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Surface Defect Formation in Steel Continuous Casting

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Abstract. Serious defects in the continuous casting of steel, including surface cracks and depressions, are often related to thermal-mechanical behavior during solidification in the mold. A finite-element model has been developed to simulate the temperature, shape, and stress of the steel shell, as it moves down the mold in a state of generalized plane strain at the casting speed. The thermal model simulates transient heat transfer in the solidifying steel and between the shell and mold wall. The thermal model is coupled with a stress model that features temperature-, composition-, and phase-dependent elastic-visco-plastic constitutive behavior of the steel, accounting for liquid, δ-ferrite, and γ-austenite behavior. Depressions are predicted to form when the shell is subjected to either excessive compression or tension, but the shapes, severity, and appearance differ with conditions. Cracks appearing without depressions are suggested to form in the lower ductility trough when the shell is colder but more brittle. The local thickness of the shell and austenite layer appears to have major effects as well. The model reveals new insights into the formation mechanisms and behavior of surface depressions and longitudinal cracks in the continuous casting process.

Introduction

Continuous casting accounts for more than 96% of the world's steel manufacturing. The large scale of the operation means that even minor improvements in this important process can lead to tremendous gains in quality, efficiency, and profit. Defects during solidification in the mold can lead to serious quality issues downstream. Fig. 1 shows cross sections through some typical examples of surface defects, which include depressions with and without cracks. While their appearance is well known, understanding the specific mechanisms of how different types of defects form is still somewhat of a mystery. When proper maintenance and operational settings are used in the caster, uniform heat transfer can help to ensure good surface quality. However, changes in the heat transfer around the casting, even seemingly small variations, can lead to substantial changes in local heat transfer. This is complicated by the important influence of the interfacial slag gap on heat transfer between the solidifying steel shell and the copper mold.

In this work, a coupled thermal-mechanical finite-element model of steel continuous casting is developed with temperature-, strain-rate-, and phase-dependent steel properties, as well as a temperature dependent thermal resistor model of the interfacial gap. This model is applied to explore the mechanisms of surface defect formation in the mold region of a slab caster, using different representative mechanical constraints and thermal conditions.

Model Description

The thermal-mechanical model in this work focuses on a two-dimensional (2-D) slice through the solidifying steel shell in a state of generalized plane strain [1,2]. The model predicts the temperature, displacement, strain, and stress histories of the shell. The governing equations are solved using the finite-element method in ABAQUS/Standard (implicit) [3]. The transient analysis uses coupled-temperature displacement elements and step-wise coupling between the thermal and mechanical calculations [1]. The 20 mm thick x 40 mm wide simulation domain shown in Fig. 2 is a representative portion of the solidifying steel shell located somewhere along the broad face away from the corner region.

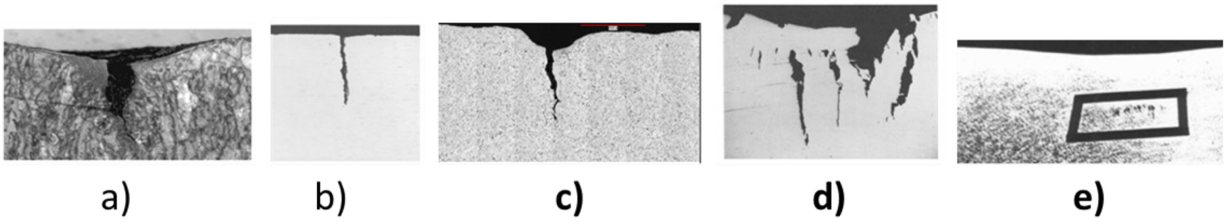

Figure 1: Observed types of surface defect shapes and openings: a) depression with high aspect ratio opening, b) surface crack with no depression, c) depression with narrow opening above crack, d) depression with multiple sub-surface cracks, e) depression with only subsurface cracks [4]

The material properties used in this work are similar to commercially cast low-carbon (0.045 wt%C) steel. Details on this grade including composition, properties, and transition temperatures can be found in previous work [1]. Prior work with this model [4] used one-way coupling to handle the thermal relationship to stress. In this new work, the thermal resistor model, shown in Fig. 3, [2] was used to couple interfacial heat flux between the solidifying steel shell and the water cooled copper mold, including the evolving size of the gap from the mechanical model.

