

Preface

Large ingots remain indispensable raw materials for key components in energy, transportation, aerospace, and heavy equipment manufacturing. With the continuous increase in the scale and performance requirements of modern engineering structures, the demand for large and ultra-large ingots with high internal quality has grown rapidly. However, during the solidification of large ingots, complex transport phenomena involving heat, mass, momentum, and phase transformation inevitably lead to a series of metallurgical defects, among which macrosegregation is one of the most critical and difficult-to-control problems.

Macrosegregation refers to large-scale, composition inhomogeneities formed during alloy solidification, typically manifesting as positive or negative segregation bands, A-type segregation, V-type segregation, and centerline segregation. Unlike microsegregation, macrosegregation cannot be eliminated by subsequent heat treatment or plastic deformation and therefore has a direct and irreversible influence on the mechanical properties, service reliability, and safety of large-scale components. In large steel ingots and aluminum alloy ingots, macrosegregation is often accompanied by shrinkage cavities and porosity, further deteriorating internal quality and increasing the risk of premature failure.

Research Background and Challenges (Chapter 1 and Chapter 2)

The formation of macrosegregation is fundamentally governed by the coupling of solidification shrinkage, thermal and solutal convection, phase interaction, and dendritic growth kinetics. As ingot size increases, solidification time is significantly prolonged, thermal gradients become highly non-uniform, and melt flow driven by buoyancy, solidification shrinkage, and feeding becomes increasingly complex. These factors result in multi-scale, strongly coupled transport behavior that poses great challenges to both experimental observation and theoretical description.

Traditional experimental methods, such as chemical analysis of sectioned ingots or macro-etching techniques, can only provide post-solidification information and are unable to capture the transient evolution of macrosegregation. Moreover, industrial-scale experiments on large ingots are costly, time-consuming, and difficult to repeat, which severely limits systematic parametric studies. As a result, numerical simulation has become an indispensable tool for understanding and predicting macrosegregation in large ingots.

Development of Numerical Modeling for Macrosegregation (Chapters 3 - 5)

Over the past several decades, significant progress has been made in the numerical modeling of macrosegregation. Early models were primarily based on simplified assumptions, such as treating the mushy zone as a porous medium and neglecting the relative motion between solid and liquid phases. While these models could capture general segregation trends, their predictive accuracy was limited, especially for large ingots with complex solidification conditions.

With the advancement of computational fluid dynamics (CFD) and multiphase flow theory, more sophisticated models have been developed. The Euler-Euler multiphase framework, combined with volume averaging theory, provides a solid theoretical basis for describing the interactions among liquid melt, solid crystals, and inter-dendritic liquid. On this basis, spherical crystal models, dendritic crystal models, and later multi-phase dendrite models have been successively proposed to improve the physical realism of macrosegregation simulations.

In particular, dendritic solidification models that explicitly consider dendrite morphology, permeability evolution, and solute partitioning have demonstrated superior capability in predicting segregation patterns such as A-segregation and negative segregation zones beneath hot tops. Further extensions to three-phase and four-phase models, which incorporate gas phases and shrinkage-induced feeding behavior, have enabled the simultaneous prediction of macrosegregation, shrinkage cavities, and porosity, marking an important milestone in the numerical simulation of ingot solidification.

Control of Macrosegregation and Process Innovation (Chapters 5 - 10)

While numerical models provide powerful insight into the formation mechanisms of macrosegregation, the ultimate goal of research in this field is process control and defect mitigation. Traditional approaches, such as hot tops, electromagnetic stirring, and optimized pouring parameters, have achieved partial success but are often insufficient for ultra-large ingots.

In recent years, layered casting technology has emerged as a promising process innovation for controlling macrosegregation. By dividing the pouring and solidification process into multiple stages, layered casting can effectively modify the thermal field, reduce large-scale melt convection, and suppress solute enrichment and depletion. When combined with advanced concepts such as gradient cooling and low-position pouring, layered casting offers

new degrees of freedom for regulating solidification behavior in large ingots.

However, the industrial application of layered casting still faces challenges related to process optimization, parameter selection, and mechanism understanding. Due to the complexity of the process, experimental trial-and-error alone is insufficient. Therefore, high-fidelity numerical simulations based on advanced multiphase dendritic models are essential for revealing the underlying mechanisms and guiding process design.

Against this background, this work systematically investigates the macrosegregation behavior of large ingots through a combination of advanced numerical modeling and experimental validation. Starting from fundamental theories of fluid mechanics and multiphase flow, a series of progressively refined models-including dendritic solidification models, three-phase and four-phase dendrite models-are developed and applied to ingots of different sizes and alloys.

Special emphasis is placed on the interaction between macrosegregation, shrinkage cavities, and porosity, as well as on the comparative analysis between traditional casting and layered casting processes. Furthermore, innovative layered casting strategies, such as gradient cooling and stepwise gradient cooling methods, are explored for ultra-large steel ingots, aiming to provide practical guidance for industrial production.

Overall, this book not only advances the theoretical understanding of macrosegregation formation mechanisms in large ingots but also demonstrates the potential of combining advanced numerical simulation with innovative casting processes to achieve effective control of internal defects. The results are expected to contribute to the development of high-quality large ingot manufacturing technologies and to provide valuable references for both academic research and industrial applications.