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Mechanism Of Hook And Oscillation Mark Formation In Ultra-Low Carbon Steel

THOMAS, Brian G.[1], *SENGUPTA, Joydeep*[2], *OJEDA, Claudio*[1]

(1. University of Illinois, Mechanical Engineering., Urbana, Illinois USA; 2. Dofasco, Hamilton, Ontario, Canada)

Abstract: A new mechanism for the formation of hooks and oscillation marks during continuous casting of ultra-low carbon steels is developed, based on: (i) observation of hook characteristics on specially-etched micrographs, (ii) metallographic studies near the line of hook origin using EDX, EPMA, and EBSD, and (iii) computations using separate models of fluid flow, solidification, and thermal stress. The mechanism is presented as a schematic, which illustrates the details of events leading to formation of hooks and oscillation marks. Its predictions are consistent with the trends observed in previous work, mold simulators and operating casters. This mechanism has important implications for the entrapment of inclusions and other surface defects.

Key words: Initial solidification**;** Meniscus; Oscillation; Hooks; Mechanism; Computational models; Lubrication; Fluid flow; Thermal distortion; Metallography; Surface defects

0 Introduction

Oscillation marks and sub-surface hooks in continuously-cast steel slabs are important because they are associated with quality problems, including the entrapment of argon bubbles and alumina inclusions beneath the hooks, transverse cracks near the oscillation mark roots, and slivers in rolled product. The entire slab surface (~2-4mm deep) must sometimes be ground or "scarfed" to remove them. Oscillation marks, such as shown in Figure 1, are periodic transverse depressions running across the slab surface. They occur during each vertical oscillation of the water-cooled copper mold, which is needed to prevent sticking of the shell to the mold wall.

Subsurface "hooks" are distinctive microstructural features that accompany some oscillation marks in low (<0.1%C) steels and are seen in etched transverse sections through the slab surface, such as Figure 2.[1] Figure 2 a) (top) shows a typical curved hook, with an entrapped particle. Hooks and oscillation marks form due to complex initial solidification phenomena, involving time-varying changes in meniscus shape due to dynamic fluid flow, solid flux rim oscillation, and surface tension effects in the flux channel, superheat transport to the meniscus, local heat transfer to the mold, liquid undercooling, nucleation and meniscus solidification, and thermal stress and distortion of the shell in the meniscus region.

Many previous mechanisms for these phenomena have been proposed, including:
1) Discontinued shell growth – based mechanism [2, 3]: Sticking to the mold wall during initial solidification disrupts shell growth. Subsequent solidification heals the disjointed shell edges, creating an oscillation mark.
2) Shell bending and overflow – based mechanism [4]: The initial shell tip is forced to deform and bend away from the mold surface. Subsequent overflow of liquid steel over the curved shell surface creates a hook and oscillation mark.
3) Meniscus solidification and overflow – based mechanism [5, 6]: The curved meniscus solidifies. Subsequent overflow over this frozen meniscus forms the hook, and its associated

oscillation mark.

