The Visualization of Defect Formation during Casting Processes

Brian G. Thomas and Joydeep Sengupta

As the demand for higher-quality components increases, a variety of casting defects that compromise final-product integrity continues to challenge both scientists and engineers. Understanding the defect-formation mechanisms is challenging because casting processes involve complex interactions between a multitude of transient physical phenomena, such as heat transfer, mass transport, fluid flow, solidification, microstructural evolution, and thermal distortion.

State-of-the-art methods to study the formation of casting defects include in-situ observation and computer simulations. Visualizing the results using video animations is a powerful tool for understanding multi-dimensional, transient phenomena. The *JOM-e* articles introduced in this commentary feature animations of the results from ongoing efforts around the world to gain new insights into the formation of a variety of defects in steel and aluminum castings.

ENTRAPPED INCLUSIONS

Exposure of molten metal to air causes reoxidation that generates inclusions, degrading both mechanical properties and surface appearance. For example, the entrapment of oxide dross greatly lowers the quality of aluminum ingots poured on a wheel caster. The article by M. Prakash et al. discusses the application of a new grid-free computer simulation method called smoothed-particle hydrodynamics to predict and visualize the evolution of transient fluid flow and oxide content during the pouring and mold filling of this complex process. (Abstracts, images, and web addresses for all articles in this issue of *JOM-e* are presented in the sidebars.) The animations show striking realism. Moreover, the authors provide practical evaluations of different configurations, which resulted in optimized wheel and nozzle designs.

In the continuous casting of steel, inclusions may become entrapped in the final product, from particles entering the mold from upstream or from the entrainment of surface slag. The article by B. Thomas et al. uses large-eddy simulations of inclusion transport in turbulent flow to show how the transient fluid flow pattern in the nozzle and mold controls these detrimental phenomena.

SURFACE DEFECTS

Initial solidification at the meniscus, where the free surface of the molten metal touches the mold wall, creates the surface of the final cast product. Complex interacting phenomena at this critical location often cause surface defects that become apparent only after many expensive downstream processes. The article by J. Sengupta and B. Thomas presents animations that clearly visualize how sub-surface microstructural defects called "hooks" and surface grooves called "oscillation marks" arise at the meniscus during mold oscillation in the

THE DESIGN MODIFICATION AND OPTIMIZATION OF AN INGOT CASTING WHEEL USING SPH

By Mahesh Prakash, Paul W. Cleary, John Grandfield, Patrick Rohan, and Vu Nguyen

www.tms.org/pubs/journals/JOM/0612/Prakash/Prakash-0612.html

In aluminum re-melt ingot casting, the quality of ingots produced can depend to a large extent on the wheel and nozzle design. The nature of the flow through the wheel and nozzle can result in increased exposure of aluminum to air, thus increasing the amount of dross (oxide) in the system. This oxide reduces the quality and surface finish of the ingots that are finally formed. At present there is no way of experimentally evaluating the amount of oxide present in the ingots and pilot-scale experimentation is expensive and difficult. The challenge addressed here is to develop better wheel designs that operate at higher flow rates and reduce the extent of oxide generation. The grid-free smoothed-particle hydrodynamics method was used as the primary computational modeling tool with full-scale testing using a pilot caster setup to complement the modeling. This article reports on the various stages of design modifications to the wheel and nozzle based on results obtained from earlier designs, finally leading to an optimized wheel design.

Figure 3. A flow pattern as the fluid impacts the area directly into the spout. Left, experiment; right, smoothed-particle hydrodynamics simulation.

TRANSIENT FLUID-FLOW PHENOMENA IN THE CONTINUOUS-STEEL-SLAB CASTING MOLD AND DEFECT FORMATION

By Brian G. Thomas, Quan Yuan, Bin Zhao, and S. Pratap Vanka

www.tms.org/pubs/journals/JOM/0612/ThomasII/ThomasII-0612.html

Phenomena associated with the turbulent flow of molten steel in a continuous-casting mold are responsible for many defects in the final product, including surface slivers, frozen meniscus hooks, captured inclusions that enter the mold from upstream, and mold slag entrapment. Animations of some of these transient flow phenomena are presented from large-eddy simulations of a typical slab caster with a three-port nozzle. The illustrated phenomena include the transport of superheat with the turbulent transient flow of molten steel, surface-level fluctuations, and the transport and entrapment of inclusion particles.

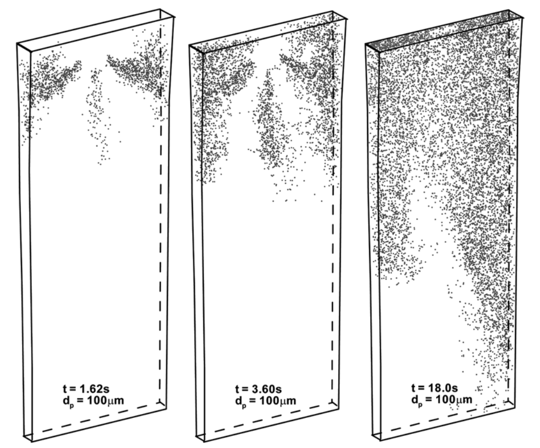

Figure 7. The transport of 100 μm inclusions in the strand at different times after entering through the nozzle.

continuous casting of steel. Deep hooks entrap inclusions and transverse surface cracks often initiate at the roots of deep oscillation marks.

