 4.99</td>
<td>210 24</td>
<td>1035</td>
<td>450</td>
<td>0.099</td>
</tr>
<tr>
<td>3</td>
<td>1399 4.68</td>
<td>218 24</td>
<td>1035</td>
<td>470</td>
<td>0.082</td>
</tr>
</tbody>
</table>

Trial 1 is the original ArcelorMittal process, while Trial 2 and Trial 3 were process parameters recommended by the senior design team.

**Results**

The micrographs below represent experimental etchant testing on steel samples from Trials 1, 2, and 3. Four etching techniques listed in Table 2 were tested in order to achieve and document the optimal method for revealing solidification hook structures within the steel microstructure. The red arrow indicates the casting direction of the samples. The red curve line indicates the solidification hook shape.

**Table II. Etchants and etching conditions**

<table>
<thead>
<tr>
<th>Etching Method</th>
<th>Composition of Etchants</th>
<th>Temperature (℃)</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ethanol 9.5ml</td>
<td>Room Temp</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Ethanol 96ml</td>
<td>Room Temp</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>Ethanol 9.5ml Picric Acid 1.1g</td>
<td>Room Temp</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>Ethanol 9.5ml Picric Acid 1.1g</td>
<td>Room Temp</td>
<td>30</td>
</tr>
</tbody>
</table>

**Discussion**

Three separate casting trials were conducted by ArcelorMittal during the duration of this project, and their casting velocity and oscillation frequency inputs had a pronounced effect on hook length and depth. Trial 1 was the original, unchanged ArcelorMittal casting parameters for this steel grade, with its inputs listed in Table I. Research conducted by Brian Thomas et al. led to our first recommendation, listed as Trial 2. This trial proposed an increase in casting velocity in order to decrease hook length and depth. Trial 3 was similar, but increased oscillation frequency as well.

Trials 1 and 3 were sampled from the ‘narrow’ face of the steel slabs, whereas Trial 2 was sampled from the ‘broad’ face. Narrow face refers to the thinner surface on the sides of the steel slab, while broad face refers to the longer top and bottom surfaces. For this reason, Trial 2 samples were unable to be compared directly with Trials 1 and 3. Figure 8 shows a significant decrease in hook length and depth from Trial 1 parameters to Trial 3 parameters. Figure 9 shows the comparison of hook measurements between the broad faces and the narrow faces. Hooks from the broad face have proven to be longer and deeper, on average, than the narrow face hooks. This might be due to the slab steel bulges in the spaces between the top side containment rolls and in the spaces between bottom side containment rolls. After the slab bulges, the next roll down in the caster pushes the bulge flat again, causing some amount of deformation to the hook.

**Etching Techniques**

The nital used in Figure 4 only reveals the segregation of different grain structures below and above the hook. This segregation of different hook structures may be due to the fact that the solidification rate differs on either side of the hook. But nital does not bring out the clear outline of the hook structure, making it difficult to identify the starting and ending points of the hook shape. In Figure 5 Picric acid and ethanol bring out clearer hook structures than nital etching. The limitation is that this process takes up to 31 hours. Picric acid with additions of Zephiramine reveals the clearest outline of the hook structure indicated in Figure 6(a). With this surfactant, the reaction of the etchants accelerates. But the limitation is it still takes up to 13 hours to reveal the hook shape.

**Mold Powder**

The solidification temperature of mold powder from Trial 1 & 3 are the same. The mold powder from Trial 2 has higher solidification temperature. The hook dimensions and shape will be influenced by the high solidification temperature of the mold powder.[2]

**Recommendations**

- An increase in casting speed and oscillation frequency can relatively decrease solidification hook length and depth.
- Etching with Picric acid and Zephiramine bring out the clearest outline of the hook structures.

**References**

[1] Lee, G.-G. (2009). Prediction and control of subsurface hooks in continuous cast ultra-low-carbon steel slabs. [Research conducted by Brian Thomas et al. led to our first recommendation, listed as Trial 2. This trial proposed an increase in casting velocity in order to decrease hook length and depth. Trial 3 was similar, but increased oscillation frequency as well.]

[2] This work is sponsored by ArcelorMittal Indiana Harbor, East Chicago, IN.