Agenda

August 12, 2010

Continuous Casting Consortium Annual Meeting 2010

Brian G. Thomas, Director

Department of Mechanical Science & Engineering

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

ABB	*Olof Hjortstam*
Baosteel:	*Yingchun Wang*
Corus:	*G. Abbel*
LWB Refractories:	*Rob Nunnington, Shane Cox*
Arcelor-Mittal:	*Metin Yavuz, Ken Blazek, Hongbin Yin, Rich Gass (Inland) Joydeep Sengupta.*
Nucor Steel:	*Ron O'Malley, Rob Williams (Decatur, AL), Curtis Glenn, Steve Wigman & Dean Burke? (Crawfordsville, IL)*
Nippon Steel:	*Junya Iwasaki, Eiichi Takeuchi, Hideaki Yamamura & Norimasa Yamasaki*
Postech:	*Seon-Hyo Kim, Seong-Mook Cho, and Hyung-Jun Lee*
POSCO:	*Seong-yeon Kim*
Ansys / Fluent Inc.:	*Ashwini Kumar & Mohammad (Peyman) Davoudabadi*
University of Illinois:	Brian G. Thomas, Joseph Bentsman, Rajneesh Chaudhary, Bryan Petrus, Kun Xu, Xiaoxu Zhou, Lance Hibbeler, Vivek Natarajan, Hemanth Jasti, Seid Koric, Matt Rowan, Varun Singh, Rui Liu, Chuanbo Ji.
Other CCC researchers:	Seong-Mook Cho, Hyung-jun Lee, YingChun Wang, K. Thomas.

Day 1: Morning Session

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

1. 8:10	B.G. Thomas:	Overview of projects
		Transient flow in slab casting with electromagnetic effects:
8:20	R. Chaudhary	1) Evaluation of turbulent flow models with DNS benchmarks
8:40	R. Chaudhary & C. Ji	2) Evaluation with measurements in flowing liquid-metal
9:00	R. Liu	Quantitative measurement of molten steel surface velocity with nailboards and SVC sensor measurements in CC molds
9:20	R. Liu	Transient turbulent fluid flow,level fluctuations, and mold slag
6. 9:50	S-M. Cho	Clogging effects on Asymmetric Flow and Vortex Formation
10:10	*Break*	
10:30	K. Thomas & BGT	Animations of Initial Solidification during Mold Oscillation
10:45	H. Jasti	User-friendly interface for CON1D heat transfer model of CC
11:30	Z. Zhou	Heat transfer during spray cooling: Lab measurements, CON1D model predictions, & plant measurements
12:00		Discussion of flow and heat transfer projects
12:30pm	*Lunch*	2005 Mech. Eng. Lab

Day 1: Afternoon Session

11. 1:00	B. Petrus	Online Control of Spray Cooling using CONONLINE
1:30	K. Xu	Modeling Heat Transfer, Precipitate Formation, and Grain Growth in Secondary Spray Cooling
2:10	L. Hibbeler	Thermal-Mechanical Behavior of the Solidifying Shell, Ideal Taper, and Longitudinal Crack Formation in a Funnel Mold Multi-physics model of shell-growth in a beam-blank mold including effects of fluid flow and thermal distortion
2:40	M. Rowan	Stress and Hot Tearing of Solidifying Steel Shells: Experiment and Simulation
3:00	*Break*	
3:20	J. Iwasaki	Analysis of off-corner longitudinal crack formation in slab casting and comparison of hot-tearing criteria
16. 3:50	V. Singh	User-friendly Model of Heat Transfer in Submerged Entry Nozzles during Preheating and Casting
4:10	V. Natarajan	Modeling and Control of Mold Oscillation
4:30	X. Zhou	Heat Transfer in Scarfing Processes
5:00		Group discussion of future projects and directions
5:30	Adjourn meeting	
6:00	*Dinner*	General Lounge, Illini Union Building

