Multi-scale Modeling and Simulation of Low Pressure Die Casting of Aluminum Alloys

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Abstract: Aluminum alloys distinguish themselves through their notable properties, including low weight, robust strength, and versatile formability, which facilitate the production of extensive, intricate, and thin-walled castings using low pressure die casting processes.These distinctive features significantly contribute to the advancement of automotive lightweighting initiatives, which are essential in optimizing fuel consumption and mitigating environmental footprints. This study aims to optimize the low pressure die casting process of Al-Si alloys for automotive components through integrated numerical simulations. A software framework has been developed to couple macro-simulation of mold filling and solidification with microstructural evolution and mechanical property prediction. A novel nucleation model, validated with experimental data, enhances the accuracy of primary phase growth simulations. Models for dendritic and eutectic phase growth are also presented, considering solute diffusion, growth kinetics, and interface anisotropy. This multiscale approach enables the prediction of microstructures and mechanical properties, facilitating the optimization of casting parameters to enhance the final properties of the castings. The results demonstrate the potential to reduce production costs and accelerate the development cycle for aluminum alloy castings.

Keywords: aluminum alloys; simulation; modelling; low pressure die casting

1 Introduction

Al-Si alloys are widely used in the fabrication of complex components in automobiles [1]. Low pressure die casting is a common method for manufacturing aluminum alloy castings. The casting process determines the evolution of microstructures at different scales, which in turn dictates the final mechanical properties of castings (see Figure 1).
Employing numerical simulation to replace the traditional Trial and Error method can optimize the manufacturing process [2].

After decades of development, macro-simulation has matured, with some commercial software being applied in production [3]. However, most commercial software only focuses on mold filling and solidification simulation, and little attention was paid to microstructure and mechanical property prediction [4]. Therefore, through simulation, explaining the relationship between the casting process, microstructure, and properties is a key direction in numerical simulation, which is aimed at optimizing the casting parameters to get better mechanical properties. In this work, we developed software to conduct a coupled study of the casting process, microstructure, and properties, proposing a new casting solution for the development of aluminum alloy castings.

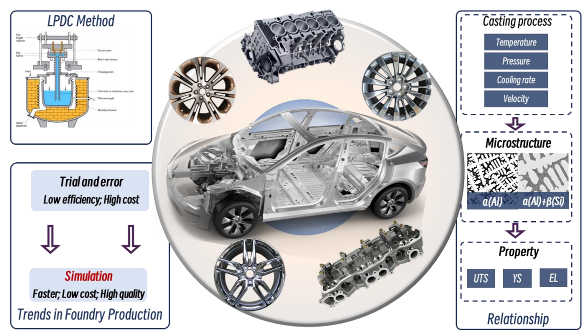

Figure 1 Casting process-structure-property relationship diagram of low pressure die casting of aluminum alloy

2 Mathematical modeling

The physical and mathematical modeling process pertaining to low pressure die casting can be methodically delineated into five interconnected components(see Figure 2). Firstly, the calculation of the solidification path, which lays the foundation for predicting the phase transformation behavior during casting. Secondly, macro-simulation, encompassing the broader-scale phenomena influencing the casting process, such as temperature distributions and fluid flow. Thirdly, the establishment of nucleation models, an important step that governs the initiation of solidification by modeling the formation of crystal nuclei. Fourthly, primary phase growth simulation, focusing on the detailed evolution of the initial solid phase, crucial for understanding microstructure development. Lastly, eutectic phase growth simulation, addressing the simultaneous growth of multiple phases, often occurring at eutectic temperatures, which is instrumental in refining the final microstructure and properties of the casting. This segmented approach ensures a comprehensive and accurate portrayal of the low pressure die casting process, facilitating process optimization and the production of high-quality castings.

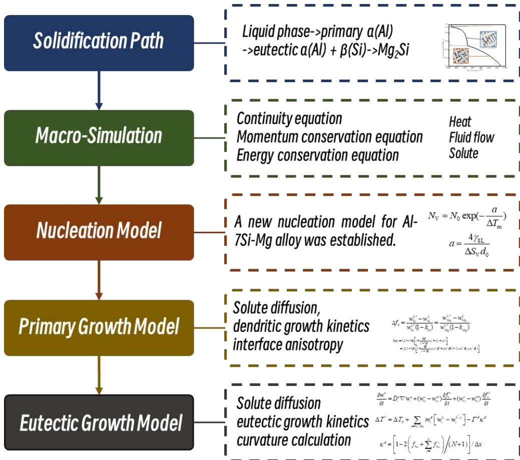

Figure 2 Mathematical modeling of low pressure die casting

3 Result and discussion

The mold filling and solidification processes of step casting were simulated. Temperature changes were acquired by inserting thermocouples at the center of each step. Subsequently, dendrite growth on the step casting, coupled with the macro-simulation, was simulated in both two and three dimensions. Given that different steps correspond to varying solidification conditions, the final dendrite microstructure was derived from these simulations.

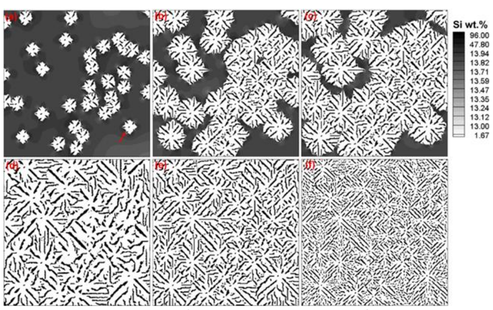

Figure 3 Dendrite growth for steps obtained from simulation and experiment

The evolution of unmodified and Strontium-modified Al-Si eutectic alloys was simulated by us under varying degrees of undercooling (see Figure 3). During the growth process, the eutectic colonies emerged in a nearly spherical form, with the two eutectic phases alternating in their growth patterns.

4 Conclusion

In conclusion, this study presents a novel casting methodology that significantly advances the current practices in the field. By developing a comprehensive nucleation model tailored specifically for Al-Si-Mg alloys and experimentally determining the crucial parameters, we have gained a deeper understanding of the underlying mechanisms governing alloy solidification. This model enabled the simulation of both the primary and eutectic phases of the aluminum alloy, which were seamlessly integrated with macro-scale simulation results, fostering a holistic view of the casting process.

Furthermore, we propose an innovative casting solution that harmoniously incorporates casting process dynamics, microstructural evolution, and material properties, thereby offering a robust framework for optimizing casting procedures and ensuring the production of defect-free castings. The practical application of this research to critical automotive components manufactured by Dicastal Company underscores its potential to revolutionize casting process optimization, leading to enhanced productivity and efficiency in industrial settings. In essence, this work represents a pivotal step forward in the development of advanced casting technologies, paving the way for future advancements in materials science and engineering.

5 Acknowledgments

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