Surface defects are also affected by flow conditions in the mold. Insufficient superheat transported to the meniscus aggravates hook formation. Excessive turbulence and level fluctuations at the surface lead to longitudinal facial cracks, slivers, and breakouts. The article by B. Thomas et al. also extends the large-eddy simulations to gain insight into some of these phenomena.

INTERNAL DEFECTS

Segregation leads to severe internal defects in alloy castings. At the micro-scale, internal hot-tear cracks become permanent defects if they fill with enriched interdendritic liquid. At the macro-scale, segregated liquid frequently concentrates near the casting center line. The article by M. Wu and A. Ludwig applies a multiphase model of thermal-fluid flow, solidification, and grain sedimentation to visualize macrosegregation, columnar-equiaxed transition, and grain size distribution in ingot castings. The model includes the effects of thermal, solutal, surface-tension, and phase-dependent forces on the convection and composition distribution.

Porosity can downgrade the integrity of a casting by providing initiation sites for hot-tear cracks during solidification and fatigue crack propagation during service. The article by P. Lee, J. Wang, and R. Atwood presents animations of in-situ measurements and advanced computations to clearly visualize the tortuous three-dimensional shapes of interdendritic microporosity in aluminum-alloy castings. Meso-scale simulations including heat transfer, dendritic solidification, grain structure, gas distribution, pore nucleation, and growth match well with the measurements. These simulations further reveal the relative importance of gas supersaturation and shrinkage effects on microporosity size and shape.

RESEARCH TOOLS

These five articles in this *JOM-e* topic exploit a range of modeling and experimental techniques to study casting defects. All of them apply computational models that have been validated with experimental measurements. At their best, such modeling tools can now serve as a virtual laboratory for developing casting processes, with advantages over a real laboratory. Computer animations enable researchers to visualize transient phenomena that are difficult to observe and quantify during the actual casting process, such as reoxidation (Prakash), superheat and inclusion transport (Thomas), segregation (Wu), grain sedimentation (Wu), dendritic solidification (Wu and Lee), and porosity formation (Lee).

VISUALIZING HOOK AND OSCILLATION MARK FORMATION IN CONTINUOUSLY CAST ULTRA-LOW-CARBON STEEL SLABS

By Joydeep Sengupta and Brian G. Thomas

www.tms.org/pubs/journals/JOM/0612/ Sengupta/Sengupta-0612.html

Oscillation marks accompanied by sub-surface hooks routinely appear on the surface of continuously cast steel slabs, and are especially severe in ultra-low-carbon steel. This article presents a new detailed mechanism for their formation, which has been developed by combining existing theoretical modeling results, experimental observations, and analyses based on optical and scanning-electron microscopy. Hooks form by solidification and dendritic growth at the liquid meniscus during the negative strip period. Oscillation marks are generated when molten steel partially overflows over the frozen meniscus shortly afterward and incompletely fills in the gap before solidifying. The results are presented in the form of a graphical animation of the various events occurring near the meniscus that lead to the formation of these defects.

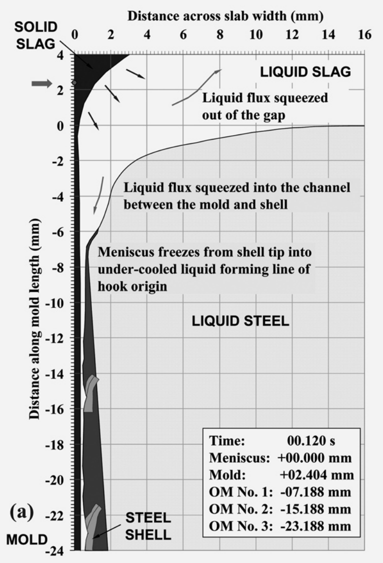

Figure 10. Meniscus freezing: a crucial event in the formation of a hook and oscillation marks.

MICROPOROSITY FORMATION DURING THE SOLIDIFICATION OF ALUMINUM-COPPER ALLOYS

By Peter D. Lee, Junsheng Wang, and Robert C. Atwood

www.tms.org/pubs/journals/JOM/0612/Lee/Lee-0612.html

The formation of microporosity during the solidification of aluminum-copper alloys was quantified using three techniques: an x-ray temperature gradient stage (XTGS), x-ray microtomography, and mesoscale simulations. The mesoscale simulations solved for the nucleation and diffusion limited growth of both the solid and gas phases from the molten alloy, predicting both the growth kinetics and final morphology of the solid and pores. To experimentally validate this model, an XTGS was used to quantify the pore growth in real time, but only in two dimensions. X-ray microtomography was then performed on the as-cast microstructure to allow three-dimensional (3-D) visualization of the final morphology of the pores. A comparison of the predicted and experimentally observed growth rates illustrated the importance of incorporating gas, shrinkage, and curvature effects. The tomographic results illustrated that including the interaction of the gas and solid phases is critical if the tortuous 3-D shapes and maximum sizes are to be predicted.