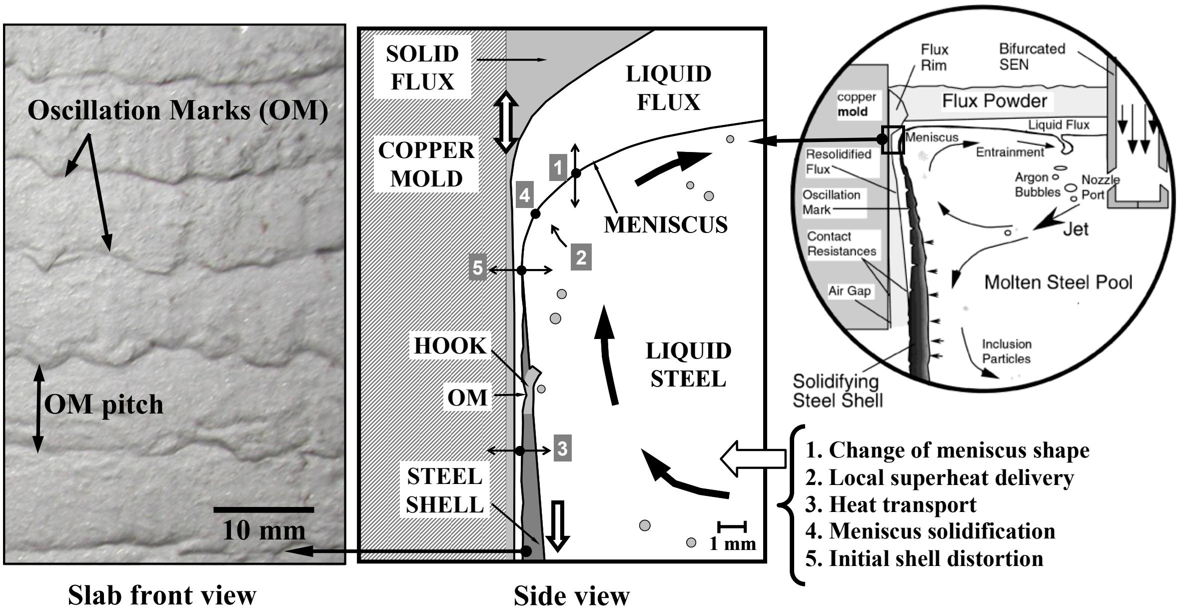


Figure 1 Inside a continuous caster mold (right), a range of complex phenomena in the meniscus region (middle) creates periodic oscillation marks (OM) (left) on the slab surface.

