Study on Hook Formation in Ultra-low Carbon Steel Slabs

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Types of oscillation marks

POSCO casting trials on ultra-low carbon slabs (2004):
• Typical OM depth = ~0.2 – 0.6 mm
• OMs with hooks > 98% on narrow face for different casting conditions (12 out of 13) = 100% on wide face (7 out of 10) – 70-90% (3 out of 10)

Szekeres, Iron & SteelMaker, 1996
Hook-type OMs are generally deeper and can be distinguished visually
Types of hook marks  
(ultra-low carbon steel)

- Entrapped inclusion
- Curved hook
- Straight hook

~20-35% straight hooks (wide + narrow faces) based on 13 POSCO trials in 2004
- OMs with curved hooks are generally deeper (~1.5 times)
- Scarfing is usually done to remove hooks & related defects

OM/Hook formation more severe with decreasing carbon content

- Ultra-low carbon steels have deeper OMs and are more prone to form hooks
- Higher solidus (1535 °C ↔ 1500 °C for high carbon steels) & thinner mushy zone (15 °C ↔ 50 °C for high carbon steels)
OM/Hook formation in meniscus region

- Combined effect of heat transfer, solidification, mechanical interactions & fluid flow
- Meniscus region: extends to ~10 mm below the metal level
- Influencing events last for a very short time-span but occurs periodically

Influential event #1

Heat transfer between shell and mold:
- Heat is conducted into the mold via liquid flux & re-solidified flux layers
- Governed by size & properties of interfacial gap (contact resistance)
- Dynamic mold distortion can lower contact resistance locally

Meng and Thomas, Met. Trans. B, 2004

Li and Thomas, Private Communication, 2005
Periodic rise in heat flux near meniscus

Rise in heat flux attributed to release of latent heat (meniscus freezing)

Badri et al., Met. Trans. B, 2005

Measurements for ultra-low carbon steel in a laboratory scale simulator at CMU

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Link between periodic rise in heat transfer & OM formation

Oscillation marks on a ultra-low carbon steel slab

Periodic rise in heat flux during NST

Badri et al., Met. Trans. B, 2005

Measurements for ultra-low carbon steel in a laboratory scale simulator at CMU
Influential event #2

Meniscus shape:

- Shape determined by balance of surface tension, pressure & gravity forces (equilibrium shape can be predicted by Bikerman’s equation)
- Strong function of sulfur content of steel
- Pressure forces due to mold oscillation is transmitted to meniscus via flux layer (both temporal & spatial variations)

Equilibrium meniscus shape

\[ x - x_0 = -\sqrt{2a^2 - z^2} + \frac{a}{\sqrt{2}} \ln \frac{a\sqrt{2} + \sqrt{2a^2 - z^2}}{z} \]

\[ x_0 = a \frac{a}{\sqrt{2}} \ln(\sqrt{2} + 1) \]

\[ a = \sqrt{\frac{2\gamma}{\rho_{\text{steel}} g}} \]

- \( x \) = distance perpendicular to the mold wall in mm
- \( Z \) = distance along the mold wall in mm
- \( \gamma \) = surface tension between liquid steel and vapor (or flux) in N m\(^{-1}\)
- \( \rho_{\text{steel}} \) = density of liquid steel = 7000 kg m\(^{-3}\)
- \( g \) = gravitational acceleration = 9.81 m s\(^{-2}\)

*From Bikerman, Physical Surfaces, Academic Press, 1970*
**Effect of %S on surface tension**

Lee and Morita, ISIJ International, 2002

Meniscus shape – affected by sulfur content

Temperature = 1550 °C
Density of liquid steel = 7000 kg m⁻³
Influential event #3

**Meniscus Freezing:**

Partial solidification of meniscus can occur in presence of a water-cooled mold (*Saucedo, 1991*)

- Preservation of instantaneous frozen shape
- Rapid cell growth in the presence of under-cooled liquid (heterogeneous nucleation)
- Incorporated into OM mechanisms (*Takeuchi & Brimacombe in 1984*)

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*Yamamura et al., ISIJ International, 1996*
Influential event #4

Fluid flow effects:

• Steel jets perturb free surface (standing waves)

• Level fluctuations due to chaotic turbulence & presence of particles/bubbles (buoyancy forces)

• Abrupt changes in operating conditions (e.g. release of nozzle clog)

Local level fluctuations

Lai et al., ISS Steelmaking Conference, 2000
Influential event #5

**Delivery of local superheat:**

- Distributed via metal jets & follows the fluid flow patterns to reach meniscus
- Meniscus typically retains ~30% of total superheat available (no freezing)

