Flow patterns and re-melting during filling of a large composite casting

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The filling and remelting of an industrial scale composite casting has been simulated to investigate the effect of fluid flow patterns in the liquid metal on the remelting of the shell material of the composite casting. In the composite casting under investigation, an outer shell material is first cast inside a large cylindrical mould, which is then assembled to additional mould parts, and the core material is poured into the shell/mould assembly. During casting of the core, a thin layer of the shell material re-melts and mixes with the core material producing a bonding layer of intermediate composition. Obtaining the optimum re-melting and thus intermediate bonding zone between the shell and core is critical to producing high quality rolls. The present numerical model employs the volume of fluid method and an enthalpy-porosity technique to couple the filling of the core material and re-melting of the shell material. The interface between the solid and liquid phases is tracked and can be used as a guide to examine the extent of remelting and, to some degree, mixing of the shell and core material. Simulations have shown that the circulation loops that form in the liquid metal pool significantly affect the amount of shell material that remelts.

Keywords: Composite Casting, Remelting, Casting Flow Patterns

Introduction

Composite metal castings are typically a multipart assembly where one material is cast in or around another pre-cast part that has a different composition and/or material properties. The motivation for this is the ability to have a single casting composed of different materials that are solidly bonded or adhered together. The multipart casting process needed to create such a composite brings additional challenges in manufacturing, primarily developing a casting procedure that ensures good bonding or cohesion between each material. This can be particularly difficult for large-scale metallurgical castings where the production conditions and nature of the non-transparent materials are such that direct observation of casting and solidification is not possible. This presents an opportunity to develop a numerical model that can lend additional insight into the filling, remelting, transport and solidification processes that take place during casting.

The casting process examined in this investigation begins with a horizontal spin casting of the shell with a diameter of 750 mm, thickness of 90 mm, and length of nearly 3 m. A first shell layer of high Cr steel is cast followed by a second layer that serves as an intermediate barrier material between the outer shell and inner core material. Upon solidifying, the shell and its mould are assembled with the moulds for the upper and lower neck of the casting. The core material is then poured from a ladle into the mould assembly. During the last casting step a layer of the shell will remelt as it comes into contact with the molten core material, creating a mixed-intermediate bonding layer between the core and shell materials.

Model description

The casting under investigation is over 6 m in length (including the shell mid-section and the upper and lower neck regions) and to date only a macroscopic enthalpy based approached has been used to calculate the evolution of the liquid, solid, and mushy zone regions. The current model aims to examine the amount of shell melting which occurs, the amount of shell-loss (shell material that is transported away and mixed with the core material) and subsequently the solidification of the entire assembly. Model development is carried out within the framework of the computational fluid dynamics software FLUENT.

Modelling the filling of the core material and melting of the shell material must be carried out concurrently since the shell material begins to melt upon first contact with liquid core material. This model treats the shell material and core material as a single material since upon melting the two materials will be miscible and will have relatively similar physical properties. FLUENT's volume of fluid (VOF) method is used to model the filling and air-liquid interactions. The VOF model is a surface-tracking technique used with a fixed Eulerian mesh and is based on the assumption that the fluids under consideration are not interpenetrating (in this case

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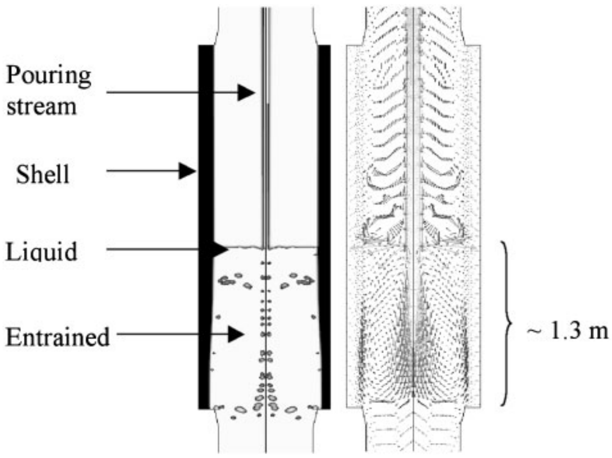
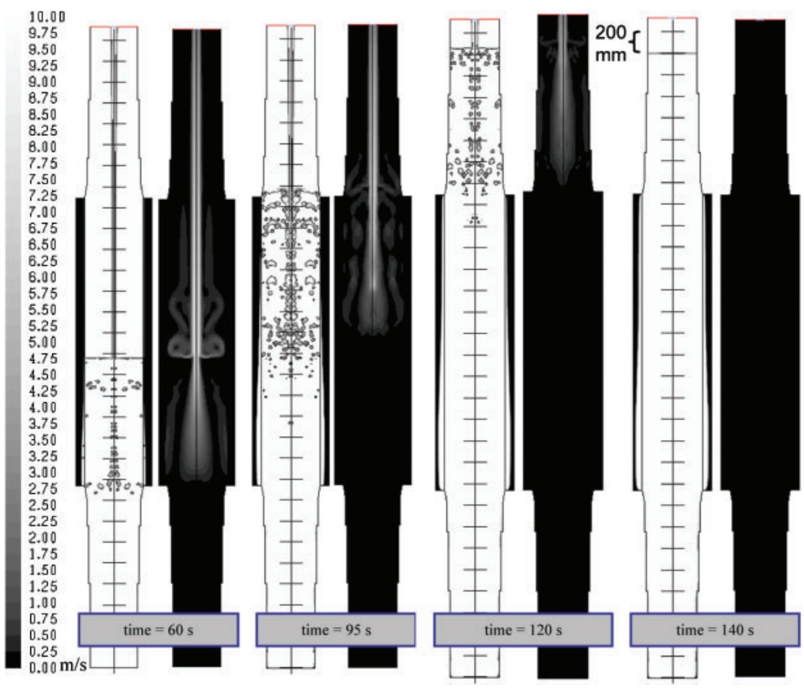