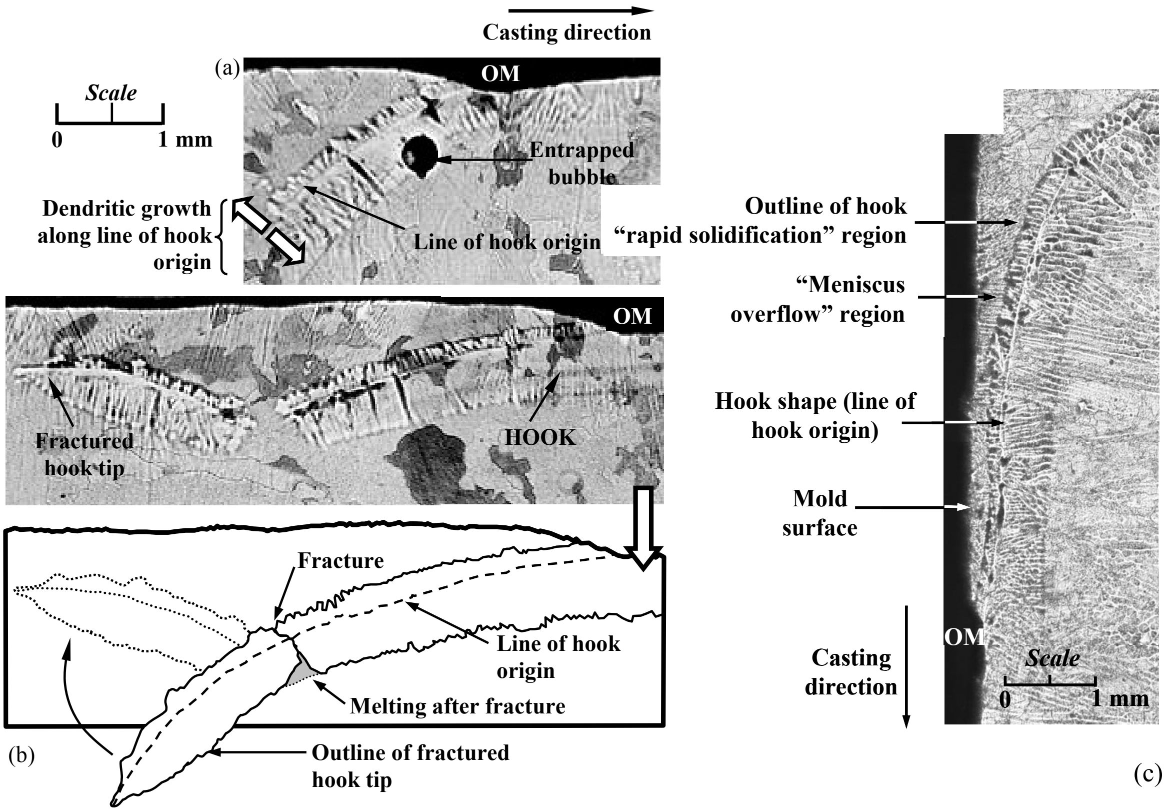


Figure 2 Hook features in ultra-low carbon steel samples: optical micrographs showing (a) entrapment of argon bubble by a hook-type oscillation mark; (b) a fractured hook tip; and c) unidirectional growth of dendrites from the line of hook origin (the frozen meniscus).

This work presents a new detailed mechanism for the formation of oscillation marks and hooks in ultra-low carbon steels, based on combining the results of previous experimental measurements, metallographic examination, computations using separate models of fluid flow, solidification, and thermal stress, and trends observed in commercial casters.

1 METALLOGRAPHIC EXAMINATION

Samples from the surface of ultra-low carbon steel slabs obtained from an extensive experimental campaign at a 230-mm thick, parallel-mold slab caster, #2-1 at POSCO Gwangyang Works, South Korea [1, 7] were evaluated using optical microscopy with a special etchant, electron back scattering diffraction (EBSD), and energy dispersive x-ray spectroscopy (EDX). Typical casting conditions are given in Tables 1 & 2.

The etched hook sample in Figure 2 c) clearly reveals dendrites originating from several different nucleation sites located on or near the frozen meniscus, or "line of hook origin". Some dendrites grew away from the mold wall. Others grew into the liquid overflow region towards the mold wall, stopped growing and coarsened. The rest of the overflowed region solidified later, producing a finer structure, as heat was rapidly removed into the mold wall.

Figure 2 b) illustrates that a portion of the hook can break off from the solidified meniscus. This indicates brittle fracture (hot tearing) of the fragile semi-solid hook caused by inertial forces of the molten steel during overflow of the curved hook. The outline of the separated hook tip aligns almost exactly with the fractured hook. Usually, the fractured shell tip completely melts or is transported away, giving rise to the truncated end observed in most hooks.

Figure 3 shows an EBSD map of crystallographic orientations (left) obtained from an area near the line of hook origin on the slab sample shown in Fig. 2 (a). The location of this area relative to the hook is indicated on a backscattered electron SEM image (right). Grain misorientation measurements reveal that grains below the solid black line have higher relative misorientation than the grains above this line, which is a long grain boundary. This boundary persisted even after two phase transformations (from δ-ferrite to austenite to α-ferrite). The SEM image clearly shows that this line is part of the line of hook origin. The drastic difference in relative grain orientations arises because solidification above and below the line of hook origin occurred at different times during the oscillation cycle. First, the lower region solidified while the interface (meniscus) was covered with mold flux, and then the upper side solidified during subsequent liquid steel overflow. Further details are given elsewhere.[8]

2 Models of Meniscus Behavior

To understand meniscus phenomena, separate computational models of dynamic fluid flow,[9] solidification, and thermal stress[10] have been developed and applied to simulate events during oscillation. Figure 4 shows the velocity and position of the mold during an oscillation cycle for typical operating conditions, given in Tables 1 and 2. The negative strip time, where the mold moves downward faster than the shell at the casting, is needed to preventing sticking of the shell to the mold wall. A coupled heat transfer and fluid flow simulation was developed of the molten flux region, molten steel, and interface between them in the meniscus region. The model solves the 2-D Navior Stokes equations using the VOF method to compute the location of the interface. Figure 5 shows an example of the computed temperature contours, and shows the interface shape. The shape of the meniscus, computed as part of the flow simulation, depends on a dynamic balance between the ferrostatic pressure and the interfacial surface tension. Under equilibrium conditions, this balance creates the classic curved shape described by “Bikerman’s” equation.[8, 10]

