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Editorial

Optimization of Industrial Casting Processes

Steve Cockcroft

TIMET Professor of Advanced Titanium Processing, Department of Materials Engineering, The University of British Columbia, Vancouver Campus, Frank Forward Building, 309-6350 Stores Road, Vancouver, BC V6T 1Z4, Canada; Steve.Cockcroft@ubc.ca

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1. Introduction and Scope

Casting processes have seen continuous technological development for close to 5000 years, largely through a process of trial-and-error improvement. While modern casting is a sophisticated, technologically-advanced process capable of producing high quality parts economically, there remain significant opportunities for the optimization of the existing technologies and the development of innovative new technologies.

In the context of casting technology, and for a given alloy chemistry, optimization may be thought of as obtaining a desired design objective(s) through manipulation of the process parameters and/or altering the geometry of the mold system subject to constraints. The design objective may include, for example, elimination of shrinkage porosity above a certain size threshold, minimization of the overall solidification time, achieving a target secondary dendrite arm spacing at a given location, or minimization of the metal contained within the feeding system (process scrap).

Given the sophisticated state of the commercial solidification software now available, and the availability of significant computational resources at reasonable cost, we are starting to see an increase in the application of numerical optimization methodologies to casting processes, both from the commercial software vendors and from academia. The ability to optimize industrial casting processes at scale represents a formidable challenge, requiring highly accurate simulation capabilities, fast simulation capabilities, effective optimization algorithms, and the identification of suitable process objective functions and design constraints. We are still largely at the stage where sophisticated models are employed using a simulation-based, trial-and-error methodology to optimize casting processes. While this represents a step forward in comparison to conventional trial-and-error methodologies, there is the potential to realize additional improvement through the adoption of a fully numerical approach.

This Special Issue entitled Optimization of Industrial Casting Processes presents some of the latest research devoted to exploring the application of numerical methods to simulate and optimize casting methodologies.

2. Contributions to the Special Issue

Scholars have been invited to submit research papers dealing with the application of numerical models to optimize industrial casting processes. Among the submitted manuscripts, eight papers have been published in the issue. Four of the papers accepted had a focus on multi-physics modeling for fluid flow in continuous casting process technology (two on the tundish and two on the mold); two focused on feeding system analysis in near-net shape casting; one was on segregation in near-net-shape casting; and the final contribution was related to analysis of a nitride-based inoculant intended to enhance wear performance in a steel casting.

The study by Cwudziński [1] undertook an examination of the impact of different subsurface turbulence controllers (STC) and ladle shrouds (LS) on fluid flow in a 30 ton wedge-shaped tundish. The paper outlines the critical role that the tundish plays in continuous casting operations as it acts to both distribute the liquid metal to the mold(s) and serve as a reservoir of molten metal to allow continuous operation during the switching of ladles. To this end, it is critical that we understand the behavior of fluids within the tundish during typical operation in an industrial setting. The numerical simulation captured the velocity, pressure, and temperature fields in the tundish for the different cases examined. The flow field within the tundish was described in terms of the stagnant flow volume, dispersed plug flow volume, well-mixed volume flow, and transient zone volume. It was found that flow field within the tundish could be improved by the appropriate selection of the position of the STC and LS. Optimization was undertaken using a simulation-based, trial-and-error approach.

In another study of the tundish, the effect of channel heating was examined. Channel heating is argued to be beneficial for producing a consistent steel product quality by maintaining an optimal metal temperature. However, the fluid flow, temperature distribution, and the removal behavior of non-metallic inclusions will be much different from that in a conventional tundish, due to the input of heat. In the present work by Tang et al. [2], the flow and temperature fields in a tundish were investigated using hydrodynamic modeling coupled with mathematical simulation under isothermal and non-isothermal conditions, respectively. The results of the isothermal experiment indicate that the prototype tundish examined in the study has severe "short-circuiting flow" in the second and sixth strands, which might have caused the increased inclusion amounts observed in the billets produced from the two strands. The flow field within the tundish can be greatly improved by changing the channel design and adding two high dams at each side of the tundish. The non-isothermal analysis showed that the fluid presents an obvious rising tendency when it flows out from the heating induction channel. The larger the temperature difference inside and outside the channel, the more consistent the fluid flow between different strands and the more homogeneous the flow field in the whole tundish. A mathematic model has been proposed accordingly, which can explain the hydraulic phenomena observed. The inclusion removal rates of different cases were compared by mathematical simulation, and their removal mechanism was also studied.

In a study by Zhang et al. [3], a 3-D multi-physical numerical model was developed to predict the macro transport phenomena in a continuous casting mold while being subject to an electromagnetic (EM) field. The model described in the study is based on the ANSYS commercial software package and was formulated to investigate the effect of current intensity (0, 150, 200, and 240 A) on the heat, momentum, and species transport in a 160 × 160 mm billet. The results show that when the EM field is on, the flow pattern the temperature field within the mold is substantially altered. As the current is increased, the two longitudinal flow cells that form within the mold become more intensive, and the flow velocity of the molten steel at the solidification front increases. Additionally, the momentum of the metal input stream is dissipated over a shorter distance. The increased circulating flow results in increased heat transport toward the developing shell, resulting in a reduced shell thickness at the mold exit and the inverse segregation of carbon at the billet subsurface. The study does not make a specific recommendation as to an optimal current input.