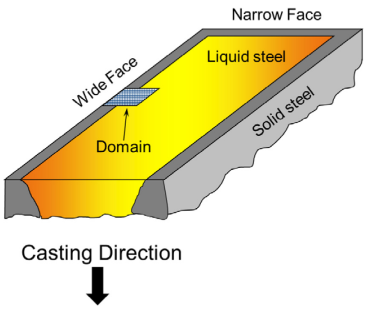

Figure 2: Model domain shown in cutaway continuous cast slab [1]

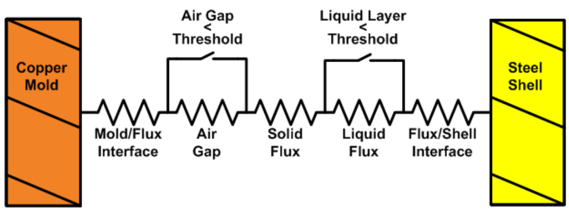

Figure 3: Thermal resistor model of the interfacial gap

It has been estimated that this gap accounts for as much as 84% of the total resistance to strand cooling [5]. Disruptions within the gap [6] can cause severe changes in heat transfer. These disruptions can take many forms, including local inhomogeneities in the glassy and crystalline slag layers [7], changes in thickness or contact resistance, foreign particles, and gas bubbles. Even very slight disruptions can initiate changes in shell surface shape, such as longitudinal depressions or transverse oscillation marks, leading to local drops in heat transfer [8]. While they are often insignificant, sometimes these small variations in heat transfer and gap size can grow together with increasing severity, and compounding effects causing significant surface quality problems.

The coupled gap heat transfer model was implemented into ABAQUS using a GAPCON subroutine [9], which is described elsewhere [2]. Given the mold hot face and steel shell surface temperatures, and the total gap thickness at each time step, this model calculates appropriate local solid and liquid layer thicknesses using the properties given in Table 1. D_{Air}, D_{Sol}, and D_{Liq} are the thickness of the air gap, solid slag, and liquid slag layers respectively, and T_{ls} is the temperature of the liquid slag/steel shell interface. For simplicity, in this work the mold hot face temperature was held fixed at a typical temperature of 150 °C. The gap contributes only to the thermal behavior, as its shape is assumed to be constant in the mechanical model. Mechanical interaction between the mold “master” and steel shell “slave” surfaces is handled with frictional contact in ABAQUS using a typical coulomb friction coefficient of 0.1 for mold slag on copper [10].

Table 1: Parameters in thermal gap model

Location	Resistance [mm^2 K/mW]
Mold/Slag Interface	0.0004
Air Gap	$D_{Air}/0.06$
Solid Slag Layer	$D_{Sol}/0.5$
Liquid Slag Layer	$D_{Liq}/3.0$
Slag/Shell Interface	$0.251 \exp(-0.0054T_{ls})$

At the high temperatures seen in this work, three steel phases exist: Liquid, δ-Ferrite, and γ-Austenite. The liquid phase solidifies as δ-Ferrite, followed by a solid-state transformation into γ-Austenite. Elastic-viscoplastic constitutive models are used for the δ and γ phases which vary with strain rate and temperature in order to capture both plasticity and time-dependent creep. Liquid is treated as an extremely weak perfectly-plastic solid with a low yield stress. Details on the constitutive models and their implementation are described elsewhere [1,11,12]; however, it should be noted that ferrite is about an order of magnitude weaker than austenite, so most of the load across the shell is carried by the stronger austenite phase [1].

This work investigates the effect of a 25 mm-wide disruption in heat transfer across the gap. The total slag thickness is set at 1 mm on the surface, and the disrupted region is increased to 2 mm thickness, increasing the overall thermal resistance and dropping the heat transfer by up to 30%.

Three mechanical conditions were applied to the domain in this model: 1. An ideal case (ideal taper), where the shell is allowed to shrink with only frictional interaction with the mold to oppose its contraction. 2. A pull case (insufficient taper) where tension is applied to stretch the wide face shell, opposing its shrinkage, such as caused by lubrication issues or bulging of the narrow face shell from lack of NF taper. 3. A push case (excessive taper) where compression is applied to the shell, in excess of its desired shrinkage, such as caused when the NF mold has too much taper.