![Graph showing superheat flux vs distance below meniscus](Zhang and Thomas, POSCO Report, 2004)

Casting width: 1300 mm
Center of narrow face

Influential event #6

**Shell tip deformation:**

Shell tip may move away or towards the mold surface due to thermal stresses (temperature gradients) and/or mechanical effects

- Solidification mode (large shrinkage is associated with \(\delta \rightarrow \gamma\) transformation)
- Local shell thinning due to presence of air gap & OMs (coupled effect)
- Mechanical interaction between shell tip and solid rim (negative strip period)
- Sticking of shell tip to mold wall in absence of flux (hot tearing)
- Sudden level fluctuation exposing shell interior to flux
Level drop effect: shell bending

- During level drop:
  Shell interior exposed to flux
  Left edge of shell cools rapidly
  Shell tip bends away from mold

- After level rise:
  New shell forms on existing solid
  Bending of shell increased further

B.G. Thomas and H. Zhu,
Solidification Science & Processing Conference, 1996

OM formation mechanism I

Steel solidifies first against mold wall forming a secondary meniscus & attaches to shell during negative strip time

Healing: (i) Sato (Proc. of NOH & BOS Conf.), 1979
(ii) Szekeres (Iron & Steel Engineer), 1996
Tearing: Savage and Pritchard (Iron and Steel), 1954
OM formation mechanism II

Shell distortion (away from mold) & subsequent overflow

(i) Schwerdtfeger and Sha (Met. Trans. B), 2000: Beam bending theory
(ii) Thomas and Zhu, 1996: Level drop causes surface depressions
(iii) Emi et al. (Proc. of NOH & BOS Conf.), 1978: Solid flux rim effect

OM formation mechanism III

Meniscus freezing & subsequent overflow

(i) Takeuchi and Brimacombe (Met. Trans. B), 1984: Metallography
(ii) Saucedo (SteelMaking Conf. Proc.), 1991: Metallography
(iii) Putz et al. (Steel Research), 2003: Heat transfer/Fluid flow model
Two mechanisms for hook formation have been considered in this study

I. Solidification of curved liquid steel meniscus

II. Solidification of steel shell against the mold wall and then subsequent distortion due to thermal stress / pressure forces

Re-evaluate mechanisms by:
- Analysis of hook metallography (POSCO/Postech)
- EBSD analysis of hooks
- Meniscus shape calculation
  - Thermal-stress analysis of initial solidification

Propose new mechanism of hook formation

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Hook characteristics

Hook depth, \( D = 1.82 \) mm
Hook height, \( H = 5.37 \) mm
Hook length, \( L = 5.65 \) mm
Hook thickness, \( T = 0.78 \) mm
OM depth, \( d = 0.228 \) mm
Final hook angle, \( \theta = 69^\circ \)

Ultra low carbon steel (0.003% C)
POSCO Sample No.:
B58077-02-2 No.1-1 (Curved hook)
Hook shapes: Case I

Ultra low carbon steel:
0.003C-0.009S-0.08Mn-0.013P-0.039Al-
0.047Ti-0.01Ni-0.01Cr-0.01Cu

Casting conditions:
Casting speed: 1.42 m/min
Frequency: 155 cpm
Stroke: 6.34 mm
Superheat: 25 °C

POSCO Casting No.: B58077-02
Samples taken within ~100mm of slab length

Hook shapes: Case II

Ultra low carbon steel:
0.003C-0.009S-0.08Mn-0.013P-0.039Al-
0.047Ti-0.01Ni-0.01Cr-0.01Cu

Casting conditions:
Casting speed: 1.61 m/min
Frequency: 181 cpm
Stroke: 6.82 mm
Superheat: 27 °C

POSCO Casting No.: B58075-06
Samples taken within ~100mm of slab length
Variations in hook angle, and meniscus shape before & after “meniscus overflow”

Different shapes of meniscus: (a) almost straight to (c) very bent
Different shapes of overflow region: (a) shallow contact angle, (b) near-vertical contact angle, & (c) strange angle and shape

Hooks with particles showing capture before and after “meniscus overflow”

Bubble A entrapped by frozen meniscus but
Bubble B flows along with the overflowing liquid steel

Debris trapped on both sides of the line of hook origin:
Below the line of hook origin: particles flow up with the steel, reach the meniscus, but do not get entrained into slag layer
Above the line of hook origin: particles flow along with the overflowing liquid steel when it overflows the meniscus
Features of a hook tip

