Centerline depletion in direct-chill cast aluminum alloys: the avalanche effect and its consequence for turbulent jet casting

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Abstract

Avalanche dynamics of sedimenting grains in direct-chill casting of aluminium ingots is investigated as a primary driving force for centerline segregation. An analytical model predicting the importance of avalanche events as a function of casting parameters is proposed and validated with prior art results. New experimental results investigating the transient and steady-state centerline segregation of DC casting with a turbulent jet are reported.

Introduction

Direct Chill (DC) casting is one of the major current processing routes for producing large scale castings before subsequent mechanical deformation e.g. rolling or extruding. In spite of many years of research into the development and advancement of this technology, the fundamental defects remain consistent: hot and cold cracks, inclusions, rough or uneven surface, and macrosegregation. This final defect has received our attention in the recent years and in particular, centerline segregation is addressed in this paper.

The mechanisms driving macrosegregation are generally known and their review is available elsewhere[1,2]. The typical location of interest for macrosegregation in DC cast ingots is the centerline region, where up to a 15% difference from the nominal alloy composition can be observed[3,4]. This difference in composition is ultimately deemed responsible for physical property variations in rolled plate products[5,6]. Two mechanisms are traditionally proposed for centerline segregation: shrinkage induced flow, and sedimenting (or floating) grains. In a previous study[4] we put forth the later mechanism as dominant for centerline depletion in DC cast aluminum ingots. We subsequently demonstrated that centerline depletion could be minimized by the introduction of a turbulent jet, which impinges on the base of the molten pool and causes the resuspension of sedimented grains[Error! Bookmark not defined.]. We have also previously reported evidences that the degree of centerline depletion varies as a function of cast length within the ingot itself for standard practices[4]. Numerous investigators have concluded that the depth of the solidification interface (sump) impacts the degree of macrosegregation caused by shrinkage induced flow[2]. Herein, in the context of the sedimenting grain hypothesis, we propose to apply the basics of avalanche dynamics and evaluate its possible role in DC casting. In particular, we postulate that the sump depth not only impacts shrinkage induced flow, but also the volume of sedimenting grains found at the ingot center. We therefore first propose an analytical model describing the role of the inclination of the sump on grain accumulation (stacking) in traditional DC casting. We then compare the prediction with prior experimental reports. Secondly, we present new experimental results obtained with a turbulent jet designed to re-suspend grains.

Theory and Model

The solidification path of a given aluminum alloy is marked by several distinct events occurring in the sump. The onset of nucleation begins at approximately the *liquidus temperature*. The young grains are mobile and free to move independently of one another. Once the grains have grown sufficiently they begin to interact and form a coherent mass, appearing at the *coherency temperature*. At this point grains can no longer move independently, and solidification continues to completion at the *solidus temperature*. While the grains are mobile, i.e. between the liquidus and coherency temperatures, we propose that as a bulk, they exhibit similar characteristics to other granular piles (sand dunes, snow drifts etc.). The static angle of repose of a pile[7,8] is determined by the properties of the grains and the surrounding fluid (coarseness, cohesive forces etc). This angle sets the geometric stability of the pile. When the angle of repose of the pile exceeds the static angle of repose, the pile becomes unstable and avalanche events occur. This leads to the movement of the excess grains from the top of the pile to the bottom until the angle of repose reaches again the static angle of repose.

Error! Reference source not found. is a representation of the angle of inclination of the sump as a function of both the casting speed and ingot width as specified by the relationship derived by Roth[9]. Recognizing that the angle of inclination varies with position along the ingot width, the *average* angle of inclination for a given condition is presented. The plot has been colored by angle of inclination to aid in viewing. Rectangular ingots, as opposed to billet, have distinct length and width; and the width (shorter dimension) determines the sump depth[2]. Since the cooling boundary conditions have been assumed constant in this analysis, an increase in ingot width or casting speed causes an increase in sump depth. This increase in sump depth leads to a larger angle of inclination of the sump walls.

In discussions of sedimenting grains in casting, reference is made to *fine*- and *coarse-cell dendrites*, named after their metallographic appearance. In discussion of granular media however, different notation is used. *Coarse media* is often dendritic (snowflakes etc), while *smooth media* is more spherical (gravel or sand). The colorbar to the right of **Figure 1** represents the full range of sump angle of inclinations from horizontal to vertical. The two values indicated along the bar represent the static angle of repose expected for *coarse and smooth media*.

