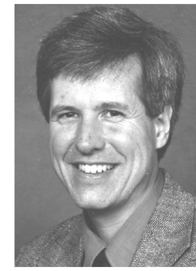
Casting Process Simulation and Visualization: A *JOM-e* Perspective



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With the increasing power of computer hardware and software, computational simulation and visualization are becoming increasingly important tools to understand and improve industrial processes, such as metal casting. Computer-aided visualization is increasing the power of all of the tools available to the solidification process engineer, including previous literature, mathematical modeling, laboratory experimentation, and online measurement of the casting processes. This article exemplifies all four of these.

This article is possible only through the format of on-line publication. The article features six separate contributions, published by TMS in the electronic portion of this journal: *JOM-e,* at www.tms.org/pubs/journals/JOM/articles.html. Each contribution provides several state-of-the-art computer animations and explains how these visualizations are being used to increase understanding and to improve a wide range of different casting processes. This relatively new format of archival publication allows anyone with an Internet browser to search and read the articles and watch the animations, all at no cost. Video publication was pioneered in 1996 with the Wiley journal, *Visualization of Engineering Research,* edited by V. Voller. Online publication in *JOM-e* and elsewhere now provides researchers a powerful medium to showcase their results through animation, and to thereby communicate their knowledge faster and better than ever before.

The first four articles feature advanced computational simulations of transient solidification phenomena. As solidification is inherently a transient process, it should not be surprising that our understanding of the modeling results is greatly aided by animations. A diverse range of casting process phenomena are simulated in these articles, starting with fluid flow during the filling of foundry castings in "The Mold Filling and Solidification of a Complex Foundry Casting," by S.G.R. Brown et al. Also reviewed is transient flow during the continuous casting of aluminum, in "The Multiphysics Modeling of Solidification and Melting Processes," by M. Cross et al., and "The Numerical Simulation of Continuous and Investment Casting," by P. Thévoz et al.; steel (Thévoz et al., and "Transient Fluid Flow in a Continuous Steel-Slab Casting Mold," by Thomas et al.); magnesium (Thévoz et al.) and copper (Thévoz et al.). Other casting process simulations include horizontal and twin-roll continuous casting, and the directional solidification of turbine blades (Thévoz et al.). Most of the simulations also feature coupling with the accompanying evolution of solidification phenomena, temperature, grain structure, even stress fields. Simulations even illustrate the coupling of fluid flow with electromagnetic forces and solidification in cold-crucible melting and levitated droplet processes (Cross et al.). Models have been further extended to predict important microstructural properties, such as dendrite arm spacing (Brown et al.) and grain size distributions (Thévoz et al.) and defects such as porosity (Thévoz et al.) cold shuts (Cross et al.) and hot cracking sensitivity (Thévoz et al.).

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As shown in these contributions, mathematical models of casting processes are now tackling multiphysics problems of staggering complexity. This sophistication is necessary to contribute to understanding and solving the complex problems that affect real processes. This modeling revolution is possible because computer speed and memory have both increased many orders of magnitude in recent years, while simultaneously, hardware costs have dramatically decreased. As computing power continues to improve, advanced computational simulations will play an increasing role in process development, often replacing traditional experiments.

Computer advances for laboratory experiments now enable the rapid capture of digital images and their processing into powerful visualizations. One contribution (Thomas et al.) compares transient computations with animated velocity vectors from digital particle image velocimetry measurements of fluid flow in a 1m high water model of the continuous-casting process for steel slabs. Creating such videos used to take weeks, but now can be viewed in real time. Another contribution, "The Observation of Coalescence and Hot Tear Formation in Organic Alloys" by P.-D. Grasso et al., shows close-up slow-motion videos of hot tearing proceeding between individual dendrites, while subjected to tensile loading during solidification. These powerful advances in computer-assisted measurement and visualization are enabling more insights to be derived from laboratory experiments of any size.

JOM-e: CASTING PROCESS SIMULATION AND VISUALIZATION

"The Multiphysics Modeling of Solidification and Melting Processes," by M. Cross et al.

www.tms.org/pubs/journals/JOM/0201/Cross/Cross-0201.html

Solidification and melting processes involve a range of physical phenomena and their interactions (i.e., multiphysics). Computational modeling of such processes presents a significant challenge, both in representing the physics involved and in handling the resulting coupled behavior. Two methods for the computational modeling of multiphysics processes in complex geometries are highlighted in the context of four challenging applications. Visualization of the key results aids the understanding of what is often a complex, highly dynamic behavior.