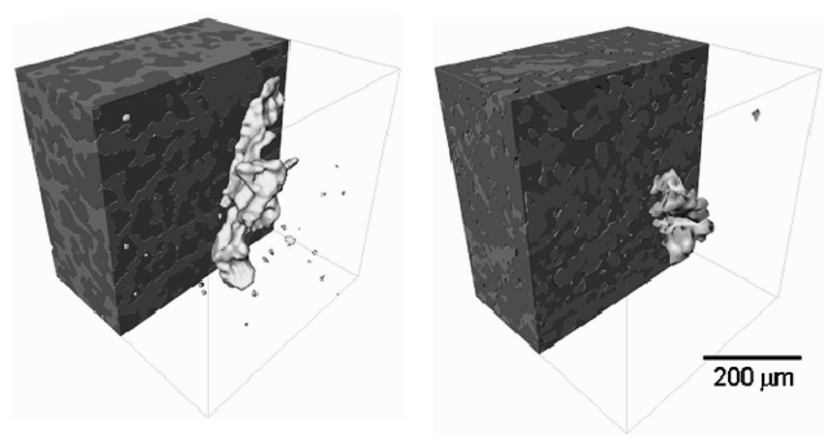

Figure 7. (left) An x-ray microtomography-measured 3-D grain and microporosity morphology and (right) a mesomodel-predicted grain and pore morphology.

MODELING MACROSEGREGATION WITH A MULTIPHASE APPROACH: EXAMPLES AND DISCUSSIONS

By Menghuai Wu and Andreas Ludwig

www.tms.org/pubs/journals/JOM/0612/Wu/Wu-0612.html

A multiphase approach is used to study the macrosegregation phenomena that occur during solidification. Some modeling examples with accompanying animations are presented in this article to increase the understanding of different mechanisms of macrosegregation formation. Examples are presented consecutively with increasing complexity of the mechanisms: macrosegregation in columnar solidification, macrosegregation in globular equiaxed solidification, macrosegregation in the mixed equiaxed-columnar solidification, and Marangoni convection induced macrosegregation.

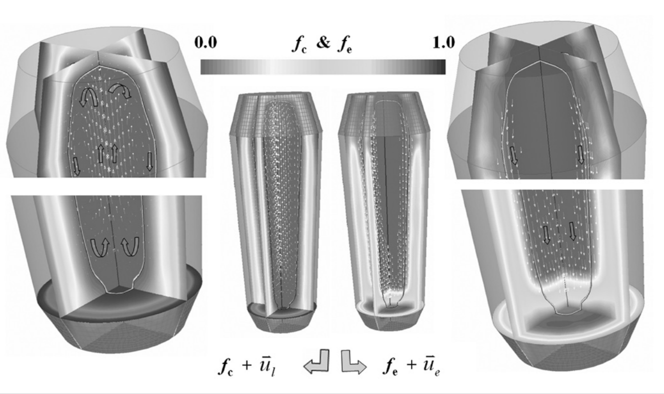

Figure 5. A simulated solidification sequence (at 20 s) of a steel ingot.

Turbulent fluid flow in a full-scale water model behaves similarly to molten-metal flow and is used to validate the computational flow models (Thomas). Micrographs of etched ultra-low carbon steel samples and other experimental observations are combined with computer model results to develop the animation of oscillation mark and hook formation (Sengupta). Real-time video (Lee) of internal microstructure evolution during laboratory solidification experiments shows in-situ x-ray temperature gradient stage and x-ray microtomography techniques in real metals.

VIDEO ANIMATIONS

These research articles showcase more than 25 animations, which are published by TMS in the electronic portion of this journal, *JOM-e*, at *www.tms.org/pubs/journals/JOM*. The on-line journal provides an important archival medium to convey research results through animations, as the human brain processes moving visual information better than any other form of communication. Animation technology itself is a powerful tool to study the subtle complexities of casting defect formation.

In conclusion, the progressive development of both sophisticated mathematical models and advanced experimental techniques has allowed a better understanding of specific physical phenomena responsible for the formation of casting defects. Researchers and engineers continue to translate this new scientific information into real industrial processes and product quality improvements. Computer-aided visualization has emerged as one of many powerful tools available to today's process engineer, and the articles and animations presented in this issue of *JOM-e* are just the tip of the iceberg representing worldwide research in the field of casting technology.

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