Model Validation

The model was validated in part by comparing the predicted depression shape with measurements [4] (shown in Fig. 4). Both applied tension and compression can cause depression formation. This snapshot (at 10 s) shows a rough match in predicted shape, for a tension (pull) case, with a defect from previous literature [13]. The figure also shows contours of stress parallel to the mold wall, which are especially concentrated towards the surface at depression center.

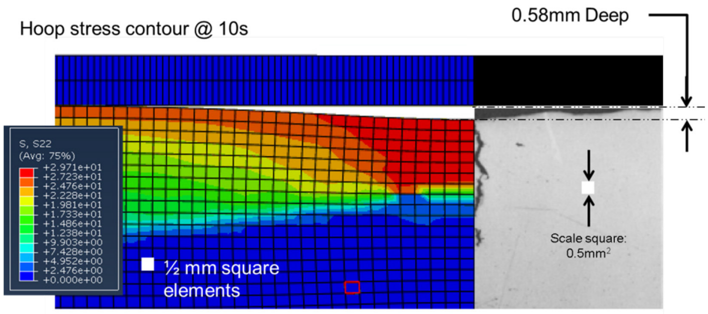

Figure 4: Simulated necking depression shape at 10 s (3 mm shell growth, 7.5% applied tensile strain) compared to literature micrograph of a depression and crack in a continuous-cast slab [4]

Results and Discussion

As explained earlier and observed in the literature, a drop in surface heat flux leads to a rise in shell surface temperature [8,13], and a drop in mold hot face temperature. Results with the current model show that the surface temperature at the depression center increases dramatically for all 3 cases. This is due partly to the increased slag thickness/resistance, and in much larger part to the insulating effect of the thin air gap that is able to form with this new model. As shown in Fig. 5, the formation of a depression causes a significant drop in heat flux across the growing interfacial gap. For all 3 cases, the far-field surface temperature of the shell has fallen to ~870 °C after 16 s of cooling in the mold. At the same time, the depression center in the pull case is almost 500 °C higher, at ~1300 °C. Comparing results to previous work without an evolving air gap [4] the current model shows larger changes in surface temperature and shell thickness, due to the strong influence of the air gap, which agrees with previous findings [8].

Temperatures above 1100 °C are hot enough for significant grain growth, as well as dynamic recrystallization, if there is also sufficient strain [14,15]. These higher temperatures can also lead to intergranular crack formation along the austenite grain boundaries, as any applied strain is concentrated at the weakest (hottest) grain boundaries, found at the base of the depressions, and are fewer in number when the grain size is larger after growth is allowed to occur [16].

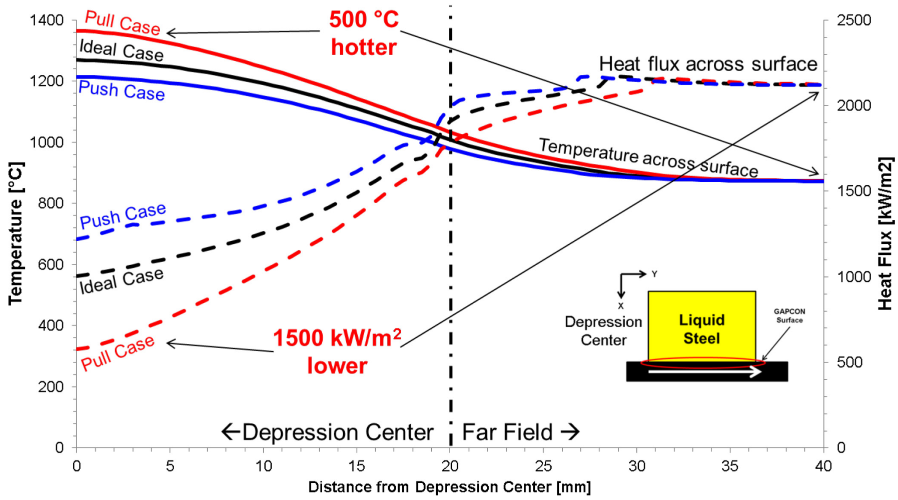

Figure 5: Temperature and Heat flux variations across the surface for a 25 mm slag disruption (16 s)

