ANNUAL REPORT 2007

June 12, 2007

Continuous Casting Consortium
Annual Meeting 2007

Brian G. Thomas, Director

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University of Illinois at Urbana-Champaign

Objectives

- To develop computational models of continuous casting of steel and related processes
- To apply these models to problems of practical interest to the steel industry

Tentative Attendees

Algoma Steel:	*?*
Baosteel:	*?*
Corus:	*Begonia Santillana, Arnoud Kamperman, Arie Hamoen*
Delavan / Goodrich:	*Stephen Swoope*
Labein:	*Jon Barco*
LWB Refractories:	*Rob Nunnington, & John McCauley*
Mittal:	*Bruce Foreman*
Nucor Steel, Decatur, AL:	*Ron O'Malley & ?*
Postech:	*?*
Steel Dynamics Inc.:	*Clayton Spangler + ?*
Fluent Inc.:	*?*
U Helsinki, Finland	*Seppo Louhenkilpi*
University of Illinois:	Brian G. Thomas, Joseph Bentsman, Seid Koric, Bryan Petrus, Kun Xu, Huan Li, Lance Hibbeler, Aravind Sundararajan, Vivek Natarajan, Kevin Cukierski, Michael Okelman, Ramesh Chaudhary, Matt Rowan, Oluwaseun Araromi, Cathy Mao, P. Sokolovsky
Other UIUC students:	Gogi Lee, Sami Vapalahti, Zaher Hashisho, Bret Rietow

Day 1: Morning Session

8:00am	*Breakfast & Introductions*	2005 Mech. Eng. Lab. (Deere Pavilion)
8:10	B.G. Thomas:	"Overview of projects"
8:20	B. Rietow / BG Thomas	"Flow in a Thin-Slab Mold" and "Quantitative analysis of steel surface velocity from Nailboard tests"
8:50	K. Cukierski	"Electromagnetic Control of Fluid flow in the Mold"
9:25	GG Lee / BG Thomas	"Multi-phase flow and inclusion entrapment in the slab casting mold"
10:00	*Break*	
10:15	R. Chaudhary	"Stopper Rod Misalignment and Effect on Nozzle Flow"
10:40	C. Ojeda / BG Thomas	"Modeling 3D Meniscus Shape, Flow, Corner Effects, Heat Transfer, & Consumption during Mold Oscillation"
11:20	O. Araromi	"Modeling of Clogging / Erosion of Nozzle Refractories"
11:50	Discussion of flow projects	
12:15pm	*Lunch*	2005 Mech. Eng. Lab.

Day 1: Afternoon Session

12:45	B. Petrus	"Online control of spray cooling using CONONLINE"
1:20	S. Vapalahti	"Spray heat transfer research at Cinvestav, Mexico"
1:40	H. Li	"Temperature evolution in the spray zones: plant measurements and CON1D prediction"
2:05	K. Xu	"Modeling of precipitate formation during secondary spray cooling"
2:35	V. Natarajan	"Modeling of mold oscillation"
2:45	*Break*	
3:00	L. Hibbeler	"Thermal-mechanical behavior of the solidifying shell and ideal taper in a funnel mold"
3:30	K Xu / L Hibbeler	"Heat transfer and distortion of a beam-blank mold: plant measurements and model computations"
3:45	S. Koric	"Thermal-mechanical behavior of the solidifying steel shell in a beam-blank mold and ideal taper design"
4:10	*Break*	
4:20	M. Okelman	"Design & installation of novel thermal sensors into the continuous casting mold"
4:40	A. Sundararajan:	"Modeling heat transfer & depression formation in Al strip casting"
5:00	Discussion of future projects and directions	
5:30	Adjourn meeting	
6:00	*Dinner*	Colonial Room, Illini Union Building

Day 2

8:00 am-? *B.G. Thomas: 356 Mech. Eng. Bldg.*
Informal discussions on future projects
(Prior appointments would be helpful)

8:00 am-? *Research group: 345 Mech. Eng. Bldg.*
Informal discussions
Further details on current projects and software
CON1D and CON2D operation
Questions