Continuing on the theme of the multi-physics numerical modeling of fluid flow in continuous steel casting, Liu et al. [4] conducted a large eddy simulation (LES) of turbulent flow under a single-ruler electromagnetic brake (EMBr) in a laboratory-scale, continuous-casting mold. The influence of different electrically-conductive boundary conditions on the Magneto-Hydro-Dynamic (MHD) flow and electromagnetic field was studied, considering two different wall boundary conditions: insulating and conducting. Both the transient and time-averaged horizontal velocities predicted by the LES model agreed well with the measurements of the ultrasound Doppler velocimetry (UDV) probes. It was determined that the turbulent flow could be suppressed by both configurations of the experiment's wall (electrically-insulated and conducting walls). For the electrically-insulated walls, the flow was more unstable and changed with low-frequency oscillations. However, the time interval of the changeover was flexible. For the electrically-conducting walls, the low-frequency oscillations of the jets were suppressed and a stable double-roll flow pattern was generated. Electrically-conducting walls can dramatically increase the induced current density and electromagnetic force; hence they contribute to stabilizing the MHD turbulent flow. The study does not make a specific recommendation as to an optimal boundary condition.

Switching to near-net-shape casting, in the study by Papanikolaou et al. [5], a multi-objective optimization framework was combined with computational fluid dynamics (CFD) simulations to investigate the effect of the feeder(s) geometry on shrinkage porosity, the goal being to optimize casting quality and yield for a novel counter-gravity casting process (CRIMSON). The weighted sum technique was employed to convert this multi-objective optimization problem to a single objective one. Moreover, an evolutionary multi-objective optimization algorithm (NSGA-II) was applied to estimate the trade-off between the objective functions and support decision makers on selecting the optimum solution based on the desired properties of the final casting product and the process characteristics. This study is one of the first attempts to combine CFD simulations with multi-objective optimization techniques in counter-gravity casting. The obtained results indicate the benefits of applying multi-objective optimization techniques to casting processes.

Continuing with the design of the metal feeding system in a near-net-shape casting process, the article presents an attempt to optimize a gating system for a steel casting. The approach adopted in the study by Jezierski et al. [6] is based on John Campbell's theory and presents the original results of computer modeling of a typical gating system and an optimized system for cast steel components. The current state-of-the-art in a foundry was compared with several proposals for an optimized gating system. The aim was to find a compromise between the best, theoretically proven gating system version, and a version that would be affordable in industrial conditions. The results show that it is possible to achieve a uniform and slow pouring process even for heavy castings to preserve their internal quality.

In another study on near-net-shape casting by Fan et al. [7], silicon macrosegregation was investigated in the low-pressure die casting of aluminum alloy (A356) automotive wheels. The model results were compared with silicon distribution maps measured using an optical, phase area-based technique. The model of the wheel casting process was implemented within FLUENT, a commercial computational fluid dynamics (CFD) software package. In the formulation adopted, liquid metal flow is driven solely by solidification shrinkage due to the variation in density between the liquid and solid phases. Buoyancy and die filling were ignored. Additionally, the model includes Darcy flow in the two-phase mushy zone, the release of latent heat, and solute redistribution at the micro-scale using the Scheil approximation. The model was validated against temperature and segregation data taken from a commercially cast wheel and shown to be qualitatively correct in predicting trends in temperature and segregation. A closer inspection of the data reveals that the model is quantitatively accurate to within 10–30%, depending on the location.

As a final contribution, the paper by Vdovin et al. [8], examined possible industrial applications of inoculating high manganese steel castings with a new ferroalloy, vanadium nitride. Ferrovanadium nitride was found to enhance the surface wear resistance of castings both in the as-cast state and following heat treatment. A fine grain structure was formed in the surface layers; specifically layers in direct contact with abrasive particles. The deformation twins that were present at the solid solution grain boundaries tended to change their orientation and characteristics. The impact-abrasion wear also led to a hardened layer formation at the working surface due to deformation twinning. The carbides (nitrides) present in the surface wear did not produce any significant impact on the process of deformation twinning. As the wear line extends deeper into the casting surface, the carbides and nitrides are ripped out and cavities occur in the wearing zone. The wear was reported to be controlled by the solidification rate in the original casting. Thus, at lower rates, a hardened layer is formed, which accommodates adjacent areas with differing twin characteristics such as orientation and spacing.

3. Conclusions

The Special Issue "Optimization of Industrial Casting Processes" includes papers covering the numerical based analysis and optimization of several ingot casting and near-net-shape casting processes.

The papers cover thermal-fluid flow phenomena, thermal-fluid-electromagnetic flow phenomena, segregation phenomena, and thermal-fluid-inclusion phenomena. One additional paper looks at the impact of a novel inoculant containing nitrogen and its impact on the wear characteristics of a steel casting. All of the papers point to the need for increased use of numerical analysis to help quantify and understand the complex phenomena occurring in commercial casting processes, setting the stage for process optimization and innovation.

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