Investigation of Slivering Defect Formation in Continuously Cast Steel Slabs

PURDUE MATERIALS ENGINEERING

Jonathan Hilsmier, Karen Martinez, Ziheng Wu, Hans Yovento
Faculty Advisors: Professor David Johnson, Professor Robert Spitzer
Industrial Sponsors: James Hancock, ArcelorMittal, Riverdale, IL

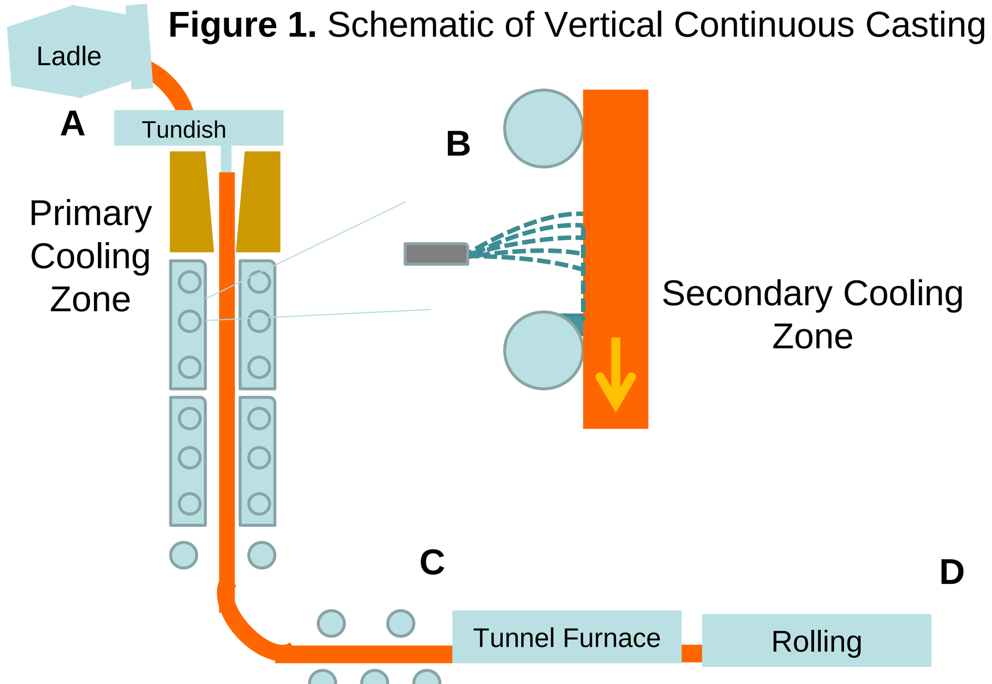
ArcelorMittal
This work is sponsored by ArcelorMittal in Riverdale, IL

ArcelorMittal Riverdale requested an investigation of slivering – a surface defect which is postulated to originate from the solidification stages of the casting process. The goal was to identify the formation mechanism of slivers, and to identify process changes to prevent sliver formation. Using a combination of literature reviews, thermal modeling, and extensive characterization (scanning electron microscopy, optical microscopy, x-ray diffraction) of samples from various stages of the process, a root cause analysis of the defect was carried out. Through our analysis we developed a hypothesis and gathered supporting evidence: surface temperature oscillation in the secondary cooling zone cause surface stresses, and inclusions found near slivering defects are defect initiators.

Project Background

- **Riverdale Continuous Casting Mill Process:**
  Molten steel passes through the primary cooling zone, a water-chilled copper mold (A), where the surface of the slab is solidified, forming a solid shell. Next, the molten slab core continues its vertical path into the secondary cooling zone where the surface temperature is moderated with a spray cooling system (B). The solidified slab passes through a reheat furnace (C) before it enters the rolling mill (D).

