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Collaborative Research: Contacting and Solidification in Casting-by-Design

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Abstract: A technology to enable continuous casting of molten metals, in a single step, to the specifications of the designer is being developed[1]. For example, casting aluminum foil in a single step could reduce CO_2 emissions to the atmosphere by 250,000 tons per year, in the US alone. Furthermore every kilogram of aluminum saved by reducing manufacturing waste translates into electricity saved at the energy-hungry smelter. The technology is based on controlling length scales previously uncontrolled. Tunable casting uses substrate modification to manipulate product quality.

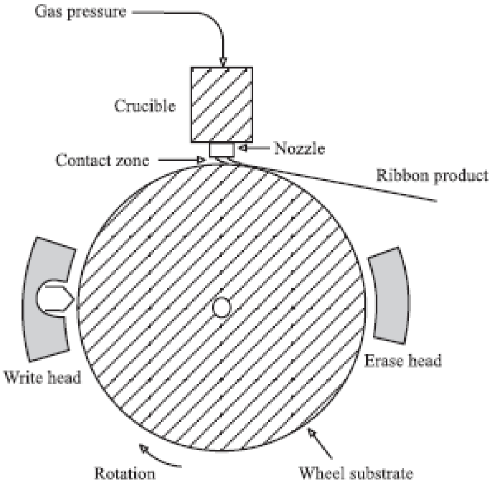

Fig. 1 Single roll casting schematic with 'write' and 'erase' head concept.

1. Overview: Single roll casting is an economical technique to produce foil or ribbon, a technique limited, however, by the ability to influence the contacting and solidification event within the contact zone. Molten metal is forced through a nozzle onto the substrate where it forms a puddle. Heat extracted to the rotating substrate causes a solidification front to grow from it as it translates and eventually a solid ribbon product is spun off. Casting rates of 10 *m/s* (tangential velocity) are achievable with our apparatus that uses a wheel of 3 *m* circumference. In the zone between nozzle and wheel, there is contact under pressure, phase-change, and large concentration (for alloys), velocity and thermal gradients. The complicated interplay between contacting, wetting and solidification physics is not well understood. Features of the ribbon product range over 6 orders of magnitude in length scale, from the product macroscale (50 *m*) to the grain size (10^{-5} *m*). Interest is in influencing the smaller scales ($<10^{-2}$ *m*) since these lead to surface irregularities, unacceptable product and waste. Controlling these irregularities would enable a new technology for manufacturing strip product with desired surface design and texture.

The goal is to condition the substrate by imposing either thermal or compositional gradients before the contact zone[1]. To realize this goal, one first needs to understand how 'natural' substrate modifications influence the solidified ribbon product. For example, the cross-stream wave defect appears frequently in the cast product as a row of pits on the wheel side of the ribbon correlate with trenches on the opposite side (air side). It is not clear how the pit formation on the wheel side relates to the trenches on the air side.

2. Progress: Thickness can be predicted from gap variations that change the resistance to fluid flow, confirming that fluid flow and heat transfer decouple to first order in this process. Indeed, a deterministic model for through-cast thickness is obtained by accounting for the substrate expansion during heat-up which decreases the gap and hence the flow and thickness. Other progress includes understanding the origin of the cross-stream wave defect and enhancing the stability of the melt puddle.

To understand the thickness prediction, consider first the heat absorbed by the wheel. The heat-up of the wheel at any time is proportional to the mass of ribbon solidified up to that time, since latent heat dominates the heat flux. The gap reduces proportionally to the thermal expansion of the wheel. Hence, knowing the mass solidified gives the gap which, by means of the pressure-drop flow-resistance proportionality, gives the thickness for any applied pressure. Thus, an integro-differential equation predicts the instant-by-instant ribbon thickness throughout the cast[7].