Day 2

B.G. Thomas: 356 Mech. Eng. Bldg.
Informal discussions on future projects
(Prior appointments would be helpful)

8:00 – 9:00	Posco (Seon-yeon Kim)
9:00 – 10:00	Nucor Steel discussion (R. O'Malley)
10:00 – 11:00	LWB discussion (R. Nunnington)
11:00 – 12:00	Mittal discussion (M. Yavuz)
1:00 – 2:00pm	Corus Discussion (G. Abbel)
2:00 – 3:00pm	ABB discussion (Olof Hjortstam)
3:00 – 4:00pm	Nippon Steel (E. Takeuchi)

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

Day 3 (Aug. 7) ??

Research Summaries

Flow Dynamics and Electromagnetic Effects in Continuous Casting of Steel

B.G. Thomas,* R. Chaudhary, R. Liu, and C. Ji

*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 has been incorporated. The effect of 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 investigated. Models to compute the transport and entrapment of inclusion particles are being tested through water model experiments, laboratory measurements with molten metal, steel plant trials, and metallographic measurements at several steel companies who are cosponsoring this research. Plant measurements include magnetic field strength for ruler-fields, and nail-board velocity and surface profile measurements.

Entrapment of Bubbles and Inclusions during Flow in the Mold

B.G. Thomas,* S.H. Kim, R. Chaudhary, R. Liu, 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

Computational Methods for Transient Turbulent Fluid Flow Analysis

B.G. Thomas,* P. Vanka, R. Chaudhary, R. Liu, Chuanbo Ji.

*Continuous Casting Consortium***

Modeling of transient turbulent fluid flow is a difficult and time-consuming computational task, especially when phenomena such as electromagnetic fields and multiphase flow are incorporated. A systemic study is being conducted to assess available numerical methods, by comparing their performance on simplified test problems where solutions are known or evaluated using accurate Direct Numerical Simulations. The best models are then evaluated by comparison with measurements conducted at Dresden on molten metal flow, with and without electromagnetic field application. The project is aided by development of a new transient flow modeling system that runs on Graphical Processing Units.

Effect of Stopper-Rod Movement on Transient Mold Flow and Product Quality

B.G. Thomas,* R. Liu, R. Chaudhary, J. Sengupta, D. Crosbie, M. Yavuz.

*Continuous Casting Consortium***

Transient events in the mold, such as sudden stopper-rod movement cause changes in turbulent flow of molten steel through the continuous casting nozzle and mold pool, leading to level fluctuations, inclusion entrainment, and internal defects in the final product. Transient three-dimensional models of turbulent flow are being developed, including the effects of dynamic flow oscillations and surface waves. They are being applied to model specific events involving stopper-rod movement, which have been linked to specific product defects. Detailed plant measurements to support this project are being performed at ArcelorMittal Dofasco to measure mold flow parameters, including changes in stopper movement with time, and surface velocity and profile in the mold, and to correlate them quantitatively with specific sliver defects in ultra-low-carbon steel coils. The results will lead to new understanding and better methods to predict and improve product quality through online detection.

Research Summaries

Thermal Stress Analysis of Solidifying Steel Shells

B.G. Thomas,* L. Hibbeler, S. Koric, 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 include the effects of mold distortion, and superheat in the liquid pool, and 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.

Modeling of Heat Transfer, Clogging and Erosion of Nozzle Refractories

B.G. Thomas,* V. Singh.
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. Fundamental computational models are being developed to study the complex coupled phenomena which govern this process: 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 molten steel, the diffusion of compounds such as Al_2O_3 and CaO through the nozzle wall, and the thermodynamics of the chemical reactions that form solid precipitates, or change the composition of the inclusions to liquefy them, allowing them to erode from the walls. With the support of experimental measurements, the models provide new insights into this process, and estimates of clogging and erosion rates. In addition, a computational tool has been developed to predict transient temperature evolution during preheating, cooling, and casting, including a model of flame temperature, and solidified steel-skull formation during the initial stages of casting with a cold nozzle.