1 Flow patterns and melting of shell material during casting of a large composite casting. The solid, unmelted shell is shown in black and the bubbles within the liquid metal are shown as a density contour between liquid and air. The impact of the pouring stream on the liquid metal surface creates large recirculation loops in the liquid metal pool. The lower portion of the shell has remelted, primarily due to effects of the circulating flow of liquid metal

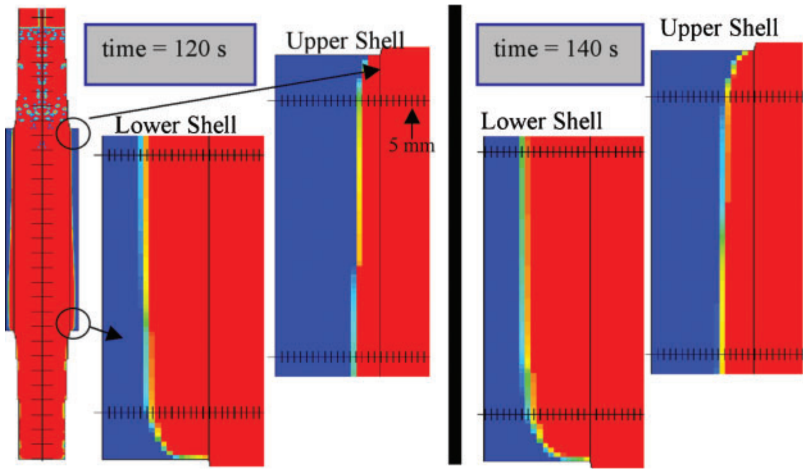
molten metal and air). A single set of momentum equations is shared by all fluids and the volume fraction of each of fluid in each computational cell is tracked throughout the domain.

Solidification and melting are handled with an enthalpy–liquid fraction technique that treats the two-phase (solid/liquid) 'mushy' region as a porous medium with the porosity in each cell equal to the liquid fraction in that cell. This enthalpy-based approach is based on the work of Voller and coworkers.[1–3] The phase change from liquid to solid is handled with a Darcy's law type source term in the momentum equation, such that velocities in the mushy region are suppressed and approach zero as the material solidifies. The source term relies on a parameter related to dendrite spacing in the mushy zone and is estimated based on a description similar to that found in Gu and Beckerman.[4] The combination of the VOF model and enthalpy-porosity technique creates an ideal model capable of capturing key flow phenomena during filling of the core and the extent of remelting and loss of the shell material that occurs during filling. A variation of the k–ε turbulence model is used, which includes refinements for rapidly strained from and swirling flows and utilises a effective viscosity that accounts for low-Reynolds-number effects. Buoyancy is not accounted for in the simulations presented here. A more in depth description of this modelling approach can be found in a previous publication.[5]

The full scale casting, 6134 mm in length and 372 mm at its greatest width, is modelled with a 2D axisymmetic structured grid with a total of 40,468 cells, which are 10×10 mm in the core of the casting are and $2{\cdot}5\times2{\cdot}5$ mm in the region of the shell-core interface where melting is expected to occur. The inlet is modelled as a 70 mm diameter opening, concentric within the axisymmetric domain. The inlet velocity of the core material is set at $2{\cdot}7$ m s^{-1} for a duration of 120 s. Heat transfer coefficients are 600 W m^{-1} K^{-1} for outer walls of the upper neck of the casting, 700 W m^{-1} K^{-1} for the mid section and lower neck, and 500 W m^{-1} K^{-1} at the bottom since it is effectively insulated by the earth. The top boundary, open to the surroundings, is modelled with a user defined function that sets the