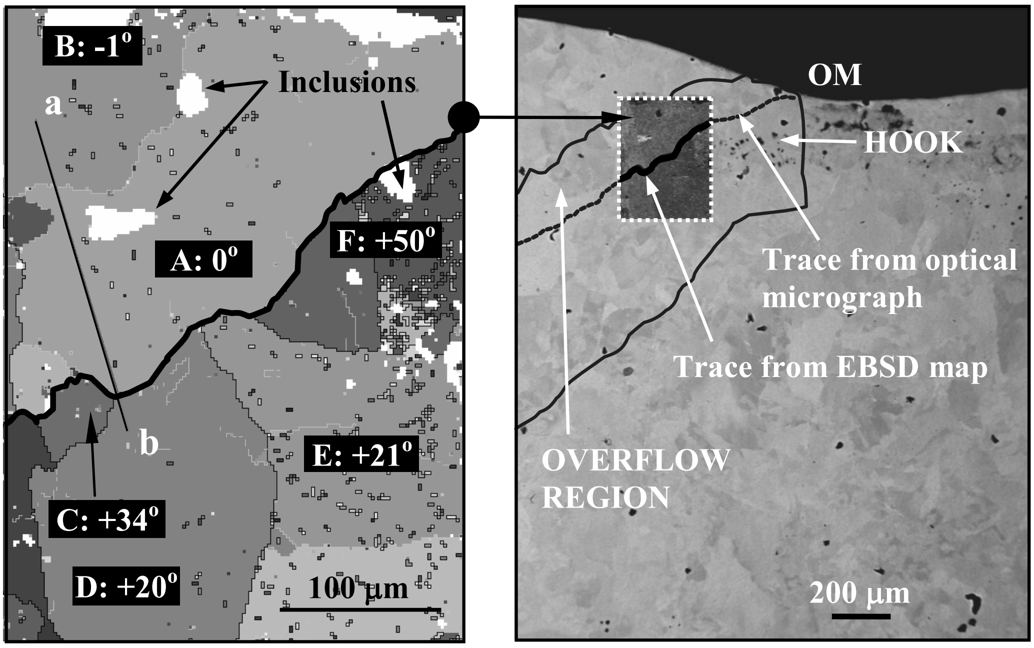


Figure 3 - EBSD map of grain misorientation measured near the hook shown in Fig. 2 (a), and far-away view (backscattered electron image) showing location at line of hook origin.

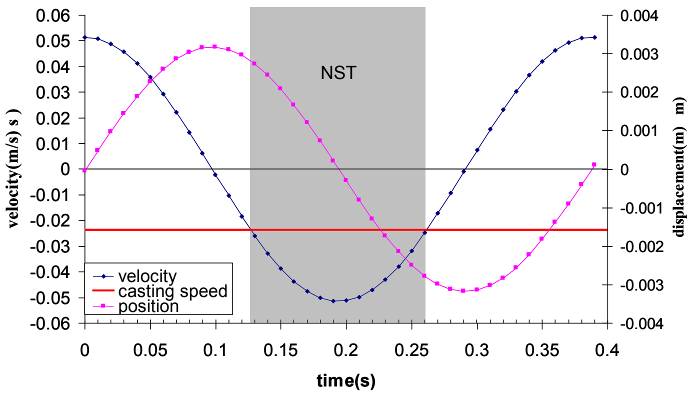
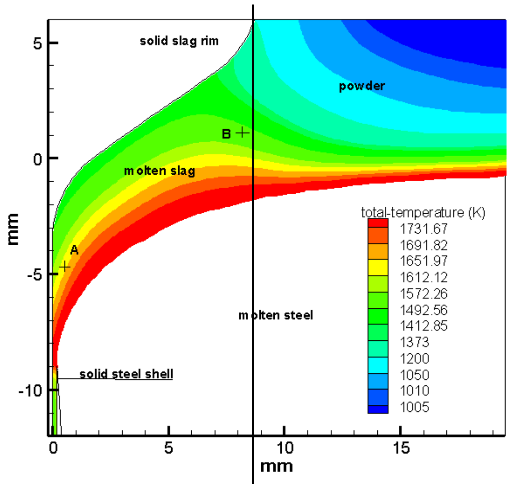


