Characterization and Elimination of Solidification Hooks in Continuous Slab Castings

Samantha Chon-Briggs, Yuzhe Liu, Stephen Schriver, Fan Zhang
Faculty Advisor: Prof. Matthew Krane
Industrial Sponsor: Richard Gass

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.

This work is sponsored by ArcelorMittal Indiana Harbor, East Chicago, IN

Project Background

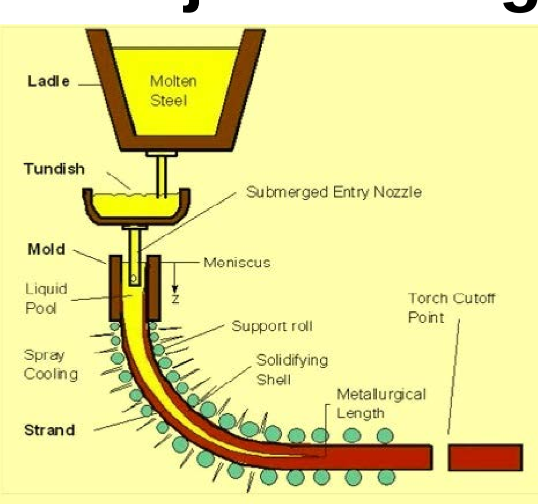

Figure 1. Schematic of continuous casting process [1]

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

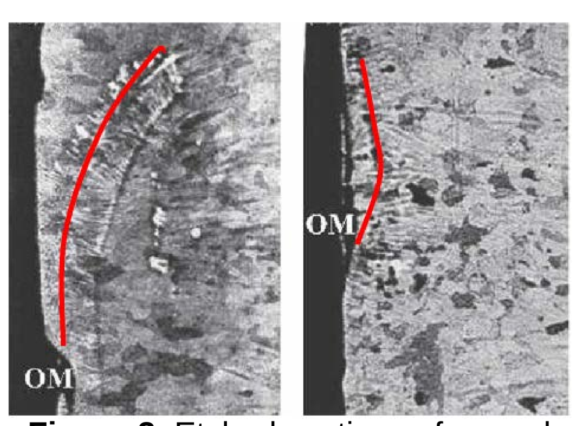

Figure 2. Etched sections of curved hooks (left) and straight hooks (right) [2]

Criterion for Identifying Solidification Hooks

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

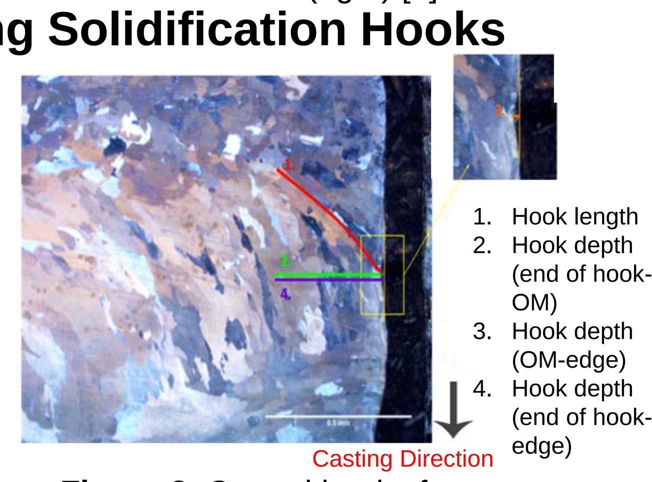

Figure 3. Curved hooks from narrow face samples.

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:

$$= 10^{-31.0874} \times V_c^{-0.61416} \times F^{-0.46481} \times T_s^{-0.18782} \times L_F^{0.041863} \times T_{sol}^{10.692} \quad [3]$$

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 difference, L_F is mean level fluctuation during sampling, T_{sol} is the solidification temperature of mold powder.

Table I. Casting Parameters for 3 separate trials

Trial	Casting Speed (mm/min)	Oscillation Stroke Length (mm)	Oscillation Frequency (cycles/min)	Superheat (℃)	Mold Fluctuation (mm)	Negative Strip Time (seconds /cycle)	Mold Powder Solidification Temp(℃)
1	1303	5.47	159	21	1	0.128	1035
2	1504	5.98	159	30	2	0.124	1115
3	1499	4.99	210	24	3	0.099	1035

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

Table II. Etchants and etching conditions

Etching Method	Composition of Etchants	Temperature	Time
1	Ethanol 9.5ml Concentrated Nitric Acid 0.5ml	Room Temp	45 s
2	Ethanol 96ml Picric Acid 4g	Room Temp	31 hr
3	Water 100ml Picric Acid 1.1g Zephiramine (1%) 0.75ml	Room Temp	13 hr
4	$Cucl_2$ 2.5g $Mgcl_2$ 10g Concentrated HCl 5ml Ethanol 250ml	Room Temp	5 min

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.