Independently of our approach, Livanov et al[10] performed a series of trials at various casting speeds and mold dimensions for AA2024 (3.8-4.9%Cu, 1.2-1.8%Mg, 0.3-0.9%Mn) ingots. For each mold dimensions, they identified a critical casting speed below which the ingot exhibits positive centerline segregation (solute enriched). Above this speed, the ingot exhibits negative centerline segregation (solute depleted). This critical speed has been represented by a white demarcation line in the lower plot of Figure 1.

The demarcation line is remarkably found to represent the same angle of inclination for all casting conditions. This finding suggests a key role of stacking grains in a solidifying ingot in addition to the traditional convective currents that drive the movement of free moving grains to the center of the casting[11].

The simultaneous appearance of fine and coarse microstructures in ingots was the original justification of the sedimenting grain theory. The underlying postulate was that one set of the dendrites transported to the centerline had nucleated elsewhere. Recently, Eskin et al.[12] performed electron-probe microanalysis (EPMA) on both fine and coarse dendrites and suggested that *coarse-cell dendrites* are the transported phase responsible for centerline depletion.

Assuming that *coarse-cell dendrites* correspond more closely to *smooth media*, our model suggests that the grains responsible for centerline segregation are the most susceptible to avalanche dynamics. Thus, for a given mold width, increasing the casting speed such that the sump angle of inclination surpasses the static angle of repose for *coarse-cell dendrites* will trigger avalanche events. As the casting speed is increased, thus increasing the angle of inclination, additional avalanche events will occur thereby increasing the degree of centerline depletion. The forthcoming experimental study has been designed to test this hypothesis using a turbulent jet.

Experimental method

Given the above model and theory, it is proposed to investigate centerline segregation effects in DC casting using a turbulent jet in transient and steady state regimes. Indeed, large changes in sump depths are anticipated at the beginning and end of a cast, expected to lead to large variation in centerline segregation. The black dashed line in Figure 1, extending from Δ to ∇ indicates the casting conditions investigated in this study. During the startup (Δ to ∇) as the sump deepens, an increasing frequency of avalanche events is anticipated thereby increasing the degree of negative centerline depletion. During the shutdown of a cast (∇ to Δ) the opposite behavior is anticipated as the sump becomes shallower.

A series of experiments with varying jet Reynolds have been conducted to evaluate the degree of centerline segregation throughout the length of a rolling slab ingot. Using a 600mm x 1750mm Wagstaff LHC mold a series of 4 meter long Al4.5Cu ingots were cast with turbulent jets with characteristic Reynolds numbers 64 000, 69 000, 81 000, 97 000, and 121 000. We have defined the Reynolds numbers of our jets by the following relationship:

$$Re_j = \frac{2M_l M_w U_c}{\pi b_0 \nu} \tag{1.}$$

where M_l and M_w represent the mold length and width respectively (m); and ν, U_c, and b_0 are the dynamic viscosity (kg m^{-1} s^{-1}), casting speed (m s^{-1}), and jet radius (m).

Following the cast, the ingots were sliced longitudinally, and samples taken every 150mm from the butt to the head of the ingot along the centerline as represented in Figure 2. Each of these samples was analyzed for copper content using a laboratory OES spectrometer. The samples were all analyzed 6 times, at distinct locations on the sample face.

Results

Figure 3 is a surface plot representing the experimentally determined centerline segregation values for the five turbulent jets evaluated through the entire cast length.

It is noticed that for all of the jets except the most turbulent (Re=121 000), the degree of segregation gradually decreases to a steady state value of approximately -15% from furnace composition at approximately 20% of cast length. This behavior is similar to that reported in reference (**Error! Bookmark not defined.**) for the traditional casting method. For these four ingots the centerline composition remains relatively constant until approximately 80% of cast length. In the case of the most turbulent jet, a nearly opposite behavior is observed, with the composition rapidly descending to -25% before rising to -5% at approximately 20% of cast length. For the remaining 60% of the cast, the trend is fairly non-uniform characterized by fluctuations between -5% and -18% of furnace composition.