Figure 4 Velocity and position curves during an oscillation



cycle□

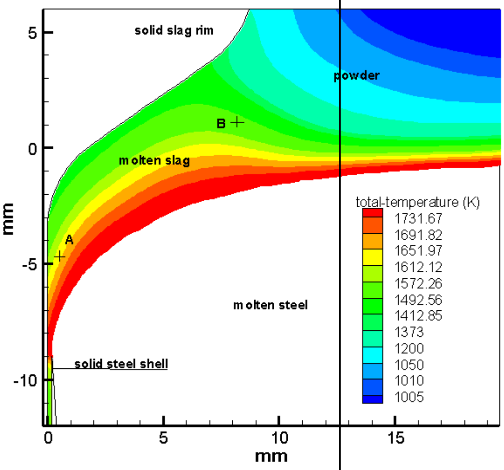


Figure 5 Temperature field of the mold slag in the meniscus region□□

Figure 6 shows the computed development of flow velocity in the liquid slag and steel layers, superimposed on the mold velocity during the oscillation cycle. During the positive strip time (until 0.06s), upward movement of the slag rim opens up the space above the meniscus and draws in liquid slag. Liquid slag is drawn out of the gap between the steel shell and the mold and the slag steel interface (meniscus) is pulled towards the mold. Just before negative strip starts, the meniscus overflows the top of the shell. After this point, there is positive slag consumption into the gap. During the negative strip time, downward mold movement generates positive pressure and squeezes slag out of the shrinking meniscus region. Also during this period, the overflowed steel solidifies in the mold / shell gap, while a new meniscus forms and is pushed away from the mold. As the positive strip period begins again, the pressure decreases and the slag again flows beneath the rim and pulls the interface towards the mold.

Results from other simulations show that although the overflow event is consistent for a given set of conditions, minor changes in the flow, such as caused by level fluctuations or a different flux rim shape can cause overflow to occur at a different time in the cycle. The range of meniscus shapes computed during the cycle are shown in Figure 7, together with the equilibrium shape from Bikerman's equation. This figure also shows the shapes of hooks measured from micrographs of steel samples with hooks obtained from the plant under the same casting conditions. The range of predicted meniscus shapes matches the measured lines of hook origin quite closely, indicating that meniscus freezing is responsible for hook formation.

Figure 7 also shows the shape of the solidified steel shell predicted by a thermal stress model, which was developed to simulate events such as a liquid level fluctuation. This 2-D finite element simulation features solidification heat transfer during the process, thermal contraction dependent on steel grade, and elastic-viscoplastic constitutive behavior to simulate the inelastic creep strain that affects the steel shell at high temperature. The predicted curvature of the shell due to thermal distortion is much more gradual than the measured hook shapes, but is still sufficient to have a significant influence on both the hook and shell surface curvature. The latter controls the depth and shape of oscillation marks.

Table 1. Steel and slag properties in the model

Density of steel	7000 kg/m^3
Viscosity of steel	0.063 Poise
Density of slag	2500 kg/m^3
Viscosity of slag	2.62 Poise
Surface tension	1.6 N/m
Contact angle	60 deg

Table 1. Oscillation and casting parameters

Casting speed	1.42 m/s
Frequency	155 cpm
Stroke	6.34 mm
Pour temp.	1564 °C
Slab width	1300 mm