2 Sequence of filling images (left of each pair) and corresponding velocity contours (right) show the mixing region moving upwards as filling progresses. The liquid level and entrained bubbles can be identified in the filling images. The circulation loops in the mixing region reach to a depth of approximately 1·5 m below the surface, with fluid velocities up to 2 m s^{-1}; below this depth the fluid is fairly quiescent and transport of shell material is unlikely. The black tick-marks are spaced at 200 mm



3 Comparison of the amount of remelting in the lower and upper parts of the shell at 120 s (the end of filling) and 140 s. At 140 s the vortex circulation due to filling has subsided (see Figure 2) and simulations show that the liquid metal is quiescent, thus further erosion of the upper shell will not occur, leaving a discrepancy in shell loss along the length of the shell

temperature, pressure, and turbulence quantities of top cells of the domain equal to their neighbouring internal grid cells.

Results and discussion

Results from these casting simulations have been particularly interesting in terms of the flow patterns which develop in the liquid pool during filling, particularly since it is this flow phenomena which influences the bonding region between shell and core, yet cannot be observed in practice. Strong mixing and large circulation patterns develop due to the impingement of the pouring stream on the liquid surface as is shown in Figure 1. The impact of the pouring stream drags the centre liquid downwards forcing a recirculation of fluid downwards in the centre of the casting and upwards along the shell-core interface. These circulation patterns and strong mixing are the primary causes of shell loss. It is critical to differentiate between shell melting, with no transport of shell material (which may occur when convection is weak), and shell loss, which refers to shell material that melts and is transported away mixing with the core material. An optimal amount of shell loss is that which creates a good bonding layer yet does not remove more than the intermediate shell material that serves as a buffer between the high Cr outer shell material and the nodular cast iron core.

In Figure 2 a sequence a filling images is shown in which the melting of shell material can be seen over the course of filling. Velocity contours are shown along with the filling images to highlight the regions of fluid motion in the casting; the fluid motion and velocities are highest in the region below the surface to a depth of 1·2 to 1·5 m. The degree of mixing or strength of circulation just below the liquid surface is directly tied to the impact of the pouring stream on the liquid pool and as filling progresses this impact decreases. During the filling of the lower half of the casting the pouring stream has a longer distance to fall, a higher velocity (8–11 m s^{-1}), thus a greater impact and stronger circulation loops to transport the shell material. At the top of the shell the pouring stream velocity is lower upon impact (4–8 m s^{-1}) and as a result the circulation loops are weaker and have less energy to contribute to 'erosion', transport and mixing of the shell material into the bulk fluid. In addition to having lower velocities in the upper half of the casting, the flow patterns transition from large, smooth circulation loop in comparison to the a more chaotic flow with numerous smaller circulation loops. The evolution of these mixing patterns has a direct effect on the amount of shell material that is lost to the bulk. Indeed, melting is particularly noticeable at the bottom end and greater than melting that occurs at the top, which corresponds to observations in actual production of the casting.

A closer view of the top and bottom shell melting is shown in Figure 3, where the differences in the amount of melted shell material at different times can be seen. In this figure the darkest /blue shading indicates solid, the gray/red area to the right is liquid, and the transition shading between these two represents the mushy zone. Considering the velocity fields shown in Figure 2 and noting that melting is still occurring in upper shell during the period from 120 s to 140 s we might conclude that at this stage it is possible that shell material is *only* melting and is not transported away from the shell.

Summary

Simulation of the filling and shell remelting of a full size industrial composite casting has been described here with particular emphasis on the import phenomena effecting remelting of the shell material. The results shown here show that the effects of pouring and melt circulation at the shell interface strongly influence the extent of remelting. Ongoing improvements in the model include implementation of species tracking, particularly to identify movement of shell material, more accurate solid fraction curves, temperature dependent physical properties, species tracking, grid refinement, and numerous parameter studies.

Acknowledgements

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References

1. V. R. Voller and C. Prakash: *Int. J. Heat and Mass Transfer*, 1987, **30**(8), 1709–1719.
2. V. R. Voller and C. R. Swaminathan: *Numerical Heat Transfer*, Part B, 1991, **19**, 175–189.
3. V. R. Voller, A. D. Brent and K. J. Reid: Computational modelling framework for analysis of metallurgical solidification processes and pheonomena. Proc. Conf. Solidification Processing, Ranmoor House, Sheffield, U.K., September 1987.
4. Gu and C. Beckerman: *Metallurgical and Materials Transactions*, 1999, **30A**(5), 1357–1366.
5. A. Fjeld and A. Ludwig: TMS Annual Meeting, EPD Congress 2008 Proceedings, Warrendale, PA, 2008, 281–292.