Fractured hook tip

Brittle fracture

Location of brittle fracture

Location of melting after fracture

Actual position of hook and fractured tip on slab

Original position of fractured tip prior to brittle fracture

Truncated hooks

Fractured hook tip

Truncated hook

Truncated hook and unmelted fractured tip

Truncated hook (Fractured tip melted away)
Cell growth near hook

- Random orientation of dendrites $\rightarrow$ *Heterogeneous nucleation*
- Fine dendrite arms near origin line $\rightarrow$ *rapid solidification of undercooled liquid*
- Coarser dendrite arms $\rightarrow$ *Lower temperature gradient*
  $\rightarrow$ long time surrounded by liquid before solidification continued (ripening)
- Large sudden change of growth direction $\rightarrow$ *[Movement of fractured hook tip]*

SEM Images

- Hook shape transferred (to scale)
- Micrograph from optical microscope
- Backscattered SEM image
- Backscattered SEM image with 70 degrees tilt
Electron Back Scattered Diffraction (EBSD) Map near hook region

Grains can be identified on the sample by superimposing an EBSD map containing grain orientation information on the Backscattered SEM image.

Quantification of grain misorientation

EBSD postprocessor software can provide local grain misorientation data.
Location of line of hook origin on EBSD image compares well with micrograph.

CON2D Finite-element model to compute thermal distortion of solidifying steel shell

Simulation Details
- Domain Size: 3 mm x 30 mm
- 6 noded triangular elements
- Mesh resolution: 0.1 mm x 0.5 mm

Assumptions:
- Effect of ferrostatic pressure is ignored
- No constraint at the mold edge
- No mold taper, slag, oscillation, friction
- Drop in heat transfer due to air gap ignored
- Level is assumed to drop suddenly
- No kinetics & undercooling effects

Solidifying steel shell

Position of meniscus $z = v \times t$
Simulation conditions

<table>
<thead>
<tr>
<th>Grade</th>
<th>Ultra-low C steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>0.003C-0.009S-0.08Mn-0.013P-0.039Al-0.047Ti-0.01Ni-0.01Cr-0.01Cu</td>
</tr>
<tr>
<td>$T_{solidus}$</td>
<td>1519.3 °C</td>
</tr>
<tr>
<td>$T_{liquidus}$</td>
<td>1533.9 °C</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>14.6 °C</td>
</tr>
<tr>
<td>$\Delta T_{superheat}$</td>
<td>30 °C</td>
</tr>
<tr>
<td>Casting speed</td>
<td>1.2 m/min</td>
</tr>
<tr>
<td>$T_{mold}$</td>
<td>250 °C</td>
</tr>
<tr>
<td>$T_{flux}$</td>
<td>1000 °C</td>
</tr>
<tr>
<td>Sudden level drop at</td>
<td>0.8 s (for 16, 8, 5 &amp; 3 mm)</td>
</tr>
<tr>
<td>Sudden level rise at</td>
<td>1.2 s</td>
</tr>
<tr>
<td>Total time for analysis</td>
<td>1.5 s (0.001 s time step size)</td>
</tr>
</tbody>
</table>

Phase fractions

![Phase fraction diagram](image)

- Delta-ferrite
- Austenite
- Liquid

Temperature (°C)

Phase fraction
Thermophysical properties

Thermal conductivity at $T > T_{liquidus} = 259.35 \text{ W m}^{-1} \text{ K}^{-1} (~6.65\times)$

Thermal conductivity

Enthalpy

Mechanical properties

Young's modulus at $T > T_{liquidus} = 100 \text{ MPa}$

Young's Modulus

Thermal linear expansion coefficient
Constitutive behavior

Strain Rate = $1 \times 10^{-1}$ sec$^{-1}$

Lines: CON2D (Kozlowski III)

Kozlowski III Law for Austenite

Power Law for $\delta$-ferrite

Heat Transfer Calculations

Mold - solidifying shell interface:
$Q_{\text{mold}} = h_{\text{mold}} \times (T_{\text{shell}} - 250)$
$h_{\text{mold}} = 4000 \text{ Wm}^{-2}\text{K}^{-1}$

Slag - shell interface:
$Q_{\text{slag}} = h_{\text{slag}} \times (T_{\text{shell}} - T_{\text{slag}})$
$h_{\text{slag}} = 2300 \text{ Wm}^{-2}\text{K}^{-1}$
$T_{\text{slag}} = 1000 \degree \text{C}$

Computational Domain
3 x 30 mm

Meniscus
Liquid steel
Shell
A: Before Level Drop
B: During Level Drop
C: After Level Rise
Shell deformation during level fluctuation

- Normal solidification & shell growth
- Shell cools without growth & bends
- Shell grows again with further bending