3 Mechanism of Hook and Oscillation Mark Formation

These model results give new insight into the mechanism for hook and oscillation mark formation. Alternating pressure due to mold oscillation and interaction with the solidified flux rim causes meniscus motion, and overflow just before the negative time starts, although the results suggest that overflow could happen at various times during the oscillation cycle. If the molten steel in the region becomes supercooled, the meniscus could solidify at some time during the cycle before overflow, leading to hook formation. This explains why the predicted range of hook shapes agrees so well with the measurements. The curvatures also agree well, although there appears to be slightly more curvature in the measured hooks. This suggests that other phenomena, such as level fluctuations or thermal distortion may have altered the hook shape. Thermal distortion is the most likely explanation, however, as the heating provided from the molten steel to the outside of the hook during overflow would cause it to expand and distort, increasing its curvature from the predicted shape of the meniscus to that observed in the solidified hook. The steps in this mechanism are illustrated in Figure 8.

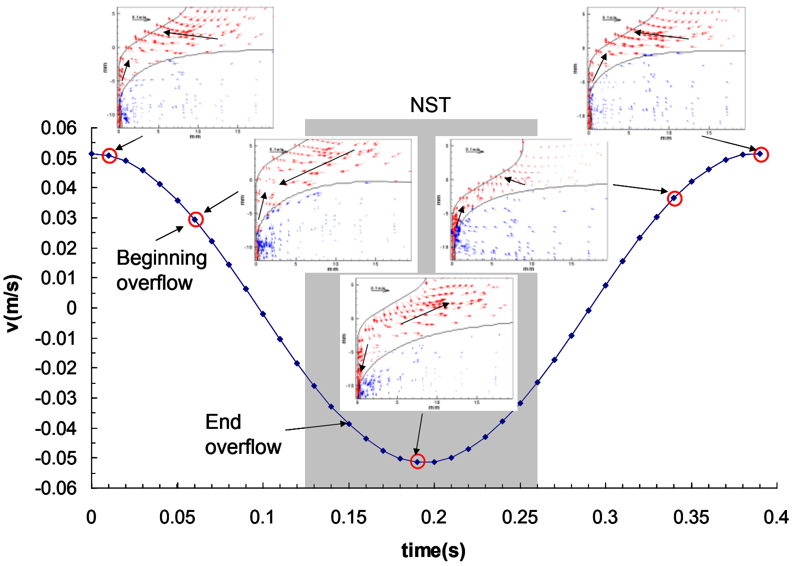


Figure 6 Meniscus shape evolution during one oscillation cycle

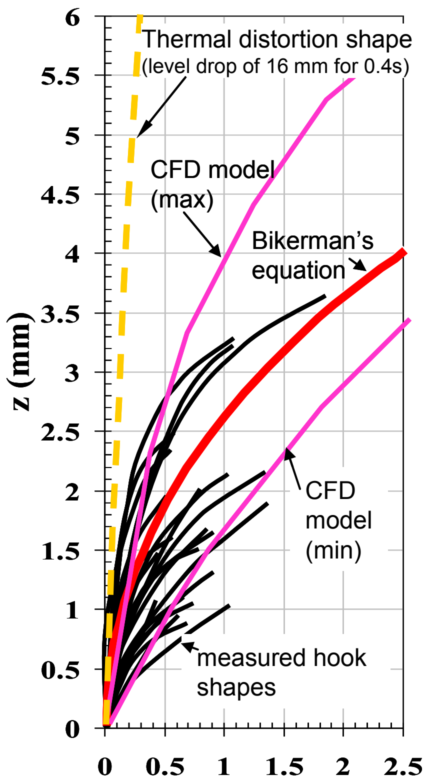


Figure 7 Comparison of computed interface shapes with measured hook shapes [8]