Figure 1. Schematic of Vertical Continuous Casting



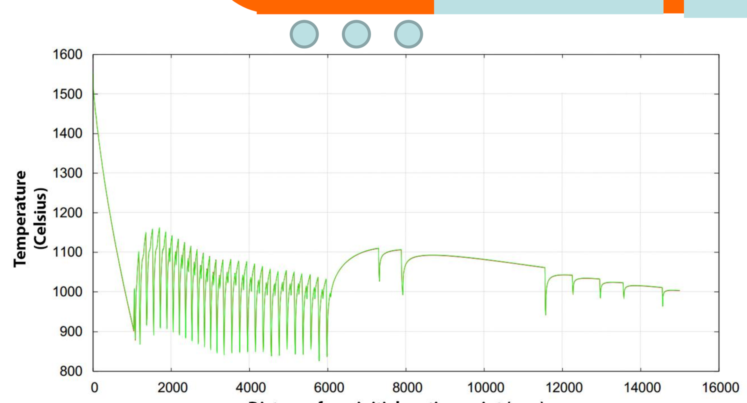


Figure 2. Slab surface temperatures in primary and secondary cooling zones from CON1D model [1]. The region of high frequency oscillations is secondary zone spray cooling.

- **Slivering defect:**
  Found on the slab surface within 6” of the slab edges, slivering appears as an intergranular surface crack and surface delamination. Inclusions and oxidation frequently accompany slivering. Propagation of the defect was localized to the spray cooling zones, where Figure 2 shows the temperature oscillations experienced on the slab surface.
- **Slivering impact:**
  In 2014: A single customer rejected 500 tons due to slivering. Internally, 0.57% (3480 tons) of steel produced was rejected due to slivering. Slivering is the largest internal reject reason.

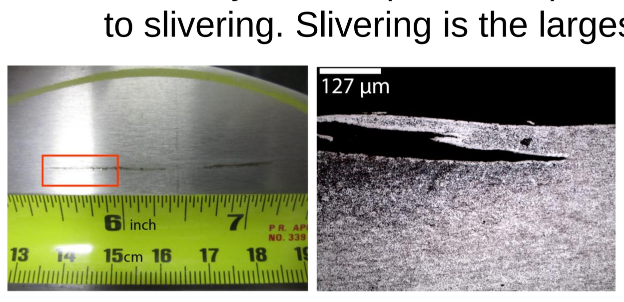


Figure 3. Slivering in customer-returned flexplate samples. Length and depth of sliver on right is 0.508 and 0.07 mm, respectively.

Goal

Identify the slivering formation mechanism and relevant process parameters linked to the propagation of slivers into surface cracks.

Approach

1. Review continuous casting defect literature
   Summarize findings into logic map
2. Analyze physical slivering samples
   -Post primary and secondary cooling zones
   -Post tunnel furnace and rolling
   -From customer returned samples
3. Validate formation hypothesis with physical sample observations