Level drop = 16 mm
Level rise = 24 mm
Casting speed = 20 mm/s

<table>
<thead>
<tr>
<th>Level Drop</th>
<th>Level Rise</th>
<th>Temperature *° C</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Level Drop</td>
<td>5 mm drop</td>
<td>5 mm drop</td>
</tr>
<tr>
<td>∆u = +0.02 mm</td>
<td>∆u = +0.05 mm</td>
<td>∆u = +0.175 mm</td>
</tr>
</tbody>
</table>

Final distorted shape for different level drop distances (0.3s after overflow over shell tip)

No Level Drop
5 mm drop
8 mm drop
16 mm drop

<table>
<thead>
<tr>
<th>Temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500 1450 1400 1350 1300 1250 1200 1150 1100 1050 1000 950 900 850 800 750 700 650 600 550 500</td>
</tr>
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</table>
Jog formation

Fredriksson and Elfsberg, Scandinavian J. of Met., 2002

Comparison between hook and distorted shell shapes

Mechanism of hook formation due to shell distortion associated with a level drop event

Shell distortion will affect OM & hook formation during large level drops

University of Illinois at Urbana-Champaign • Metals Processing Simulation Lab • J. Sengupta
### Hook depth measured from POSCO samples (2004 data)

<table>
<thead>
<tr>
<th>Sample</th>
<th>CM #</th>
<th>Hook #</th>
<th>Surface hook #</th>
<th>Curved hook #</th>
<th>% Curved hooks</th>
<th>Mean hook depth (mm)</th>
<th>Max hook depth (mm)</th>
<th>Min hook depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B32793-02</td>
<td>49</td>
<td>48</td>
<td>11</td>
<td>37</td>
<td>22.9</td>
<td>0.83</td>
<td>1.53</td>
<td>0.39</td>
</tr>
<tr>
<td>B32793-05</td>
<td>49</td>
<td>47</td>
<td>9</td>
<td>38</td>
<td>19.1</td>
<td>0.83</td>
<td>1.30</td>
<td>0.44</td>
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<tr>
<td>B32793-52</td>
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<td>61</td>
<td>15</td>
<td>46</td>
<td>24.6</td>
<td>0.73</td>
<td>1.60</td>
<td>0.29</td>
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<td>B31075-04</td>
<td>51</td>
<td>44</td>
<td>19</td>
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<td>43.2</td>
<td>0.77</td>
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<td>0.34</td>
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<td>B31075-05</td>
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<td>47</td>
<td>14</td>
<td>33</td>
<td>29.8</td>
<td>1.11</td>
<td>1.83</td>
<td>0.38</td>
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<tr>
<td>B31077-04</td>
<td>52</td>
<td>51</td>
<td>9</td>
<td>42</td>
<td>17.6</td>
<td>0.96</td>
<td>2.10</td>
<td>0.62</td>
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<td>B31077-54</td>
<td>48</td>
<td>48</td>
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<td>37</td>
<td>22.9</td>
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<td>B26848-04</td>
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<td>B26848-54</td>
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<td>26</td>
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<td>34.6</td>
<td>65.4</td>
<td>1.03</td>
<td>1.58</td>
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<tr>
<td>B30967-01</td>
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<td>53</td>
<td>17</td>
<td>35</td>
<td>32.7</td>
<td>67.3</td>
<td>1.12</td>
<td>3.21</td>
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<tr>
<td>B30969-02</td>
<td>48</td>
<td>48</td>
<td>19</td>
<td>29</td>
<td>39.6</td>
<td>60.4</td>
<td>1.05</td>
<td>1.91</td>
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<tr>
<td>B30969-51</td>
<td>51</td>
<td>51</td>
<td>20</td>
<td>32</td>
<td>38.5</td>
<td>61.5</td>
<td>1.79</td>
<td>3.21</td>
</tr>
<tr>
<td>B30969-55</td>
<td>51</td>
<td>50</td>
<td>22</td>
<td>28</td>
<td>44.0</td>
<td>56.0</td>
<td>1.60</td>
<td>2.61</td>
</tr>
</tbody>
</table>

**Min hook depth (mm)**

**Max hook depth (mm)**

**Mean hook depth (mm)**

**% Curved hooks**

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### Proposed mechanism for hook formation

**HOOK FORMATION**

**Mechanism:**
- Meniscus freezing & Liquid overflow in the presence of uncooled liquid during negative strip time

**Mechanism:** Shell distortion during negative strip time

**STRAIGHT HOOK**

**CURVED HOOK**
Development of a detailed hook formation mechanism

- Events dictating formation of OMs and hooks are complex, inter-dependent and transient
- Plant experiments cannot reveal detailed steps that lead to final microstructure and morphology
- Development of a comprehensive computational model is a daunting task
- **Alternative methodology:**
  - Combine existing modeling results & plant observations
  - Construct a series of schematics illustrating the mechanism
  - Will not predict formation of hooks, but will lead to model development