"Transient Fluid Flow in a Continuous Steel-Slab Casting Mold," by B.G. Thomas et al.

www.tms.org/pubs/journals/JOM/0201/Thomas/Thomas-0201.html

Transient flow in a continuous-casting mold is quantified using two recent tools for studying flow: large eddy simulation calculations and particle image velocimetry measurements. The two methods produce similar results and reveal transient flow features that are very different from time-average flow patterns. Inlet swirl causes jet oscillations, and complex vortex structures evolve and decay in both the upper and lower recirculation zones. These flow structures are visualized with three transient animations. In addition, inclusion particle trajectories through the flowing liquid are animated and compared successfully with measurements.

"The Mold Filling and Solidification of a Complex Foundry Casting," by S.G.R. Brown et al.

www.tms.org/pubs/journals/JOM/0201/Brown/Brown-0201.html

The design of a generic structural automotive component as an aluminum casting is described. Computer simulation and visualization has enabled the part to be designed simultaneously for both in-service performance and ease of manufacture.

"Analyzing Casting Problems by the On-line Monitoring of Continuous Casting Mold Temperatures," by P. Hemy et al.

www.tms.org/pubs/journals/JOM/0201/Hemy/Hemy-0201.html

A fully instrumented continuous casting funnel mold employed online at Algoma's thin slab casting machine has helped operating personnel gain valuable insight into shell behavior during casting. The effects of several process upsets—steady state and transient, on the solidifying shell such as broad face crack, detachment of off-corner broad face from the mold wall, loss of taper, SEN rupture, and detachment of narrow face can be readily observed in-situ during casting. In this article, some of these phenomena are demonstrated in a series of AVI files that can be played back. Information from the instrumented mold coupled with breakout prediction algorithms and heat flux data have provided a powerful diagnostic tool to monitor the shell behavior in the mold and to restore steady-state conditions if and when process upsets occur.

"The Observation of Coalescence and Hot Tear Formation in Organic Alloys," by P.-D. Grasso et al.

www.tms.org/pubs/journals/JOM/0201/Grasso/Grasso-0201.html

Hot tear formation has been observed during the solidification of a succinonitrile–acetone (SCN-acetone) alloy by pulling the columnar dendrites in the transverse direction with a stick. Cracking of the mushy zone (hot tears) always occurs at grain boundaries. At low volume fraction of solid, the opening can be compensated for by leaner-solute interdendritic liquid (i.e., "healed" hot tears). At higher volume fraction of solid, hot tears directly nucleate in the interdendritic liquid or develop from pre-existing micropores or air bubbles induced by solidification shrinkage. Moreover, coalescence/bridging of dendrite arms has been carefully observed and the temperature at which this occurs has been measured. This article reviews the results of those observations, shedding new light on the formation of hot tears in metallic alloys.

"The Numerical Simulation of Continuous and Investment Casting," by P. Thevoz et al.

www.tms.org/pubs/journals/JOM/0201/Thevoz/Thevoz-0201.html

The casting industry has seen rapid advancements in commercially available numerical simulation technology. Software is available, not only for thermal and flow modeling, but for calculation of grain structure, porosity, hot tearing, and solid-state transformation. This paper presents a review of numerical simulation applications for the continuous casting of steel, aluminum alloys, magnesium alloys, and copper alloys, along with investment casting.

Finally, computer advances now enable real-time, online measurement, visualization, and control of real casting processes. The final contribution, "Analyzing Casting Problems by the On-line Monitoring of Continuous Casting Mold Temperatures," P. Hemy et al., shows evolving temperature contours in the mold of the thin slab caster at Algoma Steel, which were calculated during casting from the online measurements of thermocouples embedded in the funnel mold. Several different sample visualizations are provided (Hemy et al.), which illustrate how the color temperature maps evolve during upsets in the casting process, such as longitudinal cracks, meniscus tears, SEN ruptures, loss of taper, and breakouts. Videos such as these, together with other data, enable the process engineer to perform "forensic metallurgy" to understand how defects evolve. By recognizing characteristic patterns in the signals, impending problems can be diagnosed before they happen. Armed with this understanding, casting operators can monitor the video images in real time during casting, and take appropriate preventative action, such as lowering the casting speed. Finally, the encoding of this knowledge into computer logic allows active online computer control of the casting process parameters to anticipate and avoid defects during the process.

In summary, computer advances are enabling better process model simulations, laboratory experiments, and communication of the results. As process understanding increases, and both computer monitoring and control capabilities improve, advanced online control methods will become commonplace in achieving more consistent quality from materials processes. Computer visualizations are improving all of the tools of the process engineer to help make this happen.

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