Samples

Table 1. Characterization samples and techniques

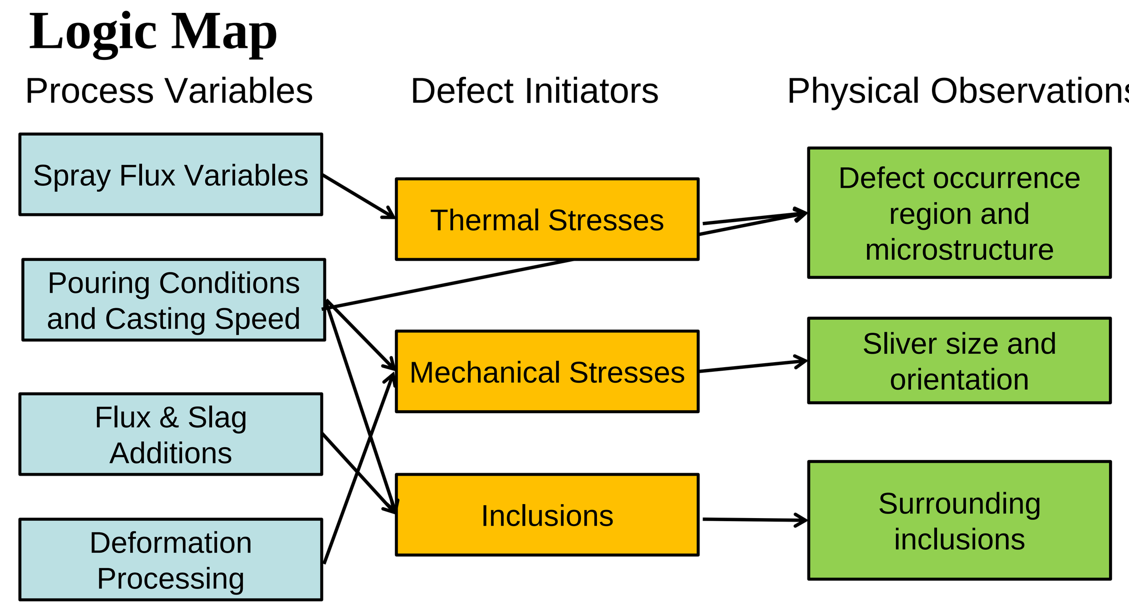
Samples	Optical	SEM EDS	XRD	Vickers	In Figure 1
Mold Powder Ladle Flux	-	-	●	-	A
As-Cast	●	●	-	●	C
As-Rolled	●	●	-	●	D
Customer-Returned	●	●	-	●	See Figure 3

Process History

- 1050 Steel
- Casting Speed: 4.57 meters / minute
- Secondary cooling surface temperature: 850 to 1150^{o}C (with oscillations as shown in Figure 2.)

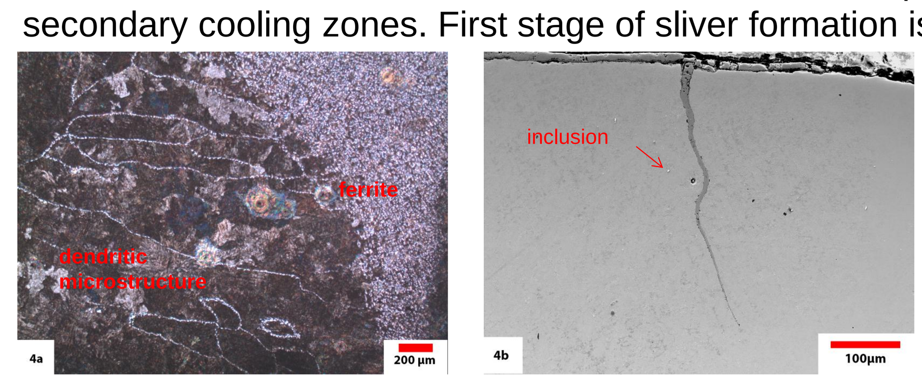
Results

Logic Map



As-Cast Samples

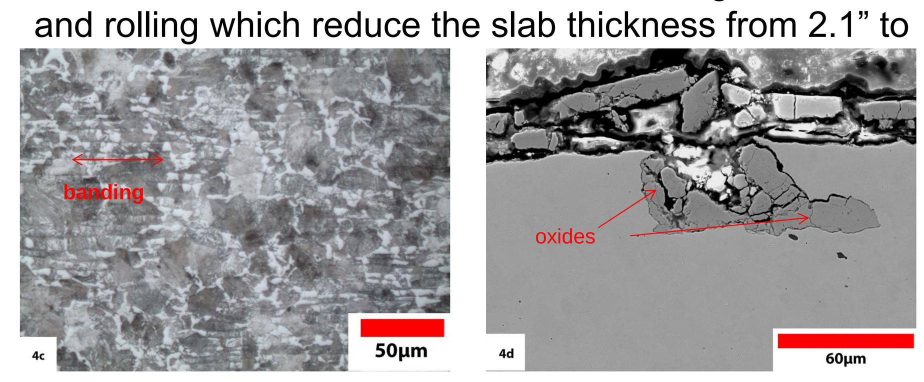
Reflect the slab microstructure after solidification in the primary and secondary cooling zones. First stage of sliver formation is observed.