Fig. 6 shows temperature contours, corresponding to the different steel phases, and deformed shape results for the three cases investigated. The depression depth increases by ~0.80 mm for the pull case, due to the important effect of necking; this is much greater than ~0.15 mm for the ideal case. The applied compression (push) scenario, corresponding to excessive narrow-face taper, causes complicated buckling behavior, lifting the depression by only ~0.003 mm at this time. This explains why the surface temperature increase in Fig. 5 is greatest for the pull case and smallest for the push case. Total shell thickness reduction of 30-40% is observed at the depression center. As shown in Fig 6, the thermal changes that accompany the depression for the three mechanical loading cases also greatly affects the respective thickness of the phases that make up the solidifying shell. This has significant implications when the comparative strengths of the phases are considered.

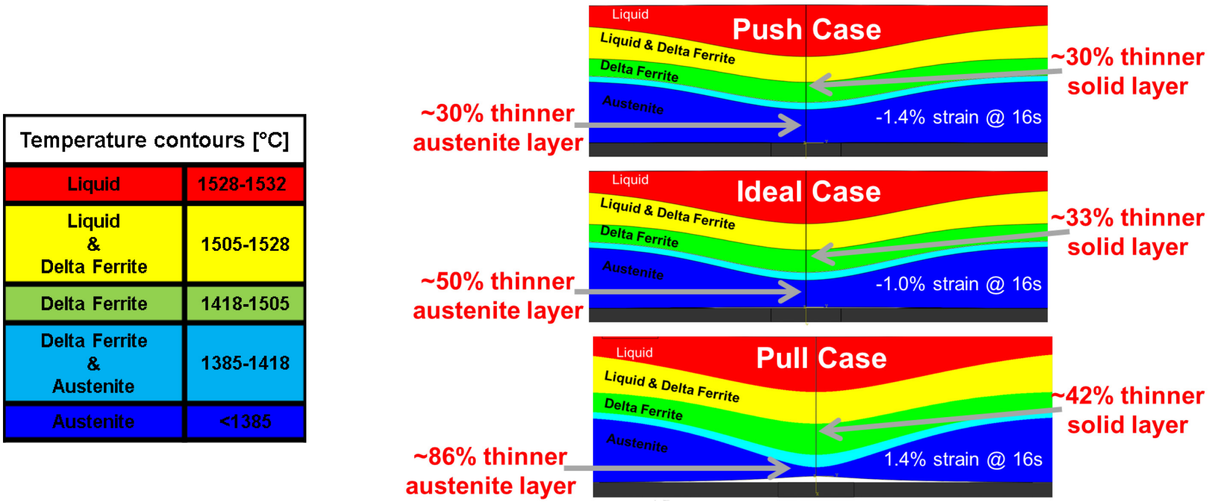

Figure 6: Phase fraction contours within the 25 mm thick shell domain with a thermal non-uniformity for the three mechanical loading cases (deformed mesh with no magnification)

A drastically thinner austenite layer means that there is less cross sectional area to distribute any mechanical loading. When tension is present, this reduced cross section can lead to necking and a U-shaped depression [4]. This is consistent with plant observations, where it is common to see U-shaped surface depressions, especially in the aftermath of a breakout where the shell has become thin enough that it ruptures and drains the molten steel core.

Conclusions

A coupled thermal-mechanical finite element model has been developed to investigate surface defect formation in continuous casting. It features a specialized thermal model to capture heat transfer behavior across the time-evolving shape of the interfacial gap between the water cooled copper mold and the surface of the solidifying steel shell. Thinning of the shell is observed in all cases, which represent conditions of: insufficient, ideal, and excessive taper. It is observed that the applied tension case (insufficient taper / pull case) is the most severe, developing an ~0.8 mm deep depression. For the given slag thermal non-uniformity, applying tension to the domain causes increased necking (over the ideal case), deeper surface depressions, more severe thinning of the shell and austenite layer, and quality issues; these problems are less severe with tangential compression (push case). Results also indicate that surface temperatures and local heat flux vary substantially near surface defects: surface temperature increases of more than 350 °C above the far-field were found at the center of depressions, with corresponding drops in heat flux of more than 1 MW/m^2. These increased surface temperatures are accompanied by 30-40% reduction in the thickness of the solid steel shell, and up to 86% reduction of the stronger austenite layer.