In all of the ingots, a sudden drop in centerline composition to approximately -20% is observed at approximately 80% of cast length. Immediately follows a linear increase in composition until the end of the cast.

Figure 4 is a plot of the centerline data for the Re=97,000 cast, along with the average composition measured 50mm from the center of the ingot (data taken from reference (**Error! Bookmark not defined.**)). Those data show that the area adjacent to the geometric center displays significantly less macrosegregation, on the order of a few percent.

Discussion

The initial transient behavior of the jets characterized by Reynolds numbers smaller than 121 000 is in agreement with the model and analysis inherited from traditional DC cast results. As the sump deepens, the frequency of avalanche events increases with increasing angle of inclination of the solidification front. Once reaching steady state, the degree of centerline sedimentation of grains remains constant thereby generating a uniform deviation from furnace composition. At the end of the cast, a decrease in sedimentation can explain the linear increase in composition reported in Figure 3. As the bottom of the sump rises and exhibits a smaller average angle of inclination, avalanche events will become less frequent and the degree of grain sedimentation is expected to decrease. This decrease in avalanche events and grain sedimentation will correspondingly decrease the amount of centerline segregation.

All of the plots show a sudden decrease in composition at approximately 80% of cast length. Since our measurements are reported along the ingot centerline, this position would normally correspond to the bottom of the sump when the metal flow into the mold was shut off and casting ceased. Assuming grains were suspended by the impinging jet, such reduction in turbulent kinetic energy caused a significant fraction of the larger grains to suddenly fall out of suspension. This fallout would increase the amount of sedimented grains at the bottom of the sump, thus locally increasing the compositional deviation. This sudden change in composition, not normally observed in a traditional DC cast, confirms the ability of the jet to remove a certain fraction of the sedimented grains as previously described**Error! Bookmark not defined.**.

The rather erratic behavior of the most turbulent jet (Re=121 000), even during steady state conditions is an argument for the optimization of the jet system, a topic to be addressed in a subsequent report.

The drastic change in composition 50mm away from the exact centerline displayed in Figure 4 illustrates that the area directly underneath the jet allows for sedimenting grains to accumulate in spite of the jet. The description of the impinging jet distribution on the sump bottom will need to be described in order to confirm the origin of such observation.

Conclusion

We have proposed an addendum to current sedimenting grain theory based on the experimental results of Livanov et al[10] and avalanche dynamics. Deeper sumps formed by higher casting speeds, larger ingots, or alloys of low thermal conductivity will have larger angles of inclination. Once a threshold value of inclination is reached (static angle of repose), avalanche events promote the sedimentation of mobile grains to the center of the ingot, thereby enhancing centerline depletion. Any action during transient regimes which increases or decreases the sump depth will then generate a corresponding increase or decrease in centerline depletion. The experimental results during transient casting regimes (start-up and shut-down) are in good agreement with this proposal. We have demonstrated that below a certain energetic threshold, impinging jets are capable of generating uniform longitudinal segregation patterns. Once this threshold is surpassed, we have found that the longitudinal segregation profile becomes much more erratic due to the non-uniform erosion of the cohesive mushy zone. Regardless of the jet energy, we have found that the longitudinal segregation profile continues to exhibit depleted regions in the zone of impingement. Further investigations should be performed in determining the reason for this effect.

Acknowledgements

We would like to thank the Novelis Solatens Technology Center for their invaluable assistance in completing this work.

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[1] S.R. Wagstaff :Experimental Observations and Analysis of Macrosegregation in Rolling Slab Ingots. MIT MS Thesis. 2015.

[2] D.G. Eskin: *Physical Metallurgy of Direct-Chill Casting of Aluminum Alloys*, CRC Press, Boca Roton, FL, 2008.

[3] M.G. Chu, J.E. Jacoby: Light Metals, TMS, 1990, pp. 925-930.

[4] S.R. Wagstaff and A. Allanore: Light Metals, TMS, 2015, pp. 877-882.

[5] L. Swartzendruber, L. Ives, W. Boettinger, S. Covcill, D. Ballard, D. Laughlin, R. Clough, F. Biancello, P. Blau, J. Cahn, R. Mehrabian, G. Free, H. Berger and L. Mordfin. Report PB81-172348, National Bureau of Standards, National Measurement Lab. Washington D.C., December 1980.