In Figure 4a) fine ferrite microstructure found up to 1 cm in from slab corners represents initial solidification. The dendritic microstructure is formed in the secondary cooling zone as the slab center solidifies. Slivers are found within the fine ferritic microstructure regions. The sliver in Figure 4b) found adjacent to a glassy, calcium, alumina, silicate inclusion.

As-Rolled Samples

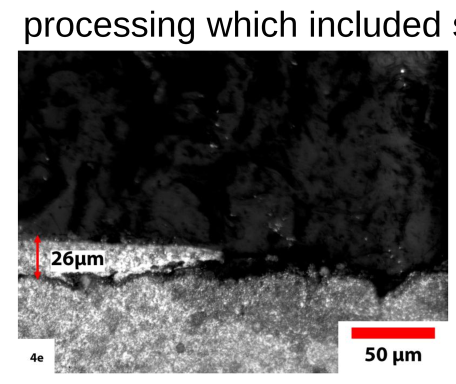
Reflect the slab microstructure and slivering after rehomogenization and rolling which reduce the slab thickness from 2.1” to 0.125”.



In Figure 4c) shear banding from rolling is apparent in the microstructure. Grain size remains finer at corners and edges, but ferrite now rings larger pearlite colonies throughout. The sliver opening has widened, and the crack is lined with oxide in Figure 4d).

Customer Returned Samples

Reflects the slab microstructure and slivering after customer processing which included spheroidization, pickling and hot stamping.



In Figure 4e) the sliver profile is now parallel to the surface. In customer returned samples examined internally by ArcelorMittal glassy inclusions of alumina and silicate were found at crack roots.

Table 2. Summary of Metallographic Analysis

Sample	As-Cast	As-Rolled	Customer Returned
Phases	Ferrite, Cementite	Ferrite, Pearlite Colonies	Ferrite, Pearlite Colonies
Average grain size (austenitic)	490 μm by 240 μm	12.1 ± 2.2μm	Spheroidized, N/A
Sliver morphology	Narrow, profile is perpendicular to surface, extends longitudinally into rolling direction.	Sheared, profile wider with thick oxide layer, extends longitudinally into rolling direction.	Profile is parallel to surface, extends longitudinally into rolling direction.
Sliver profile length	65 μm to 290 um	30 μm to 80 μm	500 μm to 990 μm

Inclusion Analysis

- Alumina, silicate & calcium inclusions are found throughout the entire slab: with .33 per square mm density at the midface, and .99 per square mm density at edges.
- Inclusions range in size from 15 to 50 μm so possible sources are: ladle, tundish or mold additions.
- Aluminum and silicon are added to steel as deoxidants. Calcium is added to control the absorption of inclusions into slag and to soften inclusions that remain in steel. The average composition of inclusions analyzed is shown in Table 3.

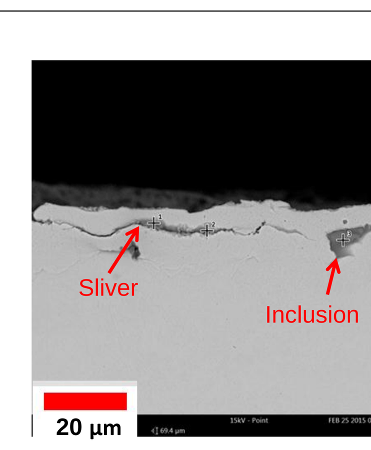


Figure 5. Representative 41 at. % Si, 2 at. % Al inclusion found at sliver root in an as-cast corner sample.

