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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. To cast aluminum foil, e.g., in a single step, would reduce CO_2 emissions to the atmosphere by 250,000 tons per year, in the US alone. Every kilogram of aluminum saved in 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.

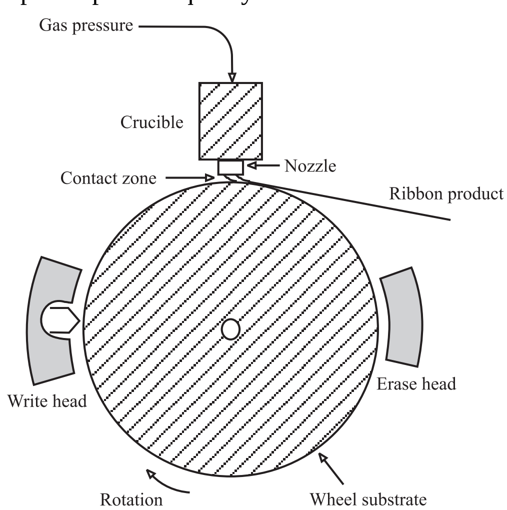

Fig.1 Single roll casting schematic with 'write' and 'erase' head concept.

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. The rotating substrate causes a solidification front to grow from it as it translates and eventually a 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 in length scale over 6 orders of magnitude, from the product macroscale (50 *m* long) 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 of 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. 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. It is not clear how the associated pit formation seen on the wheel side of the ribbon relates to the trenches on the opposite side (air side).

2. Progress: Progress has come on three main fronts: the origin of the cross-stream wave defect; enhanced stability of the melt puddle; and the relating of the substrate deformation (due to thermal loading) to the variations in the product thickness.

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. This defect consists of a series of closely spaced pits on the wheel-contact side and a continuous 'trench' on the air-side. Our previous work correlates the frequency of this defect with an observed oscillatory frequency in the liquid metal puddle. Our most recent work has found these puddle oscillations to be capillary in nature and can be readily described by the simple inviscid-capillary time scale used to describe the oscillations of a plucked sphere[1]. A coarse map of regions in parameter space where the defect appears has been identified. We have speculated, based on our high speed imaging of the upstream contact line, that the actual formation mechanism for the pits and trenches is the capture of air as the upstream meniscus oscillates. Using computations (U. Illinois, collaboration), an air pocket has been introduced and the influence on solidification and final geometry has been followed. 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 (Figure 2). Further work to validate these results and to model the behavior of the ribbon with compositional gradients (heat-transfer interruptions, like the air pocket) has been undertaken.

We have developed a simple hydrodynamic model of the puddle oscillations to account for the observed vibrations frequencies and meniscus shape deviation. A fluid is confined by a channel on three sides, with a deformable meniscus being the remaining boundary. This problem is similar to that of standing gravity waves except that the gravity term is replaced by capillarity, which modifies the pressure at the boundary based on the interface curvature. Using potential flow theory we solve for the eigenfrequencies for each distinct eigenmode[1]. It turns out that the m=2 mode agrees with the observed interface deviations from the high speed imaging.

Geometry and solidification influence the pressure distribution in the long thin puddle region between nozzle and wheel. Previous work obtained the pressure distribution in the puddle. More recent work extends this 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[2]. Furthermore, this modeling indicates enhanced stability by imposing a pressure or pulling a vacuum on the upstream meniscus of the puddle. This technologically difficult endeavor is novel for melt spinning. A device capable of altering these pressures has been built and reduced to practice, demonstrating the predicted extended stability[2].

In this process, principal control parameters are gap size between the nozzle and the wheel, flow rate of the molten metal, and wheel speed. One goal is to understand the influence of these input control parameters on the foil quality and features. The molten metal puddle is subject to a variety of disturbances, which are examined by both experimental and theoretical means. The out-of-roundness of the wheel, which is small compared to the diameter of the wheel (~1m), is significant when compared to the gap distance from the nozzle to the wheel. Therefore, the gap height varies in a periodic manner and the foil also shows thickness variations at the corresponding frequency. Interestingly, the amplitude of the thickness variations is strongly dependent on the processing conditions. Macroscopic mass and momentum balances are used to examine the puddle's dynamic response to disturbances. A model whose predictions relate the amplitude of the thickness variations to periodic gap-forcing as well as to the processing conditions is currently being tested experimentally.

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

4. References.

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2. Byrne, CJ, SJ Weinstein, and PH Steen, "Capillary stability limits for liquid metal in melt-spinning," under review

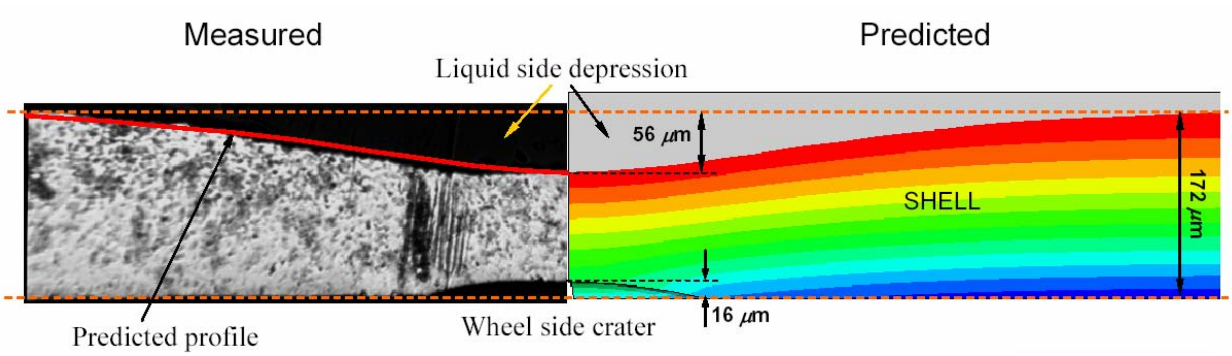

Figure 2. Comparison between measured and predicted oscillation defect