ANNUAL REPORT 2008

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Continuous Casting Consortium Annual Meeting 2008

Brian G. Thomas, Director

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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

Attendees

Baosteel:	*Chengbin Li*
Corus:	*Begoña Santillana & Gert Abel*
Delavan / Goodrich:	*Stephen Swoope*
Labein:	
LWB Refractories:	*Don Griffin, & Shane Cox*
Mittal:	Metin Yavuz, *Joydeep Sengupta, P. Gardin, M. Bobadilla, R. Gass, Michael Okelman.*
Nucor Steel, Decatur, AL:	*Ron O'Malley, Steve Wigman, & Tony Bryan*
Postech:	
Steel Dynamics Inc.:	
POSCO:	*Seong-Yeon Kim*
Ansys / Fluent Inc.:	*Ashwini Kumar*
Nippon Steel:	*Eiichi Takeuchi & Norimasa Yamasaki*
Other:	*Kevin Cukierski*
University of Illinois:	Brian G. Thomas, Joseph Bentsman, Rajneesh Chaudhary, Bryan Petrus, Kun Xu, Xiaoxu Zhou, Lance Hibbeler, Vivek Natarajan, Choul-Hong Min, Matt Rowan, Ge Shi, Zhaohui Yuan, Rui Liu.
Other CCC researchers:	Gogi Lee, Seong-Mook Cho, Sami Vapalahti, A. Sundararajan, Seid Koric.

Day 1: Morning Session

8:00am Breakfast & Introductions 2005 Mech. Eng. Lab. (Deere Pavilion)

8:10	B.G. Thomas:	Overview of projects
8:20	R. Chaudhary	1) Well-bottom vs. Mountain-bottom nozzles 2) Stopper-Rod Misalignment Effects
9:10	C.-H. Min	Electromagnetic Control of Fluid flow in the Mold
9:30	GG Lee / BG Thomas	Multi-phase flow, argon bubble size, and inclusion entrapment in the slab casting mold
10:00	*Break*	
10:15	X. Zhou	1) Spray heat transfer research at Cinvestav, Mexico 2) New features of Con1D: Version 9.6 3) Temperature evolution in the spray zones
11:00	B. Petrus	Online control of spray cooling using CONONLINE
11:30	Discussion of flow and heat transfer projects	

12:00pm Lunch 2005 Mech. Eng. Lab.

Day 1: Afternoon Session

12:30	K. Xu	Modeling heat transfer, precipitate formation, and grain growth during secondary spray cooling
1:00	V. Natarajan	Modeling of mold oscillation
1:20	L. Hibbeler	Thermal-mechanical behavior of the solidifying shell and ideal taper in a funnel mold
2:15	*Break*	
2:30	L. Hibbeler	Heat transfer and distortion of a beam-blank mold: plant measurements and model computations
2:45	G. Shi	Thermal-mechanical behavior of the solidifying steel shell in a beam-blank mold and ideal taper design
3:15	Z. Yuan	Thermal distortion of a slab mold with cavity for electromagnetics
3:40	*Break*	
4:00	M. Rowan:	Modeling of experiment to measure solidification stress and cracks
4:20	M. Rowan:	Modeling heat transfer & depression formation in Al strip casting
4:40	M. Okelman:	Novel in-mold sensors
5:00	BGT:	Summarize CCC Reports on Meniscus oscillation modeling, etc.
5:15	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 – 10:00	Nippon Steel Discussion
10:00 – 11:00	Labein
12:00 – 2:00pm	Mittal group discussion
8:00 am-?	*Research group: 345 Mech. Eng. Bldg.* Informal discussions with students Further details on current projects and software CON1D and CON2D operation Questions
Day 3 (Aug. 8)	Corus Group Discussion

Research Summaries

Flow Dynamics and Electromagnetic Effects in Continuous Casting of Steel

B.G. Thomas,* K. Cukierski, R. Chaudhary, and C.H. Min

*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.

Entrapment of Bubbles and Inclusions during Flow in the Mold

B.G. Thomas,* S.H. Kim, G. Lee, R. Chaudhary, and S.M. Cho

*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 effect of asymmetric flow, such as caused by stopper-rod misalignment, and nozzle design parameters are also investigated. 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*, B. Petrus, X. Zhou, S. Vapalahti, 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 controlled lab experiments and in the steel plant.

Precipitation and Surface Crack Formation in Continuous Casting

B.G. Thomas,* Kun Xu

*Continuous Casting Consortium***

Surface cracks are caused by metallurgical embrittlement and tensile stress in the steel shell as it moves down through the mold and below between the rolls in the secondary cooling zones. Mathematical heat flow and stress models have been developed to predict the temperature, strain, and stress development during this process. Fundamental models of precipitate formation and grain size are being developed to predict ductility as a function of steel grade and the thermal history. Criteria for crack formation arising from these models will be evaluated with microstructure observations, steel ductility measurements, and crack frequency to establish practices that can minimize cracking problems.

Research Summaries

Initial Solidification and Meniscus Hook Formation in Continuous Slab Casting

B.G. Thomas*, C. Ojeda, G. Lee, H-J. Shin, 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

Manipulating the Contacting and Solidification of Molten Metal in Continuous Casting

B.G. Thomas,* Matt Rowan

National Science Foundation, Collaborative Research: NSF CMII 07-27620

Stress and strain that arise during initial solidification of aluminum and steel is important to the formation of surface defects. Small gaps forming due to gas entrainment or meniscus oscillation generate complex coupling between heat transfer and thermal stress. A fundamental understanding of how key phenomena such as alloying, cooling rate and thermal-mechanical behavior influence this behavior could enable improvements in the control of surface quality. This would make single-wheel strip casting a feasible alternative to other solidification processes. Advanced computational models are being applied to study these phenomena, including constitutive models that relate strain rate to stress and microstructure for aluminum solidification and other temperature dependant material properties.

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 new process has been developed to insert sensors into the mold coating layer. Tests of sensor integrity are being 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

Control of Nozzle Clogging

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

*Continuous Casting Consortium**, LWB Refractories*

Fundamental modeling studies are being performed to understand and control nozzle clogging. Argon gas bubbles are known to prevent clogging. The flow of argon gas through the porous refractory walls has been modeled to determine the gas distribution entering the molten steel. Skulling is a type of clogging caused by insufficient steel temperature combined with heat loss through the refractory walls. To develop active means of clogging minimization, the heat transfer equations governing steel solidification in the nozzle are being transcribed into a control-oriented dynamic model of nozzle clogging. The manipulability of the clogging formation through upstream heat input, as well as possible sensing arrangements are also being investigated. Suitable control laws for heat input are being formulated to prevent skull clogging.

Modeling of Clogging and Erosion of Nozzle Refractories

B.G. Thomas,*

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 experimental measurements, computational models will be developed to increase understanding of this important, yet complex problem.

Research Summaries

Numerical Study of Cooling Water Behavior around Cooling Header and Steel Strip in Run-Out-Table Processing

B.G. Thomas,* M.J. Cho

POSCO, Pohang, South Korea

The mechanical properties of steel strip after hot rolling depend greatly on cooling conditions in the run-out-table. Computational models of water flow and heat transfer between the header and the steel surface are being developed and applied to understand and optimize these cooling conditions. Three-dimensional CFD models of fluid flow are validated with test problems and laboratory experiments are applied to predict the free surface of the liquid pool in the commercial plant. Differences between water depths in the laboratory and plant may explain differences in the vapor barrier, and consequently in cooling behavior. Optimizing header design and flow rates could increase heat transfer rates and improve control of cooling and steel properties.