[6] L. Ives, L. Swatzendruber, W. Boettinger, M. Rozen, S. Ridder, F. Biancello, R. Reno, D. Ballard, R. Mehrabian. Internal Report 83-2669. National Bureau of Standards. Washington D.C., January 1983.

[7] R.L. Brown and J.C. Richards: *Principles of Powder Mechanics*, Pergamon Press, Oxford, 1970.

[8] H.M. Jaeger, C.H. Liu, and S.R. Nagel: Phys. Rev. Lett., 1989, vol. 62, pp. 40.

[9] W. Roth : Aluminium. 1943, vol. 25, pp. 283–91.

[10] V.A. Livanov, R.M. Gabidullin, and V.S Shipilov : *Continuous Casting of Aluminum Alloys,* Moscow, Metallurgiya, 1977.

[11] C.J. Vreeman and F.P. Incropera. Int. J. Heat Mass Transfer, 2000, vol. 43, pp. 687–704.
[12] D.G. Eskin, R. Nadella and L. Katgerman. Acta Materialia, 2008, vol. 56(6), pp. 1358-1365.

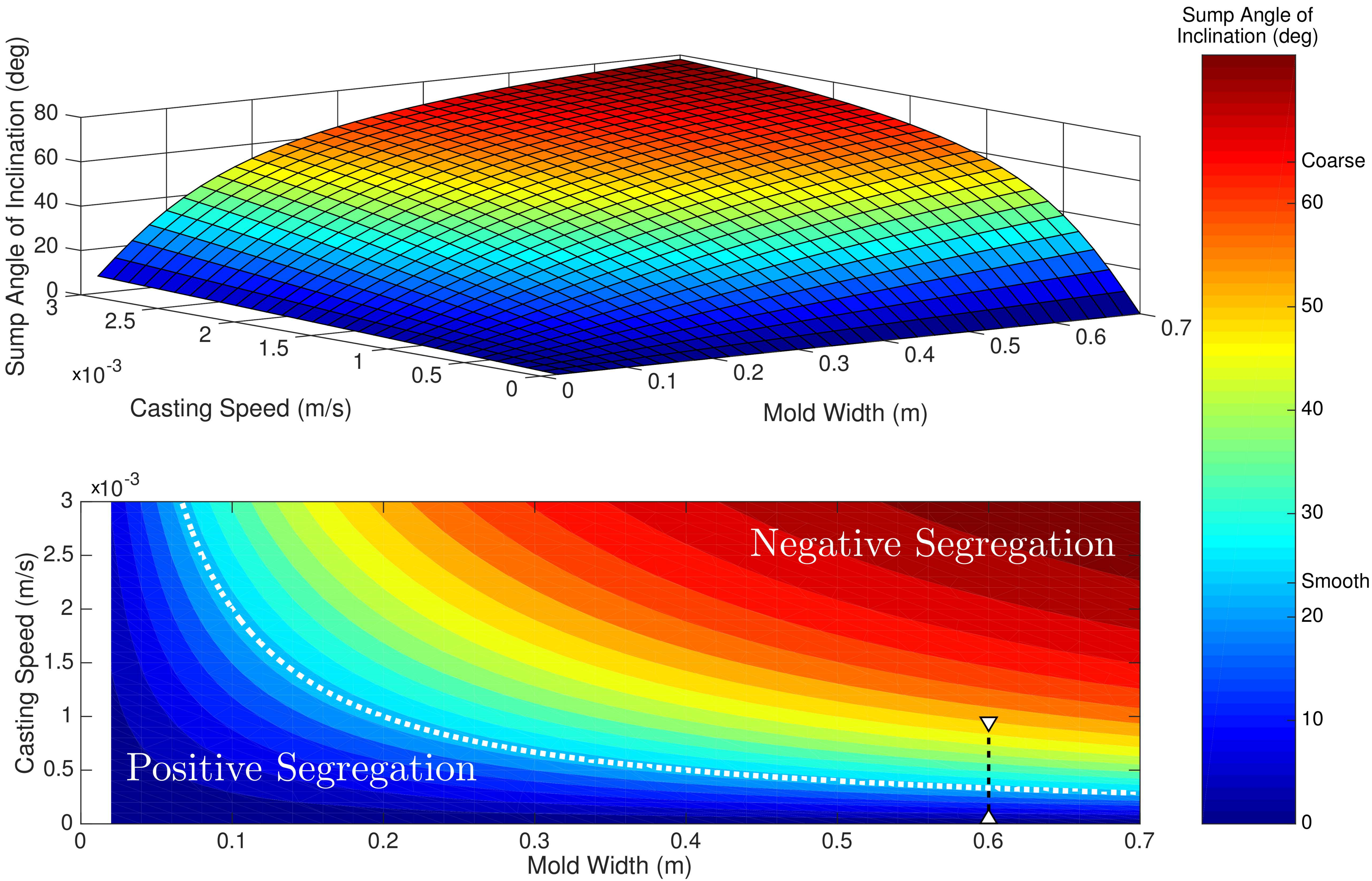
List of Figure Captions

Figure Error! Main Document Only.**:** (top) Variation of the angle of inclination of the sump walls with casting speed and mold width. Colors represent the angle of inclination from horizontal (dark blue) to vertical (dark red). The inset colorbar to the right represents the entire range of inclination, with specific references to the static angle of repose for smooth and coarse *grains*. (bottom) Top figure with the angle of view rotated perpendicular to the Casting Speed and Mold Width plane. The dashed white line represents the experimentally determined delineation between positive and negative segregation as specified by Livanov et al[10]. The dashed black line with triangular endpoints represents the casting parameters used in this investigation.

Figure 2: Location of the longitudinal centerline samples.

Figure 3: Surface plot representing longitudinal centerline segregation as a function of the jet Reynolds. Segregation is determined as a percentage deviation from furnace composition. Length position has been normalized by the overall cast length. The horizontal grid represents the 0% deviation plane.

Figure 4 : Centerline segregation data taken from the Re_J=97 000 cast. Adjacent segregation points were taken from reference (**Error! Bookmark not defined.**), and represent the average segregation 50mm from the geometric center of the ingot (impingement point). Trendlines have been added only to guide the eyes.