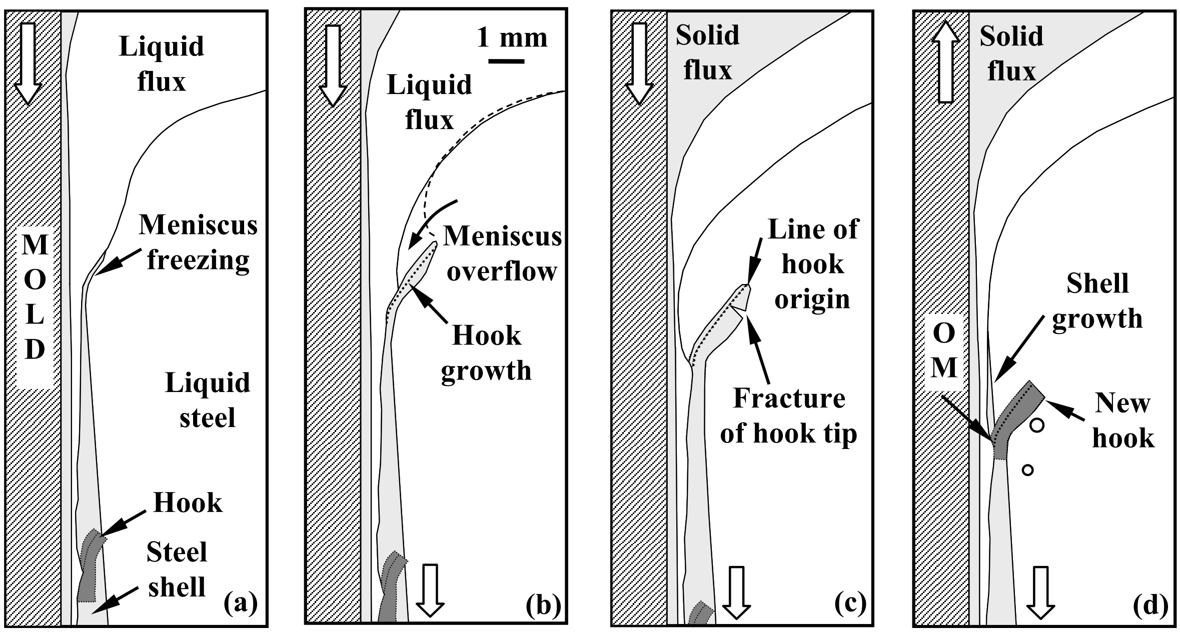


Figure 8 Schematics illustrating new mechanism of formation of curved hook in an ultra-low carbon steel slab by meniscus solidification and subsequent liquid steel overflow.

4 Conclusions

Sub-surface hooks and oscillation marks form in continuously cast steel slabs through a complex mechanism involving many inter-dependent, transient thermal-fluid flow phenomena that occur during initial solidification near the meniscus. The steps in the mechanism for ultra-low carbon steel are summarized as follows:

(i) At the start of the negative strip time, the undercooled meniscus suddenly solidifies. The shape of the meniscus at this instant dictates the curvature of the line of hook origin.
(ii) Next, dendrites quickly grow into undercooled liquid steel from nucleation sites on the frozen meniscus, creating the hook shell thickness below the line of hook origin.
(iii) As the shell tip moves downwards, the meniscus supported above the hook becomes unstable and overflows. Overflow usually occurs near the start of negative strip, increasing heat flux to the mold. Level fluctuations may initiate this overflow event at other times, however, resulting in pitch variations.
(iv) Reheating from the overflowing liquid also causes thermal expansion , increasing the curvature of the hook. Variations in this thermal distortion from the δ-γ transformation shrinkage explains the variation in oscillation mark shape with steel grade.
(v) Dendrites quickly solidify into the undercooled overflowed liquid from the line of hook origin towards the mold wall. Growth soon stops as the meniscus region reheats, coarsening the dendrites and distinguishing the hook edges.
(vi) Final shape of the hook is completed as the hook tip fractures and melts away.
(vii) The remaining overflowed, supercooled liquid solidifies. Liquid penetrates into the gap and re-melts some of the flux layer, which determines the final shape of the upper side of the oscillation mark. Debris trapped in the overflow creates surface defects.
(viii) The hook protruding from the solidifying shell further captures inclusions and bubbles rising up the solidification until the shell finally solidifies past the hook.

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