Future Work

Future work on this ongoing project includes collecting and characterizing cracks, depressions, and other surface defects from operating casters as permitted, as well as more advanced forms of caster data collection [17,18]. Further simulations are planned to investigate these scenarios using the gap model developed in this work. Prediction of the thermal behavior of the mold in the scenarios where defects appear is also desired, as well as the thermal signatures that may be read by instrumentation. As well as the addition of real mold geometries including water channels and the thermal behavior of the cooling as well as potential fouling. Eventually, a full ¼ symmetry domain of a slab caster mold, including corner effects, is desired. Additionally, implementing a quantitative damage or crack criterion is desired, as well as expanding this work to investigate the effects of steel grade, especially into the peritectic range.

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References

[1] Matthew L.S. Zappulla, Lance C. Hibbeler, and Brian G. Thomas: *Metall. Mater. Trans. A*, 2017, vol. 48, pp. 3777–93.

[2] Matthew L.S. Zappulla: Master's Thesis, The University of Illinois at Urbana-Champaign, 2016.

[3] ABAQUS: *ABAQUS 6.13 Theory Manual*, DS SIMULIA Corp, Providence, RI, 2013.

[4] Matthew L.S. Zappulla and Brian G. Thomas: in *Mater. Soc. Annu. Meet.*, San Diego, CA, 2017, pp. 501–10.

[5] Seizo Watanabe, Kazuo Harada, and Fujita Hitoshi-Shiro: *Tetsu-to-Hagané*, 1972, vol. 58, p. S393.

[6] Brian G. Thomas, M. Jenkins, and R. B. Mahapatra: *Ironmak. Steelmak.*, 2004, vol. 31, pp. 485–94.

[7] B. Stewart, M. McDonald, M. Hopkins, and R. Burniston: *Metall. Ital.*, 2009, vol. 101, pp. 55–62.

[8] Brian G. Thomas, David Lui, and B. Ho: in *Mater. Soc. Annu. Meet.*, The Minerals, Metals & Materials Society, Orlando, FL, 1997, pp. 117–42.

[9] ABAQUS: *ABAQUS 6.13 Subroutine Manual*, DS SIMULIA Corp, Providence, RI, 2013.

[10] Y. Meng, Brian G. Thomas, Andreas a. Polycarpou, a. Prasad, and H. Henein: in *Mater. Sci. Technol.*, New Orleans, 2004, pp. 79–94.

[11] P.F. Kozlowski, Brian G. Thomas, J.A. Azzi, and H. Wang: *Metall. Mater. Trans. A*, 1992, vol. 23, pp. 903–18.

[12] S. Koric and Brian G. Thomas: *J. Mater. Process. Technol.*, 2008, vol. 197, pp. 408–18.

[13] J.K. Brimacombe, F. Weinberg, and E. B. Hawbolt: *Metall. Mater. Trans. B*, 1979, vol. 10, pp. 279–92.

[14] Reza Abbaschian and Robert E. Reed-Hill: *Physical Metallurgy Principles*, 3rd ed., PWS Publishing Company, Boston, MA, 1991.

[15] B. Mintz, S. Yue, and J. J. Jonas: *Int. Mater. Rev.*, 1991, vol. 36, pp. 187–220.

[16] R.J. Dippenaar, S.C. Moon, and E.S. Szekeres: *Iron Steel Technol.*, 2007, vol. 4, pp. 105–15.

[17] Ton Spierings, Arnoud Kamperman, Herman Hengeveld, Jan Kromhout, and Edward Dekker: *AISTech 2017 Proc.*, 2017, pp. 1655–64.

[18] G. Hedin, A. Kamperman, M. Seden, K. Frojdh, and J. Pejnefors: *5th Int. Conf. Process Dev. Ironmak. Steelmak. Lulea, Sweden, 12-15 June 2016*, 2016, pp. 1–10.