Sump Angle of Inclination (deg)
80
60
40
20
0
3
2.5
2
1.5
1
0.5
0
x10^-3
Casting Speed (m/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Mold Width (m)
x10^-3
Casting Speed (m/s)
Negative Segregation
Positive Segregation
Mold Width (m)
Sump Angle of Inclination (deg)
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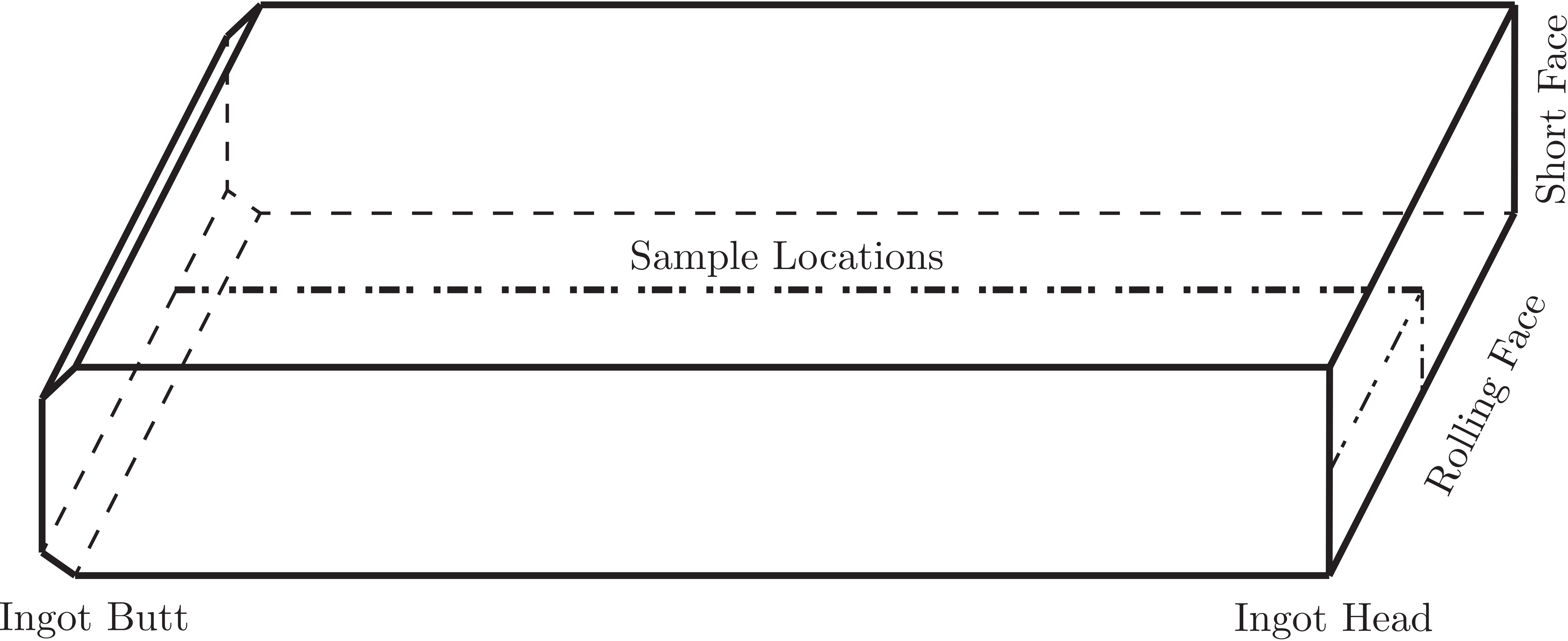
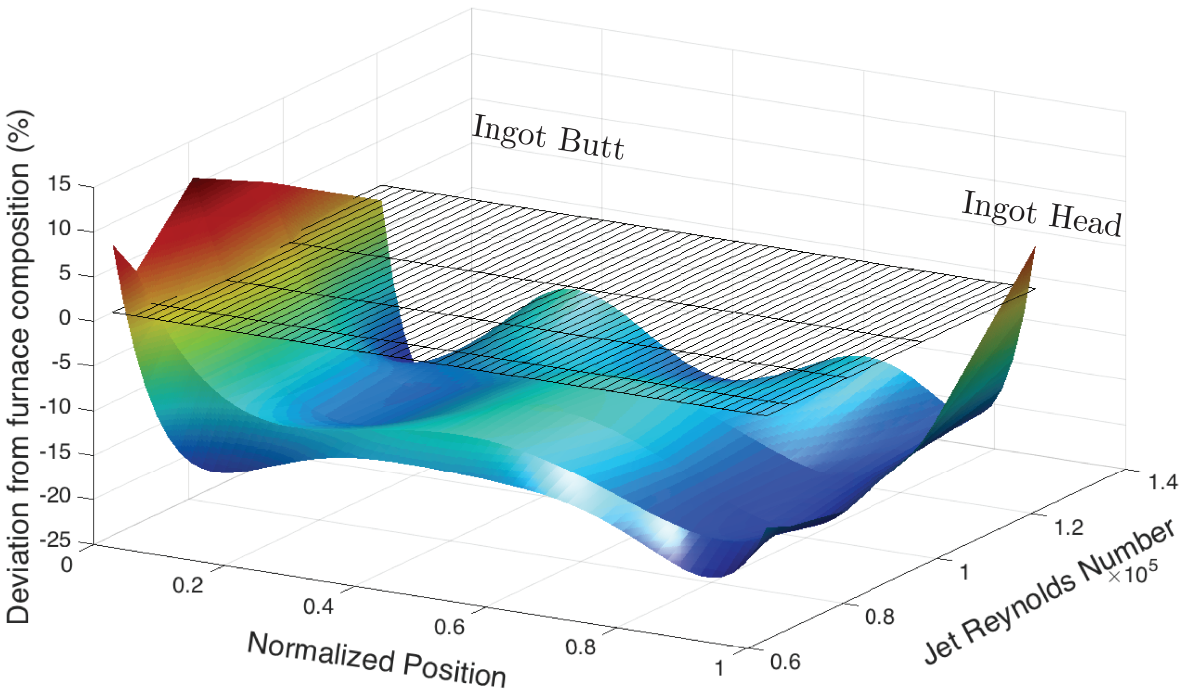
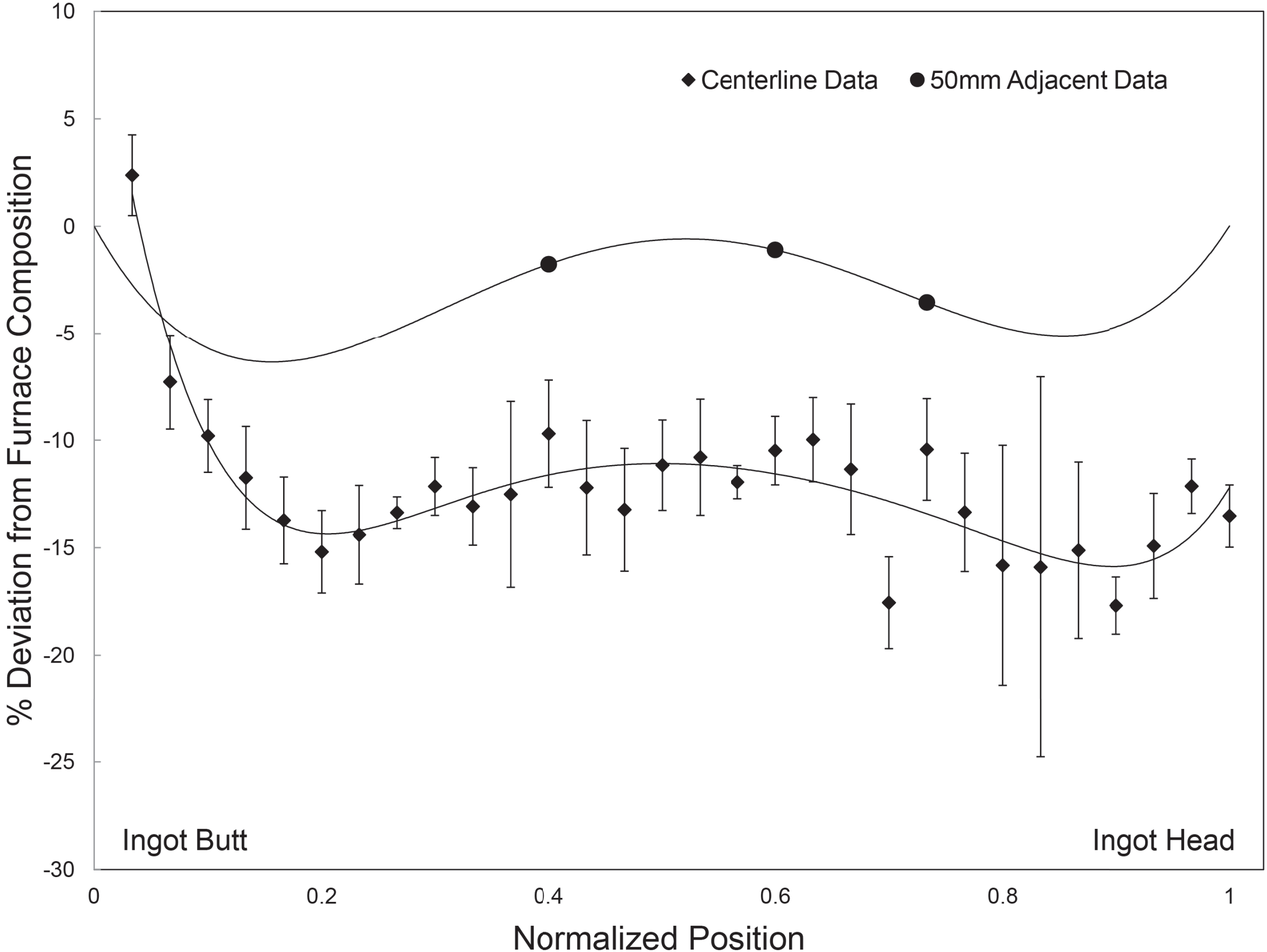
50
40
30
Smooth
20
10
0


Short Face
Sample Locations
Rolling Face
Ingot Butt
Ingot Head



Ingot Butt
Ingot Head
Deviation from furnace composition (%)
15
10
5
0
-5
-10
-15
-20
-25
0
0.2
0.4
0.6
0.8
1
Normalized Position
0.6
0.8
1
1.2
1.4
Jet Reynolds Number
×10^5



Centerline Data
50mm Adjacent Data
% Deviation from Furnace Composition
Normalized Position
Ingot Butt
Ingot Head
10
5
0
-5
-10
-15
-20
-25
-30
0
0.2
0.4
0.6
0.8
1