Discussion

Based on the results section the proposed sliver formation path:

1. Increases in aluminum additions for deoxidation, ladle stirring speed, and stirring duration increase inclusion density of the slab. The inclusions analyzed reflect a heat with extra aluminum additions.

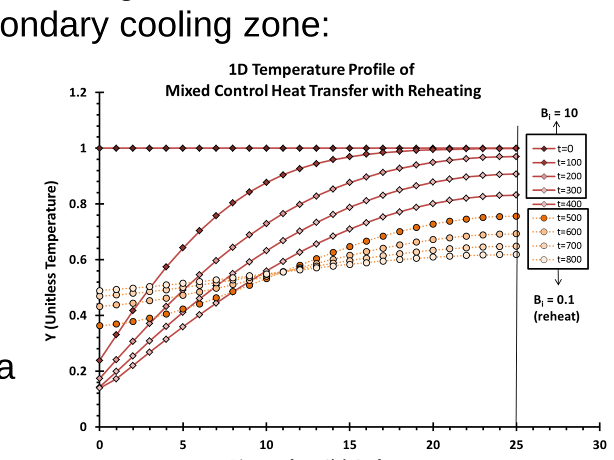
Table 3. Components of Mold Flux and Inclusions

Common Mold Flux Composition Ranges	Inclusion composition (EDS) (Average relative %)
SiO_2 (17-56%)	Silicon (35%)
CaO (22-45%)	Calcium (22%)
Al_2O_3 (0-13%)	Aluminum (39%)

2. Slivers form in the primary cooling zone and propagate due to thermal surface stresses in the secondary cooling zone.
   - Slivers observed in as-cast sample occur in initial solidification region and are intergranular within the fine ferritic microstructure. Must originate in first or second zone.

Origins of thermal stress in secondary cooling zone:

Figure 6. Upon transition from mold cooling to spray cooling, the slab surface temperature rises while the interior of the slab continues to cool. This effect is called reheat. The stress generated could initiate a sliver at an inclusion.



One dimensional heat model development:

1. Solve second law for one dimensional conduction
$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) = \rho c_p \frac{\partial T}{\partial t}$$
2. Convert to finite difference calculation where position increments across rows and time increments down columns in spread sheet
3. Set mixed-control boundary condition at surface
$$\rho V C_p \frac{dT}{dt} = h_A(T_\infty - T_0) + kA\frac{dT}{dx}$$
4. To model thermal history make changes to the Biot number
$$Bi = \frac{hx_0}{k}$$

The secondary cooling zone has periodic instances of higher heat transfer when the slab is impinged by sprays or when in contact with rolls. The slab surface temperature oscillates as it travels through this zone, generating surface thermal stresses.

Surface temperature is harmonic and thermal amplitude is magnified at slab edges where the spray water flux is higher. The slab surface undergoes several shifts from high tensile to compressive stresses in the casting direction.

Further processing such as hot rolling, cold rolling, and stamping further propagate the sliver and alter the silver morphology. The hot rolling deformation reorients slivering precursors from the cast state so that the sliver is oriented laterally, allowing for delamination to occur.

Sliver Formation Conclusions

- Inclusions from upstream ladle metallurgy, tundish and mold powder additions contribute to sliver formation
- Slivers are observed on slab edges due to thermal stress induced by oscillating surface temperatures and increased spray flux experienced in the secondary cooling zone.
- Slivers further propagate with deformation processing
- Slivers are primarily found in slab regions with initial solidification front microstructure, as shown in Figure 4a. Sliver formation is associated with the thermal history of this region.

Process Recommendations

- Minimize process stoppage times so that further Al additions and prolonged stirring do not cause increased inclusion density.
- Monitor Ca additions to match increases in Al additions to improve steel cleanliness and inclusion morphology (current proportion summarized in Table 3).
- Spray flow control adjustments could be made to minimize the overcooling of edges which amplifies thermal stresses at the slab edge.

Acknowledgements

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