---

Three hooks observed on a POSCO slab

**I. Steel Composition:**
- C (0.003%) - Mn (0.08%) - Si (0.005%) - P (0.015%) – S (0.01%) - Cr (0.01%) - Ni (0.01%) - Cu (0.01%) – Ti (0.05%) - Al (0.04%)

**II. Steel Properties:**
- Liquidus temperature (in °C): 1533
- Solidus temperature (in °C): 1517
- Density of liquid steel (in kg m⁻³): 7000
- Surface tension at 1550 °C (in N m⁻¹): 1.6

**III. Slag Properties:**
- Solidification temperature (in °C): 1149
- Melting temperature (in °C): 1180
- Viscosity at 1300 °C (in Poise): 3.21

**IV. Casting conditions:**
- Casting speed: 1.394 m min⁻¹
- Frequency of mold oscillation: 174 cpm
- Stroke of mold oscillation: 5.89 mm
- Theoretical pitch for oscillation marks (speed/frequency): 8.01 mm
- Superheat: 32 °C
Objectives

I. Graphically track the positions of the following on a Cartesian space for one mold oscillation cycle:
- Meniscus, mold, solid/liquid flux interface, shell, OM/Hook mark nos. 2 & 3

II. Using above positions and final morphology of the cast slab sample as templates, events leading to formation of OM & hook mark no. 1 will be identified

Equilibrium shape of meniscus

Assumptions:
I. Far field metal level remains unperturbed at all times (z = 0 mm)
II. x = 0 mm corresponds to mold wall
III. Dynamic effects active for x < 35 mm
Meniscus shape is assumed to be in equilibrium at \( t_{\text{start}} = 0 \) s

- Mold acceleration is zero → Inertia force is absent at this instant
- Positive flux pressure built-up during NST has been dissipated completely
- Hence, only surface tension forces will determine the shape of meniscus
Profile of solid flux rim

- Profile of solid rim above the meniscus has been reported in literature, with:
  Solidus for steel = 1399 °C  
  \textit{(actual 1517 °C)}
  Solidus for slag = 1130 °C  
  \textit{(actual 1180 °C)}
  Superheat = 5 °C

- The shape has to be modified to correspond to actual superheat of 20 °C

Evolution of shell thickness predicted by CON1D

- Note: Fraction solid used by CON1D for shell location = 0.5
OM area for OM nos. 1, 2 & 3:
\[(0.2 + 0.16 + 0.24)/0.236 = 2.54 \text{ mm}^2/\text{cm at } \sim 20 \text{ mm below meniscus}\]

Based on literature, about \(\sim 16\%\) reduction in shell thickness should be observed at each oscillation mark.

\((\text{Actual for OM#3 } = 17\%)\)

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**Summary of events in one oscillation cycle**

**NEGATIVE STRIP**

- **Meniscus has equilibrium shape**
- **Freezing of meniscus**
- **Meniscus overflow begins**
- **Rapid growth of new hook**
- **Equilibrium shape of meniscus is restored as a new cycle of mold oscillation begins**
- **Brittle fracture of hook tip**
- **New shell begins to grow above hook & OM is formed**

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From B.G. Thomas et al.,
*Sensors & Modeling in Mat. Processing*, 1997
Experimental observations on a Sn-Pb alloy/stearic acid based casting simulator

Sudden decrease in $\gamma$, during NST caused by liquid steel overflow over a hook & subsequent solidification

Sudden rise in tracer velocity during PST caused by creation of additional space in tracer channel due to OM formation

Tsutsumi et al., ISIJ International, 2000

Summary

I. A new mechanism of hook formation proposed based on:
   - Analysis of hook micrographs & EBSD images
   - Meniscus shape predictions by Bikerman equation
   - Prediction of distorted shell shapes by modifying CON2D
   - Comparison of hook shapes with both meniscus shapes and distorted shell shapes

(Most hooks match best with meniscus shape)
Summary

II. Hook formation has been graphically animated & depicts:
- Change of meniscus shape during one oscillation cycle
- Menicus freezing during negative strip period
- Overflow of liquid steel over curved hook (frozen meniscus) during negative strip period
- Hook formation & growth and subsequent fracture of tip

III. The new mechanism can satisfactorily explain the formation of oscillation marks and hooks in ultra-low carbon steel slabs. However, shell distortion can still play an important role during oscillation mark formation in peritectic steels.
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University of Illinois

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POSCO, South Korea
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Canada