Research Summaries

Flow Dynamics and Electromagnetic Effects in Continuous Casting of Steel

B.G. Thomas,* K. Cukierski and R. Chaudhary
*Continuous Casting Consortium***

Computational models of transient, multiphase fluid flow are being developed, validated, and applied to improve understanding of transient flow, inclusion transport and defect formation in the mold region during the continuous casting of steel slabs. The important effect of electromagnetic forces to slow down and control the flow pattern are being incorporated. Process parameters, such as nozzle geometry and gas injection rate, which are easy to change and yet profoundly influence both flow and product quality, are being optimized. Models to compute the transport and entrapment of inclusion particles are being tested through water model experiments, steel plant trials, and metallographic measurements at several steel companies who are cosponsoring this research. The effect of asymmetric flow, such as caused by stopper-rod misalignment is considered.

Entrapment of Bubbles and Inclusions during Flow in the Mold

B.G. Thomas,* S.H. Kim, G. Lee, and R. Chaudhary
*Continuous Casting Consortium**, POSTECH, Korea*

Inclusion particles and bubbles carried by the turbulent flow of molten steel through the continuous casting nozzle and mold pool lead to serious surface and internal defects in the final product. Three-dimensional turbulent fluid-flow models are being applied to understand and quantify inclusion transport and entrapment for different casting conditions. The models incorporate the effects of nozzle clogging, and inclusion entrapment by the solidifying dendritic interface. Experimental and water model studies are being conducted and analyzed to determine the argon bubble size. The computations are validated and augmented with measurements, metallographic analysis, and plant trials conducted at POSCO and elsewhere.

Research Summaries

GOALI: Online Dynamic Control of Cooling in Continuous Casting of Thin Steel Slabs

B.G. Thomas,* J. Bentsman*, S. Vapalahti, B. Petrus, H. Li, A.H. Castillejos, F.A. Acosta
*Continuous Casting Consortium** and National Science Foundation GOALI DMI 05-00453*

Temperature variations during cooling cause quality problems such as cracks, especially under transient conditions such as caused by changes in casting speed. Setting the spray water flow rates to maintain optimal temperature profiles during process changes becomes increasingly difficult when the casting speeds are high and response times must be fast. This project aims to develop a fundamentally-based online system to dynamically control the water flow rates in order to continuously optimize and stabilize cooling conditions in the thin slab casting process. The system will use model-based predictive control, incorporating both online measurements of mold heat removal and on a high-speed finite-difference model of heat conduction and solidification during the process. Model accuracy will be validated with measurements of spray heat transfer in controled lab experiments and in the steel plant.

Precipitation and Surface Crack Formation in Continuous Casting

B.G. Thomas,* Kun Xu
*Continuous Casting Consortium***

Thermal stress in the steel shell as it moves down through the mold and below between the rolls in the secondary cooling zones contributes to many different problems, including transverse cracks, slab shape problems, and support roll wear. Mathematical heat flow and stress models are being developed to predict the temperature, and the associated distortion, stresses and strains, both in and below the mold. In addition, criteria for crack formation will be developed, based on steel ductility measurements and a model of grain size and nitride, oxide, and sulfide precipitation to track the susceptibility of different steel grades to ductility problems. Results will be compared with experience prior to establishing cracking criteria and applying the models to understand and explore ways of preventing cracking problems.

Research Summaries

Initial Solidification and Meniscus Hook Formation in Continuous Slab Casting

B.G. Thomas*, C. Ojeda, G. Lee, and SH Kim*.
*Continuous Casting Consortium**, POSTECH, Korea, and Labein, Spain.*

The first few seconds of solidification at the meniscus create the final cast product surface, and may include defects such as deep oscillation marks, surface depressions, and subsurface hooks in the microstructure, if conditions are not optimal. Computational fluid flow, heat flow and stress models of the meniscus region are being developed and applied to simulate these phenomena. Plant measurements such as mold temperature, liquid surface shape, and metallographic examination of oscillation marks and hooks are being conducted on slabs cast at POSCO. Together, ways to optimize casting conditions such as speed, level control, superheat, mold oscillation practice, and mold powder composition are being investigated to minimize meniscus hook depth.