Etching Method 1

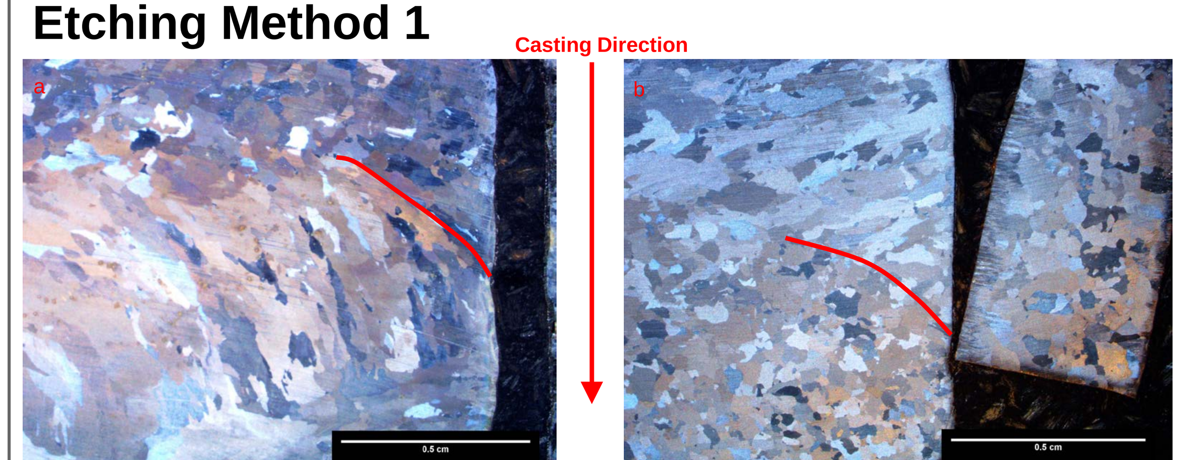

Figure 4(a)&(b) Narrow face samples from Trial 1 casting parameters.

Etching Method 2

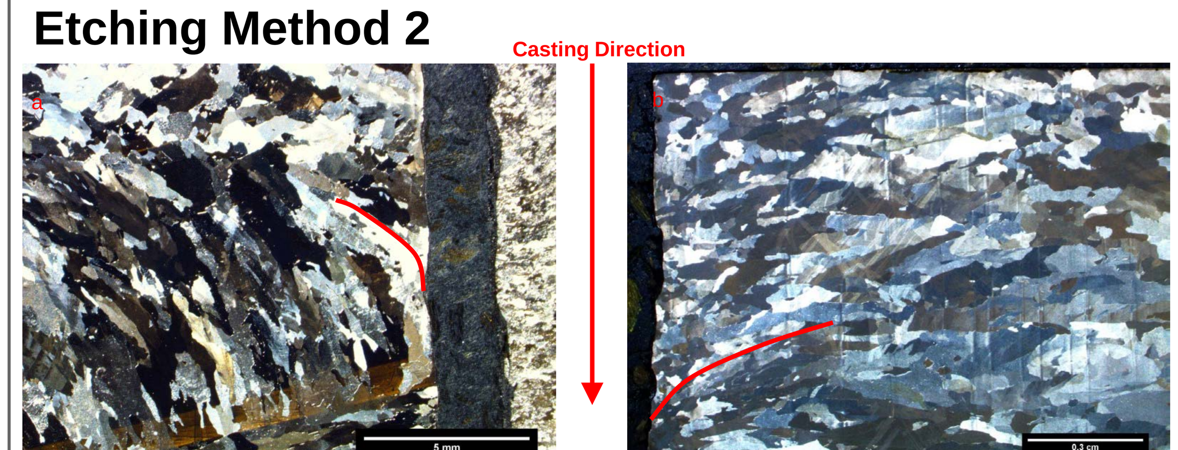

Figure 5(a) Narrow face samples from Trial 1 casting parameters. **Figure 5(b)** Broad face samples from Trial 2 casting parameters.