Research Summaries

User-Friendly Interface for CON1D

B.G. Thomas,* H. Jasti.
*Continuous Casting Consortium;***

CON1D is an efficient computational model for calculating heat transfer and related phenomena in the continuous-casting of steel slabs including both the mold and strand. Its predictions of mold temperature, shell thickness, mold heat flux, interfacial friction, structure, strand-temperature in the spray zones, metallurgical length, and other casting parameters have been validated with many different plant measurements. It is already in use in several steel plants and has been incorporated into a real-time online control system. To enable easier application of this powerful tool, a new user-friendly interface is being developed. This interface will enable coupling the model with other models, off-line data bases, and post-processors, using an intuitive graphical interface. This will increase the usage of the model in industry, and will facilitate new applications.

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 - NSF

Manipulating the Contacting and Solidification of Molten Metal in Continuous Casting

B.G. Thomas,* O. Alber, V. Singh.

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.

GOALI: Online Dynamic Control of Cooling in Continuous Casting of Thin Steel Slabs; Hybrid Control of Continuous Casting for Whale and Crack Prevention

B.G. Thomas,* J. Bentsman*, B. Petrus, X. Zhou, A.H. Castillejos, F.A. Acosta

*Continuous Casting Consortium;** National Science Foundation GOALI DMI 05-00453; CMMI-09-00138*

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 uses 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 is being validated with measurements of spray heat transfer in controlled lab experiments and in the steel plant.

Research Summaries - related

Prediction of Hot Tearing Cracks during High-Alloy Continuous Casting at Baosteel

B. G. Thomas,* C. Li, M. Rowan.

Baosteel, Shanghai, PRC.

High-alloy steel products are susceptible to internal "hot-tear" cracks during continuous casting. Efficient and robust computational models of transient thermal-stress have been developed to predict temperature, strain, and stress evolution during the solidification of steel. Fundamental controlled experiments are being conducted to measure the critical strain needed to produce hot tear cracks in different steel grades. By accurately modeling of the experiments, better criteria and methodologies to predict these cracks are being developed. Continuous-casting simulations of realistic plant conditions are being run, including the effects of bulging and bending forces, to predict internal crack formation. The modeling system will then be applied to understand the causes of internal cracks, and to optimize the process to minimize cracks.

Evaluation of Funnel Shapes for Thin Slab Casting

B.G. Thomas,* L. Hibbeler.

CORUS, Netherlands; POSCO, Pohang, S. Korea

Continuous-casting molds with a central funnel-shape are used to cast thin slabs using conventional flow nozzles. They have the disadvantage of generating additional stress and strain in the solidifying steel shell, leading to increased tendency for longitudinal facial crack (LFC) formation. Advanced computational models of heat transfer, stress, strain, and crack formation are being developed to understand the mechanisms of LFC formation, and to investigate designs of funnel shape and narrow-face tapers, to lessen the chance of LFC formation. In addition to handling the complex geometries, the models incorporate accurate constitutive models of the mechanical behavior, and criterion functions to predict the formation of hot-tear cracks. Model validation is assisted by experimental measurements of heat transfer and crack incidence in operating thin-slab casters.

New CCC Software

Excel Spread-sheet software (included on CD):

- User-friendly interface for CON1D

  Creates input file with grade and spray tables, choice of units
  Runs con1d, Graphs results

  H. Jasti

- Nozzle Heat Conduction Model

  1. Flame temperature; gas composition; heat transfer coefficients, etc.
  2. Nozzle temperature during preheating, cooling, and casting

  V. Singh

2010 CCC Reports 1 (on CD)

Fluid Flow: Practical

Investigation of Mold Flux Entrainment in CC Molds Due to Shear Layer Instability
L.C. Hibbeler and B.G. Thomas CCC Report 201001