Thermal Stress Analysis of Solidifying Steel Shells

B.G. Thomas,* L. Hibbeler, S. Koric, K. Xu, M. Rowan
*Continuous Casting Consortium***

A coupled, two-dimensional, transient finite-element model has been developed to predict temperature, shrinkage, and stress development in both horizontal and vertical sections through the solidifying shell as it moves down through the caster. The model includes the effects of the volume change during phase transformation, ferrostatic pressure, the generalized plane strain stress state, the constraining influence of the mold, creep plasticity, and the dynamic effect of solidification shrinkage on heat transfer across the interfacial gap between the mold and the shell. The model is being applied to simulate the early stages of solidification, ideal taper for different steel grades, maximum casting speed to avoid excessive bulging, and understanding crack formation. Finally, the model is being extended to simulate behavior in complex shapes including ideal taper of beam blank molds, and crack formation in thin slabs cast in funnel molds, using full three dimensional simulations.

Research Summaries

Contacting and Solidification in Casting-by-Design

B.G. Thomas,* Aravind Sundararajan
National Science Foundation, Collaborative Research: NSF DMI 04-23794

The continuous casting of thin aluminum strip with a single-wheel melt spinning process offers great potential for low-cost production of finished products with unique surface textures. To perfect this process requires fundamental understanding of the phenomena which control solidification shape, including flow oscillations in the melt pool, meniscus interaction with the wheel surface, intermittent solidification against the moving wheel, and thermal distortion. Aided by measurements by collaborators at Cornell, advanced computational models are being applied at UIUC to achieve this new understanding. Recent simulations match the contoured shape of the strip surface, based on the initial shape of the solidified meniscus, which is also the subject of model investigation.

SIRG/Collaborative Research: Distributed Subwavelength Photonic Sensors for In-situ High Spatial and Temporal Resolution Monitoring in Manufacturing Environments

B.G. Thomas,* M. Okelman
National Science Foundation SIRG DMI # 05-28668 and *Continuous Casting Consortium***

Monitoring of mold level and meniscus behavior is important for controlling quality during the continuous casting process. This project aims to develop new sensors to measure temperature in the mold very near to the meniscus, initially to use as a new research tool to investigate meniscus behavior to better understand defect formation. The ultimate goal is to revolutionize online thermal monitoring of industrial continuous casting molds. A process will be developed to insert sensors manufactured at UW Madison into the mold coating layer. Tests of sensor integrity will be conducted, data collected, and the signals analyzed using computational models. The meniscus region will further be modeled computationally to predict events during an oscillation cycle – including modeling of the sensor itself. This will determine the relationship between the sensor signal and the actual meniscus events. Insights gained will enable optimization of the size and location of the new sensors and interpretation of their signals to gain maximum benefit from their installation into operating molds.

Research Summaries

Fluid flow, Heat transfer and Interfacial Phenomena in Nozzle Refractories

B.G. Thomas,* J. Bentsman,* V. Natarajan

*Continuous Casting Consortium**, LWB Refractories*

Dolomite nozzles differ from conventional nozzles in having higher resistance to alumina clogging but are more easily eroded. Fundamental modeling studies are being performed to understand and characterize the behavior of these nozzles, to compare them with conventional nozzles, and to optimize their use in service. Specific studies include an analysis of the flow of argon gas within the porous refractory walls to learn the gas distribution upon entering the molten steel. Heat transfer through the refractory walls is being modeled for a variety of realistic conditions, to understand the role of steel skulling on clogging for different refractory properties. Finally, the interfacial behaviors which govern the clogging attachment, the dissolution of the refractory, and the thermodynamic reactions are being studied.

Modeling of Clogging and Erosion of Nozzle Refractories in Steel Casting

B.G. Thomas,* O. Araromi

Continuous Casting Consortium, LWB Refractories

Depending on their composition relative to the inclusions in the steel, the walls of nozzle refractories can clog or erode, leading to severe quality problems in cast products. These phenomena have rarely been subjected to fundamental modeling, and never to computational modeling involving the several coupled phenomena that govern it: the turbulent flow of molten steel through the nozzle, contacting of solid inclusions in the steel with the nozzle wall, heat transfer in the wall and steel, the diffusion of compounds such as Al2O3 and CaO through the nozzle wall, and the thermodynamics of the chemical reactions that form solid precipitates, or liquefy the inclusions, allowing them erode from the walls. With the support of numerous experimental measurements that have been made for this project, computational models will be developed to increase understanding of this important, yet complex problem.