NSF GRANT # 0726813
NSF PROGRAM NAME: MPM

Collaborative Research: Manipulating the Contact and Solidification of Molten Metal in Continuous Casting

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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[7]. 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.

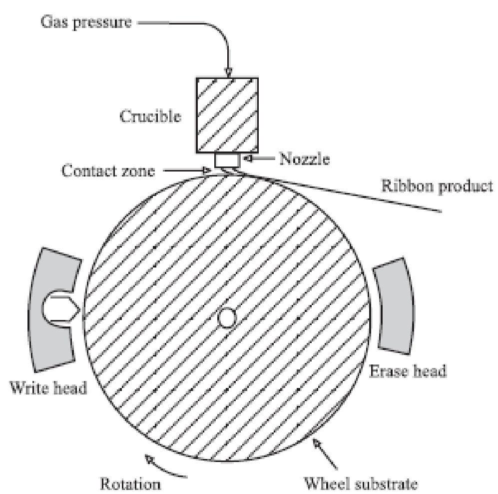

Fig. 1 Single roll casting schematic with 'write' and 'erase' head concept.

1. Overview: Single roll casting (Fig. 1) 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 poorly 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 (< centimeter) since these lead to surface irregularities, unacceptable product and waste. Controlling these scales would enable manufacturing strip product with properties of specified uniformity.

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 that correlates with trenches on the opposite side (air side). "How does pit formation on the wheel side relate to trenches on the air side?" is a central question.

2. Progress: Thickness can be predicted from gap variations that affect the resistance to fluid flow. That is, feed rate rather than heat-transfer rate limits the product thickness. Other progress includes: an improved understanding of the origin of ribbon defects; the relating of the substrate deformation (due to thermal loading) to the variations in the product thickness (which, coupled with the effect of gap on thickness, yields a deterministic model for through-cast thickness); and the development of a model for solidification rate which captures the important features in the dynamics throughout a cast.

Visible surface defects in the ribbon product represent localized variations in thickness and may be indicative of other unintended variations in metallurgy, such as relative concentration of alloying agents. The presence of surface defects in continuous castings is common and generally undesirable. Two of the most common defects in spin-casting, termed "crosswave" and "herringbone," are periodic with wavelengths that scale with the geometry of the contact zone and fluid properties. Our previous work correlates the frequency of the crosswave defect with an observed oscillatory frequency in the liquid metal puddle. Recent work has found these puddle oscillations to be due to surface tension, related to the inviscid-capillary time scale used to describe oscillations of a plucked sphere. A coarse map of regions in parameter space where each defect appears has been identified. Current research explores the criteria that determine whether crosswave or herringbone appears in the ribbon, likely related to constraints on the geometry of the puddle[2].

Based on high-speed imaging of the upstream contact line, we have speculated that the formation mechanism for crosswave and herringbone defects 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 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, consistent with observations of the defect through optical profilometry (Fig. 2). Further work to validate these results and to model the solidification dynamics with heat-transfer interruptions, including both air pockets and boron nitride deposits (via 'write head'), is underway. Preliminary results are consistent with observation[3,5].

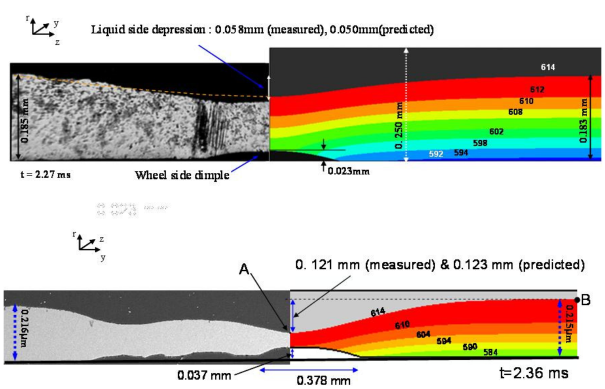

Fig. 2 Measured (left) versus predicted (right) transverse solidified shapes for (top) BN deposit and (bottom) air gap entrained during meniscus oscillation.

In the planar-flow melt spinning process, principal control parameters are gap size between the nozzle and the wheel, pressure driving the flow of molten metal, and wheel speed. One goal is to understand the influence of these input control parameters on the foil quality and features.

To gain further insight into the fundamental relationships between process variables, computational models of fluid flow and heat transfer have been developed of the complete process (at UIUC, as part of the collaboration). This includes quantifying the pressure drops through the inlet crucible and nozzle, which drives the flow, and simulating turbulent fluid flow in the liquid puddle (Fig. 3a), which also controls the distribution of superheat during initial solidification (Fig. 3b). Models further compute solidification of the strip, and transient temperature evolution in the wheel itself[1,5].

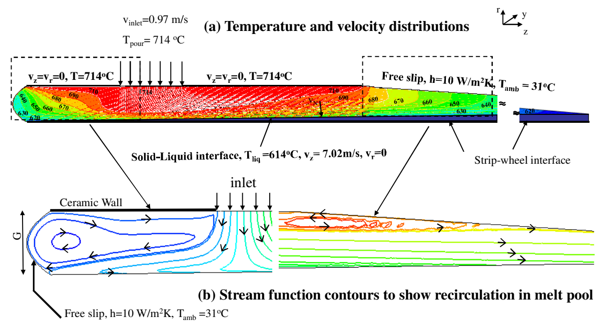

Fig. 3 Fluid flow model velocity and temperature distributions in the puddle region[5].

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, small compared to the diameter of the wheel (~1m), is significant when compared to the gap between nozzle and wheel. The gap height varies in a periodic manner and the foil also shows thickness variations at the corresponding wavelength. Interestingly, the amplitude of the thickness variations is strongly dependent on the processing conditions. Macroscopic mass and momentum balances are used to examine the dynamic response of the puddle to disturbances. A model to predict foil thickness from nozzle geometry has been tested against the extensive database of past casts available in our laboratory, with favorable results. Further, model predictions were also successful when applied to the thickness of ribbon cast by Hitachi-Metglas, an industrial practitioner of planar flow spin-casting, despite distinct differences in the materials and practices[4].

The periodicity in the gap couples with thermal loading of the substrate to cause a periodically decaying trend in both through-cast gap and ribbon thickness. The thermal loading of the substrate may be characterized as a function of the thickness of ribbon, and thus allows the gap to be modeled as a function of time. This model for the gap, through the puddle mass balance, allows for a deterministic integro-differential equation for thickness as a function of time throughout the cast, which depends entirely upon measurable or estimable process and material parameters. Recent improvements in our capacity to capture high-speed images of the puddle region have allowed reliable quantification of the puddle length. These measurements may be combined with information about thickness and wheel-speed to calculate solidification velocity. From these data, we have developed an empirical model for solidification velocity that captures important features of the dynamics throughout a cast[6].

3. Acknowledgements: National Science Foundation grants # DMI-0423791, DMI-0423794 and CMMI-0726813.

10. References:

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