Abstract

Shrinkage or volumetric expansion due to different densities of liquid and solid phases is a prevalent phenomenon associated with solidification process. Therefore, physics based understanding of the influence of shrinkage or volumetric expansion on the micro and macro scale solidification mechanism is of utmost importance to regulate and improve final cast products with superior micro and macro-structural attributes. To accomplish the above objective, the present work focuses on investigating the effect of shrinkage and associated convection on solidification of metals and alloys, mainly through developing analytical and numerical models along with experimental investigations to reinforce the model predictions.

The first section of the study is attributed to the development of simple one dimensional solidification models with shrinkage or volumetric expansion being inherently accounted for. The existing analytical models of solidification are limited to semi-infinite domain only. Also, incorporation shrinkage or volumetric expansion effect in these models is hardly attempted. To overcome these limitations, a one-dimensional semi-analytical solidification model is developed, addressing the effects of shrinkage or volumetric expansion in a finite domain. The size variation in domain volume during solidification process due to shrinkage or volumetric expansion effect is addressed by using mass conservation. The proposed semi-analytical solidification model for finite domain devoid of shrinkage or volumetric expansion effect is validated with the results obtained from the existing enthalpy updating based numerical model. Water has been considered as the model phase change material for this validation. Once validated, the semi-analytical model is extended to include shrinkage and volumetric expansion effect, and predictions are made considering paraffin-wax and water as model phase change materials. The next set of study is attributed to the development of an inverse solidification model to predict the cooling curve for desired growth rate of solid front. To improve the quality of cast products, it is important to control the crystal growth during unidirectional solidification. Both equiaxed and dendritic grain structures depend strongly on growth rate along the crystallographic direction. Uncontrolled solidification possibly leads to the formation of porous and columnar material with an extremely non homogeneous composition distribution. These undesirable micro-structures can be avoided by adopting an optimal cooling rate (K/s) during the crystal growth. A semi-analytical model is developed capable to determine suitable cooling curves to obtain desired unidirectional crystal growth rates. The analysis is performed using properties of pure aluminium (Al) and the results are compared with existing experimental findings furnishing excellent agreements between model predictions and experimental observations.

The next set of analysis involves the development of a numerical model to address shrinkage induced flow during the directional solidification of metals and amorphous substance in a bottom cooled cavity. The numerical scheme proposed involves fix grid-based volume fraction updating method to track the solid-liquid interface. The riser-cavity assembly with bottom cooling orientation is selected to study the interaction between shrinkage induced flow with stably stratified thermal buoyancy field. The interaction between shrinkage induced flow with stably stratified thermal buoyancy field is found to instigate flow reversal within the melt. This flow reversal phenomenon uniquely predicted by the proposed numerical model is validated with the experimental observations using coconut oil as the model phase change material. Reasonably good qualitative and quantitative agreements are obtained between numerical predictions and experimental observations. Once validated, parametric studies are performed considering solidification of pure aluminium with varying casting conditions and geometric configurations to check the robustness and consistency of the proposed numerical model. The model is

extended further to analyse the compositional heterogeneity due to interaction between the solutal convection and shrinkage induced flow during the bottom up solidification of metal alloys. The system analysed for this set of investigation is always thermally stable. However, depending on the alloy composition and difference in solubility of the solute in the solid and liquid phases the solutal buoyancy field might be stable or unstable. In the presence of unstable solutal buoyancy field the mushy region (consisting of both solid and liquid phases) is characterized by channel or freckle formation along with the existence of plume type convection in the melt region. The proposed model is validated with the existing numerical model for the case of compositional segregation during the solidification of aluminium (Al)-4.1 wt.% copper(Cu) alloy in a bottom-cooled casting, devoid of freckling phenomena. Once verified, simulations were carried out to investigate the effect of shrinkage induced flow on freckle formation and associated solutal instabilities during the solidification of aluminium (Al)-30 wt.% magnesium (Mg). The strength of the shrinkage induced flow is directly related to riser opening size and cold boundary condition; thus, it played a major role in defining the onset of solutal instability and final macro-segregation. The results manifested unprecedented flow patterns and macro-segregation.

The concluding work involves capturing evolution of free surface during the solidification process owing shrinkage effect. The model domain consists of four phases namely: solid, liquid, mushy and void. The void density is considered to be very small as compared to other phase densities; and, the void phase is present at the upper-most region only. This develops a determinable void phase distribution and orientation of the free surface. Shrinkage cavity or free surface evolution is captured using the conventional volume of fluid method. The method approximates the interface reconstruction and estimates the flux volume across the face that is used to determine the void fraction across the free surface. The proposed numerical model is compared with the existing numerical and experimental results. Once validated, case studies are performed for varying the aspect ratio, cold boundary condition, and riser and mould cavity configurations. The study mainly focuses on developing a model capable to predict the macro-scale shrinkage defects during alloy solidification.

The proposed analytical and numerical models contribute towards physics based interpretation of solidification processes associated with pure substance and binary alloys and provide an underlying basis for the development of multi-scale solidification model.

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