The presence of surface defects in continuous castings is common and generally undesirable. In single roll casting a periodic wave defect, called the cross-wave defect, typically occurs. Our previous work correlates the occurrence of this defect with an observed oscillatory frequency in the liquid metal puddle. We have shown this frequency to be due to surface tension. It can be readily described by the simple inviscid-capillary time scale used to describe the oscillations of a plucked sphere[4]. We have speculated, based on high-speed imaging of the upstream contact line, that the actual formation mechanism for the defect is the capture of air as the upstream meniscus oscillates. Using computations, an air pocket has been introduced and the influence on solidification and final geometry has been observed. Modeling (using three-dimensional finite element analysis) indicates that rows of air bubbles captured under the upstream meniscus would in fact lead to a continuous trench on the air-side of the ribbon (Fig 2a). Similar modeling of interfacial boron nitride deposits has also been performed, and results are consistent with experimental observation (Fig 2b)[3,6].

Geometry and solidification influence the pressure distribution in the long thin puddle region between nozzle and wheel. Our work models this distribution and predicts the stability window by using the capillary pressures as stability bounds. There is good agreement with empirically-determined stability window from the literature[5]. Furthermore, this modeling predicts that imposing a pressure or pulling a vacuum on the upstream meniscus enhances puddle stability. A device capable of so-altering this pressure has been built, and the predicted stability enhancement is observed[2,5].

A simple hydrodynamic model of the puddle oscillations accounts for the observed vibrations frequencies and meniscus shape deviation. A liquid is confined by a channel on three sides, with a deformable meniscus being the remaining boundary. Using potential flow, a symmetric two node oscillation is predicted and identified as similar to that seen by high speed imaging, The corresponding frequency compares favorably with observation.

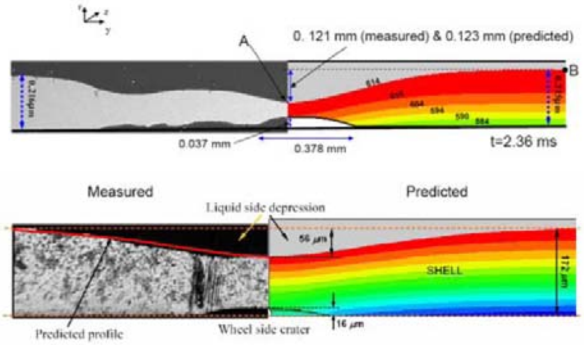

Fig. 2 Measured (left) versus predicted (right) transverse solidified shapes for (top) BN deposit and (bottom) air gap entrained during meniscus oscillation.

3. Acknowledgements: National Science Foundation grant # DMI-0423791 and DMI-0423794.

10. References:

[1] US Patent 7,082,986 "System and method for continuous casting of a molten material, " 2006.

[2] US Patent Application 11/413,748, “Planar Flow Melt Spinning with Pressure Adjustments and methods thereof,” pending.

[3] Byrne, CJ, AM Kueck, SP Baker, PH Steen, “In situ manipulation of cooling rates during planar-flow melt spinning processing,” *Mat. Sci. and Eng. A*, vol. 459, pp. 172-181, 2007.

[4] Byrne, CJ, EA Theisen, BL Reed and PH Steen, “Capillary puddle vibrations linked to casting-defect formation in planar-flow melt spinning,” *Met. & Mat. Trans. B*, vol. 37B, pp. 445-456, 2006.

[5] Byrne, CJ, SJ Weinstein, and PH Steen, “Capillary stability limits for liquid metal in melt-spinning,” *Chem. Eng. Sci.*, vol. 61, pp. 8004-8009, 2006.

[6] Sundararajan, A and BG Thomas, “Heat transfer during melt spinning of Al-7%Si Alloy on a Cu-Be wheel, parts 1 and 2.” Under review.

[7] Theisen, EA, CJ Byrne, MJ Davis, SJ Weinstein, PH Steen, "Transient behavior of the Planar-flow Melt-spinning process." In preparation.