Etching Method 3

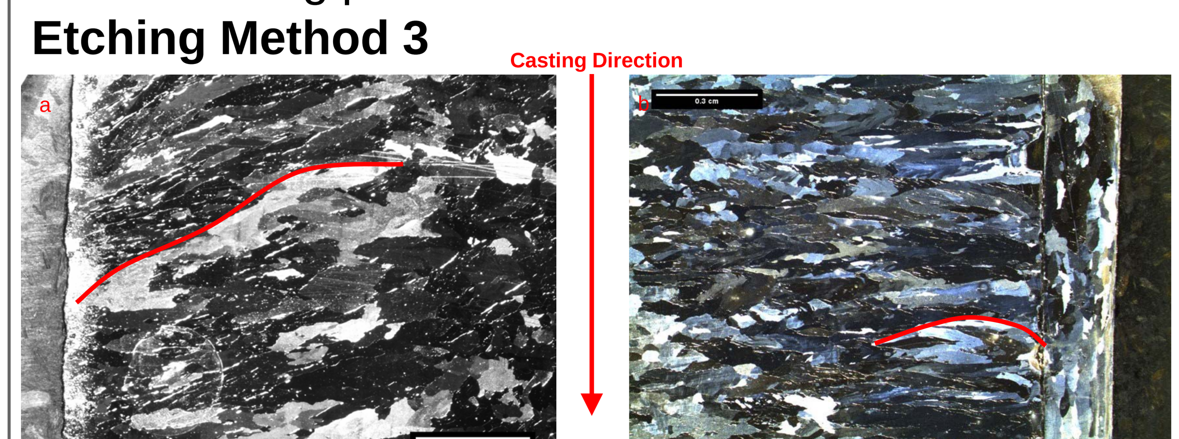

Figure 6(a) Broad face samples from Trial 2 casting parameters. **Figure 6(b)** Broad face samples from Trial 3 casting parameters.

Etching Method 4

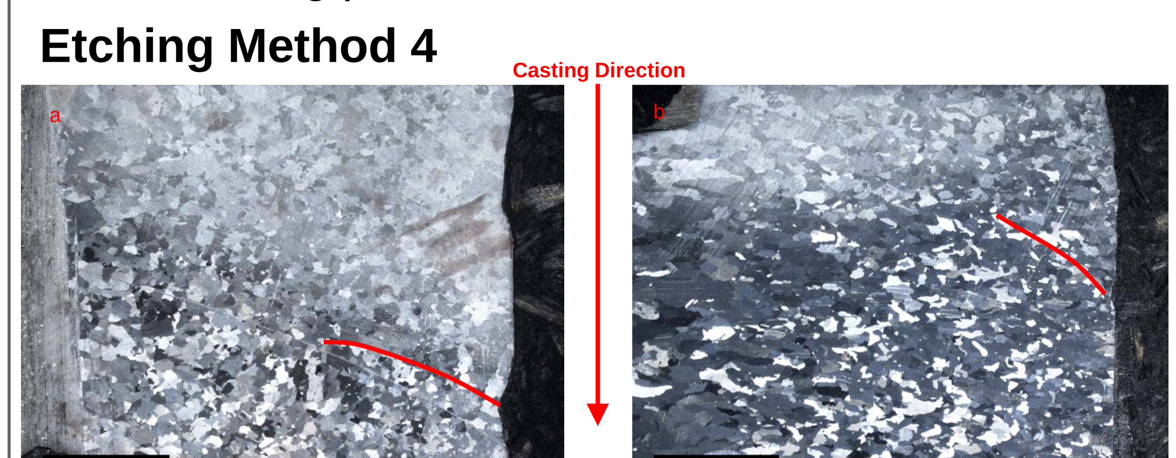

Figure 7(a)&(b) Narrow face samples from Trial 3 casting parameters.

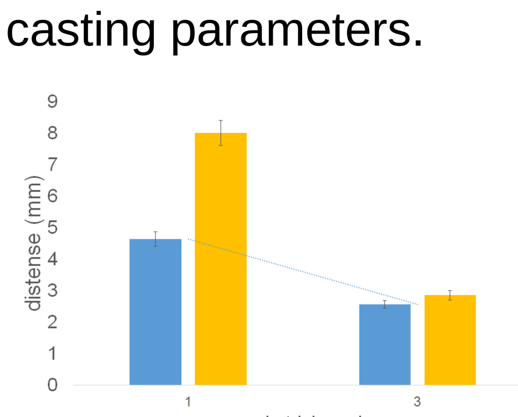

Figure 8. Graph of sample Trial 1 and 3 (narrow face only)vs. the solidification hook depth and length.

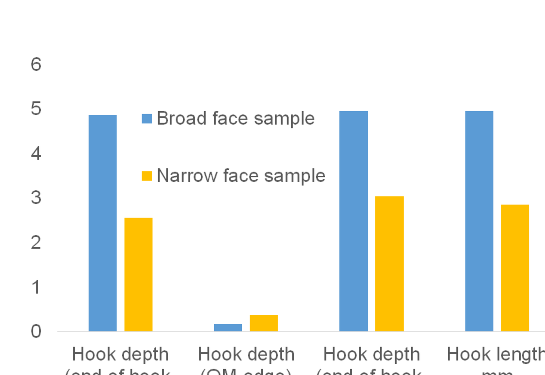

Figure 9. Comparison of hook dimensions between broad face and narrow face sample of Trial 3.

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 face samples and the narrow face samples. 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 shell 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.[3]

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. Intro to Continuous Casting - CCC - U of I. (n.d.). Retrieved April 19, 2016, from http://ccc.illinois.edu/introduction/overview.html#techniques
2. Sengupta, Joydeep. (2006). A New Mechanism of Hook Formation during Continuous Casting of Ultra-Low-Carbon Steel Slabs. *Metallurgical & Materials Transactions. Part A, 37A*(5), 1597-1612.
3. Lee, G.-G. (2009). Prediction and control of subsurface hooks in continuous cast ultra-low-carbon steel slabs. *Ironmaking & Steelmaking, 36*(1), 39-50.