Effect of Stopper-Rod Misalignment on Fluid Flow in Continuous Casting of Steel CCC Report 201011
R. Chaudhary, G.G. Lee, B.G. Thomas, S.M. Cho, S.-H. Kim, and O.-D. Kwon

Effect of Stopper-Rod Misalignment on Asymmetric Flow and Vortex Formation in Steel Slab Casting
S.M. Cho, G.G. Lee, S.H. Kim, R. Chaudhary, O.D. Kwon, B.G. Thomas (TMS Evans)

2010 CCC Reports 2 (on CD) new

Fluid Flow: Model Evaluation and Improvement

Assessment of LES and RANS turbulence models with measurements in liquid metal GaInSn model of continuous casting process
R. Chaudhary, C. Ji, and B. G. Thomas CCC Report 201013

Evaluation of turbulence models in MHD channel and square duct flows
R. Chaudhary, S.P. Vanka, and B.G. Thomas

Direct Numerical Simulations of Magnetic Field Effects on Turbulent Flow in a Square Duct
R. Chaudhary, S.P. Vanka, and B.G. Thomas CCC Report 201012

2010 CCC Reports 3 (on CD)

Heat Transfer

A Novel Steady-state Technique for Measuring the Heat Extracted by Secondary Cooling Sprays
C.A. Hernández, A.H. Castillejos, F.A. Acosta, X. Zhou* and B.G. Thomas*
AISTech 2010

Real-Time Model-Based Spray-Cooling Control System for Steel Continuous Casting (revised)
Bryan Petrus, Kai Zheng, Brian G. Thomas, Joseph Bentsman

Calibration of Mold Heat Transfer Models with Breakout Shell Measurements
J. Iwasaki and B.G. Thomas — CCC Report 201015

User-friendly Interface Design and Development for Continuous-Casting Model CON1D
H. Jasti (MS Thesis) — CCC Report 201004

2010 CCC Reports 4 (on CD)

Precipitate Formation

Equilibrium Model of Precipitation in Microalloyed Steels
K. Xu, B.G. Thomas, and R.J. O'Malley
Met Trans B, in press.

Microalloy Precipitation in Hot Charged Slabs
M.S. Dyer, J.G. Speer, D. K. Matlock, A. J. Shutts, S. Jansto, K. Xu, B.G. Thomas
AISTech 2010

Particle-Size-Grouping Model of Precipitation Kinetics in Microalloyed Steels
K. Xu and B.G. Thomas — CCC Report 201014

Stress and Cracking

Measuring Mechanical Behavior of Steel During Solidification: Modeling the SSCC Test
M. Rowan, B.G. Thomas, C. Bernhard, R. Pierer — CCC Report 201002.

2010 CCC Reports 5 (on CD)

Computational Modeling

Multiphysics Model of Metal Solidification on the Continuum Level
S. Koric, L. Hibbeler, R. Liu, and B. G. Thomas CCC Report 201016

Enhanced Latent Heat Method to Incorporate Superheat Effects into Fixed-Grid Multiphysics Simulations
Koric, S., B.G. Thomas, and V.R. Voller
Numerical Heat Transfer B, 2010.

Related Processes

Modeling Steel Slab Heat Transfer During Scarfing Processing
X. Zhou and B.G. Thomas CCC Report 201003

2010 CCC Reports 6 (on CD)

Reprints

Effect of Refractory Properties on Initial Bubble Formation in Continuous Casting Nozzles (reprint)
G.-G. Lee, B.G. Thomas, and S.-H. Kim
Met. Mater. Int., Vol. 16, No. 3 (2010), pp. 501~506

Industry Implementation of Mathematical Models: Examples in Steel Processing; Howe Memorial Lecture, 2009
B. G. Thomas
Iron and Steel Technology, July, 2010

Modeling of Hot Tearing and Other Defects in Casting Processes (reprint)
B.G. Thomas
ASM Handbook V. 22, 2009